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By Author, Author, and Author

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Foreword

Although often overlooked, groundwater is increasingly important to all of our lives. Groundwater in the Nation’s principal reserve of freshwater. It provides half our drinking water and is essential to U.S. food production while facilitating business and industry in promoting economic well-being. Groundwater is also an important source of water for sustaining the ecosystem health of rivers, wetlands, and estuaries throughout the country.

Large-scale development of groundwater resources with accompanying declines in groundwater levels and other effects of pumping have led to concerns about the future availability of groundwater to meet all our Nation’s needs. The depletion of groundwater to satisfy the country’s thirst and the compounding effects of recent droughts emphasize the need for an updated status of the Nation’s groundwater resources. Assessments of groundwater resources provide the science and information needed by the public and decision makers to evaluate water availability and its effects on the water supply, as well as, to manage and use the water resources responsibly. Adding to this already complex task of resource assessment is the analysis of potential future effects due to climate variability, which can further exacerbate an already challenging situation.

The U.S. Geological Survey’s (USGS) Groundwater Resources Program is conducting large-scale multidisciplinary regional studies of groundwater availability, such as this study of the uppermost principal aquifer systems of the Williston Basin. These regional studies are intended to provide citizens, communities, and natural resource managers with clearer knowledge of the status of the Nation’s groundwater resources and how changes in land use, water use, and climate have affected those resources, and to develop tools to forecast how these resources may change in the future. Over time, the findings from these individual regionally integrated groundwater assessments of principal aquifer systems will be combined to provide a national assessment. Results derived from these studies will provide much needed answers to basic questions about the Nation’s ability to meet current and future demands for groundwater.

-Associate Director for Water

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Conversion Factors

U.S. customary units to International System of Units

|  |  |  |
| --- | --- | --- |
| 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) |
| mile, nautical (nmi) | 1.852 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| Area | | |
| acre | 4,047 | square meter (m2) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.4047 | square hectometer (hm2) |
| acre | 0.004047 | square kilometer (km2) |
| square foot (ft2) | 929.0 | square centimeter (cm2) |
| square foot (ft2) | 0.09290 | square meter (m2) |
| square inch (in2) | 6.452 | square centimeter (cm2) |
| section (640 acres or 1 square mile) | 259.0 | square hectometer (hm2) |
| square mile (mi2) | 259.0 | hectare (ha) |
| square mile (mi2) | 2.590 | square kilometer (km2) |
| Volume | | |
| barrel (bbl; petroleum, 1 barrel=42 gal) | 0.1590 | cubic meter (m3) |
| ounce, fluid (fl. oz) | 0.02957 | liter (L) |
| pint (pt) | 0.4732 | liter (L) |
| quart (qt) | 0.9464 | liter (L) |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter (m3) |
| gallon (gal) | 3.785 | cubic decimeter (dm3) |
| million gallons (Mgal) | 3,785 | cubic meter (m3) |
| cubic inch (in3) | 16.39 | cubic centimeter (cm3) |
| cubic inch (in3) | 0.01639 | cubic decimeter (dm3) |
| cubic inch (in3) | 0.01639 | liter (L) |
| cubic foot (ft3) | 28.32 | cubic decimeter (dm3) |
| cubic foot (ft3) | 0.02832 | cubic meter (m3) |
| cubic yard (yd3) | 0.7646 | cubic meter (m3) |
| cubic mile (mi3) | 4.168 | cubic kilometer (km3) |
| acre-foot (acre-ft) | 1,233 | cubic meter (m3) |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer (hm3) |
| Flow rate | | |
| acre-foot per day (acre-ft/d) | 0.01427 | cubic meter per second (m3/s) |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year (m3/yr) |
| acre-foot per year (acre-ft/yr) | 0.001233 | cubic hectometer per year (hm3/yr) |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| foot per minute (ft/min) | 0.3048 | meter per minute (m/min) |
| foot per hour (ft/h) | 0.3048 | meter per hour (m/h) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| cubic foot per second (ft3/s) | 0.02832 | cubic meter per second (m3/s) |
| cubic foot per second per square mile ([ft3/s]/mi2) | 0.01093 | cubic meter per second per square kilometer ([m3/s]/km2) |
| cubic foot per day (ft3/d) | 0.02832 | cubic meter per day (m3/d) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day (m3/d) |
| gallon per day per square mile ([gal/d]/mi2) | 0.001461 | cubic meter per day per square kilometer ([m3/d)]/km2) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second (m3/s) |
| million gallons per day per square mile ([Mgal]d)/mi2) | 1,461 | cubic meter per day per square kilometer ([m3/d]/km2) |
| inch per hour (in/h) | 0.0254 | meter per hour (m/h) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| mile per hour (mi/h) | 1.609 | kilometer per hour (km/h) |
| Mass | | |
| ounce, avoirdupois (oz) | 28.35 | gram (g) |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| ton, short (2,000 lb) | 0.9072 | metric ton (t) |
| ton, long (2,240 lb) | 1.016 | metric ton (t) |
| Pressure | | |
| atmosphere, standard (atm) | 101.3 | kilopascal (kPa) |
| bar | 100 | kilopascal (kPa) |
| inch of mercury at 60 °F (in Hg) | 3.377 | kilopascal (kPa) |
| pound-force per square inch (lbf/in2) | 6.895 | kilopascal (kPa) |
| pound per square foot (lb/ft2) | 0.04788 | kilopascal (kPa) |
| pound per square inch (lb/in2) | 6.895 | kilopascal (kPa) |
| Density | | |
| pound per cubic foot (lb/ft3) | 16.02 | kilogram per cubic meter (kg/m3) |
| pound per cubic foot (lb/ft3) | 0.01602 | gram per cubic centimeter (g/cm3) |
| Energy | | |
| kilowatthour (kWh) | 3,600,000 | joule (J) |
| Radioactivity | | |
| picocurie per liter (pCi/L) | 0.037 | becquerel per liter (Bq/L) |
| Specific capacity | | |
| gallon per minute per foot ([gal/min]/ft) | 0.2070 | liter per second per meter ([L/s]/m) |
| Hydraulic conductivity | | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| Hydraulic gradient | | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| Transmissivity | | |
| foot squared per day (ft2/d) | 0.09290 | meter squared per day (m2/d) |
| Application rate | | |
| pounds per acre per year ([lb/acre]/yr) | 1.121 | kilograms per hectare per year ([kg/ha]/yr) |
| Leakance | | |
| foot per day per foot ([ft/d]/ft) | 1 | meter per day per meter ([m/d]/m) |
| inch per year per foot ([in/yr]/ft) | 83.33 | millimeter per year per meter ([mm/yr]/m) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the [insert datum name (and abbreviation) here; for example, North American Vertical Datum of 1988 (NAVD 88)].

Horizontal coordinate information is referenced to the [insert datum name (and abbreviation) here; for example, North American Datum of 1983 (NAD 83)].

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

Supplemental Information

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness ([ft3/d]/ft2)ft. In this report, the mathematically reduced form, foot squared per day (ft2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Note to USGS users: Use of hectare (ha) as an alternative name for square hectometer (hm2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter.

