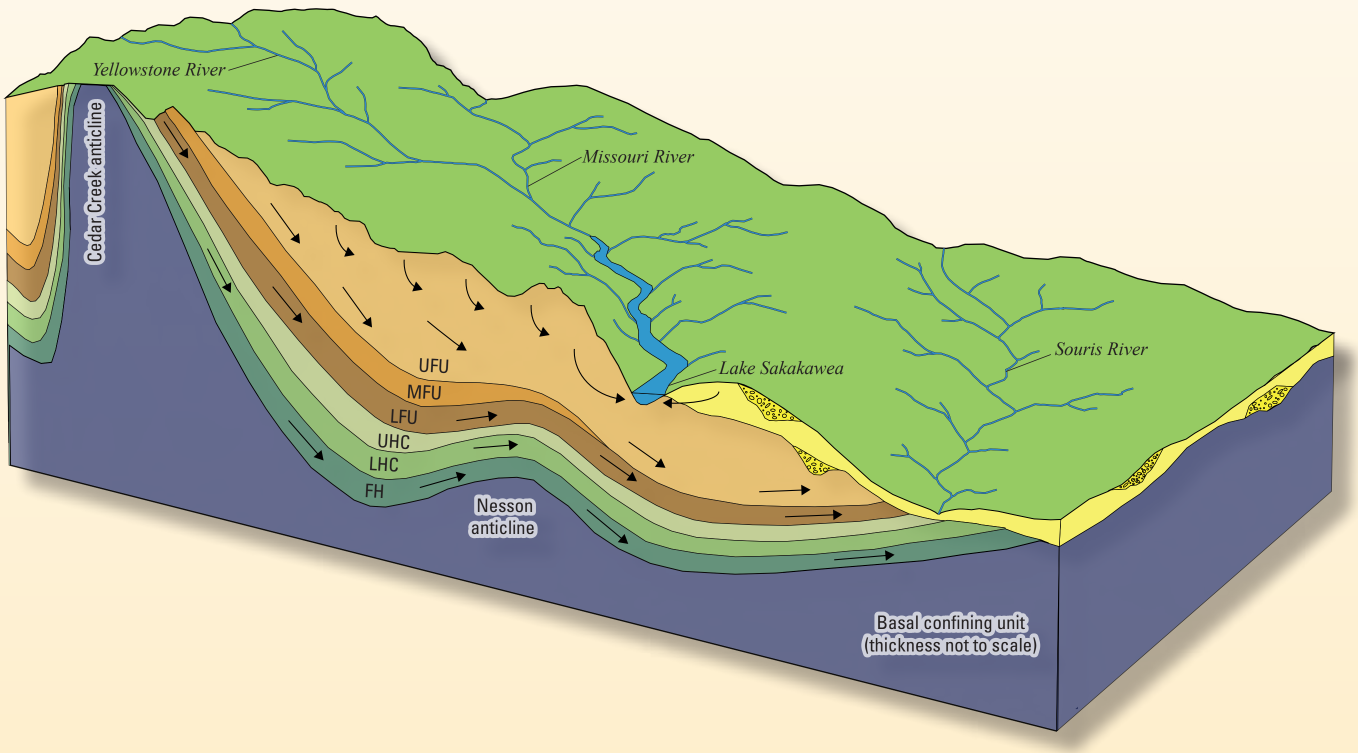
Groundwater Resources Program

Conceptual Model of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada



Scientific Investigations Report 2014–5055

U.S. Department of the Interior
U.S. Geological Survey

Cover. Conceptual block diagram of groundwater flow in the Williston structural basin.

Conceptual Model of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada

By Andrew J. Long, Katherine R. Aurand, Jennifer M. Bednar, Kyle W. Davis, Jonathan D.R.G. Mckaskey, and Joanna N. Thamke

Groundwater Resources Program

Scientific Investigations Report 2014–5055

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Long, A.J., Aurand, K.R., Bednar, J.M., Davis, K.W., Mckaskey, J.D.R.G., and Thamke, J.N., 2014, Conceptual model of the uppermost principal aquifer systems in the Williston and Powder River structural basins, United States and Canada: U.S. Geological Survey Scientific Investigations Report 2014–5055, 41 p., with appendix, *http://dx.doi.org/10.3133/sir20145055*.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank Jon Reiten and Kevin Chandler of the Montana Bureau of Mines and Geology; Alan Wanek and Kimberly Fischer of the North Dakota State Water Commission (NDSWC); and Tom Wood, Mitch Plummer, and Luanjing Guo of Idaho National Laboratories for their participation in bimonthly technical conference calls to discuss and provide their insights about the principal aquifers in the Williston structural basin. Michael Swenson of the U.S. Army Corps of Engineers provided reservoir data and other useful information. Cory Hein of the Water Survey Division of Environment Canada assisted in obtaining, formatting, and explaining data from Canadian databases. We thank Ed Heffern (Bureau of Land Management, retired) for sharing his knowledge, advice, and data regarding clinker deposits. Fred Anderson of the North Dakota Geological Survey assisted in gathering geologic information. Kei Lo of the Saskatchewan Water Security Agency provided insights and publications regarding the glacial geology of Saskatchewan.

The work in this report was supported by the U.S. Geological Survey (USGS) Groundwater Resources Program. Paul Barlow of the USGS is thanked for guidance and assistance in resolving issues concerning the interaction of groundwater and surface water. We thank Donald Rosenberry (USGS) for his knowledge and willingness to assist with this study. Al Rutledge (USGS, retired) assisted in understanding the PART software program. Special thanks are extended to Steve Westenbroek, Jared Trost, Tim Cowdery, and Mark Nardi (USGS) for assistance with the soil-water-balance (SWB) model. Rick Healy and Geoff Delin (USGS) provided guidance with the local recharge-estimation methods. David Blodgett (USGS) helped with the Geo Data Portal. Sincere appreciation goes to Kimberly Fischer (NDSWC) and Bryant Jurgens (USGS) for their insightful colleague reviews of this report. Finally, the work in this report is the product of a USGS team effort that included many individuals, specifically, Gary Lecain, Derek Ryter, T. Roy Sando, Timothy Bartos, Diane Rauch, Adel (Eddie) Haj, Joshua Valder, Curtis Price, Mark Mayfield, and Melissa Heron.

Contents

Figures

Appendix Figures

Tables

Appendix Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

®	registered trademark
CMB	chloride mass balance
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
SWB	soil-water balance
USGS	U.S. Geological Survey
WTF	water-table fluctuation

Conceptual Model of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada

By Andrew J. Long, Katherine R. Aurand, Jennifer M. Bednar, Kyle W. Davis, Jonathan D.R.G. Mckaskey, and Joanna N. Thamke

Abstract

The three uppermost principal aquifer systems of the Northern Great Plains—the glacial, lower Tertiary, and Upper Cretaceous aquifer systems—are described in this report and provide water for irrigation, mining, public and domestic supply, livestock, and industrial uses. These aquifer systems primarily are present in two nationally important fossil-fuel-producing areas: the Williston and Powder River structural basins in the United States and Canada. The glacial aquifer system is contained within glacial deposits that overlie the lower Tertiary and Upper Cretaceous aquifer systems in the northeastern part of the Williston structural basin. Productive sand and gravel aquifers exist within this aquifer system. The Upper Cretaceous aquifer system is contained within bedrock lithostratigraphic units as deep as 2,850 and 8,500 feet below land surface in the Williston and Powder River structural basins, respectively. Petroleum extraction from much deeper formations, such as the Bakken Formation, is rapidly increasing because of recently improved hydraulic fracturing methods that require large volumes of relatively freshwater from shallow aquifers or surface water. Extraction of coal-bed natural gas from within the lower Tertiary aquifer system requires removal of large volumes of groundwater to allow degasification.

Recognizing the importance of understanding water resources in these energy-rich basins, the U.S. Geological Survey (USGS) Groundwater Resources Program (*http://water.usgs.gov/ogw/gwrp/*) began a groundwater study of the Williston and Powder River structural basins in 2011 to quantify this groundwater resource, the results of which are described in this report. The overall objective of this study was to characterize, quantify, and provide an improved conceptual understanding of the three uppermost and principal aquifer systems in energy-resource areas of the Northern Great Plains to assist in groundwater-resource management for multiple uses.

The study area includes parts of Montana, North Dakota, South Dakota, and Wyoming in the United States and Manitoba and Saskatchewan in Canada. The glacial aquifer system is contained within glacial drift consisting primarily of till, with smaller amounts of glacial outwash sand and gravel deposits. The lower Tertiary and Upper Cretaceous aquifer systems are contained within several formations of the Tertiary and Cretaceous geologic systems, which are hydraulically separated from underlying aquifers by a basal confining unit. The lower Tertiary and Upper Cretaceous aquifer systems each were divided into three hydrogeologic units that correspond to one or more lithostratigraphic units.

The period prior to 1960 is defined as the predevelopment period when little groundwater was extracted. From 1960 through 1990, numerous flowing wells were installed near the Yellowstone, Little Missouri and Knife Rivers, resulting in local groundwater declines. Recently developed technologies for the extraction of petroleum resources, which largely have been applied in the study area since about 2005, require millions of gallons of water for construction of each well, with additional water needed for long-term operation; therefore, the potential for an increase in groundwater extraction is high. In this study, groundwater recharge and discharge components were estimated for the period 1981–2005.

Groundwater recharge primarily occurs from infiltration of rainfall and snowmelt (precipitation recharge) and infiltration of streams into the ground (stream infiltration). Total estimated recharge to the Williston and Powder River control volumes is 4,560 and 1,500 cubic feet per second, respectively. Estimated precipitation recharge is 26 and 15 percent of total recharge for the Williston and Powder River control volumes, respectively. Estimated stream infiltration is 71 and 80 percent of total recharge for the Williston and Powder River control volumes, respectively. Groundwater discharge primarily is to streams and springs and is estimated to be about 97 and 92 percent of total discharge for the Williston and Powder River control volumes, respectively. Most of the remaining discharge results from pumped and flowing wells.

Groundwater flow in the Williston structural basin generally is from the west and southwest toward the east, where discharge to streams occurs. Locally, in the uppermost hydrogeologic units, groundwater generally is unconfined and flows from topographically high to low areas, where discharge

to streams occurs. Groundwater flow in the Powder River structural basin generally is toward the north, with local variations, particularly in the upper Fort Union aquifer, where flow is toward streams.

Introduction

The lower Tertiary and Upper Cretaceous aquifer systems are principal aquifer systems of the Northern Great Plains (Whitehead, 1996; Reilly and others, 2008) and primarily are present in two nationally important fossil-fuel-producing areas: the Williston and Powder River structural basins (fig. 1). A glacial aquifer system, composed of sand and gravel aquifers, is a third principal aquifer system that overlies parts of the lower Tertiary and Upper Cretaceous aquifer systems. These three uppermost principal aquifer systems provide water for irrigation, mining, public and domestic supply, livestock, and industrial uses. Development of new technologies for the extraction of energy resources has resulted in increased demand for relatively freshwater (Schuh, 2010), particularly since about 2005 (Anna and others, 2011); therefore, the potential for increases in water extraction from these three aquifer systems is high. Although numerous water-production wells have been installed since about 1960, the largest increases in withdrawals have coincided with increased extraction of energy resources. The predevelopment period is considered to be prior to 1960, and groundwater recharge and discharge components were estimated for the period 1981–2005.

The Williston and Powder River structural basins consist of lithostratigraphic units of the Paleozoic, Mesozoic, and Cenozoic eras that overlie Precambrian rocks (Sandberg, 1962; Downey, 1986; Downey and Dinwiddie, 1988; Dolton and others, 1990). The lower Tertiary and Upper Cretaceous aquifer systems are the uppermost bedrock aquifers in these structural basins and are contained within the upper part of the Northern Great Plains aquifer system described by Whitehead (1996). In the Williston structural basin, these aquifer systems primarily are present in North Dakota and Montana and are present in smaller areas of South Dakota, Saskatchewan, and Manitoba; in the Powder River structural basin, these aquifer systems are present in Wyoming and Montana (fig. 2). Glacial deposits overlie the lower Tertiary and Upper Cretaceous aquifer systems in the northeastern part of the Williston structural basin (fig. 2). Sand and gravel aquifers within these deposits compose a principal aquifer system described by Whitehead (1996) that hereafter is referred to as the glacial aquifer system. This aquifer system provides most of the total groundwater supply in North Dakota, and the lower Tertiary and Upper Cretaceous aquifer systems provide the second largest groundwater supply in this State (Carr and others, 1990). The Upper Cretaceous aquifer system overlies the Lower Cretaceous and Paleozoic aquifer systems (Whitehead, 1996), the latter being more than 18,000 feet (ft) deep in the study area (Dolton, 1990). The Upper Cretaceous aquifer system is as deep as 2,850 and 8,500 ft in the Williston and Powder River structural basins, respectively (Thamke and others, 2014).

Extraction of fossil fuels can affect groundwater availability in these three principal aquifer systems. The Williston structural basin has been a major petroleum and natural-gas producing region in the United States for more than one-half century (Anna and others, 2011). To meet current and future energy needs, petroleum extraction from deep formations, such as the Bakken and Three Forks Formations (Gaswirth and others, 2013), is rapidly increasing, particularly since about 2005, because of recently improved hydraulic fracturing methods that allow extraction from shale formations that previously were inaccessible. Large volumes of water from shallow aquifers or surface water are required for drilling fluid (133,000 gallons per well), mixing concrete for surface casing, hydraulic fracturing (1.5–4 million gallons per well), secondary recovery processes, general operation, petroleum refining, and brine dilution (Schuh, 2010). About 10 percent of petroleum-producing wells require freshwater (526,000 gallons per year per well) to dilute salt-saturated brine entrained with produced oil to prevent accumulation of salt on the well workings (Schuh, 2010; Fischer, 2013). Other potential sources of fossil fuel in the Williston structural basin include coal and coal-bed natural gas. In North Dakota, synthetic gas, or syngas, is produced from lignite, a type of soft coal (Schuh, 2010). These resources are present primarily within lithostratigraphic units that contain parts of the lower Tertiary and Upper Cretaceous aquifer systems. Coal extraction commonly requires strip mining that removes large volumes of the host rock and aquifer material. Coalbed natural-gas extraction requires removal of substantial volumes of groundwater to allow degasification. For example, McLaughlin and others (2012) described the decline in hydraulic head from 2006 to 2009 in the lower Tertiary aquifer system in the Powder River structural basin that resulted from the extraction of coal-bed natural gas.

Petroleum and coal have been extracted from the Powder River structural basin since the 1880s (Beikman, 1962; Flores and Bader, 1999). Prior to 1960, the cumulative production of petroleum from this basin constituted about one-half of the total produced from Wyoming and more than that produced from any other structural basin in the Rocky Mountain region (Beikman, 1962). In the mid-1960's, coal production from the Powder River structural basin expanded in response to the demands of newly built coal-fired powerplants that required high-quality coal to meet emission standards (Flores and Bader, 1999). The onset of coal-bed natural-gas production in the Powder River structural basin began during the late 20th century (Flores and others, 2010).

Recognizing the importance of understanding water resources in these energy-rich basins, the U.S. Geological Survey (USGS) Groundwater Resources Program (*http://water.usgs.gov/ogw/gwrp/*) began a groundwater study of the Williston and Powder River structural basins in 2011 to quantify this groundwater resource, the results of which are described in this report. This study is one component of a large effort by

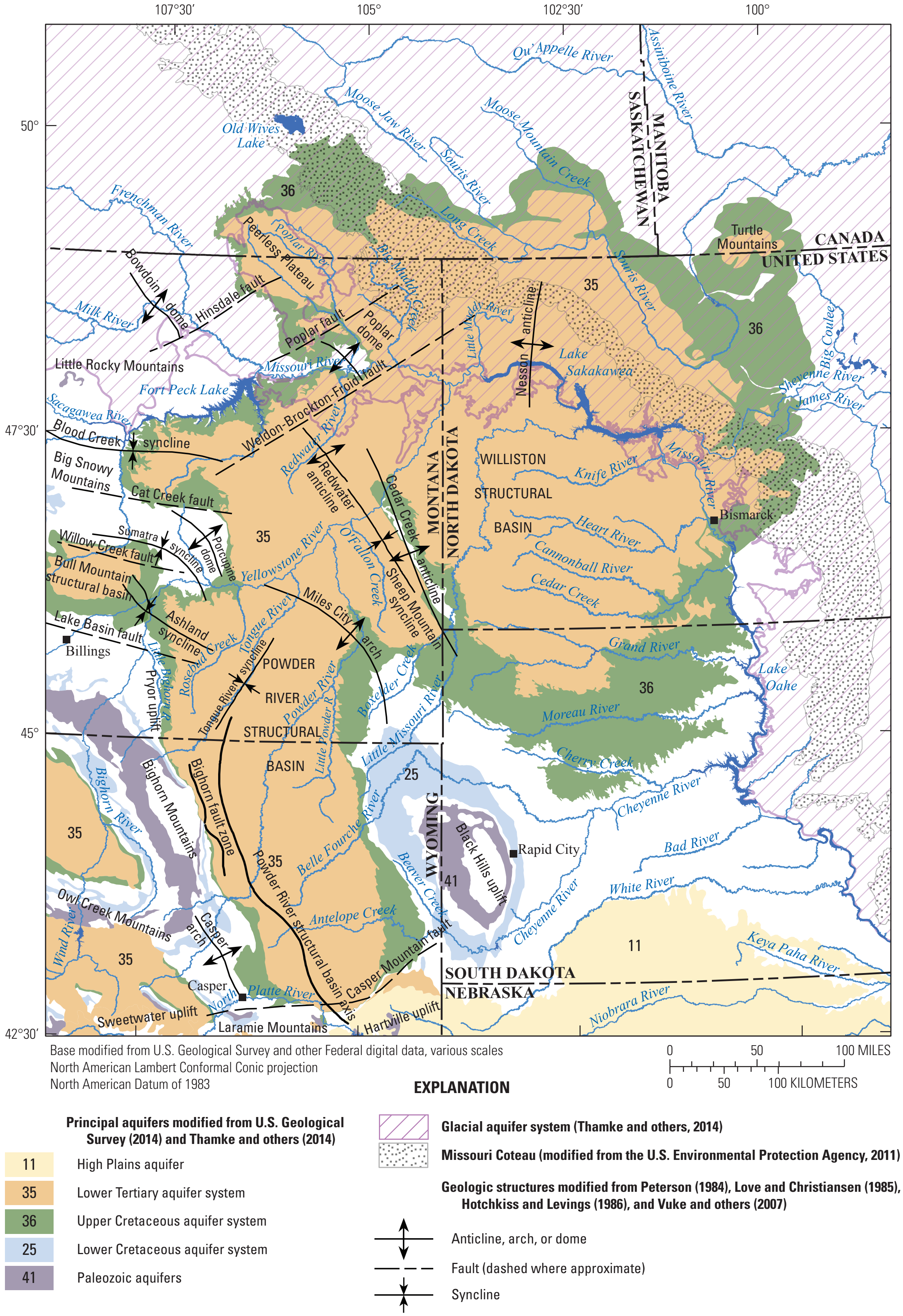


Figure 1. Study area and principal aquifer systems of the Northern Great Plains that are exposed at the land surface or covered by the overlying glacial aquifer system (modified from Thamke and others, 2014).

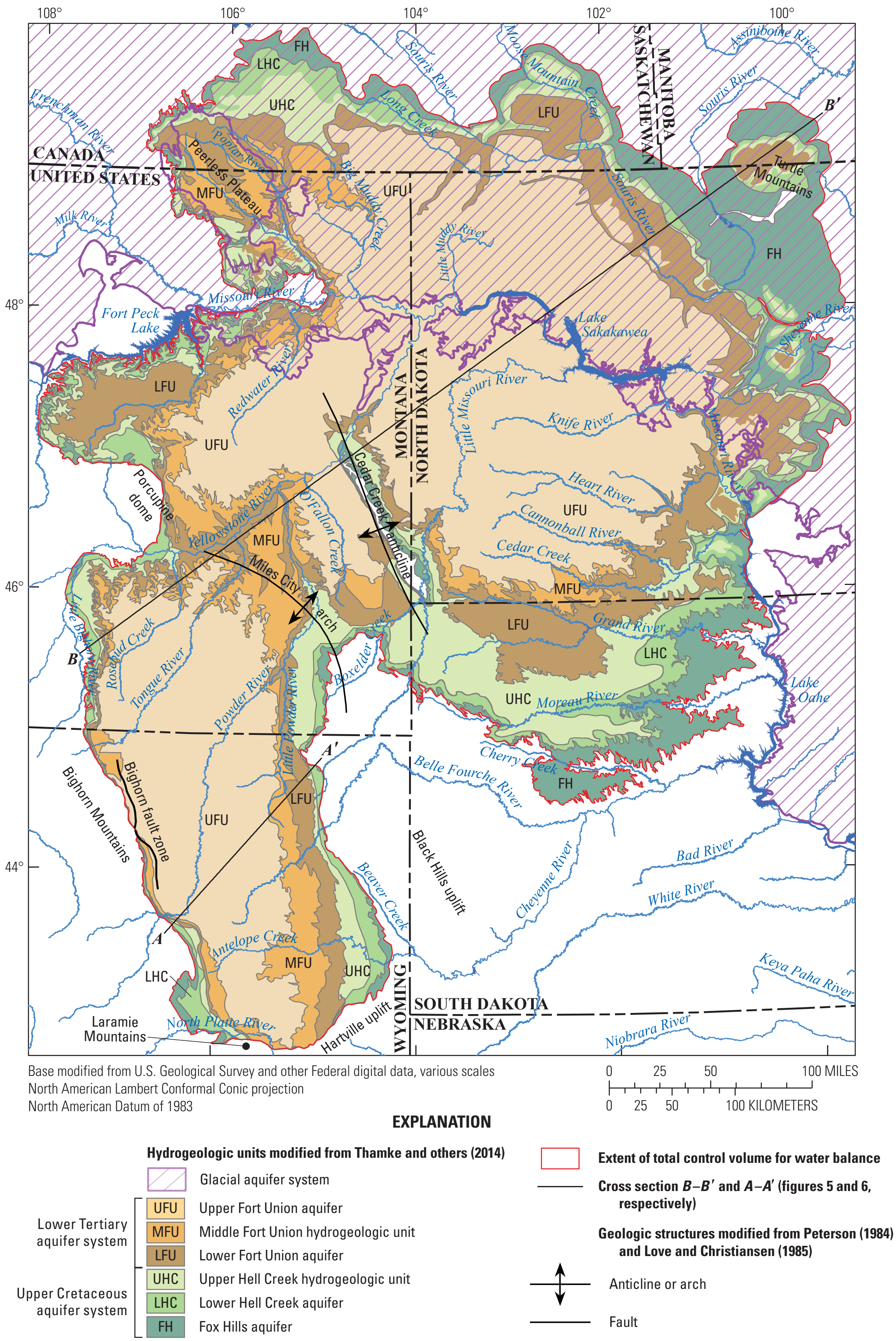


Figure 2. Outcrops or subcrops (underlying the glacial aquifer system) of hydrogeologic units of the lower Tertiary and Upper Cretaceous aquifer systems in the Northern Great Plains.

the Groundwater Resources Program to assess the Nation's groundwater availability. The overall objective of this study was to characterize, quantify, and provide an improved conceptual understanding of the three uppermost principal aquifer systems in energy-resource areas of the Northern Great Plains to assist in groundwater-resource management for multiple uses.

