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Potential Effects of Energy Development on Environmental Resources of the Williston Basin in Montana, North Dakota, and South Dakota—Physiography, Climate, Land Use, and Demographics

Chapter B of
Potential Effects of Energy Development on Environmental Resources of the Williston Basin in Montana, North Dakota, and South Dakota

Scientific Investigations Report 2017–5070–B

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

Front cover. An oil well pump jack in a grassland in Stark County, North Dakota. Photograph by Larry D. Igl, U.S. Geological Survey.

Back cover. An oil well pump jack in a grassland in Fallon County, Montana. Photograph by Larry D. Igl, U.S. Geological Survey.

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Preston, T.M., 2018, Macroinvertebrate and water quality data from the Prairie Pothole Region of the Williston Basin (2014–2016): U.S. Geological Survey data release, https://doi.org/10.5066/F7DB8141.

Preston, T.M., 2019, Water quality data from the Goose Lake study site, eastern Montana 1989–2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9IMF7CH.

U.S. Geological Survey, 2017, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

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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)
inch (in.)	25,400	micrometer (µm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million barrels (Mbbl; petroleum, 1 million barrels=42 million gallons)	0.1590	million cubic meters (Mm^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per month (in/mo)	25.4	millimeter per month (mm/mo)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pound, avoirdupois (lb)	4.54×108	microgram (µg)

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 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.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), parts per billion (ppb), or micrograms per cubic meter ($\mu g/m^3$).

Particulate matter diameter size is given in micrometers (µm).

Abbreviations

STEPPE	Science Team about Energy and Plains and Potholes Environments
USGS	U.S. Geological Survey

Potential Effects of Energy Development on Environmental Resources of the Williston Basin in Montana, North Dakota, and South Dakota—Physiography, Climate, Land Use, and Demographics

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Abstract

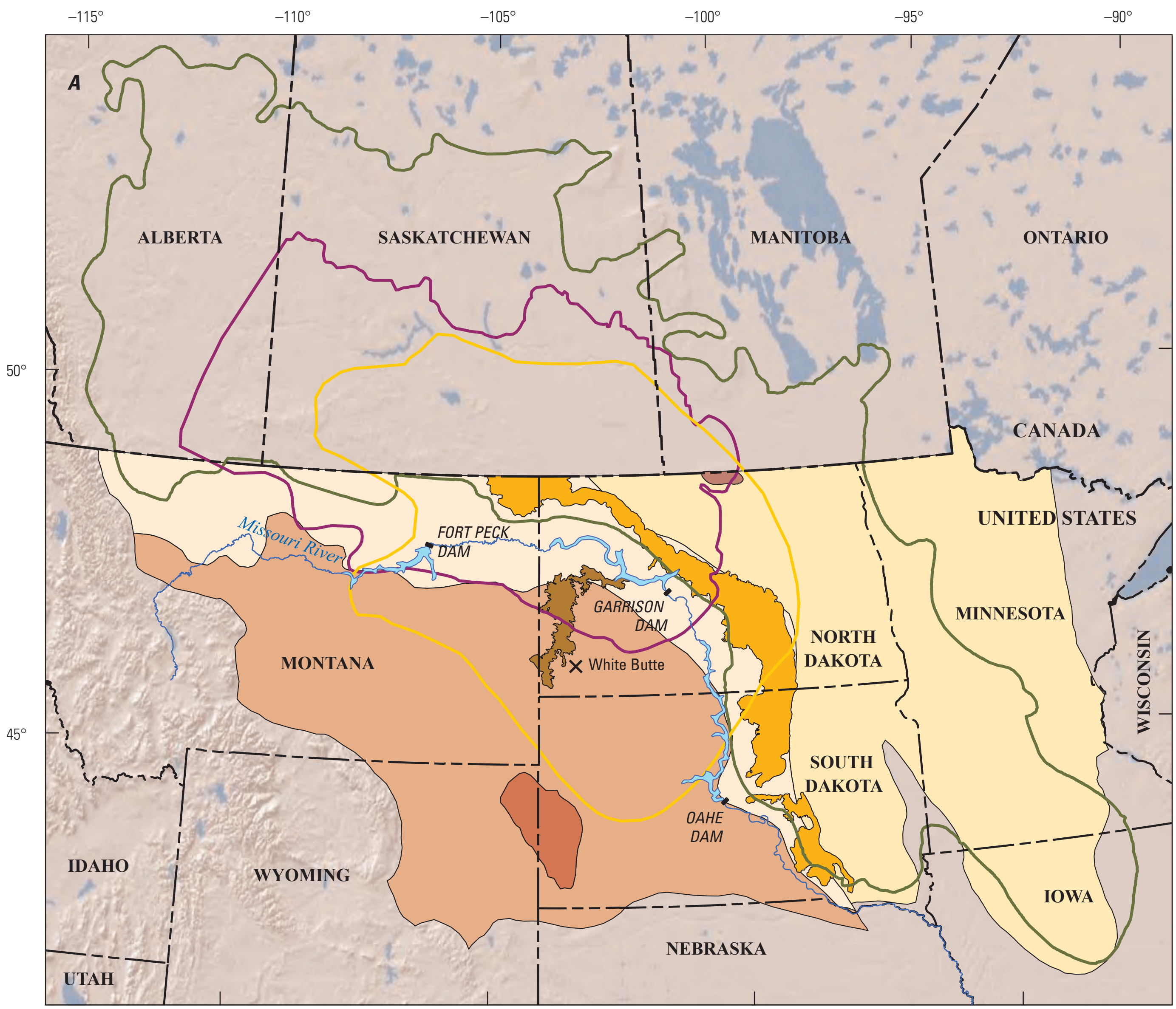
The Williston Basin has been a leading domestic oil and gas producing region. As energy demands have increased, so has energy development. A group of 13 Federal agencies and Tribal groups formed the Bakken Federal Executive Group to address common challenges associated with energy development, with a focus on understanding the cumulative environmental challenges attributed to oil and gas development throughout the basin. To better understand the natural resources in the Williston Basin, the U.S. Geological Survey, in cooperation with the Bureau of Land Management, began work to synthesize existing information on science topics that will support management decisions related to energy development. This report is a compilation of information regarding the natural setting, energy development history, demographics, and related investigations related to energy development in the Williston Basin of Montana, North Dakota, and South Dakota. Completed and ongoing investigations include the topical areas of unconventional oil and gas assessments, water quality, water availability, air quality, effects on human health, and ecological effects.

Introduction

The Williston Basin includes parts of Montana, North Dakota, and South Dakota in the United States and the provinces of Manitoba and Saskatchewan in Canada (fig. 1). The basin, roughly bisected by the Missouri River and containing many other rivers, lakes, and wetlands (fig. 2), has been a leading domestic oil- and gas-producing region for more than 50 years (Anna and others, 2011; Gleason and Tangen, 2014; Thamke and others, 2014). As demands for energy have increased, energy development in the Williston Basin has increased substantially since the mid-2000s, primarily because of improved precision horizontal drilling and hydraulic fracturing methods in previously inaccessible formations, such as the Bakken and Three Forks Formations (Gaswirth and others, 2013).

Rapid changes in energy-development activities in the Williston Basin, along with Executive Order no. 13604 (March 22, 2012) requiring improved timeliness of the permitting process for extraction of publically owned minerals while minimizing negative effects to other resources (Federal Register, 2012), have increased the need to understand how development may affect resources Federal agencies are tasked with managing. Management of public minerals falls mainly on the Bureau of Land Management, who must make decisions about leasing minerals and also issuing permits to extract public oil and gas resources. Part of the leasing and permitting process is to determine whether to include stipulations to limit unforeseen negative consequences or ameliorate potential conflicts of future development. Other Federal agencies, like the U.S. Forest Service, U.S. Fish and Wildlife Service, and Bureau of Indian Affairs, also may issue special permits to oil and gas developers if energy development might negatively affect resources that agency is tasked with managing.

In response to Executive Order 13604, a group of 13 Federal agencies and Tribal groups formed the Bakken Federal Executive Group to address common challenges associated with energy development, with a focus on understanding the cumulative environmental challenges attributed to oil and gas development throughout the Williston Basin (table 1). To better understand the natural resources in the Williston Basin, the U.S. Geological Survey (USGS), in cooperation with the Bureau of Land Management, began to synthesize existing information on science topics that will support management decisions related to energy development.



Base map modified from U.S. Geological Survey, Esri, U.S. Environmental Protection Agency, and Nature Conservancy digital data variously dated, various scales. Base map image is the intellectual property of Esri and is used herein under license.

Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

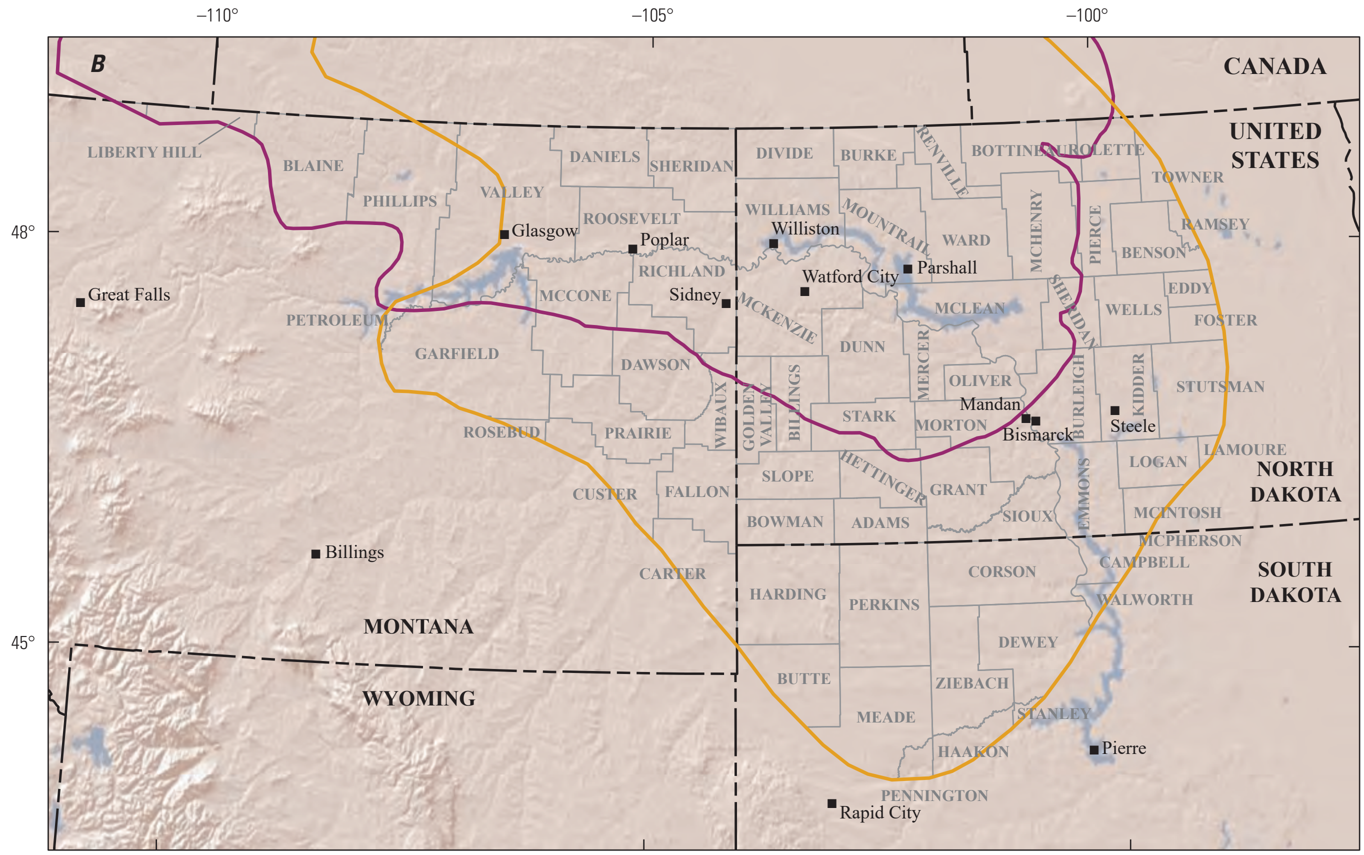
EXPLANATION

Physiographic provinces (U.S. Environmental Protection Agency levels III and IV ecoregions)

- Missouri Plateau, glaciated
- Missouri Plateau, unglaciated
- Western Lake
- Black Hills
- Little Missouri Badlands
- Turtle Mountains
- Missouri Coteau

- **Williston Basin boundary**
- **Bakken Formation boundary**
- **Prairie Pothole Region boundary**

Figure 1. Locations of *A*, physiographic provinces, *B*, counties and cities, and *C*, petroleum wells in the Williston Basin, United States (Montana, North Dakota, and South Dakota) and Canada (Manitoba and Saskatchewan).



Base map modified from U.S. Geological Survey, Esri, and U.S. Census Bureau digital data, variously dated, various scales. Base map image is the intellectual property of Esri and is used herein under license.

Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

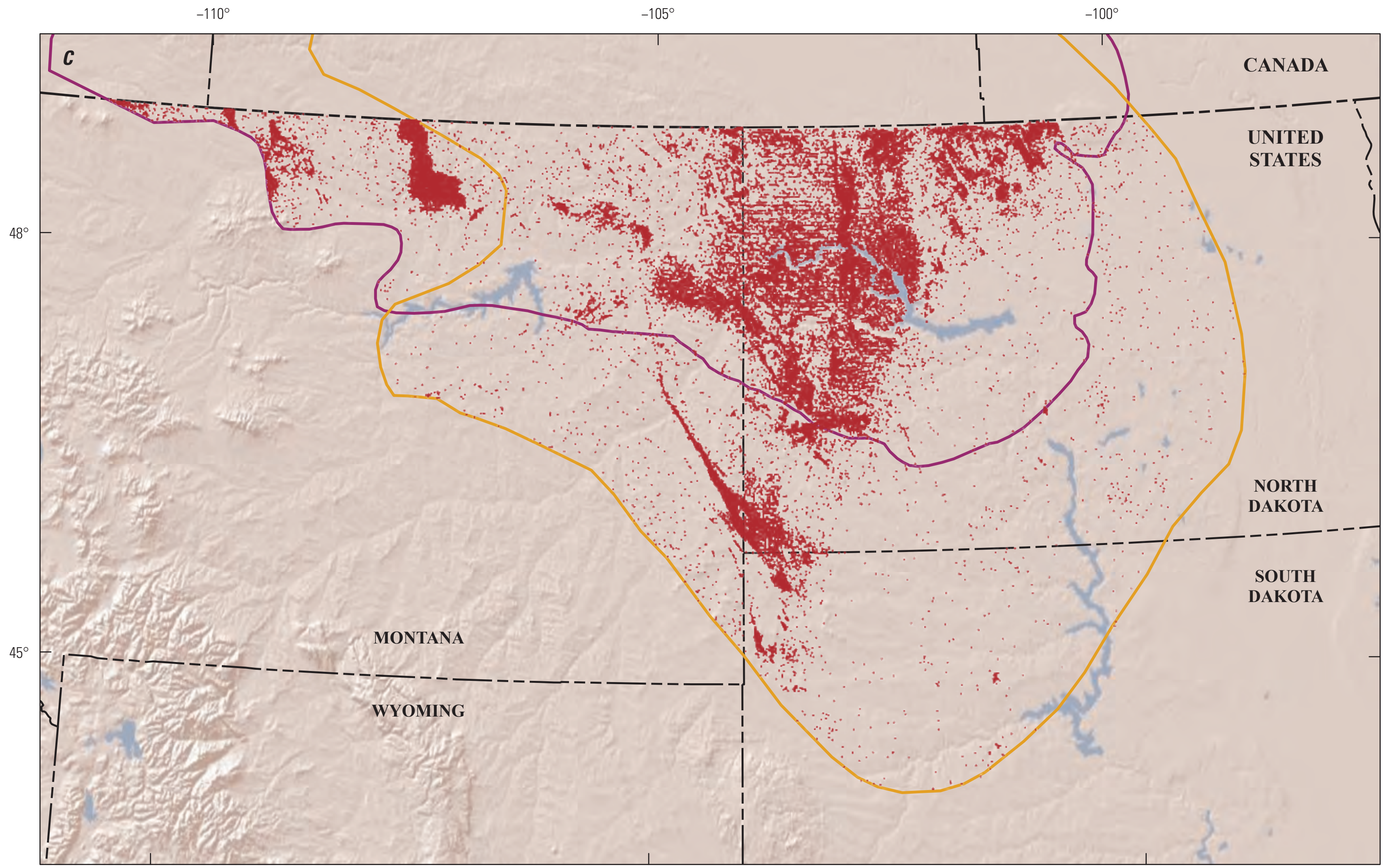
0 50 100 MILES
0 50 100 KILOMETERS

EXPLANATION

Williston Basin boundary

Bakken Formation boundary

Figure 1. Locations of *A*, physiographic provinces, *B*, counties and cities, and *C*, petroleum wells in the Williston Basin, United States (Montana, North Dakota, and South Dakota) and Canada (Manitoba and Saskatchewan).—Continued.



Base map modified from U.S. Geological Survey, Esri, Montana Board of Oil and Gas, North Dakota Oil and Gas Division, and South Dakota Department of Enviornmental and Natural Resources digital data, various scales, variously dated.
Well data current as of July, 2016. Base map image is the intellectual property of Esri and is used herein under license.

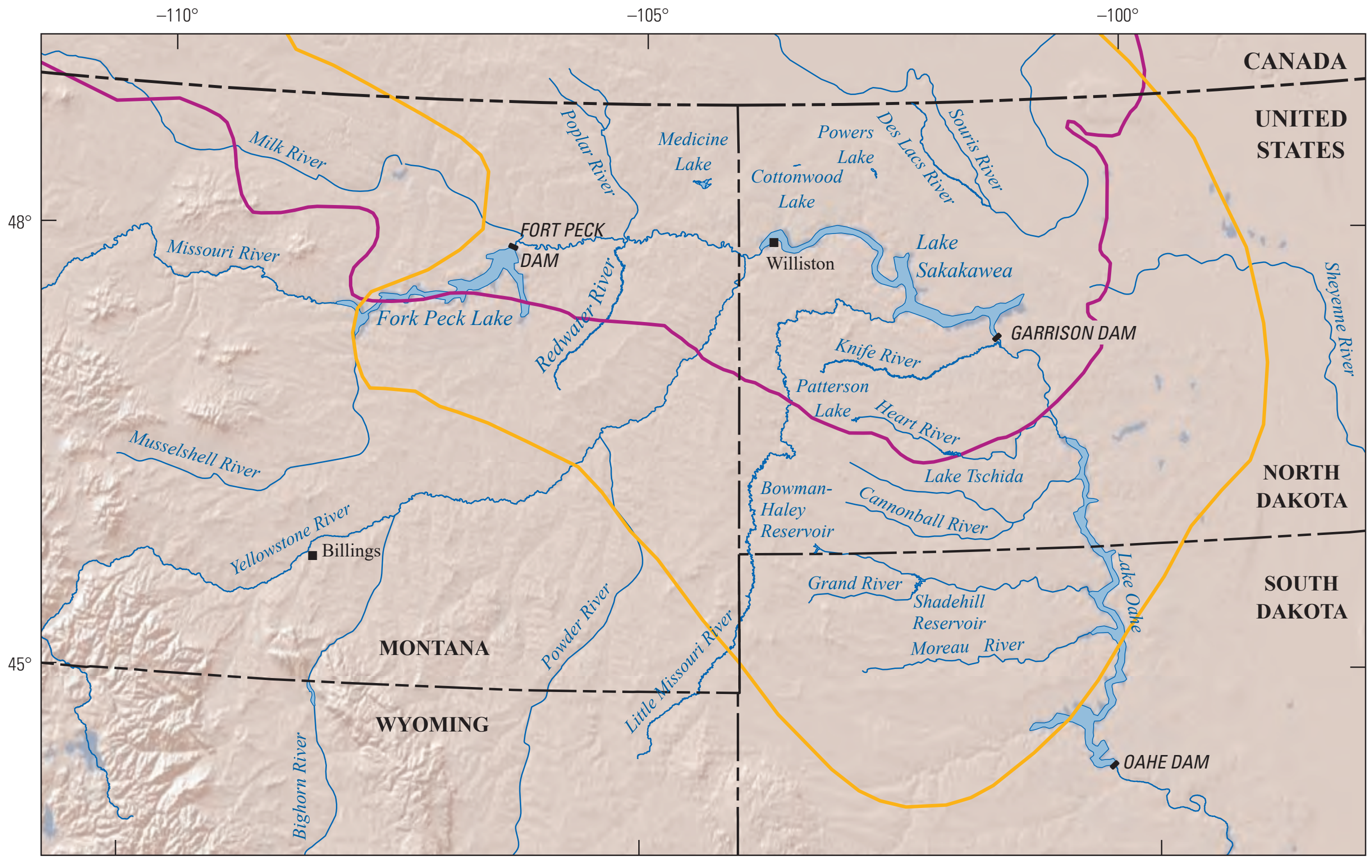
Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum 1983

EXPLANATION

- Williston Basin boundary
- Bakken Formation boundary
- Petroleum well

0 50 100 MILES
0 50 100 KILOMETERS

Figure 1. Locations of *A*, physiographic provinces, *B*, counties and cities, and *C*, petroleum wells in the Williston Basin, United States (Montana, North Dakota, and South Dakota) and Canada (Manitoba and Saskatchewan).—Continued.



Base map modified from U.S. Geological Survey, Esri, and Commission for Environmental Cooperation digital data variously dated, various scales. Base map image is the intellectual property of Esri and is used herein under license.

Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

0 50 100 MILES
0 50 100 KILOMETERS

EXPLANATION

Williston Basin boundary

Bakken Formation boundary

Figure 2. Surface-water features of the Williston Basin, United States (Montana, North Dakota, and South Dakota) and Canada (Manitoba and Saskatchewan).

Table 1. Federal agencies participating in the Bakken Federal Executive Group, as of November 2014.

[–, not applicable]

Agency	Last name	First name	Title
Bureau of Indian Affairs—Great Plains Region	LaPointe	Timothy	Acting Regional Director—Great Plains Region
	Clifford	Rick	Deputy Realty Officer
Bureau of Indian Affairs—Office of Indian Economic and Energy Development	Hunt	Jeffrey	Supervisory Petroleum Engineer
Bureau of Indian Affairs—Rocky Mountain Region	LaCounte	Darryl	Acting Regional Director—Rocky Mountain Region
	Bemer	Howard	–
Bureau of Land Management	Connell	Jamie	Montana/Dakota State Director
	Kitchell	Kate	Montana/Dakota Associate State Director
Bureau of Reclamation	Ryan	Michael	Regional Director
	Rosenkrance	David	Area Manager, Dakotas Area Office
National Park Service	Trap	Patty	Acting Regional Director
	Ross	Wendy	Theodore Roosevelt National Park Acting Superintendent
Office of Natural Resources Revenue	Gibbs Tschudy	Deborah	Deputy Director
	Walsh-Bayani	Theresa	Director for Audit and Compliance Management
Office of the Special Trustee for American Indians	James	Jim	Deputy Special Trustee, Field Operations
	Gillette	Austin	Fiduciary Trust Officer
U.S. Army Corps of Engineers	Cross	Colonel Joel	Commander, Omaha District
	Janis	Larry	Chief, Recreation and National Resource Branch
U.S. Department of Agriculture— Farm Services Agency— Montana	Nelson	Bruce	State Executive Director
	Webbink	Amy	Montana Chief Administrative Officer
U.S. Department of Agriculture— Farm Services Agency— North Dakota	Krauter	Aaron	State Executive Director
	Bubach	Russ	Administrative Officer
U.S. Department of Agriculture—Natural Resources Conservation Service—Montana	Swartzendruber	Joyce	Montana State Conservationist
	Pratt	David	Montana Assistant State Conservationist
U.S. Department of Agriculture—Natural Resources Conservation Service—North Dakota	Podoll	Mary	North Dakota State Conservationist
	Lund	Lisa	State Administrative Officer
U.S. Department of Energy	Johnson	Robin	–
U.S. Environmental Protection Agency	McGrath	Shaun	Regional Administrator, Region 8
	Beeler	Cindy	Energy Advisor
U.S. Fish and Wildlife Service	Walsh	Noreen	Regional Director
	Thabault	Michael	Deputy Regional Director
U.S. Forest Service	Krueger	Faye	Regional Forester, Region 1
	Neitzke	Dennis	Grassland Supervisor, Dakota Prairie Grasslands
U.S. Geological Survey	Lynch	Dennis	Associate Regional Director, Northwest Region
	Kilpatrick	John	Director, Wyoming-Montana Water Science Center
	Carl	Leon	Regional Director, Midwest Region
	Morlock	Scott	Science Coordinator, Midwest Region

Energy Production in the Williston Basin

The first commercial gas production in the Williston Basin was from shallow Late Cretaceous-age geologic units in 1913 in Montana, and the first commercial oil production was established with the completion of the Clarence Iverson no. 1 well in 1951 in North Dakota (Anna and others, 2011). There have been three energy-production cycles in the Williston Basin. The first cycle began about 1951, and oil production increased to a maximum of 2.5 million barrels (Mbbl) per month in 1966. The second cycle began in 1973, and oil production increased to more than 7 Mbbl per month in 1984. Oil production leveled off until a third cycle began in 2008 and increased to a 2015 level of more than 30 Mbbl per month. Gas production cycles generally mimicked the oil production cycles (Anna and others, 2011). As of July 1, 2016, more than 47,000 petroleum-related wells have been drilled or permitted throughout the Williston Basin (fig. 1*C*).

In association with the oil, extremely saline water that contains more than 35,000 milligrams per liter (mg/L) of dissolved solids, often called brine (USGS, 2013), is produced in the Williston Basin often at a rate much greater than oil (Thamke and Craigg, 1997; Wanty, 1997). Until 2008, almost all oil-production wells were drilled vertically into oil reservoirs in the Mississippian-age Madison Group and Late Ordovician-age Red River Formation of the Bighorn Group (fig. 3). Brine-to-oil production ratios of 10:1 were not uncommon (Wanty, 1997). Produced water from the Madison Group is extremely saline; dissolved-solids concentrations can exceed 200,000 milligrams per liter (Preston and others, 2012, Thamke and Smith, 2014, Blondes and others, 2015). Since 2008, oil-production wells have included horizontal drilling and hydraulic fracturing into the Late Devonian and Early Mississippian-age Bakken and Three Forks Formations (fig. 3). Brine from the Bakken and Three Forks Formations is generally more saline than from the Madison Group; dissolved-solids concentrations can exceed 300,000 mg/L (Preston and others, 2012; Blondes and others, 2015). These oil- and brine-producing geologic units occur at depths below many of the major aquifers and other hydrogeologic units included in the uppermost principal aquifer systems (glacial aquifer system, Lower Tertiary aquifer system, and Upper Cretaceous aquifer system), which are the most accessible sources of groundwater in the Williston Basin (Thamke and others, 2014) (fig. 3 and 4). Most produced waters are disposed into the Late Cretaceous-age Inyan Kara Formation (Dakota Sandstone) buried below these three principal aquifer systems.