Abbreviations

DOD U.S. Department of Defense

EPA U.S. Environmental Protection Agency

ppm parts per million

USGS U.S. Geological Survey

Groundwater Availability of the Williston Basin, United States and Canada

By Author, Author, and Author [Authors]

# Executive Summary

# Introduction

The Williston Basin is geologically defined as a sedimentary basin—a geologic bowl-like structure filled with layered sedimentary rocks. This basin is as deep as 10,000 feet, consisting of formations of Paleozoic, Mesozoic, and Cenozoic age that overlie rocks of Precambrian age (Sandberg, 1962; Downey and Dinwiddie, 1988; Dalton and others, 1990). The Williston Basin is a nationally important area for the production of energy resources, spanning Montana, North Dakota, and South Dakota in the United States and Manitoba and Saskatchewan in Canada. The three uppermost principal aquifer systems in the Williston Basin—the glacial, lower Tertiary, and Upper Cretaceous aquifers systems—are the most accessible and the primary sources of potable groundwater in much of this area (Figure 1). The glacial aquifer system, present in the northern and eastern parts of the Williston Basin, is composed primarily of glacial drift. The lower Tertiary and Upper Cretaceous aquifer systems, present in the central and southern parts of the basin, are composed of sedimentary rocks including shale, silt, sandstone, and coal. In the Williston Basin, these three aquifer systems are as deep as 2,850 feet below land surface and overlie 800–2,000 feet of relatively impermeable Upper Cretaceous marine shale that serves as a basal confining unit that impedes groundwater flow (Anna, 1986; Downey, 1986; Downey and Dinwiddie, 1988; Thamke and others, 2014). This report provides a broad-scale assessment of the complex topic of groundwater availability in the Williston Basin and describes tools that can be applied to help manage this resource.

1. General Location of Williston Basin and hydrogeologic unit layers. Line *B*-*B*’ is shown in cross-section in Figure 5. Hyrogeologic units and geologic structures modified from Peterson (1984), Love and Christiansen (1985), and Thamke and others (2014). Williston Basin extent from Hamke and others (1966).

## Energy Resources and Water Use

The lower Tertiary and Upper Cretaceous aquifer systems in the Williston Basin also extend into the Powder River Basin of Montana and Wyoming (Figure 1). The Northern Great Plains aquifer system, which consists of all bedrock aquifers in that physiographic region, including the Williston and the Powder River Basins (Whitehead, 1996), provides 101 million gallons per day (Mgal/day) of water to irrigation (66.6 Mgal/day), public-supply (33 Mgal/day), and self-supplied industrial use (1.62 Mgal/day) (Maupin and Barber, 2005). Most of this water is from the lower Tertiary and Upper Cretaceous aquifer systems (Wesolowski, 1991).

As energy demands increase, horizontal drilling and hydraulic-fracturing methods are applied to access previously inaccessible formations in the Williston Basin, namely the Bakken and Three Forks Formations (Gaswirth and others, 2013; U.S. Energy Information Administration, 2013). Although the Williston Basin has yielded a large supply of domestic oil and natural gas since the 1950s, these recently developed technologies require large amounts of freshwater resulting in increased demand, with the largest increases occurring since 2005 (Schuh, 2010; Anna and others, 2011; Haines and others, 2017). Water use for hydraulic-fracturing per oil well increased by about 6 times from 2005-2014, totaling 24.5 × 109 gallons for about 10,140 wells (Scanlon and others, 2016). The increased demand for freshwater resulted in an increase of water pipelines by hundreds of miles and water-permit transfers from irrigation to oil production (Scanlon and others, 2016). Geologic units of lower Tertiary and Upper Cretaceous age contain most of the nation’s reserves of coal, in the form of lignite, and CBNG (Bluemle, 1998); extracting this resource has large potential to affect groundwater as a result of strip mining and removal of groundwater to release stored gas (Thamke and others, 2014). Continued development in the region, including alternative energy, industry, irrigation, and growing demands for domestic and municipal water in the Northern Great Plains, depends on the quantity and quality of groundwater available from these shallow and accessible aquifers.

The increasing freshwater demands of energy production in the Williston Basin, in addition to the resulting population growth, have led to a need for new tools to assess groundwater resources. Because of the importance of groundwater in this energy-rich area, the U.S. Geological Survey (USGS) began a study in 2011 to assess and provide better tools to manage groundwater availability in the Williston and Powder River Basins.

## Physiography and Climate

The study area extent includes most of the Williston Basin (Figure 1), the extent of which is not precisely defined but has been estimated by Hamke and others (1966), Pitman and others (2001), and Pollastro and others (2013). Topography in the study area is characterized by relatively low relief, except near large river channels, with a gently rolling land surface, underlain by glacial drift and sedimentary rocks composed primarily of sandstone, coal, and shale. Large river systems such as the Missouri and Yellowstone Rivers erode the relatively soft sedimentary rocks and create several hundred feet of local topographic relief.

Surface-water resources in the Williston Basin include rivers, streams, lakes, and wetland ponds. In this area, the Missouri River flows toward the east and southeast, with the Yellowstone and Little Missouri Rivers entering from the south (Figure 1). The study area includes three large surface-water reservoirs: Fort Peck Lake, Lake Sakakawea, and Lake Oahe, all located along the Missouri River (Figure 1). Several other tributaries in the southeastern part of the Williston Basin flow easterly and enter the Missouri River from the west. Numerous natural lakes and wetland ponds are scattered across the landscape, north of the Missouri River, where the glacial aquifer system is present. Much of this area is characterized by a non-integrated drainage pattern, where few streams cross (Figure 1). Surface water is heavily appropriated in most of the study area (Schuh, 2010), and this water supply is not always dependable in upper stream reaches where flow is variable.

The climate is semiarid, with monthly precipitation exceeding monthly potential evapotranspiration by 0 to 5 inches per year (in/yr) (Reilly and others, 2008). Within the study area, precipitation ranges from 11 in/yr in the western part to 24 in/yr in the eastern part (Figure xx) (Thornton and others, 1997, 2012; Long and others, 2014). Pasture and hayland covers 70 percent of the study area (Multi-Resolution Land Characteristics Consortium, 2011). Population density is low, with the exception of a few towns, generally less than 10 people per square mile (U.S. Census Bureau, 2001; Statistics Canada, 2001).

## Hydrogeologic Framework

Groundwater resources used in the Williston Basin in the United States and Canada are located primarily in three uppermost principal aquifer systems composed of late Cretaceous, Tertiary, and Quaternary-age lithostratigraphic units (Figure 2). Thamke and others (2014) constructed a three-dimensional hydrogeologic framework that defined and described these three aquifer systems in the Williston Basin for the United States and Canada with emphasis on the lower Tertiary and Upper Cretaceous bedrock aquifer systems. Davis and Long (2017a) further developed the hydrogeologic framework for the glacial aquifer system by spatially defining five different glacial-material zones and extending this analysis to the edges of the model domain. Presented herein is a brief summary of the hydrgeologic framework described in the two aforementioned reports, which include greater detail of the lithostratigraphic and hydrogeologic units.

From shallowest (youngest) to deepest (oldest), the three aquifer systems are the glacial, lower Tertiary, and Upper Cretaceous aquifer systems, the latter two of which are contained within bedrock (Figure 2). These three aquifer systems are hydraulically separated from deeper aquifers by a basal confining unit composed primarily of 800–3,000 feet (ft) of low-permeability Upper Cretaceous marine shale, the top of which is shown in Figure 3. The bowl-shaped structure and layered geology of the Williston Basin results in bedrock hydrogeologic units that are exposed to the land surface or in contact with the overlying glacial aquifer system near the outer parts of the basin (Figure 1, Figure 4). The glacial aquifer system overlies parts of the lower Tertiary and Upper Cretaceous aquifer systems in the northeastern part of the Williston basin (Figure 1).

1. Lithostratigraphic and corresponding hydrogeologic units of the Williston 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.
2. Three-dimensional view of the top of the basal confining unit in the Williston and Powder River Basins. Selected hydrogeologic cross sections also are shown.
3. Hydrogeologic cross-section B-B’ showing the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston basin.