Purpose and Scope

This report describes a conceptual model for the three uppermost principal aquifer systems in the Williston and Powder River structural basins in the United States and Canada, consisting of an assessment of groundwater resources for 1981–2005. This conceptual model provides a basis on which to characterize system response to future anthropogenic and environmental stresses. Described in this report is a characterization of groundwater flow and an estimation of groundwater recharge and discharge for the three uppermost principal aquifer systems. The information in this report, together with a description of the hydrogeologic framework of the same three principal aquifer systems (Thamke and others, 2014), could be used to construct a numerical groundwater-flow model to test aquifer stresses, such as the effects of changes in water use and climate.

Previous Investigations

Principal aquifers of the Northern Great Plains, including the lower Tertiary and Upper Cretaceous aquifer systems, were described and characterized by Whitehead (1996). Lewis and Hotchkiss (1981) estimated the thickness, percentage of sand, and altitudes of four hydrogeologic units within the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin. Downey and Dinwiddie (1988) provided an overview of hydrogeologic units in the Williston structural basin that are contained within formations of the Paleozoic, Mesozoic, and Cenozoic eras. Lobmeyer (1985) described groundwater temperatures and potentiometric surfaces of the lower Tertiary and Upper Cretaceous aquifer systems. Thamke and others (2014) described and created digital maps for the hydrogeologic framework and hydraulic conductivity for the glacial aquifer system and hydrogeologic units within the lower Tertiary and Upper Cretaceous aquifer systems and potentiometric surfaces for the lower Tertiary and Upper Cretaceous aquifer systems. Digital and printed maps of principal aquifers of the United States also are available (U.S. Geological Survey, 2014).

Several investigators have provided hydrologic characterization of the lower Tertiary and Upper Cretaceous aquifer systems through numerical simulation of groundwater flow. Koch and others (1982) and Peacock (1997) simulated shallow regional groundwater flow for the Powder River structural basin to assess possible effects of surface coal mining and coalbed-methane extraction. Hotchkiss and Levings (1986) simulated groundwater flow in the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin and estimated transmissivity for these aquifers on the basis of geophysical borehole logs. Downey (1986) simulated groundwater flow in the Upper Cretaceous aquifer system in the Williston and Powder River structural basins. Anna (2011) simulated groundwater flow in the Fox Hills aquifer in the northwestern part of the Williston structural basin. Fischer (2013) simulated groundwater flow in the Hell Creek and Fox Hills aquifers in the central part of the Williston structural basin.

Description of Study Area

The study area includes the three uppermost principal aquifer systems in the Williston and Powder River structural basins: the glacial, lower Tertiary, and Upper Cretaceous aquifer systems (fig. 2; Whitehead, 1996). The topography is characterized by low relief or gently rolling hills, except near large river channels with steep banks. Surficial glacial deposits are present in the northern part of the Williston structural basin (fig. 2). The Missouri Coteau (fig. 1) primarily consists of glacial till and outwash, where the till is characterized by a hummocky knob-and-kettle topography abounding in prairie potholes and lacking an integrated drainage pattern (Eisenlohr and Sloan, 1968). Underlying these glacial deposits, or exposed at the land surface where glacial deposits are absent, are sedimentary rocks composed primarily of sandstone, coal, and shale. Large river systems, such as those of the Missouri and Yellowstone Rivers, erode the semi-consolidated sedimentary rocks and create several hundred feet of local topographic relief. The climate is semiarid. In the Williston structural basin, precipitation ranges from about 11 inches per year (in/yr) in the western part to 22 in/yr in the eastern part; in the Powder River structural basin, precipitation ranges from about 11 to 19 in/yr (Thornton and others, 1997, 2012; fig. 1–1, appendix). Pasture and hayland exist in 70 percent of the study area (Multi-Resolution Land Characteristics Consortium, 2011). Fort Peck Lake, Lake Sakakawea, and Lake Oahe are large reservoirs in the study area that control flow in the Missouri River (fig. 2).

In the Williston structural basin, the Missouri River flows toward the east and southeast, with the Yellowstone and Little Missouri Rivers entering from the south (fig. 2). Several other tributaries in the southeastern part of the Williston structural basin flow easterly and enter the Missouri River from the west. Streams south of the Missouri Coteau (fig. 1) flow into the Missouri River from the north. Streams north of the Missouri Coteau generally flow southeasterly, except for parts of the Souris River that flows northerly near the Turtle Mountains. Few streams cross the Missouri Coteau because of its nonintegrated drainage pattern (fig. 1). The Tongue and Powder Rivers are large streams in the Powder River structural basin that originate within or near the Bighorn Mountains and flow northeasterly into the Williston structural basin; the Belle

Fourche River flows northeasterly out of the Powder River structural basin and to the north of the Black Hills uplift; and Antelope Creek flows easterly out of the Powder River structural basin, where it joins the Cheyenne River near the southern Black Hills uplift (fig. 2).

Hydrogeologic Setting

The glacial aquifer system overlies the lower Tertiary and Upper Cretaceous aquifer systems in the northeastern part of the Williston structural basin, primarily north of the Missouri River (fig. 2). The lower Tertiary and Upper Cretaceous aquifer systems are contained within lithostratigraphic units of Tertiary and Upper Cretaceous ages (figs. 3 and 4). Underlying these aquifers are lithostratigraphic units of the Mesozoic and Paleozoic eras that are more than 16,000 ft deep in the Williston structural basin (fig. 4; Downey and Dinwiddie, 1988) and more than 18,000 ft deep in the Powder River structural basin (Dolton, 1990). The petroleum-rich Bakken and Three Forks Formations, more than 10,000 ft deep in some places, are at or below the base of Mississippian rocks (fig. 4).

Lithology

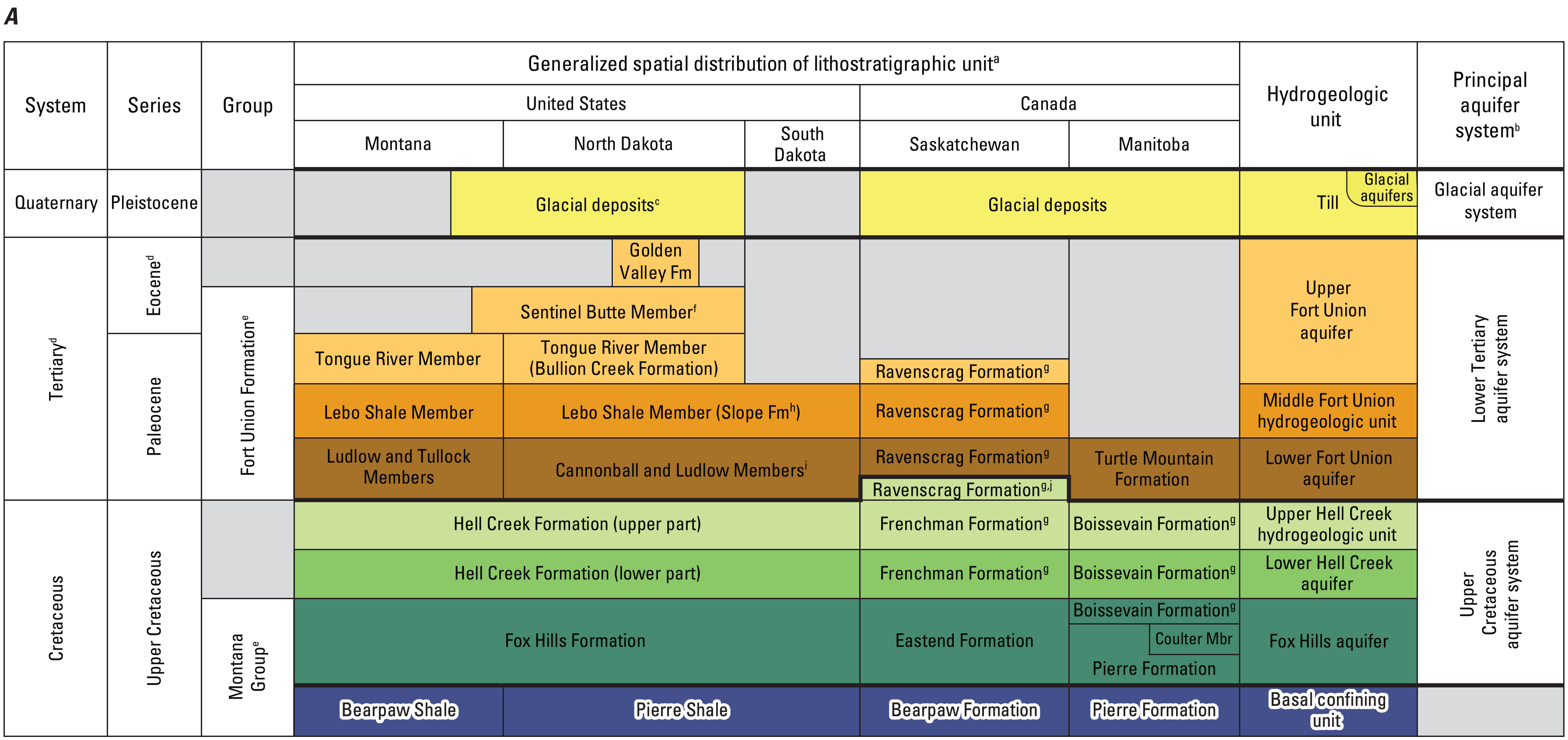
Glacial deposits of the Pleistocene series in the Williston structural basin are composed of till and glacial outwash sands and gravels and are underlain by the Golden Valley and Fort Union Formations of the Tertiary geologic system (fig. 3*A*). The lithology of the lower Tertiary and Upper Cretaceous lithostratigraphic units is described in detail by Thamke and others (2014) and is summarized in this section of the report. The Fort Union Formation extends throughout most of the two structural basins and is overlain by the Golden Valley Formation in North Dakota and by the Wasatch Formation in Wyoming and Montana (figs. 3*A and* 3*B*). The Fort Union Formation comprises several lithostratigraphic units in the two structural basins in the United States but is not recognized as a lithostratigraphic name in Canada (fig. 3*A*).

Some of the lithostratigraphic units in Canada do not correspond laterally to those in the United States because of inconsistencies between the United States and Canada in the way that vertical sequences of strata were assigned to formally named formations. The upper part of the Ravenscrag Formation in Saskatchewan is lithostratigraphically equivalent to the lower part of the Fort Union Formation in the United States (fig. 3*A*). The lower part of the Ravenscrag Formation and upper part of the Frenchman Formation in Saskatchewan are lithostratigraphically equivalent to the upper parts of the Hell Creek and Boissevain Formations in the United States and Manitoba, which are part of the Cretaceous geologic system; however, the entire Ravenscrag Formation is considered by Saskatchewan geologists to be part of the Tertiary geologic system (fig. 3*A*). This apparent inconsistency could have resulted from lithostratigraphic units crossing geologic-age categories or because of differing opinions among geologists. Other lithostratigraphic units of the Upper Cretaceous series are shown in figure 3.

The Fort Union Formation and equivalent units in Canada contain alternating beds of sandstone, siltstone, shale, and coal. Thick coal seams interbedded with sandstone or fine-grained sediments can have fractures and bedding planes that store and transmit groundwater. Depositional environments for the Fort Union Formation include fluvial, deltaic, tidal, barrier-shoreface, and marine settings (Flores and others, 1999). These depositional environments have resulted in complex interbedding of low-permeability layers of discontinuous lateral extent. The Hell Creek and Lance Formations and equivalent units in Canada (fig. 3) contain sandstone, siltstone, and shale (Murphy and others, 2009; Thamke and others, 2014). The Fox Hills Sandstone and equivalent units in Canada contain poorly cemented to well-cemented sandstone, siltstone, and mudstone (Murphy and others, 2009; Thamke and others, 2014). Detailed geologic descriptions of lithostratigraphic units shown in figure 3 are in Bluemle (1983), Love and Christiansen (1985), Macdonald and Slimmon (1999), Martin and others (2004), Vuke (2007), Murphy and others (2009), Nicolas and others (2010), North Dakota Water Commission (2013a), and Thamke and others (2014).

Hydrogeologic Units

The surficial geology of the northeastern part of the Williston structural basin is dominated by glacial deposits called drift, which contains the glacial aquifer system and overlies parts of the lower Tertiary and Upper Cretaceous aquifer systems (fig. 2). The areal extent of the glacial aquifer system was defined by Thamke and others (2014) and does not include areas where glacial deposits are thin or discontinuous. The spatial distribution of different types of glacial drift is shown in figure 1–1, as indicated by the hydrologic soil groups. Till consists of all material deposited directly by a glacier that is not reworked by meltwater. Although till may consist of clay, silt, sand, cobbles, and boulders, the permeability generally is determined by the clay and silt because these compose the till's matrix. The sand and gravel deposits within the glacial drift contain productive aquifers that are separated by low permeability till and exist either at the land surface (glaciofluvial hydrologic soil group, figure 1-1) or buried beneath the till. These aquifers, including some that are buried, were mapped in North Dakota (North Dakota Water Commission, 2013b) indicating that till is the dominant medium and that sand and gravel aquifers occupy only a small percentage of the glacial drift. Where till overlies the lower Tertiary and Upper Cretaceous aquifer systems, it acts as an upper confining unit for these aquifer systems. Sand and gravel aquifers directly overlying the lower Tertiary and Upper Cretaceous aquifer systems may be hydraulically connected to these aquifer systems. In this report, the glacial aquifer system is defined as that which occupies the full thickness of the glacial drift, which includes



[a] Spatial distribution of lithostratigraphic units from Bluemle (1983); Love and Christiansen (1985); Macdonald and Slimmon (1999); Martin and others (2004); Vuke and others (2007); Murphy and others (2009); and Nicolas and others (2010).

[b] Whitehead (1996).

[c] Generally located north of the Missouri River.

[d] Upper Tertiary units (Pliocene, Miocene, and Oligocene) exist only in a small part of study area and are not included in this study.

[e] This name applies only in the United States.

[f] Present in central part of Williston structural basin and a small contiguous area in Montana. Eocene Golden Valley Member also is present in local areas.

[g] Divided formation to correspond to hydrogeologic units in this regional study.

[h] Pinches out north of the Missouri River. Mapped as Tongue River Formation in South Dakota by Martin and others (2004).

[i] Cannonball Member present in the southern and eastern parts of the Williston structural basin. Slope Member is above the Cannonball Member in southern North Dakota. Ludlow Member is present in the southern part of North Dakota.

[j] Lower Ravenscrag Formation is part of the Upper Hell Creek hydrogeologic unit but is part of the Tertiary System.

EXPLANATION

Fm **Formation**

Mbr **Member**

Figure 3. Lithostratigraphic and corresponding hydrogeologic units in *A*, the Williston structural basin and *B*, the Powder River structural basin (from Thamke and others, 2014). Bold lines separate aquifer systems, and colors separate hydrogeologic units. Some lithostratigraphic units are split between two or more hydrogeologic units, as indicated by these colors.

B

System	Series	Group	Generalized spatial distribution of lithostratigraphic unit[a]		Hydrogeologic unit		Principal aquifer system[b]
			Wyoming	Montana	Names from previous studies[c]	Names used in this study	
Tertiary[d]	Eocene[d]		Wasatch Formation	Wasatch Formation	Tongue River aquifer	Upper Fort Union aquifer	Lower Tertiary aquifer system
Tertiary[d]	Paleocene	Fort Union Formation	Tongue River Member	Tongue River Member	Tongue River aquifer	Upper Fort Union aquifer	Lower Tertiary aquifer system
Tertiary[d]	Paleocene	Fort Union Formation	Lebo Shale Member	Lebo Shale Member	Lebo confining unit	Middle Fort Union hydrogeologic unit	Lower Tertiary aquifer system
Tertiary[d]	Paleocene	Fort Union Formation	Tullock Member	Tullock Member	Tullock aquifer	Lower Fort Union aquifer	Lower Tertiary aquifer system
Cretaceous	Upper Cretaceous		Lance Formation (upper part)	Hell Creek Formation (upper part)	Upper Hell Creek confining unit	Upper Hell Creek hydrogeologic unit	Upper Cretaceous aquifer system
Cretaceous	Upper Cretaceous		Lance Formation (lower part)	Hell Creek Formation (lower part)	Fox Hills–Lower Hell Creek aquifer	Lower Hell Creek aquifer	Upper Cretaceous aquifer system
Cretaceous	Upper Cretaceous	Montana Group	Fox Hills Formation	Fox Hills Formation	Fox Hills–Lower Hell Creek aquifer	Fox Hills aquifer	Upper Cretaceous aquifer system
Cretaceous	Upper Cretaceous	Montana Group	Pierre Shale; Lewis Shale	Bearpaw Shale	Basal confining unit	Basal confining unit	

[a] Spatial distribution of lithostratigraphic units from Love and Christiansen (1985) and Vuke and others (2007).

[b] Whitehead (1996).

[c] From Lewis and Hotchkiss (1981) and Hotchkiss and Levings (1986).

[d] Upper Tertiary units (Pliocene, Miocene, and Oligocene) represent a small part of study area and are not included in this study.

Figure 3. Lithostratigraphic and corresponding hydrogeologic units in *A*, the Williston structural basin and *B*, the Powder River structural basin (from Thamke and others, 2014). Bold lines separate aquifer systems, and colors separate hydrogeologic units. Some lithostratigraphic units are split between two or more hydrogeologic units, as indicated by these colors.—Continued

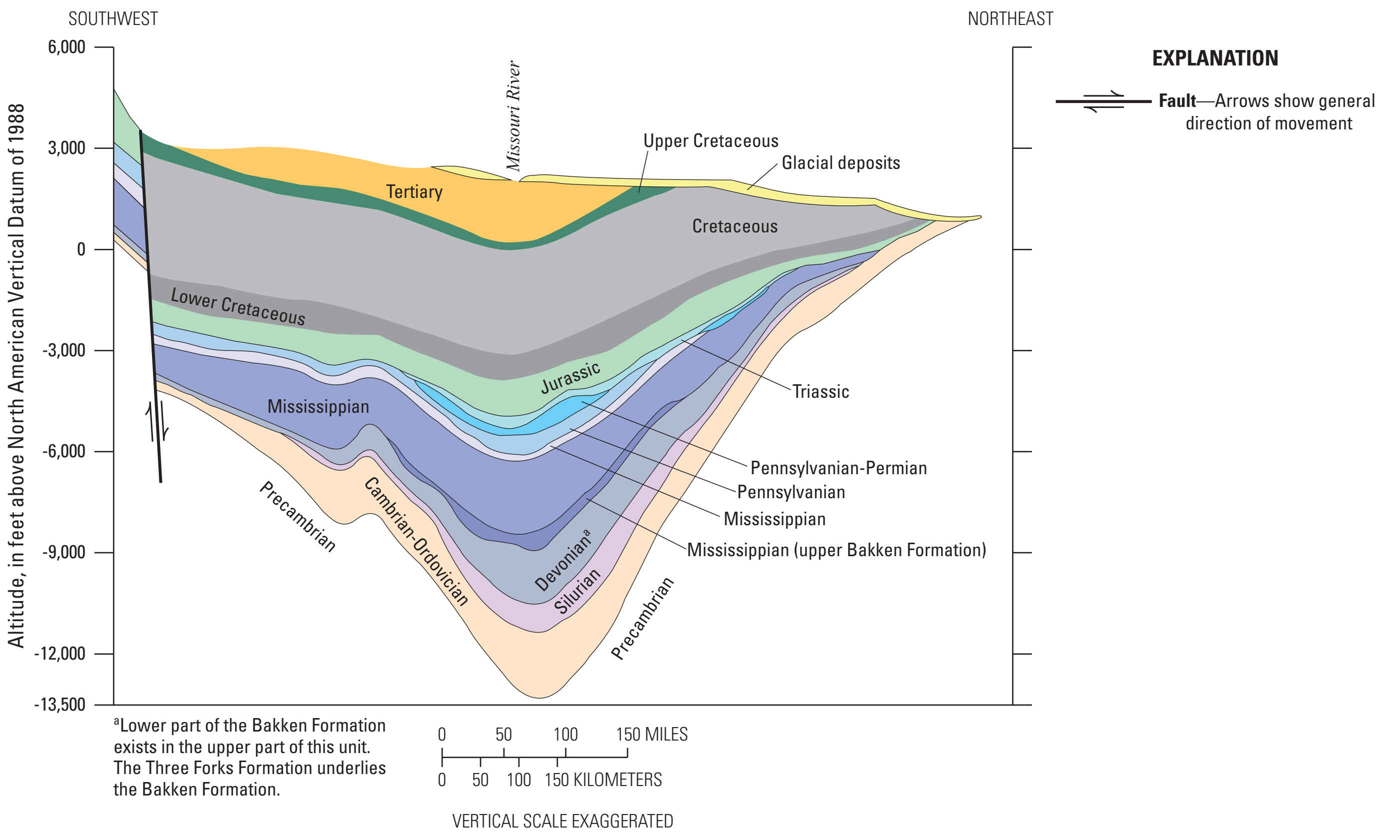


Figure 4. Generalized southwest-northeast cross section of the Williston structural basin showing lithostratigraphic units with geologic periods (modified from fig. 4 in Downey and Dinwiddie, 1988).

sand and gravel aquifers and till. The glacial aquifer system in the study area ranges in thickness from 0 to 756 ft (table 1, fig 1–1).