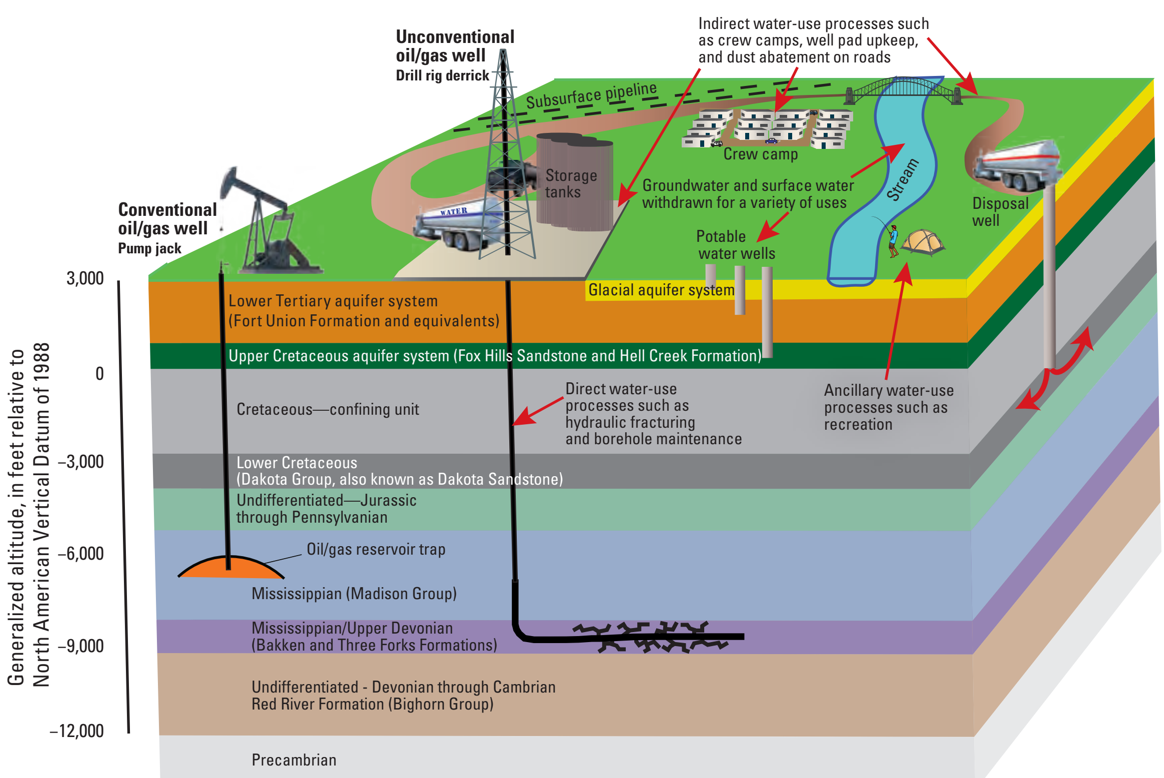


Figure 3. Geologic and hydrogeologic units and water-use and energy-development components of the Williston Basin (modified from Carter and others, 2016; North Dakota Geological Survey, n.d.). Individual hydrogeologic units composing the Lower Tertiary and Upper Cretaceous aquifer systems are shown in figure 4.

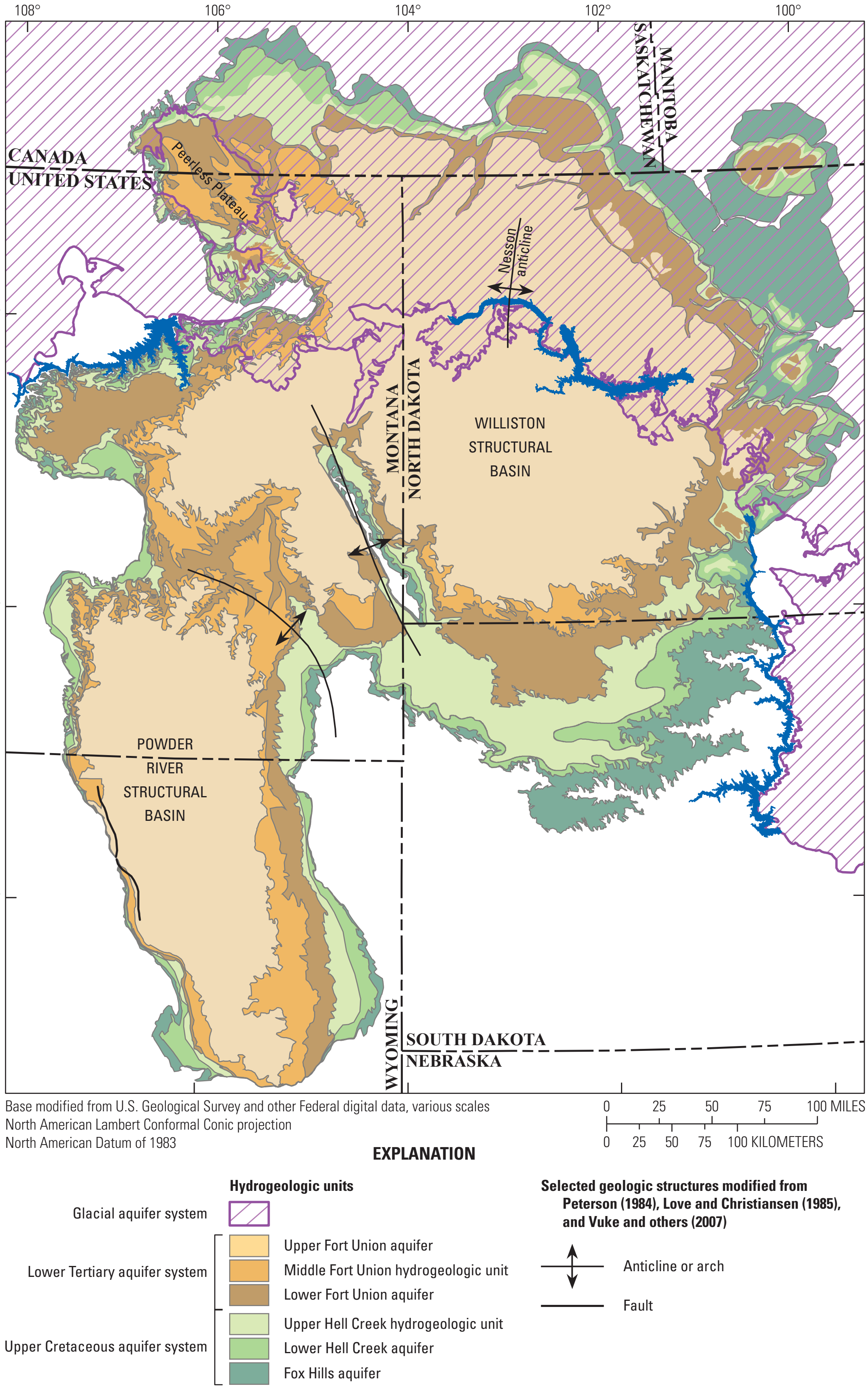


Figure 4. Hydrogeologic units of the uppermost principal aquifer systems in the Williston Basin, United States (Montana, North Dakota, and South Dakota) and Canada (Manitoba and Saskatchewan) (from Thamke and others, 2014; U.S. Geological Survey, 2014).

Mishaps during handling, storage, and disposal of the brine in this area have resulted in surface-water and groundwater contamination (Murphy, 1983; Murphy and Kehew, 1984; Beal and others, 1987; Murphy and others, 1988; Reiten and Tischmak, 1993; Thamke and Craigg, 1997; Peterman and others, 2010; Preston and others, 2010; Rouse and others, 2013; Gleason and Tangen, 2014). Contamination from brine often causes marked changes in the chemistry of water resources (Reiten and Tischmak, 1993) that could affect primary productivity in aquatic systems. Contamination that happened in the 1960s is still evident and is expected to persist for tens to hundreds of years (Murphy and others, 1988; Preston, 2011).

Purpose and Scope

The purpose of this report is to provide a brief compilation of information regarding the physiography, climate, land use, and demographics of the Williston Basin in Montana, North Dakota, and South Dakota (fig. 1). This report provides guidance on information and data that can be used to develop effective techniques to adequately assess issues related to energy development activities.

Physiography of the Williston Basin

Topographically, the Williston Basin is a large, roughly circular depression, centered at about Williston, North Dakota, that covers several hundred thousand square miles across parts of the Great Plains of North Dakota, South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan (North Dakota Geological Survey, n.d.) (fig. 1*A*). This area has a gently rolling land surface underlain mostly by the sedimentary rocks, sandstone and shale. The Williston Basin is included almost entirely in the Great Plains physiographic region or ecosystem region (Omernik, 1987; Bailey and others, 1994).

The Williston Basin has extensive geologic structures that contain thick sedimentary rocks and considerable mineral resources (Keefer, 1974). The basin is a major source of coal, oil, and natural gas, which formed as a result of regional geologic processes. Shallow seas alternatively covered but then receded from the area while the basin was forming. The remains of animal and plant organisms in or near the seas were deposited on the seabed and became the energy resources of the basin.

Landscape

The Williston Basin lies almost entirely within the glaciated and unglaciated areas of the Missouri Plateau of the Great Plains physiographic region (Fenneman, 1931; Keefer, 1974) (fig. 1*A*). The glaciated areas lie mostly to the north and east of the Missouri River and are characterized by smooth to rolling landscapes. The area southwest of the Missouri River is mostly unglaciated, with broad valleys, hills, and buttes of the Missouri Plateau that resulted mostly from the erosion of ancient sediments (fig. 1*A*). These sediments had been deposited by ancient rivers flowing away from the rising Rocky Mountains millions of years ago. The Missouri Plateau stretches west to east across Montana, west to south across western North Dakota, then south across western South Dakota (Fenneman, 1931; Keefer, 1974). The eastern segment of the Missouri Plateau contains a 15- to 25-mile (mi) wide strip of irregular terrain, which was pushed up by advancing glaciers about 10,000 to 15,000 years ago. This strip cuts diagonally northwest to south across central North Dakota into South Dakota and is commonly referred to as the Coteau du Missouri (Keefer, 1974), but referred to as the Missouri Coteau in this report (fig. 1*A*).

The northeast corner of the Williston Basin is characterized by nearly flat to rolling plains (Keefer, 1974) (fig. 1*A*). Elevations rise from about 1,500 feet (ft) above the North American Vertical Datum of 1988 (NAVD 88) along the valley floors to 2,000 ft at the margin of the Turtle Mountains on the northeast and to 1,700–2,000 ft along the foot of the Missouri Coteau on the southwest (fig. 1*A*). The Turtle Mountains are a group of rolling hills generally less than 200 ft high; maximum elevations reach 2,400 to 2,500 ft above NAVD 88 in that area (fig. 1*A*). Elevations rise gradually from about 2,000 ft above NAVD 88 at the eastern edge of the Missouri Plateau to 5,000–6,000 ft at the foot of the Rocky Mountains in Montana. White Butte, at 3,506 ft above NAVD 88 in the southwestern corner of North Dakota (fig. 1*A*), is the highest point in North Dakota (Bluemle and Biek, 2007). The highest points in Montana and South Dakota are in the Rocky Mountains and Black Hills, respectively, but areas of the western Williston Basin in Montana and South Dakota have elevations greater than 3,000 ft above NAVD 88 (Alden, 1932; Malo, 1997).

The Williston Basin is drained mostly by the eastward- and southeastward-flowing Missouri River and a major tributary, the northeastward-flowing Yellowstone River (Keefer, 1974) (fig. 2). Other rivers flow into the Missouri and Yellowstone Rivers, mostly from the west and south. In the extreme northeast corner, the Williston Basin is drained by the Souris River and its tributaries. No major streams drain the Missouri Coteau region (Malo, 1997).

North and east of the Missouri River in the Williston Basin is a landscape characterized by a rolling, hummocky, or hilly surface with thousands of closed depressions between the hills and hummocks occupied by lakes or potholes from melting blocks of ice, called the Prairie Pothole Region (fig. 1*A*; Sloan, 1972). Glacial moraines and tills accumulated along the terminal ends of glaciers and formed ridges of low, rolling hills and the Missouri Coteau in a northwest to southeast orientation. Where glaciers retreated quickly, large, gently rolling areas of glaciated plains were formed, and extremely flat lake beds developed where glaciers dammed meltwater. Because of the geologically young nature of the landscape and moderate rainfall, there are few natural surface drainage systems;

consequently, most wetlands in the Prairie Pothole Region are not connected by overland flow but can be connected by groundwater (Sloan, 1972).

Geology

Sedimentary rocks contained within the Williston Basin accumulated largely as a result of the advancement and retreat of shallow seas that periodically covered the area from about 570 million years ago until about 70 million years ago (Trimble, 1980). A thick sequence of layered sediments, mostly between 5,000 and 10,000 ft thick, was deposited onto the floor of the shallow seas. About 70 million years ago, the seas were displaced from the Williston Basin by uplift of the land, and the landscape that appeared was simply the extensive, nearly flat floor of the former sea (Trimble, 1980). Molten rock rose in various regions, causing undulations in the sedimentary rocks and landscape, and resulted in low areas such as the Williston Basin.

For about 65 million years, sediments from the rising Rocky Mountains were deposited by ancient rivers (Trimble, 1980). Beginning about 5 million years ago, regional uplift of the western part of the continent forced streams to cut into the layers of sediment. The predecessor of the present-day Missouri River eroded into the northern Great Plains and developed a tributary system that excavated deeply into the accumulated deposits near the mountain front and carried away huge volumes of sediment from the Great Plains. By 2 million years ago, streams had eroded downward to within a few hundred feet of their present level. Continental glaciers then advanced southward from Canada into the United States. At the north and east extent of the present-day Missouri River, the glaciers left deposits that covered the bedrock surface and forced streams that had flowed north into new courses along the ice margins (Trimble, 1980).

The Little Missouri River began to carve the Little Missouri Badlands (fig. 1*A*) about 600,000 years ago when the river was diverted by glaciers from its northerly route into Canada (Bluemle and Biek, 2007). The Badlands are a deeply eroded area along the Little Missouri River that stretches from far southwest North Dakota north to the confluence with the Missouri River. These Badlands, carved into the sediments of the Missouri Plateau, were formed by the cutting action of streams flowing down over a sloping face of softer, fine-grained material composed mainly of clay and silt (Trimble, 1980). The carving by many small streams produced the distinctive gullied badland terrain.

Landforms in the Missouri Plateau and Little Missouri Badlands resulted primarily from the differences in resistance to erosion. Buttes, for example, formed when easily eroded sediments were protected by a hard layer of sandstone or limestone. Where beds of lignite caught fire and burned, adjacent sediments were baked and fused into a natural brick-like material called clinker. The red clinker also protected underlying sediments from erosion. In other places, mineralized groundwater passed through the sediments, forming materials such as flint, petrified wood, and concretions of many shapes and sizes. These materials are quite hard, resist erosion, and accumulated at the surface, such as the cannonball concretions along various rivers in southwest North Dakota (Biek, 2002).

Water

The Missouri River is the major river in the Williston Basin (fig. 2). The Missouri River begins in southwestern Montana, flows north then east across northern Montana, and enters North Dakota southwest of Williston. A primary tributary of the Missouri River is the Yellowstone River, which flows free of major dams for its entire 671 mi, making it the longest free-flowing river in the United States (Higgins, 1996). The Yellowstone River winds north through mountains in southwest Montana, then flows east and northeast through Billings and through lower-topography regions of eastern Montana before joining the Missouri River in North Dakota. Another tributary, the northward-flowing Little Missouri River in southeast Montana and southwest North Dakota, has eroded extensive areas classified as open high hills and created the Little Missouri Badlands.