The glacial aquifer system consists of Quaternary-age unconsolidated till, silt, clay, outwash sand and gravel, and occasional cobbles and boulders. Estimated glacial aquifer system volume in the study area is 150 trillion cubic feet (ft³). Widely varying lithologic characteristics results in an aquifer system that is characterized by multiple disconnected, locally productive sand and gravel aquifers buried beneath till and other glacial or surficial deposits, and typically are located in pre-glacial valleys that exist on the buried bedrock surface (Kehew and Boettger, 1987; Cummings and others, 2012; Pugin and others, 2014). Thickness of the glacial aquifer system in the Williston Basin varies locally; maximum thickness is estimated to be about 750 ft and thickest in northern North Dakota and Canada. Hydraulic characteristics of the glacial aquifer system vary widely because of highly variable lithology. Hydraulic conductivity values estimated by Thamke and others (2014) for the glacial aquifer system are as large as 25 feet per day, varying more than for the lower Tertiary and Upper Cretaceous aquifer systems.

Davis and Long (2017a) separated the glacial aquifer system into two layers and subdivided these layers horizontally to represent different materials present in the glacial drift. The upper layer was subdivided into three material zones: (1) low-permeability material consisting of till, (2) medium-permeability material consisting of glaciolacustrine and glaciotectonic deposits, and (3) high-permeability material consisting of glaciofluvial, loess, and eolian deposits. The lower layer was subdivided into two material zones: (1) low-permeability material consisting of till and (2) high-permeability material consisting of sand and gravel that filled pre-glacial valleys. These valley-fill aquifers may be covered by different materials of low, medium, or high permeability. The spatial distribution of these five glacial-material zones are shown in Davis and Long (2017a) .

The lower Tertiary aquifer system in the Williston basin consists of the upper and lower Fort Union aquifers separated by the middle Fort Union hydrogeologic unit (Figure 2). This aquifer system is as thick as 2,250 ft, and estimated volume is 1,000 trillion ft³. Rocks composing the lower Tertiary aquifer system represent many depositional environments, most commonly continental (fluvial, deltaic, tidal, barrier-shoreface) depositional environments and less commonly, marine depositional environments (Flores and others, 1999).

The upper Fort Union aquifer is composed of as much as 1,920 ft of thickness of massive, crossbedded, light yellow to light-yellow-gray sandstone, sandy mudstone, gray shale, carbonaceous shale, and thick coal beds and associated clinker deposits (permeable rocks created by the natural burning of coal beds). Rocks composing the aquifer generally are light-colored compared to the underlying middle Fort Union hydrogeologic unit. Thickness of the upper Fort Union aquifer is greatest in the central part of the Williston Basin, near the Montana and North Dakota border, and thins at the edges where erosion has removed most of the unit (Figure 4).

Present throughout the central part of the Williston Basin, the middle Fort Union hydrogeologic unit thins toward the northeast and is not present in the northeast one-third of the basin. Composed of as much as 520 ft of thickness of alternating beds of sandstone, siltstone, mudstone, claystone, and lignite, rocks in the middle Fort Union hydrogeologic unit generally are finer-grained and darker-colored than the overlying upper Fort Union aquifer and underlying lower Fort Union aquifer. Because of spatially variable lithology, the middle Fort Union hydrogeologic unit may act as a confining unit in some areas and as an aquifer in other areas. The lower Fort Union aquifer is composed of as much as 670 ft of thickness of yellow-weathering sandstones and light-gray-weathering sandy mudstones interfingering with alternating brown and gray beds of sandstone, siltstone, claystone, mudstone, and lignite deposited in continental and marine environments.

The Upper Cretaceous aquifer system is the deepest and most areally extensive of the three aquifer systems and consists of, from top to bottom, the upper Hell Creek hydrogeologic unit, lower Hell Creek aquifer, and the Fox Hills aquifer (Figure 2). The volume of this aquifer system is about 1,000 trillion ft³ in the Williston Basin. The upper Hell Creek hydrogeologic unit is composed of as much as 740 ft of thickness of alternating layers of gray and brown mudstone, siltstone, sandstone, and sparse lignite beds deposited by meandering streams with point bars and channel plugs. Because of spatial variability, this lithology may act as a confining unit in some areas and as an aquifer in other areas. The general lithology of the lower Hell Creek aquifer is similar to the upper Hell Creek hydrogeologic unit, except that the latter has a smaller percentage of sandstone. Stream-channel deposits and erosional surfaces are common in the lower Hell Creek aquifer (Flores, 1992), with a maximum thickness of as much as 550 ft in the Williston Basin. The Fox Hills aquifer is as much as 420 ft thick and consists of interbedded sandstone, siltstone, and mudstone.

## Conceptual Model of Groundwater Flow

Average long-term precipitation recharge (1985–2011) for the study area ranges from zero to about 10 inches per year (Long and others, 2014), generally with low values in the west and high values in the east. Precipitation in the form of snow primarily is stored during winter and infiltrates during spring melting periods. Groundwater recharge in the study area also results from stream reaches that lose flow as they infiltrate the ground and reservoir water that potentially seeps into the ground (Whitehead, 1996; Aurand, 2013; Bednar, 2013; Long and others, 2014). Groundwater loses flow to streams and reservoirs by exfiltration through the streambed material or reservoir bottom sediment. Exfiltration to streams provides important base flow that sustains many streams during dry seasons (Figure 5). Groundwater withdrawals are used for agriculture, public supply, industry, and domestic needs.

Long and others (2014) estimated the groundwater-flow budget, or balance of total groundwater inflows and outflows, for a control volume within the study area; this control volume was defined as a volume of the earth consisting of the lower Tertiary and Upper Cretaceous aquifer systems and the glacial aquifer system directly overlying these bedrock aquifer systems in the Williston basin (Table 1). The Upper Cretaceous aquifer system defines the horizontal extent (Figure 1) and bottom of the control volume, and the land surface defines the top. Davis and Long (2017a) used a numerical model to estimate the groundwater-flow budget for this same control volume, and a comparison to the estimates of Long and others (2014) is provided in Table 1.

The glacial aquifer system contains productive buried sand and gravel aquifers that are the source of water for thousands of shallow wells (Whitehead, 1996; Davis and Long, 2014). The glacial aquifer system has a wide range of hydraulic conductivities and is characterized by disconnected local flow systems. The underlying bedrock aquifers largely are under confined conditions, except along the basin margins or in the shallowest aquifers. In the areas where the bedrock aquifer systems are overlain by the glacial aquifer system (Figure 1; Figure 4), water percolates downward through the glacial deposits and into the bedrock aquifers. Groundwater flow in the study area, particularly in the deeper aquifers, generally is from west and southwest to the east, where discharge to streams and springs occurs; in the shallower aquifers, however, groundwater flow largely is controlled by land-surface topography, with steeper potentiometric surfaces than in the underlying aquifers (Figure 5) (Long and others, 2014). Further description of groundwater flow characteristics are in the section “Comparison of Conceptual and Numerical Models.”

1. Conceptual model of groundwater flow (modified from Long and others, 2014)
2. Estimated and simulated average groundwater recharge and discharge components for 1981–2005 within a control volumea of the model domain (modified from Davis and Long, 2017a).

Declining groundwater levels have occurred locally in the Fox Hills and Hell Creek aquifers as a result of flowing artesian wells that were installed to supply water for domestic and agricultural use; these wells flow continuously as a result of hydrostatic pressure. Fischer (2013) described 521 flowing artesian wells in North Dakota that are open to the Fox Hills and lower Hell Creek aquifers, primarily near the Yellowstone, Little Missouri, and Knife Rivers. Collectively, these wells have a total flow rate of about 1.6 ft3/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 that area (Smith and others, 2000; Fischer, 2013). Flowing artesian wells that discharge water from the Upper Cretaceous aquifer system might allow leakage into the overlying lower Tertiary aquifer system because of inadequate sealing or corrosion of these wells (Fischer, 2013).

