Brine Contamination to Aquatic Resources from Oil and Gas Development in the Williston Basin, United States

Scientific Investigations Report 2014–5017

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

Covers. Wetland and nearby oil well in Sheridan County, Montana, September 2011. Photographs by Tara Chesley-Preston, U.S. Geological Survey.

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Edited by Robert A. Gleason and Brian A. Tangen

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Volume comprises chapters A, B, C, and D

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Volume Contents

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
hectare (ha)	0.003861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per year (m/yr)	3.281	foot per year (ft/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
megagram (Mg)	1.102	ton, short (2,000 lb)

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

°F=(1.8×°C)+32

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

Apparent conductivity of the soil water matrix is given in millisiemens per meter (mS/m).

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

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Executive 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 for more than one-half a century. Currently, there are renewed efforts to develop oil and gas resources from deep geologic formations, spurred by advances in recovery technologies and economic incentives associated with the price of oil. Domestic oil and gas production has many economic benefits and provides a means for the United States to fulfill a part of domestic energy demands; however, environmental hazards can be associated with this type of energy production in the Williston Basin, particularly to aquatic resources (surface water and shallow groundwater) by extremely saline water, or brine, which is produced with oil and gas. The primary source of concern is the migration of brine from buried reserve pits that were used to store produced water during recovery operations; however, there also are considerable risks of brine release from pipeline failures, poor infrastructure construction, and flow-back water from hydraulic fracturing associated with modern oilfield operations.

During 2008, a multidisciplinary (biology, geology, water) team of U.S. Geological Survey researchers was assembled to investigate potential energy production effects in the Williston Basin. Researchers from the U.S. Geological Survey participated in field tours and met with representatives from county, State, tribal, and Federal agencies to identify information needs and focus research objectives. Common questions from agency personnel, especially those from the U.S. Fish and Wildlife Service, were “are the brine plumes (plumes of brine-contaminated groundwater) from abandoned oil wells affecting wetlands on Waterfowl Production Areas and National Wildlife Refuges?” and “are newer wells related to Bakken and Three Forks development different than the older, abandoned wells (in terms of potential for affecting aquatic resources)?” Of special concern were the wetland habitats of the ecologically important Prairie Pothole Region, which overlays a part of the Williston Basin and is recognized for the production of a majority of North America’s migratory waterfowl.

On the basis of the concerns raised by on-the-ground land managers, as well as findings from previous research, a comprehensive study was developed with the following goals: summarize existing information pertaining to oil and gas production and aquatic resources in the Williston Basin; assess brine plume migration from new and previously studied sites in the Prairie Pothole Region; perform a regional, spatial evaluation of oil and gas production activities and aquatic resources; assess the potential for brine contamination to wetlands and streams; and hold a decision analysis workshop with key stakeholders to discuss issues pertaining to oil and gas production and environmental effects and to identify information gaps and research needs.

This report represents an initial, multidisciplinary evaluation of measured and potential environmental effects associated with oil and gas production in the Williston Basin and Prairie Pothole Region. Throughout this report there are reviews of current knowledge, and discussions relating to data gaps and research needs. On the basis of the information presented, future research needs include: regional geophysical and water-quality assessments to establish baselines for current conditions and estimate the extent of previous brine contamination, investigations into the direct effects of brine to biotic communities, and evaluations to identify the most effective techniques to mitigate brine contamination.

Principal Findings

Brine Contamination of Prairie Pothole Environments at Three Study Sites in the Williston Basin, United States

Surface-water and shallow groundwater samples were collected and electromagnetic geophysical surveys were performed at three study sites in the Prairie Pothole Region to assess saline contamination from produced waters (brine) from nearby oil and gas production. Water-quality results indicated that 34 of the 48 samples were moderately or extremely contaminated with brine, and another 7 were potentially contaminated. Much of the salinity present in surface water and shallow groundwater during 2009 and 2010 at two of the study sites likely came from buried reserve pits that were installed in the mid- to late-1960s, indicating that contamination can persist for at least four to five decades. Geophysical surveys performed at the three study sites measured elevated apparent conductivity near most of the oilfield facilities. Analysis of groundwater samples confirmed that areas of elevated apparent conductivity were areas of brine-contaminated groundwater. Therefore, interpretation of electromagnetic geophysical data in conjunction with water-quality data provides an effective method to identify brine-contaminated groundwater in the Prairie Pothole Region.

The lateral migration of brine in groundwater appears to be controlled, in part, by the type of near-surface sediments, with observed migration distances of at least 600 and 800 meters in glacial outwash deposits and at least 400 meters in glacial till. The vertical migration of brine in groundwater is also controlled by sediment type and is measurable with geophysical methods. Apparent conductivity decreased substantially with decreasing frequency (depth) where glacial outwash deposits overlie clay-rich, glacial till. No substantial change in apparent conductivity was observed as a function of frequency (depth) in the clay-rich glacial till deposits. Apparent conductivity values increased substantially with depth where silt and clay lacustrine deposits overlie clay-rich glacial till.

Strontium isotope data from samples of produced waters, surface water, and groundwater confirmed that the source of high salinity contamination at the three study sites is brine produced with hydrocarbons. Potential mechanisms for the release of brine in the Williston Basin include discharges from oil and gas wells, tank batteries, reserve pits, and pipelines, as well as illegal dumping.

Spatial Characterization of Oil and Gas Development and Aquatic Resources in the Williston Basin, United States

A spatial characterization of the Williston Basin and various county-level assessments of the distribution of aquatic resources and oil- and gas-related wells were performed using databases describing wells, wetlands and streams, and critical riparian habitats for a federally threatened bird species. The purpose of the county-level assessments was to identify areas within the Williston Basin that have the greatest likelihood of containing brine-affected aquatic resources. These assessments were founded on the premise that counties with the greatest numbers and densities of wells and aquatic resources would have a greater probability of containing wetlands and streams affected by brine than counties with fewer of these features. Further, counties with more wetlands and streams adjacent to, or in close proximity to, wells were identified. These proximity analyses were performed because aquatic resources in close proximity to oil and gas producing wells are more likely to be affected by brine because of soil and surficial geologic properties that have been shown to limit subsurface brine migration.

The overall spatial characterization identified more than 30,000 oil- and gas-related wells that were permitted and drilled from approximately 1901 to 2011, nearly 30,000 square kilometers (km^2) of wetlands, and about 190,000 kilometers (km) of streams within the boundaries of the Williston Basin and Bakken Formation. A majority of the wells were drilled after 1950 and are located primarily on privately owned lands in northeastern Montana and western North Dakota. A proximity analysis performed in the Prairie Pothole Region of the study area identified about 290,000 wetlands covering almost 1,800 km^2, more than 7,000 km of streams, and nearly 80 km^2 of piping plover (*Charadrius melodus*) critical habitat within 1.6 km of oil- and gas-related wells, an observed distance of subsurface brine migration over time through some coarse-grained glacial outwash soils. About one-third of all wetlands in the Prairie Pothole Region part of the Williston Basin are located within 1.6 km of oil and gas wells, demonstrating the considerable vulnerability of these aquatic resources to brine contamination in the region. Similar analyses were performed using only oil and gas wells completed prior to 1980, the approximate date when associated reserve pits were required to be lined. Additionally, a more focused proximity analysis identified greater than 1,200 oil and gas wells, greater than 80,000 km^2 of wetlands, and nearly 3,000 km of streams on or adjacent to U.S. Fish and Wildlife Service lands in the Prairie Pothole Region part of the study area. Lastly, it was determined that a 1.6-km radial buffer around wells intersected greater than 3,500 U.S. Fish and Wildlife Service conservation easement contracts in the Prairie Pothole Region of the Williston Basin.

This spatial characterization, along with information presented in chapter B of this report, lays the foundation for understanding the potential for past and current oil and gas production to affect the vast aquatic resources within the Williston Basin. With the county-level assessments, an initial step was taken towards identifying areas of the Williston Basin and Prairie Pothole Region with the greatest number of oil and gas wells and aquatic resources. This information can be used to focus monitoring efforts and scientific studies for assessing potential contamination of aquatic resources from oil and gas development. Further, the information provided in this report, along with the identification of important data gaps, can help guide future efforts to perform more formal risk assessments of oil and gas production to aquatic resources.

Charting a Course Forward—Identifying Research and Decisionmaking Priorities in the Williston Basin, United States

A formal decision analysis workshop was held in Bismarck, North Dakota, during April 2011. Although performed within the context of the work described in previous chapters of this report, the overarching goal of this workshop was to frame the issues surrounding natural resource management and conservation decisionmaking with regard to oil and gas development within the Williston Basin. This decision analysis framework provides a clearer understanding of the decision context and provides guidance on how future applied scientific studies will provide the most value to decisionmakers. Additionally, this framework will clarify means to effectively communicate information about oil and gas development to those decisionmakers.

This chapter outlines the process used to develop the decision analysis framework. During the workshop, participants completed a modeling exercise designed to illustrate how oil well siting decisions might affect wetland and agricultural resources. While this exercise was not intended to inform an actual decision, it did highlight a number of issues that need to be addressed in moving forward with a more detailed analysis. These issues include making sure that all relevant stakeholders are represented in the analysis, properly defining the scale and extent of the problem, and assessing the value of resolving critical uncertainties regarding effects of oil and gas development. Charting a clear course forward, using decision analysis tools, will provide direction for continuing studies about oil and gas development that are decision relevant within the Williston Basin.

Oil and Gas Production, Aquatic Resources, and Brine Contamination in the Williston Basin, United States

By Brian A. Tangen, Seth S. Haines, Todd M. Preston, and Joanna N. Thamke

Chapter A of

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Figures

Oil and Gas Production, Aquatic Resources, and Brine Contamination in the Williston Basin, United States

By Brian A. Tangen,[1] Seth S. Haines,[1] Todd M. Preston,[2] and Joanna N. Thamke[1]

Synopsis

The Williston Basin is an intracratonic basin that underlies parts of Montana, North Dakota, and South Dakota in the United States, and Manitoba and Saskatchewan in Canada. The Williston Basin has been a top domestic oil-producing region since the 1960s. Recent oil and gas assessments have identified substantial reserves associated with the Devonian-Mississippian Bakken and underlying Devonian Three Forks Formations, and the region is currently in the midst of a major oil boom triggered by advances in oil and gas recovery technologies and high oil prices. Past research detailing contamination of surface waters and groundwater by produced waters (brine), in conjunction with observed increases in oil and gas development and spills of highly saline brine, has raised concerns about possible effects of oil and gas production to sensitive aquatic resources. The primary source of concern is the migration of brine from buried reserve pits that were used to store produced waters during recovery operations; however, there also are considerable risks of brine release from pipeline failures, poor infrastructure construction, and enhanced hydraulic connectivity between abandoned well bores and modern oil and gas operations from hydraulic fracturing.

Overlying the northeastern half of the Williston Basin is the Prairie Pothole Region (PPR), which includes critical wetland breeding and nesting habitats for a large proportion of North America's waterfowl. The PPR is most often recognized for its vast number of pothole wetlands, with water chemistry that is highly variable and often differs significantly from brines in terms of salinity and ionic composition. The plant and invertebrate communities of pothole wetlands, which are critical to the provisioning of various ecosystem services, can be sensitive to salinity levels as well as specific salts (Gleason and others, 2009), and there are concerns over the ecological effects of brine contamination to these systems; however, there has been very little research pertaining to the direct effects of brines to biotic communities, especially in the Williston Basin.

The United States has a long history of oil and gas production, and there are standard methods for the remediation of brine-affected soils and groundwater, but there are no standard guidelines for remediating surface waters such as pothole wetlands. In addition to data gaps associated with the effects of brine to biotic communities, studies are needed to identify and evaluate remediation techniques for closed-basin surface waters such as pothole wetlands.

Oil and Gas Production in the Williston Basin

The Williston Basin Province has been the subject of numerous U.S. Geological Survey (USGS) oil and gas resource assessments in recent years (Anna and others, 2008; Pollastro and others, 2008b; Gaswirth and others, 2013), and detailed descriptions of the geology and hydrocarbon-producing formations are widely available (Sandberg, 1962; Peterson, 1995; Thamke and Craigg, 1997; Iampen and Rostron, 2000; Anna and others, 2008; Pollastro and others, 2008b; Anna and others, 2011; Gaswirth and others, 2013). The current oil development boom produces from the Bakken Formation and the underlying Three Forks Formation. The Bakken Formation is composed of shale and other rock types deposited during the Devonian and Mississippian periods and the USGS estimated that the portion of the Bakken Formation located in the United States (fig. A–1) contains 3,649 million barrels of oil (MMBO), 89 billion cubic meters (m^3) of gas (BCMG), and 246 million barrels of natural gas liquids that are recoverable with existing technologies (Gaswirth and others, 2013). The Three Forks Formation is composed of Devonian dolostone, mudstone, and anhydrite. The portion located in the United States is estimated to contain 3,734 MMBO, 101 BCMG, and 281 million barrels of natural gas liquids (Gaswirth and others, 2013). Each of the aforementioned assessment quantities is the mean value of a probability distribution function that expresses the uncertainty inherent in the associated measurements and methods. These formations in the Williston Basin have been identified as one of the world's greatest potential oil and gas reserves, with estimated volumes comparable to those of many leading oil-producing nations (Durham, 2010).

Oil and gas production in the Williston Basin began prior to the 1920s with gas production in the Cedar Creek anticline

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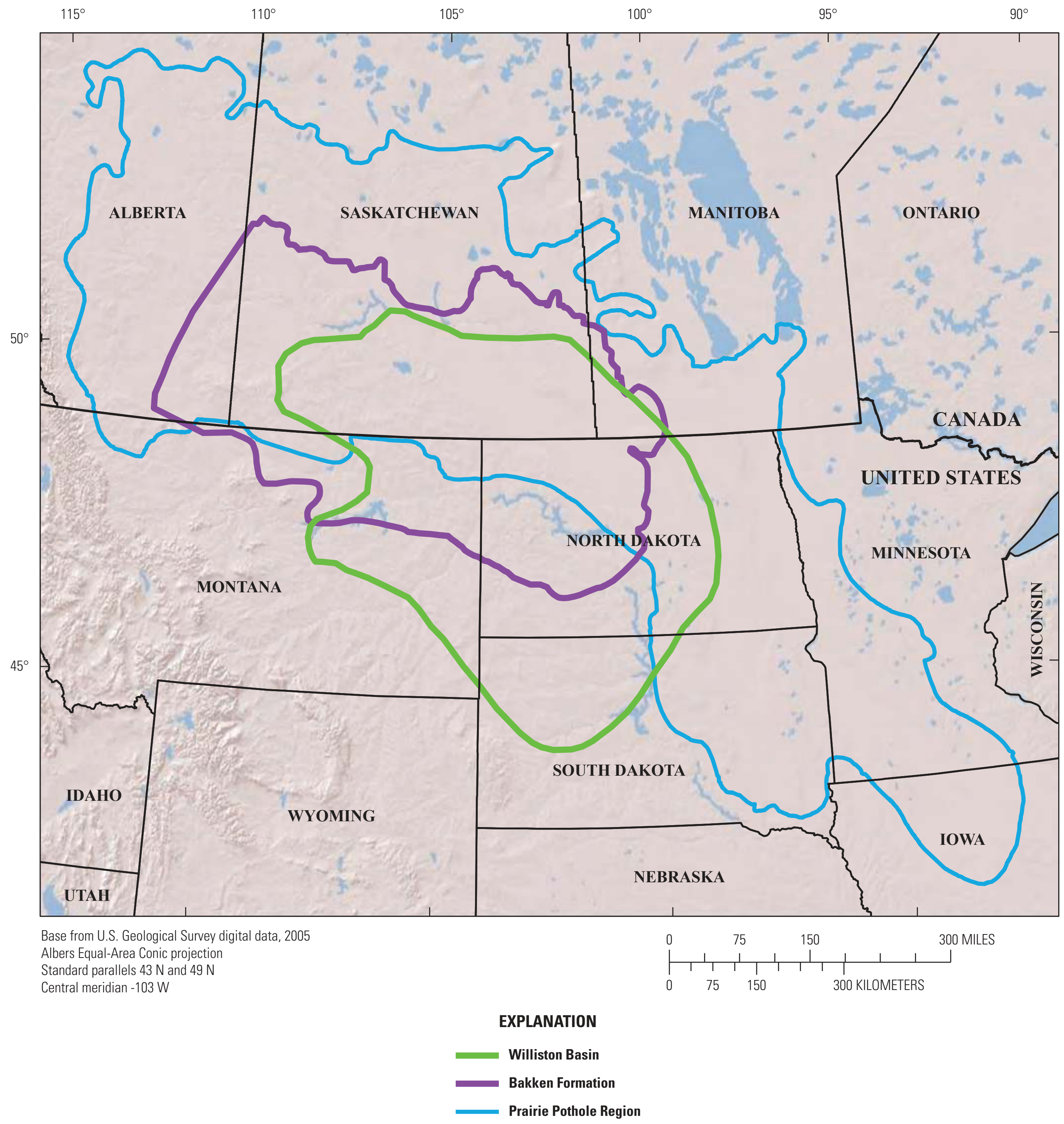
[1] U.S. Geological Survey

[2] Parallel, Inc.



Base from U.S. Geological Survey digital data, 2005
Albers Equal-Area Conic projection
Standard parallels 43 N and 49 N
Central meridian -103 W

Figure A–1. The Williston Basin, Bakken Formation, and Prairie Pothole Region.

area of Montana. Production increased substantially during the 1950s, with major oil discoveries throughout the basin (Gerhard and others, 1991; Peterson, 1995). These discoveries largely focused on the Mississippian Madison Group, though discoveries in the subsequent decades targeted other strata, and wells in the Williston Basin often produce oil and gas from several formations.

The Bakken Formation is generally considered the primary source rock for much of the hydrocarbons in the Williston Basin (Gerhard and others, 1991). In recent years, however, the Bakken Formation has become an exploration target, largely because of technological advances that make possible the extraction of large quantities of oil from this shale/sandstone formation. The development of high-precision horizontal drilling facilitates precise targeting of the sandstone middle member of the Bakken Formation along well bores that extend laterally up to approximately 3 kilometers (km). These wells are productive because of the development of sophisticated methods for hydraulic fracturing that create permeable fracture networks in low-permeability rocks. Hydraulic fracturing is a procedure in which large quantities of water (commonly 3,785–37,850 m^3 per well), sand, and a suite of chemicals are pumped under high pressure into the well bore. Hydraulic fracturing has been used for decades to improve well productivity, and contamination as a direct result has rarely been documented (DiGiulio and others, 2011; Papoulias and Velasco, 2013). Recent technological advances have vastly enhanced hydraulic fracturing’s effectiveness and stimulated its widespread use, particularly in the production of oil and gas from formations that would otherwise be too impermeable for economic production.

Since 2001, the Bakken Formation has been the primary target for new wells drilled in the Williston Basin. The number of wells drilled has increased each year and at least 756 wells in the Bakken Formation were drilled in the North Dakota and Montana parts of the basin in 2010 (IHS Energy, 2011). It is anticipated that as many as 1,800 new wells per year over the next 10 years may be completed in the Bakken Formation in North Dakota (Schuh, 2010; Dyke and others, 2011). The rapid rate of development in the Williston Basin brings associated infrastructure such as roads, transportation pipelines, storage facilities, and well casings.

Geology

The Williston Basin is a structural sedimentary, intracratonic depression that formed in the North American craton during Ordovician time, likely because of interaction between two Archean shear systems (Gerhard and others, 1991; Peterson, 1995; Pollastro and others, 2008a). The Williston Basin underlies a large part of the northern Great Plains in the United States and extends into the Canadian provinces of Manitoba and Saskatchewan. In the United States, the Williston Basin occupies 249,703 square kilometers (km^2) and includes parts of Montana, North Dakota, and South Dakota (fig. A–1). The Canadian part of the basin covers 102,057 km^2. The basin is generally dish-shaped (sedimentary rocks are thickest in the center and thinner toward the edges), with approximately 5,400 meters (m) of Cambrian through Tertiary strata (Gerhard and others, 1991). During the Paleozoic, deposition was largely dominated by carbonates; Mesozoic and Cenozoic deposition included considerably more clastic processes. Hydrocarbon generation and production has largely occurred in the deeper sedimentary strata, principally those that were deposited during the Paleozoic.

Overall, the Williston Basin is characterized by slight topographic relief (Peterson, 1995), with surficial sediments consisting mainly of materials transported by erosional processes such as glaciation and running water. The northeastern part of the basin is primarily a glacial till plain deposited during multiple Pleistocene glaciations, and the southwestern part is generally characterized by rolling plains, buttes, and badlands formed during the late Cretaceous and Tertiary periods (Eyles and Menzies, 1983; Bluemle, 2000). The glaciated northeastern part of the Williston Basin (PPR; fig. A–1) was the focus of the field studies described in Chapter B of this report; the following paragraphs provide an overview of the surficial geology of this focal area.

At the end of the Pleistocene, stagnation and ablation processes including melt-out, fluvial outwash, sediment slumping, and melt-water lake formation left behind a widespread ground moraine, which despite local variations in textural and mineralogical properties can be laterally homogenous over large geographic areas (Fullerton and others, 2004). The near-surface stratigraphy is a complex three-dimensional mixture of poorly sorted glacial till, fine-grained glaciolacustrine deposits, and coarse-grained glacial outwash channel deposits (Grisak and Cherry, 1975; Miall, 1983; Hendry, 1988; Fullerton and others, 2004). Glacial till consists primarily of clay-loam soils, outwash is characterized by sand and gravel, and lacustrine deposits are made up of silt, clay, and fine-grained sand. Glacial outwash is relatively permeable, and till and lacustrine deposits often form aquitards, with secondary, vertical fractures accounting for most of the water movement (Grisak and Cherry, 1975; Reiten and Tischmak, 1993).

Lands covered by glacial sediments in this region are part of the PPR (fig. A–1). The landscape of the PPR is characterized by ice-decay features, hummocky topography, poorly developed drainages, and hundreds of thousands of depressional wetlands, which are often referred to as prairie potholes (see section, “Prairie Pothole Region”). Key physiographic regions of the PPR are the Missouri Coteau, Prairie Coteau, and Glaciated Plains (Bluemle, 2000; Gleason and Laubhan, 2008). The Glaciated Plains region was formed principally as a result of ground-moraine processes that created a gently rolling landscape, and the Missouri and Prairie Coteaux were formed by stagnant and dead-ice moraines that created a rugged area of closely spaced hills and depressions (Bluemle, 2000). The study sites described in Chapter B of this report were within the Missouri Coteau.

Produced Waters

A major environmental challenge facing the energy industry is the handling and disposal of the substantial volume of brine that is produced with oil and gas during drilling and production (Wanty, 1997; Gorman, 1999). In general, brine is defined as having a total dissolved solids (TDS) concentration greater than 35,000 milligrams per liter (mg/L) (Kalkhoff, 1993); however, brine from the Williston Basin has some of the highest TDS levels (greater than 450,000 mg/L) in the United States (Otton, 2006). Typically, the ratio of brine to oil and gas produced is at least 2 to 1 in traditional oil wells, but much larger proportions are common, and the fraction of brine produced increases as the amount of recoverable oil is reduced (Veil and others, 2004). For example, in 1993, oil production in the United States resulted in the extraction of 2.5 billion barrels of crude oil and 25 billion barrels of produced waters (Wanty, 1997). On the basis of these estimates, approximately 10 barrels of brine are produced per barrel of oil extracted using traditional methods. Consequently, production of brine is the major potential environmental contamination hazard associated with oil and gas production within the Williston Basin.

Disposal methods of brine in the United States have varied historically. Prior to the 1960s and 1970s, discharge of brine to streams, oceans, and unlined reserve or evaporation pits was unregulated, resulting in both onsite and offsite contamination of surface waters and groundwater throughout the United States (McMillion, 1965; Baker and Brendecke, 1983; Murphy and others, 1988; Kalkhoff, 1993; Gorman, 1999). Similarly, previous studies in the Williston Basin have identified brine contamination of surface waters (Reiten and Tischmak, 1993; Thamke and Craigg, 1997; Nelson, 2006; Rouse and others, 2013), soils (Lang and Doll, 1983; Beal and others, 1987; Murphy and others, 1988), and groundwater (Levings, 1984; Payne and Reiten, 1991; Reiten and Tischmak, 1993; Thamke and Craigg, 1997; Thamke and Midtlyng, 2003; Smith and others, 2006; Peterman and others, 2010; Preston and others, 2013; Rouse and others, 2013).

The main source of historical contamination in the Williston Basin is attributed to inappropriate handling of brine and drilling fluids associated with reserve pits, which are dug at each well location to store produced fluids (Murphy and Kehew, 1984; Beal and others, 1987; Reiten and Tischmak, 1993). Guidelines enacted during the 1970s require that these reserve pits are lined with plastic to reduce the potential of offsite contamination; however, prior to these regulations, pits were unlined and prone to the leaching of brine. More recently (2012), the State of North Dakota established rules prohibiting usage of reserve pits for storage of fluids generated during well completion (North Dakota Century Code, 2013). At present, the most common disposal practice of produced waters in the Williston Basin is through injection into deep geologic formations where the fluids are far removed from surface waters or shallow aquifers. Nevertheless, there are inherent risks of contamination from brine associated with modern recovery operations. Sources of brine releases include breaks in transport pipelines, leaks or unregulated discharges from storage tanks or tanker trucks, and failures of well casings and aging infrastructure (Reiten and Tischmak, 1993; Thamke and Craigg, 1997).

Current exploration and production focuses mainly on the Bakken Formation, which generally contains less formational water than other Williston Basin geologic units. However, flow-back water (hydraulic fracturing fluids that return to the surface when well production is initiated) can present similar storage and disposal challenges, and there is the potential for releases during the tanker-truck transport of the 3,785–18,925 m^3 of fracturing fluid to develop each well; thus, while the greatest potential for contamination is from the legacy unlined reserve pits, other potential sources are associated with aging oilfield infrastructure and with current production activities.

Aquatic Resources

Prairie Pothole Region

Overlying the northeastern part of the Williston Basin is the PPR (fig. A–1), which spans approximately 770,000 km^2 in the north-central United States and south-central Canada. The PPR is characterized by abundant wetland habitats (prairie potholes) that are associated with the production of the majority of North America’s waterfowl. In total, about 283,850 km^2 of the PPR overlie the Williston Basin or the Bakken Formation; more than a quarter of this area is in the United States. Pothole wetlands, which are described in detail by Kantrud and others (1989) and van der Valk (1989), also are recognized for numerous ecosystem services provided to society including outdoor recreation, wildlife habitat, sequestration of atmospheric carbon, and floodwater storage (Gleason and others, 2008, 2011). Prairie potholes, along with streams and man-made stock ponds, also function as important water sources for livestock and crop irrigation in much of the semiarid Williston Basin.

Historically, the PPR was composed of short-, mixed-, and tall-grass prairie that contained countless isolated wetlands and streams. Currently, land use in the region is dedicated primarily to agricultural production, and a majority of the original wetlands have been lost or altered (Dahl, 1990; Dahl and Johnson, 1991; Gleason and Laubhan, 2008). Because of the land-use effects on these vital habitats such as draining, sedimentation, and additions of agri-chemicals, many public and private conservation organizations are focused on protecting existing wetlands and restoring affected sites. In addition to these obvious land-use effects on wetlands, there are several environmental threats associated with oil and gas production.

The primary risk to surface water and shallow groundwater from oil and gas production in the Williston Basin is the addition of highly saline brine. Effects of brine spills to soils are often evident as barren salt scars, but direct contamination of wetlands and streams can go unnoticed. Brine from point sources such as unlined reserve pits can migrate undetected in shallow groundwater over large distances before discharging to surface-water habitats, and brine can accumulate over time in discharge wetlands that are typically low points in the landscape. Because many wetlands lose most of their water through evapotranspiration, the flushing rate of any contaminant that enters the system is low. Additional risks to environmental resources include routine operational activities such as truck and pipeline transport that can lead to accidental spills and road and infrastructure construction that can result in habitat fragmentation and increased sedimentation.

Prairie wetlands and lakes are distinguished by extreme variability in their ionic composition and salinity (TDS and specific conductance) levels (Mitten and others, 1968; Stewart and Kantrud, 1972; Gorham and others, 1983; Swanson and others, 1988; LaBaugh, 1989). Salinity levels often differ considerably among pothole wetlands and lakes and can vary temporally on a seasonal and yearly scale within a single site. Swanson and others (1988) reported that specific conductance from one pothole wetland ranged from 522 to 7,700 microsiemens per centimeter (µS/cm) between wet and dry years, and Hammer (1978) described a Canadian lake where salinity increased by 80 percent within a season. Further, Mitten and others (1968) reported variances in 5-year mean salinity values of approximately 80 percent (23,100–127,000 parts per million [ppm]) and 90 percent (6,500–60,700 ppm) from opposing ends of two North Dakota lakes where water exchange is limited.

The primary sources of water for pothole wetlands are spring snowmelt and direct precipitation and runoff during the growing season; evapotranspiration is responsible for the majority of water loss. Climate of the PPR varies along a northwest-to-southeast gradient (Euliss and others, 1999), with precipitation and temperature increasing toward the southeast. While some pothole wetlands contain water throughout most years, a large proportion of these systems dry up seasonally because annual evapotranspiration exceeds precipitation. The topographic position in the landscape also affects salinity and ionic composition as some potholes receive inputs from the groundwater (groundwater discharge sites), whereas others function as groundwater recharge or flow-through sites (Winter, 1989; Winter and Rosenberry, 1995); thus, wetland salinity and ionic composition at any point in time is governed by natural physical processes such as the timing and total amount of precipitation, evaporation, and dilution, as well as interactions with the shallow groundwater system (Winter, 1977).

Chemistry of Surface Water, Shallow Groundwater, and Brine

Numerous investigations of PPR wetlands have included measures of salinity because of its influence on ecosystem ecology and the composition of the biotic communities. Pothole wetlands are known for their unique vegetation (Stewart and Kantrud, 1971, 1972) and invertebrate (Euliss and others, 1999) communities, which can be sensitive to salinity (Stewart and Kantrud, 1972; Swanson and others, 1988; Euliss and others, 1999; Gleason and others, 2009). Wetlands of this region have concentrations of dissolved solids that encompass the gradient from fresh to saline (LaBaugh, 1989), and in some cases, salinity levels exceed that of seawater. Specific conductance values reported for wetlands and lakes of the Williston Basin and PPR range from 30 to 73,000 µS/cm, although most sites were lower than 20,000 µS/cm (Gorham and others, 1983; Swanson and others, 1988; Euliss and Mushet, 2004; Tangen and others, 2013). Despite the elevated salinities that can occur, often because of late-season evapoconcentration, specific conductance for most prairie pothole wetlands does not exceed 10,000 µS/cm and is often less than 1,000 µS/cm (LaBaugh and Swanson, 2003; Euliss and Mushet, 2004; Anteau and Afton, 2008; Badiou and others, 2011). Streams throughout the North Dakota part of the Williston Basin have mean TDS concentrations around 1,000 mg/L, with values that rarely exceed 2,000 mg/L (North Dakota Department of Health, unpublished data, 2012; U.S. Geological Survey, unpublished data, 2012). Additionally, Gorham and others (1983) suggest that, in some cases, shallow groundwater in the Dakotas may have TDS levels as high as 3,000 mg/L.

Various investigations have documented that the primary cations present in prairie wetlands are calcium, magnesium, sodium (Na^+), and potassium; primary anions are bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-) (Gorham and others, 1983; Swanson and others, 1988; LaBaugh, 1989; LaBaugh and Swanson, 2003). Swanson and others (1988) identified 7 water types on the basis of the ionic composition of 178 prairie lakes located in south-central North Dakota: calcium bicarbonate, magnesium bicarbonate, sodium bicarbonate, magnesium sulfate, sodium sulfate, sodium chloride (NaCl), and magnesium chloride. Of these lake types, a majority were classified as SO_4^{2-} (62.4 percent) and HCO_3^- (33.1 percent) dominated, while only a small proportion were identified as being Cl^- (4.5 percent) dominated (Swanson and others, 1988).

Otton (2006) depicts brine from areas of the Williston Basin as having some of the highest TDS concentrations in the United States. However, the chemistry of produced brines is dependent on the location within the Williston Basin and the producing geologic formation(s). For example, Iampen and Rostron (2000) reported that TDS concentrations of Williston Basin brines can range from less than 30,000 mg/L on the east and southwest flanks to greater than 380,000 mg/L throughout the deeper parts of the basin. Reiten (1991) reported a mean TDS value of nearly 320,000 mg/L, and Thamke and Craigg (1997) reported TDS concentrations as large as 201,000 mg/L for Williston Basin brine samples from wells producing predominately from the Mississippian-aged Madison Formation in northeastern Montana. A mean TDS value of approximately 245,000 mg/L (maximum value of 540,500 mg/L) was calculated using data from over 2,100 oil and gas wells (representing approximately 7,600 samples) producing from numerous formations throughout North Dakota (North Dakota Geological Survey, 2002). Moreover, Williston Basin brines often are characterized as being chloride dominated (Reiten, 1991; Reiten and Tischmak, 1993; Thamke and Craigg, 1997; Iampen and Rostron, 2000). As a comparison, pothole wetlands are typically SO_4^{2-} and HCO_3^- systems with reported salinity values ranging from less than 500 to 70,000 µS/cm (Swanson and others, 1988). Using a model (µS/cm = 2,289 + 0.68TDS) presented by Swanson and others (1988), the maximum specific conductance value of 70,000 µS/cm converts to a TDS value of 99,575 mg/L. However, 70,000 µS/cm is unusually high, and specific conductance values ranging from 1,000 to 10,000 µS/cm are considered typical (Swanson and others 1988; LaBaugh and Swanson, 2003; Euliss and Mushet, 2004; Anteau and Afton, 2008; Badiou and others, 2011). This range converts to a TDS of less than 11,340 mg/L and is significantly less than the values reported for Williston Basin brines.

Brine Contamination

Ecological Effects of Oil and Gas Production

There is growing public concern over potential contamination of aquatic resources associated with oil and gas production in the Williston Basin. Numerous studies have demonstrated the effects of brine contamination on the environment (Beal and others, 1987; Reiten, 1991; Reiten and Tischmak, 1993; Thamke and Craigg, 1997), but there is a dearth of information pertaining to the effects of oil and gas production on biological communities, especially those communities associated with aquatic resources. Notable exceptions include a literature review of the effects of energy development on ungulates (for example, deer, elk, pronghorn) in Montana (Hebblewhite, 2008), and a report by Dyke and others (2011) detailing the effects of oil and gas activities on fish and wildlife in North Dakota and the citizens that utilize those resources. Both of these studies relied primarily on existing information (population surveys, habitat requirements, technical reports), and Hebblewhite (2008) concluded that rigorous experiments specifically designed to evaluate the effects of energy development were needed.

Hereafter discussions primarily focus on potential effects of brine contamination to biotic communities associated with wetlands and streams; however, other ecological effects are associated with oil and gas production activities such as pad and road construction, infrastructure development, and increased water usage and vehicle traffic (Hebblewhite, 2008; Dyke and others, 2011). For example, pad or road construction can result in the filling in or increased sedimentation of wetlands, and new road networks can disrupt migration routes and fragment habitat critical to a multitude of taxa including ungulates, grassland-dependent birds, and predators. Increased traffic leads to a greater frequency of vehicle collisions with all manner of wildlife, from small rodents, amphibians, snakes, and birds to large ungulates and predators. Increased disturbance and human presence can also stress wildlife during vulnerable times of the year such as nesting, calving, and winter (Hebblewhite, 2008; Dyke and others, 2011). The enormous amounts of water required for hydraulic fracturing (up to 37,850 m^3 per well) also can affect recreational lakes, shallow aquifers (Fischer, 2013), and agricultural irrigation.

There is a lack of scientific information describing the ecological effects of brines on aquatic resources in the Williston Basin. Despite this, assumptions regarding the potential effects of brine on water quality and biotic community structure can be made based on differences in water chemistry between surface and produced waters and the broad suite of literature describing effects of salinity to biotic communities. In general, comparisons of existing data have shown that salt concentrations of Williston Basin brines are significantly greater than the surface water and shallow groundwater of the region (see section, "Chemistry of Surface Water, Shallow Groundwater, and Brine"); thus, the addition of brine to wetlands, streams, and shallow aquifers has the potential to increase salinity. The available water chemistry information further suggests that the ionic composition is quite different between natural and produced waters, with produced waters having much greater Cl^- concentrations than most natural surface waters; in fact, Pennak (1989) states that NaCl concentrations in fresh waters seldom exceed 5 percent of the TDS. On the basis of this information, it is reasonable to assume there is some potential for highly saline brine to raise the salinity levels and to alter the composition of salts in natural aquatic systems. Both of these factors have been shown to affect aquatic biota (Burnham and Peterka, 1975; Swanson and others, 1984; Mount and others, 1997; Zalizniak and others, 2006). Significant inputs of brine could also make water unsuitable for domestic livestock and wildlife, which often rely on natural wetlands and streams or manmade stock ponds for drinking water. The effect of brine contamination to biotic communities, however, would be highly variable depending on factors such as the relative amount of brine introduced to the system, background salt type and concentration, the composition of the biota, and the relation between the wetland and groundwater (recharge, flow through, discharge).

The relation between biotic communities and salinity has been examined in great detail (Poljakoff-Mayber, 1975; Jennings, 1976; Wollheim and Lovvorn, 1995; Parida and Das, 2005; Kefford and others, 2007; Nielsen and others, 2007; Gleason and others, 2009), and most freshwater organisms are restricted to salinity levels that do not exceed 10,000 mg/L (Pennak, 1989; Wetzel, 2001). Salinity influences plant and invertebrate community composition (Stewart and Kantrud, 1972; Hammer and Heseltine, 1988; Hammer and others, 1990; Gleason and others, 2009) and at certain levels has been shown to reduce survival rates, growth, and development of ducklings (Swanson and others, 1984; Mitcham and Wobeser, 1988; Moorman and others, 1991; DeVink and others, 2005). Williston Basin brines are characterized not only by high salinity levels but by the dominant ions Na^+ and Cl^-. Elevated

NaCl concentrations can reduce the germination success of salt-tolerant plants (Baskin and Baskin, 1998), and increased sodicity can affect soil structure, thus impairing plant growth (Bohn and others, 2001; Gleason and others, 2009).

In addition to the overall efforts relating salinity to biotic communities, there have been numerous investigations of the toxicity of produced waters to organisms associated with aquatic ecosystems in other oil and gas producing areas. For example, brines from petroleum production in Texas were found to be toxic to the salt-tolerant sheepshead minnow (*Cyprinodon variegatus*) when diluted with seawater to a salinity of approximately 52,000 mg/L (Andreasen and Spears, 1983), and survival and reproduction of a freshwater water flea (*Ceriodaphnia dubia*) were affected when exposed to water collected downstream from a Wyoming oilfield (Boelter and others, 1992). Rattner and others (1995) also identified nonlethal effects, such as reduced liver weight, to western sandpipers (*Calidris mauri*) that were attributed to chronic exposure to brine in Texas.

Remediation of Brine Contamination

There are a variety of approaches that are employed to remediate brine and hydrocarbon spills throughout the country; however, there is little guidance or relevant scientific research pertaining to remediation in the Williston Basin, especially with regards to surface water and groundwater. Most remediation efforts are focused on affected soils where vegetation no longer grows because of increased Cl^- concentrations. One conventional practice for remediation of brine-affected soils is excavation and removal; however, this dig-and-haul method is expensive and not practical over a large geographic area. The excess Na^+ typically associated with brine causes clays to swell, reducing permeability and decreasing the downward movement of water; consequently, one of the primary goals of remediation is to increase soil permeability in order to encourage leaching of Na^+ from the root zone, thereby promoting revegetation. Perhaps the most common method for increasing permeability is to treat affected soils with a calcium-based salt, such as gypsum, with the goal of replacing the Na^+ in the clay matrix (De Jong, 1982; Liang and others, 1995; Merrill and others, 1990; Bohn and others, 2001). This cation exchange increases infiltration and enhances the leaching of Na^+ from the upper soil profile. Although this type of treatment is effective for enhancing plant growth at affected sites, ions leached from the upper soil profile could still be transported to wetlands through shallow groundwater flow.

In addition to chemical treatments, alternative soil-remediation methods include tillage, irrigation, incorporation of various soil amendments (organic soil, manure, hay, sand, fertilizer), phytoremediation, and installation of subsurface drainage tile or downslope trenches to enhance lateral transport and intercept contaminated water (Korphage and others, 2003; Harris and others, 2005; Sublette and others, 2005). Tillage and the addition of soil amendments increase soil permeability through direct disturbance and the mixing of porous materials with tight clays. Similarly, establishment of salt-tolerant plants enhances permeability through the root zone, and these plants can also fix salts in their leaves and stems. Recently developed methodologies include the use of hydraulic fracturing of soils to enhance water recovery for desalinization and disposal (Robertson and others, 2006).

In addition to affecting soils, brine often contaminates the shallow groundwater system. The most common technique employed to remediate brine-affected groundwater is the pump-and-treat method, which consists of pumping contaminated water to the surface where it is treated and reinjected (Keely, 1989). The relative success and time involved to achieve site remediation using these various approaches differs according to factors such as soil properties (porosity and permeability), amount and concentration of brine introduced, precipitation, and groundwater flow paths and velocities.

In a review of publications pertaining to brine remediation, Vavrek and others (2004) identified information relating to brine spills, site characteristics, and restoration success as primary information gaps and suggested that phytoremediation is a feasible alternative to the dig-and-haul method, and assessments of recovered plant communities may be the best way to evaluate remediation and restoration of affected soils in the long term. Within the Williston Basin, especially in the PPR, contamination of wetlands is a primary concern. Hence, in addition to addressing data gaps related to remediation of contaminated soils and groundwater, baseline research is required to identify and evaluate remediation approaches for surface waters.

Summary

The Williston Basin has a long-standing history of oil and gas production and is in the midst of a modern oil boom made possible by advancements in drilling technologies, which allow for the recovery of oil from deep, low-permeability geologic formations. Along with the many economic benefits associated with oil and gas production, there are potential environmental effects linked to legacy reserve pits, modern recovery operations, fluid transport by tanker trucks and pipelines, and infrastructure construction. The Prairie Pothole Region has been widely recognized for its freshwater habitats, which have potential to be chemically and biologically altered by contamination from brine produced in the Williston Basin. Although brine contamination has been identified in areas of the Williston Basin, little research has been performed to assess potential ecological effects or to evaluate remediation techniques. Therefore, monitoring and research are required to identify contamination and any associated ecologic effects, as well as to determine the most appropriate ways to remediate contaminated sites.

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Brine Contamination of Prairie Pothole Environments at Three Study Sites in the Williston Basin, United States

By Todd M. Preston, Joanna N. Thamke, Bruce D. Smith, and Zell E. Peterman

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Brine Contamination of Prairie Pothole Environments at Three Study Sites in the Williston Basin, United States

By Todd M. Preston,[1] Joanna N. Thamke,[2] Bruce D. Smith,[2] and Zell E. Peterman[2]

Overview

This chapter describes field investigations examining produced water (brine) contamination of surface water and shallow groundwater resources at three study sites within the Prairie Pothole Region (PPR) and Williston Basin. Previous research on brine contamination was performed at two of these sites by the Montana Bureau of Mines and Geology (MBMG) or the U.S. Fish and Wildlife Service (USFWS), and results from these studies are presented with recent U.S. Geological Survey (USGS) results to examine the temporal changes in brine contamination. In order to better discuss the results from these multiple studies, information on brine chemistry in the Williston Basin, sources of brine contamination, identification of brine contamination, as well as descriptions of the three study sites and previous research are presented in the “Introduction.” The “Data-Collection Methods” section describes the collection and analysis of water-quality and geophysical data. The “Data Results” section lists the published sources for all data from the water-quality sample analyses and geophysical surveys. The “Study Sites Results and Discussion” describes the extent and magnitude of brine contamination at each of the three study sites based on these data, as well as provides information on the fate and transport of brine contamination in geologic settings common to the PPR of the Williston Basin.