Three large reservoirs have been developed on the Missouri River in or near the Williston Basin—Fort Peck Lake, Lake Sakakawea, and Lake Oahe (fig. 2; U.S. Army Corps of Engineers, 2012). Fort Peck Lake is about 134 mi in length and has a damming height of about 220 ft. The reservoir began filling in 1937, and the lake can retain about 18,500,000 acre-feet (acre-ft) of water. Lake Sakakawea is about 178 mi long and has a damming height of about 180 ft. The reservoir began filling in 1953 and can retain about 23,800,000 acre-ft of water, making the lake the third largest reservoir in the United States. Lake Oahe is about 231 mi long and has a damming height of about 200 ft. The reservoir began filling in 1958 and can retain about 23,100,000 acre-ft of water.

Other smaller lakes and reservoirs are in the Williston Basin. Many of these lakes and reservoirs, such as Bowman-Haley Reservoir, Lake Tschida, Patterson Lake, and Shadehill Reservoir (fig. 2), were constructed by the U.S. Army Corps of Engineers or the Bureau of Reclamation for flood control, water supply, and recreation. Many of the natural lakes in the basin, such as Medicine Lake, Powers Lake, and Cottonwood Lake, are associated with national wildlife refuges and are used mostly for recreation.

The Souris River in the northeast corner of the Williston Basin is the only river that flows northward out of the basin (Picha and others, 2008). The Souris River originates in the Williston Basin part of southeastern Saskatchewan in Canada, flows for about 210 mi through North Dakota, then reenters Canada and empties into the Assiniboine River in Manitoba. The Souris River is a major perennial river with deep, broad, well-established valleys that were originally cut by torrents of glacial meltwater.

Wetlands, or prairie potholes, in North Dakota are small, often less than 2 acres, and contain water mostly temporarily and seasonally during spring snowmelt and during large rainstorms (Kantrud and others, 1989). Wetlands once covered about 11 percent of North Dakota and likely a similar percentage of the Williston Basin. By the 1980s, the percentage of land area as wetlands had decreased by about 45 percent, caused mostly by drainage for agricultural development (U.S. Geological Survey, 2015). Wetlands were drained through the installation of drainage tiles and drainage ditches. The scale of wetland drainage has coincided with the scale of agricultural activities.

Soils

Soils throughout the world are the result of the interaction of geologic material, climate, topography, vegetation, and time (Yong and Warkentin, 1966). These factors combine to create different soil types, and varying physical and chemical properties of each soil type, that can exist across short distances. Soils also continually change in response to the environment through weathering, growth and decay of plants, and animal activities, but these soil properties naturally change over long periods.

The parent materials that weathered to form soils in the Williston Basin are primarily associated with ancient seas or glacial activity (Trimble, 1980). Seas came into the southwestern basin area and receded several times, leaving sediment behind, which became sandstone, limestone, and shale bedrock formations over time. Glacial movements deposited sand and gravel along with boulders and other sediments as the glaciers melted and retreated. Rivers that flowed from the melting glaciers moved large amounts of sand and gravel into outwash plains. Many soils in the Williston Basin were formed in parent materials deposited by the glaciers, often referred to as glacial till, or on soft sedimentary bedrock (Aziz and others, 2006). Since the end of the ice ages, the basin has had a generally semiarid climate with extensive grasslands that tend to favor the development of deep prairie soils. The geological history of the basin resulted in the formation of five major soil orders (alfisols, entisols, inceptisols, mollisols, and vertisols) as described in the following paragraphs (Brady, 1974; U.S. Department of Agriculture, 2015; fig. 5). Aridisols, also shown on figure 5, are not present in the Williston Basin and are not described.

Alfisols are present in a band in the southern Williston Basin (fig. 5), mostly in Harding County and Perkins County, S. Dak. These are mineral soils, generally gray to brown in color, which formed in semiarid to moist regions under native grass or mixed vegetative covers. They result from weathering that leaches clay materials from the surface into the subsoil where those materials can retain water and nutrients for plants. These soils are relatively productive, and many of these soils in the Williston Basin are used for rangelands.

Entisols cover areas of the western Williston Basin and most often occur in river and stream valleys (fig. 5). Entisols, or recent soils, are mineral soils with poorly or no developed soil layering or soil profile. The soils are present on recent alluvium, flood plains, and barren sands where the rate of material deposition is greater than the rate of soil development. Entisols are in a wide variety of climate conditions and are often used for grazing lands. Agricultural production on these soils depends on soil depth, water availability, and fertility.

Inceptisols are present in the western part of the Williston Basin, mostly in Montana (fig. 5). These soils form in semiarid to humid environments and are often termed young soils because they have only slight to moderate development. Productivity of these soils varies greatly, but if they are deep enough and fertile enough, they can be used for the production of small grains, like wheat.

Mollisols, commonly called soft soils or prairie soils, are the most common soils in the Williston Basin (fig. 5). Generally, the soils are thick and dark in color with abundant soil organic matter that formed under prairie vegetation. The soils are naturally fertile, can hold adequate moisture, and are commonly cultivated with very good crop production. Mollisols that contain many rocks are often used for rangeland.

Vertisols cover parts of the far southern Williston Basin in South Dakota (fig. 5). These soils have high clay content that makes them vulnerable to shrinking and swelling as the soils dry and wet. Large cracks can form in the soils that let topsoil fall in, thus the name vertisol or soils that turn over. The soils tend to transmit water slowly and water will pond on the soil surface during intense rains. Vertisols are often good for crop production.

Climate of the Williston Basin

The climate of the Williston Basin is characterized by large temperature variations, light to moderate irregular precipitation, plentiful sunshine, low humidity, and nearly continuous wind (Enz, 2003; Potts, 2011; Todey, 2011). The location of the Williston Basin at the geographic center of North America results in a strong semiarid to continental climate controlled by the mountains to the west (Enz, 2003). The mountains greatly reduce oceanic effects on the climate by blocking some of the Pacific Ocean air masses from moving eastward, or by modifying the temperature and water content of the air masses that move eastward; however, there are no barriers to the north or south, so air masses that move into the Williston Basin from these directions have little modification of temperature or water content. Movements of these air masses cause the wind to blow nearly continuously and often result in large temperature fluctuations in all seasons. This temperature variation is an important feature of the climate of the Williston Basin (Enz, 2003).

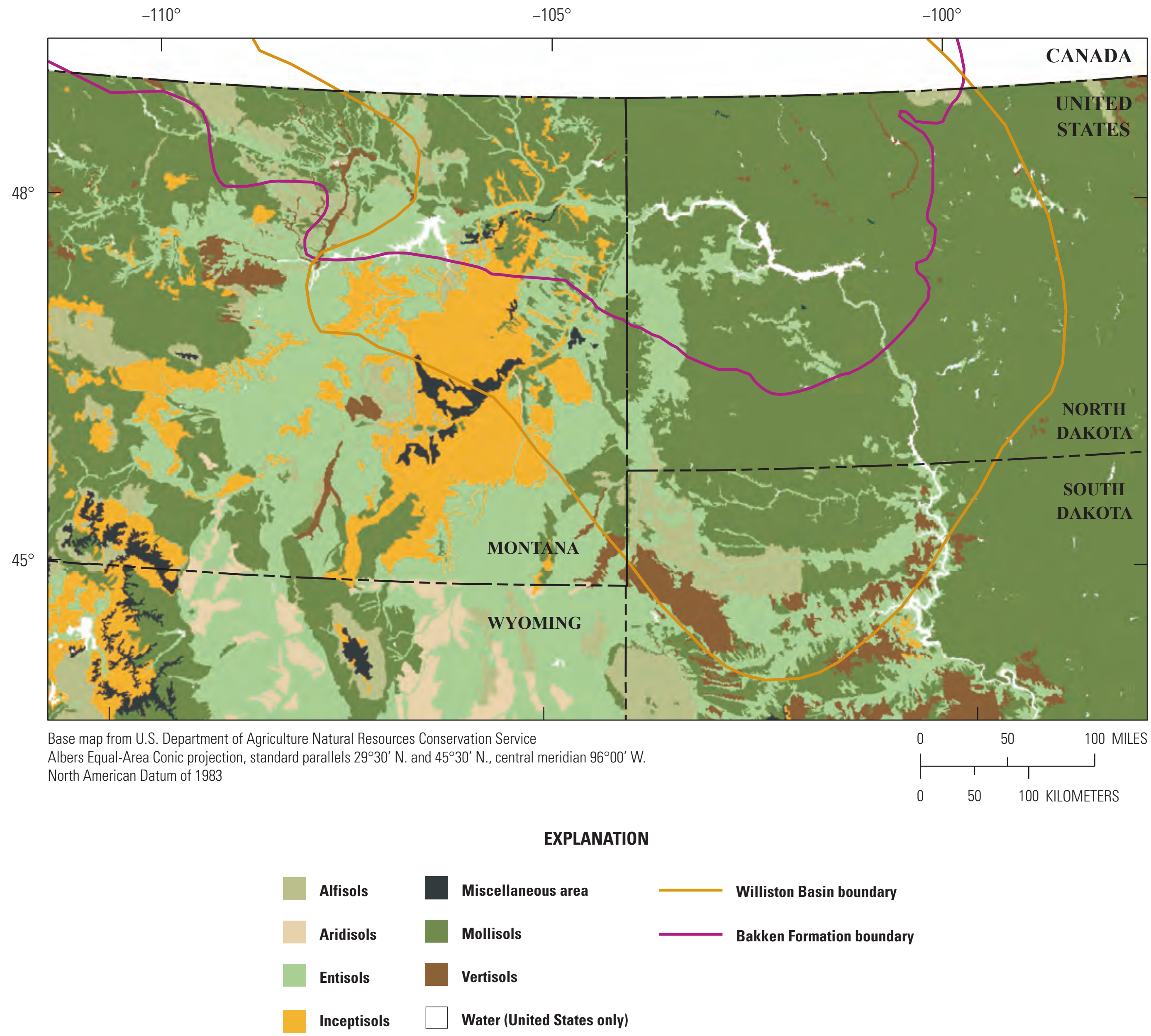


Figure 5. Soils of the Williston Basin and surrounding areas in Montana, Wyoming, North Dakota, and South Dakota (from U.S. Department of Agriculture, 2015).

Temperature

The generally dry, continental climate of the Willison Basin results in a relatively low average temperature but also results in extremes. The average annual temperature ranges from about 37 degrees Fahrenheit (°F) in the northern part of the basin to 44 °F along the southern border (Enz, 2003). Monthly average maximum temperatures can be above 90 °F during summer months, whereas monthly average minimum temperatures can be below 0 °F during winter months (Todey, 2011). January is the coldest month in the area with average temperatures ranging from near 0 °F in the northeast to about 15 °F in the southwest, whereas July is the warmest month with average temperatures ranging from about 65 °F in the northeast to about 72 °F in the south (Enz, 2003). The 1981–2010 monthly average maximum and minimum temperatures for Bismarck, N. Dak., Williston, N. Dak., and Glasgow, Mont. are shown in figure 6 (Arguez and others, 2010).

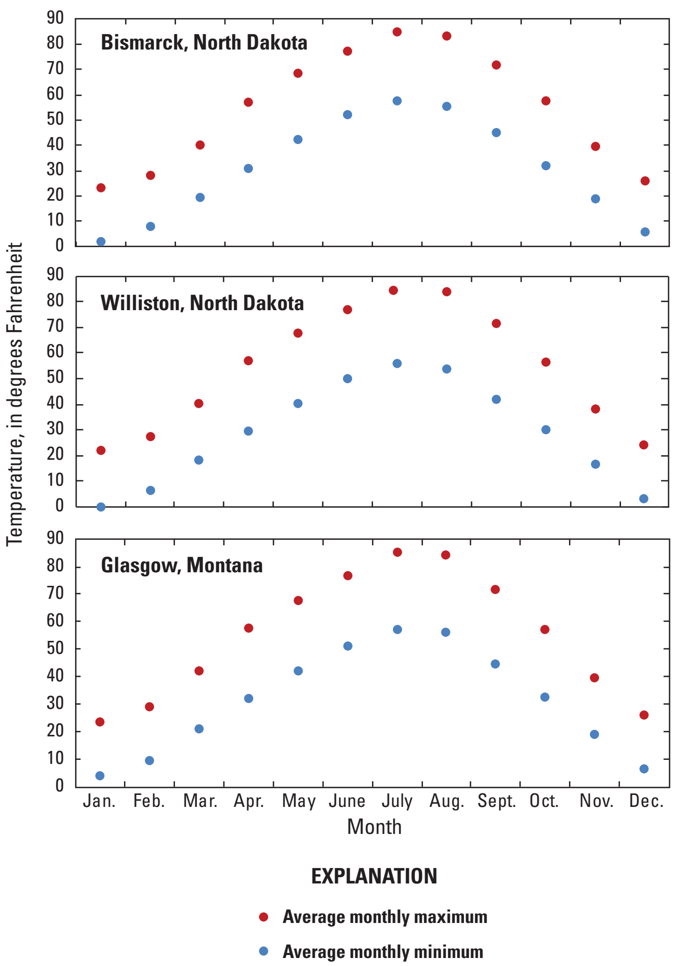


Figure 6. The 1981–2010 average monthly maximum and minimum temperatures for Bismarck, North Dakota, Williston, North Dakota, and Glasgow, Montana (Arguez and others, 2010).

The average annual temperature range for the Williston Basin (the difference between July and January average temperatures) is large, ranging from about 65 °F in the north and northeast to 56 °F in the southwest. Temperature extremes in the Williston Basin range from a record low of –60 °F at Parshall, N. Dak., on February 15, 1936, to a record high of 121 °F at Steele, N. Dak., on July 6, 1936 (Jensen, 1972). This temperature range of 181 °F in a span of 5 months illustrates the continental climate of the basin.

Temperature extremes can cause many problems in the Willison Basin. Extremely low wind chills can accompany high winds or blizzards. Many livestock have been lost during extremely cold conditions and blizzards. People caught outside can lose all sense of direction during a blizzard and perish only a short distance away from shelter. Hot conditions impose a strong evaporative demand that can wilt growing crops and lead to livestock deaths, particularly when humidity is also high.