Thamke and others (2014) described the lower Tertiary and Upper Cretaceous aquifer systems for the United States and Canada (fig. 3), which is summarized in this section of the report. The lower Tertiary aquifer system in the two structural basins is contained within the Fort Union and Wasatch Formations in the United States and equivalent formations in Canada (fig. 3). The Upper Cretaceous aquifer system is contained within formations of the Upper Cretaceous geologic series that overlie the basal confining unit, which consists of the Pierre, Bearpaw, and Lewis Shales in the United States and the Pierre and Bearpaw Formations in Canada (fig. 3). The lower Tertiary and Upper Cretaceous aquifer systems consist of six hydrogeologic units that correspond to lithostratigraphic units defined in the United States (fig. 3). Hydrogeologic units previously defined for the Powder River structural basin by Lewis and Hotchkiss (1981) and Hotchkiss and Levings (1986) were redefined herein so that the unit names would be consistent throughout the entire study area (fig. 3*B*). In cases where Canadian lithostratigraphic units do not correspond to those of the United States, they were assigned to hydrogeologic units by separating them so that hydrogeologic units would be stratigraphically consistent and continuous across the international border (Thamke and others, 2014). For example, the upper part of the Frenchman Formation in Saskatchewan was assigned to the upper Hell Creek hydrogeologic unit, and the lower part of the formation was assigned to the lower Hell Creek aquifer (fig. 3*A*). The lower Tertiary and Upper Cretaceous aquifer systems are as thick as 2,246 ft and 1,047 ft, respectively, for the Williston structural basin and 7,180 and 5,070 ft, respectively, for the Powder River structural basin (table 1).

Hydrogeologic units contained within the lower Tertiary and Upper Cretaceous aquifer systems (fig. 3) are confining units, in some cases, that are not necessarily continuous across the entire study area. The middle Fort Union and upper Hell Creek hydrogeologic units were considered to be confining units by Hotchkiss and Levings (1986); however, in the Williston structural basin, the estimated hydraulic-conductivity values were spatially variable and did not conclusively indicate that these were confining units in all areas (Thamke and others, 2014). Therefore, if the confining properties are discontinuous or uncertain, the term “hydrogeologic unit” is used in the name, whereas the term “aquifer” is used in the name if the unit is considered an aquifer (fig. 3). The middle Fort Union hydrogeologic unit does not exist in the northeastern part of the Williston structural basin (Thamke and others, 2014). The Fox Hills aquifer and lower Hell Creek aquifer are productive aquifers and are the only sources capable of producing large

Table 1. Volumes, thicknesses, and horizontal hydraulic conductivity values (K_h) of hydrogeologic units in the Williston and Powder River structural basins (from Thamke and others, 2014).

[ft^3, cubic feet; ft/d, feet per day; HU, hydrogeologic unit; --, no data or not applicable]

<table>
<tr><th rowspan="2">Hydrogeologic unit or aquifer system</th><th colspan="3">Williston structural basin</th><th colspan="3">Powder River structural basin</th></tr>
<tr><th>Volume, in 10^{12} ft^3</th><th>Thickness, in feet</th><th>K_h, in ft/d</th><th>Volume, in 10^{12} ft^3</th><th>Thickness, in feet</th><th>K_h, in ft/d</th></tr>
<tr><td>Glacial aquifer system</td><td>150</td><td>0–756</td><td>0.01–24</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Lower Tertiary aquifer system</td><td>1,002</td><td>0–2,246</td><td>--</td><td>1,381</td><td>0–7,180</td><td>--</td></tr>
<tr><td>Upper Fort Union aquifer</td><td>549</td><td>0–1,917</td><td>0.14–9.8</td><td>562</td><td>0–4,458</td><td>0.23–11</td></tr>
<tr><td>Middle Fort Union HU</td><td>145</td><td>0–520</td><td>0.01–7.8</td><td>378</td><td>0–3,643</td><td>0.10–7.1</td></tr>
<tr><td>Lower Fort Union aquifer</td><td>307</td><td>0–668</td><td>0.14–5.5</td><td>440</td><td>0–2,913</td><td>0.26–6.4</td></tr>
<tr><td>Upper Cretaceous aquifer system</td><td>1,005</td><td>0–1,047</td><td>--</td><td>938</td><td>0–5,070</td><td>--</td></tr>
<tr><td>Upper Hell Creek HU</td><td>337</td><td>0–738</td><td>0.10–5.5</td><td>355</td><td>0–3,002</td><td>0.03–5.7</td></tr>
<tr><td>Lower Hell Creek aquifer</td><td>296</td><td>0–548</td><td>0.10–1.7</td><td rowspan="2">583</td><td rowspan="2">0–3,274</td><td rowspan="2">0.02–1.4</td></tr>
<tr><td>Fox Hills aquifer</td><td>372</td><td>0–422</td><td>0.06–1.0</td></tr>
</table>

quantities of fresh groundwater in much of western North Dakota (Fischer, 2013).

The division between the Williston and Powder River structural basins is defined herein by the Miles City arch (fig. 2), which is evident in deep lithostratigraphic units, such as the Madison Limestone of the Mississippian geologic series (Bergantino and Feltis, 1985). This arch is subdued in the comparatively shallow lower Tertiary and Upper Cretaceous aquifer systems, within which the Cedar Creek anticline is a prominent feature (figs. 2 and 5). The Upper Cretaceous aquifer system in the Powder River structural basin is as deep as 8,500 ft below land surface (fig. 6), which is more than three times deeper than in the Williston structural basin (fig. 5) at a maximum depth of 2,850 ft below land surface (Thamke and others, 2014). The basal confining unit is from 800 to more than 3,000 ft thick, composed of Upper Cretaceous marine shale (Anna, 1986; Downey, 1986; Downey and Dinwiddie, 1988) that is assumed to hydraulically separate groundwater flow in the Upper Cretaceous aquifer system from underlying aquifers. The basal confining unit also surrounds the lower Tertiary and Upper Cretaceous aquifer systems in the study area at the land surface, except where the Bull Mountain structural basin and the Bighorn Mountains are adjacent to the Powder River structural basin (fig. 1).

Clinker, which is present in the lower Tertiary aquifer system primarily in the Powder River structural basin, is a type of metamorphic rock formed when coalbeds exposed at the land surface are ignited by wildfires or lightning and burned to depths at which the oxygen supply in the beds is depleted. A reduction in volume of the coal results, along with fracturing of the interbedded and surrounding baked shale, siltstone, and sandstone. These metamorphosed rocks tend to collapse and fill the void left after the coalbed has burned, resulting in high porosity for water infiltration and storage (Heffern and Coates, 1999). Clinker zones, which are extremely permeable and can extend a considerable distance into the buried parts of the coalbeds, form productive aquifers from which springs flow if the water table intersects the land surface (Whitehead, 1996). Heffern and others (2013) estimated that clinker exists in about 1,472 square miles (mi^2) in the Powder River structural basin (1,094 mi^2 in Montana and 378 mi^2 in Wyoming; fig. 1–1). Aquifer pumping tests at several coal mines in clinker areas have resulted in little or no drawdown, with associated transmissivity estimates of as much as 1 million feet squared per day (Heffern and Coates, 1999). Lowry and Rankl (1987) indicated that the occurrence of clinker in the Powder River structural basin resulted in a decrease in streamflow, presumably because streams were infiltrating into this highly permeable medium. Areas of clinker indicated by Heffern and others (2013) coincide with evergreen forests in the northern part of the Powder River structural basin (fig. 1–1).

Conceptual Model

Groundwater flow in the lower Tertiary and Upper Cretaceous aquifer systems generally is from southwest to northeast in the Williston structural basin (fig. 7) and from south to north in the Powder River structural basin. Altitudes of the tops and bottoms of the hydrogeologic units described in figure 3 were constructed by Thamke and others (2014) on the basis of geologic and resistivity bore-hole logs for the Williston structural basin and from Lewis and Hotchkiss (1981) for the Powder River structural basin (table 1). This section describes groundwater flow as interpreted from potentiometric maps (Hotchkiss and Levings, 1986; Thamke and others, 2014) with an assessment of groundwater recharge and discharge. These potentiometric surfaces are available in digital format from Thamke and others (2014).

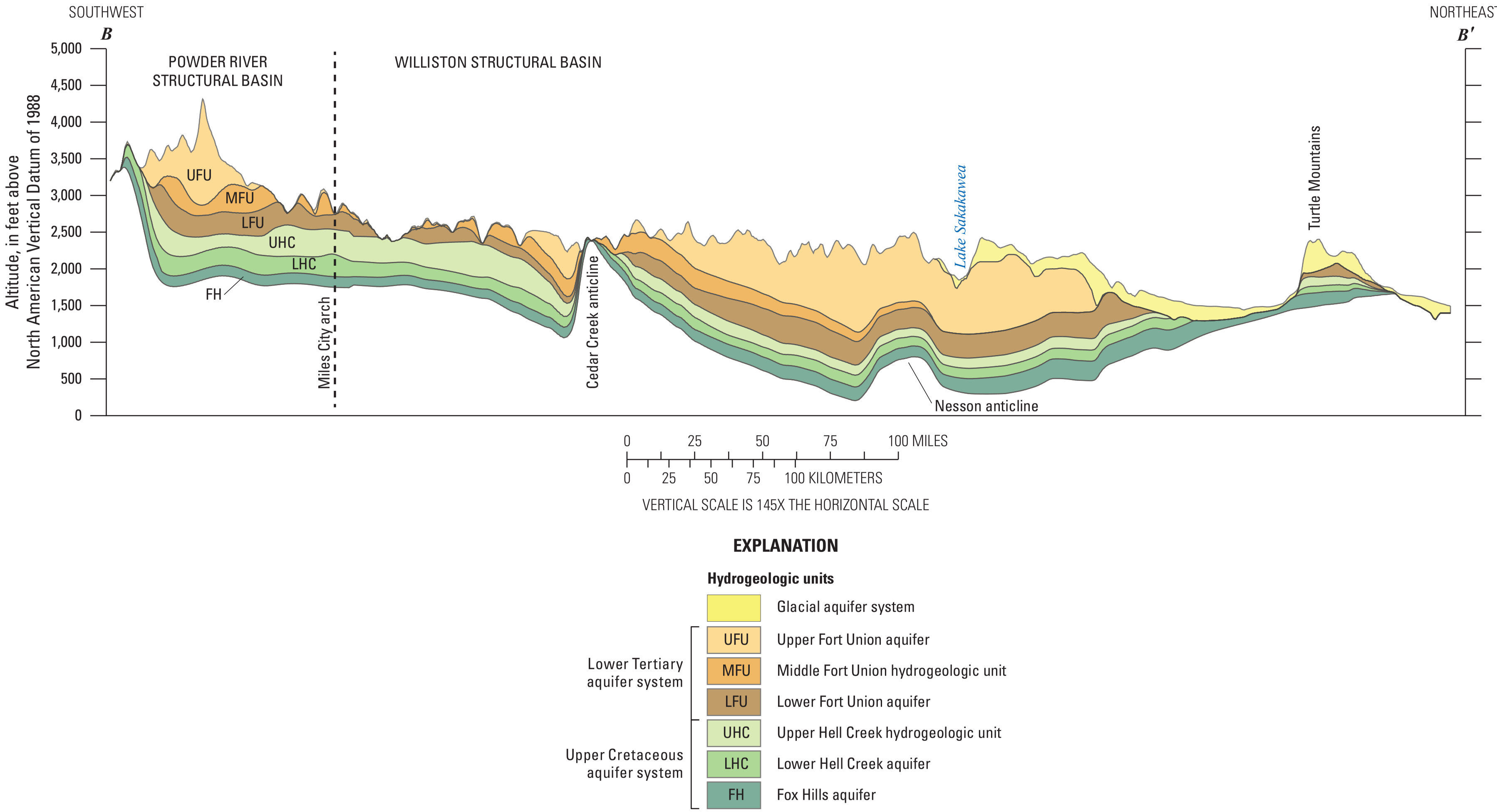


Figure 5. Hydrogeologic cross-section *B–B´* showing the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins. Line of section shown on figure 2.

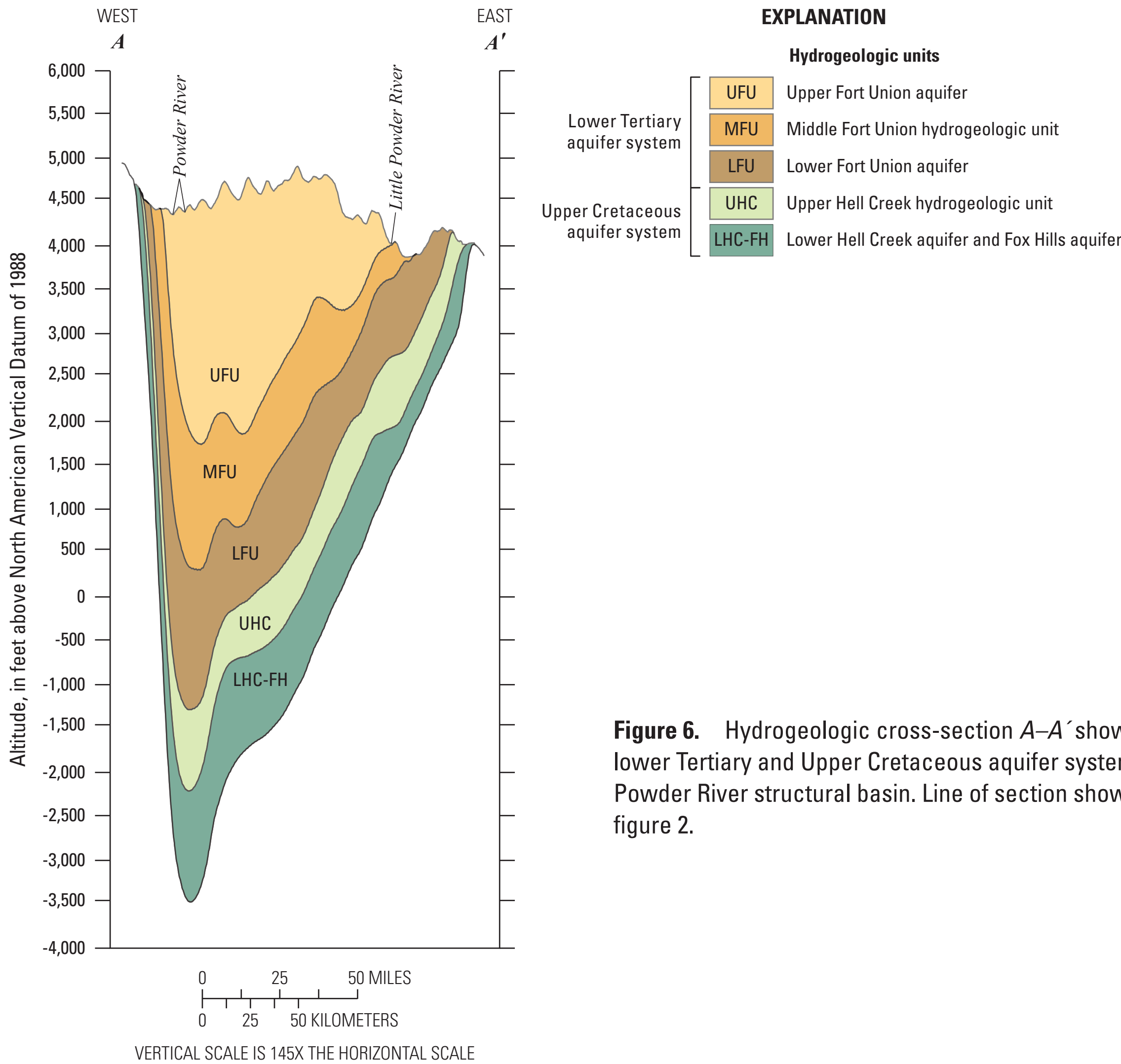


Figure 6. Hydrogeologic cross-section *A–A´* showing the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin. Line of section shown on figure 2.

Groundwater Recharge and Discharge

Groundwater recharge and discharge components were estimated for a control volume that herein is defined to contain the glacial, lower Tertiary, and Upper Cretaceous aquifer systems within the areal extent (fig. 2) of the Upper Cretaceous aquifer system in the two structural basins. This control volume has a smaller areal extent than the extent of the entire structural basins that includes the Paleozoic system. This control volume also defines the horizontal extent for the glacial aquifer system that overlies the lower Tertiary and Upper Cretaceous aquifer systems. Components of recharge (inflow) and discharge (outflow) were quantified for this control volume (fig. 8) and also separately for the two structural basins (table 2) that are referred to as the Williston control volume and the Powder River control volume, with the Miles City arch defining the division between the two (fig. 2). The areas of the Williston and Powder River control volumes are 91,300 and 24,800 mi^2, respectively, and the combined area is referred to as the total control volume.

Precipitation recharge is defined as groundwater recharge from the land surface resulting from the infiltration of precipitation below the root zone. Stream infiltration is defined as groundwater recharge from infiltrating streams. Irrigation recharge is defined as water applied to agricultural areas that is not used by crops and infiltrates below the root zone. Estimates in table 2 represent the period 1981–2005, in which the net change in groundwater storage is assumed to be negligible. Thamke and others (2014) assessed water levels observed prior to 2000 and concluded that large or consistent regional changes in hydraulic head were small during this period. Data for the period 1903–2005 was used to estimate stream infiltration and groundwater discharge to streams because this period provided the most spatially extensive estimates possible. Groundwater flow to or from the basal confining unit (fig. 3) was assumed to be negligible. The period prior to 1960 is defined as the predevelopment period when little groundwater was extracted.