Introduction

The Williston Basin is located in the Northern Great Plains (fig. B–1) and has been a leading domestic oil and natural gas producing region for more than one-half a century. Rapid oil and gas development is currently occurring from deep formations such as the Bakken and Three Forks Formations to meet current and future energy needs. Large volumes of brine, defined as very saline water with greater than 35,000 milligrams per liter (mg/L) of total dissolved solids (TDS) (Kalkhoff, 1993), are produced along with the oil. Saline drilling fluids are also composed of halite and other minor salts and are often used to prevent the dissolution of numerous evaporite beds, which are encountered while drilling deep oil and gas wells in the Williston Basin. Brine and drilling fluids have historically been placed in reserve pits and ponds or disposed of through injection wells into deep formations. Handling, storage, and disposal of brine in the Williston Basin have resulted in contamination of surface water and groundwater resources (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, 2013; Rouse and others, 2013). Brine contamination from produced waters and drilling fluids often results in marked changes in the chemistry of surface water and groundwater (Reiten and Tischmak, 1993). These changes can affect primary productivity in aquatic systems, degrade and destroy domestic and stock water resources, and cause declines in crop production or loss of arable acreage.

Geology and climate often control the length and extent of contamination, unless remediation action is taken. For example, at an oilfield in Alabama, highly permeable sediments and high precipitation rapidly decreased brine contamination in groundwater during a 10-year period (Powell and others, 1973). However, in the semiarid PPR, which is predominately underlain by relatively low permeability clay-rich tills, contamination from the 1960s is still evident and is expected to persist for tens to hundreds of years (Murphy and others, 1988; Preston, 2011).

Brine Chemistry in the Williston Basin

The brine chemistry of an individual deep formation in the intracratonic Williston Basin is influenced by the origin of the brine, subsequent diagenetic processes, and regional and local hydrogeology (Iampen and Rostron, 2000; Warren, 2010). Local and basinwide variations affect the subsurface spatial distribution of brine chemistry. Three pre-Mississippian brine zones, developed in response to basinwide, topographically controlled groundwater flow initiated by Laramide uplifts to the west (Bachu and Hitchon, 1996), can be differentiated in the Williston Basin based on major-ion chemistry (Iampen and Rostron, 2000). The recharge zone, located along the western

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[1] Parallel, Inc.

[2] U.S. Geological Survey

Base from U.S. Geological Survey digital data, 2005
Albers Equal-Area Conic projection
Standard parallels 43 N and 49 N
Central meridian -103 W

Boundaries from U.S. Geological Survey

Figure B–1. Location of the three study sites and the extent of the Williston Basin, Bakken Formation, and the Prairie Pothole Region.

edge of the Williston Basin, is brackish calcium (Ca^{2+})–sulfate (SO_4^{2-}) dominated water with average TDS values less than 30,000 mg/L. The central zone is a slow moving to stagnant sodium (Na^+)–Ca^{2+}–chloride (Cl^-) brine with anomalously low SO_4^{2-} and TDS values greater than 300,000 mg/L. The northern zone is Na^+–Cl^- brine with TDS values between 100,000 and 200,000 mg/L (Iampen and Rostron, 2000). Unlike many other intracratonic basins, oxygen and hydrogen isotopic compositions in pre-Mississippian Williston Basin brines do not systematically increase with depth (Rostron and Holmden, 2003). Much of the oil and gas production in the Williston Basin occurs within the stagnant groundwater-flow system in the central zone and produced waters are extremely saline. Iampen and Rostron (2000) documented an average TDS concentration of 300,000 mg/L from 50 actively producing oil wells, with some samples exceeding 380,000 mg/L.

Sources of Brine Contamination

The primary source of brine contamination throughout the Williston Basin appears to be from historical storage and disposal of brine and drilling mud in unlined reserve pits that were prone to seepage (Murphy, 1983; Murphy and Kehew, 1984; Beal and others, 1987; Reiten and Tischmak, 1993; Rouse and others, 2013). Reserve pits were typically excavated at each oil well site to separate drilling mud and cuttings as well as to store and evaporate brine. The average reserve pit measured 46 meters (m) long by 18 m wide by 3 m deep and contained between 1,529 and 2,549 cubic meters (m^3) of salt-saturated drilling fluid (Murphy and Kehew, 1984). In addition to reserve pits, other potential sources of brine contamination could include uncontained discharges (dumping), injection well failures, corrosion of abandoned production and injection well casings, and breaks in pipelines that transport oil and brine to treatment and injection facilities (Reiten and Tischmak, 1993; Thamke and Craigg, 1997; Preston, 2011). While the majority of contamination documented to date appears to be from preexisting reserve pits, the potential exists for new releases of brine and oil in the PPR, with contamination from these releases likely to increase because of the rapid development of the Bakken and Three Forks Formations and aging oilfield infrastructure. For example, 1,696 incidents involving the release of oil, brine, or other contaminants were reported to the North Dakota Department of Health between November 1, 2012, and November 11, 2013. Of these incidents, 1,305 were contained releases that remained within the boundaries of the production or exploration facility, and 391 were uncontained releases that overflowed the boundaries of the facility or leaked from a facility pipeline (North Dakota Department of Health web site, accessed January 2014, at *http://www.ndhealth.gov/ehs/spills/*).

The rate of brine movement from abandoned, unlined reserve pits depends on the initial quantity of salt produced at a given site, hydraulic conductivity of the sediments, topography, and precipitation (Murphy and others, 1988). The average reserve pit is estimated to contain 236 megagrams of salt derived from produced waters and drilling muds upon burial (Reiten and Tischmak, 1993). Soluble salts and exchangeable Na^+ ions were the main constituents added to drilling mud and are the most detrimental to plants and soils (Moseley, 1983). The hydraulic conductivity of glacial sediments varies considerably depending on the type of material (glacial outwash compared to glacial till) and can range from 1.2×10^{-3} to 1×10^{-12} meters per second (m/s) (Schwartz and Zhang, 2003). Investigations of brine contamination from an oilfield site within glacial till sediments in North Dakota determined that pore waters within the saturated and unsaturated zones below reserve pits abandoned for 10 to 25 years had the same ionic composition as the waters contained in the reserve pits (Murphy and others, 1988). Cl^- ions move significantly slower than the average groundwater-flow velocity in fractured till because of diffusion of the solutes into the porous media of the till (Grisak and others, 1980). Average annual precipitation in the Williston Basin is small, and major recharge events are limited, which results in minimal natural flushing of brine contamination. As a result, it is estimated that brine contamination from reserve pits in the Williston Basin will persist for tens to hundreds of years (Murphy and others, 1988; Preston, 2011).

Strategies for the storage and disposal of brine and drilling fluids in the Williston Basin have changed through time with the recognition of the environmental damage caused by historic construction and reclamation processes of evaporation and reserve pits (Murphy and Kehew, 1984). Although the regulations pertaining to reserve pits are determined by each individual state and province, the general practices and timing of environmental regulations were likely similar across much of the Williston Basin; therefore, the focus of the following discussion is only on reserve pits in North Dakota. The majority of the older reserve pits were constructed without any lining because prior to 1974, the Oil and Gas Regulatory Division of the North Dakota Industrial Commission did not have the authority to require the use of an artificial or synthetic liner (Beal and others, 1987); but, after 1974, liners were often only required if the reserve pit was located in permeable sediments (for example, glacial outwash deposits). The use of plastic liners was not mandated until 1982 or 1983 (Cody VanderBusch, Reclamation Specialist, North Dakota Industrial Commission Department of Mineral Resources Oil and Gas Division, written commun., March 4, 2013).

Just as construction practices have changed through time, so have reclamation processes. However, in most onsite pit reclamation scenarios, the low viscosity liquid is first pumped out for reuse in another well or transported to an injection well, leaving behind a saline slurry, which is then buried. During reclamation in the 1950s and 1960s, excavated materials were gradually added from the sides of the pit, covering the remaining slurry. Because of the small area of the reserve pit and inability of the fluids to desiccate rapidly, pit reclamation could take anywhere from 1 month to 1 year. More recently, unlined and plastic-lined reserve pits were often reclaimed by the trenching method, which greatly reduced the time required for reclamation. In this method, trenches were dug that emanated from the reserve pit, and excavated material was added from the side, forcing the saline slurry to drain outward into the unlined trenches where it was then buried (Beal and others, 1987). The use of trenching for pit reclamation was discontinued by 1992 or 1993 (Cody VanderBusch, Reclamation Specialist, North Dakota Industrial Commission Department of Mineral Resources Oil and Gas Division, written commun., March 4, 2013). In unlined and trenched reserve pits, the buried saline slurry is in direct contact with the underlying sediments and capable of leaching into the shallow groundwater system. Once trenching was discontinued, reclamation of reserve pits in North Dakota required the plastic liner to be folded over the reserve pit and then capped with clay; however, the liners could be ripped or punctured as they are manipulated with heavy machinery.

Alternative strategies to the use of reserve pits to store brine and drilling fluids are available and are now required in the North Dakota portion of the Williston Basin. Reserve pits (now called drilling pits) can only accept solid or stabilized fly-ash drill cuttings and no liquids as of April 2012 (North Dakota Oil and Gas Division, 2013). These rules apply to all wells drilled deeper than 1,524 m and include all the major oil producing units such as the Bakken and Three Forks Formations. Tanker trucks replace the reserve pit during these “pit-less” drilling operations and perform the separation of drilling fluids and cuttings, which can allow for the recycling of the drilling mud. The use of “pit-less” drilling eliminates one of the most pervasive potential sources of brine contamination in the Williston Basin.

Identification of Brine Contamination

Several methods have been used to identify brine contamination to surface water and shallow groundwater resources within the Williston Basin. Geochemical methods are useful because brine often alters salinity and strontium isotope ratios in surface water and shallow groundwater. Geophysical methods are used to determine increases in the electromagnetic conductance of soil and shallow groundwater from brine. These methods were integral in determining the presence and magnitude of brine contamination at the three study sites described in this report.

Salinity

The salinity of surface water and shallow groundwater in the PPR is distinctly different than the salinity of deep formational groundwater produced during oil and gas development. The water quality of surface water and shallow groundwater is often controlled by the hydrologic position within the landscape, with TDS generally increasing from areas of recharge to areas of discharge (Swanson and others, 2003). Consequently, surface water and shallow groundwater in discharge areas are often enriched in SO_4^{2-} and bicarbonate and depleted in Cl^-, resulting in SO_4^{2-} and carbonate dominated water (Custer, 1976). In contrast, deep formational groundwater in the Williston Basin (brine) is enriched in Cl^- and Na^+. Although TDS values can be large in surface water and shallow groundwater, as well as in the deep formational groundwater, the differences in major-ion chemistry allow for identification of surface water and shallow groundwater contaminated by brine.

Uncontaminated and brine-contaminated surface water and shallow groundwater can be quickly and easily distinguished in northeastern Montana by using a rapid assessment method developed by Reiten and Tischmak (1993). This rapid assessment method uses a contamination index (CI) that is defined as the ratio of Cl^- concentration in milligrams per liter to specific conductance in microsiemens per centimeter (µS/cm) in a water sample. The CI allows for field or laboratory determination of Cl^- contamination in waters ranging from fresh to extremely saline. Additionally, CI values remain relatively stable in groundwater wells that develop vertical density gradients. Surface water and shallow groundwater with a CI value greater than 0.035 was empirically determined to be contaminated by brine in eastern Sheridan County, Mont. (Reiten and Tischmak, 1993; Jon Reiten, Senior Research Professor/Hydrogeologist, Montana Bureau of Mines and Geology, written commun., August 13, 2013); however, this value likely varies throughout the Williston Basin depending on background Cl^- concentrations, local soil conditions, precipitation, and evapotranspiration. Two of the three study sites discussed in this chapter are located in eastern Sheridan County, Mont., and the other is located approximately 75 kilometers (km) to the east in Williams County, N. Dak., where soil types and precipitation and evapotranspiration rates are similar. Therefore, the use of the 0.035 value to indicate brine contamination is considered applicable at all three study sites.

Strontium Isotopes

Strontium (Sr) isotopes can be used to identify the presence of small amounts of brine (Peterman and others, 2010). Strontium is an alkaline-earth element closely following Ca^{2+} in the geochemical cycle with a Ca^{2+}/Sr ratio of about 100 to 200 in most surface water and shallow groundwater and approximately 30 in saline formation waters. The strontium-87 isotope (^{87}Sr) is the daughter of rubidium-87 through beta decay with a half-life of about 49 billion years. The relative abundance of the other isotopes, strontium-84, strontium-86 (^{86}Sr), and strontium-88, are invariant as they do not fractionate appreciably in nature. Consequently, the $^{87}Sr/^{86}Sr$ ratio is an extremely useful parameter for determining water-rock interaction, mixing of waters of different origins, and degree of hydrologic isolation among units (for example, cross flow and stratigraphic compartmentalization).

Values of $^{87}Sr/^{86}Sr$ in past and present sea water are well known (McArthur and others, 2001). Saline formation waters were likely formed by evaporation of seawater, dissolution of evaporates, or long-term water-rock interaction (Kharaka and Hanor, 2003). Surface water and shallow groundwater in the

PPR will dissolve Sr from the near-surface rocks and unconsolidated material. The Late Cretaceous Bearpaw/Pierre Shale, which occurs throughout the Williston Basin, has an average $^{87}Sr/^{86}Sr$ value of 0.7150 ± 0.0050 (U.S. Geological Survey, unpub. data, 2013). The overlying Late Cretaceous sandstones and Early Tertiary rocks likely would have even larger values because of detritus derived in part from Precambrian source rocks fluvially transported from the west and southwest. Glacial deposits in the northern part of the Williston Basin likely will have elevated $^{87}Sr/^{86}Sr$ ratios because of a component of crystalline rock derived from the Canadian Shield located to the northeast. In addition to unique $^{87}Sr/^{86}Sr$ signatures, brines in the Williston Basin have very large Sr concentrations typically up to 1,000 mg/L or more (Peterman and others, 2012). Thus, exceedingly small amounts of brine in surface water and shallow groundwater in the PPR of the Williston Basin can be detected with Sr isotopes.

Electromagnetic Properties

Electromagnetic (EM) surveys measure the cumulative electrical properties of pore water and the soil matrix and are capable of detecting differences in salinity in the saturated and vadose zones. The basic operation of EM instrumentation involves two coils, a transmitter and receiver coil, separated by a known distance. The transmitter coil is energized with an alternating current, inducing small currents in the earth, which in turn create a secondary magnetic field. The receiver coil senses the primary and secondary magnetic fields and converts the time-varying signals into electrical conductivity. Electromagnetic readings are expressed as apparent conductivity, which is an integration of all the subsurface material sensed by the equipment. Enhanced subsurface characterization is obtained by changing the dipole orientation or the coil spacing, resulting in different depth integration curves and exploration depths (McNeill, 1980). However, the effective exploration depth decreases for all EM equipment as the conductivity of the medium decreases (Greenhouse and Slaine, 1986).

Saline groundwater will have larger apparent conductivity than fresh groundwater in electromagnetic surveys (Reiten and Tischmak, 1993; Thamke and Craigg, 1997). Textural composition, soil saturation, and water salinity can affect apparent conductivity values, with increasing clay, water content, and salinity causing increasing apparent conductivity. However, in the semiarid climate of northeastern Montana, soil salinity is likely the most dominant variable contributing to apparent conductivity (Corwin and Lesch, 2005). In areas of similar clay and water content, the salinity of groundwater and soil primarily affects apparent conductivity values (Reiten and Tischmak, 1993). Naturally saline and brine-contaminated groundwater and soil can both result in elevated apparent conductivity, so the availability of groundwater chemistry data is important to differentiate between the two types of salinity.

Study Sites and Previous Research

The PPR was formed by Pleistocene glaciations, and the three study sites were selected to represent the primary glacial deposits within the PPR (fig. B–1). Additionally, the selection of study sites was based on proximity to Federal lands, presence of oilfield activity, and previous research that indicated brine contamination. In-depth surficial geology was determined from maps produced by Reiten and Tischmak (1993) of eastern Sheridan County, Mont., that delineated areas of glacial till, glacial outwash, and glaciolacustrine deposits. The Goose Lake site represents coarse-grained, glacial outwash deposits within and adjacent to a USFWS Waterfowl Production Area (WPA). Several oil-production wells and a tank battery (a collection of storage tanks designed to separate oil and brine) are within the Goose Lake site. Research at the Goose Lake site began in 1989. The Anderson site represents clay-loam glacial till deposits within a WPA. There are several oil-production wells and a tank battery within the Anderson site. Research at the Anderson site began in 2004. Analysis of the eastern Sheridan County surficial geology map failed to identify a site with oilfield activity within glaciolacustrine deposits; therefore, the search was expanded to western North Dakota. The Fuller site was identified from surficial geology maps produced by the North Dakota Geological Survey and represents silt and clay glaciolacustrine deposits within and adjacent to a WPA. The Fuller site contains an oil-production well and a tank battery. No previous research had been conducted at the Fuller site. All three study sites are located in the Missouri Coteau portion of the PPR.

Goose Lake Study Site

Potential sources of brine to surface water and shallow groundwater resources at the Goose Lake site consist of two active (during 2009) and six abandoned oil wells and associated reserve pits, transport lines, and a tank battery. A transport line, located along the northern section line that leads to the tank battery, ruptured in 2006 and discharged an unknown volume of oil and brine onto the land surface.

Glacial stagnation processes have resulted in an approximately 5 m thick undulating blanket of moderately well sorted to very poorly sorted silty sand and gravel outwash deposits that overlie a basal confining bed of relatively impermeable, pebbly clay loam (till). Additionally, there are locally interbedded and mantling deposits of silt and clay from glacial and modern lacustrine environments (Reiten and Tischmak, 1993). The outwash deposits are saturated beneath the modern drainages and wetlands and are unsaturated below topographic rises, creating unconfined aquifer conditions in the saturated outwash deposits (Reiten and Tischmak, 1993).

In total, the Goose Lake study site includes 39 monitoring wells and 19 wetlands where field parameters or water samples were collected during 1988, 1989, 1990, 2004, 2005, 2006, 2009, or 2011. The MBMG installed 35 monitoring wells, the USFWS installed two wells in 2005, and the USGS installed two additional wells in 2011 for a separate study. All monitoring wells are located near potential sources of brine or along potential groundwater-flow paths. A sample of the produced waters was collected from the tank battery in 2009. All water-quality samples were analyzed for major ions and a subset of samples were analyzed for trace elements and Sr isotopes. Discussion of water-quality samples collected at the Goose Lake study site will focus solely on 18 monitoring wells and 11 wetlands sampled by the MBMG (1988, 1989, or 1990) or the USFWS (2004, 2005, or 2006), as well as the USGS (2009).

Anderson Study Site

Potential sources of brine contamination in surface water and shallow groundwater resources at the Anderson site consist of five active and abandoned oil wells and associated reserve pits, transport lines, and a tank battery within the Anderson WPA. Additionally, there are six active and abandoned oil wells with associated reserve pits and another tank battery adjacent to the WPA.

Glacial stagnation processes have resulted in a layer of clay-rich pebbly loam (glacial till), at least 13 m thick at the deepest groundwater-monitoring well, and underlying much of the Anderson study site. In some parts of the study site, the till is mantled by moderately well sorted to very poorly sorted silty sand and gravel outwash deposits, or glaciolacustrine sediments. However, all groundwater-monitoring wells are completed in glacial till. As with the majority of glacial tills in the PPR, the till at the Anderson study site is unsaturated and oxidized in the near surface and saturated and unoxidized at depth.

In total, the Anderson study site includes 15 monitoring wells and 10 wetlands where field parameters or water samples were collected during 2004, 2005, 2010, or 2011. The MBMG and USFWS installed 13 monitoring wells during 2004, and the USGS installed two monitoring wells in 2011 for a separate study. All monitoring wells are located adjacent to potential sources of brine or along potential groundwater-flow paths. A sample of the produced waters was collected from the tank battery in 2010. All water-quality samples were analyzed for major ions, and a subset of samples were analyzed for trace elements and Sr isotopes. Discussion of the Anderson site water-quality data focuses solely on analytical results from 10 monitoring wells and 5 wetlands sampled by the USFWS (2004 or 2005) and the USGS (2010).

Fuller Study Site

Potential sources of brine to surface water and shallow groundwater resources at the Fuller study site consist of one abandoned oil well and associated reserve pit, transport lines, and a tank battery. Additionally, there are several active and abandoned oil wells and associated reserve pits located upgradient from the sampled sites.

Glacial stagnation processes at the Fuller study site have resulted in collapsed lake plain deposits within a low-relief ground moraine. The lake plain, or glaciolacustrine deposits, consist primarily of silt and clay that are at least 2 m thick at the deepest groundwater-monitoring well. The surrounding ground moraine consists primarily of till. Both monitoring wells were completed in the shallow glaciolacustrine deposits.

The Fuller study site includes two monitoring wells, a reservoir, a wetland below the reservoir, and three oil-production wells that were sampled during 2010. Two temporary monitoring wells were installed and sampled by the USGS during June 2010 along potential groundwater-flowpaths downgradient from potential sources of brine contamination. The well casings were removed, and the boreholes were filled by the USGS in late summer 2010. Water-quality samples were collected from a reservoir upgradient and a wetland downgradient from the tank battery adjacent to the Fuller WPA. Water-quality samples also were collected during 2010 from the tank battery adjacent to the WPA as well as two additional oil/brine separation tanks in close proximity to the WPA that receive oil and brine from wells producing from the Bakken Formation. Water samples were analyzed for major ions, trace elements, and Sr isotopes.

Data-Collection Methods

Water Quality

Surface-water and groundwater sample-collection methods used by the USGS during 2009–10 are described in Preston and others (2012) and summarized below. Water-quality data from three different time periods and studies are presented in this chapter: 1989 research by the MBMG, 2004–6 research by the MBMG and USFWS, and 2009–10 research by the USGS. The MBMG analytical procedures follow U.S. Environmental Protection Agency methods for inorganic constituent analysis (J. LaFave, Senior Research Hydrogeologist, Montana Bureau of Mines and Geology, oral commun., May 1, 2009). Samples submitted to the USGS National Water Quality Laboratory (NWQL) were analyzed using the methods described by Fishman (1993) for major ions, selected trace elements, and iodide and bromide. Strontium isotope analyses were performed during 2009–10 at the USGS Yucca Mountain Project Branch Strontium Isotope Laboratory (now USGS Crustal Geophysics and Geochemistry Center's Strontium Isotope Laboratory) using methods summarized by Peterman and others (1985).

The accuracy of laboratory determined Cl^- concentrations and specific conductance values from MBMG's Analytical Laboratory are reported to be within 10 percent, but variability could be as high as 20 percent because of dilution (Steve McGrath, Organic Chemist, Montana Bureau of Mines and Geology Analytical Laboratory, written commun., May 1, 2009). Similarly, measurement accuracies were likely within

5 percent for water samples analyzed at the NWQL. This accuracy estimate is based on data from the USGS Branch of Quality Systems inorganic blind sample program, which continuously runs double blind, environmental matrix based (from natural water samples as opposed to a deionized water based synthetic matrix samples) samples with known concentrations on most of the analytical equipment at NWQL. For example, during June 2009, when water samples from the Goose Lake study site were analyzed, the maximum standard errors for 12 Cl^- and 14 specific conductance blind samples were 4.9 and 4.0 percent, respectively (data available from *http://bqs.usgs.gov*). Similar errors were reported for the timeframes when samples from the Anderson and Fuller study sites were analyzed.

Field measurements were made at numerous wetlands at the Goose Lake site throughout 1989–90 and 2004–5 and at the Anderson site throughout 2004–5. Field data were collected using the same procedures and equipment in 1989–90 and 2004–5 with Cl^- concentrations determined using QuanTab Cl^- Titrators, numbers 1175 (range 60–480 parts per million [ppm] Cl^-) or 1176 (range 300–6,000 ppm Cl^-), and specific conductance determined with a YSI Model 30 probe. Parts per million is equivalent to milligrams per liter for pure water at 3.89 degrees Celsius (Hem, 1985) and can be used only as a general comparison to milligrams per liter for all other waters. Cl^- concentrations ranging from 60 to 6,000 ppm were read directly from the titrator strip, while samples with higher Cl^- concentrations required dilution with deionized water. Field Cl^- concentrations and specific conductance data were used to estimate CI values when water samples were not submitted to an analytical laboratory.

Geophysical Surveys

Complete descriptions of geophysical data-collection methods and apparent conductivity measurements are provided in Preston and others (2012) and summarized below. Geophysical data presented in this chapter are from surveys performed with a Geonics EM–31 by the MBMG and the USFWS during 2004 and a Geonics EM–31, Geonics EM–34, and a Geophex GEM–2 by the USGS during 2009–10. The apparent conductivity data required spatial interpolation for visual display using ArcGIS 9.3.1 for the EM–31 and EM–34 data and GEOSOFT Oasis for the GEM–2 data. Spatial interpolation in ArcGIS 9.3.1 was performed using the inverse distance weighting function on a neighborhood of three points and default power of two. Spatial interpolation in GEOSOFT Oasis was performed using minimum curvature. The spatially interpolated surface created in ArcGIS 9.3.1 is a rectangle with dimensions based on the furthest data points in each cardinal direction. Therefore, to provide data only in areas with sufficient geophysical control, these spatially interpolated surfaces were clipped to buffers created around the measurement points. All buffers were between 25 and 75 m.

EM–31

A Geonics EM–31 was used to measure apparent conductivity and delineate the lateral extent of brine-contaminated groundwater plumes (referred to as brine plumes hereafter) at all three study sites. All EM–31 surveys were performed in the vertical dipole mode, which has an exploration depth of approximately 6 m. EM–31 surveys were conducted at the Goose Lake study site in July 2004 and September and October 2009. Surveys were also performed at the Goose Lake study site by the MBMG in 1989, but the original data has been lost and attempts to georectify the images in Reiten and Tischmak (1993) proved unsuccessful. At the Anderson study site, EM–31 surveys were performed in July and September 2004 and October 2010. The EM–31 surveys at the Fuller study site were performed in October 2010. No previous geophysical surveys had been performed at the Fuller site for comparison with the 2010 survey.

Background apparent conductivities were determined from several (greater than 15) measurements in areas upgradient from oilfield facilities at each study site during all years. Apparent conductivity values less than approximately 30 millisiemens per meter (mS/m) are considered representative of background conductivity at the Goose Lake and Anderson study sites. Background apparent conductivity values were slightly higher at the Fuller study site, in the range of 25–50 mS/m, with the higher values likely because of the greater clay content of the glaciolacustrine deposits.

EM–34

A Geonics EM–34 was used in September 2009 to measure apparent conductivity, characterize the three-dimensional geometry of brine plumes, and examine the potential for stratigraphic controls on the transport of contaminated groundwater at the Goose Lake study site. Apparent conductivity measurements were collected at 10-, 20-, and 40-m intercoil spacings in the horizontal and vertical dipole orientations. Exploration depths in the horizontal dipole orientation for the 10-, 20-, and 40-m intercoil spacings are 7.5, 15, and 30 m, respectively. Respective exploration depths for the vertical dipole orientation are 15, 30, and 60 m; however, the horizontal dipole mode receives the majority of the signal from immediately below the land surface compared to roughly 0.4 times the intercoil spacings in the vertical dipole mode (McNeill, 1980). Therefore, even though the exploration depths may be equal, the horizontal dipole mode receives much more of its signal from shallower depths in the subsurface relative to the vertical dipole mode.

Background apparent conductivity measurements for all dipole orientations and intercoil spacing combinations were determined from several (greater than 10) measurements in areas upgradient from oilfield facilities. In the horizontal dipole orientation, measurements below approximately 20, 25, and 40 mS/m are considered representative of background conductivity for the 10-, 20-, and 40-m intercoil spacings, respectively. In the vertical dipole orientation, measurements below approximately 25, 35, and 40 mS/m are considered representative of background conductivity for the 10-, 20-, and 40-m intercoil spacings, respectively.

GEM–2

A Geophex GEM–2 was used in October 2010 to measure apparent conductivity, characterize the three dimensional geometry of brine plumes, and examine the potential for stratigraphic controls on the transport of contaminated groundwater at the Anderson and Fuller study sites. Apparent conductivity measurements were collected from seven frequencies; however, only the results from three frequencies (93,030, 47,970, and 1,530 hertz [Hz]) that span the range of exploration depths are presented in this chapter. Exploration depths for the 93,030, 47,970, and 1,530 Hz frequencies are 2, 4, and 7 m, respectively.

Background conductivity at each frequency was determined as the mean value from the survey data. The respective background conductivity values for 93,030, 47,970, and 1,530 Hz frequencies were 114, 150, and 140 mS/m, respectively, at the Anderson study site and 86, 109, and 101 mS/m, respectively, at the Fuller study site.

Data Results

Results for the various studies discussed in this chapter are published in several sources described below. For the Goose Lake study site, field parameters and analytical results for all water samples are available from the following sources: MBMG samples collected during 1988, 1989, or 1990 in Reiten and Tischmak (1993), USFWS samples collected during 2004, 2005, or 2006 in Rouse and others (2013), and USGS samples collected during 2009 in table 1–1 of Preston and others (2012). Geophysical data collected by the USFWS in 2006 and by the USGS in 2009 are located in table 1–4 of Preston and others (2012).

For the Anderson study site, field parameters and analytical results for all water samples are available from the following sources: USFWS samples collected during 2004 or 2005 in Rouse and others (2013) and USGS samples collected during 2010 in table 1–2 of Preston and others (2012). Geophysical data collected by the USFWS in 2004 and by the USGS in 2010 are located in table 1–4 of Preston and others (2012).

Analytical results for water samples collected by the USGS in 2010 at the Fuller study site are located in table 1–3 of Preston and others (2012). Geophysical data collected by the USGS in 2010 are located in table 1–4 of Preston and others (2012).

In order to facilitate the following discussion, summary water-quality data containing site name, Cl^- concentration, specific conductance, Na^+/Cl^- molar ratio, and CI values are presented for the Goose Lake study site (table B–1), the Anderson study site (table B–2), and the Fuller study site (table B–3).

Study Sites Results and Discussion

In the following discussion and accompanying figures, the names of individual oil wells at the three study sites are identified by the “unique well identifier” number from the American Petroleum Institute (API) well number. API numbers are in the following format 11-222-33333-44-55 with the first two digits being the State code, the next three being the county code, the five-digit number in the middle being the unique well identifier, the next two digits being the directional side track code, and the last two digits being the event sequence code. The State and county codes for Sheridan County, Mont., and Williams County, N. Dak., are 25–091 and 33–105, respectively. Oilfield site numbers used by Reiten and Tischmak (1993) are in parentheses following the API unique well identifier in the discussion of the Goose Lake site. For example, the oil well with the API well number 25091210560000, located in Sheridan County, Mont., and labeled oilfield site 128 by Reiten and Tischmak (1993), is labeled 21056 (128) in this report.

Water Quality

The quality of surface water and shallow groundwater at the three study sites is highly variable and is dependent on location relative to sources of brine contamination. Sodium, magnesium, bicarbonate, SO_4^{2-}, and Cl^- are the common dominant ions in uncontaminated and contaminated water at these sites. Na^+ and Cl^- are the dominant ions in the brine. The CI developed by Reiten and Tischmak (1993) using field and analytical Cl^- and specific conductivity was used and expanded upon with Na^+ to identify brine contamination at the three study sites. Figure B–2 shows the distribution of Na^+/Cl^- molar ratio, CI value, and Cl^- concentration for 96 samples from tables B–1, B–2, and B–3; 25 samples from Reiten and Tischmak (1993) that were not collected at the Goose Lake study site; 35 samples from Eisenlohr and others (1972); and 21 samples from LaBaugh and Swanson (1992, 2003). Samples from Eisenlohr and others (1972) and LaBaugh and Swanson (1992, 2003) are in areas with little or no oil development and represent background water-quality conditions for the PPR. Information about the sampled sites was used to select thresholds for water classification. The majority of background samples have CI values below 0.035 (green horizontal line, fig. B–2) and plot to the right of the 1:1 Na^+/Cl^- molar ratio (black vertical line, fig. B–2) indicating water chemistry that is dominated by the presence of Na^+. In contrast, all but 1 of the 87 water samples with CI values above 0.1 (orange horizontal line, fig. B–2) plot to the left of the 1:1 Na^+/Cl^- molar ratio line indicating a distinct shift in the molar ratio towards

Table B–1. Summary of water-quality data for the Goose Lake study site, Sheridan County, Montana.

[Summarized from table 1–1 (Preston and others, 2012). Onsite (field) water-quality data are in italics. Na^+/Cl^- molar ratio is the quotient of the Na^+ and Cl^- concentrations converted to molar equivalents. Contamination index is calculated by dividing Cl^- concentration (mg/L) by specific conductance value (µS/cm). Cl^-, chloride; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Na^+, sodium; --, no data]

Site name	1989				2005–2006				2009			
	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index
117F	*450*	*2,080*	--	*0.216*	--	--	--	--	2,941	10,750	0.53	0.274
117J	2,560	9,211	0.45	0.278	3,434	11,000	0.48	0.312	1,550	5,980	0.59	0.259
124C	10,600	29,096	0.90	0.364	1,678	5,810	0.83	0.289	2,330	7,540	0.75	0.309
124D	*5,060*	*11,090*	--	*0.456*	--	--	--	--	3,280	10,600	0.71	0.309
124E	*16,870*	*34,700*	--	*0.486*	--	--	--	--	7,020	22,000	0.86	0.319
124F	*12,790*	*27,030*	--	*0.473*	--	--	--	--	4,870	14,700	0.68	0.331
124H	36,500	78,617	0.79	0.464	13,263	31,000	0.88	0.428	19,500	50,000	0.73	0.390
124J	18,000	44,480	0.81	0.405	4,129	11,950	0.87	0.346	6,150	17,900	0.77	0.344
124N	12,000	22,557	0.84	0.532	4,217	12,640	0.90	0.334	3,340	10,300	0.85	0.324
124O	7,840	21,375	0.28	0.367	2,574	8,510	0.62	0.302	17,200	44,500	0.51	0.387
124P	16,300	40,603	0.71	0.401	20,126	41,600	0.84	0.484	4,370	13,600	0.80	0.321
126A	1,060	6,233	1.05	0.170	--	--	--	--	6,100	17,900	0.77	0.341
126B	23,600	59,538	0.73	0.396	15,382	32,900	0.80	0.468	15,800	41,300	0.63	0.383
126C	6.6	1,203	6.29	0.005	--	--	--	--	964	3,630	0.08	0.266
264A	66,900	*180,500*	0.90	*0.371*	30,841	47,000	0.88	0.656	37,500	91,700	0.75	0.409
264B[1]	32,800	78,626	0.75	0.417	22,638	39,500	0.80	0.573	762	3,400	0.78	0.224
264D	18,600	48,105	0.80	0.387	7,302	16,220	0.81	0.450	5,330	16,800	0.78	0.317
264E[1]	*15,000*	*22,880*	--	*0.656*	--	--	--	--	--	--	--	--
264J	*350*	*1,740*	--	*0.201*	3,349	13,360	0.85	0.251	661	2,680	0.50	0.247
264K	*2,190*	*6,800*	--	*0.322*	1,794	6,550	0.71	0.274	396	2,030	0.58	0.195
264M	*140*	*890*	--	*0.157*	2,687	7,270	0.61	0.370	1,270	4,500	0.67	0.282
264P	*80*	*840*	--	*0.095*	1,172	5,650	0.70	0.207	98	2,160	0.93	0.045
264Q	10,300	28,810	0.76	0.358	--	--	--	--	3,940	12,500	0.70	0.315
264R	195	2,182	0.79	0.089	--	--	--	--	732	3,460	0.43	0.212
264S	2,810	8,800	0.52	0.319	--	--	--	--	1,910	6,290	0.55	0.304
264T	12.3	761	2.56	0.016	--	--	--	--	1,030	4,650	0.52	0.222

Table B–1. Summary of water-quality data for the Goose Lake study site, Sheridan County, Montana.—Continued

[Summarized from table 1–1 (Preston and others, 2012). Onsite (field) water-quality data are in italics. Na^+/Cl^- molar ratio is the quotient of the Na^+ and Cl^- concentrations converted to molar equivalents. Contamination index is calculated by dividing Cl^- concentration (mg/L) by specific conductance value (µS/cm). Cl^-, chloride; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Na^+, sodium; --, no data]

Site name	1989				2005–2006				2009			
	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index
264Y	--	--	--	--	--	--	--	--	120	1,080	0.57	0.111
307B	*4,480*	*41,680*	--	*0.107*	--	--	--	--	4,050	66,600	8.76	0.061
BGWL	--	--	--	--	--	--	--	--	9	394	3.89	0.022
PW1	--	--	--	--	--	--	--	--	121,000	223,000	0.90	0.543
RAB2	--	--	--	--	1,578	5,050	0.62	0.312	975	3,970	0.52	0.246

Cl^- dominance in water with CI values above 0.1 and provide strong evidence of brine contamination. It should be noted that 6 of the 18 samples with CI values between 0.035 and 0.1 are in areas with little or no oil development; however, these samples were collected further south and east of the three study sites and, as discussed previously, the higher CI value may be because of regional changes across the PPR and Williston Basin.

To better define the water quality in the PPR, a combination of CI value, Cl^- concentration, and Na^+/Cl^- molar ratio was used to classify uncontaminated water and three levels of contaminated water (fig. B–2). Uncontaminated water has CI values less than 0.035, Cl^- concentrations generally less than 250 mg/L, and Na^+/Cl^- molar ratios generally above 1. Potentially contaminated water has CI values between 0.035 and 0.1, Cl^- concentrations generally less than 10,000 mg/L, and Na^+/Cl^- molar ratios generally less than 10. Moderately contaminated water has CI values between 0.1 and 0.35, Cl^- concentrations generally between 250 and 10,000 mg/L, and Na^+/Cl^- molar ratios generally less than 1. Extremely contaminated water has CI values greater than 0.35, Cl^- concentrations generally between 10,000 and 100,000 mg/L, and Na^+/Cl^- molar ratios less than 1. The five brine samples had CI values greater than 0.543, Cl^- concentrations greater than 109,000 mg/L, and Na^+/Cl^- molar ratios less than 1.

Goose Lake Study Site

Water was collected during 1989 from monitoring wells 126C and 264T within the study site and during 2009 from a wetland (BGWL) adjacent to the study site and upgradient from potential brine sources to represent background (CI less than 0.035) water for comparison with water samples that were collected from potentially contaminated wetlands and wells. Background Cl^- concentrations were low in samples collected from these three sources and did not exceed 13 mg/L. Nearly all other major-ion and trace-element concentrations in the background water samples were much lower than the concentrations in the contaminated water samples. In 2009, water (PW1) was collected to determine the chemistry of the brine from an oil/brine separation tank located at the tank battery (264) within the study area that receives oil and brine from wells producing from the Ratcliffe Formation.

Monitoring wells with background water samples in 1989 had become moderately contaminated by 2009 (table B–1). Well 126C is adjacent to a pipeline break that occurred in 2006. In 1989, the Cl^- concentration and CI value of water from 126C were 6.6 mg/L and 0.005, respectively. By 2009, the Cl^- concentration and CI value measured in water from this well were 964 mg/L and 0.266, indicating that brine had affected the groundwater quality at this site. Well 264T is along a groundwater-flow path mapped by Reiten and Tischmarck (1993) that flows from the tank battery to West Goose Lake, a large saline lake that occupies a topographically low point and is the likely groundwater discharge area for the Goose Lake study site. The respective Cl^- concentration and CI

Table B–2. Summary of water-quality data for the Anderson study site, Sheridan County, Montana.

[Summarized from table 1–2 (Preston and others, 2012). Onsite (field) water-quality data are in italics. Na^+/Cl^- molar ratio is the quotient of the Na^+ and Cl^- concentrations converted to molar equivalents. Contamination index is calculated by dividing Cl^- concentration (mg/L) by specific conductance value (µS/cm). Cl^-, chloride; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Na^+, sodium; --, no data]

Site name	2004–2005				2010			
	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contamination index
A-1MW	4.59	902	16.70	0.005	7.05	1,300	14.11	0.005
A-2MW	18,770	36,800	0.92	0.510	13,600	37,300	0.96	0.365
A-4MW	4,954	13,670	0.79	0.362	3,490	13,100	0.91	0.266
A-8MW	4,789	13,480	0.48	0.355	6,110	18,400	0.41	0.332
A-10MW	341	22,000	23.55	0.016	323	29,400	34.43	0.011
A-11MW	360	24,800	21.35	0.015	798	37,900	11.62	0.021
A-14MW	43,213	52,500	0.58	0.823	56,600	115,000	0.56	0.492
A-15MW	163	23,600	60.78	0.007	133	26,600	11.59	0.005
A-16MW	10,612	21,900	0.44	0.485	23,900	56,400	0.42	0.424
A-17MW	2,542	9,340	0.74	0.272	3,010	11,700	0.64	0.257
AND4	*31,660*	*68,366*	--	*0.463*	19,100	48,100	0.75	0.397
AND8	*2,589*	*26,286*	--	*0.098*	1,360	17,800	3.72	0.076
AND9	*12,948*	*89,693*	--	*0.144*	1,790	18,800	3.15	0.095
AND10	*9*	*260*	--	*0.034*	7.37	235	0.60	0.031
AND11	*6,550*	*44,819*	--	*0.146*	6,100	18,000	0.63	0.339
AND-PW	--	--	--	--	149,000	229,000	0.82	0.651

Table B–3. Summary of water-quality data for the Fuller study site, Williams County, North Dakota.