## Summary of Numerical Modeling

Two calibrated numerical groundwater-flow models were documented by Davis and Long (2017a, 2017b) . The first model represents average hydrologic conditions for 1981‒2005 and is executed in steady-state mode (Harbaugh, 2005), hereafter referred to as the “steady-state model.” The second model was calibrated to temporally-varying conditions for 1961‒2005, hereafter referred to as the “transient model.” The transient model was designed to be a tool for forecasting the outcomes of different hydrologic scenarios. Thamke and others (2014) provided the bedrock hydrogeologic framework and initial (uncalibrated) aquifer-property values for the numerical models. Long and others (2014) described a conceptual model of groundwater flow, including a groundwater-flow budget, that provided a basis for numerical modeling. The purpose of the steady-state model was to test this conceptual model and to calibrate many of the adjustable parameters, such as hydraulic conductivity, the values of which were then used in the transient model (Davis and long, 2017a).

The transient model is not fully continuous with respect to time but rather represents distinct blocks of time called “stress periods,” within which all hydrologic conditions are assumed constant. Model output represents the end of each stress period. The transient model consists of an initial steady-state stress period to simulate a long-term period prior to 1961, which represents a period prior to most groundwater withdrawals, hereafter referred to as the “predevelopment period.” Following this initial stress period are four 5-year stress periods representing the calendar years,1961–1965, 1966–1970, 1971–1975, and 1976–1980, which are followed by 25 annual stress periods representing each of the calendar years, 1981–2005. The transient model was used herein to simulate groundwater responses to hydrologic scenarios involving flowing wells, drought, and increased groundwater withdrawal, which are described in sections that follow.

## Purpose and Scope

The purpose of this report is to describe current groundwater availability of the three uppermost principal aquifer systems—the glacial, lower Tertiary, and the Upper Cretaceous—in the Williston Basin, evaluate how these resources have changed over time, and provide a basis to assess system response to anthropogenic and environmental stresses. The scope of this report is focused on the Williston Basin and summarizes previous publications that resulted from this study describing a hydrogeologic framework, a conceptual model and groundwater-flow budget, and a numerical model of groundwater flow (Long and others, 2014; Thamke and others, 2014; Davis and Long, 2017a). This report presents hydrologic forecasts simulated with this numerical model to assess the potential for drought, pumped groundwater, and free-flowing wells to affect future groundwater availability. An example of the use of this model to help determine high-value locations to establish new hydrologic-monitoring stations also is presented. The study described herein has benefitted from numerous publications dating from the 1960s until present, most of which were summarized by Long and others (2014), Thamke and others (2014), and Davis and Long (2017a) ; additional publications are acknowledged herein.

This report is one in a series of reports summarizing the findings of studies conducted by the USGS to assess groundwater availability of principal aquifers throughout the United States. These reports include “*Groundwater Availability of the Central Valley Aquifer, California*” (Faunt, 2009), “*Groundwater Availability in the Atlantic Coastal Plain of North and South Carolina*” (Campbell and Coes, 2010), “*Water availability and use pilot—A multiscale assessment in the U.S. Great Lakes Basin*” (Reeves, 2010), “*Groundwater availability of the Denver Basin aquifer system, Colorado*” (Paschke, 2011), “*Groundwater availability of the Mississippi embayment*” (Clark and others, 2011), and “*Groundwater availability of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho*” (Kahle and others, 2015). A map of principal aquifers of the United States is accessible at <https://water.usgs.gov/ogw/aquifer/map.html>.

# Assessing Groundwater Availability

Groundwater availability of a regional groundwater system is a complex topic, dependent of many interconnected and uncertain factors. These factors include climate variability, human use of groundwater, complex aquifer characteristics, continual changes in groundwater storage that are influenced by numerous factors, and changes in the ease of extracting groundwater. For example, aquifers that are highly productive but small in volume are most vulnerable to severe dewatering if local water demands are high. The groundwater stored in a regional aquifer overall might be minimally affected by local groundwater withdrawal but heavily affected locally in the withdrawal area. If the saturated zone of an aquifer is several hundred feet thick, a lowered water table might cause minimal change as a fraction of total groundwater storage but could result in increased difficulty extracting groundwater from a deepening source. Compounding this issue, in many cases, is that water quality decreases with depth, or the aquifer could become permanently compacted as a result of reduced hydrostatic pressure.

A groundwater-flow budget that quantifies all inflows and outflows of the overall groundwater system is a valuable starting point to assess groundwater availability but falls short of addressing numerous considerations that are important to making groundwater available for human and ecological needs. The total volume of groundwater stored provides little information useful for managing groundwater because only a small fraction of stored groundwater can be extracted sustainably, in most cases, as a result of decreased groundwater levels and quality. However, the change in groundwater storage that results from changing inflows and outflow is a useful metric to assess the long-term sustainability of an aquifer, and a monthly or annual groundwater-flow budget provides an estimate of this metric. A groundwater-flow budget also is useful for comparing the relative flow magnitudes of different inflows and outflows. For example, human water use ideally should be small in comparison to total groundwater recharge for long-term sustainability.

An assessment of the hydrogeologic framework defines the properties and characteristics of an aquifer system in a simplified form that can be used, along with a groundwater-flow budget, to develop a conceptual understanding, or model, of groundwater flow. The hydrogeologic framework, groundwater-flow budget, and conceptual model described by Long and others (2014) and Thamke and others (2014) were used to construct a numerical model of groundwater flow (Davis and Long, 2017a). This model was used herein to assess changes in groundwater storage and water levels that might result from human activity and climate variability, and therefore, affect groundwater availability.

# Analysis of Precipitation and Recharge

An analysis of precipitation patterns for the study area indicates that climate varies widely, spatially and temporally. An analysis of the annual cumulative departure from the mean (ACDM) for precipitation is one way to visualize multi-year or decadal pattern in precipitation rates across the study area. The ACDM representing the spatial average of spatially-distributed (or gridded) precipitation estimates for the study area was calculated for 1930–2014 (Figure 6*A*). Daily precipitation values from Parameter-elevation Regressions on Independent Slopes Model (PRISM; <http://prism.oregonstate.edu/>) averaged over the study area were accessed through the USGS GeoData Portal (GDP; <http://cida.usgs.gov/gdp/>). However, the PRISM data were not available for the Canadian part of the study area. Maurer and others (2002) provided a similar dataset with spatially distributed precipitation estimates for the entire study area, but for a shorter period (1950–1999). Comparison of total annual precipitation for these two datasets indicates similarity, and therefore, the PRISM data were used to assess long-term changes by analysis of the ACDM (Figure 6*A*).

Downward slopes in the ACDM indicate dry periods, and upward slopes indicate wet periods. There were three distinct dry periods that lasted at least 4 years since 1930, which are evident for periods where the slope of the ACDM is relatively steep and downward overall (Figure 6*A*). These periods are most of the 1930s, the late 1950s, and the late 1980s. The wettest periods include the early 1940s, the early 1960s, and 2007 to present.

1. Annual cumulative departure from the mean for, *A*, precipitation and simulated groundwater recharge as a spatial average within the control volume (Davis and Long, 2017b) and, *B*, precipitation for selected weather stations. Climatically dry periods are shown in gray.