Total estimated recharge to the Williston and Powder River control volumes is 4,560 and 1,500 cubic feet per

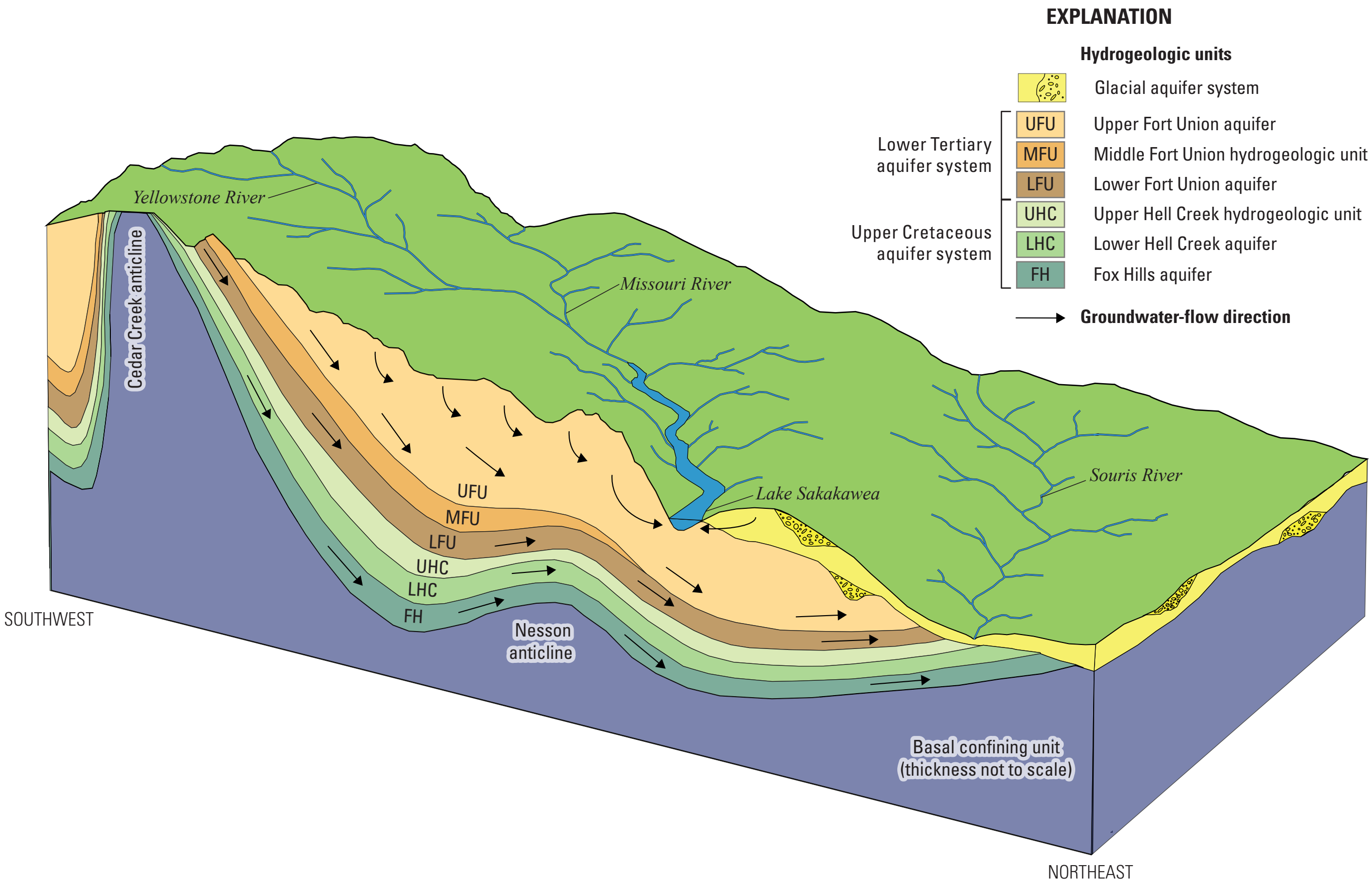


Figure 7. Conceptual block diagram of groundwater flow in the Williston structural basin, as viewed from the southeast.

second (ft^3/s), respectively, with equal values attributed to groundwater discharge (table 2). The large difference between these values is because the Williston control volume is 3.7 times larger than the Powder River control volume and receives greater precipitation (fig. 1–1). Estimated precipitation recharge is 26 and 15 percent of total recharge for the Williston and Powder River control volumes, respectively (table 2). Estimated stream infiltration is 71 and 80 percent of total recharge for the Williston and Powder River control volumes, respectively. The higher percentage for the Powder River control volume likely results from faults near the Bighorn Mountains and clinker zones, which provide areas of high permeability for streams to recharge the aquifers. Clinker is much more prevalent in the Powder River structural basin than in the Williston structural basin (Heffern and others, 2013; Montana Bureau of Mines and Geology, 2013; fig. 1-1). Estimated groundwater discharge to streams is 97 and 92 percent of total discharge for the Williston and Powder River control volumes, respectively (table 2). Estimated groundwater withdrawal is 3 and 7 percent of the total discharge for the Williston and Powder River control volumes, respectively (table 2).

Precipitation Recharge

Estimated precipitation recharge for the Williston and Powder River control volumes is 1,190 and 221 ft^3/s, respectively, or about 26 and 15 percent, respectively, of total recharge to each control volume (table 2). A numerical soil-water-balance (SWB) model (Dripps and Bradbury, 2007; Westenbroek and others, 2010) was used to estimate precipitation recharge. The SWB model is a two-dimensional, distributed-parameter model based on the approach of Thornthwaite and Mather (1957) and is used to estimate groundwater recharge as infiltration below the root zone to each model cell on a daily time step. Inputs for the SWB model include daily precipitation and air temperature data, land-cover classification, several soil-type parameters, and the general surface-water-flow direction for each model cell. The inflows and outflows of water within each model cell are determined by the SWB model on the basis of input data, as described by equation 1:

$$R = (p + s + f_{in}) - (c + ET + f_{out}) - \Delta m \qquad (1)$$

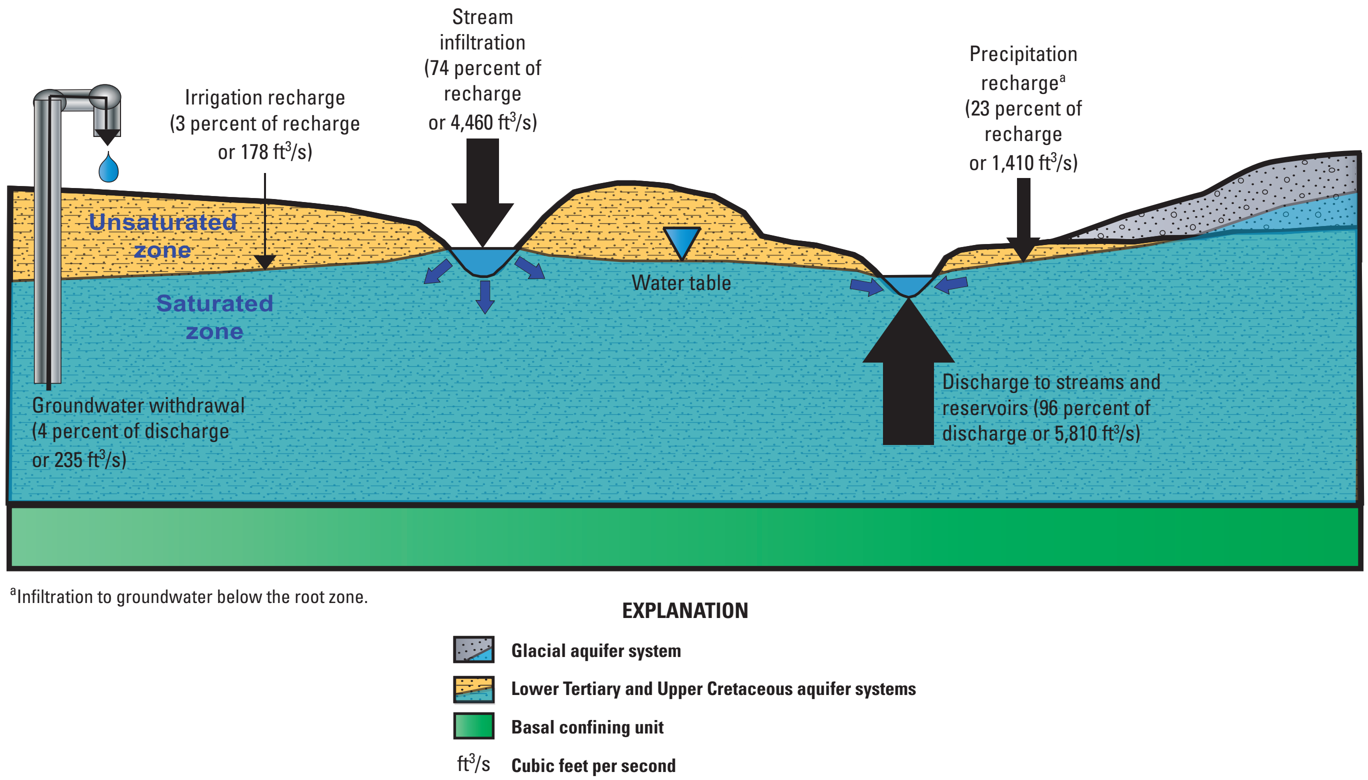


Figure 8. Groundwater budget, including recharge and discharge estimates as percentages of total recharge and total discharge for the total control volume (table 2).

where all equation terms are expressed as the height of water, in inches, for each model cell, and

R is the daily recharge,
p is precipitation,
s is snowmelt (*water equivalent*),
f_{in} is surface-water inflow,
c is interception (*precipitation that does not reach the land surface because it is intercepted by standing vegetation*),
ET is evapotranspiration,
f_{out} is surface-water outflow, and
Δm is the change in soil moisture (*positive when increasing*).

Model Inputs

Aurand (2013) applied an SWB model to the Williston structural basin and a second SWB model to the Powder River structural basin. These models were applied in the study described herein, with a modification to correct for the effects of overland surface-water flow. Each of these models had rectangular grids, the extents of which correspond to the extent of the hydrologic soil groups shown in figure 1-1. Model cell size was 0.62 mi (1 kilometer; km) by 0.62 mi (1 km) to match the gridded climate data. The Williston structural basin model was 441 mi by 457 mi (710 km by 735 km) and had 521,850 cells. The Powder River structural basin model was 295 mi by 193 mi (475 km by 310 km) and had 147,250 cells.

The SWB model requires precipitation data and minimum and maximum temperature data on a daily basis for each model cell. The Daymet data (Thornton and others, 1997, 2012) are gridded climate data at a 0.39-mi^2 (1-square kilometer [km^2]) spatial resolution that were produced by interpolating ground-surface observation stations for 1981–2011. These data were obtained from the Geo Data Portal (Blodgett and others, 2011). The map projection and cell size for the SWB models were set to match the Daymet data because precipitation is the primary factor affecting groundwater recharge and is the only water source in the SWB model. Average annual precipitation for 1981–2005 was about 15.9 in/yr in the Williston structural basin and 14.3 in/yr in the Powder River structural basin (table 3).

Land-cover data from the 2006 National Land Cover Database (Fry and others, 2011) were used in the SWB model. Xian and others (2011), who estimated the change in impervious area for the United States from 2001 to 2006, estimated little change in impervious area within the Williston and Powder River control volumes, which increased by 0.014 and 0.0085 percent, respectively. The Digital General Soil Map of the United States (STATSGO2; U.S. Department of Agriculture, 2006) was used to determine soil properties in areas not covered by glacial deposits. Soil-property values used in this study are from Aurand (2013) (table 1–1 in the appendix) and

Table 2. Estimated average groundwater recharge and discharge components for 1981–2005 within the Williston and Powder River control volumes. All values rounded to three significant figures.

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

Recharge or discharge component	Williston control volume[a]		Powder River control volume[a]		Total control volume		Period of record
	ft³/s	Percent[c]	ft³/s	Percent[c]	ft³/s	Percent[c]	
Groundwater recharge							
Precipitation recharge	1,190	26	221	15	1,410	23	1981–2005
Stream infiltration	3,260	71	1,200	80	4,460	74	1900–2005[b]
Irrigation recharge	98	2	80	5	178	3	1981–2005
Groundwater inflow from the Powder River structural basin	8	<1	--	--	--	--	--
Total recharge	4,560	100	1,500	100	6,060	100	--
Groundwater discharge							
Discharge to streams	4,420	97	1,380	92	5,800	96	1900–2005[b]
Groundwater withdrawal	126	3	109	7	235	4	1981–2005
Discharge to reservoirs	10	<1	--	--	10	<1	--
Groundwater outflow to the Williston structural basin	--	--	8	<1	--	--	--
Total discharge	4,560	100	1,500	100	6,060	100	--

[a]The control volume areal extent is shown on figure 2.

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

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

consist of Natural Resources Conservation Service (NRCS) curve numbers from Cronshey and others (1986), maximum infiltration rates, available water capacity, interception values based on Westenbroek and others (2010), and root depths based on Canadell and others (1996). Surface-water runoff in the SWB model is calculated by using the NRCS curve-number method (Cronshey and others, 1986). The Hargreaves and Samani (1985) method was used to estimate evapotranspiration. This method was the only option available in the SWB model that produced daily gridded evapotranspiration values rather than a daily constant value for the model (Westenbroek and others, 2010). In SWB, recharge is not calculated for model cells identified as open water because precipitation falling in these areas is assumed to become surface-water runoff (Westenbroek and others, 2010).

For areas with glacial deposits, five additional hydrologic soil groups were created to better represent model parameters that control storage and infiltration rates that are specific to these deposits. This approach is consistent with Westenbroek and others (2010) and Feinstein and others (2010), who used Quaternary geologic maps to assign hydrologic soil groups and available water capacities based on glacial-deposit lithology. In this study, Quaternary geologic and sediment maps (Fullerton and others, 1995, 2000, 2007) were used to define the hydrologic soil groups. Where these maps did not cover parts of the glacial deposits, a Quaternary sediments map (Soller and others, 2012) was used. Surficial-geology maps were not available for the far northwestern part of the study area (fig. 1), which was assumed to be entirely till because this is the dominant glacial deposit in the study area. This area is outside of the control-volume extent. The five additional hydrologic soil groups were till, glaciolacustrine, glaciofluvial, loess and eolian, and glaciotectonic (fig. 1–1, table 1–1). Areas of open water were identified by using the Quaternary geologic and sediment maps. Additional details describing model parameters used for glacial deposits are in Aurand (2013).

The option to simulate surface-water-flow routing in SWB was not used because coarse-gridded models (1-km spacing) greatly overestimate the amount of excess surface water routed downslope for focused recharge (Feinstein and others, 2010; Westenbroek and others, 2010). Two simulations of the Powder River structural basin model were executed with and without the surface-water-flow routing option, and the average annual recharge rate using the flow-routing option was almost 200 percent more than without the flow routing option (Aurand, 2013); however, execution of a model without the flow routing option underestimates recharge because it does not capture recharge from runoff. To simulate recharge from runoff accurately, the land-surface topography must be represented adequately with a high-resolution model grid. For

Table 3. Estimates of mean annual precipitation recharge and evapotranspiration (ET) for 1981–2011.

[in/yr, inches per year; ft^3/s, cubic feet per second]

Year	Williston structural basin					Powder River structural basin				
	Recharge, in in/yr	Recharge fraction[a]	Recharge, in ft^3/s	Precipitation, in in/yr	Actual ET, in in/yr	Recharge, in in/yr	Recharge fraction[a]	Recharge, in ft^3/s	Precipitation, in in/yr	Actual ET, in in/yr
1981	0.03	0.00204	196	14.3	12.3	0.0006	0.00005	1.2	13.5	10.2
1982	0.38	0.01866	2,575	20.5	14.1	0.0713	0.00361	130	19.8	14.3
1983	0.41	0.03235	2,762	12.7	12.5	0.1746	0.01492	319	11.7	11.0
1984	0.07	0.00551	486	13.1	10.3	0.1554	0.01177	284	13.2	11.8
1985	0.05	0.00301	312	15.4	11.3	0.0102	0.00085	19	11.9	9.6
1986	0.26	0.01301	1,717	19.6	15.6	0.0314	0.00191	57	16.5	13.0
1987	0.13	0.00838	843	15.0	14.3	0.2002	0.01441	366	13.9	13.8
1988	0.00	0.00002	1	9.8	7.8	0.0051	0.00061	9	8.5	7.3
1989	0.05	0.00332	315	14.1	10.9	0.0379	0.00262	69	14.5	11.2
1990	0.01	0.00068	57	12.4	10.9	0.0630	0.00508	115	12.4	12.4
1991	0.01	0.00048	59	18.2	13.6	0.0658	0.00431	120	15.2	12.7
1992	0.05	0.00379	351	13.8	11.4	0.0033	0.00023	6	13.9	11.5
1993	0.16	0.00773	1,079	20.8	15.1	0.0688	0.00374	126	18.4	15.2
1994	0.05	0.00311	340	16.3	12.5	0.0570	0.00411	104	13.9	11.1
1995	0.77	0.04399	5,147	17.4	14.4	0.5183	0.02913	947	17.8	15.9
1996	0.23	0.01359	1,541	16.9	12.6	0.2017	0.01341	368	15.0	12.2
1997	0.79	0.05623	5,305	14.0	13.1	0.4149	0.02694	758	15.4	14.4
1998	0.05	0.00250	324	19.3	12.7	0.1405	0.00764	257	18.4	13.4
1999	0.58	0.03245	3,881	17.8	16.8	0.3386	0.02302	619	14.7	15.4
2000	0.01	0.00043	54	18.5	12.9	0.0149	0.00119	27	12.5	10.3
2001	0.19	0.01352	1,295	14.2	14.0	0.0358	0.00303	65	11.8	10.7
2002	0.01	0.00090	84	13.9	10.4	0.0141	0.00131	26	10.8	8.8
2003	0.04	0.00260	259	14.8	11.9	0.1293	0.00860	236	15.0	12.1
2004	0.07	0.00450	473	15.6	12.2	0.0165	0.00155	30	10.7	9.5
2005	0.06	0.00322	404	18.6	15.1	0.2534	0.01433	463	17.7	14.4
2006	0.09	0.00698	610	13.0	11.4	0.0931	0.00776	170	12.0	10.9
2007	0.16	0.00945	1,072	16.9	14.4	0.4678	0.02818	855	16.6	14.6
2008	0.04	0.00192	243	18.8	11.6	0.2530	0.01412	462	17.9	14.0
2009	0.96	0.05624	6,483	17.1	14.3	0.3154	0.02155	576	14.6	12.7
2010	0.17	0.00780	1,118	21.3	17.0	0.0764	0.00468	140	16.3	13.9
2011	2.47	0.11182	16,616	22.1	18.0	1.6954	0.08440	3,097	20.1	15.5
Average (1981–2005)[b]	0.18	0.011	1,190[c]	15.9	12.8	0.12	0.008	221	14.3	12.1
Average (1981–2011)	0.27	0.015	1,810[c]	16.3	13.1	0.19	0.012	349	14.7	12.4

[a]Recharge as a fraction of precipitation.

[b]Pre-development period.

[c]Rounded to three significant figures.

example, a 30-meter (m; 98-ft) grid spacing defines the local variability in land-surface slopes for simulation of runoff at that scale. A high-resolution SWB model (30-m grid spacing) was constructed and executed for a small area (3,250 ft by 3,250 ft; 990 m by 990 m) within the Williston control volume. A location that represented average precipitation for the Williston control volume was selected for this high-resolution SWB model (about 2 miles south of the Grand River at 102 degrees west longitude). Two simulations were executed for the high-resolution model for the period 1981–2005: one simulation with flow routing turned on and one with flow routing turned off. The flow-routing simulation estimated an average annual recharge rate about 1.4 times greater than for the simulation with flow-routing turned off. This factor was assumed to apply in all areas, and the estimated precipitation recharge for the study area from the coarse-gridded SWB model was increased by a factor of 1.4 to account for additional recharge from surface-water runoff.

Results of Soil-Water-Balance Simulations

The SWB model was executed for the period 1980–2011, where 1980 was used as the model initialization period, the output of which was not used because it neglects antecedent effects of the previous year. The results, which include recharge and actual evapotranspiration, were summarized for 1981–2005 and also for 1981–2011 on an annual basis (table 3). The spatial distribution of the average annual recharge is shown in figure 1–1.

The estimated average precipitation recharge for the Williston control volume for 1981–2005 is 0.18 in/yr (1,190 ft^3/s), which is about 1.1 percent of precipitation (table 3), and varies from 0 to 6.8 in/yr in different parts of the control volume, with the highest values located on glaciofluvial and loess deposits (fig. 1–1). The Peerless Plateau (figs. 2 and 1-1) and the southeastern part of the Williston control volume are the primary areas of precipitation recharge not overlain by glacial deposits. For 1981–2005, estimated precipitation recharge is 0 for about 56 percent of the Williston control volume (fig. 1–1), primarily because potential evapotranspiration was equal to or greater than precipitation in these areas or because of the presence of till, where little recharge occurs. Precipitation recharge to the glacial aquifer system primarily occurs in areas of glaciofluvial and loess deposits (fig. 1–1). The estimated average precipitation recharge for the Powder River control volume for the pre-development period is 0.12 in/yr (221 ft^3/s), or about 0.8 percent of precipitation (table 3), and varies from 0 to 5.8 in/yr in different parts of the control volume (fig. 1–1).

The recharge rates estimated for this study are similar to previous estimates. Wolock (2003) estimated long-term average groundwater recharge for the United States, which ranged from 0 to 0.5 in/yr within the total control volume. Although precipitation recharge estimates were as high as 6.8 in/yr, the range was only 0–0.5 in/yr for 94 percent of the total control volume. The difference between precipitation and potential evapotranspiration, or how much water is available for recharge to groundwater or runoff to streams, ranged from 0 to 5 in/yr for the total control volume on the basis of a national study (Roy and others, 2005).

Aurand (2013) applied the chloride mass-balance (CMB) and water-table-fluctuation (WTF) methods (Healy and Cook, 2002; Delin and others, 2007; Healy, 2010) to estimate precipitation recharge for 443 locations within the two control volumes; these consisted of 432 locations for the CMB method and 11 locations for the WTF method. Most of the CMB estimates were based on a single chloride groundwater sample, and therefore, each estimate represents recharge at the time of the sample. The WTF method was applied to long-term records of groundwater levels in 11 wells for estimation of recharge representing long-term averages. As a verification that the SWB model produced similar results to other methods, the CMB and WTF estimates from Aurand (2013) were compared to long-term average estimates (1981–2011) from the SWB model for the same locations. A comparison of the ranges of values between the CMB and SWB methods indicates similarity (fig. 9*A*). A comparison between the WTF and SWB estimates indicates larger differences than for the former comparison, with generally larger values for the WTF method (fig. 9*B*).

The highest estimated precipitation recharge for the Powder River control volume is near the Bighorn Mountains on the western side and the Laramie Mountains on the southwestern side of the structural basin and also northwest of the Tongue River (fig. 1–1, fig. 2). For 1981–2005, estimated precipitation recharge is 0 for about 63 percent of the Powder River control volume (fig. 1–1). The upper Fort Union aquifer, which is present at the land surface for most of the Powder River control volume, receives most of the precipitation recharge within the control volume.

Interaction of Groundwater and Surface Water

Base flow is defined herein as streamflow that is supplied by springflow or other groundwater discharge. A gaining reach is defined as one in which a net increase in streamflow occurs as a result of base flow; an infiltrating reach is defined as one in which a net decrease in streamflow occurs because of infiltration to the groundwater. Within these reaches, however, groundwater may flow into or out of the groundwater at different locations. Long-term average base flow was estimated for 130 reaches in the study area by using the hydrograph separation software, PART (Rutledge, 1998). PART uses daily streamflow records and linear interpolation to separate overland runoff from base flow. Daily streamflow records were obtained from the USGS National Water Information System (NWIS) database for the United States (U.S. Geological Survey, 2013) and from the HYDAT database for Canada (Water Survey of Canada, 2013). PART was used with the default parameters, as defined in Rutledge (1998). The resultant daily output files were used in the analysis.