[Summarized from table 1–3 (Preston and others, 2012). Na^+/Cl^- molar ratio is the quotient of the Na^+ and Cl^- concentrations converted to molar equivalents. Contamination index is calculated by dividing Cl^- concentration (mg/L) by specific conductance value (µS/cm). Cl^-, chloride; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Na^+, sodium]

Site name	2010			
	Cl^-, mg/L	Specific conductance, µS/cm	Na^+/Cl^- molar ratio	Contmination index
FULL-A	25.3	683	1.46	0.037
FULL-B	181	3,780	2.16	0.048
FULL-MW1	350	24,100	15.82	0.015
FULL-MW2	154	3,500	1.85	0.044
FULL-PWB1	199,000	251,000	0.64	0.793
FULL-PWB2	198,000	241,000	0.70	0.822
FULL-PWR	109,000	188,000	0.65	0.580

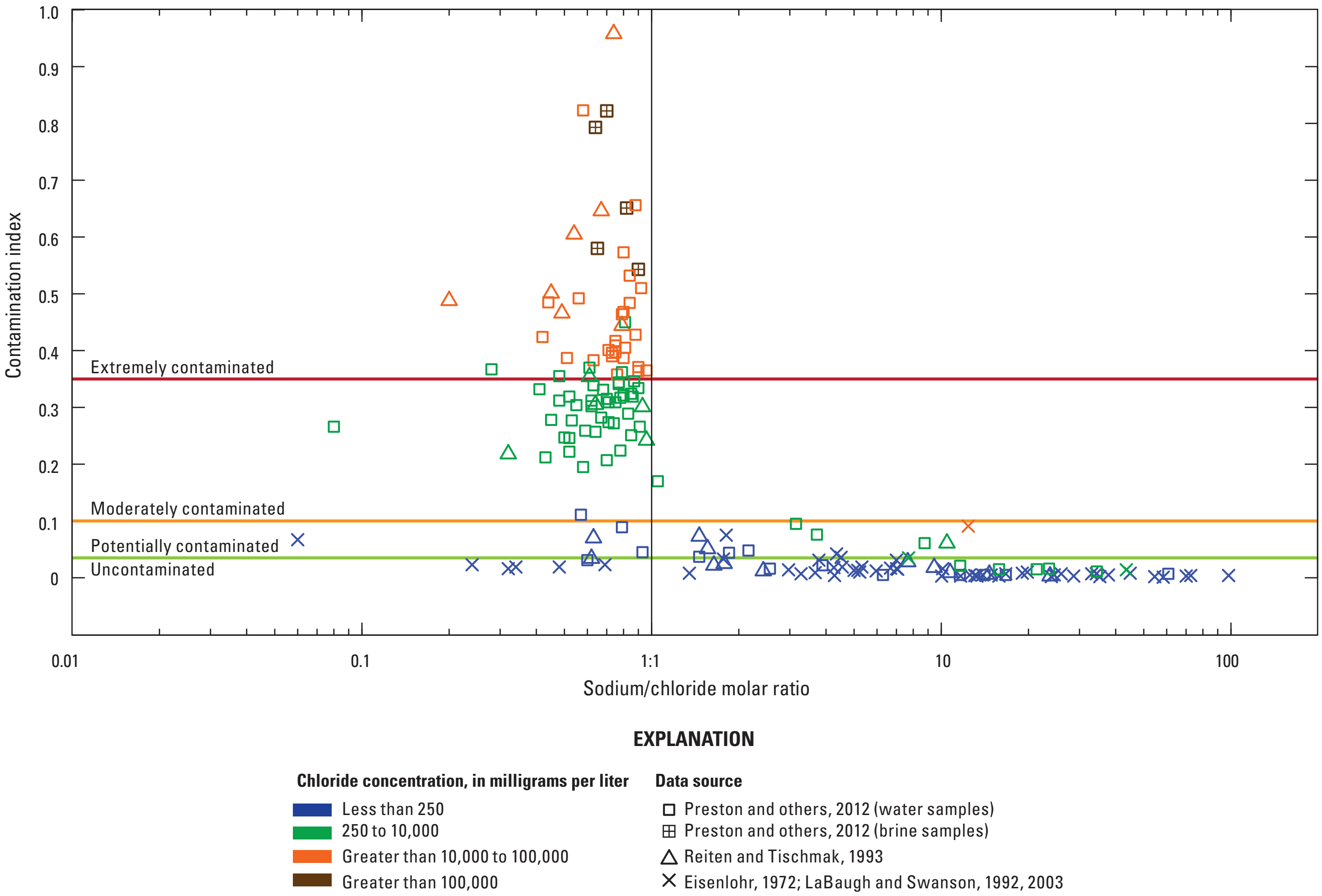
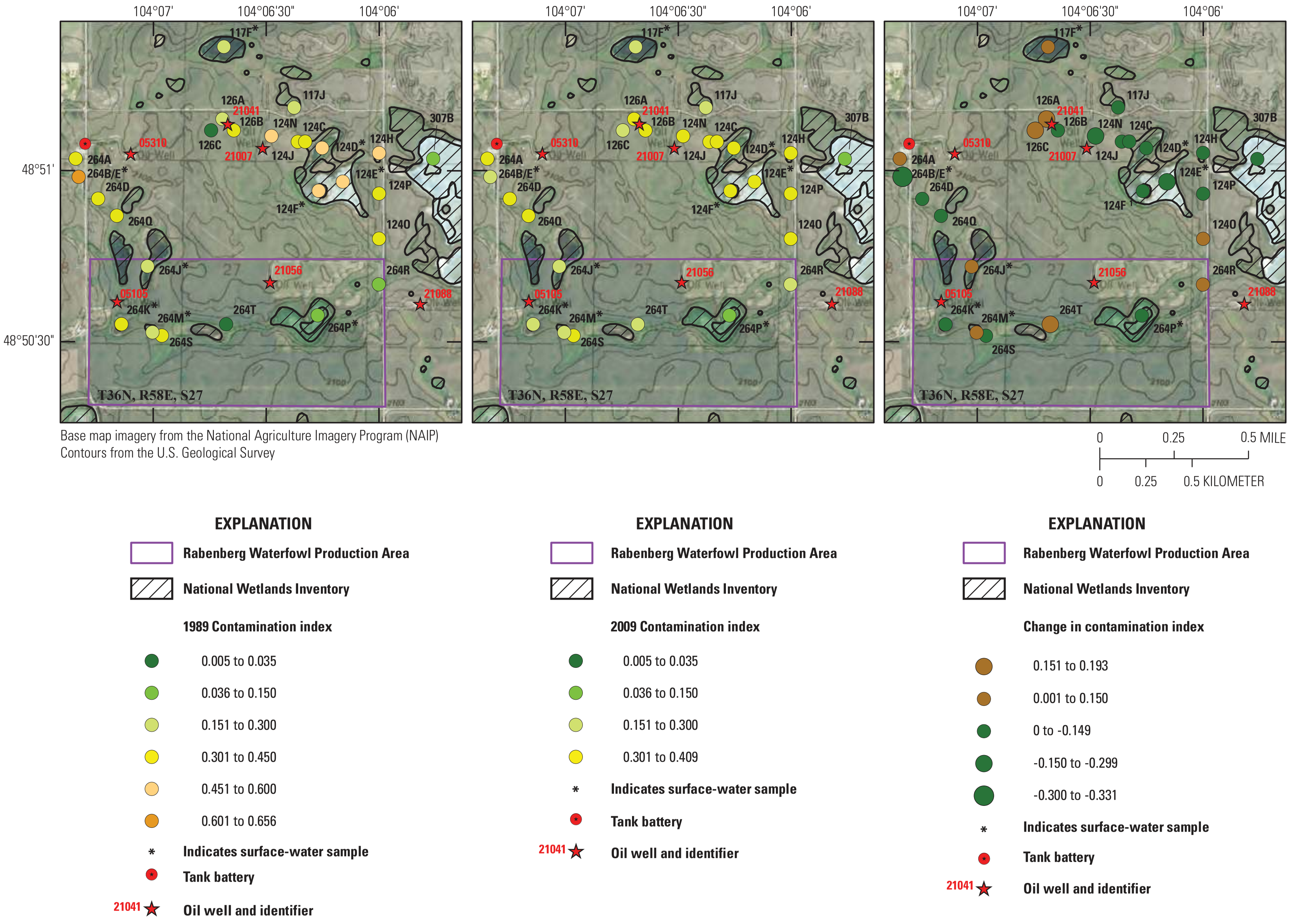


Figure B–2. Sodium/chloride molar ratio compared to contamination index for 96 water-quality samples and 5 brine samples.

value of water from 264T were 12.3 mg/L and 0.016 in 1989. By 2009, the Cl^- concentration and CI value of water from this well were 1,030 mg/L and 0.222, indicating that brine had migrated further along the groundwater-flow path to this well during the 20-year time period.

Surface water and shallow groundwater contaminated by brine in 1989 were still contaminated by brine in 2009 (fig B–3, table B–1). The CI values for water samples collected in 1989 (except for 126C and 264T) were between 0.089 and 0.532 and generally decreased with distance downgradient from active and abandoned oilfield sites. The CI values for water samples from West Goose Lake were greater than 0.035 in 1989 (0.107) and 2009 (0.061), indicating that West Goose Lake likely has been contaminated for at least two decades. As indicated by the CI values, only two sites sampled in 1989—monitoring wells 126C and 264T, had water that was not contaminated with brine. The CI values for water samples collected in 2009 were between 0.022 and 0.409, indicating that water from all sampled sites except BGWL was contaminated. Between 1989 and 2009, the CI increased in nine of the sampled sites. Although CI values decreased in 18 sites, the CI values were still elevated, indicating that the brine contamination has persisted in the environment during a two-decade period. However, much of the contamination is likely from leachates generated from reserve pits located at each oil well site and at the tank battery that collects the produced fluids (Reiten and Tischmak, 1993). The oil wells and tank battery were installed in the mid- to late-1960s; therefore, contamination has likely persisted in this environment for as many as four to five decades.

Statistically, there is a significant difference in the Cl^- concentrations, specific conductance, and CI values of water sampled from locations contaminated by brine in 1989 and 2009. A Kolmogorov-Smirnov normality test determined the changes in these parameters were not normally distributed, requiring a nonparametric analysis. The difference in median Cl^- concentrations, specific conductance, and CI values between 1989 and 2009 is nonzero (respective two-sided p-values = 0.006, 0.038, and 0.032 from a Wilcoxon signed rank test with V stats of 39, 56, and 54). The respective estimated reduction in median Cl^- concentration, specific conductance, and CI value are -4,850 mg/L, -8,513.5 µS/cm, and -0.047, with 95 percent confidence intervals of -8,885–-888 mg/L, -16,906.5–-595.1 µS/cm, and -0.087–-0.002, indicating that the magnitude of brine contamination has slightly decreased during the two-decade period.



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–3. Goose Lake study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Rabenberg Waterfowl Production Area, and the 1989 contamination index values, 2009 contamination index values, and the change in contamination index values.

The likely source of brine to surface water and shallow groundwater in the Goose Lake study site is produced waters from the Ratcliffe Formation, as indicated by Sr isotope analyses of 14 water samples from an oil/brine separation tank, surface-water bodies, and shallow monitoring wells (Preston and others, 2012, table B–1). An evaporation-mixing model was developed to interpret the Sr isotope relations of surface water and shallow groundwater at the Goose Lake study site (Peterman and others, 2012). The model is shown on figure B–4 with $^{87}Sr/^{86}Sr$ ratios plotted as a function of Sr concentration on a log axis. In surface water and shallow groundwater, these parameters can be modified by evaporation (indicated by increases in solute concentrations, but no change in $^{87}Sr/^{86}Sr$ values) and the mixing of end members, which can change solute concentrations and $^{87}Sr/^{86}Sr$. The shaded area on figure B–4 is the mixing field at the Goose Lake study site as defined by samples of surface water, shallow groundwater, and brine. The horizontal line near the top of the graph depicts the effects of evaporation, increasing Sr concentration while maintaining the $^{87}Sr/^{86}Sr$ values. In the evaporation-mixing model, this line is assumed to be the loci of least contaminated samples. The curved lines are mixing lines calculated from the Goose Lake brine sample (PW1, produced with oil from the Ratcliff Formation), through the samples with largest and smallest Sr concentrations, to intersect the evaporation line at the top of the graph. The area within these lines contains all of the Goose Lake samples analyzed and is labeled "Goose Lake Mixing Field." As discussed by Peterman and others (2012), the process of moving a sample composition from the upper part of the graph towards the brine composition may involve evaporation, brine contamination, and dilution with freshwater, perhaps repeated multiple times. The net effect of these processes is the migration of compositions towards the brine as reflected by the position of the samples on the graph and by the CI values. Using the evaporation-mixing model from the Goose Lake study site as the basis for comparison, the Sr isotope and concentrations relations for the Anderson and Fuller sites are discussed below.

Contaminated shallow groundwater has migrated at least 600 and 800 m along two separate groundwater-flow paths in the Goose Lake study site, and possibly as far as 1,600 m. There are two main groundwater-flow paths in the Goose Lake study site; one in the northern part and one in the southern part. In the northern part of the study area, groundwater flows generally eastward from wetland 117F and well 126C through monitoring wells 124H, 124P, and 124O. In the southern part of the study area, groundwater flows southward from the tank battery near groundwater well 264A, then eastward near wetland 264K though monitoring well 264R. Both of these groundwater-flow paths likely discharge into West Goose Lake. West Goose Lake was moderately contaminated in 1989 and potentially contaminated in 2009, with respective Cl^- concentrations of 4,480 and 4,050 mg/L and CI values of 0.107 and 0.061. The contamination in West Goose Lake is likely from the brine source(s) within the northern flow path, the brine source(s) within the southern flow path, or a combination from all sources. However, in 1989 and 2009, the Cl^- concentrations in the furthest downgradient wells in the northern flow paths—124H (36,500 and 19,500 mg/L, respectively), 124P (16,300 and 4,370 mg/L, respectively), and 124O (7,840 and 17,200 mg/L, respectively) —were much greater than the furthest downgradient well in the southern flow path—264R (195 and 732 mg/L, respectively). Therefore, if volume of groundwater discharge to West Goose Lake is similar from the northern and southern flow paths, then the more saline northern flow path likely has the greater effect to West Goose Lake.

Potential sources of brine along the northern groundwater-flow path include oil wells 21041 (126) and 21007 (124). In 1989, 2006, and 2009, all surface water and groundwater samples (except 126C in 1989) had CI values equal to or greater than 0.170 and Cl^- concentrations equal to or greater than 450 mg/L (table B–1), indicating moderate to extreme brine contamination throughout the entire flow path (fig. B–5). Therefore, it is unclear if the source of brine in West Goose Lake (307B) is oil well 21007 (124), oil well 21041 (126), or both. However, the approximate distances that groundwater would have to migrate along the northern flow path to reach the western shore of West Goose Lake is 800 m from oil well 21007 (124) and 1,100 m from oil well 21041 (126).

Potential sources of brine along the southern groundwater flow-path include a tank battery and oil wells 05105 (127) and 21056 (128). Respective CI values and Cl^- concentrations in all surface water and groundwater samples (except 264T in 1989 and BGWL in 2009) ranged from 0.089 to 0.656 and 80 to 66,900 mg/L in 1989, 0.207 to 0.656 and 1,172 to 47,000 mg/L in 2005, and 0.111 to 0.409 and 98 to 37,500 mg/L in 2009 (table B–1), indicating potential to extreme brine contamination throughout most of this flow path (fig. B–6). The presence of oil wells 05105 (127) and 21056 (128) make identifying the source(s) and distance of contaminant migration throughout this flow path difficult, especially between the tank battery and 264T. Monitoring well 264T was not contaminated in 1989 while wetland 264P, monitoring well 264R, and West Goose Lake (307B) were contaminated, indicating that the likely brine source downgradient from 264T in 1989 was from oil well 21056 (128). The distance along the southern flow path from oil well 21056 (128) through 264P to 264R is approximately 700 m, and approximately 1,000 m to the western shore of West Goose Lake. However, 264T had become moderately contaminated in 2009 (CI value of 0.222), and the brine source(s) between oil well 05105 (127) to 264T could be from the tank battery, this oil well, or both. Separating out these sources is further complicated as the relative trends in CI values up- and downgradient from oil well 05105 (127) change through time. In 1989 and 2005, the CI value increases between upgradient 264J and downgradient 264K, but the CI value decreases between these two sites in 2009. Therefore, while the brine source at 264T is unclear, the respective distances along the southern flow path to 264T from oil well 05105 (127) and the tank battery are approximately 600 and 1,600 m. Lastly, it should be noted that the contaminated groundwater has likely migrated beyond 264T, so these distances represent a minimum transport distance.

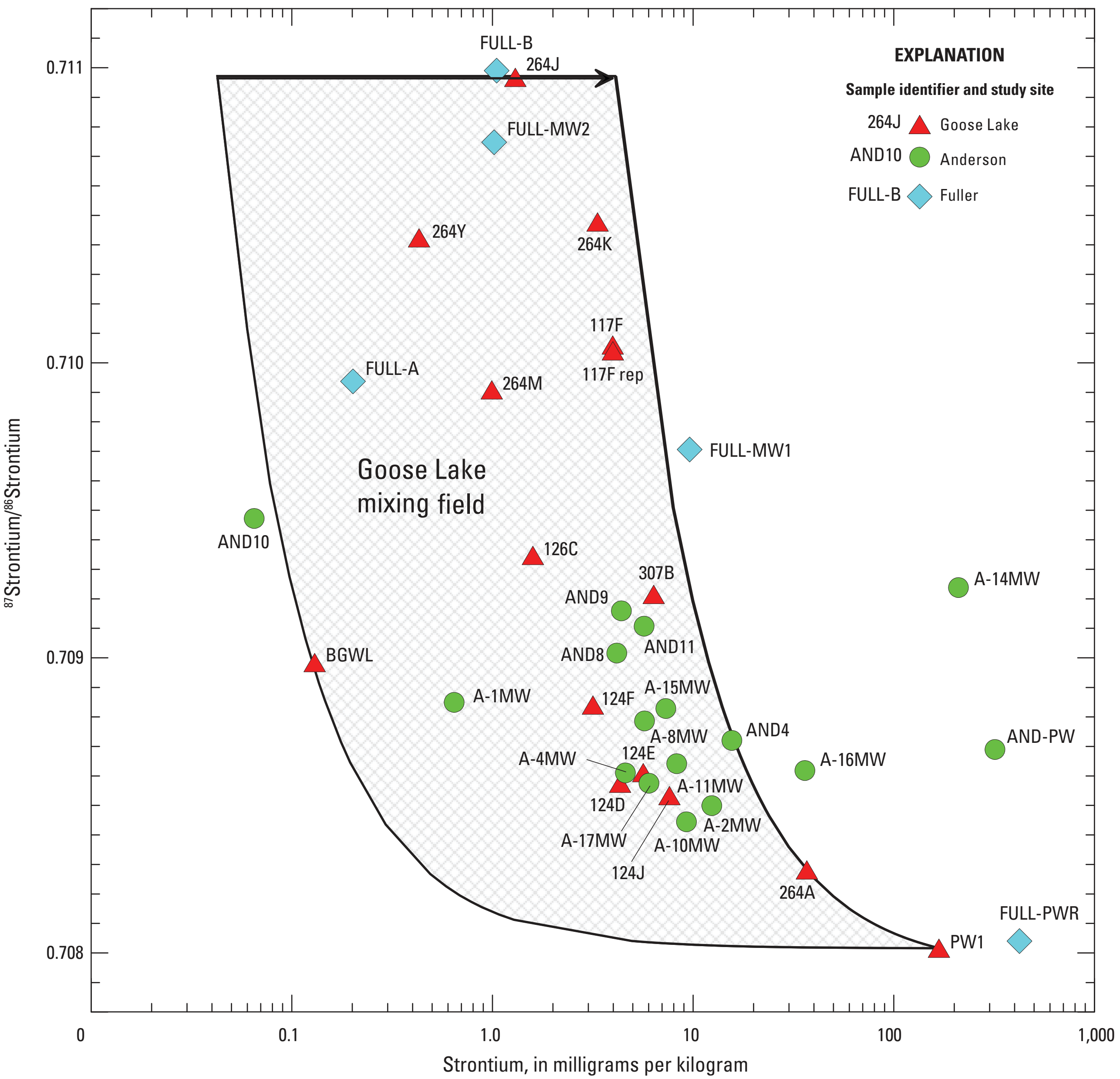


Figure B–4. Strontium (Sr) concentration compared to $^{87}Sr/^{86}Sr$ values for water samples from all three study sites: Goose Lake, Anderson, and Fuller.

Anderson Study Site

Water was collected during 2005 and 2010 from a monitoring well (A–1MW) within the study site and upgradient from potential brine sources to represent background water quality and to compare with water samples that were collected from contaminated wetlands and wells. Water was collected during 2010 from an oil/brine separation tank (AND– PW) located at the tank battery within the WPA that receives oil and brine from nearby oil wells and was assumed to represent brines from the Ratcliffe Formation. However, based on the Sr isotope data and the producing formations of nearby oil wells, the brine sampled in AND– PW likely represents, in part, the Nisku or Red River Formations.

Uncontaminated water (CI less than 0.035) was collected during 2005 and 2010 from three monitoring wells (A–10MW, A–11MW, and A–15MW) in addition to background monitoring well A–1MW (table B–2). Cl^- concentrations did not exceed 360 mg/L in these samples. Water from A–1MW (background site) contained concentrations of major ions and trace elements that were much lower than the concentrations in any other samples. During 2005 and 2010, water from A–10MW and A–11MW contained relatively higher concentrations of most major ions and trace elements except for Cl^-, which, along with specific conductance, is used as the

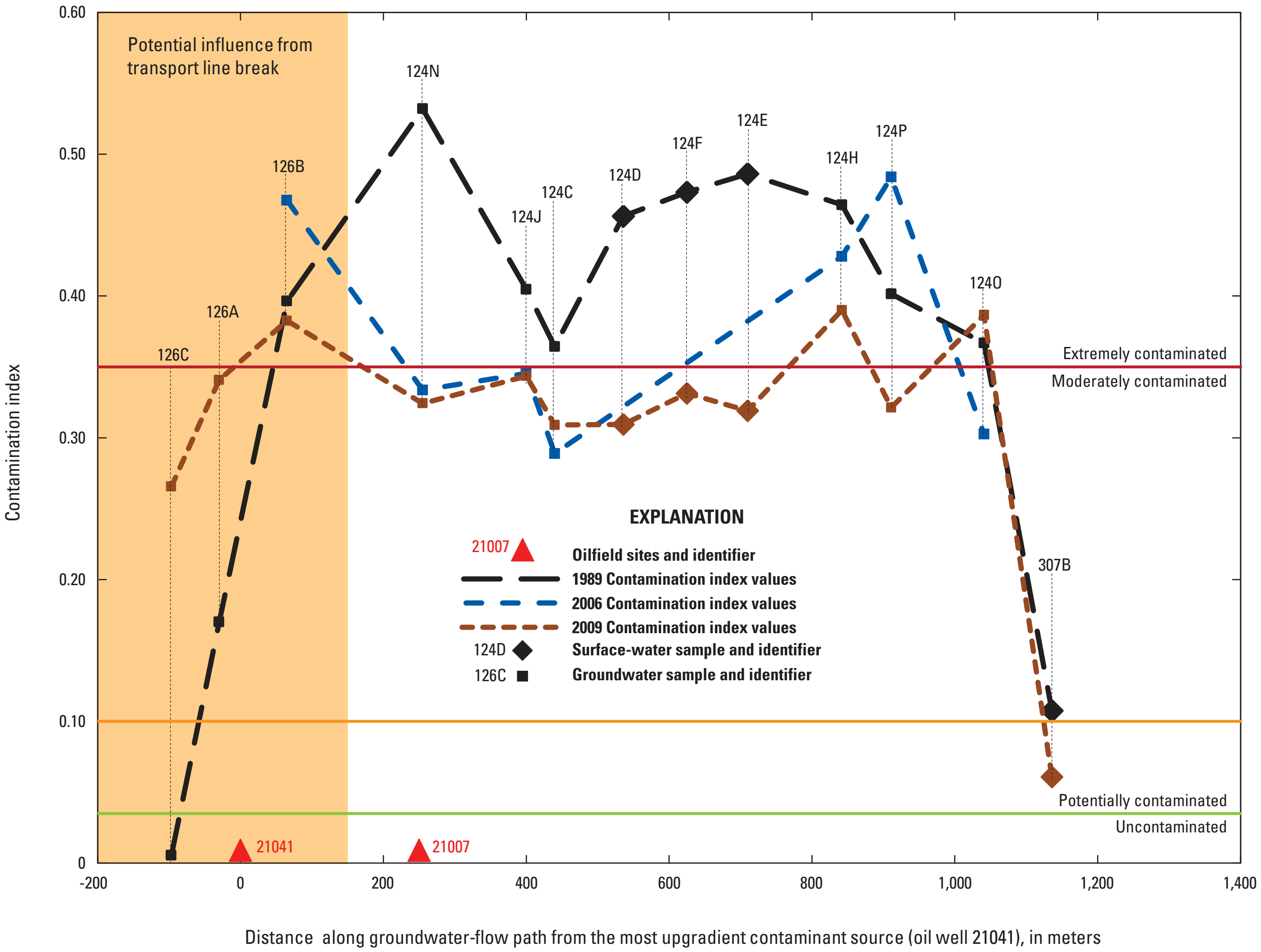


Figure B–5. Contamination index values of surface water and groundwater samples from 1989, 2006, and 2009 plotted by distance from the most upgradient brine source (oil well 21041) in the northern groundwater-flow path at the Goose Lake study site.

indicator for brine contamination. These two wells are located along a potential flow path. Analyses of water from A–11MW during 2010 indicated that the Cl^- concentration and CI value had increased from 2005; however, the CI value was still below 0.035. Monitoring well A–15MW is adjacent to an oil well and reserve pit, yet the CI values in 2005 and 2010 were below 0.035.

All surface-water and shallow groundwater sites with CI values indicating brine contamination in 2004–5 still had CI values greater than 0.035 in 2010 (fig. B–7, table B–2). The CI values for water samples collected in 2004–5 were between 0.005 and 0.823 and generally decreased with distance downgradient from potential sources of brine. The CI values for water samples collected in 2010 were between 0.005 and 0.492 and, compared to 2004–5, had decreased at 11 sites and increased or stayed the same at 4 sites, indicating that the brine has persisted in the environment during the 5–6-year period. Similar to the Goose Lake site, much of the contamination is likely from leachates generated from the reserve pits located at each oil well site and the tank battery that collects the produced fluids (Reiten and Tischmak, 1993). The oil wells and tank battery within the Anderson WPA were installed in the mid- to late-1960s, indicating that contamination likely has persisted in this environment for as many as four to five decades.

Statistically, there was no significant difference in the Cl^- concentrations, specific conductance, or CI values of water sampled from locations contaminated by brine in 2004–5 and 2010. A Kolmogorov-Smirnov normality test determined that these parameters were not normally distributed, requiring nonparametric analyses. The difference in median Cl^- concentrations, specific conductance, or CI values between 2004–5 and 2010 is nonzero (respective two-sided p-values equal 0.432, 0.160, and 0.232 from a Wilcoxon signed rank test with V statistics of 36, 42, and 15), indicating that the magnitude of brine contamination has not changed significantly over the 5–6-year period.

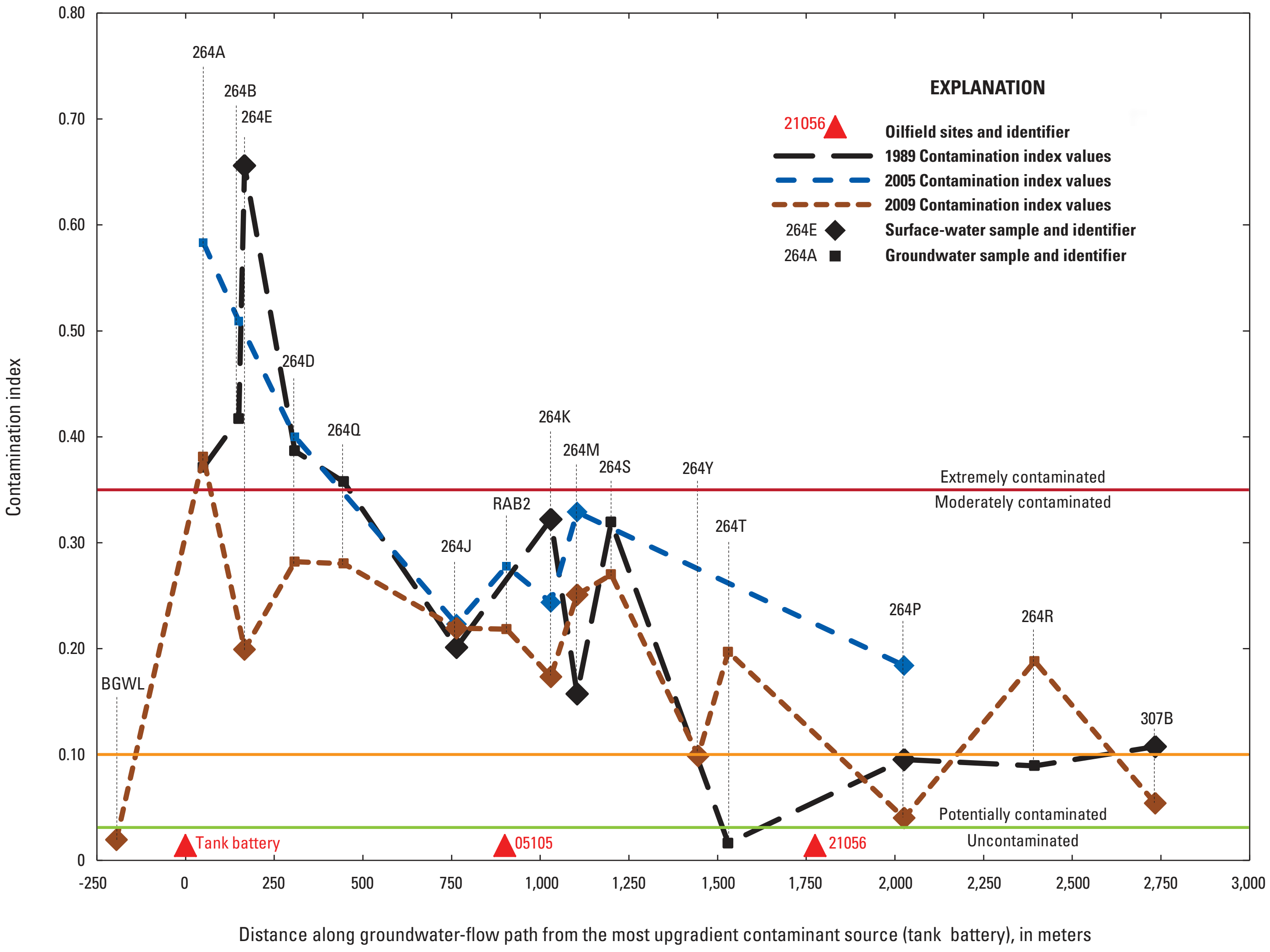
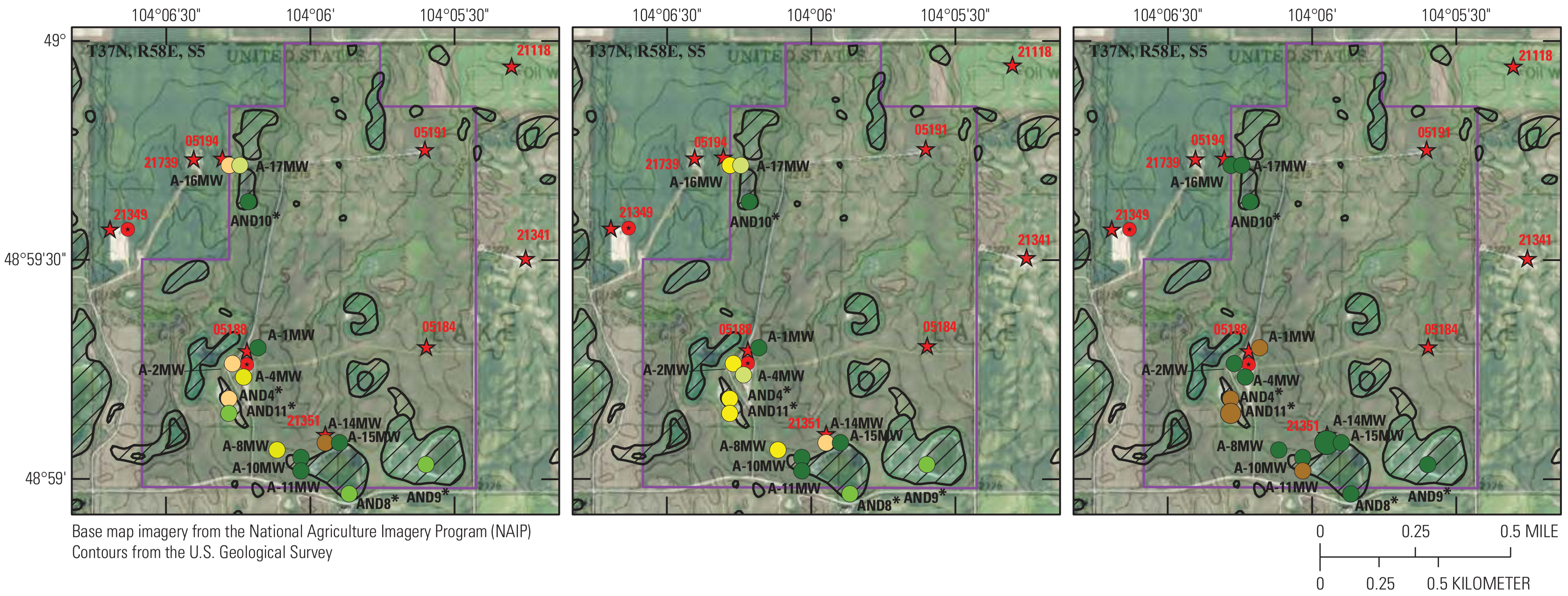


Figure B–6. Contamination index values of surface water and groundwater samples from 1989, 2005, and 2009 plotted by distance from the most upgradient brine source (tank battery) in the southern groundwater-flow path at the Goose Lake study site.

The likely source of much of the brine to surface water and shallow groundwater in the Anderson study site is produced waters from the Ratcliffe Formation, as indicated by Sr isotope analyses of 16 water samples from surface-water bodies, shallow monitoring wells, and an oil/brine separation tank (Preston and others, 2012, table B–2). The Sr concentration and ^{87}Sr/^{86}Sr values for most of Anderson samples plot within or very close to the ^{87}Sr/^{86}Sr values for the Goose Lake model (fig. B–4). Wetland sample AND10 has the lowest concentration of Sr (0.065 mg/L) and plots just to the left of the other Anderson samples. The sample from monitoring well A–16MW has the third highest concentration of Sr (36 mg/L) and, therefore, plots just to the right of most Anderson samples in figure B–4. Greater departure from the Goose Lake model is shown by monitoring well A–14MW with the highest Sr concentration (210 mg/L) and a ^{87}Sr/^{86}Sr value of 0.70924. However, the oil well adjacent to A–14MW (21351) never produced; therefore, the fluids in the reserve pit were likely derived predominantly during drilling through younger stratigraphic units, which may explain the discordance with other Anderson samples. The produced water sample (AND–PW) is similar in Sr concentration to A–14MW but has a ^{87}Sr/^{86}Sr value (0.70869) significantly larger than that of the brine sample from Goose Lake (PW1=0.70802). The ^{87}Sr/^{86}Sr value of AND–PW is larger than some of the Anderson surface-water and shallow groundwater samples; thus, AND–PW cannot have been the end member that affected samples with smaller ^{87}Sr/^{86}Sr values. Rather, the locations of Anderson samples on figure B–4 are consistent with mixing with a produced water component similar to the Goose Lake sample (PW1). The brine sample AND–PW was collected from a tank battery, which represents an aggregate sample of brines produced from numerous wells. It is likely this sample is a mixture of brines from multiple stratigraphic units, with some of these brines having a greater ^{87}Sr/^{86}Sr value. Although the oil wells that supply oil and brine to the tank battery are



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

EXPLANATION

▭ **Anderson Waterfowl Production Area**

▨ **National Wetlands Inventory**

2004–5 Contamination index

● 0.005 to 0.035

● 0.036 to 0.150

● 0.151 to 0.300

● 0.301 to 0.450

● 0.451 to 0.600

● 0.601 to 0.750

● 0.751 to 0.829

* **Indicates surface-water sample**

● **Tank battery**

21349 ★ **Oil well and identifier**

EXPLANATION

▭ **Anderson Waterfowl Production Area**

▨ **National Wetlands Inventory**

2010 Contamination index

● 0.005 to 0.035

● 0.036 to 0.150

● 0.151 to 0.300

● 0.301 to 0.450

● 0.451 to 0.492

* **Indicates surface-water sample**

● **Tank battery**

21349 ★ **Oil well and identifier**

EXPLANATION

▭ **Anderson Waterfowl Production Area**

▨ **National Wetlands Inventory**

Change in contamination index

● 0.151 to 0.193

● 0.001 to 0.150

● 0 to -0.149

● -0.150 to -0.299

● -0.300 to -0.331

* **Indicates surface-water sample**

● **Tank battery**

21349 ★ **Oil well and identifier**

Figure B–7. Anderson study site showing the location of water samples, oil wells, tank batteries, National Wetlands Inventory wetlands, and the Anderson Waterfowl Production Area, and the 2004–5 contamination index values, 2010 contamination index values, and the change in contamination index values.

unknown, the nearest producing oil well, 21712 (not shown on fig. B–7, approximately 0.5 km west of the WPA) produces from the Nisku and Red River Formations, not the Ratcliffe Formation, which was the producing unit for the oil wells in the Anderson WPA. Qing and others (2001) reported an average ^{87}Sr/^{86}Sr value of 0.7086 for the matrix dolomite in the Red River Formation, very similar to the ^{87}Sr/^{86}Sr value of AND–PW (0.70869).

Contaminated groundwater has migrated at least 400 m in the Anderson study site and possibly as far as 1,200 m (fig. B–8). These are the greatest distances between the potential source (oil well or tank battery) and the most downgradient contaminated monitoring well or wetland. Groundwater generally flows southward from A–1MW, then eastward near A–8MW towards AND8 and AND9; the likely discharge points of this groundwater-flow path. Monitoring well A–8MW is approximately 400 m from a tank battery and oil well (05188), while wetland AND9 is approximately 1,200 m from these same facilities. Water from monitoring wells A–10MW and A–11MW was uncontaminated in 2004 and 2010 indicating that contamination from the tank battery or oil well 05188 likely did not reach these wetlands through groundwater flow. However, water samples from wetlands AND8 and AND9 were moderately or potentially contaminated in 2004 and 2010 (AND8 CI value = 0.098 and 0.076, respectively; AND9 CI value = 0.144 and 0.095, respectively) but have lower ^{87}Sr/^{86}Sr values than A–14MW, which is partially completed in the reserve pit of oil well 21351 and located directly above the basin of wetland AND8; thus, the buried reserve pit at oil well 21351 cannot be the sole brine source for wetlands AND8 and AND9. Two other oil wells completed in the Ratcliffe Formation (21361 and 05174 and not shown on fig. B–7) are located approximately 0.3 km to the south of wetlands AND8 and AND9 and may be the source of brine in these wetlands. Therefore, while the brine source in wetland AND9 is unclear, if the source is the tank battery or oil well 05188, it would represent a migration distance of approximately 1,200 m.

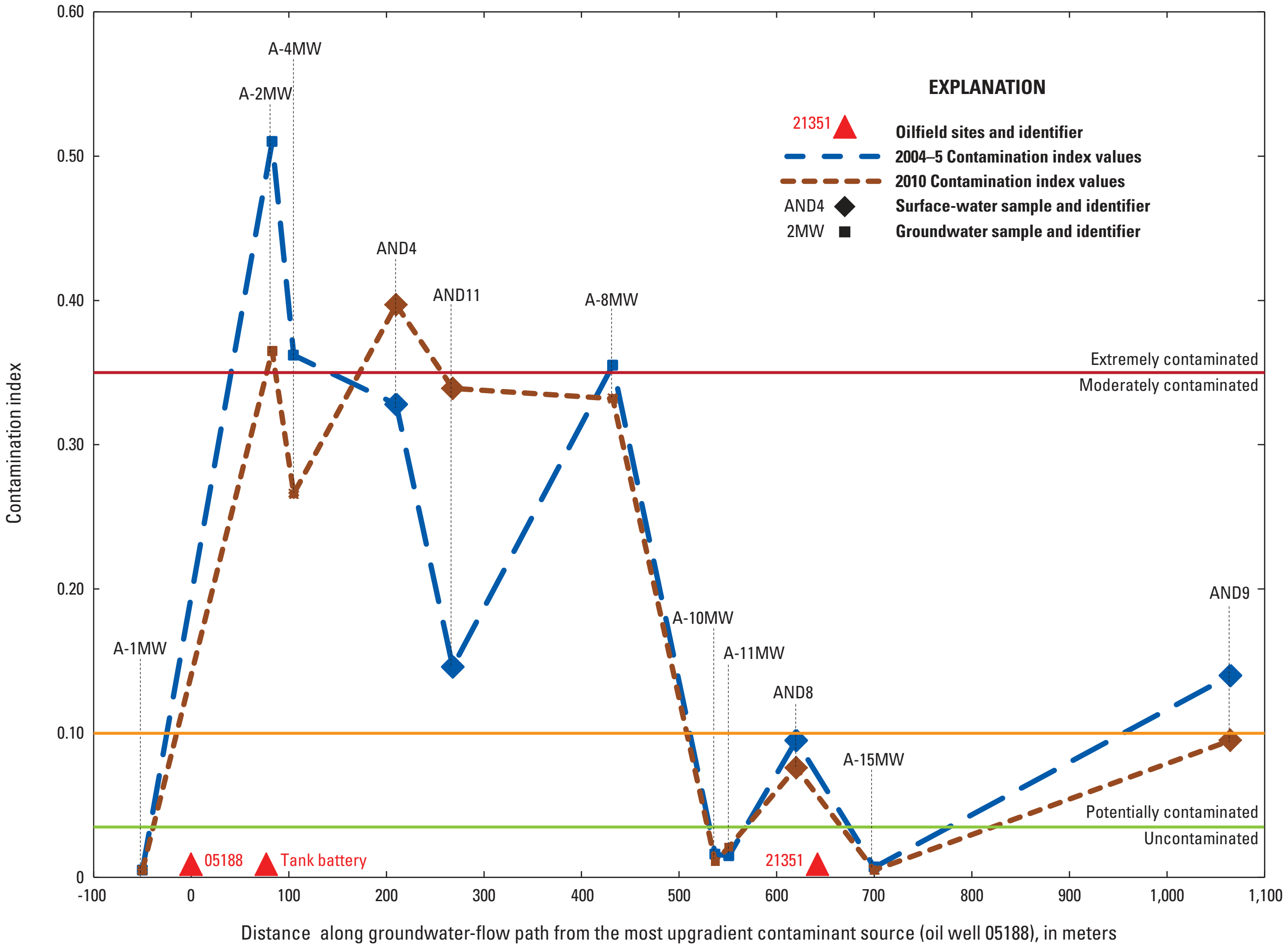


Figure B–8. Contamination index values of surface water and groundwater samples from 2004–5 and 2010 plotted by distance from the most upgradient brine source (oil well 05188) in the groundwater-flow path at the Anderson study site.

Fuller Study Site

Water was collected from one monitoring well (FULL–MW1) during 2010 that was thought to be unaffected by oil and gas activities but had unusual major ion chemistry. Although this well had the lowest CI value (0.015), the Cl^- concentration at this well (350 mg/L) was higher than concentrations in water from the three other surface-water and shallow groundwater sites that were sampled (range 25–181 mg/L; table B–3). However, water from FULL–MW1 contains higher concentrations of other major ions such as Na^+, magnesium, and SO_4^{2-}, indicating that this water type is unique from the other sample sites.

Based on the CI values, three of the four surface-water and shallow groundwater samples from the Fuller study site were potentially contaminated by brine in 2010 (table B–3, fig. B–9). The CI values for the three other water samples besides FULL–MW1 were between 0.037 and 0.048 and were highest in the wetland (FULL–B) below the reservoir (where sample FULL–A was collected).

The distance of contaminated groundwater migration is not possible to determine at the Fuller study site because of the limited number of sample sites and understanding of groundwater-flow flow paths. Surface-water sample site FULL–A is upgradient from potential brine sources within the Fuller study site, so a potential source to this site is likely located off the study site and upgradient from the reservoir.

Sr isotopes and concentrations of samples from the Fuller study site (Preston and others, 2012, table B–3) are consistent with the Goose Lake evaporation-mixing model (fig. B–4) and indicate possible brine contamination despite the relatively low CI values. Sample FULL–B plots close to Goose Lake sample 264J, which was used to show an evaporation line at the top of the field. The sample from monitoring well FULL–MW1 (9.6 mg/L Sr) plots slightly to the right of the Goose Lake field. The Fuller produced waters sample (FULL–PWR) is isotopically similar to PW1, the brine from Goose Lake, but the Sr concentration at 423 mg/L is larger. If FULL–PWR was used as an end member for a Fuller mixing plot, FULL–MW1 would plot within the field. The isotopic similarity of PW1 and FULL–PWR lends credence to the interpretation that the brine sample from Anderson (AND–PW) is not representative of the Ratcliffe Formation based on the elevated $^{87}Sr/^{86}Sr$ value.

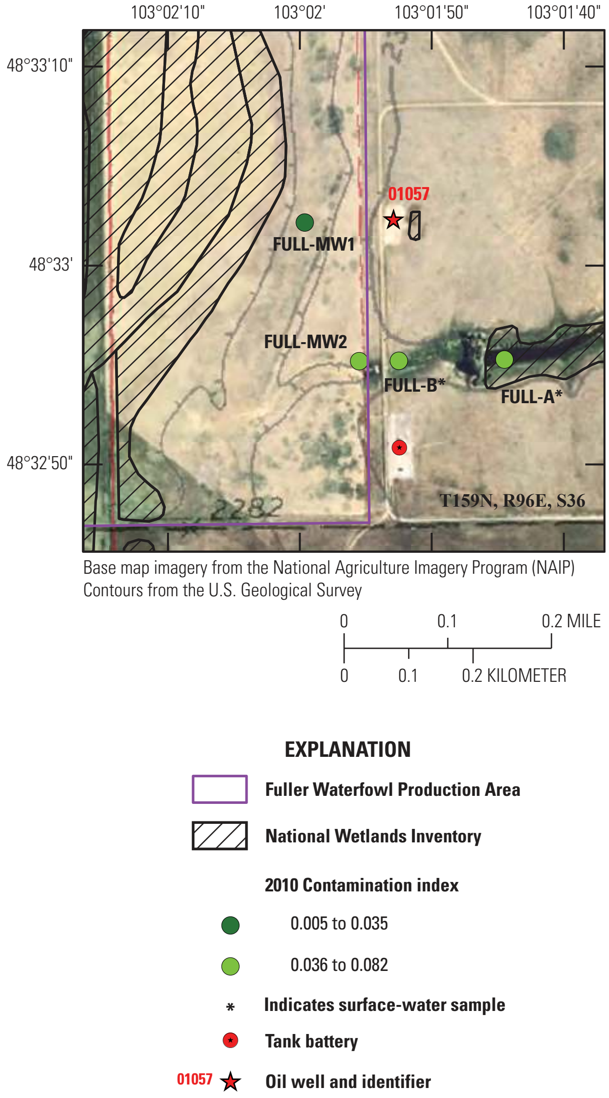


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Figure B–9. Fuller study site showing the locations of water samples, oil well 01057, tank battery, National Wetlands Inventory wetlands, the Fuller Waterfowl Production Area boundary, and the contamination index values from 2010.