Precipitation

Average annual precipitation ranges from about 12 to 20 inches from northwestern to southeastern parts, respectively, of the Williston Basin (Reilly and others, 2008). The 1981–2010 monthly average precipitation for Bismarck, N. Dak., Williston, N. Dak, and Glasgow, Mont., are shown in figure 7 (Arguez and others, 2010). On average, about 75 percent of the annual precipitation falls during the crop-growing season, April to September, with 50 to 60 percent of the annual precipitation falling during April through July (Enz, 2003). The coldest months, November through February, average only about 0.50 inch per month, mostly as snow. Measurable precipitation (0.01 inch or more) happens on an average of 65 to 100 days during the year, but more than 50 percent of these days have less than 0.10 inch of precipitation. The eastern side of Montana often has sparse rainfall, making Montana the 6th driest State overall (Potts, 2011).

Some parts of the Williston Basin get tremendous rainfall during a short period. The Black Hills of South Dakota, located at the southwestern edge of the basin (fig. 1*A*), had extreme rainfall on June 9, 1972 (Schwarz and others, 1975). An estimated 4 to 15 inches of rain fell in 6 hours, leading to the failure of a dam in western Rapid City at about 10:45 p.m. (Schwarz and others, 1975). At approximately midnight, floodwaters flowing at a rate of about 50,000 cubic feet per second—approximately 1,000 times the average flow of the creek (U.S. Geological Survey, 2017)—entered the central part of Rapid City, swept away homes and cars, killed 238 people, and injured 3,057 people (Schwarz and others, 1975; Carter and others, 2002).

The average annual snowfall of 25 to 45 inches in the Williston Basin is less than in other northern areas of the United States (Enz, 2003). Winter snowpack often persists from December through March and averages 9 to 15 inches from west to east, respectively. Blizzards are not frequent in

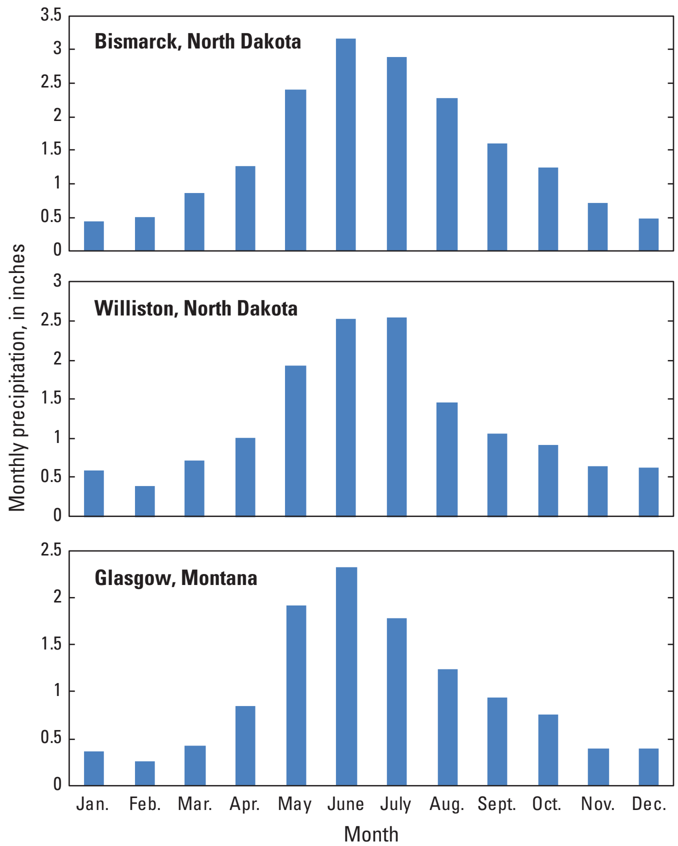


Figure 7. The 1981–2010 average monthly precipitation for Bismarck, North Dakota, Williston, North Dakota, and Glasgow, Montana (Arguez and others, 2010).

the Williston Basin (average is about three blizzards per year). The strong winds and occasional large amounts of snowfall associated with blizzards can quickly reduce visibility to only a few feet at times, resulting in the closure of highways. Blizzards were rare in the 1980s and most of the 1990s, but during the winter of 1996–97, numerous blizzards and snowstorms produced record annual snowfalls of more than 100 inches over parts of the Williston Basin (Enz, 2003).

Droughts and Floods

Drought in the Williston Basin can be defined in various ways. Any extended period of dry weather that leads to a measurable loss of crop production can be called drought (Rosenberg, 1987). Records show that dry years tended to happen in series of 2 or more years, although these series are often interspersed with occasional wet years. When such periods become long and the shortage of soil moisture becomes critical, native vegetation may suffer, and soil may erode because of wind, resulting in disastrous conditions for an area. Droughts of the 1930s, 1950s, and 1980s are remembered by residents of the Williston Basin (National Oceanographic and Atmospheric Administration, 2003). The 1930s drought came in three waves from 1934 to 1940, but some regions of the Great Plains had continuous drought conditions for as much as 8 years. During the mid-1950s into the early 1960s, many parts of the Great Plains, including the southwest part of the Williston Basin, withstood a multiyear drought. The drought of 1988–92 had the greatest effect on the northern Great Plains, including the Williston Basin, where total precipitation for April through June of 1988 was less than during the 1930s. Precipitation records, streamflow records, the Palmer Drought Severity Index, and Devils Lake water-level records indicate that the most severe droughts in North Dakota were during 1934–40 and 1988–92 (Williams-Sether and others, 1994).

The Williston Basin often floods in spring as a result of snowmelt on frozen soils that causes rapid runoff into drainages coupled with possible ice jams that cause water to back up and flood nearby riverine areas. Occasionally, spring and summer rainfall can cause localized flooding, but generally the dry landscape and scattered rainfall in the basin does not lead to widespread floods.

In 2011, the Missouri River of the Williston Basin flooded extensively because of snowmelt and rainfall (Vining and others, 2013). The flooding was caused by an exceptional winter snowpack and rainfall that fell during May through July 2011. At Glasgow, Mont., the seasonal snowfall record was established with 108.6 inches (Vining and others, 2013). The previous snowfall record was 70.7 inches set during the 2006–07 season. Williston, N. Dak., had a record 107.2 inches of snow in 2010–11 compared to the previous record of 94.7 inches set during the 1895–96 season (Vining and others, 2013). Then, during May 16–31, 2011, a slow-moving storm system produced substantial and even record-breaking precipitation amounts in parts of the Northern Plains. Precipitation amounts for May 2011 at some locations were almost as large as normal annual totals (Vining and others, 2013). The large amounts of water entering Lake Sakakawea forced new record releases of 150,600 cubic feet per second from Garrison Dam (U.S. Army Corps of Engineers, 2012), which resulted in flood emergencies for Bismarck and Mandan, N. Dak.

Other Climate Variables

The Great Plains, including the Williston Basin (fig. 1), is one of the windiest regions of the country (Rosenberg, 1987). Because the terrain is relatively flat and the land is largely cropped or in pasture grass, air masses from north and south are not blocked by forests or mountainous terrain that can reduce wind speeds in other regions. Chinook winds are a fairly common phenomenon along the eastern slope of the Rocky Mountains into the Williston Basin during the winter (Western Regional Climate Center, 2016a). The chinooks have resulted in rapid temperature rises along the Rocky Mountain foothills and in the Black Hills (Potts, 2011; Todey, 2011). The Williston Basin owes the relative cleanliness of its air to the fact that manmade and natural pollutants are moved out of the region readily by the almost continual action of the winds (Rosenberg, 1987).

The length of the growing season, often considered as lasting from the last spring frost to the first autumn frost, in much of the Williston Basin is about 120 days but may be about 150 days in areas along the Missouri and Yellowstone Rivers in Montana (Western Regional Climate Center, 2016a). The average length of the growing season in all areas is highly affected by local features of the terrain. On clear, relatively windless nights, cold air from surrounding lands flow downhill under the effect of gravity. Locations on hillsides, well above a basin or valley floor, are usually well drained of cold air and tend to be warmer. Lakeside locations also tend to have a local climate more moderate than valley bottoms. The last spring freeze in most agricultural sections of the Williston Basin normally happens in mid-May, whereas the first autumn freeze generally happens in mid-September (Jensen, 1972.).

Thunderstorms over the Williston Basin may trigger occasional tornadoes. For 1991–2010, Montana, North Dakota, and South Dakota report on average 10, 32, and 36 tornadoes per year, respectively (National Oceanographic and Atmospheric Administration, 2015). Most tornadoes in the Williston Basin happen during June and July and are more frequently in the eastern part of the basin. The 2003–12 frequency of severe hailstorms (hail greater than 1-inch diameter) in the Williston Basin is highest in the southeastern one-half of the basin, averaging 4–6 days per year, and lowest in the northwestern one-half of the basin, averaging 2–4 days per year (National Oceanic and Atmospheric Administration, 2013). The heaviest (1.94 pounds) and largest diameter (8 inches) hailstone to ever fall in the United States fell on July 23, 2010, in south-central South Dakota, just south of the Williston Basin (Todey, 2011).

Air Quality

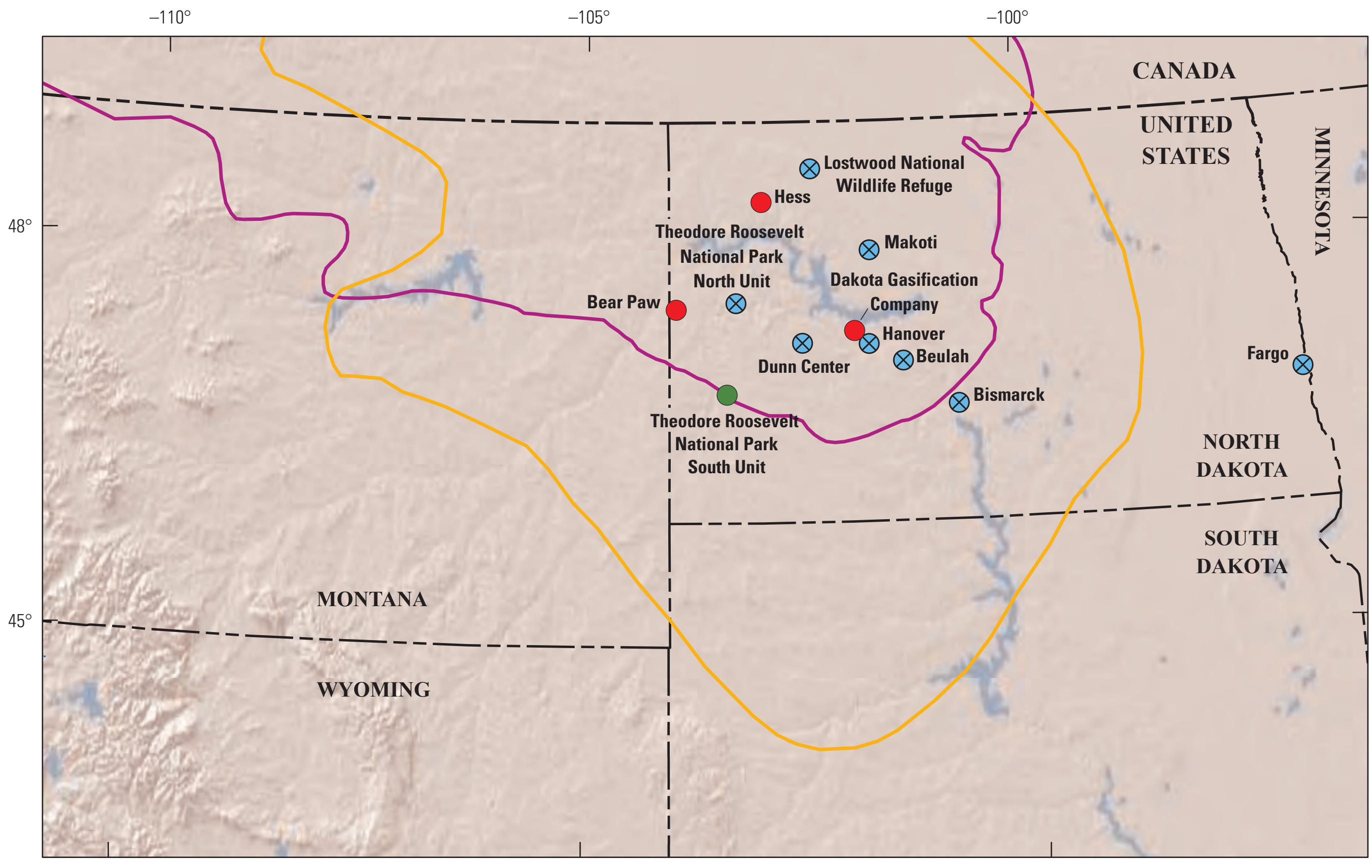
Activities surrounding the drilling of thousands of wells in the Williston Basin have raised awareness of the effects of energy exploration on air quality. The effects on air quality are complex, as emissions from exploration sources and dust from transportation and land-moving activities vary in composition, magnitude, and duration (Field and others, 2014). Emissions during well drilling and completion activities may be intensive and continue for weeks or months, whereas emissions during production activities may be less intense but could continue for years. The effect of emissions on air quality depends also on spatial scale. At a local scale, emissions from a single well or collection of wells and dust from other activities may dominate local air quality, but at the regional scale, emissions and dust may be minimal because of downwind transportation and dispersion.

Air quality has been monitored in the Williston Basin since the 1970s, which coincided with an expansion of energy production (North Dakota Department of Health, 1983; U.S. Energy Information Administration, 2016). Often, air-quality networks are sited with respect to population density or in other areas considered important to the public such as national parks. Four long-term air-quality monitoring stations at Dunn Center, N. Dak., Lostwood National Wildlife Refuge, N. Dak., Theodore Roosevelt National Park North Unit, N. Dak., and Theodore Roosevelt National Park South Unit, N. Dak., were used to define the air quality of the Williston Basin (fig. 8) (Susan Bassett, Bureau of Land Management, written commun., 2015).