The ACDM for simulated groundwater recharge is similar to, but smoother than, that of precipitation (Figure 6*A*), which indicates that the soils store infiltrating precipitation for periods long enough to damp the variability of precipitation that becomes recharge. Also, the volume of recharge is much less than the volume of precipitation as a result of evapotranspiration and direct runoff, which is evident in Figure 6*A*, where the ACDM for recharge is exaggerated by a factor of 10 in relation to precipitation.

The ACDM was calculated individually for eight weather stations in the study area (Figure 6*B*). Daily precipitation values for climate stations in the study area for 1930–2006 were available from the Global Historical Climatology Network (GHCN) (<http://www.ncdc.noaa.gov/ghcnm/v2.php>). These data were supplemented with precipitation data for the same stations from Climate Data Online (<https://www.ncdc.noaa.gov/cdo-web/datasets#ANNUAL>) to extend the period of record to 2015. The daily values were used to calculate ACDM for each station for the period 1930–2015 (Figure 6*B*). Spatially, there are differences in the occurrence of wet and dry periods between the northwest and southeast parts of the study area. However, all of the stations experienced mostly dry years during the three dry periods that were indicated for the spatial average (Figure 6*A*). The Glasgow and Regina stations in the northwest experienced wet conditions (as compared to the station’s long-term average) during the 1040s and early 1950s, compared to the other stations. The Richardson Abbey station overall was most different from the other stations, particularly after 1975, where the ACDM generally increased until 1987 and decreased until 2015. The Bismark station was almost opposite to the Richardson Abbey station after 1961.

A map of the long-term precipitation rate indicates a large change in total precipitation from west to east but less change from north to south (Figure 7), which is similar to the spatial the spatial distribution of groundwater recharge (Long and others, 2014). Differences in the ACDM for precipitation between stations indicates that temporal patterns of precipitation are related to the spatial distribution of precipitation. A spatio-temporal analysis of precipitation, therefore, provides insight by proxy into the spatio-temporal characteristics of groundwater recharge.

Consistent with the spatial distribution of precipitation are the ACDM curves for the weather stations, which also have more variability from west to east than from north to south (Figure 6*B*, Figure 7). Further, the timing of dry and wet periods are not consistent everywhere in the study area. For example, the Glasgow and Regina stations, located farthest to the northwest, overall have similar ACDM curves; to the southeast, however, the Glendive and Crosby stations have similar characteristics but are different from Glasgow and Regina (Figure 6*B*). The next station to the east, Richardson abbey, has a unique ACDM and might represent a climatic transition from west to east. Separating these weather-station groupings into categories of climatically driest, moderately dry, moderate, moderately wet, and wettest helps to visualize this pattern in relation to the long-term precipitation map (Figure 7). Although the Willow City and Dupree stations are spaced far apart, they have similar ACDM characteristics and are located in the moderately wet area. The Bismarck station, also different from the other stations, is farthest to the southeast in the wettest area. Therefore, the ACDM curves for the weather stations indicate climatic differences from west to east but similarities from north to south; this is consistent with long-term average precipitation that has a gradient from west to east.

1. Weather stations and long-term precipitation (1981‒2011) in the study area. Precipitation map from Long and others (2014).

# Comparison of Conceptual and Numerical Models

A comparison of the conceptual and steady-state numerical models serves as a qualitative evaluation of both models because these models should be reasonably consistent. Differences between the two groundwater-flow budgets helps to quantify the range of uncertainty with regard to these estimates (Table 1).

## Groundwater Flow

Long and others (2014) described general groundwater flow directions and other characteristics within the context of an overall conceptual model of the study area. In this description, the estimated potentiometric surfaces for aquifers close to the land surface closely resemble the undulating topography of the land surface, and flow directions are from upland areas toward streams; whereas in the deepest aquifers (e.g., the Fox Hills aquifer), groundwater flows from southwest to northeast, with minimal influence from the land surface and, therefore, has a smoother potentiometric surface. The lower Fort Union aquifer, having a middle range of depth, has a potentiometric surface with characteristics of deep and shallow aquifers. Davis and Long (2017a) showed that the numerical models produced these general characteristics similarly and further quantified similarities and differences of simulated and observed hydraulic-head values, spatially and temporally. Estimated groundwater flow directions for the upper Fort Union aquifer, lower Fort Union aquifer, and Upper Cretaceous aquifer system (Long and others; 2014) generally correspond to simulated flow directions.

[Add statement that ND permitted wells for glacial aquifers are clustered in areas of wet cells in layers 1 and 2 and seldom located in areas of dry cells. Shows that the model simulated areas where aquifers are unsaturated accurately.]

## Average Groundwater-Flow Budget

The groundwater-flow budget is described by equation 1, in which inflows and outflows are assigned positive and negative values, respectively.

()

where *RP* is precipitation recharge;

*RI* is irrigation recharge;

*SFin* is stream and reservoir infiltration;

*GWin* is groundwater inflow to the control volume;

*SFout* is stream and reservoir exfiltration;

*GWout* is groundwater outflow from the control volume;

*Wout* is well withdrawal and flowing wells; and

Δ*S* is storage change (positive or negative).

Long and others (2014) estimated the groundwater-flow budget for average conditions (1981‒2005) for the control volume (Table 1). Storage change (Δ*S*) was assumed to be zero for these long-term-average conditions. Simulated groundwater-flow budgets presented herein for the predevelopment period through 2005 consist of values from Davis and Long (2017a) . Similarly to the estimated groundwater-flow budget, the simulated groundwater-flow budget for average conditions is dominated by *SFin* and *SFout* and secondarily by *RP*; minor components consist of *Wout*, *GWin*, and *GWout* (Figure 8*B*, Table 1). *RP* is a major forcing component that affects streamflow, which likewise affects *SFin*; the combination of *RP* and *SFin* are the major forcings that effect *SFout*. Consequently, *RP*, *SFin*, and *SFout* account for 94 percent of total inflow and outflow for average conditions (Figure 8*B*).

Comparison of the estimated and simulated groundwater-flow budgets indicates noteworthy similarities and differences (Table 1). These differences result primarily from limitations inherent to estimating and simulating regional-scale groundwater flow. Long and others (2014) estimated precipitation recharge for the entire study area by using the Soil-Water Balance (SWB) model (Westenbroek and others, 2010). Davis and Long (2017a) initially applied these SWB estimates to the numerical model and then adjusted the original estimates slightly upward during model calibration; this increase was supported by comparison to two other recharge estimation methods for selected parts of the study area, in which the SWB estimates were similar to, but at the lower range, of estimates from the other methods (Aurand, 2013; Long and others, 2014). For the steady-state model (1981‒2005), precipitation recharge was 1.4 times higher than the estimated value (Table 1).

1. Simulated groundwater-flow budget, showing *A*, conceptual profile of the groundwater system and *B*, relative magnitudes of water-budget components for predevelopment (pre-1961), average conditions (1981-2005), and 2005. This budget applies to the control volume. Values are from Davis and Long (2017a) .

Although simulated stream infiltration was much lower than the estimated value (Table 1), uncertainty of the estimate was large (Long and others, 2014), partly resulting from uncertainty in consumptive use of surface water. Simulated stream exfiltration (Table 1) differed from the estimated value by only 5 percent. Irrigation recharge is the excess irrigation that infiltrates the aquifer, for which the simulated and estimated values were identical because this rate was specified in the model rather than calibrated. Lakes and reservoirs interact with groundwater similarly to streams. In contrast to the estimated reservoir infiltration of zero, the simulated value was large (1,575 ft3/s) and in a similar range to that of simulated precipitation recharge and stream infiltration (Table 1). Estimated reservoir exfiltration was only 10 ft3/s compared to the simulated value of 546 ft3/s.