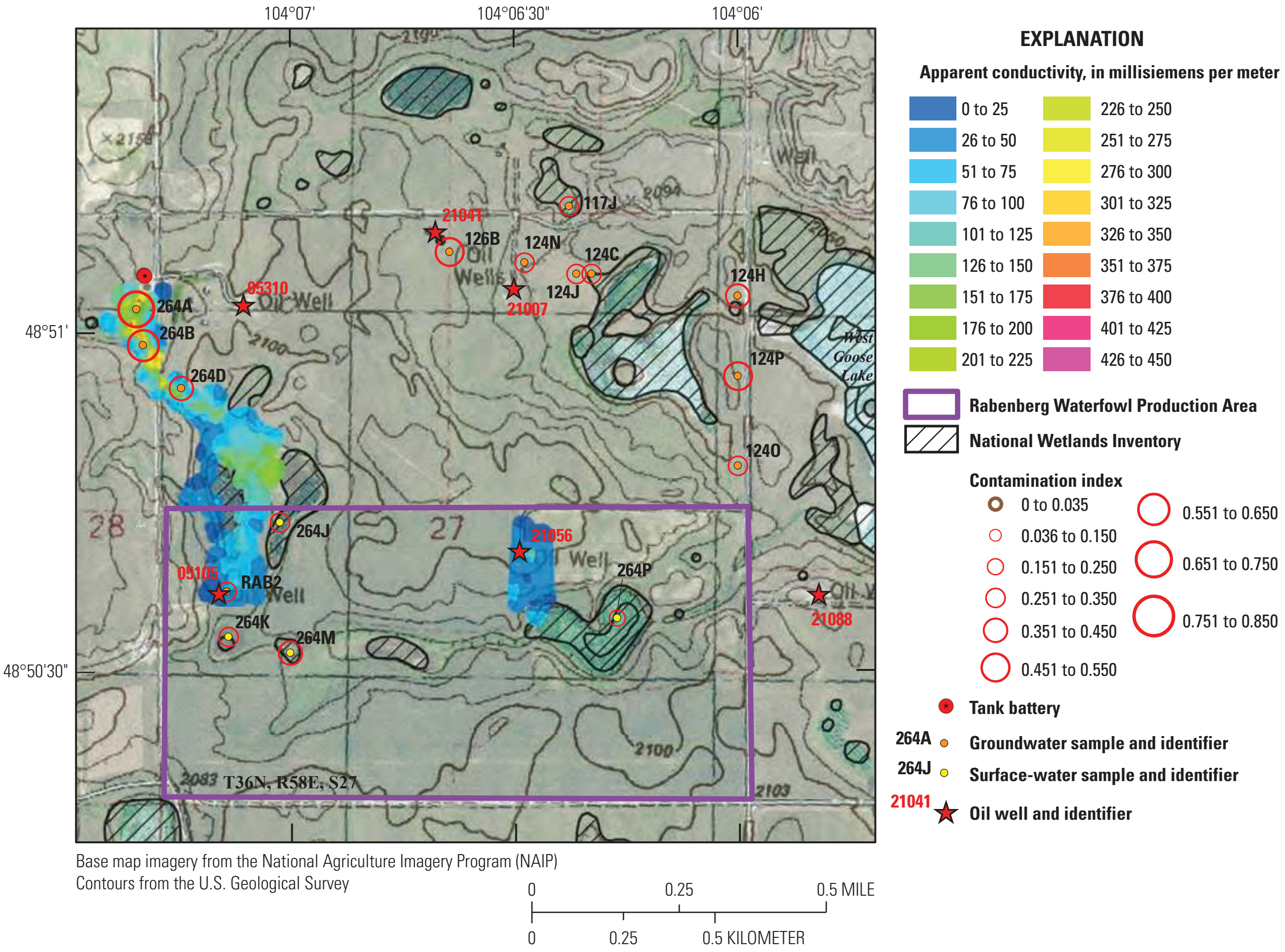
Geophysical Surveys

Geophysical results in 2004, 2009, and 2010 compared well to groundwater chemistry results, with elevated apparent conductivity readings (greater than 50 mS/m) measured near the majority of monitoring wells with high Cl^- concentrations (greater than 250 mg/L) and CI values (greater than 0.035). The presence of elevated apparent conductivities associated with brine contamination validates the use of EM surveys to delineate brine plumes. However, it should be noted that apparent conductivity increases with clay content and soil saturation, often resulting in elevated apparent conductivity in and around wetland basins. Additionally, the shallow exploration depth of the EM–31 (roughly 6 m) can make it highly susceptible to changes in the depth to the water table that commonly develop in areas of undulating topographic relief (Reiten and Tischmak, 1993). This resulted in elevated conductivities measured only when the water table was within the exploration depth of the EM–31. Finally, it should be noted that the apparent conductivity scales on the figures displaying geophysical data (figs. B–10 through B–18) are equivalent for different geophysical equipment within each study site, but differ between study sites.

Goose Lake Study Site

EM–31 Geophysical Surveys

Several areas of elevated conductivities associated with brine plumes were delineated in the EM–31 surveys at the Goose Lake study site in 2004 and 2009 (figs. B–10, B–11). A brine plume emanating from the tank battery (264) and migrating southeast down the slough (a shallow, steep-sided depression that seasonally contains flowing or stagnant water) below was suggested from EM–31 surveys in 2004 and 2009. Indeed, the largest EM–31 apparent conductivity values were measured in this slough in both 2004 (450 mS/m) and 2009 (445 mS/m). The rapid drop to background conductivity values in areas hydraulically upgradient (northwest of the tank battery; fig. B–11) are consistent with initial work by Reiten and Tischmak (1993) documenting the tank battery as the source of brine. Elevated apparent conductivities associated with this plume were evident as far downgradient as surveyed; near oil well 05105 (127) in 2004 and the northern edge of wetland 264J in 2009. The area near oil well 05105 (127) in 2009 likely delineates this brine plume as well and shows an expansion of elevated apparent conductivities to the southeast relative to 2004. However, it should be noted that elevated apparent conductivities were recorded near oil well 05105 (127) in the 2004 surveys and are likely related to the buried reserve pit at this well; therefore, the expansion seen in 2009 may be from the buried reserve pit or contaminated groundwater from the tank battery, or both. The presence of brine as the source of elevated apparent conductivity measurements in 2004 was confirmed by 2005 CI values indicating extremely contaminated groundwater from monitoring wells 264A (0.656), 264B (0.573), and 264D (0.450) and moderately contaminated groundwater from RAB2 (0.312). Similarly, CI values in 2009 indicated extremely contaminated groundwater from well 264A (0.409) and moderately contaminated groundwater from wells 264D (0.317), 264Q (0.315), and RAB2 (0.246). Additionally, the downgradient migration or dilution of the brine plume are supported by decreases in the CI values in monitoring wells 264A (-0.247), 264D (-0.133), and RAB2 (-0.066) in the upgradient portion of the brine plume between 2005 and 2009.



Base map imagery from the National Agriculture Imagery Program (NAIP)
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Figure B–10. Goose Lake study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Rabenberg Waterfowl Production Area, as well as the 2005–6 contamination index values and apparent conductivity results from the 2004 EM–31 geophysical surveys.

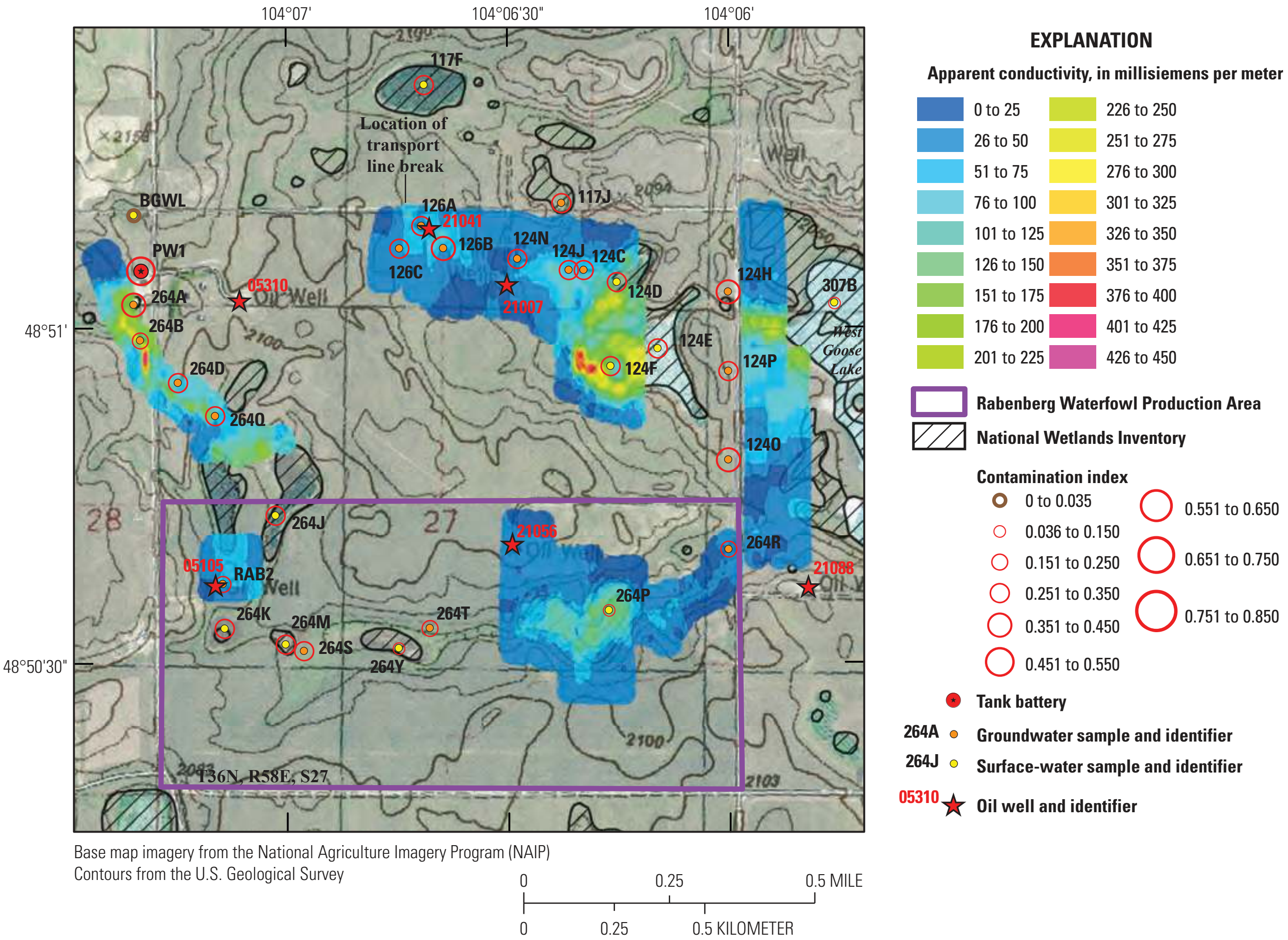


Figure B–11. Goose Lake study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Rabenberg Waterfowl Production Area, as well as the 2009 contamination index values and apparent conductivity results from the 2009 EM–31 geophysical surveys.

Elevated apparent conductivity measurements (maximum of 180 mS/m) were measured over a small area east of oil well 21056 (128) in 2004, likely delineating the old reserve pit (fig. B–10). Apparent conductivity measurements near oil well 21056 (128) in 2009 were much lower (maximum of 45 mS/m); however, unlike in 2004, the spacing between measurements was grid-based in 2009 with fewer measurement points than 2004, and no measurements were collected over the old reserve pit (fig. B–11). The surveyed area near oil well 21056 (128) was expanded in 2009 to include the basin of wetland 264P and the slough leading to monitoring well 264R. Additional surveys also were performed east of monitoring wells 264R, 124O, 124P, and 124H to the western shore of West Goose Lake. The 2009 surveys documented elevated apparent conductivities in and around wetland 264P (maximum of 155 mS/m) and in the slough leading to 264R (maximum of 82 mS/m). While the groundwater beneath the entire slough is likely moderately contaminated as evidenced by the 2009 CI value at 264R (0.212), the spatially interpolated surface shows only a thin strip of elevated conductivity in the slough. However, this is likely because of the deep water table (approximately 2 m at 264R in October 2009) and the steep-sided slough. The expansion of elevated apparent conductivities with the loss of topography from the slough near and eastward of 264R supports this conclusion.

The EM–31 surveys measured elevated apparent conductivities adjacent to abandoned oil well 21007 (124) in 2009 and defined a brine plume expanding southeastward (fig. B–11). The maximum apparent conductivities associated with this plume were measured south of wetland sample 124D (300 mS/m) and west of wetland sample 124F (420 mS/m). Although no groundwater samples were collected in the areas of maximum apparent conductivity, 2009 CI values indicated moderately contaminated groundwater from monitoring wells 124C (0.309), 124J (0.344), and 124N (0.324) in the northern portion of the plume and confirmed the presence of brine. Additionally, the 2009 CI values recorded in the aforementioned wetlands (0.309 and 0.331, respectively), as well as wetland 124E (0.319), also indicated moderate contamination and further support the hypothesis that the maximum elevated apparent conductivities are because of brine-contaminated groundwater. Elevated apparent conductivities (maximum of 240 mS/m) were also observed in the survey area located between West Goose Lake and monitoring wells 124H, 124O, and 124P and likely define the downgradient continuation of this brine plume. These three monitoring wells are along the west edge of the survey area and the 2009 CI values from monitoring wells 124H (0.390), 124O (0.387), and 124P (0.321) confirm that the elevated apparent conductivities near West Goose Lake are the result of extremely and moderately contaminated groundwater.

The EM–31 surveys near abandoned oil well 21041 (126) in 2009 documented two areas of elevated apparent conductivities near the well pad and support the conclusion that the increased CI values between 1989 and 2009 in monitoring wells 126A (0.170 and 0.341, respectively) and 126C (0.005 and 0.266, respectively) are because of the transport line break in 2006 (fig. B–11). In 1989, an area of elevated apparent conductivity delineating a brine plume with extremely contaminated groundwater, which likely was emanating from the buried reserve pit, was measured northwest of monitoring well 126B (CI value of 0.396), with apparent conductivities returning to background levels near the site access road (Reiten and Tischmak, 1993, p. B–34). Elevated apparent conductivity measurements in 2009 also defined the extremely contaminated groundwater plume associated with the buried reserve pit northwest of 126B (CI value of 0.383), and an additional area north of 126C at the approximate location of the transport line break. This new area of elevated apparent conductivity measurements defines a new, moderately contaminated, brine plume that emanates from the transport line break and has migrated south to monitoring wells 126A and 126C. These results illustrate the continued potential of brine contamination to aquatic resources in the PPR from routine oilfield operations.

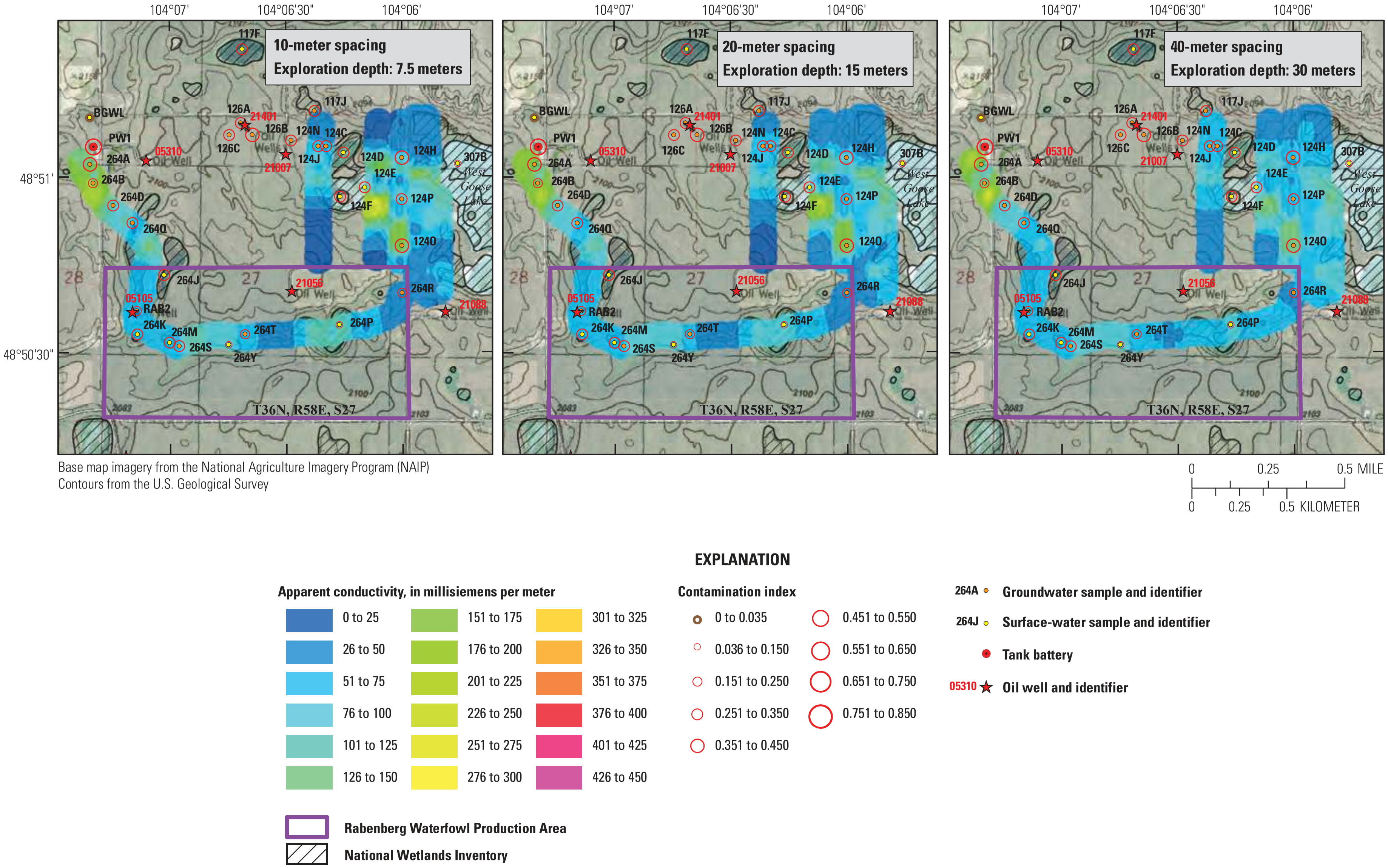
EM–34 Geophysical Surveys

The relative trends in the EM–34 surveys (figs. B–12, B–13) compared well to the EM–31 surveys (figs. B–10, B–11); however, differences existed between the two instruments and between the different dipole orientations in the EM–34. As with the EM–31 surveys, the EM–34 surveys delineated brine plumes associated with the tank battery (264), oil well 21056 (128), and oil well 21007 (124). However, the magnitudes of EM–34 apparent conductivity measurements generally were lower than the EM–31 apparent conductivity measurements. Additionally, the EM–34 measurements in the vertical dipole orientation (fig. B–13) were lower than the measurements in the horizontal dipole orientation (fig. B–12), especially in areas with elevated apparent conductivities associated with brine plumes. This implies a stratigraphic control on the migration of brine-contaminated groundwater in glacial outwash deposits overlying glacial till.

Elevated apparent conductivity measurements were recorded in the slough below the tank battery as far downgradient as the likely extent of this groundwater plume, between monitoring well 264T and wetland 264P (figs. B–12, B–13). Measurements in the horizontal dipole orientation from the 10-, 20-, and 40-m intercoil spacings had maximum values of 250, 230, and 260 mS/m, respectively. Respective maximum measurements in the vertical dipole orientation were 78, 69, and 62 mS/m. Apparent conductivities generally decreased moving downgradient in both the horizontal and vertical dipole orientations, with the exception of a large increase in apparent conductivities measured with all surveys between monitoring wells 264S and 264T. This increase likely is from the influence of a buried glaciolacustrine deposit that was observed at the base of these wells during drilling. The elevated conductivity measurements in the horizontal dipole orientation strongly suggest a brine plume in the coarse-grained outwash sediments in the slough. The high CI values observed in 2009 from monitoring wells 264A (0.409), 264D (0.317), 264Q (0.315), 264S (0.304), and 264T (0.222), and RAB2 (0.246), which are all completed within the outwash sediments, confirm the presence of extremely and moderately contaminated groundwater in the near-surface outwash sediments. In contrast, the lower conductivity measurements in the vertical dipole orientation imply that the penetration of contaminated groundwater into the till that underlies the outwash sediments is minimal. However, no monitoring wells were completed within the underlying till to confirm the presence (and magnitude) or absence of contaminated groundwater.

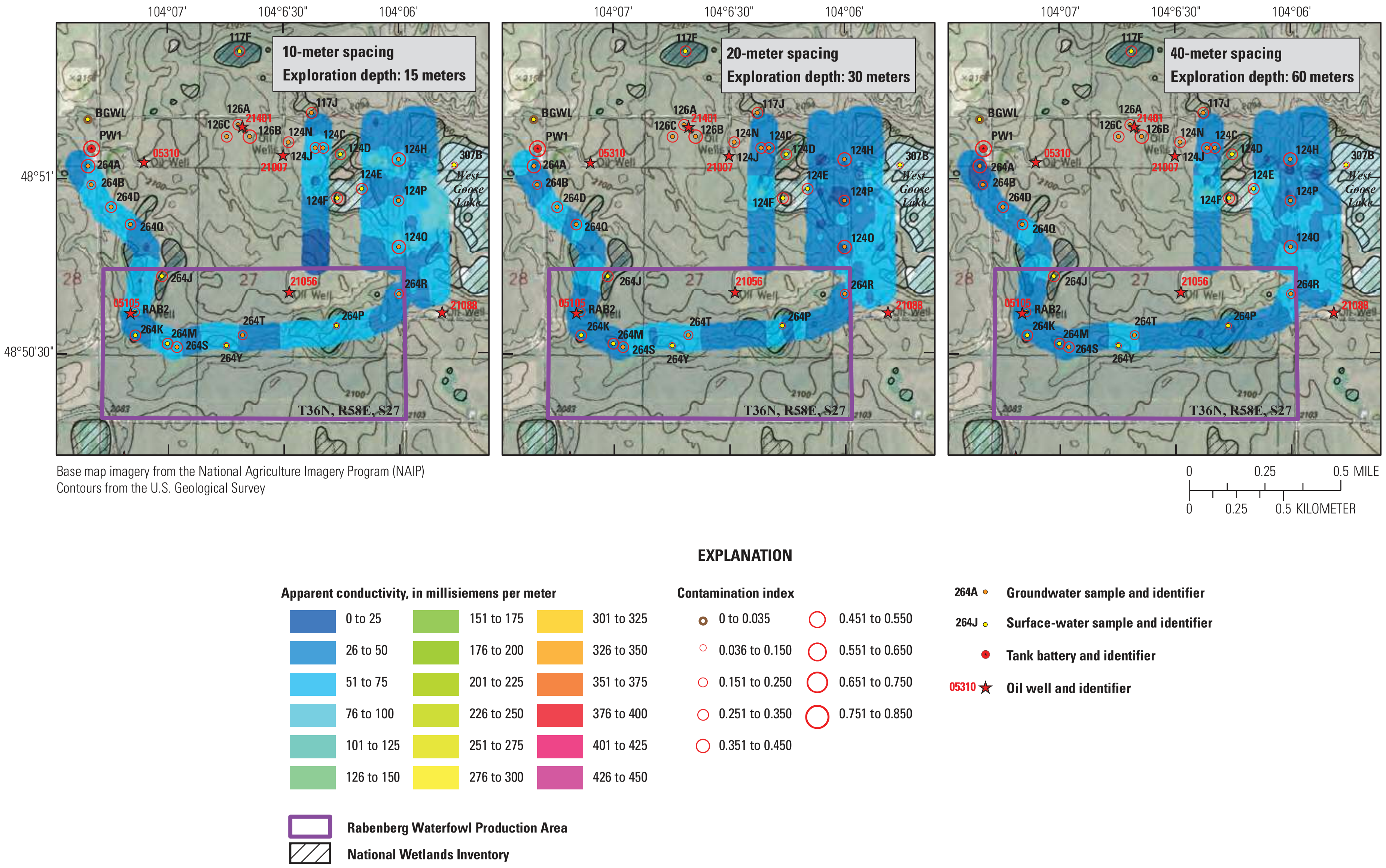
Elevated apparent conductivities were recorded east of monitoring well 264T, through wetland 264P and monitoring well 264R, to the edge of West Goose Lake (figs. B–12, B–13). The source of the elevated conductivity is likely brine from oil well 21056 (128); however, the surficial clay deposits in wetland 264P and near West Goose Lake probably contribute to the high apparent conductivities observed in these areas. The presence of moderately contaminated groundwater was confirmed by the CI value of monitoring well 264R (0.212), which is completed in the outwash deposits. The horizontal dipole surveys had greater apparent conductivity measurements than the vertical dipole surveys, with this increase also suggesting that the brine plume is mainly confined within the surficial outwash deposits.

The EM–34 surveys also recorded elevated apparent conductivities suggesting a brine plume emanating from oil well 21007 (124) that has migrated to West Goose Lake (figs B–12, B–13). Maximum apparent conductivity measurements from the 10-, 20-, and 40-m horizontal dipole orientation were 280, 250, and 259 mS/m, respectively. Respective maximum measurements from the vertical dipole orientation were 102, 93, and 108 mS/m. The sharp drop in conductivity between the horizontal and vertical dipole orientations also is interpreted as minimal penetration into the glacial till beneath the outwash deposits. The presence of extremely and moderately contaminated groundwater within the surficial outwash deposits was confirmed by the CI values from monitoring wells 124C (0.309), 124H (0.390), 124J (0.344), 124O (0.387), and 124P (0.321), all of which are completed in the outwash deposits.



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–12. Goose Lake study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Rabenberg Waterfowl Production Area, as well as 2009 contamination index values and apparent conductivity results from the 2009 EM–34 10-meter (m) horizontal dipole, 20-m horizontal dipole, and 40-m horizontal dipole geophysical surveys.



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–13. Goose Lake study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Rabenberg Waterfowl Production Area, as well as 2009 contamination index values and (see B–12) apparent conductivity results from the 2009 EM–34 10-meter (m) vertical dipole, 20-m vertical dipole, and 40-m vertical dipole geophysical surveys.

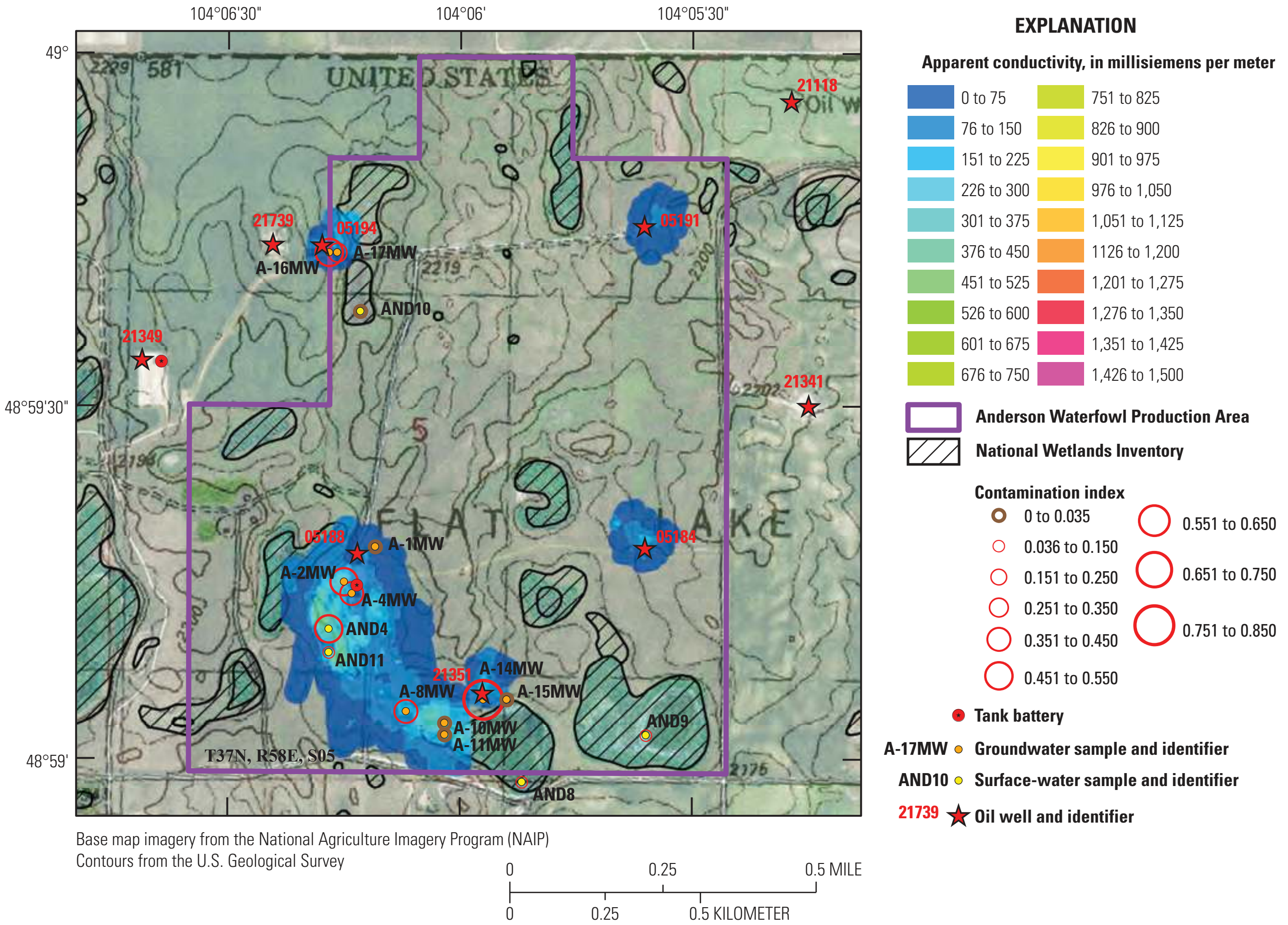
From the EM–34 surveys and CI values, it appears that the groundwater plume bifurcates around 124P, where well logs indicate a subsurface glacial till high, further illustrating the control that the underlying till has on the transport of brine-contaminated groundwater.

Results from the EM–34 surveys show that the brine contamination at the Goose Lake study site is mainly confined within the saturated coarse-grained outwash deposits, with minimal penetration into the less permeable, underlying till. This is especially evident beneath the tank battery, where some of the largest horizontal dipole apparent conductivities were measured. In contrast, the vertical dipole measurements beneath the tank battery were much lower, with several measurements near background levels. Monitoring well 264A had the highest Cl$^-$ concentration of all sampled sites in 1989 (66,900 mg/L), 2005 (30,841 mg/L), and 2009 (37,500 mg/L) and CI values indicting extremely contaminated groundwater in all 3 years (0.371, 0.656, and 0.409, respectively), illustrating the high degree of groundwater contamination within the outwash deposits. Therefore, the sharp drop in conductivity values between the horizontal and vertical dipole orientation measurements likely is from minimal penetration of contaminated groundwater into the underlying till. Although some penetration has likely occurred, without groundwater samples from the till, the depth of penetration is impossible to fully determine. However, from the EM–34 data, it appears that the depth of contamination is clearly less than 60 m and likely less than 30 m.

Anderson Study Site

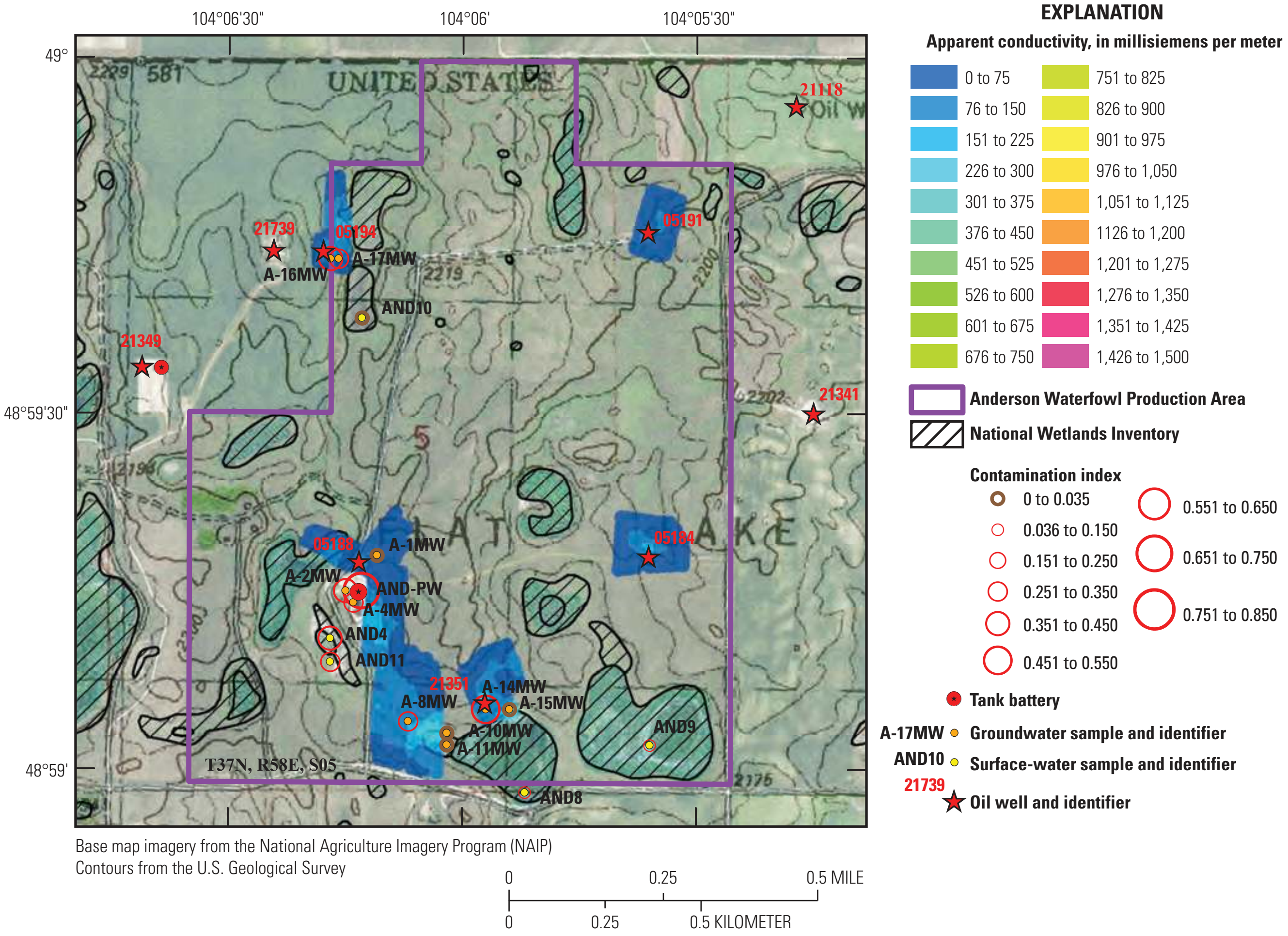
EM–31 Geophysical Surveys

Several areas of elevated apparent conductivities associated with and suggesting brine plumes were measured with the EM-31 surveys at the Anderson study site in 2004 and 2010 (figs. B–14, B–15). The largest apparent conductivity values in 2004 were measured in the basins of wetlands AND4 and AND11 (475 and 485 mS/m, respectively), both located southwest of the tank battery and near oil well 21351 (475 mS/m). The largest apparent conductivity values in 2010 were measured near oil well 21351 (310 mS/m) and between monitoring



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–14 Anderson study site showing the location of water samples, oil wells, tank battery, National Wetlands Inventory wetlands, and the Anderson Waterfowl Production Area, as well as the 2004–5 contamination index values and apparent conductivity results from the 2004 EM–31 geophysical surveys.



Base map imagery from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–15. Anderson study site showing the location of water samples, oil wells, tank batteries, National Wetlands Inventory wetlands, and the Anderson Waterfowl Production Area, as well as the 2010 contamination index values and apparent conductivity results from the 2010 EM–31 geophysical surveys.

wells A–8MW and A–10MW (300 mS/m). The area southwest of the tank battery was not surveyed with the EM–31 in 2010; however, this area was surveyed with the GEM–2. Additionally, elevated apparent conductivity values were measured near all oil well sites in 2004 and 2010; however, the apparent conductivity values measured in 2010 generally were lower than the values measured in 2004 across the study site.

The elevated apparent conductivity values south and east of the tank battery in 2004 and 2010 suggest a brine plume emanating from near the tank battery and extending as far down as the surveys were performed, near wetland AND8 (figs. B–14, B–15). The tank battery as the source of the contamination is supported by 2005 and 2010 CI values (table B–2) indicating uncontaminated groundwater from monitoring well A–1MW (0.005 in both years) upgradient from the tank battery compared to moderately and extremely contaminated groundwater from monitoring wells A–2MW (0.510 and 0.365, respectively), A–4MW (0.362 and 0.266, respectively), and A–8MW (0.355 and 0.332, respectively) downgradient from the tank battery. The downgradient migration or dilution of the brine plume is supported by decreased CI values in the upgradient end of the plume at monitoring wells A–2MW (-0.145), A–4MW (-0.096), and A–8MW (-0.023) between 2005 and 2010. Interestingly, the 2005 and 2010 CI values from monitoring wells A–10MW (0.016 and 0.011, respectively) and A–11MW (0.015 and 0.021, respectively) documented uncontaminated groundwater despite the presence of elevated apparent conductivities measured with the 2004 and 2010 EM–31 surveys. In contrast, the 2004 and 2010 CI values of surface-water samples from wetlands AND8 (0.098 and 0.076, respectively) and AND9 (0.144 and 0.095, respectively) indicated potentially and moderately contaminated surface water; however, the source of this contamination is unclear and discussed below.

A brine plume is implied near abandoned oil well 21351 from the elevated apparent conductivity values in 2004 and 2010 that delineate a brine plume emanating from the oil well pad and extending to the north and east (figs. B–14, B–15). Maximum measured apparent conductivity readings at this site showed the largest decrease between 2004 and 2010, with maximum measured apparent conductivities of 475 and 310 mS/m, respectively. The presence of brine was confirmed by CI values from monitoring well A–14MW that indicated extremely contaminated groundwater. Indeed, A–14MW, which is completed within and directly below the buried reserve pit for oil well 21351, recorded the largest CI value measured at the Anderson study site in 2005 and 2010 (0.823 and 0.492, respectively), as well as the greatest reduction in CI value (-0.331) between 2005 and 2010. The reduction in apparent conductivity measurements between 2004 and 2010 and CI values between 2005 and 2010 is likely the result of continued downgradient migration or dilution of the brine plume. Based on the direction of brine plume migration from oil well 21351 and the lower $^{87}Sr/^{86}Sr$ values of wetlands AND8 and AND9 relative to monitoring well A–14MW, the likely source of contamination in AND8 and AND9 is not the buried reserve pit at oil well 21351. However, the lack of contamination in monitoring wells A–10MW and A–11MW likely precludes the tank battery as the source of brine. Therefore, the brine source to AND8 and AND9 is unclear and may be from two other oil wells completed in the Ratcliffe Formation (21361 and 05174 and not shown on figs. B–14 and B–15) and located approximately 0.3 km to the south of AND8 and AND9.

Elevated apparent conductivity values were measured in 2004 and 2010 near oil well 05194 that likely define a brine plume that emanates near the oil well pad and heads northward into the wetland (figs. B–14, B–15). The largest measured values in 2004 and 2010 occurred near the well pad, with measured values of 320 and 260 mS/m, respectively. The 2005 and 2010 CI values from monitoring wells A–16MW (0.485 and 0.424, respectively) and A–17MW (0.272 and 0.257, respectively) confirm the presence of extremely and moderately contaminated groundwater as the source of elevated apparent conductivities. Although the maximum conductivity value in 2010 was still extremely elevated compared to background conductivity, the reduction in maximum apparent conductivity values relative to 2004 likely indicates a reduction in the magnitude of contamination because of downgradient migration or dilution of the contaminated groundwater. This interpretation is supported by groundwater data from A–16MW and A–17MW (table B–2), where a reduction in CI values (-0.021 and -0.015, respectively) was observed between 2004 and 2010.

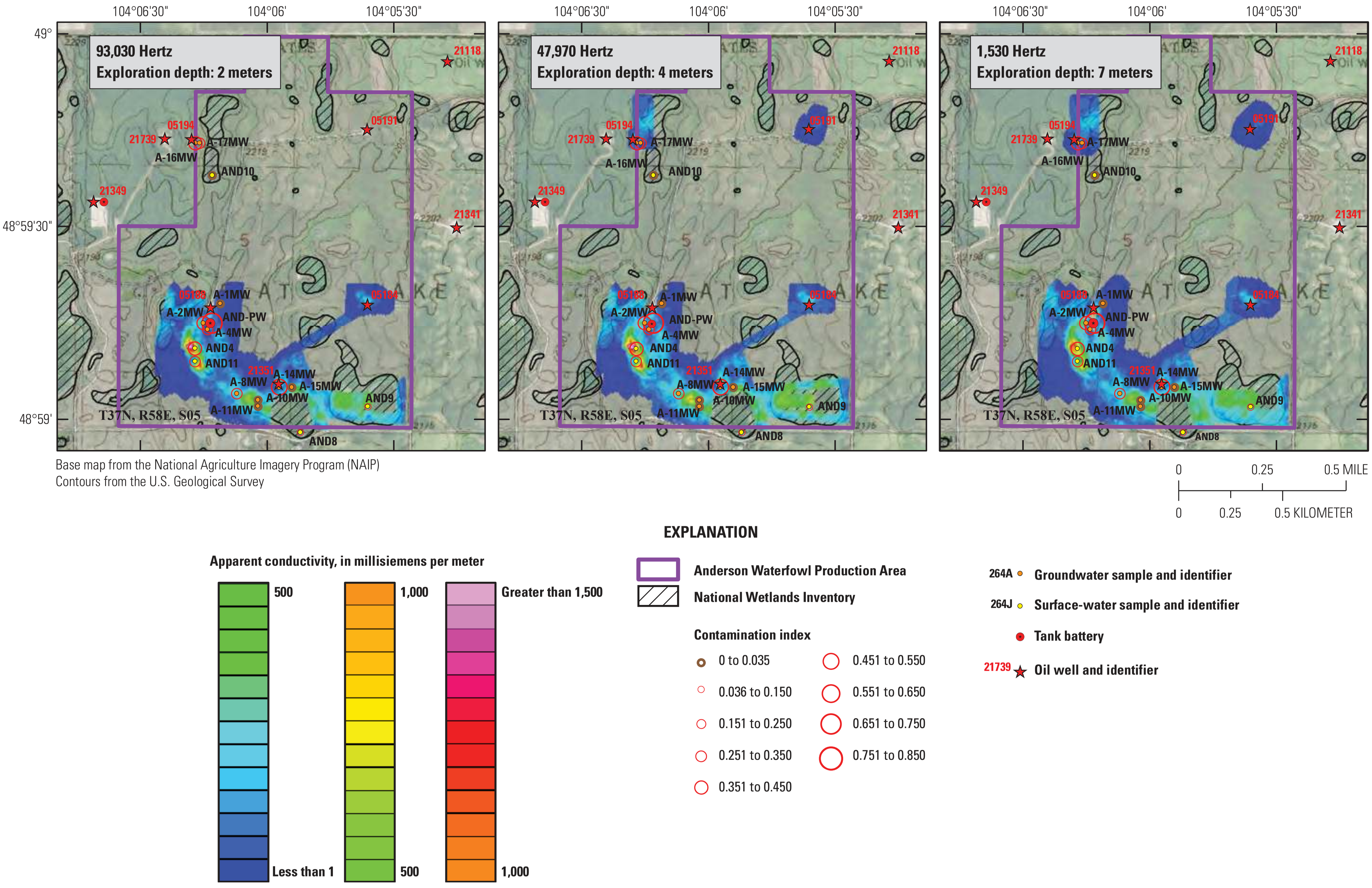
A similar decrease in maximum apparent conductivity values was observed at oil wells 05184 and 05191 between 2004 and 2010 (figs. B–14, B–15). At both oil wells, elevated apparent conductivity values suggest a brine plume adjacent to the well pads. The maximum apparent conductivity values for 2004 and 2010 at oil well 05184 were 230 and 210 mS/m, respectively. Respective maximum apparent conductivity values for 2004 and 2010 at oil well 05191 were 130 and 100 mS/m. As with oil well 05194, the reduction in the maximum measured apparent conductivity values near oil wells 05184 and 05191 is interpreted as a reduction in the magnitude of contamination, likely from downgradient migration or dilution; however, no groundwater data were available for these sites to confirm this conclusion.