The U.S. Environmental Protection Agency North Dakota Field Office has the primary responsibility for regulating air quality in the Williston Basin of North Dakota, including constituents subject to national air-quality standards (U.S Environmental Protection Agency, 2014). Constituents monitored in North Dakota under these standards include nitrogen dioxide (fig. 9*A*), ozone (fig. 9*C*), particulate matter with a diameter less than or equal to 2.5 micrometers (fig. 9*B*), particulate matter with a diameter less than or equal to 10 micrometers (fig. 9*D*), and sulfur dioxide (fig. 9*E*). Annual maximum concentrations for constituent-specific averaging periods (1 to 24 hours) indicate that most concentrations were less than the air-quality standards (North Dakota Department of Health, 2014) (fig. 9). The elevated concentrations of nitrogen dioxide and sulfur dioxide at Theodore Roosevelt National Park North Unit in 2011 (figs. 9*A* and 9*E*) were attributed to a controlled burn on nearby grasslands. U.S. Environmental Protection Agency air-quality indices determined for the four Williston Basin locations during 2011–13 indicated that at least 92 percent of the days had air quality rated “good” (Susan Bassett, Bureau of Land Management, written commun., 2015).

Visibility can be an important aspect of air quality, especially at public places of beauty such as national parks. Visibility is often assessed in terms of the horizontal visual distance at which a person can distinguish predefined objects (Susan Bassett, Bureau of Land Management, written commun., 2015). Degradation or reduction in visibility is primarily caused by sulfates and nitrates from anthropogenic sources and particulates from aeolian and wildfire sources. Air constituents affecting visibility can be transported hundreds of miles and affect local and regional-scale air quality. U.S. Environmental Protection Agency visibility data indicate no obvious trends in the clearest 20 percent of days annually and the haziest 20 percent of days annually during 2003–10 for the Lostwood National Wildlife Refuge (fig. 10*A*) and during 2003–13 for Theodore Roosevelt National Park South Unit (fig. 10*B*) (Interagency Monitoring of Protected Visual Environments, 2015).

The Bureau of Land Management Montana/Dakotas State Office completed a photochemical grid modeling study to assess potential air quality related to future oil and gas development in Montana, North Dakota, and South Dakota, but results are not yet publically available (Melissa Hovey, Bureau of Land Management, written commun., 2017). The study attempted to assess potential concentrations of the air-quality constituents of carbon monoxide, nitrogen dioxide, ozone, sulfur dioxide, particulate matter with a diameter less



Base map modified from Esri and North Dakota Deparment of Health Division of Air Quality digital data variously dated, various scales. Base map image is the intellectual property of Esri and is used herein under license.

Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

0 50 100 MILES
0 50 100 KILOMETERS

EXPLANATION

Williston Basin boundary

Bakken Formation boundary

Air-quality monitoring stations

National Park Service operated site

North Dakota ambient network site

Industry site

Figure 8. Air-quality monitoring stations in the Williston Basin, North Dakota.

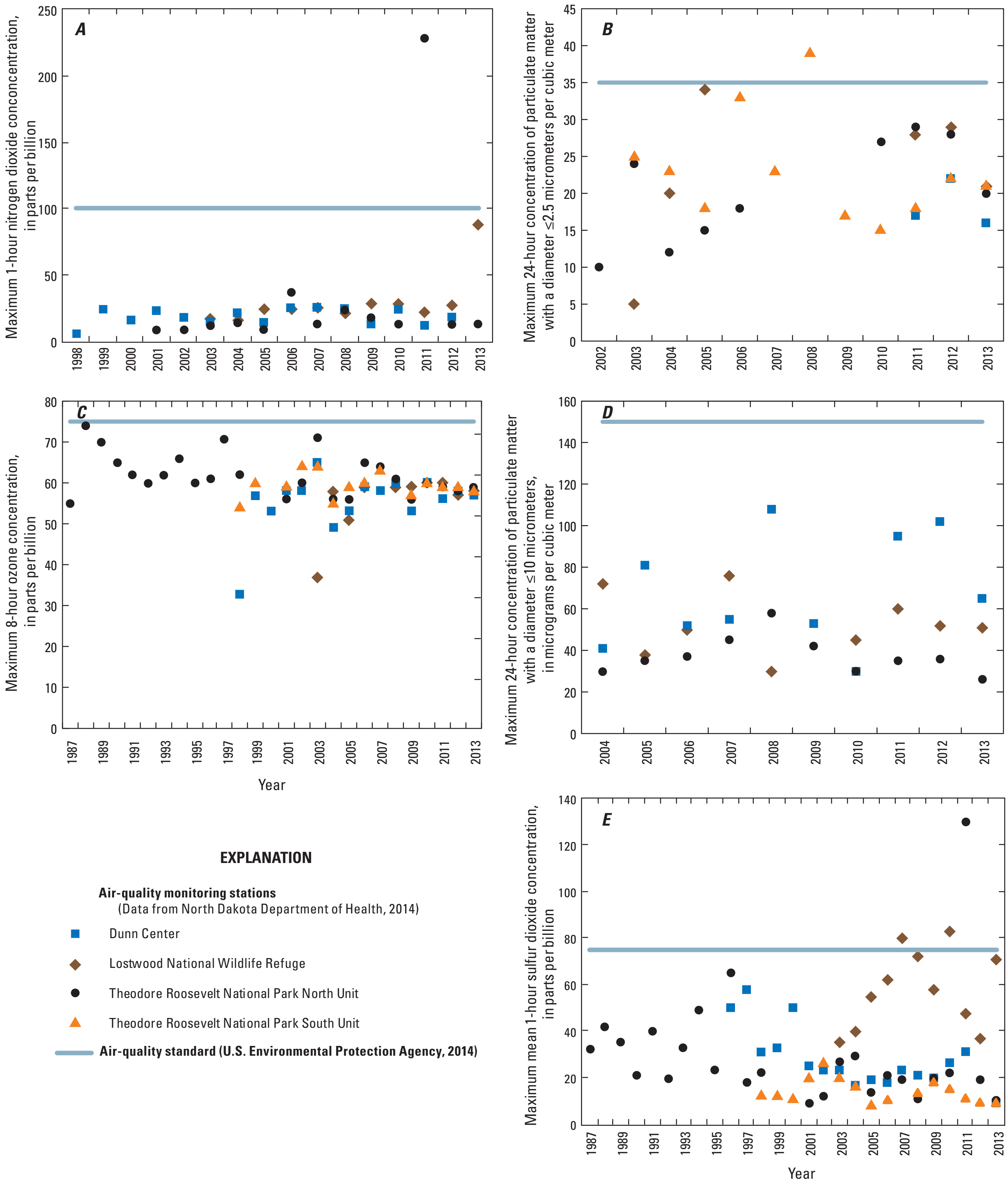


Figure 9. Annual maximum average air-quality constituents at monitoring stations in the Williston Basin, North Dakota, and the national standard for each constituent. *A*, nitrogen dioxide. *B*, particulate matter with a diameter less than or equal to 2.5 micrometers. *C*, ozone. *D*, particulate matter with a diameter less than or equal to 10 micrometers. *E*, sulfur dioxide.

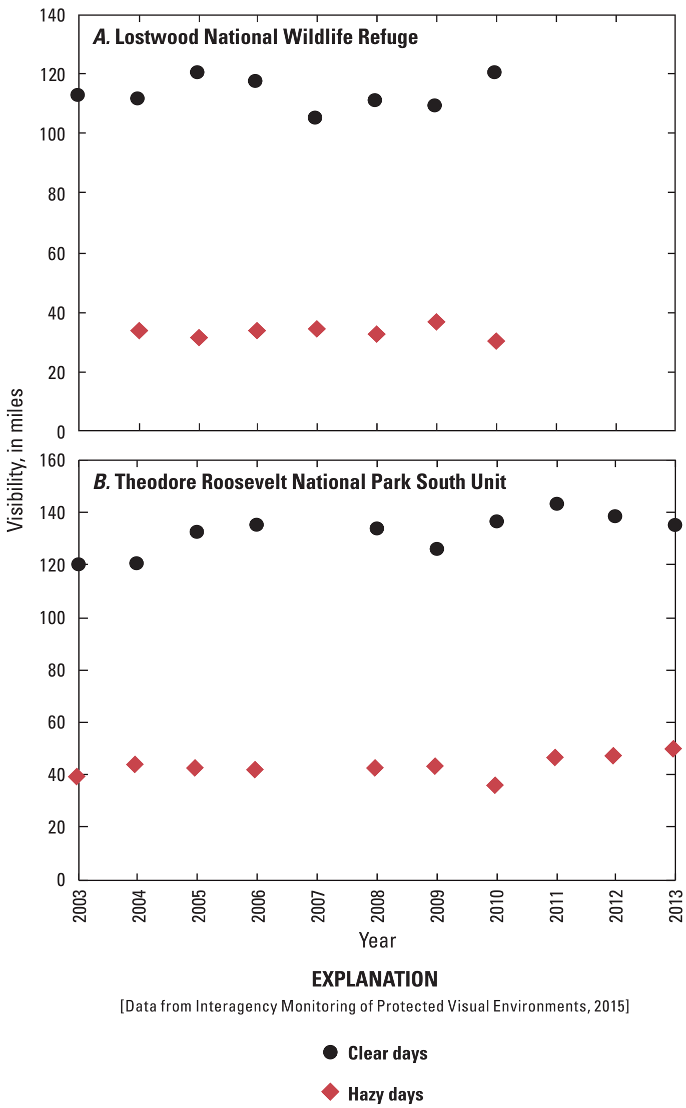


Figure 10. Average visibility for the clearest 20 percent of days annually and the haziest 20 percent of days annually, 2003–13. *A*, Lostwood National Wildlife Refuge. *B*, Theodore Roosevelt National Park South Unit.

than or equal to 2.5 micrometers, and particulate matter with a diameter less than or equal to 10 micrometers, and to assess potential effects to visibility and deposition. Potential effects related to emissions from oil and gas development activities and cumulative air-quality effects were planned to be simulated about 20 years into the future.

Sources of Climate Data

The most complete sources of climate data for the Williston Basin are the National Centers for Environmental Information (formerly the National Climatic Data Center) in the United States (National Oceanic and Atmospheric Administration, 2017) (https://www.ncdc.noaa.gov/data-access) and the Environment and Natural Resources in Canada (Government of Canada, 2017) (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html). Other sources for climate data are the Western Regional Climate Center (Western Regional Climate Center, 2016b) (http://www.wrcc.dri.edu/Climate/summaries.php) and the High Plains Regional Climate Center (High Plains Regional Climate Center, 2017) (https://hprcc.unl.edu/onlinedataservices.php#data).

Land Use in the Williston Basin

Changes in the climate of the Williston Basin since the end of the ice ages have caused fluctuations in the dominant vegetation between desert shrub, short grass, mixed grass, and tall grass prairies, and the occasional deciduous and coniferous forests (Manske, 1994). Changes in climate and vegetation have also caused fluctuations in the kinds and numbers of animals present in the landscape. All these natural changes, along with changes in lifestyles and technological advancements before and after European settlement, have affected land-use practices in the Williston Basin (Manske, 1994).

Agriculture

Most of the Williston Basin is managed as privately owned farms and ranches that operate a mixture of cropland and rangeland (U.S. Department of Agriculture, 2014). The predominant crops in the basin consist of small grains, like wheat and barley, and sunflowers. From about 1997 to 2012, acres planted to corn for grain and ethanol production increased about 10-fold. As agricultural commodity prices rise and more drought-resistant strains of corn and other crops are planted, a greater amount of highly erodible lands that are enrolled in Conservation Reserve Programs may be withdrawn and put into production. The expansion of cropland reduces the areas of both rangeland and conservation lands leading to less grassland/wetland habitat.

In the western part of the Williston Basin, more land is used for grass and rangeland because soils are generally less fertile and precipitation is generally lower. Rangeland vegetation consists of tall grass, mixed grass, and short grass prairies, and occasional deciduous and coniferous forests, with shrubby plant communities. Rocky areas and poor vegetation areas may be considered rangeland but can carry only small numbers of range animals. Cultivated crop land and grassland/pasture land are the two predominant land-cover categories of the Williston Basin, with each covering about one-half of the basin (Homer and others, 2012).

Natural and human-induced processes have had major roles in current land use in the Williston Basin. Climate and fire have been considered major processes that determine the structure of grassland communities (Anderson, 1990). In the basin, prairie vegetation, especially native grass, was adapted to seasonal fires and had an adaptive advantage over many other plant species. Wildfires were essential to shaping natural grassland and wetland communities and controlling woody species (Kantrud, 1986). Cattails, once rare on the Great Plains, have spread across thousands of prairie wetlands (Leitch and others, 1997). Hydrological processes of many landscapes have been altered, as many wetlands and soils were drained for agricultural purposes. Grazing by millions of bison was also a major process that determined the composition of plant species in grassland communities (Mac and others, 1998). Cattle have replaced bison, and native grasslands are now often isolated areas surrounded by landscape-scale agriculture.

Private and Public Lands

In North Dakota, 23 counties intersected by, or west of, 101 degrees west longitude are completely within the Williston Basin (fig. 1*B*). These counties have an area of about 34,900 square miles (mi^2). According to the 2012 Census of Agriculture, these 23 counties contained about 12,500 farming operations on about 28,900 mi^2 of the counties (U.S. Department of Agriculture, 2014). Cropland covered about 16,400 mi^2 of the farmed land. The remaining 6,000 mi^2 of the 23 counties were held by public, municipal, or private nonfarm entities (U.S. Department of Agriculture, 2014).

In total, 10 Montana counties (Daniels, Dawson, Fallon Garfield, McCone, Prairie, Richland, Roosevelt, Sheridan, and Wibaux) are completely or mostly within the Williston Basin (fig. 1*B*). The 10 counties have an area of about 21,800 mi^2. In the 10 counties, about 3,940 farms occupied about 17,900 mi^2 (U.S. Department of Agriculture, 2014). Cropland covered about 6,800 mi^2 of the farmed land. The remaining 3,900 mi^2 of the 10 counties were held mostly by public, municipal, or private nonfarm entities (U.S. Department of Agriculture, 2014).

Five South Dakota counties (Corson, Dewey, Harding, Perkins, and Ziebach) are completely or mostly within the Williston Basin (fig. 1*B*). These counties occupy an area of about 12,500 mi^2. There were 1,590 farms in these counties operating about 10,400 mi^2 (U.S. Department of Agriculture, 2014). Cropland covered about 2,050 mi^2 of the farmed land. Public areas, municipalities, and areas for other uses occupied about 2,100 mi^2 of the counties (U.S. Department of Agriculture, 2014).