PART performs best when applied to watersheds less than 500 mi^2 in area (Rutledge, 1998) but also can be applied

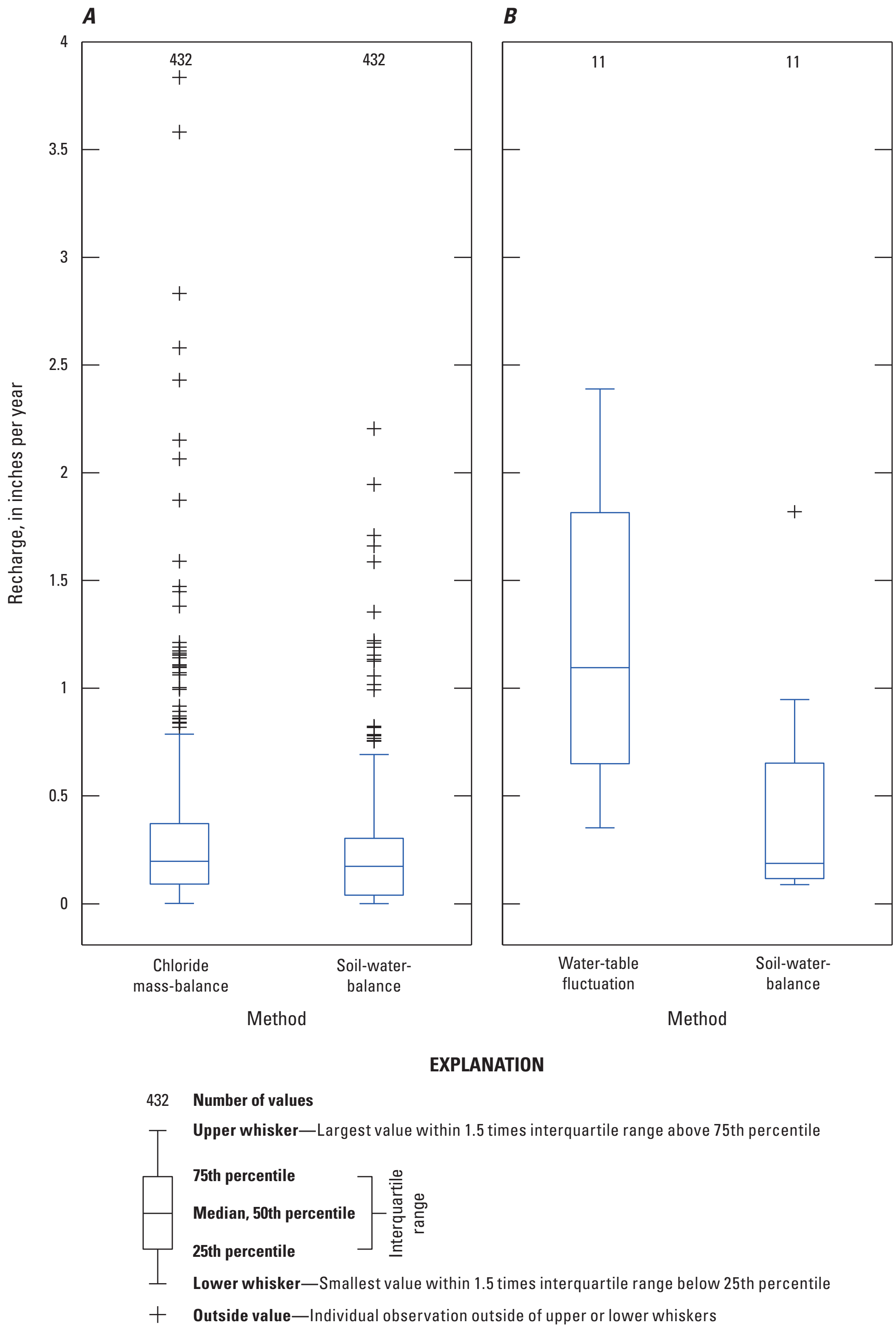


Figure 9. Estimated recharge *A*, between the chloride mass-balance (CMB) and soil-water-balance (SWB) methods and *B*, between the water-table fluctuation (WTF) and SWB methods for selected locations.

to watersheds larger than 2,000 mi^2, although there will be reduced accuracy in this case (Linsley and others, 1982). In a study of base flow in the Great Lakes region, Neff and others (2005) did not limit the application of PART to a maximum watershed area of 500 mi^2, which they indicated was acceptable for the scale of their study area.

For the study described herein, PART was applied to available daily streamflow data for 1903 through 2005 for each streamgage to estimate daily base flow for that period. Data for 2006 through 2011 also were used for about 4 percent of the streamgages, which are located in the Powder River control volume, because adequate records were not available prior to this period. The analysis described herein follows the method used by Bednar (2013), who assessed base flow for the period 1903–2011 and provided additional details of the method. Evapotranspiration, extreme precipitation events, ice damming, ground freeze, bank storage, flooding, irrigation diversions, irrigation flowback, backwater from lakes, and reservoir storage or releases are processes that degrade the accuracy of PART estimates; these processes are minimized or negligible, however, during September and October in the Northern Great Plains (Bednar, 2013). Also, Smakhtin (2001) indicated that during low-flow periods, total streamflow is a good approximation of base flow. Therefore, average base-flow estimates for September and October were used to represent long-term average base flow for each streamgage for 1981–2005.

Streams in the study area were separated into reaches defined by upstream and downstream streamgages (fig. 1–1), and long-term average base-flow estimates for each gaining stream reach were calculated as the difference between the downstream and upstream average base flows (tables 1–2 and 1–3 in the appendix). For ease of locating streamgages, numbered labels are ordered counterclockwise on figure 1–1, starting in the southeastern part of the Williston structural basin and ending in the southern end of the Powder River structural basin. Because this order generally is from downstream to upstream, streamgage labels also are ordered from downstream to upstream along individual streams. Headwater stream reaches included only a downstream streamgage, where the base flow at that single streamgage defined the base flow for the reach. If the difference between the downstream and upstream average base flows for a reach was negative (streamflow decrease), this indicated an infiltrating reach. PART is valid for quantifying base flow for gaining streams only and, therefore, was not used to estimate stream infiltration. For infiltrating reaches, the difference between long-term average upstream and downstream streamflow measurements for September and October were used as initial estimates of stream infiltration to groundwater (table 1–3). The use of fall streamflow records, however, might underestimate stream infiltration in arid and semiarid environments because storm-event streamflows frequently result in higher recharge rates than during low-flow periods in these environments (McCallum and others, 2013). Including spring and summer streamflow records in the analysis also would induce errors because of factors previously described. Additional sources of error are surface-water withdrawals for industrial uses. Therefore, these initial estimates of stream infiltration rates were assumed to be the least reliable of all water-budget components and were, therefore, adjusted by the amount that resulted in balanced total inflows and outflows for the control volumes.

For some reaches, the September and October streamflow values indicated an infiltrating reach, whereas the PART estimates indicated a gaining reach; these were assumed to be infiltrating reaches, and therefore, the streamflow values were used to estimate stream infiltration. Estimates of base flow for selected streams in the Powder River structural basin were made by Druse and others (1981) for the period 1977–78 and by Rankl and Lowry (1990) for the period 1944–77. These estimates are similar to estimates in table 1–2.

Using most of the available data for each streamgage was assumed to provide the best long-term estimates of average base flow and stream infiltration. This approach, however, sometimes resulted in different periods of record for the upstream and downstream streamgages used for each reach, which may affect the accuracy of estimates for individual reaches. Neff and others (2005) used a similar approach in that they did not use a common time period for streamflow records. Annual values were not estimated because this would greatly decrease the number of reaches that could be estimated. Although the September and October period was assumed to provide the best estimates of base flow and stream infiltration, seasonal variability may exist, especially for infiltrating reaches. There also is uncertainty in the estimates for large watersheds, as previously described, and for rivers with controlled flow, such as the Missouri River, because PART was designed for uncontrolled streamflow with natural variability. River reaches that include controlled reservoirs are noted as regulated in table 1-2 and were not included in this analysis.

In this report, stream reaches are named according to the downstream and upstream streamgage; for example, reach 93–94 is the reach of the Yellowstone River that is between streamgages 93 and 94 (fig. 1–1). Estimates were made for all reaches in the study area, but only reaches within the two control volumes (fig. 2) were included in the summary shown in table 2, which balances total recharge and discharge for the two control volumes. For any reach that crosses the control-volume boundary, the estimate for that reach was multiplied by the fraction of reach length that exists within the two control volumes. The estimated totals for the two control volumes and for all reaches quantified are listed in table 1–3.

Williston Control Volume

For the Williston control volume, the total estimated stream infiltration is 3,260 ft^3/s, and groundwater discharge to streams is 4,420 ft^3/s, which are 71 and 97 percent of total recharge and total discharge, respectively (tables 2 and 1–3). The initial estimate of total stream infiltration was 3,450 ft^3/s, which is about 6 percent larger than the final value needed to balance inflows and outflows. Because this was considered to be within the probable error for this estimate, the initial estimate was reduced by 6 percent for a final estimate of 3,260 ft^3/s (table 2). For final estimates of stream infiltration, this adjustment was applied to reach 96–97, which was determined to be an infiltrating reach on the basis of the initial estimates. Potentiometric surfaces, however, indicate groundwater flow toward this reach and also reach 94–96 (fig. 1–1), which is contradictory to an infiltrating stream. Therefore, the 6 percent reduction in the stream infiltration estimate was applied to reach 96–97, which did not change its status from infiltrating to gaining but reduced the infiltration rate somewhat (table 1–3). Flowing wells near the Yellowstone River (Smith and others, 2000; Fischer, 2013) might lower the groundwater table and capture streamflow within reach 96–97. Water from flowing wells that is not used by humans would discharge to the land surface and possibly be consumed by evapotranspiration before returning to the stream. Surface-water withdrawals in the study area are difficult to quantify; these probably occur during all months for non-irrigation uses and also introduce errors into estimating the interaction of groundwater and surface water.

Most of the reaches in the Williston control volume were estimated to be gaining reaches. Glacial aquifers discharge primarily to the Souris and Little Muddy Rivers in areas of thick glacial deposits. Infiltrating reaches exist generally where glacial deposits are thin (reaches 71–81, 60–61, and 49–50; fig. 1–1). The upper Fort Union aquifer primarily discharges to streams (fig. 1–1). In the Peerless Plateau area (fig. 2), where glacial deposits are absent (reach 77–78 and upstream from site 78), the lower Fort Union aquifer and middle Fort Union hydrogeologic unit discharge to streams. In the southeastern part of the Williston control volume, reaches 20–21 and 18–19 recharge the lower Tertiary aquifer system (fig. 1–1). The Upper Cretaceous aquifer system discharges to most reaches, with the primary exception of reach 9–10.

Powder River Control Volume

For the Powder River control volume, the total estimated stream infiltration is 1,200 ft^3/s, and groundwater discharge to streams is 1,380 ft^3/s, which are 80 and 92 percent of total recharge and discharge, respectively (tables 2 and 1–3). The initial estimate of total stream infiltration was 760 ft^3/s, which is about 37 percent smaller than the final value needed to balance inflows and outflows. This probably is not totally attributable to error in the initial estimates; more likely is that additional stream infiltration of about 440 ft^3/s occurs during high-flow periods and within stream reaches that could not be estimated. McCallum and others (2013) indicated that stream infiltration generally is highest during high-flow periods in semiarid environments and estimated that large flow events accounted for about one-half of total stream infiltration to groundwater within a large semiarid watershed in Australia. Precipitation rates indicate that the Powder River control volume is a drier environment, on average, than is the Williston control volume (fig. 1–1). Also, the prevalence of clinker in the Powder River control volume and streams flowing from the Bighorn Mountains that encounter large faults help explain additional stream infiltration that initially was unaccounted for.

During periods of high streamflow, the high permeability of clinker might accept larger amounts of recharge than were estimated from fall streamflow records, and this could have caused underestimation of stream infiltration where streams cross clinker areas. To verify that this is a possibility, full-year streamflow records were analyzed as a comparison to the original analysis of September and October records. When the full-year records were used, stream infiltration estimates were more than 200 percent larger than the initial fall-based estimates for the Powder River control volume, whereas for the Williston control volume, the full-year estimates were 10 percent smaller than the fall-based estimates. This contrast likely is partially attributable to the greater presence of clinker in the Powder River control volume than in the Williston control volume. This interpretation is consistent with Lowry and Rankl (1987), who estimated stream infiltration for the Powder River structural basin for two watersheds of equal size but with differing amounts of clinker; the watershed with the higher percentage of clinker had a much higher stream infiltration rate. Although the full-year analysis is not considered reliable because of factors previously described, this comparison indicates that stream infiltration likely occurs at a higher rate during high-flow periods than during low-flow periods in clinker areas.

Streams that enter the Powder River control volume from the Bighorn Mountains cross several large faults on the western side of the basin (Bighorn fault zone, fig. 2) through which stream infiltration occurs (Downey and Dinwiddie, 1988; Whitehead, 1996). This infiltration, however, was unaccounted for in the initial estimate of stream infiltration because of the absence of streamgages upstream from these faults. Although groundwater discharge into streams can be estimated by using only a downstream streamgage, streamflow at an upstream streamgage also must be known for determination of stream infiltration. The additional 440 ft^3/s of assumed stream infiltration was assigned to reaches near clinker areas and near the Bighorn Mountains (table 1–3). The possibility that some of the additional recharge is supplied by upward moving groundwater from deeper aquifers is noted but was not considered in the balance of recharge and discharge (table 2) because of the basal confining unit (fig. 3).

Most of the reaches in the Powder River control volume are gaining reaches, with infiltrating reaches primarily in the northern and western parts (fig. 1–1). Gaining and infiltrating reaches overlie both the lower Tertiary and Upper Cretaceous aquifer systems, and infiltrating reaches exist on all rivers and creeks in the Powder River control volume.

Groundwater Withdrawal

Groundwater withdrawal was estimated for the two control volumes by county (United States) or census division (Canada) for 1981–2005, which was separated into five 5-year periods for which average values were estimated (table 4). Estimated average groundwater withdrawal for 1981–2005 for the Williston and Powder River control volumes is 126 and 109 ft^3/s, respectively, or 3 and 7 percent, respectively, of the total discharge for each control volume (table 2). For the Williston control volume, groundwater withdrawals from the glacial aquifer system and other surficial deposits were larger than withdrawals from the lower Tertiary or the Upper Cretaceous aquifer systems (table 4). For both control volumes, groundwater withdrawals from the lower Tertiary aquifer system were larger than those from the Upper Cretaceous aquifer system (table 4). Estimated groundwater withdrawal for the two control volumes is primarily for irrigation, mining, and public supply and secondarily for livestock, industrial, self-supplied domestic, and thermoelectric power generation (table 5). Groundwater withdrawal was used primarily for irrigation in the Williston control volume and for mining in the Powder River control volume.

The main source of information for estimating groundwater withdrawal in Montana, North Dakota, South Dakota, and Wyoming was the USGS, which provides a 1-year summary of water use every 5 years for the United States (Solley and others, 1988, 1993, 1998; Hutson and others, 2004; Kenny and others, 2009). These water-use summaries provided estimates for 1985, 1990, 1995, 2000, and 2005. Water use for each of these years also was used as an estimate of water use for the previous 4 years, which provided the estimates for the 5-year periods in table 4. Individual State agencies provided groundwater-well databases that were used to appropriately distribute withdrawals within individual counties (fig. 10) within the two control volumes.

The horizontal and vertical (source aquifer) spatial distribution of groundwater withdrawal within each county was not provided by the water-use summaries. Therefore, groundwater-well information for the study area was compiled from USGS and State databases and used to distribute these withdrawal rates spatially within each county and to each hydrogeologic unit when possible. The NWIS database (U.S. Geological Survey, 2013) together with State water-well databases provided well locations and other attributes used in this analysis. State databases used consisted of the Montana Ground-Water Information Center Water Well database (Montana State Information Technology Services Division, 2012), North Dakota State Water Commission Ground and Surface Water database (North Dakota Information Technology Department, 2012), Wyoming State Engineer's Office Water Well database (Wyoming Geographic Information Science Center, 2012), and South Dakota Department of Environment and Natural Resources Water Well Completion Reports database (South Dakota Department of Environment and Natural Resources, 2013).

Estimated water use was subdivided into hydrogeologic units as described in table 4. In many cases, well information was not sufficient to assign withdrawals to a specific hydrogeologic unit, and withdrawals from unknown aquifers were classified as undifferentiated (table 4). Withdrawals from unknown aquifers were assumed to occur from the glacial, lower Tertiary, or Upper Cretaceous aquifer systems or other surficial deposits because water production seldom occurs from deeper aquifers in the study area. Withdrawals from aquifers deeper than the Upper Cretaceous aquifer system are not included in table 4.

Groundwater withdrawals for each hydrogeologic unit (table 1–4 in the appendix) were estimated on a county-by-county basis by using equations 2 through 8. Withdrawals for the water-use summaries were distributed spatially (horizontally and by hydrogeologic unit; table 4) by assuming that wells from each State database had similar spatial distributions to those from the NWIS database. Counties (fig. 10) were subdivided into subcounty areas defined by the hydrogeologic unit in outcrop or subcrop (fig. 2), which helped to distribute county withdrawals to individual hydrogeologic units. In each county *i*, the fraction of wells $P_{i,j,k}$ located within each subcounty area *j* and open to each hydrogeologic unit *k* was estimated by

$$P_{i,j,k} = \frac{N_{i,j,k}}{N_{i,j}}, \qquad (2)$$

where

- N is the number of wells from NWIS database,
- i indicates the county in which the well is located,
- j indicates the subcounty area, and
- k indicates the hydrogeologic unit to which the well is open.

State databases did not differentiate groundwater withdrawals by hydrogeologic unit, and therefore, equations 3 through 5 describe how the subcounty area *j* was used to distribute withdrawals from wells contained in State databases to each hydrogeologic unit *k*. One of four State databases previously mentioned was used for this assessment, depending on the State in which the county is located. The number of wells from the State database $S_{i,j,k}$ in each county *i*, located within each subcounty area *j*, and open to each hydrogeologic unit *k* was estimated by

$$S_{i,j,k} = P_{i,j,k} \times S_{i,j}, \qquad (3)$$

The State databases did not indicate the withdrawal rates for individual wells or hydrogeologic units. Therefore, to account for the differences in well yields from different hydrogeologic units, a weight $W_{i,j}$ was determined for wells located in each subcounty area *j* based on well attributes contained in each State database. Well diameter or maximum withdrawal rate, depending on the State database, was assumed to be correlative to the actual well withdrawal. For North Dakota, the weight $W_{i,j}$ is the average diameter of wells located in county *i* and subcounty area *j*; for Montana, South Dakota, and Wyoming, $W_{i,j}$ is the average maximum withdrawal rate for wells located in county *i* and subcounty area *j*. Next, to distribute

Table 4. Estimated groundwater withdrawal by hydrogeologic unit for 5-year periods during 1981–2005.

[Values are in cubic feet per second. HU, hydrogeologic unit; LT, lower Tertiary; UC, Upper Cretaceous]

Hydrogeologic unit	Williston control volume[a]						Powder River control volume					
	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	Average	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	Average
Surficial deposits[b]												
Surficial deposits[b]	32.2	34.3	32.9	32.4	37.4	33.9	6.4	5.6	6.7	6.0	6.5	6.3
Lower Tertiary aquifer system												
Upper Fort Union aquifer	10.3	10.8	9.9	7.0	11.7	10.0	20.8	20.3	29.3	32.3	27.4	26.0
Middle Fort Union HU	0.2	0.2	0.2	0.1	0.1	0.1	0.5	0.5	0.5	0.3	0.4	0.5
Lower Fort Union aquifer	2.6	2.5	2.5	1.5	3.2	2.5	1.0	1.0	1.0	0.6	0.9	0.9
LT aquifer system, undifferentiated	15.6	15.3	14.9	15.9	17.6	15.9	8.3	9.0	15.5	17.2	14.7	12.9
LT aquifer system total	**29**	**29**	**27**	**25**	**33**	**28**	**31**	**31**	**46**	**50**	**43**	**40**
Upper Cretaceous aquifer system												
Hell Creek aquifer and HU, undifferentiated	9.4	8.7	9.6	6.9	9.0	8.7	4.7	4.3	4.8	3.6	5.0	4.5
Fox Hills aquifer	1.9	1.6	1.6	1.3	1.6	1.6	1.0	0.9	1.0	0.9	1.5	1.0
UC aquifer system total	**11**	**10**	**11**	**8**	**11**	**10**	**6**	**5**	**6**	**5**	**6**	**6**
Undifferentiated												
Surficial[b], LT, or UC aquifer systems, undifferentiated	51.6	55.2	52.4	50.1	59.0	53.7	65.0	38.6	51.2	64.7	65.0	56.9
Overall total	**124**	**129**	**123**	**115**	**140**	**126**	**108**	**80**	**110**	**126**	**121**	**109**

[a]The overall average (1981–2005) industrial water use for Canada was assumed for each 5-year period.

[b]Primarily the glacial aquifer system for the Williston control volume.

Table 5. Estimated groundwater withdrawal by water-use category for 5-year periods during 1981–2005 as a percentage of total withdrawals.