GEM–2 Geophysical Surveys

The relative trends in all frequencies from the GEM–2 surveys (fig. B–16) compared well to the EM–31 surveys in 2004 and 2010 (figs. B–14, B–15), although the two instruments measure earth conductivity differently. As with the EM–31 surveys, brine plumes were suggested from the GEM–2 survey to be emanating from the tank battery and near oil wells 21351, 05194, 05184, and 05191. However, apparent conductivity measurements were generally much greater in the GEM–2 surveys relative to the EM–31 surveys in some areas suggesting brine contamination. Lastly, in contrast to the EM–34 surveys at the Goose Lake study site that showed large drops in conductivity at shallow depth, the GEM–2 surveys at Anderson were very consistent between different exploration depths. This implies a lack of stratigraphic control on the migration of brine in glacial till deposits.

Brine-contaminated groundwater was indicated from elevated apparent conductivities measured to the southeast and southwest of the tank battery and extending as far southeast as wetland AND9 (fig. B–16). All frequencies from the GEM–2 surveys recorded elevated apparent conductivities emanating from the tank battery with respective maximum apparent conductivities from the 93,030, 47,970, and 1,530 Hz frequencies of 1,580, 1,510 and 1,175 mS/m near wetland AND4. Despite slightly different maximum apparent conductivity values, no substantial difference in the overall apparent conductivity profiles existed between any of the frequencies used in the GEM–2 surveys. Extremely and moderately contaminated groundwater as the source of elevated apparent conductivities was confirmed by the CI values from monitoring wells A–2MW (0.365), A–4MW (0.266), and A–8MW (0.332) in 2010 (table B–2). Similar to the EM-31 surveys, elevated apparent conductivities also were measured near monitoring wells A–10MW and A–11MW, although CI values from both wells were below 0.035, indicating uncontaminated groundwater. The CI values of surface-water samples from wetlands AND8 (0.076) and AND9 (0.095) indicated potential contamination; however, as discussed previously, the brine source is unclear.

Elevated apparent conductivity measurements from all frequencies were recorded near oil well 21351 and delineated a brine plume emanating from the oil well pad and migrating to the north and east (fig. B–16). Maximum apparent conductivities from the 93,030, 47,970, and 1,530 Hz frequencies (650, 800, and 680 mS/m, respectively) were measured on the oil well pad and likely denote the location of the buried reserve pit. Despite slightly different maximum apparent conductivity values, no substantial differences in the overall apparent conductivity profiles existed between any of the frequencies used in the GEM–2 surveys. The presence of extremely contaminated groundwater as the source of elevated apparent conductivities was confirmed by the 2010 CI value from monitoring well A–14–MW (0.492). As with the EM–31 surveys at oil well 21351, the direction of the brine plume



Base map from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–16. Anderson study site showing the location of water samples, oil wells, tank batteries, National Wetlands Inventory wetlands, and the Anderson Waterfowl Production Area, as well as 2010 contamination index values and apparent conductivity results from the 2010 GEM–2 geophysical surveys for the 93,030 hertz (Hz), 47,970 Hz, and 1,530 Hz frequencies.

movement indicates that the buried reserve pit at this well is not the source of contamination in wetlands AND8 and AND9.

The GEM–2 data near oil well 05194 indicated a brine plume emanating from the oil well pad and extending into the wetland basin to the northeast (fig. B–16). Maximum apparent conductivities from the 1,530 and 47,970 Hz frequencies (300 and 200 mS/m, respectively) were measured near the oil well pad and likely define the location of the buried reserve pit. GEM–2 data in the 93,030 Hz frequency were not collected near oil well 05194. No substantial differences in the overall apparent conductivity profiles existed between the 1,530 and 47,970 frequencies despite the slightly different maximum apparent conductivity values. The presence of brine as the source of elevated apparent conductivity was confirmed by the 2010 CI values from monitoring wells A–16MW (0.424) and A–17MW (0.257) (table B–2) that indicated extremely and moderately contaminated groundwater, respectively.

Elevated apparent conductivity values also were measured near oil wells 05184 and 05191 (fig. B–16). Respective maximum apparent conductivities from the 93,030, 47,970, and 1,530 Hz frequencies were 300, 360, and 320 mS/m near oil well 05184. Maximum apparent conductivities near oil well 05191 from the 1,530 and 47,970 Hz frequencies were 85 and 75 mS/m, respectively. GEM–2 data for the 93,030 Hz frequency were not collected near oil well 05191. Again, no major differences were seen in the overall apparent conductivity profiles between the different frequencies near these two oil wells. No groundwater samples were collected within the areas of high apparent conductivities near these oil wells to confirm the presence of groundwater contamination. However, the strong correlation between elevated apparent conductivities and groundwater contamination observed across the Anderson study site indicates that brine contamination is likely.

In contrast to the EM–34 surveys at the Goose Lake study site (figs. B–12, B–13), which showed a marked reduction in apparent conductivity with depth that implies a subsurface control (the contact between the underlying till and surficial outwash deposits) on the migration of brine plumes, the GEM–2 surveys at the Anderson study site show no such systematic reduction in apparent conductivity with depth (fig. B–16). The lack of a reduction in apparent conductivity is interpreted as evidence of a lack of subsurface control on the vertical migration of brine in glacial till deposits. Therefore, without this subsurface control, the contamination is likely migrating horizontally and vertically at the Anderson study site compared to the predominately horizontal migration in the outwash deposits at the Goose Lake study site. Indeed, the distances of contaminant migration at the Goose Lake site were about 600 and 800 m, whereas at the Anderson site, the distance of migration was approximately 400 m. However, the depths of exploration for the GEM–2 (2–7 m) are much less than the EM–34 (7.5–60 m); therefore, reductions in apparent conductivity may exist in the glacial till deposits at greater depths than measured.

Fuller Study Site

EM–31 Geophysical Surveys

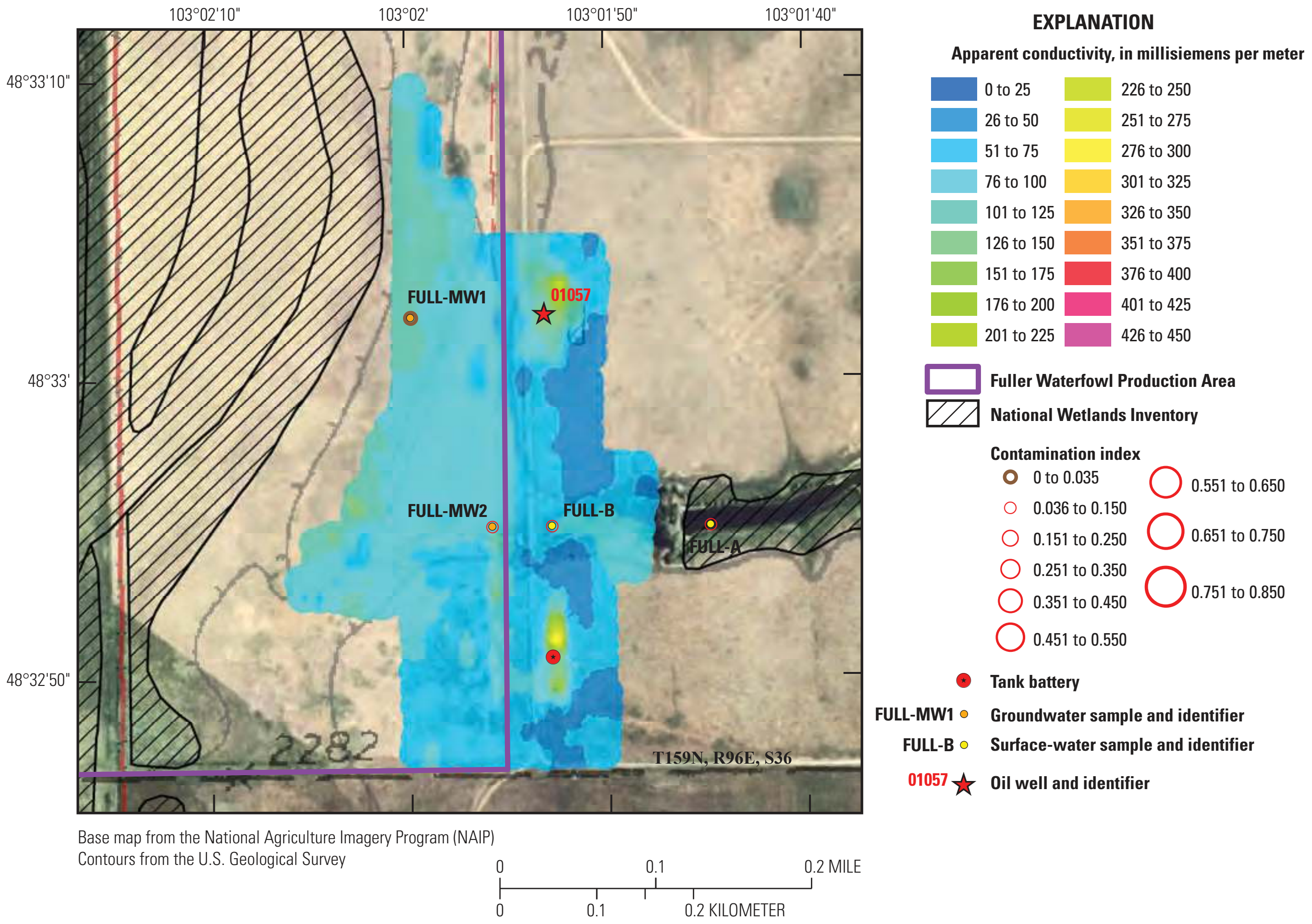
Areas of elevated apparent conductivity suggesting brine plumes were measured with the EM–31surveys at the Fuller study site in 2010 (fig. B–17). Background apparent conductivity values were slightly higher at the Fuller study site, in the range of 25–50 mS/m, with the higher values likely because of the greater clay content of the glaciolacustrine deposits. The largest apparent conductivity values were measured near the tank battery and oil well 01057. Additionally, elevated apparent conductivities were measured across much of the surveyed area. No previous geophysical surveys had been performed at the Fuller site for comparison with the 2010 survey.

The elevated apparent conductivities measured near the tank battery and oil well 01057 likely indicate brine plumes associated with these oilfield sites (fig. B–17). Respective maximum apparent conductivity values near the tank battery and oil well 01057 were 300 and 240 mS/m and likely denote the locations of buried reserve pits associated with these facilities. Although no groundwater samples were collected from these locations, the highly elevated apparent conductivities at these sites and the strong correlation between elevated apparent conductivity and brine contamination seen at the Goose Lake and Anderson study sites indicate likely groundwater contamination near the oilfield facilities at the Fuller site as well.

Elevated apparent conductivities also were measured in the slough west of the reservoir, where surface-water sample FULL–A was collected, and extended to the location of wetland FULL–B (fig. B–17). The CI value from monitoring well FULL–MW–2 (0.044) indicates potentially contaminated groundwater underlying the slough. Elevated apparent conductivities were measured in the majority of the surveyed area west of the tank battery and oil well 01057, with measured values as high as 135 mS/m near where the slough meets the lake plain. Although the CI value at monitoring well FULL–MW–1 (0.015) indicated uncontaminated groundwater, this sample had the greatest Cl^- concentration (350 mg/L) of all water samples from the Fuller study site.

GEM–2 Geophysical Surveys

Although differences existed between the two instruments, the relative trends in all frequencies from the GEM–2 surveys (fig. B–18) compared well to the EM–31 surveys (fig. B–17). As with the EM–31 surveys, elevated apparent conductivities suggesting brine-contaminated groundwater were measured near the tank battery, oil well 01057, and in the slough west of the reservoir where surface-water sample FULL–A was collected. An additional area of elevated apparent conductivity also was measured on the lake plain. Apparent conductivity measurements generally were greater in the GEM–2 surveys relative to the EM–31 surveys in areas suggesting brine contamination. Lastly, in contrast to the GEM–2 surveys at the Anderson study site that showed similar



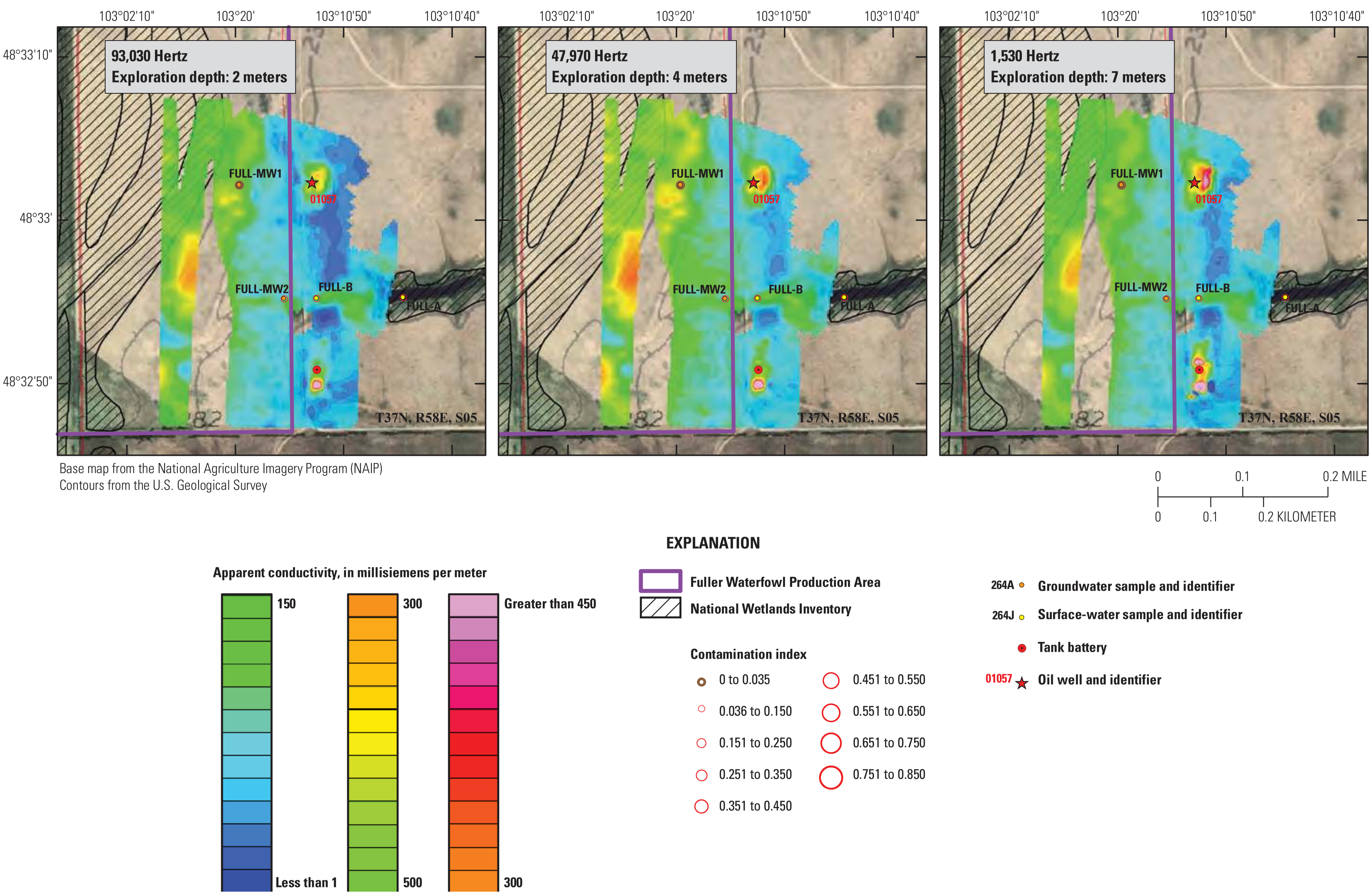
Base map from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–17. Fuller study site showing the location of water samples, oil well 01057, tank battery, National Wetlands Inventory wetlands, and the Fuller Waterfowl Production Area boundary, as well as the 2010 contamination index values and apparent conductivity results from the 2010 EM–31 geophysical survey.

maximum apparent conductivity values with depth, increases in the maximum apparent conductivity values and the area of elevated conductivity were observed with depth at the Fuller study site. The increase in maximum apparent conductivity values and area of elevated conductivity implies a possible stratigraphic control on the migration of brine-contaminated groundwater in glaciolacustrine deposits.

Elevated apparent conductivities were measured near the tank battery and oil well 01057 and indicate groundwater contamination related to these facilities (fig. B–18). Respective maximum apparent conductivities from the 93,030, 47,970, and 1,530 Hz frequencies were 750, 950, and 1,955 mS/m near the tank battery and 260, 360 and 530 mS/m near oil well 01057. Areas of maximum elevated apparent conductivity at the tank battery and oil well 01057 likely denote the locations of buried reserve pits. Extremely high values of apparent conductivity at the tank battery may reflect very high salinity of pore fluids. Groundwater samples were not collected from these areas to confirm contamination; however, the strong correlation between elevated apparent conductivities and brine contamination observed at the previous study sites indicates that brine contamination is likely. The differences between the three frequencies at both locations, namely the increase in maximum apparent conductivity values and the area of elevated conductivity with depth, may reflect increased contamination with depth.

Brine-contaminated groundwater beneath the slough where samples from wetland FULL–B and monitoring well FULL–MW2 were collected is supported by elevated apparent conductivity measurements (fig. B–18). Respective maximum apparent conductivities from the 93,030, 47,970, and 1,530 Hz frequencies were 160, 188, and 137 mS/m. The presence of contaminated groundwater as the source of elevated apparent conductivity was suggested by the 2010 CI value from FULL–MW2 (0.044) that indicated potentially contaminated groundwater. The continuation of this plume, below the lake plain to the west, is suggested by elevated apparent conductivity measurements in all frequencies; however, no groundwater samples were collected in this area to confirm the presence of brine.



Base map from the National Agriculture Imagery Program (NAIP)
Contours from the U.S. Geological Survey

Figure B–18. Fuller study site showing the location of water samples, oil well 01057, tank battery, National Wetlands Inventory wetlands, and the Fuller Waterfowl Production Area boundary, as well as 2010 contamination index values and apparent conductivity results from the 2010 GEM–2 geophysical surveys for the 93,030 hertz (Hz), 47,970 Hz, and 1,530 Hz frequencies.

The increases in maximum apparent conductivity values with increased depth observed at the Fuller site likely imply subsurface control on the migration of brine-contaminated groundwater in lacustrine deposits that overlie glacial till (fig. B–18). Near the tank battery and oil well 01057, the maximum apparent conductivity values more than double between the 93,030 Hz and 1,530 Hz frequencies and the area of elevated conductivity slightly increases. Schwartz and Zang (2003) report that the hydraulic conductivity for weathered lacustrine deposits (3.2×10^{-8} m/s) is generally lower than the hydraulic conductivity of fractured glacial till (range of 1.2×10^{-5} to 1.2×10^{-9} m/s). Therefore, it would be expected that the vertical component of brine migration would be greater in the lacustrine deposits relative to the glacial till deposits. In contrast, the horizontal component of brine migration would be the opposite, with greater lateral migration in the glacial till deposits. This is likely the reason for the increase in apparent conductivity values and greater area of elevated conductivity in the 1,530 Hz frequency relative to the 93,030 Hz frequency near the tank battery and oil well 01057. Therefore, in areas where lacustrine deposits overlie glacial till, it appears that the direction of brine migration is predominately vertical in the lacustrine deposits and becomes more horizontal once it reaches the underlying glacial till. The predominantly vertical migration of brine in the lacustrine deposits is further supported by a lack of laterally extensive brine plumes at the Fuller site compared to those seen at both the Goose Lake and Anderson sites. Although this conclusion follows the principals of groundwater flow through a heterogeneous medium (Schwartz and Zang, 2003), it cannot be confirmed because of a lack of groundwater quality and lithological data on the magnitude of brine contamination with depth and the depth of the contact between the lacustrine and glacial till deposits, respectively, near the tank battery and oil well 01057.

Summary—Brine Contamination of Prairie Pothole Environments in the Williston Basin

The presence of brine in surface water and shallow groundwater was documented at three study sites within the Prairie Pothole Region (PPR) in the Williston Basin during 2009–10. The likely brine source is water produced with oil in the Williston Basin. At the Goose Lake site, water-quality results from 26 of 29 surface-water and shallow groundwater samples collected during 2009 indicated moderate or extreme brine contamination, with 2 additional samples indicating potential contamination. The only sample with a contamination index (CI) value less than 0.035 was collected from a small wetland located upgradient from potential contaminant sources. At the Anderson site, water-quality results from 8 of the 15 surface-water and shallow groundwater samples collected during 2010 indicated moderate or extreme brine contamination, with 2 additional samples indicating potential contamination. At the Fuller site, water-quality results from three of the four surface-water and shallow groundwater samples collected during 2010 indicated potential brine contamination. Based on the results at these three sites, brine contamination in surface water and shallow groundwater located in close proximity to oilfield facilities in the PPR in the Williston Basin is more likely than in areas isolated from oil and gas development activities, and once brine is present in these systems, it can persist for several decades.

Study sites with previously documented brine contamination (Goose Lake in 1989 and 2004–6 and Anderson in 2004–5) were still contaminated when visited in 2009 or 2010. Brine contamination has persisted for at least 20 years at the Goose Lake site and for at least 6 years at the Anderson site. The brine is likely leached from buried reserve pits that were installed in the mid- to late-1960s, indicating that contamination has likely persisted for four to five decades at both study sites. Further illustrating the length of time required for natural attenuation of brine in the PPR, a statistically significant reduction in the magnitude of contamination was seen over 20 years at the Goose Lake site while no statistically significant reduction was observed over 5–6 years at the Anderson site.

The lateral migration of brine plumes appears to be controlled, in part, by the type of near-surface sediments. Based on the distribution of sample sites at two of the three study sites, brine contamination migrated at least 600 and 800 meters (m) along two separate groundwater-flow paths in coarse-grained glacial outwash deposits (Goose Lake study site) and at least 400 m along a groundwater-flow path in fine-grained, clay-rich glacial till (Anderson site). The Fuller site did not have a groundwater-flow path long enough to determine the lateral migration of brine contamination in very fine-grained glaciolacustrine deposits; however, data from the geophysical surveys at the Fuller site did not indicate the laterally extensive brine plumes that were measured at the Goose Lake and Anderson sites. These results suggest greater lateral migration of brine plumes in the coarse-grained outwash deposits relative to the clay-rich glacial tills and glaciolacustrine deposits in the PPR. This observation is consistent with the general variation in hydraulic conductivity which is lower in fine-grained, clay-rich, sediments than in coarse-grained sediments.

Geophysical surveys performed at the three study sites measured elevated apparent conductivities near the vast majority of oilfield facilities. At the Goose Lake site, elevated apparent conductivities were measured during 2004 and 2009 in areas that include a tank battery and several oil wells. At the Anderson site, elevated apparent conductivities were measured during 2004 and 2010 in areas that include a tank battery and several oil wells. At the Fuller site, elevated apparent conductivities were measured during 2010 near the tank battery and oil well. High chloride concentrations, specific conductivity, and CI values were measured in groundwater samples from several areas of elevated apparent conductivity, indicating that brine is the likely source of elevated apparent conductivity in these areas and also the likely source of elevated apparent conductivities in areas adjacent to oilfield facilities without groundwater samples for verification. Therefore, geophysical surveys provide an effective method to identify areas of possible brine contamination in the PPR within similar hydrogeologic settings.

Differences were observed in the vertical migration of brine plumes in the three different types of near-surface sediments based on the geophysical surveys. At the Goose Lake site, where coarse-grained glacial outwash deposits overlie clay-rich glacial till, elevated apparent conductivity measurements associated with brine contamination decreased substantially as the exploration depth of the geophysical surveys increased. This is interpreted as minimal penetration of the brine into the underlying till. In contrast, apparent conductivity measurements did not change substantially with decreasing frequency (depth) at the Anderson site in clay-rich glacial till. This is likely from the more homogenous subsurface at the Anderson site that does not have different geologic deposits with contrasting hydraulic conductivities, resulting in a lack of preferential flow paths. Finally, maximum apparent conductivity values increased substantially, and the area of elevated apparent conductivity expanded slightly with depth at the Fuller site where silt and clay lacustrine deposits overlie glacial till. This is interpreted as a preferential vertical migration of brine though the lacustrine deposits with brine migration becoming more horizontal in the underlying glacial till. However, it should be noted that exploration depths were much greater at the Goose Lake site (EM–34, exploration depths of 7.5–60 m) relative to the Anderson and Fuller sites (GEM–2, exploration depths of 2–7 m); therefore, lower apparent conductivity may exist at greater depths than mapped by the specific electromagnetic system.

Geophysical data and analytical results indicate the source of contamination of surface water and shallow groundwater at the three study sites is brine produced with oil. Potential brine sources are oil wells, tank batteries, reserve pits, and pipelines. The geophysical and water-quality data clearly indicate that oil and gas production sites are point sources that can and do contaminate surface water and shallow groundwater in the PPR.

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Spatial Characterization of Oil and Gas Development and Aquatic Resources in the Williston Basin, United States

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Chapter C of

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Appendix table

Spatial Characterization of Oil and Gas Development and Aquatic Resources in the Williston Basin, United States

By Brian A. Tangen,[1] Robert A. Gleason,[1] and Tara L. Chesley-Preston[2]

Synopsis

The Williston Basin (fig. A–1) has been a leading domestic oil and gas producing region for more than 50 years. A recent U.S. Geological Survey (USGS) assessment (Gaswirth and others, 2013) reported that the Montana and North Dakota part of the Bakken Formation (fig. A–1) and underlying Three Forks Formation (not shown on fig. A–1) contains a vast hydrocarbon reserve that ranks among the largest in the world. The large amount of recoverable oil and gas, combined with advancements in recovery technologies and high oil prices, have led to a modern oil boom in the region. A large volume of produced waters, or brines, can be generated during recovery operations, with some estimates exceeding 10 barrels of brine produced per barrel of oil extracted (Wanty, 1997). Brines associated with oil and gas extraction in the Williston Basin differ greatly from natural surface water and the shallow groundwater with regards to salinity and ionic composition, and these brines have total dissolved solids concentrations that are among the highest in the Nation (see chapters A and B of this report). Concerns over past methods of storage and disposal for these brines, coupled with the huge increase in oilfield activities and higher incidences of accidental discharges, have led to an elevated awareness of the potential environmental effects associated with oil and gas recovery. Of special concern in the region is the addition of brines to wetlands and streams that provide critical habitat for waterfowl and other wildlife, as well as water for agricultural irrigation and livestock.

Montana and the Dakotas have a long history of oil and gas production and a strong tradition of conservation-focused land management, much of which has focused on the region's ecologically vital prairie pothole wetlands. However, very little research has examined the potential effects of oil and gas production on aquatic resources in the region, and there are no studies that have characterized the region in terms of the distribution of oil wells and aquatic ecosystems. The objectives of this study were to gather spatial databases to support a regional characterization of oil and gas wells, wetlands, and streams in the Williston Basin and to identify areas with a greater likelihood of containing brine-contaminated aquatic resources on the basis of the number and distribution of wells, wetlands, and streams.

A key component of any large, regional assessment is the ability to describe an area using spatial databases and a geographic information system (GIS). For this study, numerous spatial databases were gathered that detail oil- and gas-related wells (referred to simply as wells hereafter), wetlands, streams, critical habitats, land ownership, and soils. These spatial layers were used to describe temporal drilling trends and the spatial distribution and general characteristics (for example, well type and land ownership) of wells within the Williston Basin. Further, areas with a greater likelihood of containing brine-contaminated aquatic resources were distinguished by identifying counties with the greatest numbers and densities of wells, wetlands, and streams.

Over 30,000 wells were permitted and drilled in the study area (the U.S. part of the Williston Basin and Bakken Formation) from approximately 1901 to 2011. A majority of these wells were drilled after 1950 and located primarily on private lands in northeastern Montana and western North Dakota. The seven counties identified as having the greatest amount and densities of wells and aquatic resources include McKenzie (N. Dak.), Phillips (Mont.), Valley (Mont.), Williams (N. Dak.), Dunn (N. Dak.), Mountrail (N. Dak.), and Bowman (N. Dak.). Within the Prairie Pothole Region (PPR) of the study area (fig. A–1), roughly 290,000 wetlands covering approximately 1,800 square kilometers (km^2), 7,000 kilometers (km) of streams, and 80 km^2 of critical habitat to the threatened piping plover (*Charadrius melodus*) were within 1.6 km of wells. Based on these estimates, approximately one-third of all wetlands within the PPR in the United States part of the study area were within 1.6 km of a well, a distance that brine could migrate over time in glacial outwash sediments. The seven counties with the greatest amounts of wetlands and streams within 0.4 km of wells (distance brine has been shown to migrate over time in glacial till sediments; see Chapter B) included Burke (N. Dak.), Bottineau (N. Dak.), Sheridan (Mont.), Divide (N. Dak.), Mountrail (N. Dak.), Phillips (Mont.), and Renville (N. Dak.). Greater than 1,200 wells, more than 80,000 km^2 of wetlands, and nearly 3,000 km of streams also were identified on or adjacent to (within 1.6 km)

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U.S. Fish and Wildlife Service (USFWS) conservation lands (national wildlife refuges [NWR] and waterfowl production areas [WPA]) in the PPR part of the study area. The five counties with the greatest amount of wells and aquatic resources on or near USFWS lands included Bottineau (N. Dak.), Sheridan (Mont.), Renville (N. Dak.), Burke (N. Dak.), and Divide (N Dak.). Further, it was concluded that a great number of private lands protected by USFWS conservation easements in the PPR were located near wells.

Methods

Spatial Databases

Various spatial databases were gathered relating to oil and gas development (for example, well location, well type, drilling date, hydrocarbon-producing formations), aquatic resources (wetlands, streams), soils, land cover, ownership, and riparian habitats critical to the threatened piping plover. The majority of these data were obtained from government agency Web pages and data outlets or through direct contact with agency personnel. General database descriptions and data sources are presented in table C–1 and a regional characterization of the wells (for example, number of wells by well type, ownership) is presented in the results section. Additional information is provided in the following paragraphs where further descriptions are warranted.

Wells

Data regarding oil and gas wells were acquired (1901–2011) from the individual State (Montana, North Dakota, South Dakota) oil and gas divisions. There is no standard method of data collection and storage between the States; therefore, a crosswalk between the databases was required (see appendix C–1 for crosswalk details). This crosswalk facilitated the creation of a single database containing consistent information regarding all of the permitted wells. Of particular interest was the development of regionally consistent terminology for the well types, which were condensed into the following categories: (1) oil, (2) dry hole, (3) gas, (4) injection, (5) other, and (6) never drilled. Wells categorized as “other” included those classified as confidential, monitor/observation, stratigraphic test, water, or unknown. Although a well is permitted for drilling, it does not necessarily mean that the well was drilled. Many drilling permits are simply cancelled or have expired, yet they still exist within the State records and databases; these sites were categorized as “never drilled” and excluded from all analyses.

Wetlands

Two distinct wetland databases were used for various analyses; a brief description follows to clarify the differences between them. The standard USFWS National Wetlands Inventory (NWI) database (U.S. Fish and Wildlife Service, 2010) was relied on for broad comparisons across the entire study area. In addition to the standard NWI database, a modified NWI database covering a large part of the PPR also was obtained from the USFWS Habitat and Population Evaluation Team (HAPET), located in Bismarck, N. Dak. Daniels County, Mont., is the western extent of this database. With the standard NWI data, it is not uncommon for the various zones (for example, temporary, seasonal) of a single wetland to be mapped separately; thus, a distinct wetland may consist of two or more polygons with unique classifications. For the modified NWI database provided by the HAPET, contiguous polygons representing a wetland were collapsed into a single polygon and classified according to the most permanent classification of the individual polygons. Figure C–1 depicts a palustrine emergent wetland from the standard NWI where temporary (area designated PEMA) and seasonal (area designated PEMC) zones were delineated and mapped with contiguous polygons. In the HAPET database, these two polygons would be combined and categorized as PEMC. This modified database allowed for inclusion of the number and the entire surface area of wetlands in various analyses and data summaries because each wetland was represented by a single polygon and could not be counted multiple times.

Streams

Stream data were obtained from the USGS, medium resolution National Hydrography Dataset (NHD) (U.S. Geological Survey, 2009). Although the NHD contains extensive spatial data representing the surface-water features within the United States, the primary focal areas of this study were flow-line features such as streams and rivers; thus, only features coded as ‘stream/river’ (feature codes are 46000, 46003, 46006, or 46007) were used for analyses.

Soils

Primary factors regulating hydraulic conductivity and the migration of brines through soils include precipitation and soil permeability. Therefore, estimates of soil permeability can be useful when assessing the potential for subsurface brine migration from a given site. There are numerous geologic databases (Soller and Packard, 1998; Stoeser and others, 2007) that can be used to estimate this variable, but they have a very coarse spatial resolution and reference the deeper geologic layers. The U.S. Department of Agriculture (2010), Natural Resources Conservation Service, Soil Survey Geographic (SSURGO) database characterizes the surface soils at a relatively fine scale (1:24,000) and includes rough surrogates for permeability such as drainage class (for example, well drained, poorly drained) and soil texture (for example, percent clay or sand). The drainage class identifies the natural drainage conditions of the soil and refers to the frequency and duration of wet

Table C–1. Description of spatial databases in the Williston Basin.

Database	Source(s)/description
Wells	Information relating to well type, permit date, location, and status was obtained from the following State regulating agencies: 1. Montana Department of Natural Resources & Conservation (web site accessed February 18, 2011, at *http://dnrc.mt.gov/#*). 2. North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division (web site accessed February 18, 2011, at *https://www.dmr.nd.gov/oilgas/*). 3. South Dakota Department of Environment and Natural Resources, Minerals and Mining Program, Oil and Gas Section (web site accessed February 18, 2011, at *http://denr.sd.gov/des/og/oghome.aspx*). • Well data were obtained for the time period January 1, 1901, to February 18, 2011.
Wetlands	Wetland data were obtained from the U.S. Fish and Wildlife Service (USFWS), National Wetlands Inventory (NWI; web site accessed May 1, 2010, at *http://www.fws.gov/wetlands/*). A modified NWI database was obtained from the USFWS, Habitat and Population Evaluation Team (HAPET) located in Bismarck, North Dakota (web site accessed July 1, 2013, at *http://www.ppjv.org/hapet/hapet_bismark.htm*). The HAPET database (version January 17, 2001) covers only the majority of Prairie Pothole Region of the study area (fig. A–1); Daniels County, Montana, is the westernmost county included.
Streams	Stream data were obtained from the U.S. Geological Survey (USGS), National Hydrography Dataset (NHD; web site accessed November 1, 2009, at *http://nhd.usgs.gov/*).
Land cover	Land cover data were obtained from the USGS National Land Cover Database 2006 (NLCD; web site accessed July 1, 2013, at *http://landcover.usgs.gov/index.php*).
Land ownership	Land ownership information was obtained from the USGS Protected Areas Database, version 1.1 (web site accessed July 1, 2013, at *http://gapanalysis.usgs.gov/padus/data/additional-data/*).
Regional and geologic boundaries	Boundaries for the Williston Basin and Bakken Formation were obtained from the USGS, National Assessment of Oil and Gas Project (web site accessed July 1, 2013, at *http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment.aspx*). The Prairie Pothole Region boundary was provided by the USGS, Northern Prairie Wildlife Research Center (web site accessed July 1, 2013, at *http://www.npwrc.usgs.gov/*).
Critical habitat	The USFWS provided two databases identifying critical habitat areas for the threatened piping plover (*Charadrius melodus*). The first is the critical habitat as outlined in the Code of Federal Register (web site accessed July 1, 2013, at *http://www.fws.gov/plover/*). The second unpublished dataset includes the critical habitat and other basins included in annual census monitoring because of their high potential to provide piping plover habitat. The extra basins are foraging basins or nesting basins that did not have the history required to be designated critical habitat.
Soils	Soils information was obtained from the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), Soil Survey Geographic (SSURGO) database (web site accessed , October 1, 2010, at *http://soils.usda.gov/survey/geography/ssurgo/description.html*). Variables obtained from the SSURGO database include land capability classification, farmland classification, and drainage class.

periods. A drainage class was assigned to each well based on the dominant soil associated with it.

Piping Plover Critical Habitat

The NWI and NHD provide general habitat (wetlands, streams) information that can be related to taxa of interest, such as waterfowl, but these data do not provide species-specific habitat information. Alternatively, spatial data were obtained that identified critical riparian habitats of the threatened piping plover, which is considered a management priority for the USFWS. These data were included in various analyses to evaluate the proximity of critical habitats to wells and provide an example of how habitat data can be used to supplement the well, NWI, and NHD information.

Spatial Characterizations

Overview

Various spatial characterizations and analyses were performed to identify areas with the greatest likelihood of containing brine-contaminated aquatic resources based primarily on locations of wells, wetlands, and streams. A generalized regional assessment was performed for the area defined by the boundaries of the Williston Basin and Bakken Formation within the United States (hereafter referred to as the study

EXPLANATION

PEMA	Temporary zone
PEMC	Seasonal zone

Figure C–1. A wetland from the National Wetlands Inventory database where the wetland zones are mapped separately with contiguous polygons.

area; fig. A–1) by identifying counties with the greatest total number and density of wells and aquatic resources. This type of spatial examination, however, presents a form of the modifiable area unit problem (Openshaw, 1984) in that it does not account for the distribution of wells and aquatic resources within the area of interest. Therefore, a more focused proximity analysis was performed for the PPR part of the study area (the part where the PPR overlays the study area; fig. A–1), which identified counties with the greatest amount of aquatic resources proximate to wells. A similar proximity analysis also was done to identify counties with the greatest number USFWS resources near wells.

Policies were enacted during the 1970s to regulate the usage of unlined, earthen reserve pits for produced waters. These regulations required the lining of pits to reduce the likelihood of leaching saline contamination into the shallow groundwater system. Comprehensive information or spatial data pertaining to the location of reserve or evaporation pits were unavailable. However, assumptions were made that wells activated prior to approximately 1980 were more likely to be associated with unlined pits, and these sites would have a higher likelihood of brines leaching into soils and the shallow groundwater system and migrating to wetlands and streams. Therefore, the proximity analyses also were performed on only those wells drilled prior to 1980 to identify counties with the greatest amount of aquatic resources proximate to wells likely associated with the older, unlined pits.

These approaches for identifying areas with a greater likelihood of containing brine-contaminated aquatic resources are based on two overall assumptions. First, areas with the greatest total number and densities of wells, wetlands, and streams have a higher probability that oil and gas production activities would affect aquatic resources. Second, it is expected that the highest probability of brine contamination would exist in areas with the greatest number of wetlands and streams proximate to wells. These theories rely on the random occurrence of potentially harmful activities or events (for example, brine spills, leaching from reserve pits) across the region. Realistically, however, older wells likely pose a greater threat because they often are associated with unlined reserve or evaporation pits, produce a greater proportion of brine to oil and gas (Veil and others, 2004), and are associated with aging infrastructure that is more likely to fail.

Oil and gas production wells are most often associated with brine contamination; however, all related well types were considered for assessments because most drilling activities result in wells that pass through geologic formations containing saline waters and require a reserve or evaporation pit. Therefore, there is some potential risk associated with leakage, seepage, or spills from well holes, leaching from reserve or evaporation pits, pipelines, storage-tank batteries, and over-the-road transportation. As an example, wells used to obtain water for drilling purposes often target deep saline reserves. Further, the classification of a well can change over time. For instance, it is uncommon to drill a well specifically for disposal; rather, expired oil and gas wells are often reopened and used as injection wells. Thus, current injection wells likely were production wells in the past. For all analyses described below, the number of wells included all types that were drilled (table C–2), wetlands included those classified as temporary, seasonal, semipermanent, lake, or riverine, and streams included segments classified as stream/river. For the characterization of the Williston Basin, wetland surface areas were calculated from the standard NWI, while the proximity analyses were performed using the modified NWI database from the HAPET; stream lengths for all analyses were obtained from the NHD.

Characterization of the Williston Basin

A general spatial characterization and evaluation were performed on the study area with the goal of identifying counties with the greatest likelihood of containing brine-contaminated aquatic resources based on the total number and density of wells, wetlands, and streams. Density is defined as the number of wells, square kilometers of wetlands, or kilometers of streams divided by the square kilometers of the county that falls within the study area. Counties were ranked (1–68, where 1 is the highest rank) by total number and density of wells, surface area and density of wetlands, and length and density of streams; overall ranks for total number and density were calculated as the mean of the three individual ranks (wells, wetlands, and streams). For this overall evaluation, counties were assessed on the basis of the mean ranks; thus, wells, wetlands, and streams were weighted equally.

Table C–2. Number of wells permitted from January 1, 1901, to February 18, 2011, by well type and State in the Williston Basin.

Well type	Montana	North Dakota	South Dakota	Total
Oil	3,627	9,243	309	13,179
Dry hole	3,234	5,813	472	9,519
Gas	4,620	327	170	5,117
Never drilled	1,053	2,564	63	3,680
Injection	768	1,259	90	2,117
Other[1]	98	1,276	--	1,374
Total	**13,400**	**20,482**	**1,104**	**34,986**

[1] Includes wells classified as confidential, monitor/observation, stratigraphic test, water, or unknown.

Proximity Analyses of the Prairie Pothole Region

The extent was estimated for the PPR part of the study area that aquatic habitats were proximate to wells in order to identify counties with the greatest likelihood of containing brine-contaminated aquatic resources. This proximity analysis accounts for the spatial distribution of wells and aquatic resources and includes a distance measure to help identify areas with the greatest potential for containing brine-contaminated aquatic resources. This evaluation was limited to the PPR because of the ecological importance of the region's aquatic resources, most notably the pothole wetlands that characterize the area. In addition, the modified NWI database provided by the HAPET covered only a majority of the PPR and did not extend to the remainder of the study area. The standard NWI data are not conducive to this type of analysis because wetlands consisting of multiple polygons are difficult to classify and could be counted more than once; additionally, it is difficult to determine the entire surface area of individual multipolygon wetlands over a large spatial extent.

To evaluate the spatial relations between wells and aquatic resources, a GIS (ArcGIS 10, service pack 1) was used to calculate radial buffers of 0.4 km, 0.8 km, and 1.6 km around each well located within the PPR part of the study area. These buffers were meant to represent distances that brine could migrate over time from a point source, such as an unlined reserve pit, to wetlands and streams. These buffer distances were selected on the basis of expert opinion supported by geophysical field surveys and water-quality monitoring aimed at evaluating subsurface brine migration within the Williston Basin (see chapter B of this report).

For proximity analyses, the number and surface area of wetlands and length of streams within the three buffers were calculated and summed by county. The entire surface area of the wetland was considered, not just the part of the wetland that fell within the buffer; however, stream length was calculated as the segment that fell within the buffer. Additionally, the area within the buffers designated as piping plover critical habitat was calculated using the spatial database provided by the USFWS. Buffers were merged when they overlapped so as not to double-count wetlands, stream segments, or parcels of critical habitat.

Proximity Analyses of U.S. Fish and Wildlife Service Lands

A more focused proximity analysis was performed to identify counties in the PPR part of the study area with the greatest number of wells and aquatic resources located on or near USFWS managed lands, specifically NWRs and WPAs. Similar to the overall PPR analysis, radial buffers of 0.4 km, 0.8 km, and 1.6 km were calculated around each USFWS parcel (instead of buffers around wells) and the wells, wetlands, and streams within each buffer (including within the parcel) were inventoried. The number of wells, surface area of wetlands, and length of streams within each buffer were summed by county, and each county was ranked based on the well, wetland, and stream summaries. These three individual county ranks were averaged by buffer distance (0.4, 0.8, 1.6 km) and counties were assigned overall rank by calculating an average across the three buffers. Only counties with at least 10 wells within each buffer were considered for the overall comparison so that counties that ranked highly for wetlands and streams, but contained only a few wells, would not unduly influence interpretation of the analysis.