Recreational land use in the Williston Basin often centers on water. The three large Missouri River reservoirs, Fort Peck Lake, Lake Sakakawea, and Lake Oahe (fig. 2), have a surface area of about 1,300 mi^2 and have more than 5,100 mi of shoreline at base flood control elevation (U.S. Army Corps of Engineers, 2012). Usage of the lakes and reservoirs surges during summer months but can also surge during winter for ice fishing. Theodore Roosevelt National Park and the State parks in the Williston Basin also attract more visitors during summer than winter.

Energy Development

Activities associated with energy development occupy a small percentage of the land in the Williston Basin, but these activities can affect alternate uses of the land. In early 2014, permits for coal mining covered about 183 mi^2 of the basin and disturbance by mining activities covered about 115 mi^2 (North Dakota Public Service Commission, 2015). Hydropower is created at three dams on the Missouri River in or near the basin—Fort Peck, Garrison, and Oahe Dams. Wind farms cover large areas, but each wind tower occupies only a small area of land and some agricultural activities can happen beneath the towers. Oil and gas wells and drilling rigs, although plentiful in the Williston Basin, occupy only a few hundred square miles of land. Other land disturbances that accompany energy production include the development of hauling and access roads, disposal pits and lagoons, and pipelines. Dust created along haul roads and freshly laid pipelines, especially during summer, can coat edges of farmlands, reducing the growth of grass or crops. The usability of land for agriculture or other activities can also be quickly altered by spills of oil, drilling liquids, brine, and other chemicals (North Dakota Department of Health, 2015).

One of the major concerns of land managers in the Williston Basin and Bakken Formation area is that increased energy production might lead to an increase in the likelihood of oil or other spills. The primary concerns in this area are focused on spills of oil and produced brine. Unfortunately, data for the entire area covered in this report are not available. States are the primary repositories for spill reporting and not all those States have easily accessible data. The State of North Dakota provides their spill information online and reports separate entries for volumes of spills as oil, brine, and other chemicals (North Dakota Department of Health, 2015).

The following is a summary of the North Dakota spills data in terms of the size, type, frequency, and rate of spills (expressed as the number of spills per every million barrels of oil produced). The total volume of oil, brine, and other compounds that are spilled each year seems to be increasing (fig. 11). The increased volume of material spilled could be attributed to the rate at which spills happen or as a result of the increase in the volume of oil and natural gas being recovered.

The volumes of spills in the State of North Dakota during 2001–14 varied considerably (table 2). Using the volume classes in table 2 as a reference point, there also seems to be an exponential increase in the number of spills across the various volume classes that happened within this period (fig. 12). There seems to be little to no change in the rate of some spills (standardized to the number of spills per 1 Mbbl), and a decline in others (fig. 13). This information indicates that the number of spills may be more strongly driven by changes in production volumes, as opposed to certain production practices.

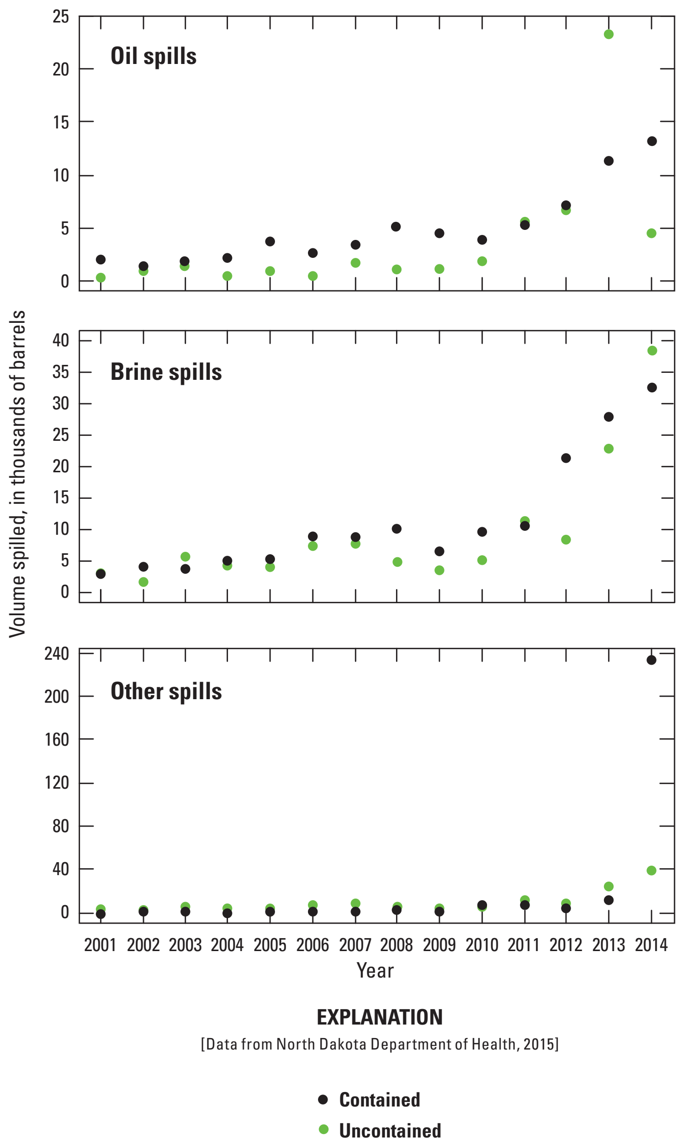


Figure 11. Total volume of oil, brine, and other compounds spilled as reported to the State of North Dakota by oil and natural gas producers during 2001–14.

Demographics of the Williston Basin

People likely have been in the Williston Basin since at least 10,000 years ago (State Historical Society of North Dakota, 2017). Hunter-gatherer and agricultural societies have existed in the basin between about 2,000 B.C. and 1860 A.D. These societies included nomadic groups who were dependent upon bison and agricultural societies who did occasional hunting. Nomadic groups consisted of the Dakota, Assiniboine, and Cheyenne tribes, who were greatly affected by the arrival of the horse to North America. Agricultural societies included the Mandan, Hidatsa, and Arikara tribes, who lived mostly in permanent residences, and whose villages served as major trading centers (State Historical Society of North Dakota, 2017).

Native Americans of the Williston Basin and Euro-Americans came into contact during the 1700s. These people traded for many decades. Euro-Americans settled permanently in the basin during the late 1800s, spurred by railroad construction. Many people of German descent from Russia and immigrants from Scandinavian countries came to the northern plains in the 1880s and settled across the basin. Many people from England, Ireland, and Scotland often immigrated first to Canada, then to the United States. Additional groups from southern Europe, Africa, and Asia also eventually settled throughout the basin (State Historical Society of North Dakota, 2017).

Estimates of ethnic composition from the 2010 census for the Williston Basin indicated that about 80 percent of the population was of Caucasian descent, and about 15 percent of the population was of Native American descent (U.S. Census Bureau, 2015). The Fort Berthold Reservation, in the Williston Basin of North Dakota, is home for the Mandan, Hidatsa, and Arikara tribes. The reservation had a total population in 2010 of about 6,340, of whom about 4,560 are members of the Mandan, Hidatsa, and Arikara peoples (North Dakota Indian Affairs Commission, 2010). People of Hispanic, Asian, and African-American descent composed about 5 percent of the population in the Williston Basin (U.S. Census Bureau, 2015).

Energy exploration activities and associated employment opportunities have greatly increased populations in parts

Table 2. Distribution of volumes of oil, brine, and other compounds spilled as reported to the State of North Dakota during 2001–14.

[All values are presented in units of barrels. One barrel is equivalent to 42 U.S. gallons. Data from North Dakota Department of Health, 2015]

Spill type	Minimum	Percentiles				Maximum
		25	50	75	99	
Oil spills	0.02	1	4	10	260	20,600
Brine spills	0.02	3	10	40	800	70,000
Other chemical spills	0.00	2	10	40	2,000	218,000

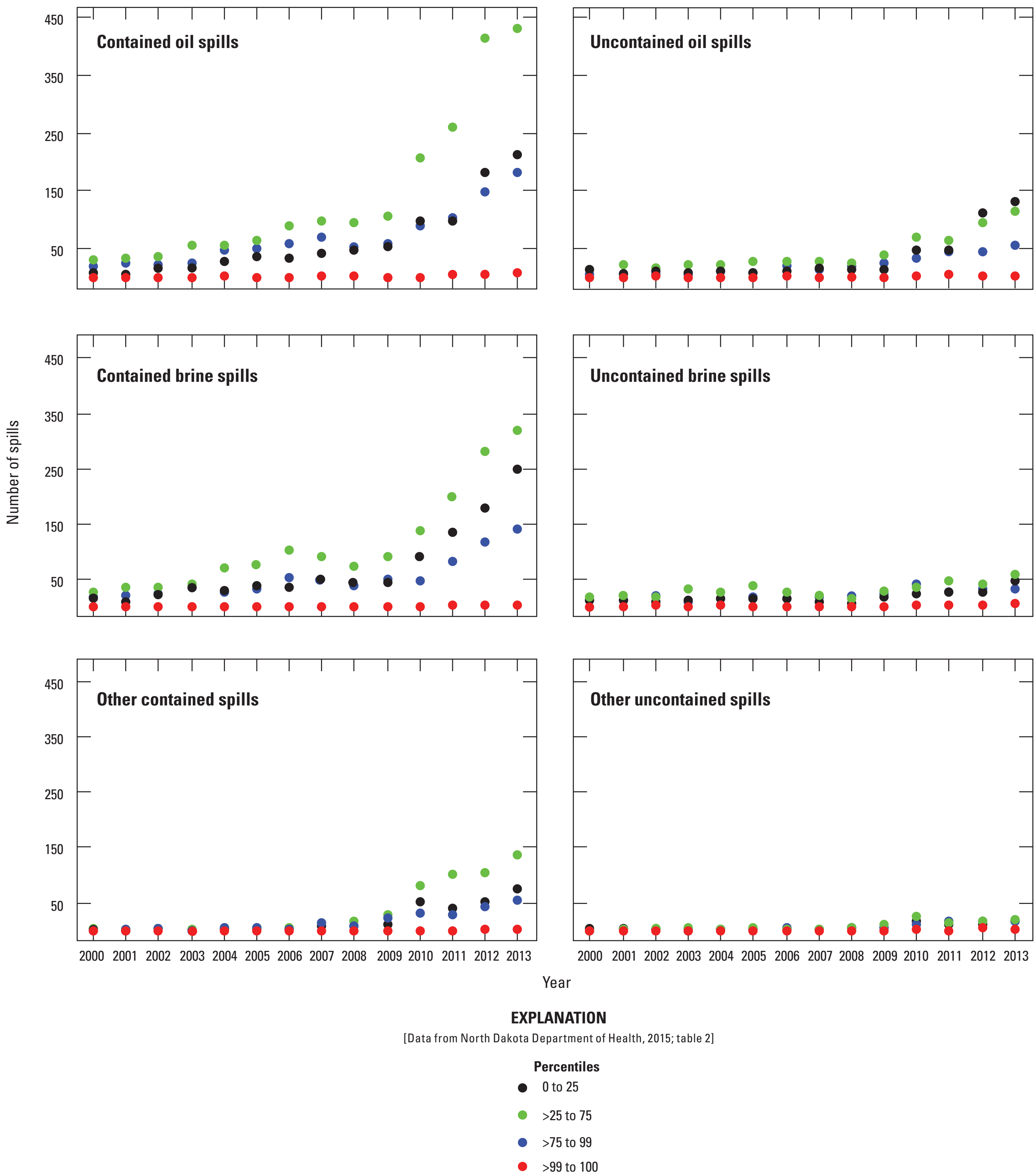


Figure 12. Number of oil, brine, and other compounds spilled as reported to the State of North Dakota during 2001–14.

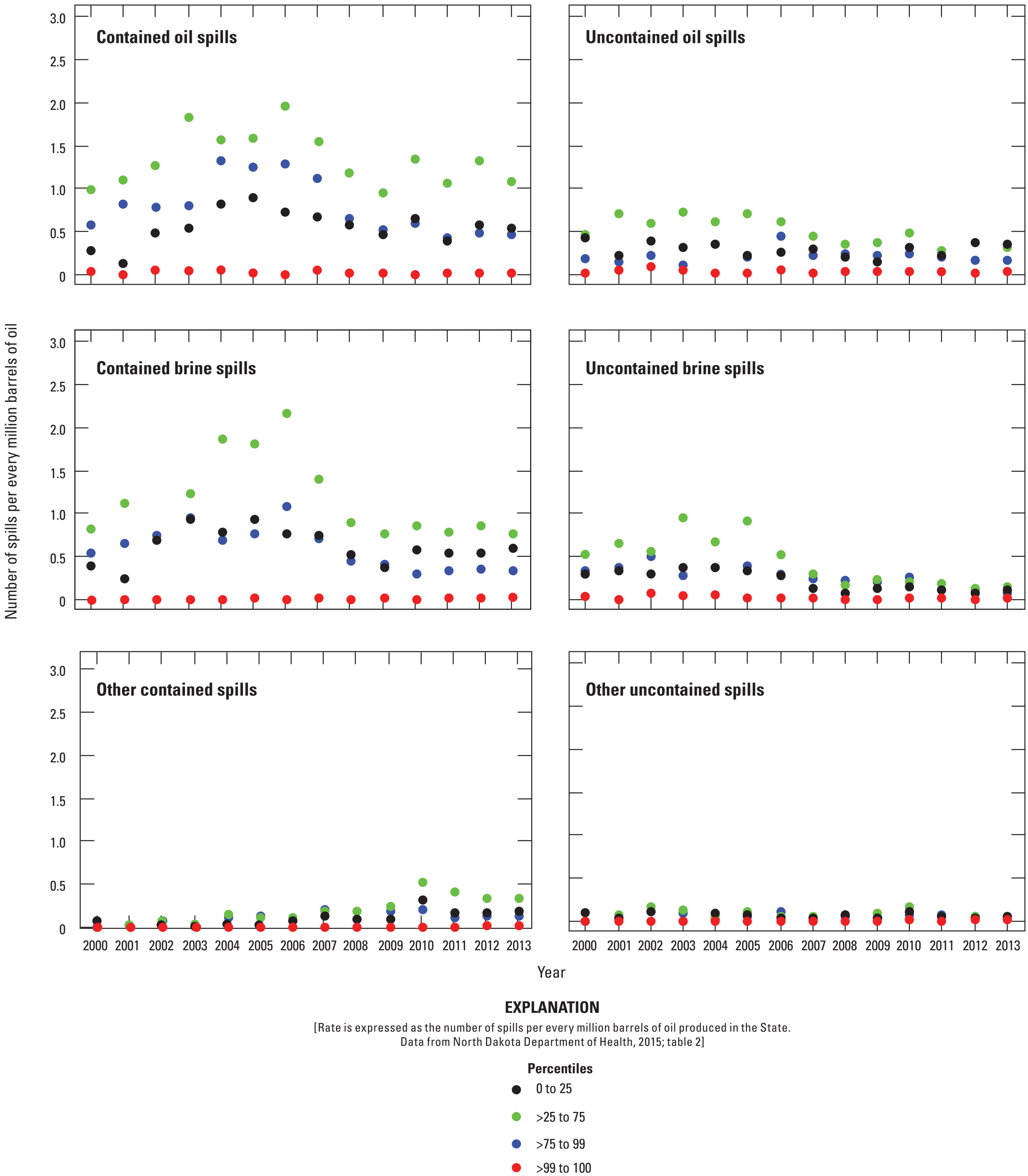


Figure 13. Rate of oil, brine, and other compounds spilled as reported to the State of North Dakota during 2001–14.

of the Williston Basin (U.S. Census Bureau, 2015). Changes in population in 23 North Dakota counties illustrate the effect of energy exploration on population. The 2010 population of the 23 counties was about 208,600, and the estimated 2014 population was about 245,500, an increase of about 18 percent. The population of four selected North Dakota counties in the heart of energy exploration activities (Dunn, McKenzie, Mountrail, and Williams Counties) is even more dramatic. The 2010 population in these four counties was about 40,000, and the estimated 2014 population was about 57,300, an increase of about 43 percent.