Water use[a]	Williston control volume						Powder River control volume					
	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	Average	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	Average
Industrial[b]	13	11	11	15	10	12	5	1	0	1	1	2
Irrigation	34	37	33	47	45	39	40	21	19	30	38	30
Public supply	26	26	26	26	20	25	17	14	11	8	11	12
Self-supplied domestic	11	9	10	10	7	9	5	4	3	2	2	3
Mining	3	4	6	0	6	4	29	46	57	58	43	47
Livestock	13	13	14	2	12	11	4	13	9	0	4	6
Thermoelectic power generation	0	0	0	0	0	0	0	1	1	1	1	1
Total	100	100	100	100	100	100	100	100	100	100	100	100

[a]Use types from Solley and others (1988, 1993, 1998), Hutson and others (2004), and Kenny and others (2009).

[b]Includes commercial use for 1981–85, 1986–90, and 1991–95.

withdrawals to each hydrogeologic unit *k*, the weighting factor $W_{i,j,k}$ was determined by

$$W_{i,j,k} = W_{i,j} \times S_{i,j,k}. \quad (4)$$

These weighting factors then were aggregated by county by summing the weighting factors for subcounty areas *j*:

$$W_{i,j,k} = \sum_{j=1}^{n} W_{i,j,k}, \quad (5)$$

where

n is the number of subcounty areas *j* in each county *i*.

Equation 5 provides the weighting factors for wells open to each hydrogeologic unit *k* in each county *i*, which were aggregated as a surrogate for the total withdrawal rate in each county *i*. The final weighting factor W_i for all hydrogeologic units in each county *i* was estimated by

$$W_i = \sum_{k=1}^{m} W_{i,k}, \quad (6)$$

where

m is the number of hydrogeologic units *k* to which wells are open within county *i*.

The ratio $P_{i,k}$ of withdrawals from hydrogeologic unit *k* to the total withdrawals for county *i* was estimated by

$$P_{i,k} = \frac{W_{i,k}}{W_i}. \quad (7)$$

County groundwater withdrawals Q_i from Solley and others (1988, 1993, 1998), Hutson and others (2004), and Kenny and others (2009) for 5-year periods from 1981 to 2005 were used to determine the withdrawal rate $Q_{i,k}$ for each hydrogeologic unit *k* in each county *i*:

$$Q_{i,k} = P_{i,k} \times Q_i. \quad (8)$$

For the glacial aquifer system, withdrawals from counties that partially extend outside of the Williston control volume were scaled by the fraction of wells in the county located within the control volume. In the United States, county withdrawals from the glacial, lower Tertiary, and Upper Cretaceous aquifer systems for 1981 through 2005 ranged from 0.00 to 49.2 ft^3/s (fig. 10), with an average withdrawal of 3.24 ft^3/s.

For water-use estimates for Canada, a similar approach to that used for counties in the United States was used to estimate withdrawals for census divisions, which are the Canadian equivalents of United States counties. Annual withdrawals were available for individual communities in Saskatchewan (Saskatchewan Watershed Authority, 2011; Kei Lo, Saskatchewan Watershed Authority, written comm., 2012). Individual community well records included the source aquifer for public-supply withdrawals. The withdrawals from public-supply wells were used directly and aggregated by census division. Industrial water use in Saskatchewan was estimated

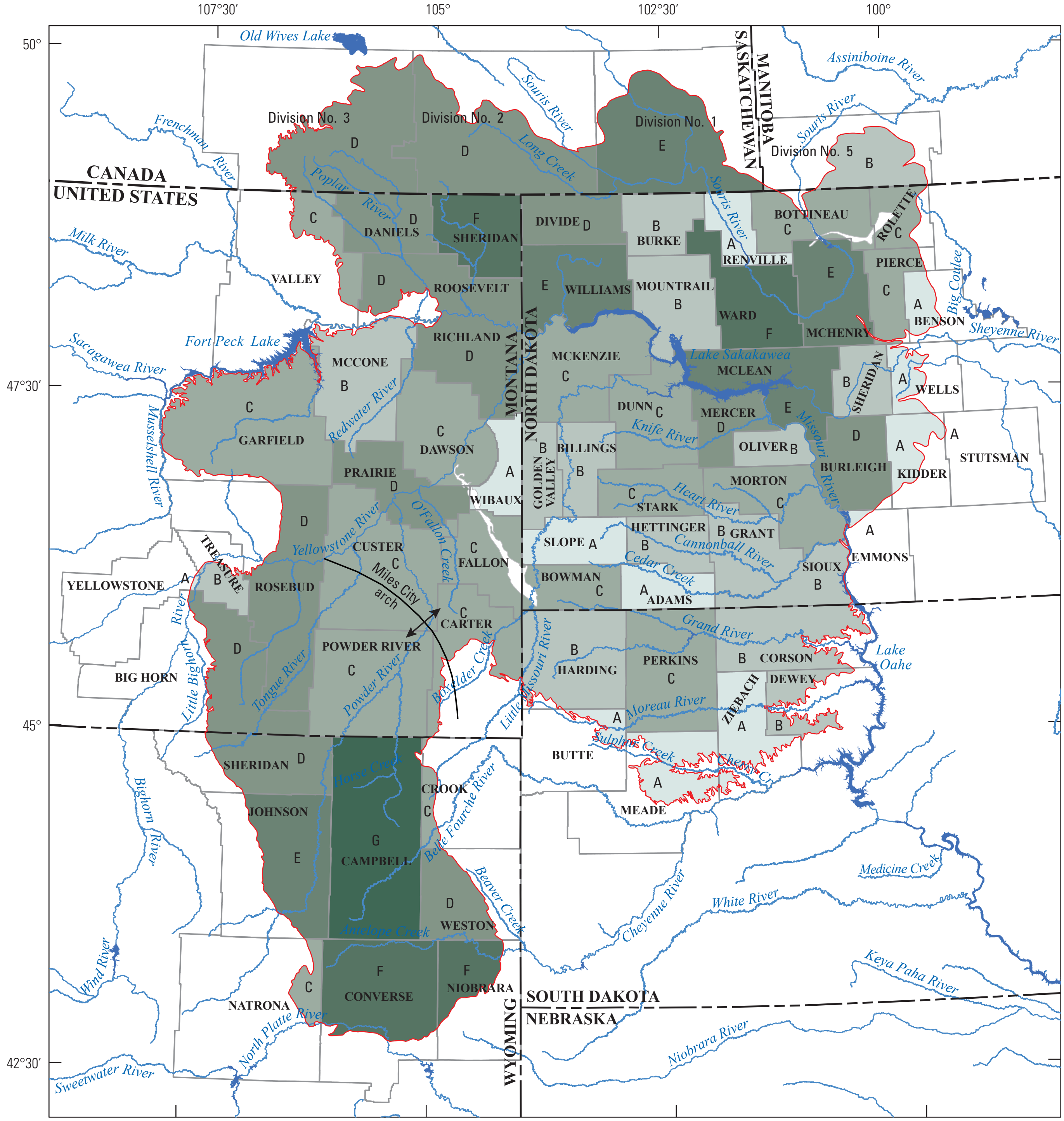


Figure 10. Estimated average (1981–2005) groundwater withdrawal in counties (United States) and census divisions (Canada) within the Williston and Powder River control volumes.

on the basis of allocated groundwater in major drainage basins within the Province (Halliday and Associates, 2009). Well data from the Water Security Agency of Saskatchewan (Information Services Corporation of Saskatchewan, 2013) were used to spatially distribute withdrawals for industrial uses. Two assumptions were made regarding industrial water use in Saskatchewan: (1) 50 percent of the annual allocated water for industrial use was actually withdrawn during 1981 to 2005, and (2) industrial water use changed little during the same time period. Domestic withdrawals were not accounted for individually in Saskatchewan or Manitoba. Community wells were identified in Manitoba based on wells from Manitoba Water Stewardship Division (Groundwater Information Network, 2013). The average community well withdrawal in Saskatchewan was applied to individual community wells in Manitoba. Water use in Canadian census divisions ranged from 0.93 to 7.04 ft^3/s (fig. 10), with an average withdrawal of 3.75 ft^3/s.

Other Flow Components

Water used for agricultural irrigation that exceeds evapotranspiration ET was assumed to result in groundwater recharge (irrigation recharge; table 2), which is listed by county in table 1–5 (appendix). Agricultural areas within the total control volume consist of about 26 percent cultivated croplands and 5 percent pasture and haylands (Fry and others, 2011). The irrigation efficiency I_e is equal to evapotranspiration divided by the consumptive use (Howell, 2002):

$$I_e = \frac{ET}{c}, \tag{9}$$

where

ET is evapotranspiration, in cubic feet per second, and

c is consumptive use, in cubic feet per second.

Consumptive use c is defined as the amount of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed (Kenny and others, 2009); implicit in this definition is the unknown quantity of irrigation recharge to groundwater R_I. On this basis, consumptive use specifically for irrigation c_I includes only two components:

$$c_I = ET + R_I, \tag{10}$$

where

R_I is irrigation recharge to groundwater, in cubic feet per second.

Combining equations 9 and 10 yields

$$R_I = c_I \left(1 - I_e\right). \tag{11}$$

In the study area, either sprinkler-irrigation or flood-irrigation systems typically are used; these systems have different irrigation efficiencies. Howell (2002) provided irrigation-efficiency estimates for these two systems, the averages of which were 74 percent for flood irrigation and 81 percent for sprinkler irrigation. These were used to estimate R_I on the basis of the relative percentages of croplands that use sprinkler or flood irrigation. Total withdrawal (surface water and groundwater) and c_I and irrigated acreage for each county in the United States were provided as a part of the water-use summaries for 1985, 1990, and 1995 (Solley and others, 1988, 1993, 1998); however, c_I was not provided in the water-use summaries for 2000 and 2005 (Hutson and others, 2004; Kenny and others, 2009).

The ratio of c_I to irrigation withdrawal was computed for each county for 1985, 1990, and 1995. The average of this ratio for each county was applied to withdrawals for 2000 and 2005 to determine c_I for these years. For each county, c_I was separated into flood and sprinkler irrigation according to the relative acreages of each irrigation type, and R_I was calculated from equation 11 for both types of irrigation. For counties partially outside of the two control volumes, R_I was scaled by the percentage of each county within these control volumes. Irrigation in Canada was assumed to be negligible because the majority of Canadian irrigators exist outside of the control volume (Clifton Associates Ltd., 2008). Estimated irrigation recharge R_I for the Williston and Powder River control volumes is 98 and 80 ft^3/s, respectively, for 1981–2005 (table 2), which is 2 and 5 percent of total estimated recharge, respectively.

Potentiometric surfaces estimated by Hotchkiss and Levings (1986) indicate that groundwater in the lower Tertiary and Upper Cretaceous aquifer systems flows from the Powder River structural basin into the Williston structural basin across the Miles City arch (fig. 2). This groundwater flow was estimated from Darcy's law (Domenico and Schwartz, 1990), in which the groundwater gradients were determined from potentiometric surfaces in Hotchkiss and Levings (1981), and hydrogeologic-unit thickness and hydraulic conductivity values were from Thamke and others (2014). This flow estimate was made for each of the hydrogeologic units in the lower Tertiary and Upper Cretaceous aquifer systems (fig. 3), the total of which is about 8 ft^3/s and is less than 1 percent of the total estimated recharge to the Williston control volume (table 2). Groundwater does not flow across the Miles City arch in the upper Fort Union aquifer because this aquifer is discontinuous in this area (fig. 2). Hotchkiss and Levings (1986) also indicated possible groundwater inflow to the Powder River structural basin from the Bull Mountain structural basin (fig. 1) in the Fox Hills and lower Hell Creek aquifers. This groundwater flow, if any, was assumed to be negligible by comparison to the Miles City arch area.

Lake Sakakawea overlies the upper Fort Union aquifer, the middle Fort Union hydrogeologic unit, and the glacial aquifer system (fig. 2). The potentiometric surface of the upper Fort Union aquifer indicates a groundwater gradient toward

Lake Sakakawea (fig. 1–2). Groundwater discharge to reservoirs in the Williston control volume was assumed to be on the same order of magnitude as groundwater flow between the two structural basins because of similar hydraulic gradients and hydraulic conductivity values. Therefore, groundwater discharge to reservoirs was assumed to be about 10 ft^3/s (table 2), which is less than 1 percent of the total estimated groundwater discharge for the Williston control volume. A potentiometric surface was not available for the glacial aquifer system, which resulted in uncertainty with respect to horizontal flow entering or exiting the two control volumes in these deposits, and therefore, inflows were assumed to be balanced by outflows.

Groundwater Flow

Groundwater discharge from the lower Tertiary and Upper Cretaceous aquifer systems occurs in the form of base flow to streams, where unconfined, and withdrawals for irrigation, public-supply, and self-supplied industrial uses. Groundwater in the hydrogeologic units within these aquifer systems largely is under confined conditions, except in the upper Fort Union aquifer and near basin margins, where not overlain by glacial deposits. Unconfined areas are characterized by local flow systems (Whitehead, 1996). The lower part of the upper Fort Union aquifer is in poor hydraulic connection with the upper part in many places because of interbedded shale layers that inhibit vertical groundwater flow (Thamke and others, 2014). In subcrop areas, the lower Tertiary and Upper Cretaceous aquifer systems probably are in hydraulic connection with the overlying glacial aquifer system, which was not assessed in terms of groundwater flow because a potentiometric surface was not available.

Potentiometric surfaces for the upper Fort Union aquifer, lower Fort Union aquifer, and Upper Cretaceous aquifer system were estimated by Thamke and others (2014) for the Williston structural basin on the basis of groundwater levels in wells and stream altitudes (fig. 1–2). Potentiometric surfaces for the Powder River structural basin estimated by Hotchkiss and Levings (1986) also are shown on fig. 1–2. For both structural basins, the potentiometric surface for the Upper Cretaceous aquifer system represents the average potentiometric surface for the lower Hell Creek and Fox Hills aquifers.

Although groundwater levels for the study area generally were steady prior to at least 2000 (Thamke and others, 2014), declining groundwater levels have occurred locally as a result of flowing wells that were installed for domestic use; these flow continuously as a result of hydrostatic pressure. Fischer (2013) described flowing wells in North Dakota open to the Fox Hills and lower Hell Creek aquifers primarily near the Yellowstone, Little Missouri, and Knife Rivers, with additional flowing wells near Lake Sakakawea. Collectively, these wells have a total flow rate of about 1.6 ft^3/s (Fischer, 2013). Near the Yellowstone River, flowing wells may have, in part, resulted in groundwater-level declines of about 1 foot per year (ft/yr) since the 1970s in the Fox Hills and Hell Creek aquifers in this area (Smith and others, 2000; Fischer, 2013). Honeyman (2007a, 2007b, 2007c) described hydraulic-head changes, mostly declines, in these aquifers near the Little Missouri River (fig. 2), which were measured in 15 observation wells and 35 flowing wells that were shut in temporarily to make hydraulic-head measurements. These rates of change during 11-year periods, either 1994–2005 or 1995–2006, ranged from -4.1 to 1.4 ft/year, with a mean rate of about -1.28 ft/yr, which was projected to result in wells ceasing to flow during the period 2007–93, depending on the well (Honeyman, 2007a, 2007b, 2007c). About 70 percent of flowing wells were installed from 1960 through 1990, and most declines were near the Yellowstone and Little Missouri Rivers (Fischer, 2013).

Williston Structural Basin

Depth to the water table in unconfined parts of the lower Tertiary and Upper Cretaceous aquifer systems in the Williston structural basin ranges from 0 to 823 ft, with a mean depth of 97 ft (table 6). The water table is shallowest near streams and deepest in upland areas. The largest horizontal hydraulic gradients are in the upper Fort Union aquifer, and the smallest are in the Upper Cretaceous aquifer system (table 6). Hydraulic head in the upper Fort Union aquifer minus that of the lower Fort Union aquifer (Δh_1) ranges from -267 to 530 ft (table 6). Δh_1 generally is positive (downward hydraulic gradient), but negative Δh_1 values (upward hydraulic gradient) occur near the Missouri, Yellowstone, and Little Missouri Rivers; near some tributaries; and below the Missouri Coteau. Hydraulic head in the lower Fort Union aquifer minus that of the Upper Cretaceous aquifer system (Δh_2) ranges from -808 to 730 ft (table 6). Positive values of Δh_2 occur below the Missouri Coteau, northwest of the Yellowstone River, and in the southeastern part of the structural basin. Negative values of Δh_2 occur in large areas near the Missouri, Yellowstone, Little Missouri, and Souris Rivers and near some tributaries.

Precipitation recharge accounts for about 26 percent of total recharge to the Williston control volume (table 2), with the largest recharge rates occurring in the lower Tertiary and Upper Cretaceous aquifer systems in the southeastern part, the glacial aquifer system in the far northeastern part, and the lower Tertiary aquifer system in the Peerless Plateau area in the northwest (fig. 1–1). Most of this recharge probably discharges to streams within these same general areas, with some groundwater possibly moving downward into the Upper Cretaceous aquifer system, where groundwater flow can occur over long distances. Precipitation recharge to the glacial aquifer system is focused within non-till areas (glaciofluvial, glaciolacustrine, loess, eolian, and glaciotectonic), except in the Turtle Mountains area (fig. 1–1). Some of this recharge discharges to local streams, and some probably moves downward into underlying bedrock aquifers. A large glacial lake (Old Wives Lake) to the north of the Peerless Plateau and outside of the Williston control volume is on glaciolacustrine deposits (fig. 1–1) through which recharge to groundwater might occur,

Table 6. Depth to the water table and hydraulic gradients for the Williston and Powder River control volumes.

[ft, feet; ft/mi, feet per mile]

Description	Williston control volume				Powder River control volume			
	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation
Depth to the water table, in ft	0	823	97	90	0	2,500	228	233
Upper Fort Union aquifer horizontal hydraulic gradient, in ft/mi	0	555	43	68	0	483	52	73
Lower Fort Union aquifer horizontal hydraulic gradient, in ft/mi	0	345	24	40	0	182	18	25
Upper Cretaceous aquifer system horizontal hydraulic gradient, in ft/mi	0	337	16	28	0	234	22	29
Hydraulic-head difference between the upper Fort Union and lower Fort Union aquifers (Δh_1), in ft	-267	530	87	185	-201	873	311	262
Hydraulic-head difference between the lower Fort Union aquifer and Upper Cretaceous aquifer system (Δh_2), in ft	-808	730	-4	205	-513	435	-12	350

depending on the vertical gradient. Some of this recharge might affect groundwater flow within the control volume.

Average estimated precipitation recharge for 1981–2005 is 0 for much of the area northwest of the Cedar Creek anticline (fig. 1–1), which is inconsistent with high altitudes in the potentiometric surfaces of the lower Tertiary aquifer system between streams in this area (fig. 1–2): this topographic control of the potentiometric surface indicates recharge from the land surface. The period 1981–2005, however, might not represent long-term averages adequately; for example, estimated precipitation recharge for most of this area for 1981–2011 is in the range of >0–0.5 in/yr (fig. 1-1). If groundwater flow is very slow, then unusually wet years might provide enough recharge to maintain topographic control of potentiometric surfaces.

The upper Fort Union aquifer is unconfined south of the glacial aquifer system (figs. 2 and 5). The potentiometric surface of the upper Fort Union aquifer is topographically controlled and generally follows the orientation of land-surface slopes, where flow is from topographically high areas toward stream valleys (fig. 1–2). Because of this topographic control, groundwater-flow directions in the unconfined upper Fort Union aquifer are highly variable. Where overlain by the glacial aquifer system, the potentiometric surface of the upper Fort Union aquifer generally has lower gradients and less topographic control than elsewhere. This aquifer does not exist near the Miles City arch because this uplifted area has been eroded (fig. 2).

The general topographic control of the upper Fort Union aquifer's potentiometric surface also exists in most areas of the lower Fort Union aquifer, except with less relief and lower hydraulic gradients (fig. 1–2), which likely result from hydraulic connection between the two aquifers. Horizontal groundwater-flow directions in the upper Fort Union and lower Fort Union aquifers generally are similar, except in the area south of Lake Sakakawea and east of the Little Missouri River, where groundwater flow directions are variable and topographically controlled in the upper Fort Union aquifer but primarily are northeast in the lower Fort Union aquifer (fig. 1–2). This contrast indicates the weakest area of hydraulic connection between these two aquifers in the Williston structural basin. The confining properties of the middle Fort Union hydrogeologic unit, which does not exist in the northeastern part of the Williston control volume, are spatially variable (Thamke and others, 2014).

In topographically high areas, groundwater probably flows downward from the upper Fort Union aquifer into the lower Fort Union aquifer because of downward hydraulic gradients. For example, in the area northwest of the Cedar Creek anticline near the headwaters of the Redwater River, the potentiometric surfaces of the upper Fort Union and lower Fort Union aquifers are about 3,200 and 3,000 ft above the

North American Vertical Datum of 1988 (NAVD 88), respectively (fig. 1–2). The likely reason for this potentiometric high area in the lower Fort Union aquifer is downward flow from the upper Fort Union aquifer. Near streams into which discharge from the upper Fort Union aquifer occurs, the two aquifers have nearly equal potentiometric surfaces, with slightly upward gradients along many stream reaches. Upward gradients indicate that the lower Fort Union aquifer probably flows upward into the upper Fort Union aquifer, where groundwater discharges to streams. A high area in the potentiometric surfaces of the upper Fort Union and lower Fort Union aquifers occurs in the location of the Missouri Coteau, and groundwater flow in both aquifers is southerly toward Lake Sakakawea and the Missouri River and northerly toward the Souris River (fig. 1–2). This situation indicates likely recharge to the lower Tertiary aquifer system from the overlying glacial aquifer system.