In addition to NWRs and WPAs owned in fee title, the USFWS also administers nearly 30,000 conservation easements throughout the Dakotas and Montana. Wetland and grassland easements are legal agreements between private landowners and the U.S. Government where, in exchange for financial compensation, landowners agree to a number of contractual stipulations designed to maintain wetland and grassland habitats. Regardless of the type of easement, landowners continue to own and manage the land; however, in the case of wetland easements, they agree to not drain, fill, level, or burn, and in the case of grassland easements, they consent to not convert the grassland to other uses. Although USFWS conservation easements do not have legal jurisdiction relative to effects of brine contamination from oil and gas development (easements typically specify physical disturbances such as draining, filling, burning), these tracts of land still represent at-risk areas of existing habitat that are important to USFWS trust species, especially migratory birds. The number of USFWS easement land parcels (summarized by contract, circa 2010) intersected by the three buffers (0.4, 0.8, and 1.6 km) around wells was identified to determine the extent at which these lands are proximate to wells. This USFWS proximity analysis differs from the one previously described because of data limitations.

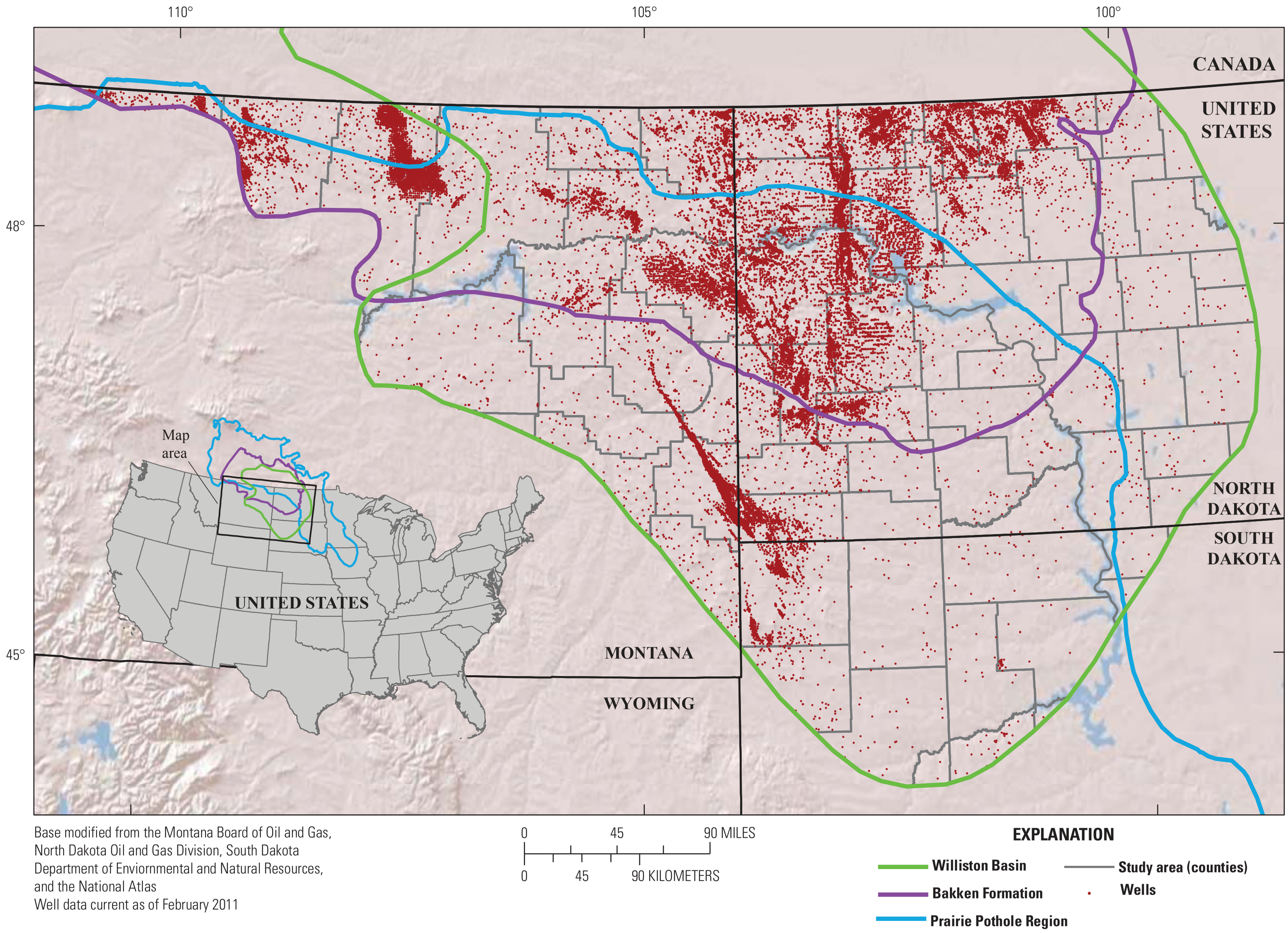
Results

Well Characteristics

The regional analyses identified 34,986 oil- and gas-related wells (table C–2) in the study area that were permitted from January 1901 to February 2011, of which 31,306 were drilled. Of the well types considered, approximately 38 percent were classified as oil, followed by dry hole (27 percent), gas (15 percent), injection (6 percent), and other (4 percent); the 10 percent classified as never drilled were excluded from all analyses. Based on the overall spatial distribution of the drilled wells, it is evident that the majority of the activity has taken place in western North Dakota and northeastern Montana (fig C–2). North Dakota contained the greatest number of wells, followed by Montana and South Dakota (table C–2). Nearly 25,000 of the wells, or 80 percent, were located on private lands, with lower proportions on U.S. Government and State/local government, and Native American lands (table C–3). A majority (89 percent) of wells were located on lands classified by the USGS National Land Cover Database as herbaceous grasslands (15,930 wells) and cultivated croplands (11,766 wells) (table C–4). On the basis of the SSURGO land capability and farmland classifications, a greater number of wells were sited on nonprime farmland than other classifications (table C–5).

A majority of the wells within the study area were permitted after 1950, with noticeable peaks in drilling activity around 1960, 1980, and the present (circa 2011; fig. C–3); these trends are consistent when examined at the State level (fig. C–4). The likelihood of aquatic resources being contaminated by brines is not solely related to the number of wells drilled near wetlands and streams. The amount of brine produced per barrel of oil typically increases as more barrels of oil and gas are extracted (Veil and others, 2004); thus, actual oil and gas production is the key. Data from the North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division (2011) show that trends in oil production closely follow trends in well drilling (fig. C–5), suggesting that well permitting and drilling activity are good surrogates for predicting trends in production and evaluating potential for brine contamination.

A drainage class was assigned to each well based on the dominant soil; however, drainage class was only determined for 30,894 out of the 31,306 permitted and drilled wells because of data limitations. On the basis of this classification, approximately 95 percent of wells were located on well drained or excessively drained soils; the remaining 5 percent of wells were situated on poorly drained soils (table C–6).



Base modified from the Montana Board of Oil and Gas, North Dakota Oil and Gas Division, South Dakota Department of Enviornmental and Natural Resources, and the National Atlas
Well data current as of February 2011

Figure C–2. Spatial distribution of drilled wells within the Williston Basin and Bakken Formation in the United States.

Table C–3. Number of drilled wells by land ownership and State in the Williston Basin.

Ownership	Montana	North Dakota	South Dakota	Total
Private	9,231	14,883	748	24,862
U.S. Government	1,992	1,786	59	3,837
State/local	736	543	154	1,433
Native American	360	699	78	1,137
Unknown	28	7	2	37
Total	**12,347**	**17,918**	**1,041**	**31,306**

Table C–4. Number of wells drilled per State by land cover classifications in the Williston Basin.

[--, no record]

Land cover	Montana	North Dakota	South Dakota	Total
Grassland/herbaceous	7,539	7,527	864	15,930
Cultivated crops	3,264	8,441	61	11,766
Shrub/scrub	995	290	46	1,331
Pasture/hay	59	710	44	813
Developed, open space	210	406	12	628
Barren land (rock/sand/clay)	108	145	2	255
Emergent herbaceous wetlands	41	195	3	239
Developed, low intensity	37	87	--	124
Woody wetlands	51	35	3	89
Deciduous forest	3	51	--	54
Evergreen forest	24	5	5	34
Open water	9	17	1	27
Developed, medium intensity	7	1	--	8
Mixed forest	--	8	--	8
Total	**12,347**	**17,918**	**1,041**	**31,306**

Spatial Characterization of Oil and Gas Development and Aquatic Resources

Williston Basin

Mean densities for the 68 counties in the study area (fig. C–6) with at least one well, wetland, and stream segment were 0.11 wells/km^2 (range less than 0.01–0.65), 0.06 km^2 of wetlands/km^2 (range less than 0.01–0.33), and 0.67 km of streams/km^2 (range 0.13–1.29). The total number and density of wells for each county are presented in table C–7; data are presented for all drilled wells (all years) and for only the 13,349 wells drilled prior to 1980. Figure C–7 depicts the five counties with the greatest number of wells drilled during all years and those drilled prior to 1980. The five counties with the highest number of wells (all years) were: (1) McKenzie, N. Dak., (2) Fallon, Mont., (3) Phillips, Mont., (4) Bottineau, N. Dak., and (5) Williams, N. Dak. The five counties with the highest number of wells drilled prior to 1980 were: (1) Bottineau, N. Dak., (2) McKenzie, N. Dak., (3) Phillips, Mont., (4) Fallon, Mont., and (5) Williams, N. Dak. Table C–8 lists the area, mean and individual ranks, number and density of wells, surface area and density of wetlands, and length and density of streams for each county within the study area. The seven counties with the greatest likelihood of containing brine-contaminated aquatic resources, based on the mean ranks (that is, greatest total number or densities of wells and aquatic resources), are depicted in figure C–8. McKenzie County (N. Dak.) was ranked highest on the basis of total numbers and densities; the six other highly ranked counties included Phillips (Mont.), Valley (Mont.), Williams (N. Dak.), Dunn (N. Dak.), Mountrail (N. Dak.), and Bowman (N. Dak.) (fig. C–8). The seven counties represent the five counties with the highest mean ranks based on density and total number; McKenzie, Williams, and Dunn Counties ranked in the top five for both categories.

Prairie Pothole Region

A general inventory of the approximately 78,200 km^2 of the PPR part of the study area identified 10,361 wells, 860,132 wetlands, 24,848 km of streams, and 436 km^2 of piping plover critical habitat. The surface area and total number of wetlands, length of streams, and area of critical habitat within each of the three radial buffers around wells are presented in tables C–9 (wetlands) and C–10 (streams, habitat). The buffer inventories were performed on all well types together and individually to allow for specific investigations or comparisons; hereafter all discussions will focus solely on analyses performed on all well types. Overall, of the 860,132 wetlands identified in the PPR, approximately 7 percent, 17 percent, and 34 percent were within the 0.4-km, 0.8-km, and 1.6-km buffers, respectively. Specifically, there were 62,718 total wetlands covering 501 km^2, 1,380 km of streams, and 5 km^2 of critical habitat proximate (within 0.4-km buffer) to wells in the PPR. The intermediate (0.8-km) buffer included 146,978 total wetlands covering 975 km^2, 3,291 km of streams, and 22 km^2 of critical habitat. Expanding the buffer area to 1.6 km resulted in a relatively large increase in all variables with estimates of 292,745 total wetlands covering 1,780 km^2, 7,147 km of streams, and 79 km^2 of piping plover critical habitat within this largest buffer.

Each county in the PPR was ranked on the basis of the surface area of wetlands and length of streams within the 0.4-km buffers around wells to identify areas where these

Table C–5. Number of wells drilled per State by land capability classification and farmland classification in the Williston Basin.

[--, no record]

Land capability classification, nonirrigated soils	Montana	North Dakota	South Dakota	Total
None	135	22	3	160
Soils have moderate limitations that reduce the choice of plants or require moderate conservation practices	--	7,963	80	8,043
Soils have severe limitations that reduce the choice of plants or require special conservation practices, or both	4,689	2,387	82	7,158
Soils have very severe limitations that restrict the choice of plants or require very careful management, or both	3,047	2,265	248	5,560
Soils have little or no hazard of erosion but have other limitations, impractical to remove, that limit their use mainly to pasture, range, forestland, or wildlife food and cover	19	8	2	29
Soils have severe limitations that make them generally unsuited to cultivation and that limit their use mainly to pasture, range, forestland, or wildlife food and cover	3,052	2,774	444	6,270
soils have very severe limitations that make them unsuited to cultivation and that restrict their use mainly to grazing, forestland, or wildlife	1,397	2,045	173	3,615
Soils and miscellaneous areas have limitations that preclude their use for commercial plant production and limit their use to recreation, wildlife, or water supply or for esthetic purposes	8	454	9	471
Total	**12,347**	**17,918**	**1,041**	**31,306**
Farmland classification				
None	1,624	--	--	1,624
All areas are prime farmland	--	2,981	2	2,983
Farmland of local importance	--	7	--	7
Farmland of statewide importance	2,156	4,079	87	6,322
Not prime farmland	7,888	10,060	920	18,868
Prime farmland if drained	--	720	--	720
Prime farmland if irrigated[1]	679	71	32	782
Total	**12,347**	**17,918**	**1,041**	**31,306**

[1] Includes soils classified as (1) prime farmland if irrigated and (2) prime farmland if irrigated and the product of I (soil erodibility) x C (climate factor) does not exceed 60.

aquatic resources have the greatest potential to be affected by oil and gas production activities. The seven counties with the greatest surface area of wetlands or kilometers of streams proximate to wells were: Burke (N. Dak.), Bottineau (N. Dak.), Sheridan (Mont.), Divide (N. Dak.), Mountrail (N. Dak.), Phillips (Mont.), and Renville (N. Dak.) (fig. C–9). County area, surface area and number of wetlands, and stream length are presented by county for each of the three buffers in table C–11. The seven counties represent the five counties with the highest mean ranks based on wetlands and streams; Bottineau, Burke, and Sheridan Counties ranked in the top five for both variables.

Of the 13,349 wells drilled prior to 1980 in the study area, 5,446 were located within the PPR part of the study area. On the basis of the buffer inventories performed on these PPR wells, it was determined that approximately 4 percent, 11 percent, and 24 percent of the 860,132 PPR wetlands fell within the 0.4-km, 0.8-km, and 1.6-km buffers, respectively. There were 285 km^2 of wetlands (37,583 wetlands), 736 km of streams, and 2 km^2 of piping plover critical habitat proximate (within the 0.4-km buffer) to all wells drilled prior to 1980 (tables C–12, C–13). The intermediate (0.8 km) buffer included 605 km^2 of wetlands (92,910 wetlands), 2,091 km of streams, and 10 km^2 of critical habitat, while the largest buffer (1.6 km) encompassed 1,288 km^2 of wetlands (206,805 wetlands), 5,002 km of streams, and 38 km^2 of critical habitat (tables C–12, C–13). For all wells drilled prior to 1980, the surface area and total number of wetlands, length of streams, and area of piping plover critical habitat within each of the three buffers are presented in tables C–12 (wetlands) and C–13 (streams, habitat) for all combined well types and for each separate well type.

Similar to the overall PPR analyses, each county was ranked on the basis of the surface area of wetlands and length

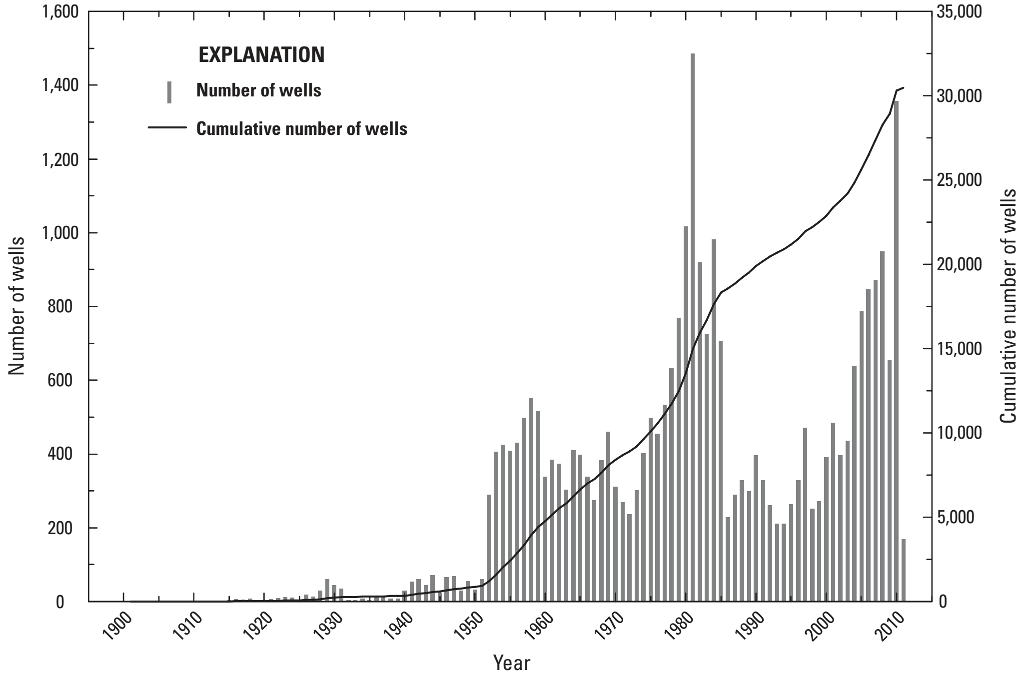


Figure C–3. Number of permitted and drilled wells by drilling year; there were 842 wells that did not have a drilling date associated with them. Data represent the entire year from 1901 to 2010 and January 1 through February 18, 2011.

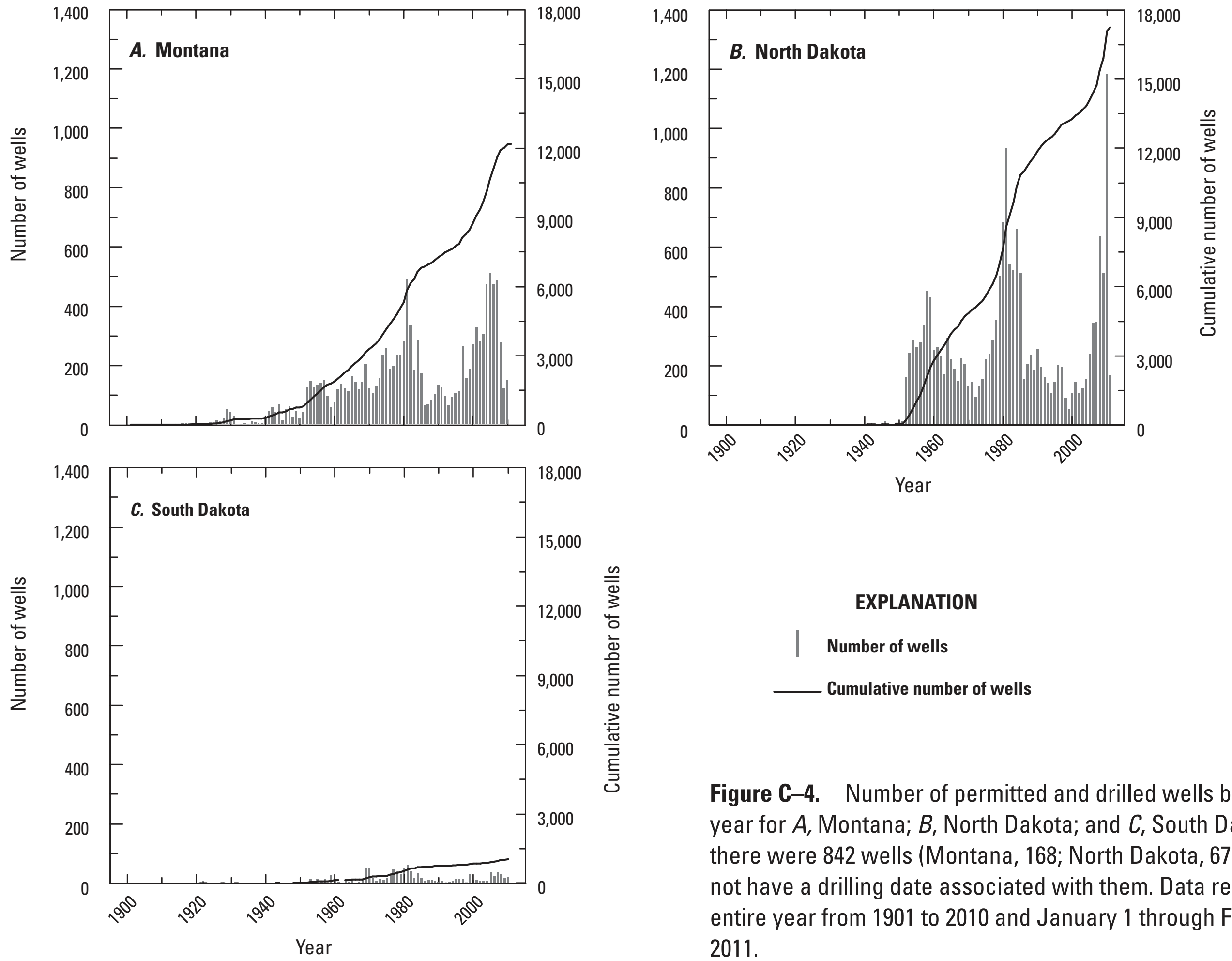


Figure C–4. Number of permitted and drilled wells by drilling year for *A*, Montana; *B*, North Dakota; and *C*, South Dakota; there were 842 wells (Montana, 168; North Dakota, 674) that did not have a drilling date associated with them. Data represent the entire year from 1901 to 2010 and January 1 through February 18, 2011.

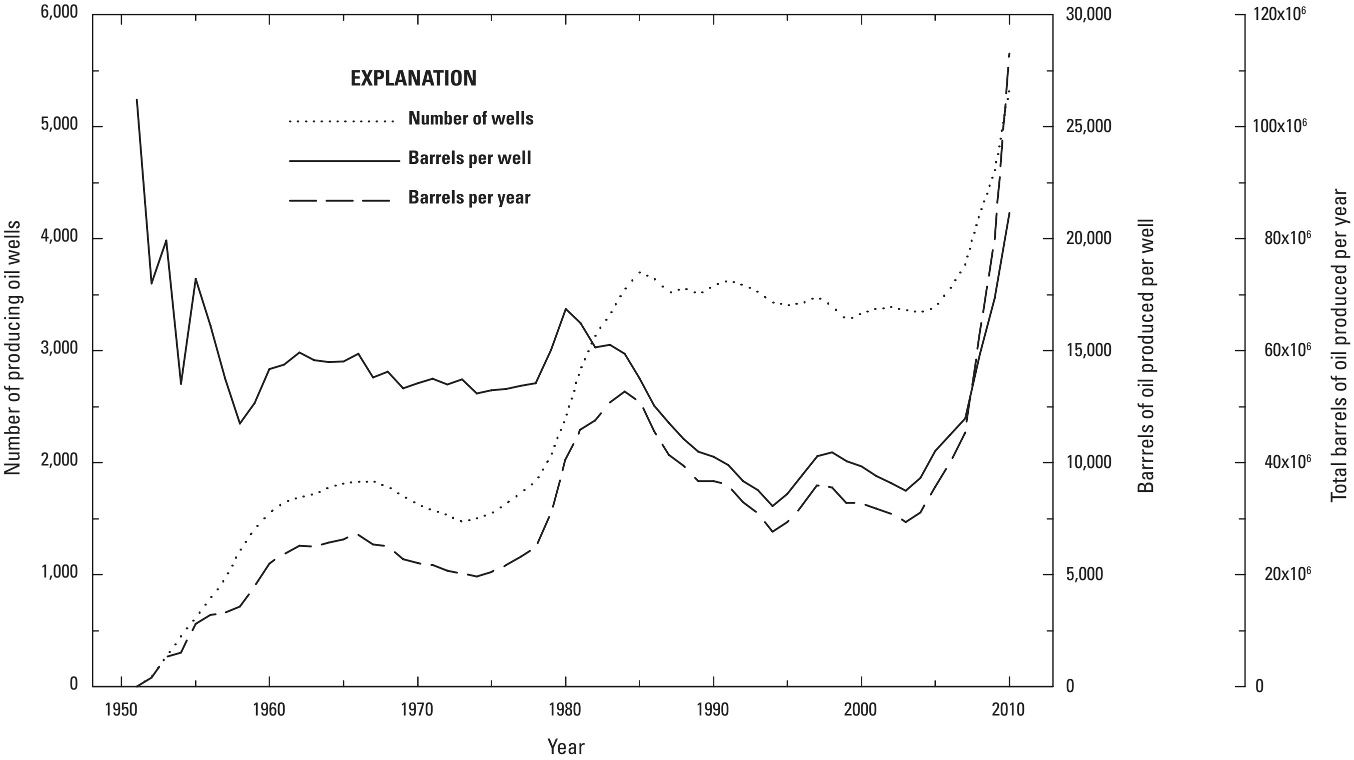


Figure C–5. Number of producing wells, barrels of oil produced per well, and total barrels of oil produced per year for North Dakota from 1951 to 2010.

of streams within the 0.4-km buffers around wells drilled prior to 1980. The seven counties with the greatest surface area of wetlands or kilometers of streams proximate to the pre-1980 wells were: Bottineau (N. Dak.), Burke (N. Dak.), Sheridan (Mont.), Renville (N. Dak.), Ward (N. Dak.), Phillips (Mont.), and Williams (N. Dak.) (fig. C–10). County area, surface area and number of wetlands, and stream length are presented by county for each of the three buffers in table C–14. The seven counties represent the five counties with the highest mean ranks based on wetlands and streams; Bottineau, Burke, and Renville Counties ranked in the top five for both variables.

U.S. Fish and Wildlife Service Lands

There were approximately 1,716 km^2 of USFWS lands in the PPR part of the study area, and 323, 604, and 1,233 wells were identified within the 0.4-km, 0.8-km, and 1.6-km buffers around these lands, respectively. Additionally, 67,110 km^2 (51,797 wetlands), 72,779 km^2 (92,628 wetlands), and 81,505 km^2 (200,629 wetlands) of wetlands and 1,215, 1,702, and 2,913 km of streams were identified within the small, intermediate, and large buffers, respectively. The area of USFWS lands, total buffer area around these lands (including parcel), number of wells, surface area of wetlands, and length of streams for each of the three buffers are presented by county in table C–15. There were five counties that contained at least 10 wells within each of the buffer zones, and these counties were assigned a mean rank based on the number of wells and extent of aquatic resources on or adjacent to USFWS lands. On the basis of these ranks, Bottineau County (N. Dak.) contained the greatest number of wells and aquatic resources on or near USFWS lands, followed by Sheridan (Mont.), Renville (N. Dak.), Burke (N. Dak.), and Divide (N Dak.) (fig. C–11).

In addition to the above proximity analysis, the numbers of USFWS conservation easement land parcels that were intersected by the three buffers around wells were identified to determine the degree at which these lands are proximate to wells. On the basis of this simple assessment, it was determined that the 0.4-km, 0.8-km, and 1.6-km buffers intersected 1,792, 2,455, and 3,613 easement contracts in the PPR of the study area, respectively. Although an accurate number of how many wetlands are associated with the easement tracts intersected by the buffers is not known, the number is likely large because data suggest that the mean wetland density in the PPR part of the study area is approximately 11 wetlands/km^2, and about one-third of wetlands were within the 1.6-km buffer around wells. The actual number of wetlands was not determined because a GIS database of easement boundaries was unavailable; a spatial layer containing the three buffers was provided to the USFWS, and they provided the aforementioned summaries.

Table C–6. Number and percentage of wells drilled in each Soil Survey Geographic database (SSURGO) soil drainage classification.

Drainage class	Number of wells	Percent of wells
Excessively drained		
Water is removed from the soil very rapidly. Internal free water commonly is very rare or very deep. The soils are commonly coarse textured and have very high saturated hydraulic conductivity class or are very shallow.	699	2.26
Somewhat excessively drained		
Water is removed from the soil rapidly. Internal free water commonly is very rare or very deep. The soils are commonly coarse textured and have high saturated hydraulic conductivity or are very shallow.	600	1.94
Well-drained		
Water is removed from the soil readily, but not rapidly. Internal free-water commonly is deep or very deep; annual duration is not specified. Water is available to plants in humid regions during much of the growing season. Wetness does not inhibit growth of roots for significant periods during most growing seasons.	26,104	84.50
Moderately well-drained		
Water is removed from the soil somewhat slowly during some periods of the year. Internal free water commonly is moderately deep and may be transitory or permanent. The soil is wet for only a short time within the rooting depth during the growing season, but long enough that most mesophytic crops are affected. The soil commonly has a moderately low, or lower, saturated hydraulic conductivity class within 1 meter of the surface or periodically receives high rainfall, or both.	2,054	6.65
Somewhat poorly drained		
The soil is wet at a shallow depth for significant periods during the growing season. Internal freewater is commonly shallow to moderately deep and transitory to permanent. Unless the soil is artificially drained, the growth of most mesophytic plants is markedly restricted. The soil commonly has a low or very low saturated hydraulic conductivity class, or a high water table, or receives water from lateral flow, or persistent rainfall, or some combination of these factors.	830	2.69
Poorly drained		
The soil is wet at shallow depths periodically during the growing season or remains wet for long periods. Internal free-water is shallow or very shallow and common or persistent. Unless the soil is artificially drained, most mesophytic crops cannot be grown. The soil, however, is not continuously wet directly below plow depth. The water table is commonly the result of low or very low saturated hydraulic conductivity class or persistent rainfall, or a combination of both factors.	477	1.54
Very poorly drained		
Water is at or near the soil surface during much of the growing season. Internal free-water is very shallow and persistent or permanent. Unless the soil is artificially drained, most mesophytic crops cannot be grown. Commonly, the soil occupies a depression or is level. If rainfall is persistent or high, the soil can be sloping.	130	0.42

Discussion

The Williston Basin of the United States is in the midst of an oil boom driven by technological advances that allow for recovery from large hydrocarbon reservoirs associated with deep, low-permeability geologic formations. Concerns have been raised over potential environmental effects associated with past and current oil and gas exploration and recovery. Chief among these concerns is the contamination of wetlands, streams, and shallow groundwater by brines produced with oil and gas. Previous studies have demonstrated brine contamination to aquatic resources, primarily from oil and gas recovery operations prior to the 1980s (Reiten, 1991; Reiten and Tischmak, 1993). However, little research has been performed to assess current effects, and regionwide assessments are lacking. This study characterized the Williston Basin in terms of oil and gas wells and aquatic resources, and counties were identified with the greatest number of wells, wetlands, and streams.

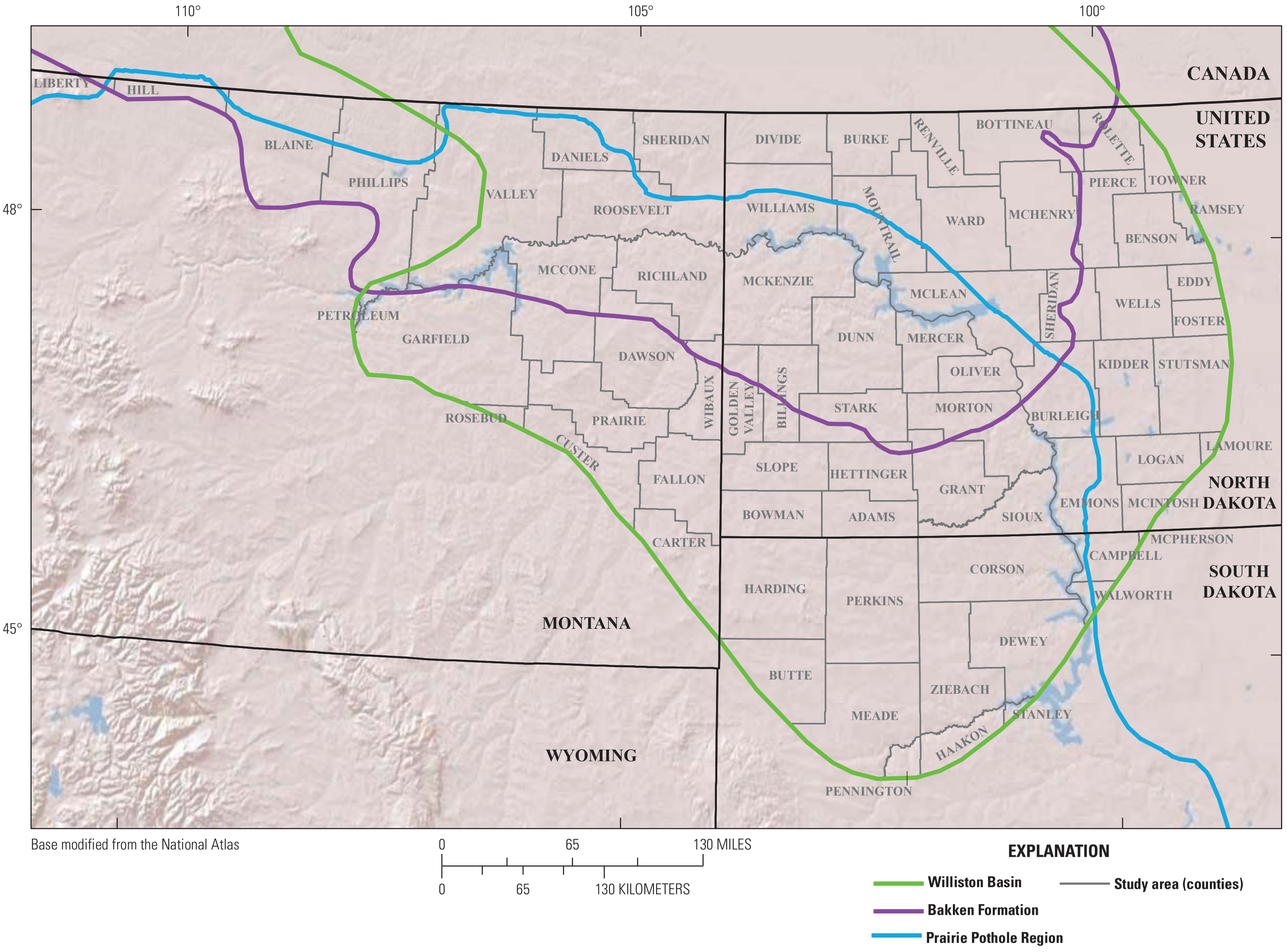


Figure C–6. Counties within the Williston Basin and Bakken Formation.

Table C–7. County area and number and density of wells per county in the Williston Basin.

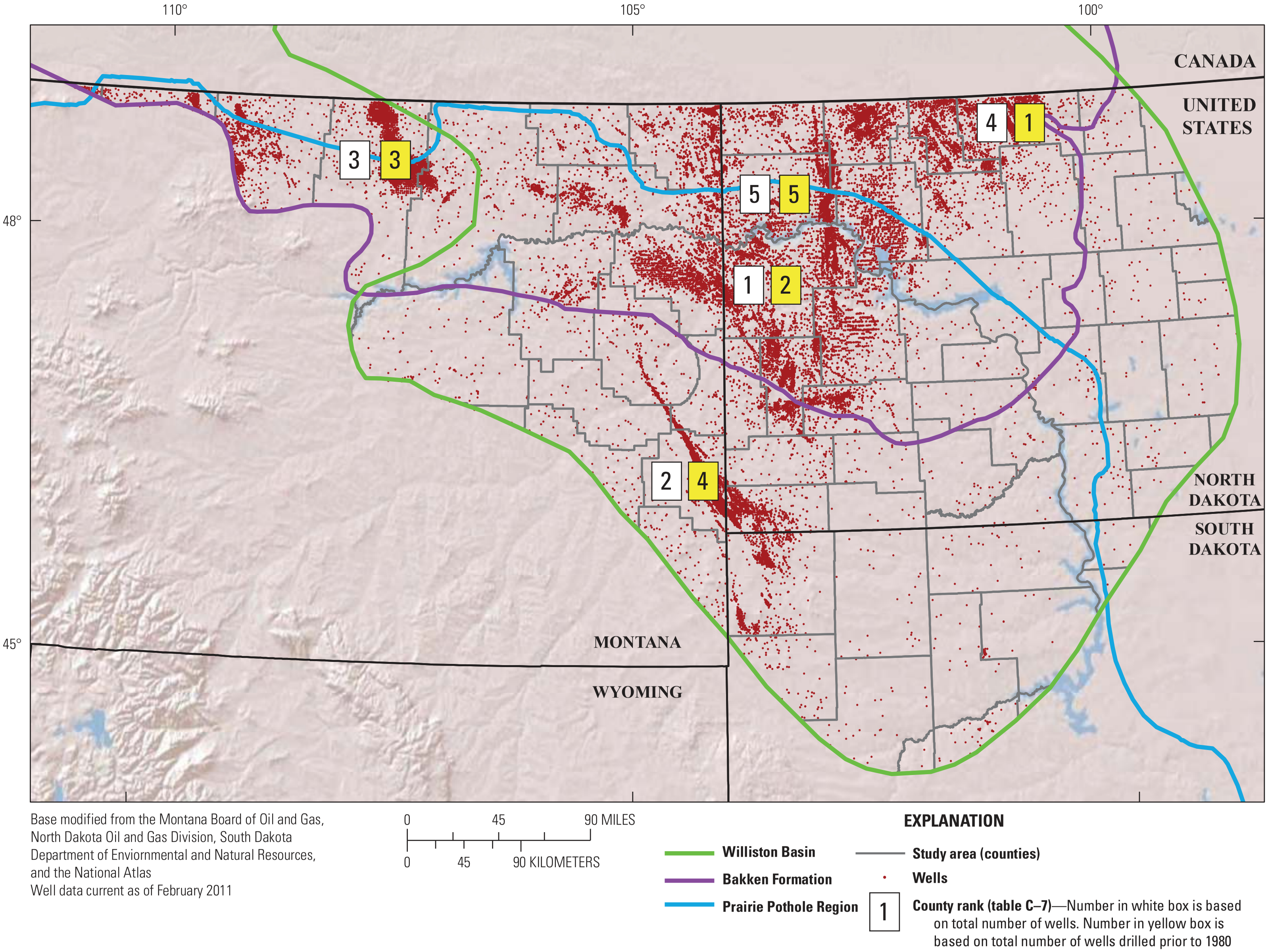
[Well information is provided separately for all wells (all years) and only those wells drilled prior to 1980. km², square kilometer; <, less than; --, no record]

State	County	County area, km^2	Number of wells		Density of wells	
			All years	Pre-1980	All years	Pre-1980
Montana	Blaine	6,686	1,099	497	0.16	0.07
Montana	Carter	3,609	98	74	0.03	0.02
Montana	Custer	3,414	55	47	0.02	0.01
Montana	Daniels	3,694	162	79	0.04	0.02
Montana	Dawson	6,173	348	209	0.06	0.03
Montana	Fallon	4,202	2,719	955	0.65	0.23
Montana	Garfield	11,354	99	75	0.01	0.01
Montana	Hill	1,244	232	81	0.19	0.07
Montana	Liberty	147	66	53	0.45	0.36
Montana	McCone	6,947	330	257	0.05	0.04
Montana	Phillips	9,461	2,447	962	0.26	0.10
Montana	Prairie	4,513	85	63	0.02	0.01
Montana	Richland	5,450	1,624	350	0.30	0.06
Montana	Roosevelt	6,134	1,006	514	0.16	0.08
Montana	Rosebud	429	3	3	0.01	0.01
Montana	Sheridan	4,414	1,050	516	0.24	0.12
Montana	Valley	13,110	621	320	0.05	0.02
Montana	Wibaux	2,303	303	156	0.13	0.07
North Dakota	Adams	2,561	11	5	0.00	0.00
North Dakota	Benson	3,434	19	19	0.01	0.01
North Dakota	Billings	2,987	1,427	412	0.48	0.14
North Dakota	Bottineau	4,397	2,154	1,381	0.49	0.31
North Dakota	Bowman	3,023	1,204	287	0.40	0.09
North Dakota	Burke	2,924	1,413	824	0.48	0.28
North Dakota	Burleigh	4,321	49	44	0.01	0.01
North Dakota	Divide	3,353	630	195	0.19	0.06
North Dakota	Dunn	5,392	1,153	285	0.21	0.05
North Dakota	Eddy	1,165	5	5	<0.01	<0.01
North Dakota	Emmons	4,029	37	25	0.01	0.01
North Dakota	Foster	1,263	11	11	0.01	0.01
North Dakota	Golden Valley	2,596	243	72	0.09	0.03
North Dakota	Grant	4,314	28	23	0.01	0.01
North Dakota	Hettinger	2,937	28	14	0.01	0.00
North Dakota	Kidder	3,711	4	4	<0.01	<0.01
North Dakota	Logan	2,553	18	18	0.01	0.01
North Dakota	McHenry	4,951	162	115	0.03	0.02
North Dakota	McIntosh	1,324	4	4	<0.01	<0.01
North Dakota	McKenzie	7,408	3,033	1,104	0.41	0.15
North Dakota	McLean	6,031	126	36	0.02	0.01

Table C–7. County area and number and density of wells per county in the Williston Basin.—Continued

[Well information is provided separately for all wells (all years) and only those wells drilled prior to 1980. km², square kilometer; <, less than; --, no record]

State	County	County area, km²	Number of wells		Density of wells	
			All years	Pre-1980	All years	Pre-1980
North Dakota	Mercer	2,882	32	22	0.01	0.01
North Dakota	Morton	5,038	38	26	0.01	0.01
North Dakota	Mountrail	5,028	1,491	330	0.30	0.07
North Dakota	Oliver	1,893	16	13	0.01	0.01
North Dakota	Pierce	2,804	43	36	0.02	0.01
North Dakota	Ramsey	549	3	3	0.01	0.01
North Dakota	Renville	2,312	1,336	761	0.58	0.33
North Dakota	Rolette	2,397	49	34	0.02	0.01
North Dakota	Sheridan	2,604	13	9	<0.01	<0.01
North Dakota	Sioux	2,922	6	5	<0.01	<0.01
North Dakota	Slope	3,159	152	88	0.05	0.03
North Dakota	Stark	3,472	544	239	0.16	0.07
North Dakota	Stutsman	4,511	21	19	<0.01	<0.01
North Dakota	Towner	1,059	5	5	<0.01	<0.01
North Dakota	Ward	5,325	450	228	0.08	0.04
North Dakota	Wells	3,342	27	21	0.01	0.01
North Dakota	Williams	5,563	1,933	935	0.35	0.17
South Dakota	Butte	3,996	78	35	0.02	0.01
South Dakota	Campbell	1,760	7	7	<0.01	<0.01
South Dakota	Corson	6,551	30	27	<0.01	<0.01
South Dakota	Dewey	5,545	33	28	0.01	0.01
South Dakota	Haakon	1,805	32	31	0.02	0.02
South Dakota	Harding	6,935	780	286	0.11	0.04
South Dakota	Meade	6,422	29	22	<0.01	<0.01
South Dakota	Pennington	718	2	1	<0.01	<0.01
South Dakota	Perkins	7,486	30	26	<0.01	<0.01
South Dakota	Stanley	236	1	--	<0.01	--
South Dakota	Walworth	624	2	2	<0.01	<0.01
South Dakota	Ziebach	5,105	17	16	<0.01	<0.01
Total		**269,997**	**31,306**	**13,349**		



Base modified from the Montana Board of Oil and Gas, North Dakota Oil and Gas Division, South Dakota Department of Enviornmental and Natural Resources, and the National Atlas
Well data current as of February 2011

Figure C–7. Five counties with the overall greatest number of wells. Numbers in white and yellow boxes, which correspond to rankings from table C–7, are based on the total number of wells and only those drilled prior to 1980, respectively.

Table C–8. Results of the regional evaluation where counties were ranked on the basis of the total number and density of wells, wetlands, and streams in the Williston Basin.