Similar, though less dramatic, population changes happened in Montana and South Dakota (U.S. Census Bureau, 2015). For 10 Montana counties in the Williston Basin (Daniels, Dawson, Fallon, Garfield, McCone, Prairie, Richland, Roosevelt, Sheridan, and Wibaux Counties), population increased from about 42,300 in 2010 to an estimated 46,300 in 2014, an increase of about 9 percent. The estimated population for 5 South Dakota counties in the Williston Basin (Corson, Dewey, Harding, Perkins, and Ziebach Counties) increased by only about 600 individuals from about 16,400 in 2010 to an estimated 17,000 in 2014, likely because energy exploration activities and associated employment opportunities were not developed in this part of the basin.

The U.S. Census Bureau (2015) indicates that the population in and near to the Williston Basin is also becoming more urban, with several clusters containing at least 2,500 people. The populations in Montana, North Dakota, and South Dakota who lived in urban areas in 1930 were about 34, 17, and 19 percent, respectively. But by 2010, the urban populations in Montana, North Dakota, and South Dakota were about 56, 60, and 57 percent, respectively.

Many cities in the Williston Basin have had population increases from 2000 to 2013 as a result of energy exploration activities and employment opportunities (Census Viewer, 2012; City-Data, 2015). The population of Williston, N. Dak., increased about 67 percent from about 12,500 in 2000 to an estimated 20,900 in 2013. The population of Watford City, N. Dak., increased by about 128 percent in 13 years from about 1,440 in 2000 to an estimated 3,280 in 2013. Sidney, Mont., had a 31 percent increase in population from 2000 to 2013. Other cities in or near to the Williston Basin have had similar percentage increases in population.

U.S. Geological Survey Investigations Related to Energy Development in the Williston Basin

Many U.S. Geological Survey investigations related to energy development in the Williston Basin have been coordinated since 2008 by the U.S. Geological Survey Science Team about Energy and Plains and Potholes Environments (STEPPE; https://steppe.cr.usgs.gov/). Investigations include the topical areas of unconventional oil and gas assessments, water quality, water availability, air quality, effects on human health, and ecological effects. The following discussion briefly identifies and describes many of these investigations.

USGS water-quality investigations have addressed selected components of groundwater and surface water resources. Baseline groundwater quality in the upper Fort Union aquifer of the lower Tertiary aquifer system (fig. 4) was determined using a limited set of 30 randomly selected domestic wells that were not necessarily near energy development (McMahon and others, 2014). Water-quality results indicated no detectable effects from energy-development activities on groundwater quality. A follow-up investigation examined the potential effects of shale-oil production on groundwater quality near production wells (McMahon and others, 2021). Water-quality sampling indicated production activities did not affect groundwater quality in sampled areas. Sampled aquifers consisted predominantly of premodern (old) recharge, indicating relatively slow groundwater movement that could inhibit widespread transport of chemicals in groundwater. A study within the Fort Berthold Reservation in west-central North Dakota was completed to provide a baseline characterization of water-quality conditions in surface water and groundwater and design a water-quality monitoring program to address data gaps and provide consistent long-term data that could be used to assess the effects of future energy development activities (Lundgren and Iorio, 2020).

The extent of brine contamination in shallow groundwater was as much as 18 mi^2 and also affected surface-water resources in the East Poplar oil field (Thamke and Midtlyng, 2003; Smith and others, 2006; Peterman and others, 2010; Thamke and Smith, 2014) on the Fort Peck Indian Reservation in northeastern Montana through 2009 (Thamke and Smith, 2014). Brine contamination not only affected the water quality from privately owned wells in the area, but also the water quality from public water-supply wells for the city of Poplar, Mont. USGS work in this area consists of determining the extent and movement of brine contamination in and near the city of Poplar (Peterman and Thamke, 2016).

Several USGS investigations have addressed various aspects of the geochemistry of produced waters related to energy development in the Williston Basin. Chemical and isotopic data for waters from the Bakken and Three Forks Formations have been collected to better characterize the inorganic geochemistry of produced waters (Engle and others, 2014; Blondes and others, 2015; Peterman and Thamke, 2016; Peterman and others, 2017). The organic composition of produced waters (flowback and formation waters) from the middle member of the Bakken Formation and the Three Forks Formation was examined to add to the limited knowledge of organics in waters from both formations (Varonka and others, 2020). Isotopes were used to understand the origins of waters with extreme salinity (brines) within the Bakken and Three Forks Formations (Peterman and others, 2017) and fluid flow within the Bakken Formation (Peterman and others, 2019). Geochemical composition, isotopes, volumes, and oil biomarkers were used to improve the understanding of tracing sources of produced water in the Williston Basin (Gallegos and others, 2021).

USGS investigations have addressed groundwater availability and water-use requirements for energy development in the Williston Basin. An investigation of regional groundwater availability of the Williston Basin has resulted in a hydrogeologic framework (Thamke and others, 2014) and conceptual model and water budgets (Aurand, 2013; Bednar, 2013; Long and others, 2014) of the uppermost principal aquifer systems (fig. 3). A numerical groundwater-flow model was developed as part of the investigation to understand stresses on the groundwater system composed of the aquifer systems and estimate changes in the groundwater budget (Davis and Long, 2018a, b, c; Long and others, 2018). The framework, water budget, and models were summarized in Long and others (2018) and Thamke and others (2018). Resource assessment methods were evaluated as potentially rapid and useful tools to estimate groundwater, surface water, and (or) proppant resources related to energy development (Haines and others, 2014; Haines, 2015; Varela and others, 2017; Valder and others, 2018); in part, these methods then were used to estimate water and proppant quantities associated with petroleum production from the Bakken and Three Forks Formations (Haines and others, 2017) and water quantities for hydraulic fracturing treatments in the Williston Basin from 2000 to 2015 (Barnhart and others, 2018). Direct, indirect, and ancillary water use associated with development of continuous oil and gas resources in the Williston Basin was estimated in North Dakota and Montana from 2007 to 2017 (Carter and others, 2016; Valder and others, 2018, 2019; McShane and others, 2020).

Several large multidisciplinary investigations described risk and environmental effects of brine contamination from energy development within the Prairie Pothole Region of the Williston Basin (Gleason and others, 2011; Preston, 2011; Peterman and others, 2012; Preston and others, 2012, 2019; Gleason and Tangen, 2014). Three study sites, representing common hydrogeologic conditions within the Prairie Pothole Region, were selected in one of the investigations to define brine contamination spatially and temporally (Preston and others, 2012). Migration of major-ion contaminants seemed to be controlled by near-surface sediments (Preston and others, 2014). These contaminants have persisted for at least 30 years at one of the sites and are estimated to take at least another 100 years to naturally attenuate (Preston and others, 2019). A second component to this investigation spatially characterized oil and gas development and aquatic resources throughout the Williston Basin (Tangen and others, 2014a, b). About one-third of all wetlands within the Prairie Pothole Region within the Williston Basin were within 1 mi of an oil or gas well. This investigation also identified research and decision-making priorities in the Williston Basin and identified a list of possible next steps to assess alternative development decisions within a broader geographic area (Post van der Burg and others, 2014). Another multidisciplinary investigation identified potential risks to water resources and environmental health associated with unconventional oil and gas waste for wetlands and creeks exposed to historic and current leaks and spills in the Williston Basin (Cozzarelli and others, 2017, 2021). Sediment, surface water, and pore water were analyzed to determine accumulation of organic compounds, radium, major ions, and trace elements related to produced waters. Aquatic health studies documented potential health effects using fish bioassays, in which fish experienced mortality, and endocrine disrupting activity was observed in surface water downstream from the spill (Cozzarelli and others, 2017).

Several USGS investigations used spatial datasets to evaluate characteristics of oil and gas development throughout the Williston Basin. Three investigations used spatial datasets to identify vulnerability of aquatic resources to brine contamination. Two of these investigations identified vulnerability to brine contamination based on two oilfield properties (the oil well age and density of oil wells) and three hydrogeological properties (surficial geology, wetland cover, and stream reach) in 1-mi² areas (Preston and others, 2014; Preston and Chesley-Preston, 2015). The latter investigation spanned most of the Williston Basin and determined that most 1-mi² areas in the Williston Basin had minimal risk. The third investigation used spatial datasets to determine vulnerability from brine contamination and identified locations throughout the Williston Basin that may require more intensive sampling or further investigation (Post van der Burg and Tangen, 2015). Spatial datasets were used to identify oil wells and control sites located in native prairie environments as part of a USGS study examining the presence and abundance of nonnative species related to energy development in Montana and North Dakota (Preston, 2015). Adjacent to well pads, nonnative species richness and cover were greater than native prairie sites, although their presence and abundance decreased with distance from the oil well pad (Preston, 2015). Other USGS investigations that used spatial datasets include the following: developing datasets relevant to oil and gas development and fish and wildlife management (Preston, 2018, 2019; Hoogenboom and others, 2020); evaluating land use changes related to energy development (Preston and Kim, 2016); determining the effects of oil and gas development on grassland birds (Thompson and others, 2015); and creating algorithms for determining land-cover change and water permanence in areas of energy development (Rover and others, 2014).

Several USGS investigations focused on toxicity and ecosystems related to energy development in the Williston Basin. These studies include the following: the acute and chronic effects of salinity on aquatic resources (Cozzarelli and others, 2017); field and laboratory assessments of toxicity to multiple species (Wang and others, 2019); effects of brine contamination on macroinvertebrates and wetland plants (Preston and Ray, 2017; Preston and others, 2018); determining the effects of unconventional oil and gas development on water quality, amphibians, and their habitats (Hossack, 2017; Hossack and others, 2018; Smalling and others, 2019); and the effects of brine contamination on amphibians in a laboratory setting (Hossack and others, 2017).

Summary

The Williston Basin, which includes parts of Montana, North Dakota, and South Dakota in the United States and the provinces of Manitoba and Saskatchewan in Canada, has been a leading domestic oil and gas producing region. As demands for energy continue to increase, energy development in the basin has increased substantially. A group of 13 Federal agencies and Tribal groups formed the Bakken Federal Executive Group to address common challenges associated with energy development, with a focus on understanding the cumulative environmental challenges attributed to oil and gas development throughout the basin. To better understand the natural resources in the area, the U.S. Geological Survey, in cooperation with the Bureau of Land Management, began work to synthesize existing information on science topics that will support management decisions related to energy development. The purpose of this report was to provide a brief compilation of information regarding the natural setting, energy development history, demographics, and investigations related to energy development in the Williston Basin of Montana, North Dakota, and South Dakota.

Topographically, the Williston Basin is a large, roughly circular depression, centered at about Williston, North Dakota, that covers several hundred thousand square miles across parts of the Great Plains of North Dakota, South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan. The basin lies almost entirely within the glaciated and unglaciated areas of the Missouri Plateau of the Great Plains physiographic region, and is a major source of coal, oil, and natural gas, which formed as a result of regional geologic processes. Major rivers in the area include the Missouri, Yellowstone, Little Missouri, and Souris Rivers.

The climate of the Williston Basin is characterized by large temperature variations, light to moderate irregular precipitation, plentiful sunshine, low humidity, and nearly continuous wind. Its location at the geographic center of North America results in a strong semiarid to continental climate controlled by the mountains to the west. Air-quality awareness has increased in the Williston Basin as a result of energy exploration. Emissions during well drilling and completion activities may be intensive and continue for weeks or months, whereas emissions during production activities may be less intense but could continue for years.

Natural changes, along with changes in lifestyles and technological advancements before and after European settlement, have affected land-use practices in the Williston Basin. Climate and wildfires have been essential in shaping natural grassland and wetland communities and controlling woody species. Hydrological processes of many landscapes have been altered, as many wetlands and soils were drained for agricultural purposes. Activities associated with energy development occupy a small percentage of the land in the Williston Basin, but these activities can affect alternate uses for the land. A major concern for alternate land use in the Williston Basin is that increased production might lead to an increase in the likelihood of oil or brine spills. The usability of small parts of land for agriculture or other activities can also be quickly altered by spills of oil, brine, and other chemicals.

Energy exploration activities and associated employment opportunities have greatly increased populations in parts of the Williston Basin. The population of four selected North Dakota counties near the center of energy exploration activities (Dunn, McKenzie, Mountrail, and Williams Counties) has increased about 43 percent from 2010 to 2014. The cities of Williston and Watford City, North Dakota, have had population increases of about 67 and 128 percent, respectively, from 2000 to 2013. The population changed less dramatically in counties in Montana and South Dakota.

Many U.S. Geological Survey investigations related to energy development in the Williston Basin have been coordinated since 2008 by the U.S. Geological Survey Science Team about Energy and Plains and Potholes Environments. Investigations include the topical areas of unconventional oil and gas assessments, water quality, water availability, air quality, effects on human health, and ecological effects.

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