Because of the general hydraulic connection between the upper Fort Union and lower Fort Union aquifers, a general assessment of groundwater flow in relation to recharge and discharge can be made. Streams are the primary features where groundwater recharge and discharge occur in the Williston control volume, with stream infiltration accounting for about 71 percent of total recharge and discharge to streams accounting for about 97 percent of total discharge (table 2). Where the glacial aquifer system is not present, most of this recharge and discharge occurs to and from the lower Tertiary aquifer system because this is the uppermost aquifer system. In this aquifer system, groundwater-flow directions generally are toward streams, where most of the discharge occurs throughout the study area. Most of the discharge to streams from the Upper Cretaceous aquifer system occurs on the eastern side of the Williston control volume. Areas of stream infiltration (fig. 1–1), however, are difficult to interpret on the basis of the potentiometric maps because groundwater-flow directions generally point toward streams in unconfined areas (fig. 1–2). Upstream reaches of the Yellowstone River and its tributaries west of the Cedar Creek anticline were determined to be infiltrating reaches (reaches 94–96 and 96–97; fig. 1–1; table 1–3), which is inconsistent with groundwater gradients (fig. 1–2). Possible sources of error are described in the section "Interaction of Groundwater and Surface Water." Numerical modeling would provide a way to test several scenarios of the interaction of groundwater and surface water and variable hydraulic connection between hydrogeologic units, which could provide insights into this apparent inconsistency.

Groundwater flow in the Upper Cretaceous aquifer system generally is easterly or northeasterly in the Williston structural basin (fig. 1–2), with lower horizontal hydraulic gradients than in the upper Fort Union and lower Fort Union aquifers (fig. 1–2; table 6). Interpretation of potentiometric surface maps (fig. 1–2) indicates that, where unconfined, groundwater in the Upper Cretaceous aquifer system flows toward several streams in the southeastern part of the Williston structural basin. Where confined, groundwater flows toward the Souris, Yellowstone, and Little Missouri Rivers and the upper part of the Missouri River, which are areas where an upward gradient exists between the Upper Cretaceous aquifer system and the lower Fort Union aquifer. This upward gradient indicates possible upward groundwater flow into the lower Tertiary aquifer system, where discharge to streams occurs. Flowing wells near these rivers discharge water from the Upper Cretaceous aquifer system and also might allow leakage into the overlying lower Tertiary aquifer system because of inadequate sealing or corrosion of these wells (Fischer, 2013). The upward hydraulic gradient near some reaches of the Yellowstone and Missouri Rivers would allow this to occur. Hydraulic gradients in the Upper Cretaceous aquifer system near the southeastern streams are steeper than those near other streams in the study area (fig. 1–2). Groundwater-flow directions for the Upper Cretaceous aquifer system (fig. 1–2) generally are consistent with those described by Downey and Dinwiddie (1988).

Powder River Structural Basin

Depth to the water table in unconfined parts of the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin ranges from 0 to 2,497 ft, with a mean depth of 228 ft (table 6). The water table is shallowest near streams and deepest in upland areas, particularly in the western part of the Powder River structural basin. The largest horizontal hydraulic gradients occur in the upper Fort Union aquifer, and the smallest occur in the lower Fort Union aquifer (table 6). The difference in hydraulic head between the upper Fort Union and lower Fort Union aquifers (Δh_1) ranges from -201 to 873 ft (table 6). Δh_1 generally is positive (downward hydraulic gradient), but negative values (upward hydraulic gradients) occur along some reaches of the Powder and Tongue Rivers. The difference in hydraulic head between the lower Fort Union aquifer and Upper Cretaceous aquifer system (Δh_2) ranges from -513 to 435 ft (table 6). Positive values of Δh_2 occur in the northern, middle, and southern parts of the Powder River control volume; negative values occur in large parts of the remaining area and have no spatial relation to streams.

Precipitation recharge accounts for about 15 percent of total recharge to the Powder River control volume (table 2), with the largest recharge rates occurring in the northern part (fig. 1–1). Most of this recharge probably discharges to streams within these same general areas, and some groundwater possibly flows downward into the Upper Cretaceous aquifer system, where groundwater flow can occur over long distances. Groundwater flow in the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin generally is northerly, except at the far southern end, where flow is toward the east and discharges to Antelope Creek, as indicated by potentiometric-surface gradients (fig. 1–2) and gaining stream reaches (fig. 1–1). These groundwater-flow directions are consistent with those described by Downey and Dinwiddie (1988) for the Upper Cretaceous aquifer system.

Locally in the upper Fort Union aquifer, groundwater flows toward and discharges into streams, primarily the Powder and Tongue Rivers, and is topographically controlled (fig. 1–2). The difference in potentiometric-surface gradients between the upper Fort Union and lower Fort Union aquifers is greater in the Powder River structural basin than in the Williston structural basin (fig. 1–2, table 6), indicating that the greatest hydraulic separation between the two aquifers occurs in the Powder River structural basin. These two aquifers are separated by the middle Fort Union hydrogeologic unit that is described as a confining unit in the Powder River structural basin (Lewis and Hotchkiss, 1981; Hotchkiss and Levings, 1986). Potentiometric surfaces for the lower Fort Union aquifer and Upper Cretaceous aquifer system are similar in the middle part of the structural basin (fig. 1–2). In the northern part of the structural basin, groundwater in the lower Fort Union aquifer flows toward the Tongue and Powder Rivers, which is not apparent in the Upper Cretaceous aquifer system (fig. 1–2).

Streams are the primary features where groundwater recharge and discharge occur in the Powder River control volume, with stream infiltration accounting for about 80 percent of total recharge and discharge to streams accounting for about 92 percent of total discharge (table 2). Groundwater-flow directions in the upper Fort Union aquifer (fig. 1–2) generally are consistent with areas of recharge and discharge (table 1–2). For example, precipitation recharge occurs east and northeast of the Bighorn Mountains (fig. 1–1), with groundwater in the lower Tertiary aquifer system flowing east and northeast from these areas (fig. 1–2). Precipitation recharge in the southwestern part of the Powder River structural basin (fig. 1–1) results in groundwater flow toward the east, as indicated by all three potentiometric surfaces in figure 1–2.

Summary

The three uppermost principal aquifer systems of the Northern Great Plains—the glacial, lower Tertiary, and Upper Cretaceous aquifer systems—are described in this report. These aquifer systems exist primarily in two nationally important fossil-fuel-producing areas: the Williston and Powder River structural basins. Recognizing the importance of understanding water resources in these energy-rich basins, the U.S. Geological Survey (USGS) Groundwater Resources Program (*http://water.usgs.gov/ogw/gwrp/*) began a groundwater study of the Williston and Powder River structural basins in 2011 to quantify this groundwater resource, the results of which are described in this report. The overall objective of this study was to characterize, quantify, and provide an improved conceptual understanding of the three uppermost principal aquifer systems in energy-resource areas of the Northern Great Plains to assist in groundwater-resource management for multiple uses.

The glacial aquifer system is contained within glacial deposits that overlie the lower Tertiary and Upper Cretaceous aquifer systems in the northeastern part of the Williston structural basin. Productive sand and gravel aquifers exist within the glacial aquifer system. The Upper Cretaceous aquifer system is contained within bedrock lithostratigraphic units as deep as 2,850 feet (ft) and 8,500 ft in the Williston and Powder River structural basins, respectively. Petroleum extraction from much deeper formations, such as the Bakken Formation, is rapidly increasing as a result of new technologies. Extraction of coal-bed natural gas from within the lower Tertiary aquifer system requires removal of large volumes of groundwater to allow degasification. Application of these technologies has resulted in increased demand for freshwater supplies, particularly since about 2005, that results in a potential for large increases in groundwater extraction.

The period prior to 1960 is defined as the predevelopment period when little groundwater was extracted. From 1960 through 1990, numerous flowing wells were installed near the Yellowstone, Little Missouri and Knife Rivers, resulting in local groundwater declines. In this study, groundwater recharge and discharge components were estimated for the period 1981–2005; these estimates were made for a control volume that is defined to contain the glacial, lower Tertiary, and Upper Cretaceous aquifer systems within the areal extent of the Upper Cretaceous aquifer system in the two structural basins.

The study area includes parts of Montana, North Dakota, South Dakota, and Wyoming in the United States and Manitoba and Saskatchewan in Canada. The glacial aquifer system is contained within glacial drift consisting primarily of till, with smaller amounts of glacial outwash sand and gravel deposits. The lower Tertiary and Upper Cretaceous aquifer systems are contained within several formations of the Tertiary and Cretaceous geologic systems that are hydraulically separated from underlying aquifers by a basal confining unit. The lower Tertiary and Upper Cretaceous aquifer systems each were divided into three hydrogeologic units that correspond to one or more lithostratigraphic units. Lithostratigraphic units within the lower Tertiary aquifer system contain sandstone, siltstone, shale, and coal, with complex interbedding of low-permeability layers of discontinuous lateral extent. Lithostratigraphic units within the Upper Cretaceous aquifer system contain sandstone, siltstone, and shale.

The lower Tertiary aquifer system contains, from top to bottom, the upper Fort Union aquifer, middle Fort Union hydrogeologic unit, and lower Fort Union aquifer. The Upper Cretaceous aquifer system contains, from top to bottom, the upper Hell Creek hydrogeologic unit, lower Hell Creek aquifer, and Fox Hills aquifer. The middle Fort Union and upper Hell Creek hydrogeologic units may act as confining units in some areas and aquifers in other areas because of spatially variable lithology. Clinker is a type of metamorphic rock that occurs near the land surface in the lower Tertiary aquifer system and results from burning coalbeds and the surrounding shale that is baked in the process. These metamorphosed rocks collapse and fill the void left after the coalbed has burned,

resulting in high porosity for water infiltration and storage. Clinker primarily exists in the Powder River structural basin.

Groundwater recharge from the land surface occurs from infiltration of direct rainfall and snowmelt (precipitation recharge), streams that sink into the ground (stream infiltration), and irrigation recharge. Total estimated recharge to the Williston and Powder River control volumes is 4,560 and 1,500 cubic feet per second (ft^3/s), respectively. The large difference in estimated recharge between the two control volumes is because the Williston control volume is 3.7 times larger than the Powder River control volume and receives greater precipitation. Estimated precipitation recharge is 26 and 15 percent of total recharge for the Williston and Powder River control volumes, respectively. Estimated stream infiltration is 71 and 80 percent of total recharge for the Williston and Powder River control volumes, respectively. The higher rate for the Powder River control volume is assumed to result from faults near the Bighorn Mountains and clinker zones that provide areas of high permeability for streams to recharge the groundwater. Estimated irrigation recharge for the Williston and Powder River control volumes is 2 and 5 percent of total estimated recharge, respectively.

Estimated groundwater discharge to streams is 97 and 92 percent of total discharge for the Williston and Powder River control volumes, respectively. Estimated groundwater withdrawal is 3 and 7 percent of the total discharge for the Williston and Powder River control volumes, respectively. For the Williston control volume, groundwater withdrawals from the glacial aquifer system and other surficial deposits were larger than withdrawals from the lower Tertiary or Upper Cretaceous aquifer systems. For both control volumes, groundwater withdrawals from the lower Tertiary aquifer system were larger than those from the Upper Cretaceous aquifer system. Fort Peck Lake, Lake Sakakawea, and Lake Oahe are large reservoirs in the study area that control flow in the Missouri River. Groundwater discharge to reservoirs in the Williston control volume was assumed to be about 10 ft^3/s, or less than 1 percent of the total estimated discharge. Groundwater in the lower Tertiary and Upper Cretaceous aquifer systems flows from the Powder River control volume into the Williston control volume at a rate of about 8 ft^3/s.

In the Williston structural basin, depth to the water table in unconfined parts of the lower Tertiary and Upper Cretaceous aquifer systems ranges from 0 to 823 ft, with a mean depth of 97 ft. The largest horizontal hydraulic gradients in this basin are in the upper Fort Union aquifer, and the smallest are in the Upper Cretaceous aquifer system. In the Powder River structural basin, depth to the water table in unconfined parts of the lower Tertiary and Upper Cretaceous aquifer systems ranges from 0 to 2,497 ft, with a mean depth of 228 ft. The largest horizontal hydraulic gradients in this basin are in the upper Fort Union aquifer, and the smallest are in the lower Fort Union aquifer.

Groundwater flow in the Williston control volume generally is from the west and southwest toward the east, where discharge to streams occurs. Locally in the uppermost hydrogeologic units, groundwater flows in accordance with land-surface slopes and discharges to streams. In the northern and western parts of the Williston control volume, the potentiometric surfaces for the upper Fort Union and lower Fort Union aquifers are similar, except with less relief for the lower Fort Union aquifer, which indicates probable hydraulic connection between the two aquifers.

Groundwater in the Powder River control volume generally flows north, with local variations, particularly in the upper Fort Union aquifer, where flow is toward streams. The difference in potentiometric-surface gradients between the upper Fort Union and lower Fort Union aquifers is greater in the Powder River structural basin than in the Williston control volume, indicating that the greatest hydraulic separation between the two aquifers occurs in the Powder River structural basin.

References Cited

Anna, L.O., Pollastro, Richard, and Gaswirth, S.B., 2011, Williston Basin Province—Stratigraphic and structural framework to a geologic assessment of undiscovered oil and gas resources, chap. 2 *of* Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010: U.S. Geological Survey Data Series 69-W, 21 p., accessed August 21, 2013, at *http://pubs.er.usgs.gov/publication/ds69W*.

Anna, L.O., 2011, Effects of groundwater flow on the distribution of biogenic gas in parts of the Northern Great Plains of Canada and United States: U.S. Geological Survey Scientific Investigations Report 2010–5251, 24 p., accessed July 31, 2013, at *http://pubs.usgs.gov/sir/2010/5251/*.

Aurand, K. R., 2013, Groundwater recharge estimates for the lower Tertiary and Upper Cretaceous aquifers in the Williston and Powder River structural basins: Rapid City, South Dakota, South Dakota School of Mines and Technology, M.S. Thesis, 101 p.

Bednar, J.M., 2013, Interaction of groundwater and surface water in the Williston and Powder River structural basins: Rapid City, South Dakota, South Dakota School of Mines and Technology, M.S. Thesis, 110 p.

Beikman, H.M., 1962, Geology of the Powder River Basin, Wyoming and Montana with reference to subsurface disposal of radioactive wastes: U.S. Geological Survey Open-File Report 62-7, 84 p. (Also available at *http://pubs.er.usgs.gov/publication/ofr627*)

Bergantino, R.N., and Feltis, R.D., 1985, Structure contour map on the top of the Madison Group, Montana: Montana Bureau of Mines and Geology, Open-File Report 159, 2 sheets, scale 1:500,000.

Blodgett, D.L., Booth, N.L., Kunicki, T.C., Walker, J.L., and Viger, R.J., 2011, Description and testing of the Geo Data Portal—Data integration framework and Web processing services for environmental science collaboration: U.S. Geological Survey Open-File Report 2011–1157, 9 p., accessed July 31, 2013, at *http://pubs.usgs.gov/of/2011/1157/*.

Bluemle, J.P., 1983, Geologic and topographic bedrock map of North Dakota: North Dakota Geological Survey, Miscellaneous Map 25, 1 sheet, scale 1:670,000.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., and Schulze, E.D., 1996, Maximum rooting depth of vegetation types at the global scale: Oecologia, v. 108, no. 4, p. 583–594. (Also available at *http://dx.doi.org/10.1007/BF00329030*.)

Carr, J.E., Chase, E.B., Paulson, R.W., and Moody, D.W., 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water Supply Paper 2350, 553 p. (Also available at *http://pubs.er.usgs.gov/publication/wsp2350*.)

Clifton Associates Ltd., 2008, The economic, social and environmental benefits of expanding irrigation in Saskatchewan: A Time to Irrigate, v. 2, Regina, Saskatchewan, prepared for Saskatchewan Irrigation Projects Association Inc., accessed August 19, 2013, at *http://www.irrigationsaskatchewan.com/SIPA/sipa_021.htm.*

Cronshey, R., McCuen, R., Miller, N., Rawls, W., Robbins, S., and Woodward, D., 1986, Urban hydrology for small watersheds, TR-55 (2d ed.): Washington, D.C., U.S. Dept. of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55, 164 p.

Delin, G.N., Healy, R.W., Lorenz, D.L., and Nimmo, J.R., 2007, Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA: Journal of Hydrology, v. 334, p. 231–249. (Also available at *http://dx.doi.org/10.1016/j.jhydrol.2006.10.010*.)

Dolton, G.L., Fox, J.E., and Clayton, J.L., 1990, Petroleum geology of the Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 88–450–P, 64 p. (Also available at *http://pubs.er.usgs.gov/publication/ofr88450P*.)

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, 824 p.

Downey, J.S., 1986, Geohydrology of bedrock aquifers in the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–E, 87 p., 3 pls. (Also available at *http://pubs.er.usgs.gov/publication/pp1402E*.)

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming summary: U.S. Geological Survey Professional Paper 1402–A, 64 p. (Also available at *http://pubs.er.usgs.gov/publication/pp1402A*.)

Dripps, W.R., and Bradbury, K.R., 2007, A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas: Hydrogeology Journal, v. 15, no. 3, p. 433–444. (Also available at *http://dx.doi.org/10.1007/s10040-007-0160-6*.)

Druse, S.A., Dodge, K.A., and Hotchkiss, W.R., 1981, Base flow and chemical quality of streams in the Northern Great Plains area, Montana and Wyoming, 1977–78: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–692, 59 p. (Also available at *http://pubs.er.usgs.gov/publication/ofr81692*.)

Eisenlohr, W.S., Jr., Sloan, C.E., 1968, Generalized hydrology of prairie potholes on the Coteau du Missouri, North Dakota: U.S. Geological Survey Circular 558, 22 p. (Also available at *http://pubs.er.usgs.gov/publication/cir558*.)

Feinstein, D.T., Hunt, R.J., and Reeves, H.W., 2010, Regional groundwater-flow model of the Lake Michigan Basin in support of Great Lakes Basin water availability and use studies: U.S. Geological Survey Scientific Investigations Report 2010–5109, 379 p., accessed January 2011 at *http://pubs.usgs.gov/sir/2010/5109/*.

Fischer, K., 2013, Groundwater flow model inversion to assess water availability in the Fox Hills-Hell Creek aquifer: North Dakota State Water Commission, North Dakota Water Resource Investigation No. 54, 325 p. (Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentPDF/PB-2246/WRI%2054.pdf*.)

Flores, R.M., and Bader, L.R., 1999, Fort Union coal in the Powder River Basin, Wyoming and Montana—A synthesis, chap. PS *of* Fort Union Coal Assessment Team, 1999 Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625-A, p. PS1–PS75. (Also available at *http://pubs.usgs.gov/pp/p1625a/Chapters/PS.pdf*.)

Flores, R.M., Keighin, C.W., Ochs, A.M., Warwick, P.D., Bader, L.R., and Murphy, E.C., 1999, Framework geology of Fort Union coal in the Williston Basin, chapter WF *of* Fort Union Coal Assessment Team, 1999 Resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625–A, p. WF1–WF64. (Also available at *http://pubs.usgs.gov/pp/p1625a/pp1625A.html*.)

Flores, R.M., Spear, B.D., Kinney, S.A., Purchase, P.A., and Gallagher, C.M., 2010, After a century—Revised Paleogene coal stratigraphy, correlation, and deposition, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Professional Paper 1777, 97 p. (Also available at *http://pubs.usgs.gov/pp/1777/*.)

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011, Completion of the 2006 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 77, no. 9, p. 858–864.

Fullerton, D.S., Bluemle, L.C., Steece, F.V., Tipton, M.J., Bretz, R., and Goebel, J.E., 1995, Quaternary geologic map of the Dakotas 4° x 6° quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series Map I–1420 (NL–14), 9 p. (Also available at *http://pubs.usgs.gov/imap/i-1420/nl-14/*.)

Fullerton, D.S., Christiansen, E.A., Schreiner, B.T., Colton, R.B., and Clayton, L., 2007, Quaternary Geologic Map of the Regina 4° x 6° Quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Series Map I–1420 (NM–13), 39 p. (Also available at *http://pubs.usgs.gov/imap/i-1420/nm-13/*.)

Fullerton, D.S., Ringrose, S.M., Clayton, L., Schreiner, B.T., and Goebel, J.E., 2000, Quaternary geologic map of the Winnipeg 4° x 6° quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Series Map I–1420 (NM–14), 16 p. (Also available at *http://pubs.usgs.gov/imap/i-1420/nm-14/*.)

Gaswirth, S.B., Marra, K.R., Cook, T.A, Charpentier, R.R., Gautier, D.L., Higley, D.K., Klett, T.R., Lewan, M.D., Lillis, P.G., Schenk, C.J., Tennyson, M.E., and Whidden, K.J., 2013, Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013: U.S. Geological Survey Fact Sheet 2013–3013, 4 p. (Also available at *http://pubs.usgs.gov/fs/2013/3013/*.)

Groundwater Information Network, 2013, Water wells, monitoring sites, and aquifers of Canada: Manitoba Water Stewardship Division, accessed January 23, 2013, at *http://ngwd-bdnes.cits.nrcan.gc.ca/service/api_ngwds:gin/en/wmc/aquifermap.html*.

Halliday and Associates, 2009, Industrial water use in Saskatchewan: Saskatchewan Environmental Society, 43 p., accessed November 7, 2012, at *http://www.environmentalsociety.ca/main/wp-content/uploads/2011/08/Industrial-Water-Use-in-SaskatchewanFinal.pdf*.