[km, kilometers; km^2, square kilometer; <, less than; --, no record]

State	County	County area, km^2	Mean rank		Wells				Wetlands				Streams			
			Density	Total number	Number	Density	Rank		Area, km^2	Density	Rank		Length, km	Density	Rank	
							Density	Total number			Density	Total number			Density	Total number
Montana	Blaine	6,686	31	18	1,099	0.16	17	13	193	0.03	36	26	4,262	0.64	39	15
Montana	Carter	3,609	40	40	98	0.03	30	31	9	<0.01	61	58	2,757	0.76	28	30
Montana	Custer	3,414	--	--	55	0.02	36	35	--		--	--	3,588	1.05	7	21
Montana	Daniels	3,694	45	41	162	0.04	28	26	22	0.01	58	55	1,642	0.44	49	42
Montana	Dawson	6,173	43	35	348	0.06	24	21	1	<0.01	65	65	3,911	0.63	40	20
Montana	Fallon	4,202	31	30	2,719	0.65	1	2	4	<0.01	63	62	3,100	0.74	30	27
Montana	Garfield	11,354	36	13	99	0.01	42	30	451	0.04	34	7	8,229	0.72	31	3
Montana	Hill	1,244	31	41	232	0.19	16	25	56	0.04	31	43	624	0.50	46	55
Montana	Liberty	147	30	55	66	0.45	6	34	2	0.01	50	64	106	0.72	33	67
Montana	McCone	6,947	36	23	330	0.05	26	22	91	0.01	49	36	4,854	0.70	34	11
Montana	Phillips	9,461	29	8	2,447	0.26	12	3	393	0.04	33	12	5,648	0.60	43	8
Montana	Prairie	4,513	41	39	85	0.02	34	32	0	<0.01	66	66	4,065	0.90	24	19
Montana	Richland	5,450	36	28	1,624	0.30	10	6	16	<0.01	60	56	3,574	0.66	38	22
Montana	Roosevelt	6,134	31	22	1,006	0.16	18	15	118	0.02	39	33	4,155	0.68	36	17
Montana	Rosebud	429	--	--	3	0.01	48	64	--		--	--	177	0.41	50	66
Montana	Sheridan	4,414	31	26	1,050	0.24	13	14	198	0.04	32	25	2,023	0.46	48	38
Montana	Valley	13,110	34	9	621	0.05	27	18	422	0.03	35	8	8,300	0.63	41	2
Montana	Wibaux	2,303	40	43	303	0.13	20	23	2	<0.01	64	63	1,589	0.69	35	43
North Dakota	Adams	2,561	41	47	11	<0.01	58	57	48	0.02	41	47	2,174	0.85	25	37
North Dakota	Benson	3,434	41	39	19	0.01	51	51	396	0.12	8	11	726	0.21	63	54
North Dakota	Billings	2,987	24	31	1,427	0.48	5	8	6	<0.01	62	61	3,197	1.07	5	25
North Dakota	Bottineau	4,397	27	22	2,154	0.49	3	4	315	0.07	22	17	1,333	0.30	56	45
North Dakota	Bowman	3,023	23	29	1,204	0.40	8	11	49	0.02	44	46	2,952	0.98	16	29
North Dakota	Burke	2,924	24	26	1,413	0.48	4	9	284	0.10	14	20	1,011	0.35	55	48
North Dakota	Burleigh	4,321	33	29	49	0.01	38	37	340	0.08	18	15	2,400	0.56	44	34
North Dakota	Divide	3,353	32	32	630	0.19	15	17	289	0.09	15	19	463	0.14	67	59
North Dakota	Dunn	5,392	21	13	1,153	0.21	14	12	386	0.07	23	13	4,358	0.81	27	14

Table C–8. Results of the regional evaluation where counties were ranked on the basis of the total number and density of wells, wetlands, and streams in the Williston Basin.—Continued

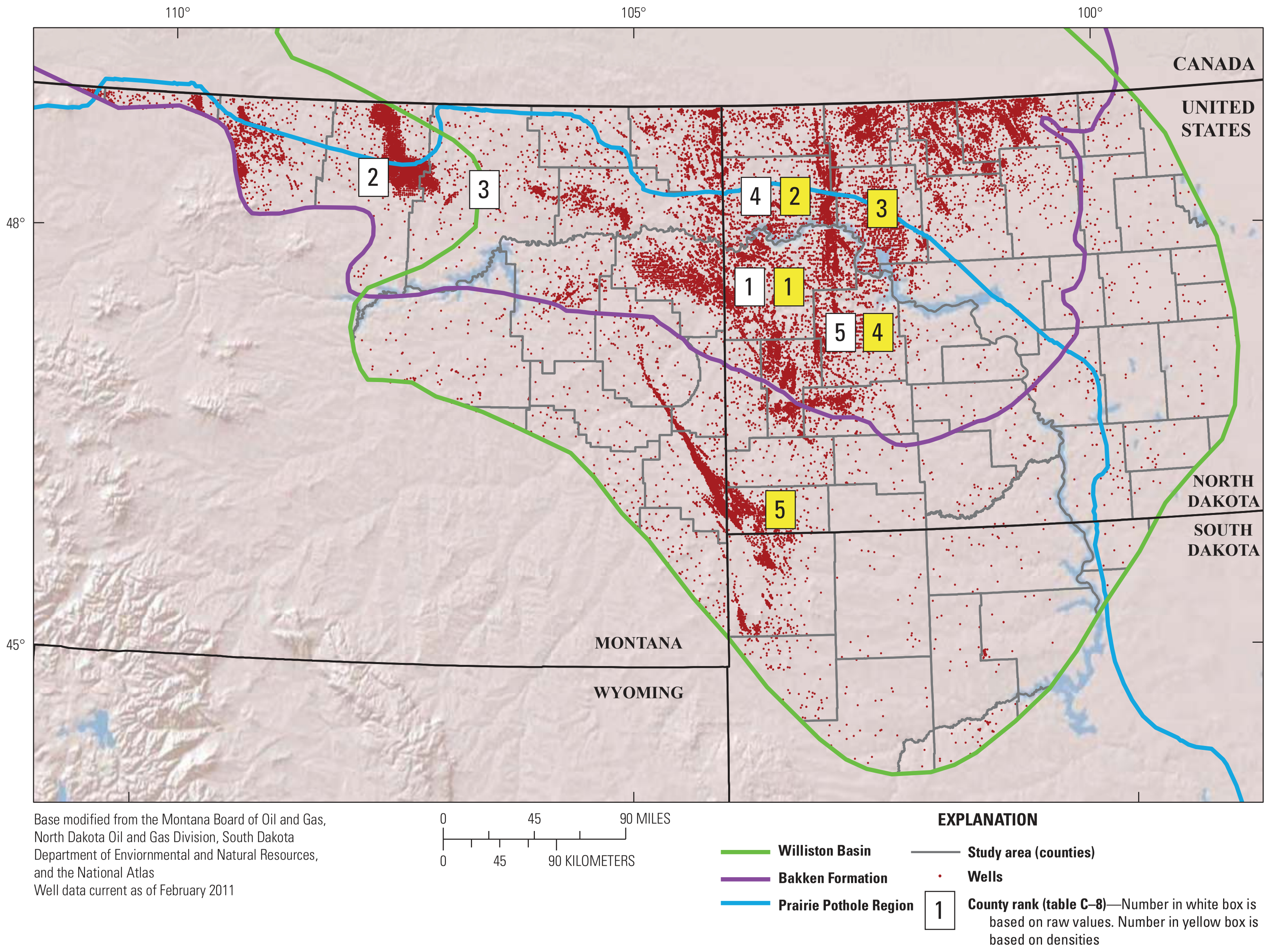
[km, kilometers; km², square kilometer; <, less than; --, no record]

State	County	County area, km²	Mean rank		Wells				Wetlands				Streams			
			Density	Total number	Number	Density	Rank		Area, km²	Density	Rank		Length, km	Density	Rank	
							Density	Total number			Density	Total number			Density	Total number
North Dakota	Eddy	1,165	44	52	5	<0.01	59	61	124	0.11	12	31	297	0.26	60	64
North Dakota	Emmons	4,029	32	29	37	0.01	41	40	230	0.06	29	24	3,420	0.85	26	23
North Dakota	Foster	1,263	39	51	11	0.01	43	56	100	0.08	17	34	374	0.30	57	62
North Dakota	Golden Valley	2,596	34	39	243	0.09	22	24	8	<0.01	59	59	2,459	0.95	20	33
North Dakota	Grant	4,314	38	36	28	0.01	49	48	62	0.01	46	42	4,114	0.95	19	18
North Dakota	Hettinger	2,937	35	41	28	0.01	40	47	55	0.02	42	44	2,690	0.92	22	31
North Dakota	Kidder	3,711	47	42	4	<0.01	68	63	519	0.14	4	4	478	0.13	68	58
North Dakota	Logan	2,553	35	40	18	0.01	47	52	310	0.12	6	18	995	0.39	51	49
North Dakota	McHenry	4,951	34	25	162	0.03	29	27	498	0.10	13	5	1,436	0.29	59	44
North Dakota	McIntosh	1,324	40	49	4	<0.01	65	62	93	0.07	24	35	952	0.72	32	50
North Dakota	McKenzie	7,408	17	4	3,033	0.41	7	1	493	0.07	27	6	7,106	0.96	18	5
North Dakota	McLean	6,031	28	22	126	0.02	31	29	1,321	0.22	2	1	2,309	0.38	52	36
North Dakota	Mercer	2,882	24	30	32	0.01	39	43	328	0.11	9	16	2,603	0.90	23	32
North Dakota	Morton	5,038	35	29	38	0.01	46	39	88	0.02	43	37	4,838	0.96	17	12
North Dakota	Mountrail	5,028	20	15	1,491	0.30	11	7	741	0.15	3	2	2,351	0.47	47	35
North Dakota	Oliver	1,893	35	49	16	0.01	44	54	26	0.01	48	53	1,869	0.99	13	41
North Dakota	Pierce	2,804	36	37	43	0.02	37	38	357	0.13	5	14	411	0.15	65	60
North Dakota	Ramsey	549	39	53	3	0.01	52	65	182	0.33	1	27	85	0.16	64	68
North Dakota	Renville	2,312	30	32	1,336	0.58	2	10	151	0.07	28	28	557	0.24	61	57
North Dakota	Rolette	2,397	32	37	49	0.02	32	36	267	0.11	10	22	846	0.35	54	52
North Dakota	Sheridan	2,604	43	46	13	<0.01	53	55	280	0.11	11	21	368	0.14	66	63
North Dakota	Sioux	2,922	38	42	6	<0.01	67	59	74	0.03	37	40	2,981	1.02	9	28
North Dakota	Slope	3,159	31	35	152	0.05	25	28	29	0.01	53	51	3,103	0.98	15	26
North Dakota	Stark	3,472	30	32	544	0.16	19	19	24	0.01	57	54	3,419	0.98	14	24
North Dakota	Stutsman	4,511	40	33	21	<0.01	55	50	528	0.12	7	3	1,321	0.29	58	46
North Dakota	Towner	1,059	38	51	5	<0.01	54	60	86	0.08	16	38	570	0.54	45	56

Table C–8. Results of the regional evaluation where counties were ranked on the basis of the total number and density of wells, wetlands, and streams in the Williston Basin.—Continued

[km, kilometers; km², square kilometer; <, less than; --, no record]

State	County	County area, km²	Mean rank		Wells				Wetlands				Streams			
			Density	Total number	Number	Density	Rank		Area, km²	Density	Rank		Length, km	Density	Rank	
							Density	Total number			Density	Total number			Density	Total number
North Dakota	Ward	5,325	32	23	450	0.08	23	20	412	0.08	20	10	1,965	0.37	53	39
North Dakota	Wells	3,342	42	42	27	0.01	45	49	261	0.08	19	23	805	0.24	62	53
North Dakota	Williams	5,563	20	10	1,933	0.35	9	5	415	0.07	21	9	4,181	0.75	29	16
South Dakota	Butte	3,996	29	32	78	0.02	33	33	40	0.01	52	50	4,553	1.14	3	13
South Dakota	Campbell	1,760	41	46	7	<0.01	62	58	120	0.07	25	32	1,164	0.66	37	47
South Dakota	Corson	6,551	35	27	30	<0.01	56	44	124	0.02	40	30	6,671	1.02	10	7
South Dakota	Dewey	5,545	33	26	33	0.01	50	41	130	0.02	38	29	5,512	0.99	12	9
South Dakota	Haakon	1,805	29	45	32	0.02	35	42	29	0.02	45	52	1,879	1.04	8	40
South Dakota	Harding	6,935	29	22	780	0.11	21	16	50	0.01	56	45	6,990	1.01	11	6
South Dakota	Meade	6,422	39	33	29	<0.01	57	46	48	0.01	55	48	7,304	1.14	4	4
South Dakota	Pennington	718	40	59	2	<0.01	66	67	6	0.01	54	60	926	1.29	1	51
South Dakota	Perkins	7,486	38	28	30	<0.01	61	45	81	0.01	51	39	8,808	1.18	2	1
South Dakota	Stanley	236	37	63	1	<0.01	60	68	13	0.06	30	57	221	0.94	21	65
South Dakota	Walworth	624	44	59	2	<0.01	64	66	42	0.07	26	49	392	0.63	42	61
South Dakota	Ziebach	5,105	39	35	17	<0.01	63	53	72	0.01	47	41	5,443	1.07	6	10



Base modified from the Montana Board of Oil and Gas, North Dakota Oil and Gas Division, South Dakota Department of Enviornmental and Natural Resources, and the National Atlas
Well data current as of February 2011

Figure C–8. Counties with the overall greatest number and density of wells, surface area and density of wetlands, and kilometers and density of streams. Numbers in white and yellow boxes, which correspond to mean ranks from table C–8, are the rankings based on raw values and densities, respectively.

Table C–9. Surface area and total number of wetlands within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 10,361 wells in the Prairie Pothole Region portion of the Williston Basin.

[km, kilometers; km^2, square kilometer; <, less than]

Wetland classification	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Area, km^2	Number	Area, km^2	Number	Area, km^2	Number
Well type—All						
Temporary	39	27,499	83	64,911	163	125,641
Seasonal	135	31,128	289	73,120	577	148,743
Semipermanent	115	3,618	218	8,006	416	16,589
Riverine	25	95	40	142	49	235
Lake	187	378	346	799	577	1,537
Total	**501**	**62,718**	**975**	**146,978**	**1,780**	**292,745**
Well type—Confidential						
Temporary	1	734	4	2,581	12	8,715
Seasonal	6	1,389	21	4,739	65	15,684
Semipermanent	7	167	18	518	56	1,686
Riverine	0.4	2	3	9	4	12
Lake	16	18	25	41	100	155
Total	**30**	**2,310**	**70**	**7,888**	**238**	**26,252**
Well type—Dry hole						
Temporary	27	17,863	74	53,710	158	116,542
Seasonal	95	19,183	246	56,972	543	129,899
Semipermanent	95	2,245	209	6,245	427	14,631
Riverine	33	86	53	131	85	227
Lake	112	295	376	679	880	1,353
Total	**363**	**39,672**	**958**	**117,737**	**2,092**	**262,652**
Well type—Gas						
Temporary	0.1	14	0.4	67	1	278
Seasonal	1	43	1	188	4	683
Semipermanent	0.2	10	1	28	4	102
Riverine	7	1	7	1	13	1
Lake	2	2	3	7	11	19
Total	**10**	**70**	**12**	**291**	**33**	**1,083**
Well type—Injection						
Temporary	3	1,980	9	6,092	20	16,711
Seasonal	12	2,446	29	6,601	66	16,870
Semipermanent	10	322	24	765	46	1,797
Riverine	8	9	17	16	30	26
Lake	31	39	171	70	317	127
Total	**65**	**4,796**	**249**	**13,544**	**480**	**35,531**

Table C–9. Surface area and total number of wetlands within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 10,361 wells in the Prairie Pothole Region portion of the Williston Basin.—Continued

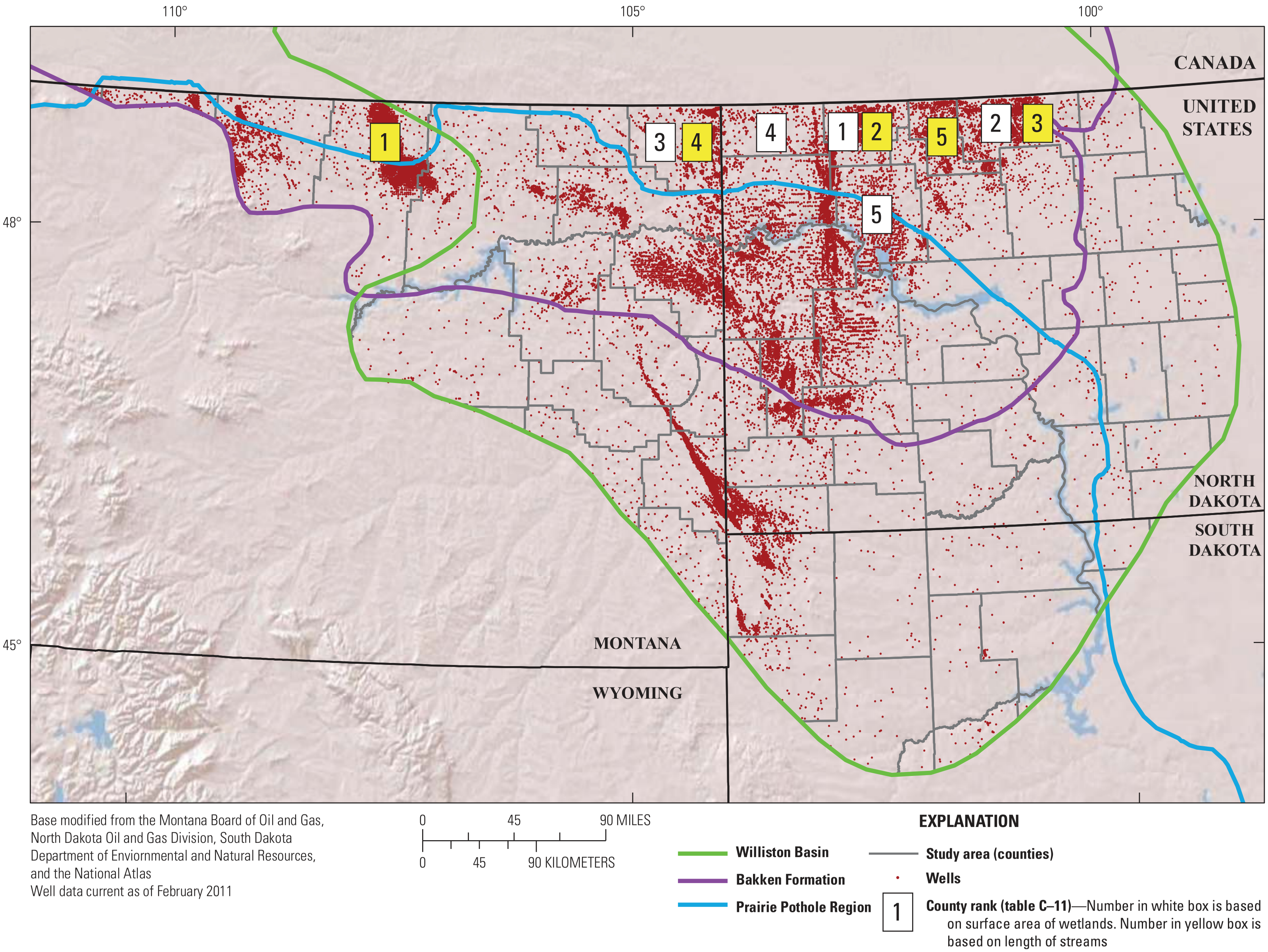
[km, kilometers; km², square kilometer; <, less than]

Wetland classification	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Area, km²	Number	Area, km²	Number	Area, km²	Number
			Well type—Oil			
Temporary	17	10,769	35	23,477	59	47,824
Seasonal	61	12,758	127	27,039	248	57,422
Semipermanent	57	1,496	110	3,031	176	6,116
Riverine	21	27	35	39	40	53
Lake	96	96	329	199	666	466
Total	**253**	**25,146**	**635**	**53,785**	**1,189**	**111,881**
			Well type—Stratigraphic test			
Temporary	<0.1	2	<0.1	6	0.1	25
Seasonal	<0.1	8	<0.1	15	0.2	46
Semipermanent	0.2	4	0.3	6	0.4	16
Riverine	0.1	1	0.1	1	7	1
Lake	36	1	37	1	37	3
Total	**37**	**16**	**37**	**29**	**44**	**91**
			Well type—Water			
Temporary	0.2	141	1	599	2	2,169
Seasonal	1	228	3	796	9	2,611
Semipermanent	2	32	2	83	5	274
Riverine	0.3	2	0.4	3	0.4	4
Lake	2	3	5	10	114	19
Total	**5**	**406**	**11**	**1,491**	**131**	**5,077**

Table C–10. Inventory of streams and piping plover critical habitat within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 10,361 wells in the Prairie Pothole Region portion of the Williston Basin.

[km, kilometer; km², square kilometer; <, less than; --, no record]

Well type	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Stream length, km	Critical habitat, km²	Stream length, km	Critical habitat, km²	Stream length, km	Critical habitat, km²
All	1,380	5	3,291	22	7,147	79
Confidential	34	0.1	151	1	546	4
Dry hole	615	3	2,175	12	5,859	50
Gas	337	<0.1	616	0.1	961	2
Injection	68	1	219	4	612	15
Oil	379	1	891	7	1,984	38
Stratigraphic test	2	0.4	4	1	9	2
Water	6	--	19	--	66	0.2



Base modified from the Montana Board of Oil and Gas,
North Dakota Oil and Gas Division, South Dakota
Department of Enviornmental and Natural Resources,
and the National Atlas
Well data current as of February 2011

Figure C–9. Seven counties with the greatest surface area of wetlands (white boxes) and length of streams (yellow boxes) within the 0.4-kilometer buffer (see table C–11) around all wells in the Prairie Pothole Region of the Williston Basin.

Table C–11. Inventory of wetlands (surface area and number) and streams (length) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 10,361 wells in the Prairie Pothole Region portion of the study area; buffer inventories were conducted for all well types together.

[km, kilometers; km², square kilometer; *, The HAPET NWI database did not include these counties; --, no record]

State	County	County area, km²	0.4-km buffer			0.8-km buffer			1.6-km buffer		
			Area, km²	Number	Streams, km	Area, km²	Number	Streams, km	Area, km²	Number	Streams, km
Montana	Blaine	2,360	*--	*--	86.5	*--	*--	185.5	*--	*--	469.4
Montana	Daniels	1,331	0.3	49	4.2	0.9	125	19.0	3.0	352	68.7
Montana	Hill	45	*--	*--	1.7	*--	*--	2.9	*--	*--	7.8
Montana	Liberty	88	*--	*--	13.2	*--	*--	42.3	*--	*--	75.7
Montana	Phillips	3,506	*--	*--	284.9	*--	*--	539.7	*--	*--	873.7
Montana	Roosevelt	440	1.1	19	8.0	1.2	49	20.0	2.2	165	57.3
Montana	Sheridan	4,414	78.7	1,929	114.5	108.8	4,185	362.0	148.0	8,174	872.6
Montana	Valley	563	*--	*--	2.4	*--	*--	13.0	*--	*--	48.2
North Dakota	Benson	3,434	2.1	279	1.2	6.0	1,027	9.4	18.8	3,656	37.9
North Dakota	Bottineau	4,397	92.5	15,507	178.0	157.0	32,681	406.8	233.4	54,902	777.2
North Dakota	Burke	2,924	93.5	11,282	203.2	171.6	24,086	437.2	250.1	43,040	719.9
North Dakota	Burleigh	1,120	0.7	74	2.2	1.5	290	4.7	10.8	1,034	14.3
North Dakota	Divide	3,353	42.4	4,495	29.4	90.4	11,366	101.9	177.7	24,427	251.5
North Dakota	Eddy	1,165	1.5	90	0.4	2.6	293	1.7	5.7	894	7.4
North Dakota	Emmons	1,698	0.9	60	9.6	6.7	264	45.0	17.3	877	188.6
North Dakota	Foster	1,263	4.2	103	2.4	5.8	341	9.8	12.1	1,316	35.1
North Dakota	Kidder	3,711	0.2	27	--	1.2	109	--	6.6	459	0.5
North Dakota	Logan	2,553	3.3	113	8.6	10.3	359	29.2	20.4	1,245	95.8
North Dakota	McHenry	4,951	16.7	1,154	17.5	48.8	3,768	55.2	143.1	11,675	180.6
North Dakota	McIntosh	1,324	0.0	6	1.5	0.1	30	13.2	0.3	144	40.2
North Dakota	McLean	2,298	1.5	99	0.3	3.4	407	4.2	11.7	1,403	11.7
North Dakota	Mountrail	2,351	40.0	3,570	80.4	78.3	9,591	184.0	137.5	20,500	396.2
North Dakota	Pierce	2,804	10.1	401	3.2	34.1	1,346	8.7	72.4	4,448	36.4
North Dakota	Ramsey	549	0.2	66	--	1.0	205	--	3.9	752	3.3
North Dakota	Renville	2,312	38.1	15,539	112.1	101.6	34,271	234.5	147.5	54,321	408.2

Table C–11. Inventory of wetlands (surface area and number) and streams (length) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 10,361 wells in the Prairie Pothole Region portion of the study area; buffer inventories were conducted for all well types together.—Continued

[km, kilometers; km², square kilometer; *, The HAPET NWI database did not include these counties; --, no record]

State	County	County area, km²	0.4-km buffer			0.8-km buffer			1.6-km buffer		
			Area, km²	Number	Streams, km	Area, km²	Number	Streams, km	Area, km²	Number	Streams, km
North Dakota	Rolette	2,397	8.8	493	12.6	20.5	1,644	52.8	59.8	6,112	150.3
North Dakota	Sheridan	2,604	0.7	161	0.8	3.2	458	2.9	13.4	1,554	11.3
North Dakota	Stutsman	4,511	3.0	151	1.4	7.5	589	6.7	29.9	2,034	35.8
North Dakota	Towner	1,059	0.4	130	1.1	1.3	560	7.6	4.9	2,005	24.5
North Dakota	Ward	5,094	28.7	4,683	88.5	64.4	13,648	253.8	158.4	34,916	655.9
North Dakota	Wells	3,342	3.7	243	2.6	8.0	844	9.5	24.6	3,476	36.6
North Dakota	Williams	2,142	26.8	1,955	103.9	36.7	4,335	213.8	61.2	8,513	509.4
South Dakota	Campbell	1,395	0.5	32	3.8	1.1	79	11.6	4.2	258	39.1
South Dakota	Walworth	272	0.3	8	0.1	0.6	28	2.3	1.2	93	5.8
Total		**77,770**	**501**	**62,718**	**1,380**	**975**	**146,978**	**3,291**	**1,780**	**292,745**	**7,147**

Table C–12. Inventory of wetlands (surface area and number) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 5,446 wells in the Prairie Pothole Region portion of the study area that were drilled prior to 1980.

[km, kilometers; km², square kilometer; --, no record]

Wetland classification	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Area, km²	Number	Area, km²	Number	Area, km²	Number
			Well type—All			
Temporary	25	16,506	56	41,880	123	91,884
Seasonal	81	18,551	180	45,313	403	102,015
Semipermanent	73	2,201	146	5,097	297	11,548
Riverine	22	79	36	110	51	181
Lake	83	246	187	510	413	1,177
Total	**285**	**37,583**	**605**	**92,910**	**1,288**	**206,805**
			Well type—Confidential			
Temporary	--	--	0.01	8	0.02	21
Seasonal	--	--	0.02	1	0.1	8
Semipermanent	--	--	--	--	0.1	2
Riverine	--	--	--	--	--	--
Lake	--	--	--	--	--	--
Total	**--**	**--**	**0.02**	**9**	**0.2**	**31**
			Well type—Dry hole			
Temporary	18	11,367	53	36,859	122	89,452
Seasonal	61	12,218	165	38,988	403	98,403
Semipermanent	65	1,460	149	4,350	313	11,093
Riverine	23	74	47	106	70	178
Lake	74	208	265	466	520	1,152
Total	**241**	**25,327**	**680**	**80,769**	**1,428**	**200,278**
			Well type—Gas			
Temporary	0.1	3	0.3	23	0.4	68
Seasonal	0.2	18	0.4	79	1	259
Semipermanent	0.01	1	0.2	9	0.5	33
Riverine	7	1	7	1	13	1
Lake	2	1	1	2	8	8
Total	**9**	**24**	**9**	**114**	**23**	**369**
			Well type—Injection			
Temporary	2	1,117	5	3,345	11	8,901
Seasonal	7	1,431	17	3,905	38	9,804
Semipermanent	5	175	14	448	29	1,073
Riverine	7	5	15	12	22	22
Lake	10	25	108	46	121	80
Total	**31**	**2,753**	**159**	**7,756**	**220**	**19,880**

Table C–12. Inventory of wetlands (surface area and number) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 5,446 wells in the Prairie Pothole Region portion of the study area that were drilled prior to 1980.—Continued

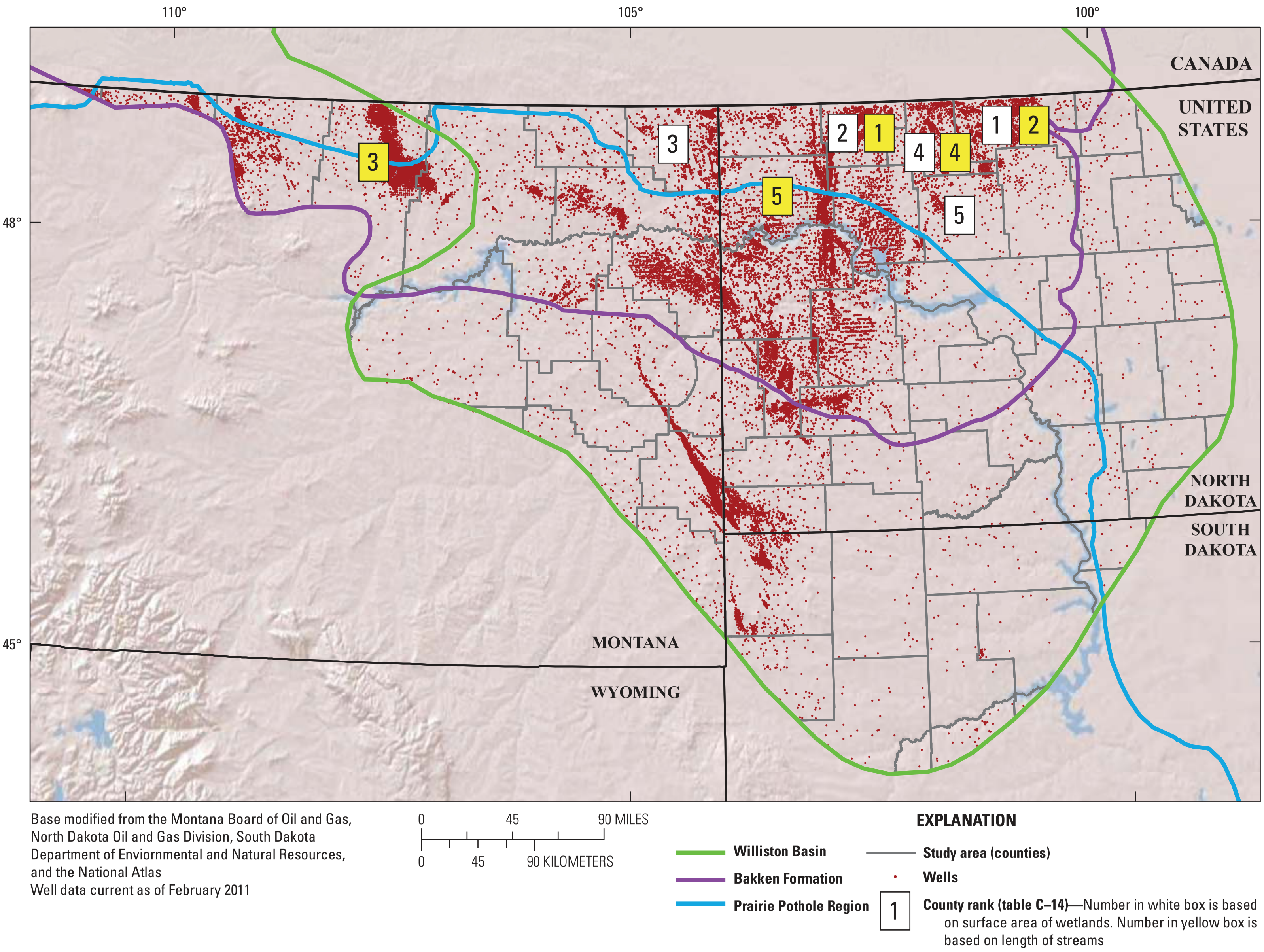
[km, kilometers; km², square kilometer; --, no record]

Wetland classification	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Area, km²	Number	Area, km²	Number	Area, km²	Number
			Well type—Oil			
Temporary	9	5,656	19	11,737	30	24,501
Seasonal	29	6,689	55	12,616	97	24,742
Semipermanent	32	797	58	1,448	74	2,724
Riverine	4	17	28	27	29	38
Lake	48	50	172	90	283	156
Total	**122**	**13,209**	**333**	**25,918**	**514**	**52,161**
			Well type—Water			
Temporary	0.1	91	0.4	386	1	1,409
Seasonal	0.5	128	2	483	6	1,611
Semipermanent	1	17	2	55	3	191
Riverine	0.1	1	0.2	2	0.1	2
Lake	2	3	2	9	13	17
Total	**3**	**240**	**6**	**935**	**23**	**3,230**

Table C–13. Inventory of streams and piping plover critical habitat within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 5,446 wells in the Prairie Pothole Region portion of the study area that were drilled prior to 1980.

[km, kilometer; km², square kilometer; <, less than; --, no record]

Well type	0.4-km buffer		0.8-km buffer		1.6-km buffer	
	Stream length, km	Critical habitat, km²	Stream length, km	Critical habitat, km²	Stream length, km	Critical habitat, km²
All	736	2	2,091	10	5,002	38
Confidential	--	--	--	--	3	--
Dry hole	411	1	1,500	6	4,353	33
Gas	110	<0.01	375	0.1	665	2
Injection	46	0.3	139	2	386	4
Oil	222	1	444	3	919	14
Water	3	--	10	--	34	0.2



Base modified from the Montana Board of Oil and Gas,
North Dakota Oil and Gas Division, South Dakota
Department of Enviornmental and Natural Resources,
and the National Atlas
Well data current as of February 2011

Figure C–10. Seven counties with the greatest surface area of wetlands (white boxes) and length of streams (yellow boxes) within the 0.4-kilometer buffer (see table C–14) around all wells in the Prairie Pothole Region of the Williston Basin that were drilled prior to 1980.

Table C–14. Inventory of wetlands (surface area and number) and streams (length) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 5,446 wells in the Prairie Pothole Region portion of the study area that were drilled prior to 1980; buffer analyses were conducted for all well types together.

[km, kilometers; km^2, square kilometer; *, The HAPET NWI database did not include these counties; --, no record]

State	County	County area, km^2	0.4-km buffer			0.8-km buffer			1.6-km buffer		
			Area, km^2	Number	Streams, km	Area, km^2	Number	Streams, km	Area, km^2	Number	Streams, km
Montana	Blaine	2,360	*--	*--	29.1	*--	*--	106.3	*--	*--	351.2
Montana	Daniels	1,331	0.3	38	2.7	0.9	91	15.6	1.6	270	48.7
Montana	Hill	45	*--	*--	1.7	*--	*--	2.9	*--	*--	7.8
Montana	Liberty	88	*--	*--	11.9	*--	*--	40.8	*--	*--	74.8
Montana	Phillips	3,506	*--	*--	111.1	*--	*--	379.3	*--	*--	703.1
Montana	Roosevelt	440	0.0	6	1.7	0.0	26	6.6	1.3	94	22.7
Montana	Sheridan	4,414	29.2	1,208	45.9	48.0	2,783	168.8	130.7	6,273	515.1
Montana	Valley	563	*--	*--	1.3	*--	*--	7.9	*--	*--	24.1
North Dakota	Benson	3,434	2.1	279	1.2	6.0	1,027	9.4	18.8	3,656	37.9
North Dakota	Bottineau	4,397	76.1	11,253	113.3	137.7	26,130	302.1	212.5	48,963	686.9
North Dakota	Burke	2,924	60.1	6,305	134.6	100.8	13,806	301.0	171.2	28,788	549.6
North Dakota	Burleigh	1,120	0.7	74	2.2	1.5	290	4.7	10.8	1,034	14.3
North Dakota	Divide	3,353	12.0	1,369	13.0	31.5	3,514	34.5	80.2	9,116	101.5
North Dakota	Eddy	1,165	1.5	90	0.4	2.6	293	1.7	5.7	894	7.4
North Dakota	Emmons	1,698	0.4	36	7.0	6.0	166	34.7	9.4	527	142.7
North Dakota	Foster	1,263	4.2	103	2.4	5.8	341	9.8	12.1	1,316	35.1
North Dakota	Kidder	3,711	0.2	27	--	1.2	109	--	6.6	459	0.5
North Dakota	Logan	2,553	3.3	113	8.6	10.3	359	29.2	20.4	1,245	95.8
North Dakota	McHenry	4,951	13.2	850	13.6	40.9	2,929	37.8	127.5	9,566	127.7
North Dakota	McIntosh	1,324	0.0	6	1.5	0.1	30	13.2	0.3	144	40.2
North Dakota	McLean	2,298	0.4	62	0.3	1.5	289	4.2	7.4	976	11.5
North Dakota	Mountrail	2,351	7.7	870	29.5	16.1	2,193	58.8	35.7	6,209	126.5
North Dakota	Pierce	2,804	9.7	354	3.2	32.5	1,169	8.7	66.1	3,969	33.8
North Dakota	Ramsey	549	0.2	66	--	1.0	205	--	3.9	752	3.3
North Dakota	Renville	2,312	25.0	10,066	79.0	77.6	23,990	178.9	124.3	43,989	339.9
North Dakota	Rolette	2,397	6.7	307	9.1	15.5	1,076	38.5	46.0	4,361	114.7
North Dakota	Sheridan	2,604	0.4	93	--	2.3	287	0.4	9.3	1,083	2.9
North Dakota	Stutsman	4,511	2.7	117	1.0	6.7	490	5.2	35.0	1,801	31.6

Table C–14. Inventory of wetlands (surface area and number) and streams (length) within each radial buffer (0.4 km, 0.8 km, 1.6 km) around the 5,446 wells in the Prairie Pothole Region portion of the study area that were drilled prior to 1980; buffer analyses were conducted for all well types together.—Continued

[km, kilometers; km^2, square kilometer; *, The HAPET NWI database did not include these counties; --, no record]

State	County	County area, km^2	0.4-km buffer			0.8-km buffer			1.6-km buffer		
			Area, km^2	Number	Streams, km	Area, km^2	Number	Streams, km	Area, km^2	Number	Streams, km
North Dakota	Towner	1,059	0.4	130	1.1	1.3	560	7.6	4.9	2,005	24.5
North Dakota	Ward	5,094	17.8	2,462	49.5	37.4	7,790	154.0	86.9	21,999	422.0
North Dakota	Wells	3,342	1.8	183	2.6	5.5	623	8.2	18.3	2,459	30.7
North Dakota	Williams	2,142	8.0	1,076	53.4	12.7	2,237	106.0	34.9	4,506	228.8
South Dakota	Campbell	1,395	0.5	32	3.8	1.1	79	11.6	4.2	258	39.1
South Dakota	Walworth	272	0.3	8	0.1	0.6	28	2.3	1.2	93	6
Total		**77,770**	**285**	**37,583**	**736**	**605**	**92,910**	**2,091**	**1,288**	**206,805**	**5,002**

Table C–15. Inventory of wells, wetlands, and streams within radial buffers (including parcel) around U.S. Fish and Wildlife Service lands in the Prairie Pothole Region portion of the study area.

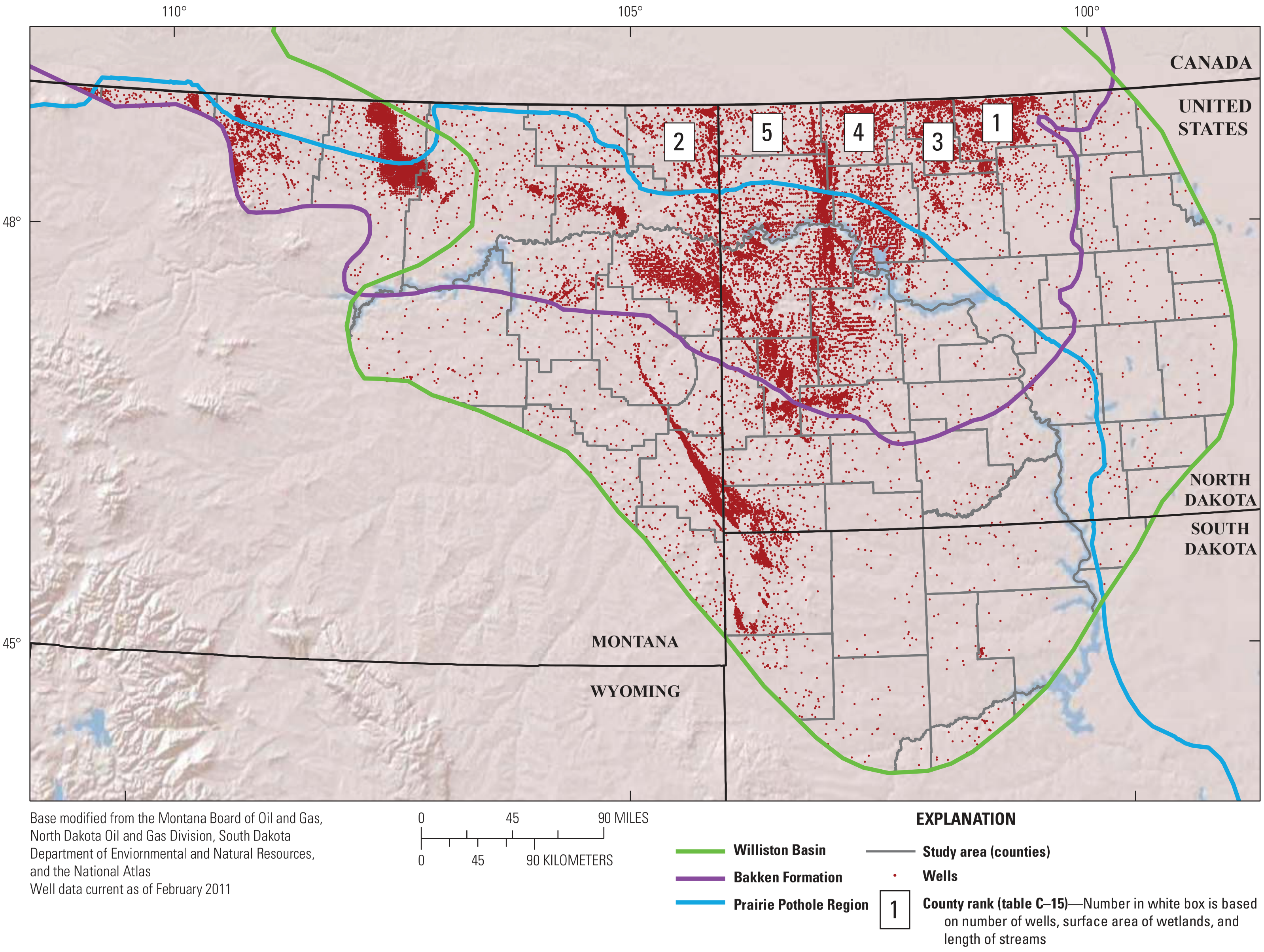
[USFWS, U.S. Fish and Wildlife Service; km^2, square kilometer; km, kilometer; --, no record; *, The HAPET NWI database did not include these counties]

State	County	USFWS lands, km^2	Number of wells			Area of wetlands, km^2			Stream length, km			Buffer area, km^2		
			0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km
Montana	Blaine	3	--	--	--	*--	*--	*--	8	11	18	7	12	25
Montana	Daniels	4	--	--	--	33	35	45	6	8	16	12	21	44
Montana	Phillips	7	--	1	1	*--	*--	*--	--	--	--	15	25	45
Montana	Roosevelt	7	--	--	--	296	308	367	13	17	31	11	15	24
Montana	Sheridan	163	90	180	321	4,190	4,353	4,484	107	134	199	289	424	695
North Dakota	Benson	40	--	--	2	758	893	2,062	23	44	101	153	311	727
North Dakota	Bottineau	98	92	155	298	8,799	10,119	10,350	113	137	192	179	269	486
North Dakota	Burke	153	34	56	106	495	514	696	76	99	149	236	323	519
North Dakota	Burleigh	57	--	1	4	1,310	1,497	1,708	29	50	96	125	206	371
North Dakota	Divide	47	46	81	155	348	409	511	15	27	52	177	350	776
North Dakota	Eddy	7	--	--	1	148	188	243	5	11	28	31	66	162
North Dakota	Emmons	6	--	--	1	70	106	169	6	12	29	18	33	73
North Dakota	Foster	4	--	--	1	50	73	136	5	8	22	15	32	82
North Dakota	Kidder	76	--	--	--	3,143	4,108	6,489	29	45	74	177	311	648
North Dakota	LaMoure	6	--	--	--	18	24	47	8	14	34	23	49	124
North Dakota	Logan	48	--	--	2	304	407	693	29	48	117	148	274	579
North Dakota	McHenry	174	1	2	9	34,455	35,676	36,415	124	159	237	282	415	765
North Dakota	McIntosh	19	--	--	--	149	198	302	23	38	69	56	101	193
North Dakota	McLean	94	--	--	1	1,846	1,982	2,535	58	85	136	200	324	607
North Dakota	Mountrail	61	9	27	72	295	404	626	32	56	116	165	298	614
North Dakota	Pierce	52	2	5	14	876	1,272	1,798	49	73	143	176	340	762
North Dakota	Ramsey	35	--	--	--	1,752	2,022	2,534	11	19	34	65	90	139
North Dakota	Renville	103	35	62	132	4,583	4,596	4,659	127	146	177	163	219	332
North Dakota	Rolette	25	1	4	12	203	252	356	27	51	105	91	172	364
North Dakota	Sheridan	50	--	1	1	227	293	439	15	28	57	147	268	589
North Dakota	Stutsman	194	1	1	7	1,049	1,182	1,463	93	133	259	440	724	1,358
North Dakota	Towner	17	--	--	1	45	75	199	41	58	96	43	72	151
North Dakota	Ward	91	2	6	31	999	1,038	1,255	99	126	184	199	328	653

Table C–15. Inventory of wells, wetlands, and streams within radial buffers (including parcel) around U.S. Fish and Wildlife Service lands in the Prairie Pothole Region portion of the study area.—Continued

[USFWS, U.S. Fish and Wildlife Service; km^2, square kilometer; km, kilometer; --, no record; *, The HAPET NWI database did not include these counties]

State	County	USFWS lands, km^2	Number of wells			Area of wetlands, km^2			Stream length, km			Buffer area, km^2		
			0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km	0.4-km	0.8-km	1.6-km
North Dakota	Wells	43	1	2	7	204	254	344	11	19	41	130	236	487
North Dakota	Williams	30	9	20	54	453	480	543	30	43	91	68	114	231
South Dakota	Campbell	3	--	--	--	14	22	36	1	3	8	15	34	91
Total		**1,716**	**323**	**604**	**1,233**	**67,110**	**72,779**	**81,505**	**1,215**	**1,702**	**2,913**	**3,853**	**6,454**	**12,718**



Base modified from the Montana Board of Oil and Gas, North Dakota Oil and Gas Division, South Dakota Department of Enviornmental and Natural Resources, and the National Atlas
Well data current as of February 2011

Figure C–11. Five counties in the Prairie Pothole Region of the study area with the greatest number of wells, surface area of wetlands, and kilometers of streams on, or adjacent to, U.S. Fish and Wildlife Service lands.