A relatively small amount of groundwater flows from the Powder River Basin into the Williston Basin through connected hydrogeologic units. The glacial aquifer system extends beyond the limits of the control volume and, therefore, allows horizontal groundwater flow into and out of the control volume. The simulated groundwater inflow and outflow for the control volume within the glacial aquifer system is a small component of the simulated groundwater-flow budget, and inflow and outflow are nearly balanced (Table 1); the estimated counterparts of this inflow and outflow were assumed to be balanced (Long and others, 2014) and, therefore, not considered in the estimated groundwater-flow budget. Groundwater withdrawal was a small part of the estimated and simulated groundwater-flow budget (Table 1); the estimated value was reduced by 32 percent in the steady-state model (1981‒2005) because of numerical instability during model calibration, as described by Davis and Long (2017a) . However, this reduction of estimated well withdrawal was not applied to the transient model and, therefore, had no effect on simulating hydrologic scenarios.

Infiltration to groundwater from domestic on-site sewage treatment, or septic, systems also was considered. About 9 percent of all well withdrawals in the control volume are from domestic wells; about 50% of all well withdrawals are from flowing wells (Long and others, 2014). On this basis, we assume that water produced from flowing wells accounts for 50% of domestic-well withdrawals. Because most of the flowing wells produce water continuously, only a small percentage of this water might be diverted to domestic septic systems. If we then assume that 50‒90% of the pumped water is diverted to septic systems, the infiltration from domestic septic systems is less than 0.3 percent of total groundwater recharge and, therefore, was assumed negligible.

# Simulated Transient Groundwater-flow budget

For transient simulations, Δ*S* balances equation 1 so that the sum of all components equates to zero; the sign of Δ*S* is determined on this basis. For example, if inflows exceed outflows, Δ*S* is negative and represents an increase in groundwater storage. The groundwater-flow budget for the predevelopment period differs little from that of average conditions (1981‒2005 ) because average well withdrawals for 1981‒2005 were a small part of the total groundwater-flow budget (Figure 8*A* and *B*).

For 2005, the last model stress period, precipitation recharge was only 11 percent of total inflow, which is in contrast to 35 percent precipitation recharge for average conditions (Figure 8*B* and *C*); this is consistent with below-average precipitation recharge for 2000‒2005, as shown by a negative slope in the cumulative-departure curve (Figure 6). Low precipitation recharge for 2005 resulted in total inflow that was only 69 percent as large as total outflow and, consequently, large storage-change, Δ*S* (Figure 8*C*).

A groundwater-flow budget for the transient model (predevelopment-2005) provides additional insight into hydrologic change, as well as differences in the three aquifer systems (Figure 9). The time increments in Figure 9 are variable, as described in the section “Summary of Numerical Modeling.” The total magnitude of the groundwater-flow budget by stress period shows wet and dry conditions at a glance; for example, the period 1995‒1999 has the largest flows for all three aquifer systems (Figure 9). Temporal changes observable in Figure 9 are consistent with the cumulative departure from average precipitation recharge (*RP*) (Figure 6*A*): the period 1961‒1975 had moderately above-average *RP*; 1971‒1986 had variable *RP* that was above and below average; 1987‒1994 represented low *RP*; 1995‒1999 represented high *RP*; and 2000‒2005 represented low *RP* (Figure 9). In each stress period, Δ*S* is either positive or negative, and if *RP* is high, total inflows generally are greater than total outflows, resulting in negative Δ*S*; whereas, low *RP* corresponds to positive Δ*S* (Figure 9).

The lower Tertiary aquifer system has the largest overall groundwater-flow budget and the greatest variability of the three aquifer systems, whereas, the Upper Cretaceous aquifer system has the smallest groundwater-flow budget and least variability (Figure 9). The Upper Cretaceous aquifer system has, on average, a groundwater-flow budget that is less than one-third as large as the other two aquifer systems but accounts for about 70 percent of the total well withdrawals for the control volume (Figure 10); this largely is because flowing wells discharging from the Upper Cretaceous aquifer system account for about 50 percent of all well withdrawals for the control volume (Davis and Long, 2017a). Groundwater pumped from the lower Tertiary and Upper Cretaceous aquifer system was below average during the period 1996‒2000 (Figure 10) as a result of high precipitation recharge during this general period (Figure 6, Figure 9), which reduced demand. This high-recharge period also corresponds to a decrease in total well withdrawals as a percentage of groundwater inflow for the control volume, although this percentage has increased overall from the predevelopment period to 2005 (Figure 10).

1. Simulated groundwater-flow budget by stress period (predevelopment-2005) for, *A*, the glacial aquifer system; *B*, the lower Tertiary aquifer system; and *C*, the Upper Cretaceous aquifer system. Values are from Davis and Long (2017a) . [\*\* Kyle will update spreadsheet to show predevelopment for the first stress period. Switch to cfs for entire report.]
2. Groundwater well withdrawals, by aquifer system (predevelopment-2005).
3. Measured water-level change in the Fox Hills aquifer, 1960-2005  *Colorflood with isopach.*
4. Groundwater-flow budget of the lower Tertiary aquifer system, 1960-2005
5. Groundwater-flow budget of the Upper Cretaceous aquifer system, 1960-2005
6. Groundwater-flow budget of local areas, western North Dakota and eastern Montana

Simulated groundwater-flow budget for, *A*, predevelopment (pre-1961); *B*, average conditions (1981-2005); and, *C*, 2005. This budget applies to the control volume

# Simulated Groundwater Response to Flowing Wells

Flowing wells are those that flow continuously as a result of hydrostatic pressure in the aquifer. Fischer (2013) described flowing wells in North Dakota, installed for domestic and agricultural use, that are 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. Flowing wells also are located parts of Montana (figure?) (reference?).

## Hydrology of Flowing Wells

About 70 percent of the flowing wells were installed 1960‒1990. Within most of the study area, groundwater levels generally were steady prior to 2000 (Thamke and others, 2014), but declining groundwater levels have occurred locally in areas where flowing wells are located as a result of their cumulative groundwater discharge, which was estimated at about 1.6 ft3/s for the wells in North Dakota (Fischer, 2013). Near the Yellowstone River, flowing wells contributed to groundwater-level declines of about 1 foot per year (ft/yr) since the 1970s in the Fox Hills and Hell Creek aquifers (Smith and others, 2000; Fischer, 2013). Honeyman (2007a, 2007b, 2007c) measured hydraulic-head changes, mostly declines, in these two aquifers near the Little Missouri River for 1994–2006. These rates of change 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). In addition to discharging to the land surface, flowing wells near the Yellowstone and Little Missouri Rivers also might allow leakage into the overlying lower Tertiary aquifer system because of inadequate sealing or corrosion of well materials (Fischer, 2013) in combination with the upward hydraulic gradient that occurs in these areas (Long and others, 2014).