Hargreaves, G.H., and Samani, Z.A., 1985, Reference crop evapotranspiration from temperature: Applied Engineering in Agriculture, v. 1, no. 2, p. 96–99.

Healy, R.W., 2010, Estimating groundwater recharge: Cambridge, U.K., Cambridge University Press, 245 p.

Healy, R.W., and Cook, P.G., 2002, Using groundwater levels to estimate recharge: Hydrogeology Journal, v. 10, no. 1, p. 91–109. (Also available at *http://dx.doi.org/10.1007/s10040-001-0178-0*.)

Heffern, E.L., and Coates, D.A., 1999, Hydrogeology and ecology of clinker in the Powder River Basin, Wyoming and Montana, *in* Miller, W.R., ed., Coalbed methane and the Tertiary geology of the Powder River Basin, Wyoming and Montana: Wyoming Geological Association, 50th Annual Field Conference Guidebook, v. 50, p. 231–252.

Heffern, E.L., Reiners, P.W., and Riihimaki, C.A., 2013, Clinker distribution and age in the Powder River structural basin: Montana Bureau of Mines and Geology Geologic Map 64.

Honeyman, R.P., 2007a, Pressure head fluctuations of the Fox Hills-Hell Creek aquifer in Billings, Golden Valley, and Slope Counties, North Dakota: North Dakota State Water Commission, Water Resources Investigation No. 42, 115 p. (Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetSubContentPDF/PB-1562/BillGVSlopReport.pdf*.)

Honeyman, R.P., 2007b, Pressure head fluctuations of the Fox Hills-Hell Creek aquifer in McKenzie County, North Dakota: North Dakota State Water Commission, Water Resources Investigation No. 43, 130 p. (Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetSubContentPDF/PB-1563/McKenzieReport.pdf*.)

Honeyman, R.P., 2007c, Pressure head fluctuations of the Fox Hills-Hell Creek aquifer in the Knife River Basin, North Dakota: North Dakota State Water Commission, Water Resources Investigation No. 44, 86 p. (Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetSubContentPDF/PB-1564/KnifeRReport.pdf*.)

Hotchkiss, W.R., and Levings, J.F., 1986, Hydrogeology and simulation of water flow in strata above the Bearpaw Shale and equivalents of eastern Montana and northeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 85–4281, 72 p. (Also available at *http://pubs.er.usgs.gov/publication/wri854281*.)

Howell, T.A., 2002, Irrigation system efficiencies: Lamar, Colorado, Central Plains Irrigation Short Course and Exposition Proceedings, p. 80–92, accessed March 5, 2013, at *http://www.cprl.ars.usda.gov/pdfs/Irrigation%20System%20Efficiencies.pdf.*

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 52 p. (Also available at *http://pubs.usgs.gov/circ/2004/circ1268/*.)

Information Services Corporation of Saskatchewan, 2013, Water wells database: Water Security Agency of Saskatchewan, accessed January 14, 2013, at *ftp://portaldata:freedata@ftp.isc.ca/PackagedData/SWA/WSA_WaterWells.zip*.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p. (Also available at *http://pubs.usgs.gov/circ/1344/*.)

Koch, D., Ringrose, C.D., Moore, R.C., and Brooks, D.L., 1982, Monitoring and modeling the shallow ground-water systems in the Powder River Basin: Englewood, Colorado, Hittman Associates, report to U.S. Bureau of Mines, 359 p.

Lewis, B.D., and Hotchkiss, W.R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I–1317, 16 maps, 6 sheets. (Also available at *http://pubs.er.usgs.gov/publication/i1317*.)

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H., 1982, Hydrology for Engineers: New York, McGraw-Hill, 512 p.

Lobmeyer, D.H., 1985, Freshwater heads and ground-water temperatures in aquifers of the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–D, 18 p. (Also available at *http://pubs.er.usgs.gov/publication/pp1402D*.)

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, WDB 904, scale 1:500,000. (Also available at *http://pubs.er.usgs.gov/publication/70046739*.)

Lowry, M.E., and Rankl, J.G., 1987, Hydrology of the White Tail Butte area, northern Campbell County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82–4117, 46 p. (Also available at *http://pubs.er.usgs.gov/publication/wri824117*.)

Macdonald, Robert, and Slimmon, W.L., comps., 1999, Geological map of Saskatchewan: Saskatchewan Industry and Resources, Saskatchewan Geological Survey, 1 sheet, scale 1:1,000,000.

Martin, J.E., Sawyer, J.F., Fahrenbach, M.D., Tomhave, D.W., and Schulz, L.D., 2004, Geologic map of South Dakota: South Dakota Geological Survey, General Map Series 10, scale 1:500,000.

McCallum, A.M., Andersen, M.S., and Acworth, R.I., 2013, A new method for estimating recharge to unconfined aquifers using differential river gauging: Groundwater, online early view, accessed at (*http://onlinelibrary.wiley.com/doi/10.1111/gwat.12046/pdf*).

McLaughlin, J.F., Rodgers, J.R., Gribb, N.W., Hays, R.J., and Cottingham, K.D., 2012, 2009 coalbed natural gas regional groundwater monitoring update—Powder River Basin, Wyoming: Wyoming State Geological Survey Open File Report OFR 12–5, 400 p. (Also available at *http://www.wsgs.uwyo.edu/public-info/onlinepubs/docs/PRB_Drawdown.pdf*.)

Montana Bureau of Mines and Geology, 2013, Geologic quadrangle maps—1:100,000: accessed July 2, 2013, at *http://www.mbmg.mtech.edu/gmr/gmr-statemap.asp*.

Montana State Information Technology Services Division, 2013, Water well database: Montana Ground Water Information Center, accessed January 10, 2013, at *http://nris.mt.gov/nsdi/nris/shape/gwicwells.zip*.

Multi-Resolution Land Characteristics Consortium, 2011, National land cover database—Conterminous United States NLCD 2006 land cover: Multi-Resolution Land Characteristics Consortium, 30-m data, accessed September 26, 2011, at *http://www.mrlc.gov/nlcd2006_downloads.php*.

Murphy, E.C., Nordeng, S.H., Juenker, B.J., and Hoganson, J.W., 2009, North Dakota stratigraphic column: North Dakota Geological Survey Miscellaneous Series 91, 1 p. (Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/pdf/Strat-column-NDGS-(2009).pdf*.)

Neff, B.P., Day, S.M., Piggott, A.R., and Fuller, L.M., 2005, Base flow in the Great Lakes Basin: U.S. Geological Survey Scientific Investigations Report 2005–5217, 23 p., accessed July 31, 2013, at *http://pubs.usgs.gov/sir/2005/5217/*.

Nicolas, M.P.B., Matile, G.L.D., Keller, G.R., and Bamburak, J.D., 2010, Phanerozoic geology of southern Manitoba: Manitoba Geological Survey Stratigraphic Map Series SM2010–1, 1 sheet, scale 1:600,000.

North Dakota Information Technology Department, 2012, North Dakota Geographic Information Systems water data sites database: North Dakota State Water Commission, accessed October 29, 2012, at *http://www.nd.gov/gis/apps/DataDownload/?clipping=Full&coord=ND83-SF&format=SHAPE&layers=NDHUB.WATERDATASITES*.

North Dakota State Water Commission, 2013a, County ground water studies: accessed March 20, 2013, at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubCategoryRecord/Reports%20and%20Publications/County%20Ground%20Water%20Studies*.

North Dakota State Water Commission, 2013b, North Dakota surficial aquifers: accessed February 12, 2013, at *http://web.apps.state.nd.us/hubdataportal/srv/en/main.home*.

Peacock, K., 1997, Assessing the cumulative impacts of surface mining and coal bed methane development on shallow aquifers in the Powder River Basin, Wyoming, *in* Brandt, J.E., ed., Proceedings of the 14th Annual National Meeting of the American Society for Surface Mining and Reclamation, Austin, Texas, May 10-15, 1997: American Society for Surface Mining and Reclamation, p. 648-666.

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–A, 34 p., 20 pls., available at: *http://pubs.er.usgs.gov/publication/pp1273A*

Rankl, J.G., and Lowry, M.E., 1990, Ground-water-flow systems in the Powder River structural basin, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Report 85–4229, 39 p., 1 pl. (Also available at *http://pubs.er.usgs.gov/publication/wri854229*.)

Reilly, T.E., Dennehy, K.F., Alley, W.M., and Cunningham, W.L., 2008, Ground-water availability in the United States: U.S. Geological Survey Circular 1323, 70 p. (Also available at *http://pubs.usgs.gov/circ/1323/*.)

Roy, S.B., Ricci, P.F., Summers, K.V., Chung, C.F., and Goldstein, R.A., 2005, Evaluation of the sustainability of water withdrawals in the United States, 1995 to 2025: Journal of the American Water Resources Association (JAWRA), v. 41, no. 5, p. 1091–1108. (Also available at *http://dx.doi.org/10.1111/j.1752-1688.2005.tb03787.x*.)

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—Update: U.S. Geological Survey Water-Resources Investigations Report 98–4148, 52 p. (Also available at *http://pubs.usgs.gov/wri/wri984148/*.)

Sandberg, C.A., 1962, Geology of the Williston Basin, North Dakota, Montana, and South Dakota, with reference to subsurface disposal of radioactive wastes: U.S. Geological Survey Open-File Report 62–115, 148 p. (Also available at *http://pubs.er.usgs.gov/publication/ofr62115*.)

Saskatchewan Watershed Authority, 2011, Community water use records 1996 to 2010: Saskatchewan Watershed Authority Report No. 24, 244 p., accessed November 26, 2012, at *http://www.saskh20.ca/pdf/sk_community_water_use_report_for_2010.pdf*.

Schuh, W.M., 2010, Water appropriation requirements, current water use, and water availability for energy industries in North Dakota—A 2010 summary: North Dakota State Water Commission Water Resources Investigation No. 49, 415 p. (Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetContentPDF/PB-1800/W&E%20RPT%20FinalR.pdf*.)

Smakhtin, V.U., 2001, Low flow hydrology—A review: Journal of Hydrology, v. 240, p. 147–186. (Also available at *http://dx.doi.org/10.1016/S0022-1694(00)00340-1*.)

Smith, L.N., LaFave, J.I., Patton, T.W., Rose, J.C., and McKenna, D.P., 2000, Ground-water resources of the lower Yellowstone River area—Dawson, Fallon, Prairie, Richland, andWibaux Counties, Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas No. 1, variously paged.

Soller, D.R., Packard, P.H., and Garrity, C.P., 2012, Database for USGS Map I-1970—Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains: U.S. Geological Survey Data Series 656, accessed July 31, 2013, at *http://pubs.usgs.gov/ds/656/*.)

Solley, W.B., Merk, C.F., and Pierce, R.R., 1988, Estimated use of water in the United States in 1985: U.S. Geological Survey Circular 1004, 82 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1004*.)

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 76 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1081*.)

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 82 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1200*.)

South Dakota Department of Environment and Natural Resources, 2013, South Dakota water well completion reports: South Dakota Department of Environment and Natural Resources database, accessed March 3, 2013, at *http://denr.sd.gov/des/wr/dblogsearch.aspx*.

Thamke, J.N., LeCain, G.D., Ryter, D.W., Sando, Roy, and Long, A.J., 2014, Hydrogeologic framework of the upper principal aquifer systems in the Williston and Powder River structural basins, United States and Canada: U.S. Geological Survey Scientific Investigations Report 2014-5047, 38 p. (Also available at *http://pubs.usgs.gov/sir/2014/5047/*.)

Thornton, P.E., Thornton, M.M., Mayer, B.W., Wilhelmi, N., Wei, Y., Cook, R.B., 2012, Daymet— Daily surface weather on a 1 km grid for North America, 1980–2011: Oak Ridge, Tennessee, Oak Ridge National Laboratory Distributed Active Archive Center, accessed August 2013, at *http://daymet.ornl.gov/*.

Thornton, P.E., Running, S.W., and White, M.A., 1997, Generating surfaces of daily meteorology variables over large regions of complex terrain: Journal of Hydrology, v. 190, p. 214–251. (Also available at *http://dx.doi.org/10.1016/S0022-1694(96)03128-9*.)

Thornthwaite, C.W., and Mather, J.R., 1957, The water balance: Centerton, N.J., Drexel Institute of Technology Laboratory of Climatology, 104 p.

U.S. Department of Agriculture, 2006, United States General Soil Map (STATSGO2): Digital data, accessed June 2012 at *http://www.soils.usda.gov/survey/geography/statsgo/*.

U.S. Environmental Protection Agency, 2011, Level III ecoregions of the conterminous United States: Corvallis, Oreg., U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, map scale 1:3,000,000.

U.S. Geological Survey, 2013, National Water Information System (NWIS): U.S. Geological Survey database, accessed March 3, 2013, at *http://waterdata.usgs.gov/usa/nwis/nwis.*

U.S. Geological Survey, 2014, Principal Aquifers of the 48 Conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands, accessed January 3, 2014, at *http://www.nationalatlas.gov/mld/aquifrp.html.*

Vuke, S.M., Porter, K.W., Lonn, J.D., and Lopez, D.A., 2007, Geologic map of Montana: Montana Bureau of Mines and Geology Geologic Map 62 C, 2 sheets, scale 1:500,000.

Water Survey of Canada, 2013, HYDAT—Archived hydrometric data online: accessed March 3, 2013, at *http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm*.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 60 p., accessed July 31, 2013, at *http://pubs.usgs.gov/tm/tm6-a31/*.

Whitehead, R.L., 1996, Ground water atlas of the United States—Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geological Survey Hydrologic Atlas 730-I, 24 p. (Also available at *http://pubs.usgs.gov/ha/730i/report.pdf*.)

Wolock, D.M., 2003, Estimated mean annual natural groundwater recharge in the conterminous United States: digital dataset, U.S. Geological Survey Open-File Report 03–311, accessed July 31, 2013, at *http://ks.water.usgs.gov/pubs/abstracts/of.03-311.htm*.)

Wyoming Geographic Information Science Center, 2012, Water wells database: State Engineer's Office, accessed November 2, 2012, at *ftp://seoftp.wyo.gov/geolibrary_data/SEOwells.zip*.

Xian, G., Homer, C., Dewitz, J., Fry, J., Hossain, N., and Wickham, J., 2011, Change of impervious surface area between 2001 and 2006 in the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 77, no. 8, pp. 758–762. (Also available at *http://www.mrlc.gov/downloadfile2.php?file=August_2011_PERS.pdf*.)

Glossary

Williston control volume the glacial, lower Tertiary, and Upper Cretaceous aquifer systems within the areal extent of the lower Tertiary and Upper Cretaceous aquifer systems in the Williston structural basin.

Powder River control volume the lower Tertiary and Upper Cretaceous aquifer systems within the areal extent of the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin.

total control volume the combined Williston and Powder River control volumes.

consumptive use the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment.

gaining stream reach a stream reach in which a net increase in streamflow occurs as a result of base flow.

infiltrating stream reach a stream reach in which a net decrease in streamflow occurs because of infiltration to the groundwater.

Appendix

Appendix 1. Interactive Maps and Additional Tables

The relation between areas where precipitation recharge exists and where groundwater discharge to streams occurs is shown in figure 1-1, which is an interactive figure containing multiple layers that can be viewed in different combinations to aid interpretation. To turn layers on or off, select the layers icon on the left sidebar to open the Layers menu. To view one or more layers, click in the boxes next to each layer name in the menu. Some layers can be viewed simultaneously; for example, "Streamgages," "Clinker," and "Precipitation." Opaque layers (for example "Precipitation") will cover any other activated layers that are listed below in the Layers menu. The figure explanation will show the corresponding information for any combination of visible layers. Estimated potentiometric surfaces for the upper Fort Union and lower Fort Union aquifers and the Upper Cretaceous aquifer system are shown in figure 1-2, which also has interactive layers. Although the three potentiometric surfaces can be viewed simultaneously, it may be confusing to do so.

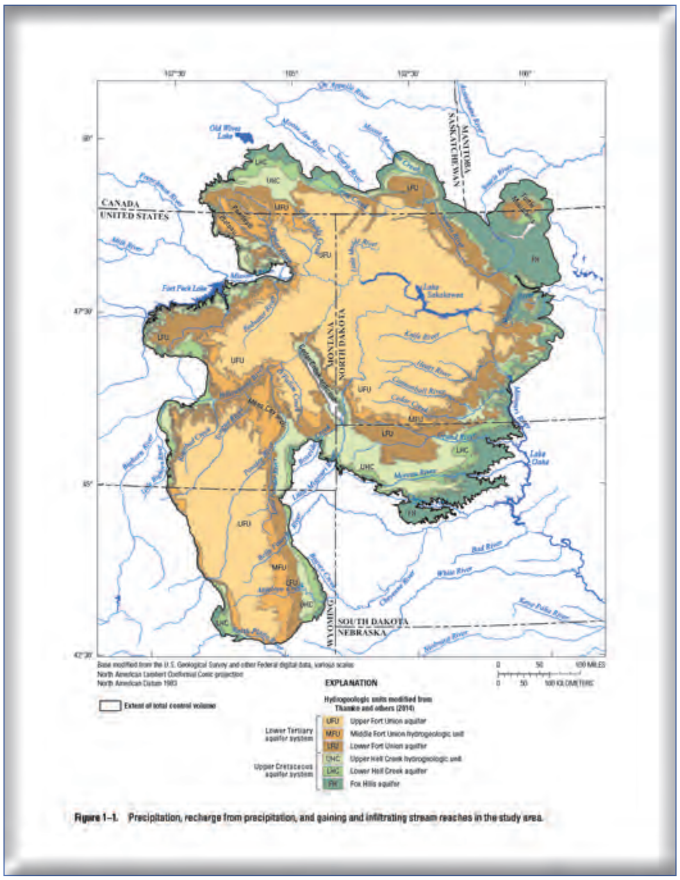


Figure 1–1. Precipitation, recharge from precipitation, and gaining and infiltrating stream reaches in the study area. Click on the thumbnail image above to view the map (*http://pubs.usgs.gov/sir/2014/5055/downloads/appendix_figures/figure1_1_sir2014-5055.pdf*).

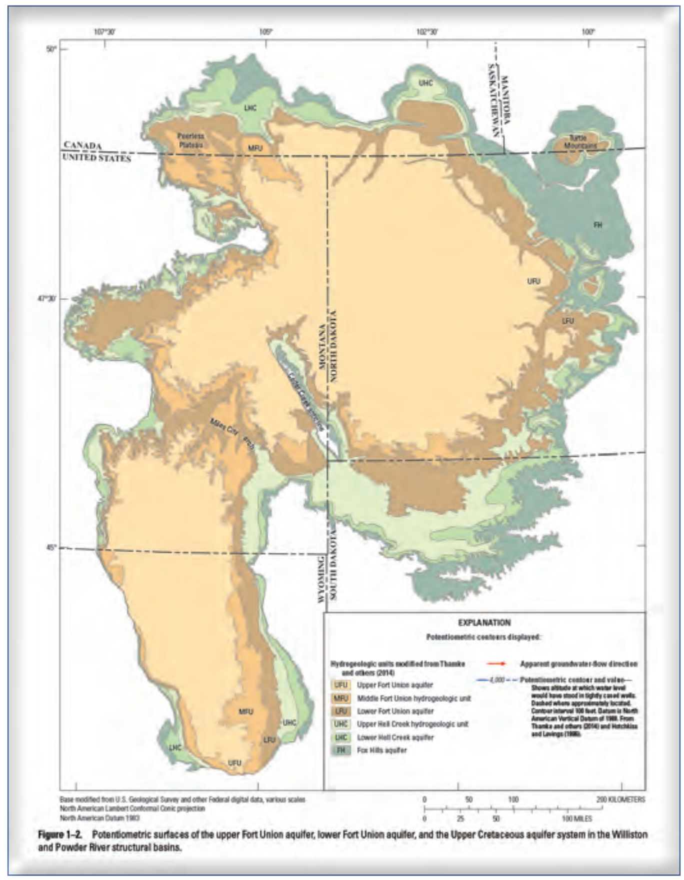


Figure 1–2. Potentiometric surfaces of the upper Fort Union aquifer, lower Fort Union aquifer, and the Upper Cretaceous aquifer system in the Williston and Powder River structural basins. Click on the thumbnail image above to view the map (*http://pubs.usgs.gov/sir/2014/5055/downloads/appendix_figures/figure1_2_sir2014-5055.pdf*).

The tables are presented as a Microsoft® Excel workbook (*http://pubs.usgs.gov/sir/2014/5055/downloads/appendix_tables_sir2014-5055.xlsx*) and as .csv file format (*http://pubs.usgs.gov/sir/2014/5055/downloads/appendix_tables_csv.zip*).

Table 1–1. Parameters used in the soil-water-balance (SWB) model.

Table 1–2. Streamgages in the Williston and Powder River structural basins with selected information.

Table 1–3. Estimated flow rates between groundwater and surface water for the Williston and Powder River control volumes.

Table 1–4. Groundwater withdrawal by county for 5-year periods during 1981–2005 for the Williston and Powder River control volumes, in cubic feet per second.

Table 1–5. Estimated irrigation recharge to groundwater in cubic feet per second for 5-year periods during 1981–2005 for the Williston and Powder River control volumes.

Publishing support provided by:
Lafayette and Rolla Publishing Service Center

For more information concerning this publication, contact:
Director, USGS South Dakota Water Science Center
1608 Mountain View Road
Rapid City, South Dakota 57702
(605) 394–3200

Or visit the South Dakota Water Science Center Web site at:
http://sd.water.usgs.gov/

Long and others—**Conceptual Model of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins**—SIR 2014–5055

ISSN 2328-0328 (online)

http://dx.doi.org/10.3133/sir20145055