## Flowing-Wells Scenario

Flowing wells were simulated as head-dependent boundary cells (Davis and Long, 2017a); that is, the rate of well discharge is influenced by hydraulic head surrounding the well and, therefore, is similar to spring discharge. The transient model was used to simulate water-level changes for 2005‒2035 (at 1-year stress periods) that would result if none of the flowing wells were capped or plugged during this time period and other conditions remained constant. The flowing-wells scenario simulation was executed for the period 1961‒2035 and was identical to the original transient model for the period 1961‒2005. The groundwater pumping rates that originally were applied to the 2005 stress period were applied in the flowing-wells scenario at a steady rate for 2006‒2035. Precipitation-recharge rates and conditions for the MODFLOW Streamflow-Routing Package that were applied to the steady-state model were applied in the flowing-wells scenario at steady rates for 2006‒2035. Applying these steady rates allowed the assessment of flowing wells without interference from other changing hydrologic conditions. The resulting aquifer drawdown for 2006‒2035 resulting from flowing wells was assessed, with the largest simulated drawdown occurring in the Fox Hills aquifer (Figure 15, Figure 16, Figure 17) … [describe results highlights, such as the effects on overlying aquifers]. The simulated effect of flowing wells resulted in hydraulic head values that were lowered below the land surface in some areas, causing many flowing wells to stop flowing. The number of simulated flowing wells declined from xx in 2005 to xx in 2015 (Figure 18). [describe anything interesting here]

1. Simulated water-level change map from 2005 to 2035 in the upper Fort Union aquifer as a result of flowing wells.
2. Simulated water-level change map from 2005 to 2035 in the lower Fort Union aquifer as a result of flowing wells.
3. Simulated water-level change map from 2005 to 2035 in the Fox Hills aquifer as a result of flowing wells.
4. Decline in the number of simulated flowing wells from 2005 to 2035, during which time simulated groundwater recharge and pumping was constant. [\*\* line graph with the number of flowing wells on the y-axis and time on the x-axis]

# Simulated Groundwater Responses During Drought

The increased freshwater demands for the production of energy resources from the Williston basin was offset by precipitation rates that were higher than average during the 2006‒2015 period (Figure 6*A*). The resulting increases in streamflow and groundwater recharge allowed for the availability of temporary surface-water and groundwater permits in North Dakota (North Dakota State Water Commission, 2017). If, however, a drought had occurred during this period of increased groundwater withdrawal, how would this affect groundwater availability? To help answer this question, a hypothetical 10-year drought was simulated for the period 2006‒2015.

## Drought Scenario 1: Steady Groundwater Withdrawals

Estimated groundwater recharge for the period 1988‒1992 was the lowest since 1960, as indicated by the decline of the annual cumulative departure from the mean (Figure 6*A*). To simulate a drought, precipitation recharge and flow conditions for the Streamflow-Routing Package that were applied to the transient model (Davis and Long, 2017a) for the period 1988‒1992 were applied twice consecutively to simulate a 10-year drought for the 2006‒2015 period. All other conditions were identical to the flowing-wells scenario, except that the simulated period was 1961‒2015. The groundwater pumping rates of the flowing-wells scenario represent the pumping rates prior to large increases in water use for energy-resource production (ERP). The flowing-wells scenario provides a baseline for comparison to drought scenarios 1 and 2 (Figure 19).

## Drought Scenario 2: Increased Groundwater Withdrawals

This scenario was identical to that of drought scenario 1, except that increased groundwater withdrawals to supply the needs of ERP for 2006‒2015 also were applied. The freshwater used for ERP was estimated by two separate methods. The first method, the consumption estimate, focused strictly on the estimated freshwater needs for ERP in the Williston Basin within the United States. The second method, the supply estimate, focused on water-withdrawal data obtained from water-use permits. The supply estimate provided pumping rates, locations, and specific aquifers for individual wells that were used in the model simulation; the consumption estimate provided an independent check on the total from the supply estimate.

For the consumption estimate, total freshwater use for ERP in the Williston basin in the United States was estimated by tabulating reported hydraulic fracturing treatment volumes for the study area using data from IHS MarkitTM (2016). Hydraulic fracturing treatment data from IHS Markit (2016) may include volumes in a variety of measurement units, and they may include multiple treatments per well. All listed treatments within the study area were converted to gallons and summed on a per-well basis, discounting any treatments for which the specified measurement units were unclear (for example, “sacks”, or “feet”). Of 3,734,380 treatments listed within the study area during the timeframe of interest, 0.7% (26,373 records) were not included. For each well, the date listed as the well completion date (typically the date of final preparation of the well for petroleum production) was considered to be the date of the water consumption. Listings for the actual treatment date are incomplete in the IHS Markit (2016) database, but generally the completion date is within a few days, or at most months, of the actual treatment date. The per-well treatment volumes were then mapped to a 1-mile grid using ArcGIS functions, and the treatment volume per grid cell per year was used to determine the consumption estimates.

This analysis did not determine specific sources of water or differentiate groundwater sources from surface-water sources. The total consumption estimate was 94,000 acre-feet for the United States and 90,000 acre-feet for North Dakota the 2006‒2015 period.

The consumption estimate for North Dakota accounted for 96 percent of the total consumption estimate for the Williston basin in the United States. Because of this and because the state of North Dakota provided detailed water-permitting data to the public, this scenario was confined to the area within North Dakota. Data for permits to use groundwater and surface water in North Dakota for ERP were obtained from the North Dakota State Water Commission (2017). In addition to the steady groundwater pumping rates applied in drought scenario 1, data from these groundwater permits also were applied in drought scenario 2 to account for the needs of ERP. Standard permits and temporary permits are two classes of permits that were obtained. Standard permits generally apply for multi-year periods, whereas temporary permits are issued for 1 year or less. For standard permits, only those issued for use in ERP were used in this scenario. All temporary permits for 2006‒2015 granted for industrial purposes were assumed to be used for ERP. Water-use rates reported by each permittee were available for the standard permits and were used in this scenario; for temporary permits, the permitted rates were used because the reported rates were not provided. A small number of permits were either outside of the model domain or open to formations below the Fox Hills aquifer and, therefore, were not included in this scenario.

Although the consumption estimate did not provide a separate estimate for groundwater use separate from surface-water use, a water-budget analysis of the two estimation methods for North Dakota indicates that the supply estimate is consistent with the consumption estimate. The total supply estimate for North Dakota groundwater was 51,000 acre-feet for the 2006‒2015 period, which is 56.3 percent of the total consumption estimate for North Dakota. Because the remaining 43.7 percent would have been supplied by surface water, this results in a ratio of groundwater to surface-water usage of about 1.3. As a comparison, the ratio of groundwater to surface-water usage from the North Dakota permit data for ERP was about 1.4 for the 2006‒2015 period. Any transport of water across state lines was not considered in this analysis, which introduces error. Although there is error in both estimation methods, this analysis provides confidence in the pumping rates used in the model simulation.

In many cases a specific aquifer was not specified in the groundwater-permit data. For example, in some cases the Fort Union Formation was listed as the source, and this formation was represented by model layers 3, 4, and 5. In these cases, the simulated well was assigned to model layer 3, 4, or 5, depending on which had the highest hydraulic conductivity to best accommodate the withdrawal rate. In some cases, the source was simply listed as groundwater, in which case the simulated well was assigned to the model layer with the highest hydraulic conductivity for standard permits; for temporary permits, however, the model layer was chosen from layers 1-5 because new permits generally are applied to aquifers represented by these model layers.

The steady-state and transient models simulated many areas where the glacial aquifer system was unsaturated in upland areas between stream valleys. Permitted wells with a glacial-aquifer source generally were clustered in areas where the models simulated saturated conditions. This indicates that the models were consist with the permit locations because water production wells would be located in areas where groundwater is available. However, a regional model cannot include a high level of spatial detail and accuracy, and therefore, adjustments to some well locations were made if a well was at a location that had unsaturated model cells. The location was moved as much as 7 miles to a new location that could better accommodate simulated pumping.

Notes: We’ll run the simulation with the GW supplying the estimated 51,000 acre-feet and then multiply all pumping rates by 1.71 to see what happens if GW had to supply all of the 90,000 arce-feet for ND. Need to explain how model layers were assigned when permit data were not specific to a single aquifer. ND permitted wells in layers 1 and 2 were moved from 1 to 7 miles from the original location, if necessary, to locate at least one mile from areas of dry cells.

## Comparison of Drought Versus Non-Drought Scenarios

A comparison of the simulated results of the three scenarios provides an estimate of the effects drought and of the more severe effects of increased groundwater extraction during drought. [\*\* Describe results by discussing Figure 19, Figure 20, Figure 21, Figure 22.]

1. Comparison of the three scenarios, showing water-level hydrographs for selected sites.
2. Simulated water-level change maps from 2005 to 2015 for drought scenarios 1 and 2 for, *A*, the glacial aquifer system and, *B*, the upper Fort Union aquifer. [\*\*four maps on one page]
3. Simulated change in groundwater-flow budget from 2005 to 2015 for the glacial aquifer system, upper Fort Union aquifer, and Fox Hills aquifer [\*\*this would likely show that most groundwater being removed from shallower aquifers and lesser stress on the deeper aquifers. We could six pie charts: glacial, UFU, and FH for 2005 and 2015.]
4. Cumulative change in groundwater storage by aquifer system, 2005-2015.

# Improving Hydrologic Monitoring Networks

Because of the costs and resources needed to install hydrologic monitoring networks, their design should be well planned and have specific objectives. If a numerical groundwater-flow model is used to inform water-management decisions, an objective might be to design a monitoring network that would provide data that best improves the model’s usefulness and defensibility.

Uncertainty of simulated hydrologic forecasts, also known as predictive uncertainty, can be reduced by providing additional data to better inform model calibration. If the new data were to come from a new observation well, for example, the degree of uncertainty reduction depends on the specific location of this well. One way to determine the best locations for a new observation well is to apply a method described by Fienen and others (2010) and White and others (2016), which hereafter is referred to as a “data-worth analysis.” For example, the model might be used to forecast the effects of a new pumping well on streamflow. If water-level data from a new observation well were used to update the model calibration, this could reduce model uncertainty associated with this forecast of interest, depending on the location of that well. The data-worth value is equal to the forecast uncertainty when a new observation well is included in model calibration divided by the forecast uncertainty without the new well. A data-worth map would show the relative value of additional groundwater-level data at different locations.

As an example, the data-worth analysis was applied to hydrologic forecasts of interest for the Williston basin simulated by the steady-state model (1981‒2005) described by Davis and Long (2017a) . Therefore, the analysis applies to equilibrium conditions, but a similar analysis could be applied to scenarios simulating a finite time period. The analysis area includes the Clear Lake and Little Muddy aquifers (Figure 23). A simulated pumping well was added to the area representing the Clear Lake aquifer in model layer 2 at a rate of 2.8 ft3/s, and seven locations along the Big Muddy Creek and its tributaries (Figure 23, sites F1-F7) were selected as sites to forecast the effects of the pumping well on streamflow. Figure 23 shows the results of the data-worth analysis applied to site F3. The simulated glacial aquifer system, represented by model layers 1 and 2, was unsaturated in upland areas, and therefore, results of the data-worth analysis primarily are restricted to lowland areas, where observation wells could be installed (Figure 23). Simulated groundwater flow generally is in the direction of surface-water flow, toward the Missouri River, except for the northeast corner of Figure 23, which is north of a groundwater divide that generally corresponds to a surface-water divide.

The streamflow forecast locations and pumping well are on the south side of the groundwater divide (Figure 23); counterintuitively, however, most of the good locations for a new observation well are on the northeast side of this divide. The first reason for this outcome is that numerous observation wells are located south of the divide (Figure 23), and therefore, little would be gained by adding more observation wells in those locations. The second reason is that water levels near the upgradient divide help inform the groundwater balance between pumped water derived from streams and groundwater from the surrounding aquifer. Site F3 is on the main stem of the Big Muddy Creek, where base flow is affected by all upstream tributaries; therefore, results of the data-worth analysis indicate that an observation well northeast of the Big Muddy Creek watershed best represents overall groundwater levels within the watershed, with respect to informing the interaction of surface water and groundwater.

The data-worth analysis also was applied to the other six stream sites shown on Figure 23. Results for sites F2 and F6 were similar to those of site F3. Site F6 is on the main stem and, therefore, responds similarly to site F3, which also is on the main stem. Site F2 is on a small tributary north of the main stem, and the data-worth analysis indicates that this site would benefit from an observation well that also would benefit sites on the main stem. Figure 24 shows results of the data-worth analysis for site F7. Although site F7 also is on the main stem, the analysis for this site differs from results for site F3: the highest data worth for site F7 is shifted to the southwest in comparison to site F3 (Figure 23 and Figure 24). Because site F7 is upstream of large tributaries on the north side of the main stem, the most beneficial observation well would be in areas closer to site F7 than those for site F3 (Figure 23 and Figure 24). Results of the analysis applied to sites F1, F4, and F5, which are on south or southwest tributaries, are dissimilar to results previously described and indicate low data worth in general, including the northeast corner of the analysis area.

The general pattern for the data-worth analysis is that stream sites on the main stem and northern tributaries have the highest data-worth values and that stream sites on south and southwest tributaries have the lowest data-worth values. The area with the highest data worth for most sites is the northeast corner of the analysis area, similar to that shown on Figure 23.

Data-worth analyses also were conducted for forecasts of groundwater level; these analyses were for six locations where groundwater-level forecasts influenced by a pumping well were desired. Figure 25 shows an example of the results for site H4; results for all sites, except for site H5, were similar to those of site H4. The greatest data worth for site H5 was in the same area as that of site F7 (Figure 24, Figure 26). Data worth for the groundwater-level forecasts can, in general, be explained by reasons similar to those for the streamflow forecasts. If forecasts were desired for all 13 sites in this analysis, the best overall location for a new observation well would be in northeast corner of the analysis area.

1. Data-worth map for streamflow forecast site F3. The map shows the relative data-worth values associated with a potential new observation well that, if installed, could reduce simulated uncertainty of a streamflow forecast.
2. Data-worth map for streamflow forecast site F7. The map shows the relative data-worth values associated with a potential new observation well that, if installed, could reduce simulated uncertainty of a streamflow forecast.
3. Data-worth map for groundwater-level forecast site H4. The map shows the relative data-worth values associated with a potential new observation well that, if installed, could reduce simulated uncertainty of a streamflow forecast.
4. Data-worth map for groundwater-level forecast site H5. The map shows the relative data-worth values associated with a potential new observation well that, if installed, could reduce simulated uncertainty of a streamflow forecast.

# Summary

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Examples:

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References from figs only: Love and Christiansen (1985); Peterson (1984);

Glossary

Calibration target

Control volume A volume of the earth consisting of the lower Tertiary and Upper Cretaceous aquifer systems and the glacial aquifer system directly overlying these bedrock aquifer systems in the Williston basin.

Lake flux

Model domain Spatial extent of the active simulated model area.

Objective function value

Observation data Measured or estimated values used in model calibration.

Pilot points

Stream flux

SWB-estimated recharge

Transient stress period A time period simulated by the numerical model that represents the change from initial conditions at the beginning of the period to the end of the period.

Vertical head targets

Appendix 1. Additional Character Style Examples

Text in the appendix uses the BodyText style as in the main body of the report. Use the following character styles in all parts of the report (main body, front matter, and back matter):

* The character style for superscript is Superscript.
* The character style for subscript is Subscript.
* The character style for italic superscript is SuperEmphasis
* The character style for italic subscript is SubEmphasis
* The character style for a URL is Hyperlink (<http://www.usgs.gov>/)

Use the paragraph style BodyNoIndent to continue a paragraph after a list of items or an equation. Then, use the paragraph style BodyText for the next paragraphs.

# Write-N-Cite

(Aurand, 2013, p. 107)

(Downey, 1986, p. E1-E87)

(Long and others, 2014)

(Thamke and others, 2014, p. 38)

(Westenbroek and others, 2010)

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