An overall depiction of the Williston Basin identified the parts of western North Dakota and northeastern Montana as having the overall greatest extent of wells (fig. C–2). Drilling began in the region around 1900, but a majority of the more than 31,000 wells (tables C–2, C–3) were drilled after 1950 (figs. C–3, C–4). Peak production periods are related to factors such as the price of oil and advancement of modern drilling technologies of horizontal drilling and hydraulic fracturing. Most of the recent activity has taken place in western North Dakota and is associated with horizontal drilling that targets oil from the Bakken and Three Forks Formations. Of the nearly 3,000 wells drilled in the study area from 2008 to 2011, nearly 70 percent were classified as oil producing and more than 90 percent of these oil wells were drilled in North Dakota. The recent upward trend in activity (fig. C–3) is predicted to continue as technology and oil prices have made it economically viable to obtain oil from vast reserves associated with the Bakken and other deep geologic formations (Gaswirth and others, 2013). In fact, State and industry officials from North Dakota predict that up to 2,000 wells per year could be drilled in the State for the foreseeable future.

Various spatial evaluations were performed with the purpose of identifying counties with the greatest likelihood of containing brine-contaminated aquatic resources. Within the overall U.S. part of the Williston Basin, counties located in the core area of oil- and gas-related activities in western North Dakota (fig. C–2) were distinguished on the basis of total number and density of wells, surface area and density of wetlands, and length and density of streams; however, Phillips and Valley Counties, two of the larger counties in the western PPR of Montana, also were singled out when only total number was considered, and the relatively small Bowman County in southwestern North Dakota was singled out based on mean density of wells, wetlands, and streams (table C–8, fig. C–8). Evaluation of counties in this manner provides a general spatial characterization of a large region while simultaneously considering multiple variables (wells, wetlands, streams). This approach, however, does not consider the distribution of wells and aquatic resources and may not always be the most appropriate for assessing the potential for contamination. For example, the five counties identified in figure C–8 all ranked relatively high for wells and had intermediate ranks for wetlands and streams (table C–8); thus, counties containing high numbers of wells do not necessarily contain a high density of aquatic resources, and the likelihood of containing brine-contaminated aquatic resources may not be strongly related to mean ranks such as those presented in table C–8.

Therefore, a proximity analysis was performed to identify not only areas containing relatively high amounts of wells and aquatic resources but also areas with the most resources proximate to wells. Results of the PPR proximity analysis indicated that there are considerable aquatic resources proximate to wells that may be affected by brines because of subsurface migration from reserve pits or various types of surface spills. In fact, over 500 km^2 of wetlands, 1,300 km of streams, and 5 km^2 of critical habitat were identified within a 0.4-km buffer of the 10,361 wells in the PPR. These numbers rose considerably as the buffer distances expanded to 1.6 km, with the area of wetlands and length of streams increasing approximately 4 to 5 times, and area critical habitat increased by roughly 16 times (tables C–9, C–10). Similar to the regional characterization, counties were described based only on wetlands and streams within 0.4 km of wells to identify the counties in the PPR with the greatest likelihood of containing brine-affected aquatic systems (table C–11, fig. C–9). The counties in northwestern North Dakota and northeastern Montana with the greatest part of their land area within the PPR ranked highest for aquatic resources adjacent to wells.

To identify areas associated with the older, unlined reserve pits, a proximity analysis was performed using only wells drilled prior to 1980. Slightly more than one-half of the wells in the PPR were drilled prior to 1980, but the amount of aquatic resources proximate to wells was still considerable with nearly 300 km^2 of wetlands, more than 700 km of streams, and 2 km^2 of critical habitat within the 0.4-km buffer. Upward trends in the amount of aquatic resources from the 0.4-km buffer to the 1.6-km buffer were consistent with the analysis of all wells. The area of wetlands and length of streams increased approximately 5 to 7 times, and the critical habitat increased by 19 times (tables C–12, C–13). County ranks based on aquatic resources within the 0.4-km buffer around the pre-1980 wells (table C–14) were also similar to those for all wells, although distribution of the high-ranking counties shifted slightly (figs. C–9, C–10).

The USFWS administers more than 1,700 km^2 of land in the PPR part of the study area. Much of these lands consist of NWRs and WPAs that include a great number and variety of wetland types. Pothole wetlands have the greatest ecological value when they exist as complexes consisting of a variety of habitat types such as multiple wetland classes nested within grasslands. Thus, the composition and ecological condition of the lands surrounding these refuges and production areas can play an important role in the relative quality of the habitats. Therefore, areas with the greatest potential for a reduction in the value of ecosystem services provided by these lands were identified by calculating the number of wells and amount of aquatic resources on or near lands managed by the USFWS (table C–15, fig. C–11). This assessment indicated that there was a substantial amount of aquatic resources associated with USFWS lands (table C–15), and there was considerable potential for brine contamination from nearby oil and gas production activity. In fact, there were more than 300 wells within the 0.4-km buffer around USFWS lands and more than 1,200 wells within the 1.6-km buffer (table C–15). This spatial characterization identified the counties with high well densities in the northernmost parts of the PPR of the study area as having the greatest potential for containing affected aquatic resources on USFWS lands (fig. C–11). Further, a large number of wetland and grassland easements were located in the vicinity of oil and gas wells in these counties. Although these are privately owned lands, the USFWS provided financial compensation in exchange for conservation benefits associated with limiting agricultural disturbance (for example, draining, filling, burning) to these habitats. This simple proximity analysis suggests that there is potential for a reduction in the ecological integrity of these sites beyond those expected because of agricultural disturbances.

The regional spatial assessment and PPR proximity analyses identified areas with a greater likelihood of containing brine-contaminated aquatic resources on the basis of their spatial relation to oil and gas wells. These assessments are based on the assumption that there is high likelihood brines will migrate from a point source to wetlands, streams, and groundwater. This belief is supported by studies demonstrating brine contamination and migration (Reiten, 1991; Reiten and Tischmak, 1993; Thamke and Craigg, 1997), and the findings of this study that the majority of the region's wells were associated with soils considered well-drained or excessively drained (table C–6). Although the soil drainage class does not specifically describe permeability, it is a suitable surrogate that allows for determination of a relative rate that water typically moves through a given soil. The soil drainage classes associated with approximately 95 percent of wells indicate that the physical properties of the soils are conducive to the migration of brines if there was a spill or leak and the hydraulic gradient was sufficient (table C–6). The rate of movement, however, is highly variable and governed by several factors including soil porosity, precipitation, and hydraulic conductivity.

Data Limitations

Assessments evaluating potential for brine contamination to aquatic resources in the Williston Basin ideally would include locations of buried reserve pits, likely groundwater flow paths, site-specific geologic data, and information pertaining to the probability and locations of brine leaks or spills. At this time, data pertaining to the location or status of active or abandoned reserve or evaporation pits do not exist because detailed records concerning these features are not maintained by State regulatory agencies. Further, funds were unavailable to purchase regional elevation data with sufficient resolution to relate elevations of wells and aquatic resources and estimate potential groundwater flow paths in the low-relief landscape. Lastly, it was difficult to determine site-level geology (for example, glacial till or outwash) using the existing coarse spatial data. The addition of high-resolution databases would allow for refinement of the analyses, downscaling to the individual site level, and for exploration of a decision-support tool for use in placing wells where they will have the least potential to affect aquatic resources.

Ecological Significance of Brine Contamination

The focus, thus far, has been on identifying areas with a greater likelihood of containing brine-contaminated aquatic resources, but the underlying question is "What are the effects of brine contamination to the biotic communities associated with these systems?" The primary goals of this overall project were to spatially describe the relations between oil and gas production activities and aquatic resources and to characterize brine migration and contamination at specific sites; therefore, direct effects of brines to aquatic ecosystems and biotic communities were not specifically assessed. Nonetheless, there is a significant amount of scientific literature describing relations between biotic communities and salinity (Stewart and Kantrud, 1972; Swanson and others, 1984; Hammer and others, 1990; Wollheim and Lovvorn, 1995; Baskin and Baskin, 1998; Gleason and others, 2009). Additions of highly saline brines can raise salinity levels as well as alter the composition of salts, and both of these factors have been shown to affect biota (Swanson and others, 1984; Mitcham and Wobeser, 1988; Zalizniak and others, 2006). Baskin and Baskin (1998) showed that concentrations of sodium chloride ranging from about 3,000 to 100,000 mg/L reduced germination success of many salt tolerant plants to about 10 percent. Further, salinity has been related to plant and invertebrate community composition (Stewart and Kantrud, 1972; Hammer and Heseltine, 1988; Hammer and others, 1990; Gleason and others, 2009), and saline waters have been shown to cause mortality and affect growth and development of ducklings (Swanson and others, 1984; Mitcham and Wobeser, 1988; Moorman and others, 1991; DeVink and others, 2005). In addition, high concentrations of sodium, which is characteristic of Williston Basin brines, can affect soil structure. However, the effects of brine contamination to individual biotic communities would be highly variable depending on factors such as the relative amount of brine introduced to the system, background salt concentration in the system, the composition of the biota, and the relation between the wetland and groundwater.

Future Research

Numerous scientific investigations, including chapter B of this report, have established that produced brines have contaminated soils, surface waters, and groundwater in the Williston Basin (Lang and Doll, 1983; Beal and others, 1987; Murphy and others, 1988; Payne and Reiten, 1991; Reiten and Tischmak, 1993, Thamke and Craigg, 1997). This chapter identifies areas with a greater likelihood of containing brine-contaminated aquatic systems by describing the spatial relations among wells, wetlands, and streams. Nonetheless, significant information gaps remain. These gaps include: characterization of the chemistry of surface waters to define natural levels or current baselines, evaluations of the regional extent and magnitude of contamination, effect of brines to biotic communities, and assessments of mitigation techniques. Requirements for spatial data include regional high-resolution elevation and geologic layers and reserve or evaporation pit locations. Information pertaining to the characteristics and the extent of spills also would be valuable.

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Appendix

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
Montana	Dry hole–abandoned	Dry hole
Montana	Dry hole–abandoned–unapproved	Dry hole
Montana	Dry hole–completed	Dry hole
Montana	Dry hole–plugged and abandoned–approved	Dry hole
Montana	Dry hole–temporarily abandoned	Dry hole
Montana	Dry hole–unknown	Dry hole
Montana	Dry hole–water well, released	Dry hole
Montana	Coalbed methane–plugged and abandoned–approved	Gas
Montana	Coalbed methane–producing	Gas
Montana	Coalbed methane–shut-in	Gas
Montana	Coalbed methane–spudded	Gas
Montana	Gas–abandoned	Gas
Montana	Gas–abandoned–unapproved	Gas
Montana	Gas–completed	Gas
Montana	Gas–domestic	Gas
Montana	Gas–plugged and abandoned–approved	Gas
Montana	Gas–producing	Gas
Montana	Gas–shut-in	Gas
Montana	Gas–spudded	Gas
Montana	Gas–temporarily abandoned	Gas
Montana	Gas–unknown	Gas
Montana	Gas–water well, released	Gas
Montana	Gas storage–completed	Gas
Montana	Gas storage–expired permit	Gas
Montana	Gas storage–plugged and abandoned–approved	Gas
Montana	Dry hole–permitted injection well	Injection
Montana	Gas–permitted injection well	Injection
Montana	Injection–disposal–abandoned–unapproved	Injection
Montana	Injection–disposal–active injection	Injection
Montana	Injection–disposal–plugged and abandoned–approved	Injection
Montana	Injection–disposal–permitted injection well	Injection
Montana	Injection–disposal–producing	Injection
Montana	Injection–disposal–spudded	Injection
Montana	Injection, enhanced oil recovery–abandoned–unapproved	Injection
Montana	Injection, enhanced oil recovery–active injection	Injection
Montana	Injection, enhanced oil recovery–plugged and abandoned–approved	Injection
Montana	Injection, enhanced oil recovery–permitted injection well	Injection
Montana	Injection, enhanced oil recovery–producing	Injection
Montana	Injection, enhanced oil recovery–shut-in	Injection
Montana	Injection, enhanced oil recovery–temporarily abandoned	Injection

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
Montana	Injection, enhanced oil recovery–water well, released	Injection
Montana	Injection, Indian lands–abandoned–unapproved	Injection
Montana	Injection, Indian lands–active injection	Injection
Montana	Injection, Indian lands–completed	Injection
Montana	Injection, Indian lands–plugged and abandoned–approved	Injection
Montana	Injection, Indian lands–shut-in	Injection
Montana	Injection, Indian lands–unknown	Injection
Montana	Oil–permitted injection well	Injection
Montana	Monitor/observation–abandoned–unapproved	Monitor/observation
Montana	Monitor/observation–completed	Monitor/observation
Montana	Monitor/observation–plugged and abandoned–approved	Monitor/observation
Montana	Monitor/observation–shut-in	Monitor/observation
Montana	Monitor/observation–temporarily abandoned	Monitor/observation
Montana	Coalbed methane–expired permit	Never drilled
Montana	Coalbed methane–permit to drill	Never drilled
Montana	Expired location–expired permit	Never drilled
Montana	Gas–expired permit	Never drilled
Montana	Gas–expired, not released	Never drilled
Montana	Gas–permit to drill	Never drilled
Montana	Injection–disposal–expired permit	Never drilled
Montana	Injection–disposal–permit to drill	Never drilled
Montana	Injection, enhanced oil recovery–expired permit	Never drilled
Montana	Oil–expired permit	Never drilled
Montana	Oil–expired, not released	Never drilled
Montana	Oil–permit to drill	Never drilled
Montana	Water source–expired permit	Never drilled
Montana	Oil–abandoned	Oil
Montana	Oil–abandoned–unapproved	Oil
Montana	Oil–completed	Oil
Montana	Oil–plugged and abandoned–approved	Oil
Montana	Oil–producing	Oil
Montana	Oil–shut-in	Oil
Montana	Oil–spudded	Oil
Montana	Oil–temporarily abandoned	Oil
Montana	Oil–unknown	Oil
Montana	Oil–water well, released	Oil
Montana	Stratigraphic test–completed	Stratigraphic test
Montana	Stratigraphic test–plugged and abandoned–approved	Stratigraphic test
Montana	Stratigraphic test–water well, released	Stratigraphic test
Montana	Unknown–plugged and abandoned–approved	Unknown/confidential

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
Montana	Unknown	Unknown/confidential
Montana	Domestic water–completed	Water
Montana	Domestic water–plugged and abandoned–approved	Water
Montana	Water source–abandoned–unapproved	Water
Montana	Water source–completed	Water
Montana	Water source–plugged and abandoned–approved	Water
Montana	Water source–producing	Water
Montana	Water source–shut-in	Water
Montana	Water source–temporarily abandoned	Water
Montana	Water source–unknown	Water
Montana	Water source–water well, released	Water
North Dakota	Confidential	Confidential
North Dakota	Coalbed methane, dry hole	Dry hole
North Dakota	Gas condensate, dry hole	Dry hole
North Dakota	Dry gas, dry hole	Dry hole
North Dakota	Oil and gas, dry hole	Dry hole
North Dakota	Stratigraphic test, dry hole	Dry hole
North Dakota	Coalbed methane, active	Gas
North Dakota	Coalbed methane, inactive (shut-in ≥3 and ≤12 months)	Gas
North Dakota	Gas condensate, active	Gas
North Dakota	Gas condensate, abandoned (shut-in >12 months)	Gas
North Dakota	Gas condensate, inactive (shut-in ≥3 and ≤12 months)	Gas
North Dakota	Gas condensate, plugged and abandoned (shut-in >12 months)	Gas
North Dakota	Gas condensate, temporarily abandoned (shut-in >12 months)	Gas
North Dakota	Dry gas, active	Gas
North Dakota	Dry gas, drilling	Gas
North Dakota	Dry gas, expired permit	Gas
North Dakota	Dry gas, inactive (shut-in ≥3 and ≤12 months)	Gas
North Dakota	Dry gas, plugged and abandoned (shut-in >12 months)	Gas
North Dakota	Oil and gas well, active	Gas
North Dakota	Oil and gas well, abandoned (shut-in >12 months)	Gas
North Dakota	Oil and gas well, plugged and abandoned (shut-in >12 months)	Gas
North Dakota	Gas injection, inactive (shut-in ≥3 and ≤12 months)	Gas
North Dakota	Gas stratigraphic test storage, plugged and abandoned (shut-in >12 months)	Gas
North Dakota	Acid gas disposal, active	Injection
North Dakota	Acid gas disposal, inactive (shut-in ≥3 and ≤12 months)	Injection
North Dakota	Air injection, abandoned (shut-in >12 months)	Injection
North Dakota	Air injection, inactive (shut-in ≥3 and ≤12 months)	Injection
North Dakota	Air injection, plugged and abandoned (shut-in >12 months)	Injection
North Dakota	Air injection, temporarily abandoned (shut-in >12 months)	Injection

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
North Dakota	Dump flood injector, active	Injection
North Dakota	Dump flood injector, abandoned (shut-in >12 months)	Injection
North Dakota	Dump flood injector, inactive (shut-in ≥3 and ≤12 months)	Injection
North Dakota	Dump flood injector, plugged and abandoned (shut-in >12 months)	Injection
North Dakota	Dump flood injector/producer, active	Injection
North Dakota	Injector, producer, active	Injection
North Dakota	Salt water disposal, active	Injection
North Dakota	Salt water disposal, abandoned (shut-in >12 months)	Injection
North Dakota	Salt water disposal, drilling	Injection
North Dakota	Salt water disposal, dry hole	Injection
North Dakota	Salt water disposal, inactive (shut-in ≥3 and ≤12 months)	Injection
North Dakota	Salt water disposal, plugged and abandoned (shut-in >12 months)	Injection
North Dakota	Salt water disposal, temporarily abandoned (shut-in >12 months)	Injection
North Dakota	Water injection, active	Injection
North Dakota	Water injection, abandoned (shut-in >12 months)	Injection
North Dakota	Water injection, dry hole	Injection
North Dakota	Water injection, inactive (shut-in ≥3 and ≤12 months)	Injection
North Dakota	Water injection, plugged and abandoned (shut-in >12 months)	Injection
North Dakota	Water injection, temporarily abandoned (shut-in >12 months)	Injection
North Dakota	Water injection, temporarily abandoned (shut-in >12 months)–observation	Injection
North Dakota	Dry gas, permitted location to drill	Never drilled
North Dakota	Dry gas, permit now cancelled	Never drilled
North Dakota	Oil and gas, expired permit	Never drilled
North Dakota	Oil and gas permitted location to drill	Never drilled
North Dakota	Oil and gas, permit now cancelled	Never drilled
North Dakota	Salt water disposal permitted location to drill	Never drilled
North Dakota	Salt water disposal, permit now cancelled	Never drilled
North Dakota	Oil and gas, active	Oil
North Dakota	Oil and gas, abandoned (shut-in >12 months)	Oil
North Dakota	Oil and gas, drilling	Oil
North Dakota	Oil and gas, inactive (shut-in ≥3 and ≤12 months)	Oil
North Dakota	Oil and gas, plugged and abandoned (shut-in >12 months)	Oil
North Dakota	Oil and gas, temporarily abandoned (shut-in >12 months)	Oil
North Dakota	Oil and gas, temporarily abandoned (shut-in >12 months)–observation	Oil
North Dakota	Stratigraphic test, active	Stratigraphic test
North Dakota	Stratigraphic test, drilling	Stratigraphic test
North Dakota	Water source, active	Water
North Dakota	Water source, abandoned (shut-in >12 months)	Water
North Dakota	Water source, drilling	Water
North Dakota	Water source, inactive (shut-in ≥3 and ≤12 months)	Water

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
North Dakota	Water source, plugged and abandoned (shut-in >12 months)	Water
North Dakota	Water source, temporarily abandoned (shut-in >12 months)	Water
South Dakota	Dry hole–dry hole fee land–plugged and abandoned	Dry hole
South Dakota	Dry hole–dry hole tribal land–plugged and abandoned	Dry hole
South Dakota	Dry hole–dry hole tribal land–temporarily abandoned	Dry hole
South Dakota	Dry hole–dry hole–converted	Dry hole
South Dakota	Dry hole–dry hole–plugged and abandoned	Dry hole
South Dakota	Dry hole–dry hole fee land–converted	Dry hole
South Dakota	Dry hole–dry hole gas show–plugged and abandoned	Dry hole
South Dakota	Dry hole–gas–plugged and abandoned	Dry hole
South Dakota	Dry hole–gas show–plugged and abandoned	Dry hole
South Dakota	Dry hole–horizontal permit–plugged and abandoned	Dry hole
South Dakota	Dry hole–horizontal–plugged and abandoned	Dry hole
South Dakota	Dry hole–oil–plugged and abandoned	Dry hole
South Dakota	Dry hole–oil show–plugged and abandoned	Dry hole
South Dakota	Dry hole–water well–converted	Dry hole
South Dakota	Dry hole–water well–plugged and abandoned	Dry hole
South Dakota	Gas–dry hole–plugged and abandoned	Dry hole
South Dakota	Oil–dry hole fee land–plugged and abandoned	Dry hole
South Dakota	Oil–dry hole–plugged and abandoned	Dry hole
South Dakota	Gas–gas–converted	Gas
South Dakota	Gas–gas–new drill	Gas
South Dakota	Gas–gas–new well	Gas
South Dakota	Gas–gas–plugged and abandoned	Gas
South Dakota	Gas–gas–private	Gas
South Dakota	Gas–gas–private gas	Gas
South Dakota	Gas–gas–producing	Gas
South Dakota	Gas–gas–temporarily abandoned	Gas
South Dakota	Gas–gas show–plugged and abandoned	Gas
South Dakota	Gas–gas stripper–plugged and abandoned	Gas
South Dakota	Gas–gas stripper–producing	Gas
South Dakota	Gas–gas stripper–temporarily abandoned	Gas
South Dakota	Gas–vertical reentry–temporarily abandoned	Gas
South Dakota	Oil–water injection permit–producing	Injection
South Dakota	Underground injection control–air–injecting	Injection
South Dakota	Underground injection control–air–plugged and abandoned	Injection
South Dakota	Underground injection control–air–reservoir monitoring well	Injection
South Dakota	Underground injection control–air–temporarily abandoned	Injection
South Dakota	Underground injection control–air horizontal–injecting	Injection
South Dakota	Underground injection control–gas injection permit–plugged and abandoned	Injection

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
South Dakota	Underground injection control–horizontal water–injecting	Injection
South Dakota	Underground injection control–horizontal water–injecting	Injection
South Dakota	Underground injection control–horizontal water reentry–new well	Injection
South Dakota	Underground injection control–salt water disposal well–injecting	Injection
South Dakota	Underground injection control–salt water disposal well–plugged and abandoned	Injection
South Dakota	Underground injection control–tribal land–plugged and abandoned	Injection
South Dakota	Underground injection control–water horizontal–injecting	Injection
South Dakota	Underground injection control–water horizontal–reentered	Injection
South Dakota	Underground injection control–water injection–injecting	Injection
South Dakota	Underground injection control–water injection–plugged and abandoned	Injection
South Dakota	Underground injection control–water injection–reentered	Injection
South Dakota	Underground injection control–water injection–temporarily abandoned	Injection
South Dakota	Underground injection control–water well–converted	Injection
South Dakota	Underground injection control–water well–producing	Injection
South Dakota	Gas–never drilled	Never drilled
South Dakota	Gas–new permit	Never drilled
South Dakota	Never drilled–gas	Never drilled
South Dakota	Never drilled–horizontaL	Never drilled
South Dakota	Never drilled–horizontal reentry	Never drilled
South Dakota	Never drilled–tribal land	Never drilled
South Dakota	Never drilled	Never drilled
South Dakota	Oil–horizontal–never drilled	Never drilled
South Dakota	Oil–horizontal–new permit	Never drilled
South Dakota	Oil–new permit	Never drilled
South Dakota	Oil–air injection permit–producing	Oil
South Dakota	Oil–air injection permit–reentered	Oil
South Dakota	Oil–gas injection permit–producing	Oil
South Dakota	Oil–horizontal–plugged and abandoned	Oil
South Dakota	Oil–horizontal–producing	Oil
South Dakota	Oil–horizontal–reentered	Oil
South Dakota	Oil–horizontal–temporarily abandoned	Oil
South Dakota	Oil–horizontal reentry–converted	Oil
South Dakota	Oil–horizontal reentry–plugged and abandoned	Oil
South Dakota	Oil–horizontal reentry–producing	Oil
South Dakota	Oil–horizontal reentry–reentered	Oil
South Dakota	Oil–horizontal reentry–temporarily abandoned	Oil
South Dakota	Oil–converted	Oil
South Dakota	Oil–plugged and abandoned	Oil
South Dakota	Oil–producing	Oil
South Dakota	Oil–reentered	Oil

Appendix C–1. Well classifications for Montana, North Dakota, and South Dakota and the overall well type used for this study.–Continued

[≥, greater than or equal to; ≤, less than or equal to; >, greater than]

State	State well classification	Well type
South Dakota	Oil–reservoir monitoring well	Oil
South Dakota	Oil–temporarily abandoned	Oil
South Dakota	Oil–fee land–plugged and abandoned	Oil
South Dakota	Oil–stripper–converted	Oil
South Dakota	Oil–stripper–plugged and abandoned	Oil
South Dakota	Oil–stripper–producing	Oil
South Dakota	Oil–stripper–reentered	Oil
South Dakota	Oil–tribal land–plugged and abandoned	Oil
South Dakota	Oil–water well–converted	Oil

Charting a Course Forward—Identifying Research and Decisionmaking Priorities in the Williston Basin, United States

By Max Post van der Burg, Karen E. Jenni, Timothy L. Nieman, and James L. Coleman

Chapter D of

Brine Contamination to Aquatic Resources from Oil and Gas Development in the Williston Basin, United States

Edited by Robert A. Gleason and Brian A. Tangen

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Charting a Course Forward—Identifying Research and Decisionmaking Priorities in the Williston Basin, United States

By Max Post van der Burg,[1] Karen E. Jenni,[2] Timothy L. Nieman,[3] and James L. Coleman[1]

Introduction

The goal of any applied science endeavor should be to provide information that leads to better decisionmaking. This means that applied science performed in the context of land and water-resource management should lead to information that is useful to resource managers as they consider and choose management actions. However, it is often not clear what the best actions are in complex situations. There are many factors that a manager would like to consider when choosing a particular management action:

- What outcomes do I want to achieve?
- Who are the stakeholders in these decisions, and what outcomes do they want to achieve?
- What management actions do I have to choose from?
- What are the likely outcomes of each of those management actions?
- What actions might other stakeholders take that affect management outcomes?
- How do I balance competing objectives when choosing a management action?
- What further information could I collect to better understand the outcomes of different actions, and is that information worth collecting?

For example, in the Williston Basin and Prairie Pothole Region (PPR), wildlife managers are uncertain about the risks posed by oil and gas development activities, such as the likelihood and effect of brine spills on wetlands. Resolving these uncertainties could improve the ability of managers to choose effective management strategies, such as best practices for well siting, to reduce such risks. There are also potential conflicts between the objectives and goals of different decisionmakers and stakeholders, which might require making tradeoffs.

Decision analysis (DA) is a formal approach for structuring, modeling, and evaluating decisions that contain these types of complexities (Keeney, 1992; Clemen and Reilly, 2001). DA has roots in statistics, economics, operations research, and organizational behavior (Smith and von Winterfeldt, 2004) and provides a foundation for the logical and transparent evaluation of alternatives to help decisionmakers choose actions that are most likely to achieve their goals. Decision analysts use a combination of qualitative structuring approaches and quantitative modeling tools to assess the various components of a decision problem. They use these tools to evaluate the outcomes of different options and make recommendations about which options should be pursued. These recommendations can be sensitive to stakeholder values (that is, the “best” decision may be different from the perspective of different stakeholders) and uncertainties (that is, the best decision may change as new information is gathered [Keeney, 1992; Keeney and Gregory, 2002]). Current scientific studies can provide the information needed to perform such an analysis. One can also use DA to help guide the identification, development, and prioritization of future scientific studies in order to ensure that the collection of information is relevant to a decision problem (Runge and others, 2011).

The previous chapters in this report outline work pertaining to the effects of oil and gas development on aquatic resources. This chapter outlines the first steps toward developing a decision analytic framework for assessing the effects of oil and gas development in the Williston Basin and PPR and for identifying areas where additional applied science work will be most useful to energy- and conservation-related decisionmaking.

Decision Analysis Workshop

A formal DA workshop was held in Bismarck, North Dakota, from April 18, 2011, to April 21, 2011. Although presented within the context of the work described in previous

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[1] U.S. Geological Survey

[2] Insight Decisions, LLC

[3] Decision Applications, Inc.

chapters of this report, the overarching context for this workshop was larger: It was to frame the issues surrounding natural resource management and conservation decisionmaking with regard to oil and gas development within the Williston Basin (fig. A–1). The goal of the workshop was to facilitate the development of a concrete example decision problem involving siting oil and gas wells relative to wetlands. The purpose of this analysis was to illustrate how the DA process and modeling can lead to concrete decision recommendations. The workshop was attended by over 30 participants from Federal and State agencies and was facilitated by professional decision analysts.

The participants worked through all the steps of a traditional DA in an abbreviated form. This included first broadly "framing" a set of decisions related to oil and gas development and resource conservation to explore the full scope of relevant issues. The scope of the workshop was narrowed to a smaller set of decisions that were relevant to the U.S. Geological Survey (USGS) project described in chapters B and C of this report. These decisions could be sufficiently modeled during the course of a 4-day workshop to allow participants to understand how the DA modeling process could be used in the future.

Framing the Decision Problem

The workshop began by discussing and developing an extensive list of relevant decisionmakers in the Williston Basin area and the types of decisions they make. "Relevant" decisionmakers were defined as those who have the ability to affect oil and gas development as well as aquatic resources and the quality of life for people living in the Williston Basin. These decisionmakers were grouped into broad categories (table D–1), and discussions were held as to whether any stakeholder groups or other perspectives were missing. Participants noted that no oil and gas industry representatives were present at the meeting, which limited their ability to thoroughly understand oil and gas development decisions. Additionally, the participants also pointed out that no community development representatives were present, which would have improved their ability to understand community decisions and concerns about oil and gas development.

The workshop then focused on a relatively narrow decision problem or decision context, for which the primary decisionmakers were well-represented among the workshop participants: *What best management practices should the U.S. Fish and Wildlife Service (USFWS) recommend for well or well pad development in the vicinity of publicly-managed resources (that is, wetlands)?*

Defining Objectives

Workshop participants developed a prototypical objectives network focused on the more limited scope of the defined decision context. In DA, *objectives* are objects of value (for example, wildlife populations) and preferences for the direction of value (for example, maximize or minimize). Different stakeholders and decisionmakers may have different objectives, and the consideration of multiple perspectives is a key part of decisionframing. These multiple perspectives ensure that a more robust and comprehensive decision-support model can be developed (Keeney and Raiffa, 1976; Keeney, 1992). This broader perspective is especially useful for agencies or individuals who are primarily interested in identifying what applied science work will be useful to a range of stakeholders.

Participants were divided into one of two hypothetical decisionmaker groups: oil and gas companies and wildlife managers, specifically USFWS managers. Each group

Table D–1. Synthesized table of relevant decisionmakers and the types of decisions made regarding oil and gas development and land management in the Williston Basin.

Decisionmakers	Decision types
Oil Industry	Lease acquisition (where to develop) Well development (where, when, and how) Operations (hydraulic fracturing, water disposal)
Land and mineral owners (including agricultural entities)	Whether to lease and under what conditions What activities to allow on their lands What activities to conduct given development (for example, cropping choices)
Regulatory agencies (varied)	Well permitting (yes/no and specific conditions) Infrastructure permitting Hauling regulations/road safety Enforcement
Land and resource management agencies (for example, U.S. Fish and Wildlife Service, National Park Service, private landowners)	Recommendations/consultation on well development on or near managed resources Management of any adverse impacts from development on those resources
Local communities	Decisions about how to manage the "boom"

developed a separate list of objectives. After discussion of the similarities and differences between the two perspectives, an integrated set of five main objectives was created. These main objectives contribute to an overall goal of maximizing the net benefits of oil and gas development. Each of these objectives could be further defined by more detailed subobjectives, but the workshop did not attempt to fully define all of the possible subobjectives. There were five main objectives identified:

1. Maximize sustainability of habitats for species of interest. Here the decisionmakers and stakeholders are interested in ensuring that habitat is capable of supporting specific populations and remains resilient to frequent disturbances and fragmentation (all of which were identified as potential subobjectives). This objective was identified as being of interest to both the oil and gas industry and the USFWS.
2. Minimize adverse effects of well development. Well development affects more than just wildlife habitat. The oil and gas industry and wildlife managers would like to minimize the potential negative environmental effects of development to air quality, water quality, and aquatic and terrestrial habitats. Likewise, both groups would like to maximize the safety of oil workers and minimize the time it takes to complete a project.
3. Maximize the economic benefits from well development. The oil and gas industry generates economic benefits for local communities and the State by creating jobs, generating revenue, and paying taxes. Workshop participants taking the oil and gas industry perspective identified several potential subobjectives for increasing economic benefits, including reducing operating costs and taking advantage of new well development opportunities.
4. Minimize conflict between stakeholders. Workshop participants identified a number of areas of conflict because of the current level of development associated with the Bakken Formation and additional conflicts that have occurred during previous oil "booms" in the region. All stakeholders are likely to benefit from minimizing conflict. Some contributors to minimizing conflict could include minimizing the regulatory burden on oil and gas companies, maximizing the simplicity of the process needed to site a new well, and minimizing the number of changes in the regulatory policies for companies. Likewise, maximizing communication between managers, regulatory agencies, and industry representatives, as well as maximizing the sensitivity of the industry to local community issues could help minimize conflict.
5. Maximize accountability of industry for adverse effects. Workshop participants taking the perspective of wildlife managers identified holding oil and gas companies accountable as a key objective. Specifically, if adverse effects do occur, they would want to maximize how much responsibility companies should take for mitigating and remediating wetlands negatively affected by well development (for example, brine spills). Participants noted that this objective is likely to be in conflict with the potential subobjective of minimizing the regulatory burden as a means for minimizing conflict discussed above.

The workshop did not explicitly define comprehensive subobjectives or specific measureable attributes for any of these objectives, as this was only a preliminary exercise. Measurable attributes refer to quantitative measures of the consequences of actions in terms of the effects on objectives (Keeney, 1992; Clemen and Reilly, 2001). Any extensions of this workshop or detailed evaluation and comparison of alternatives would require the development of such measureable attributes.

Identifying Alternative Actions

The workshop participants initially identified a broad range of decisionmakers and types of decisions regarding oil and gas development and resource management. The decision context was narrowed for the remainder of the workshop in order to illustrate all the steps of a DA process. It is important to recognize that decision "types" often include multiple individual decisions, and multiple alternative actions are possible for each of those individual decisions. This DA exercise was focused on the individual decision types that participants felt were likely to be part of any best management practice for locating well pads and the handling and disposal of produced waters. Specifically, best management practices would likely include:

- Well pad location;
- Size, type, and number of wells;
- Pit design, including pit length;
- Produced waters disposal;
- Development timing;
- Infrastructure design (locations, structure);
- Road network design;
- Reclamation requirements;
- Baseline and monitoring requirements; and
- Documentation requirements.

There may be many different options or alternatives for any of these decisions. Thus, rather than look at every possible combination of decision and alternative, a "strategy table" was developed (table D–2) to illustrate how multiple options could be organized into a set of coherent alternatives for a best management practice.

Decision types and the specific options for each of those decision types are listed in table D–2. An option for a best management practice can be defined by selecting one item

Table D–2. Strategy table for decision exercise focused on developing best management practices for siting oil wells and monitoring and reclamation requirements.

[Alternatives were not specified for all decision types (for example, timing), but all types were retained in the table because they were considered important considerations in well siting. --, no alternative specified]

Decision type	Alternative actions for each decision type			
Wells per pad	1	2	4	8
Pad location	Must be a legally drillable location			
Pad size	0.8 hectares	--	--	4 hectares
Pad type	Gravel	Clay based with berm	Elevated pad	Zero discharge
Pit design	Lined	Modified pitless	Modified pitless, netted	Pitless
Pit time	Long	--	--	Short
Produced water disposal	Open-pit	Spread on roads	Reuse	Injection well
Timing	--	--	--	--
Infrastructure	Roads and trucks	Gathering lines plus roads and trucks	Gathering lines plus pipelines	Gathering lines plus pipelines
Road networks	Road to every pad and along every pipeline	Road to every pad	Road to central collecting points	No permanent roads
Reclamation	Meets minimum legal requirement	Exceeds minimum legal requirement	Improves area	As if we were never there
Base-line requirements	Historic data	Adds to historic data	Conducts new local survey	Conducts new regional survey
Monitoring requirements	Uses historic data	Simple monitoring scheme (drilling and completion only)	Monitoring scheme around pad area	Integrated monitoring scheme around all operations
Documentation requirements	Summary of historic activity	--	--	Summary of all activity with data appendixes

from each row. For example, one option for a best management practice strategy would be four wells per pad on 4-hectare gravel pads in a legally drillable location, pitless design with injection wells for disposal of produced waters, exclusive use of roads and trucks to service the well pad, legally required baseline and monitoring requirements only, reclamation requirements to leave the area better than it was before the well, and extensive documentation required. Many other potential best management practice strategies could be developed by selecting different options for each individual decision represented in the table. Participants recognized that oil and gas company participation in future modeling efforts would greatly facilitate the definition of realistic alternatives for best management practices.

Identifying Key Risks and Uncertainties

Decision alternatives within a DA framework are evaluated based on how well they meet the various stakeholder objectives, but the ability of those decisions to meet the stated objectives may be affected to some degree by potential negative events that occur with some frequency (expressed as risk). The ability to estimate the effects of the decision alternatives is affected by the degree of knowledge about a variety of factors (uncertainties) that influence the stated objective. In relation to oil and gas production, one of the key risks is the likelihood of a brine spill during well operation, and some of the key uncertainties have to do with the potential effects of the spill on nearby wetlands. The probability of a brine spill varies based on some of the decision options, such as pit design, pit type, and various well-site operations. Other factors that also can influence how a brine spill will affect nearby wetlands include groundwater flow, the chemistry of the spill, and water chemistry of the wetland. Needless to say, the understanding of these factors is incomplete.

Figure D–1 illustrates the prototype conceptual model outlining the relations between the decision options developed during the workshop, uncertainties, and objectives. As with all parts of this analysis, the model is a simplification. Continuing to identify and quantify other risks and uncertanties will be an integral part of further developing the conceptual decision model. By careful identification of these risks and uncertainties, the decision model will provide a tool for assessing which information will provide the most value in making better management decisions.

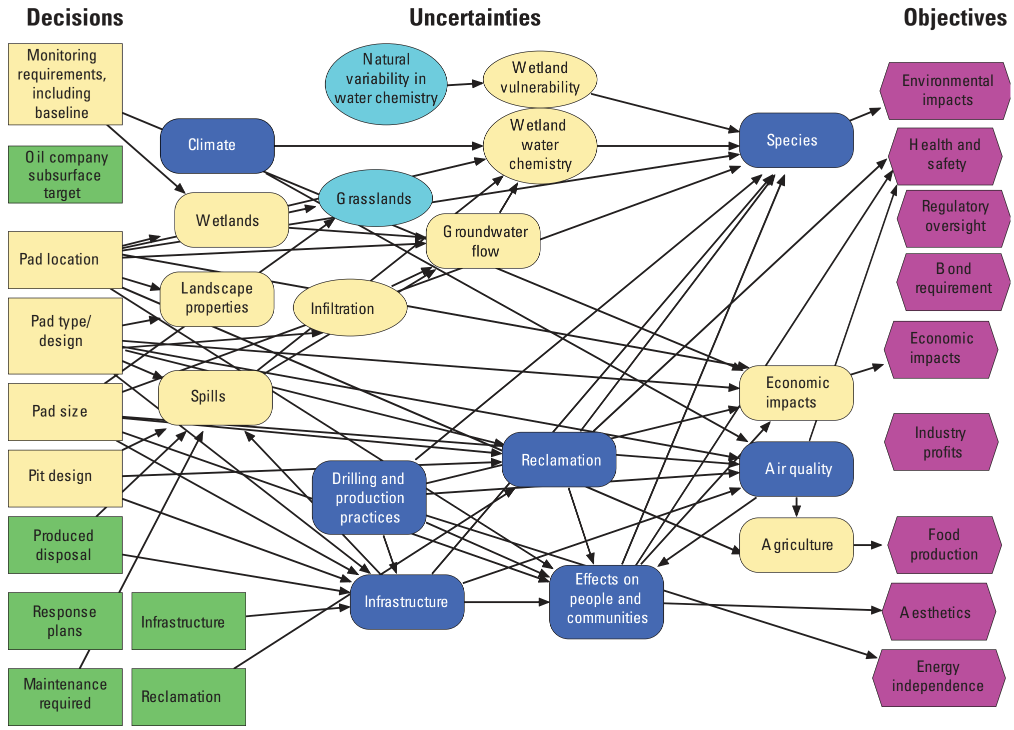

Figure D–1. Prototype decision model illustrating the relation between decisions, uncertainties, and objectives.

Illustrative Modeling

A simple exercise was used to illustrate how to analyze and compare the effects of alternative decisions regarding best management practices. This hypothetical decision problem focused on choosing one of three possible locations for the placement of a well (fig. D–2). Well placement was to occur in a simulated landscape containing two wetlands of different sizes and initial chloride (Cl^-) concentrations. A Monte Carlo simulation model was used to estimate the outcomes of each well placement strategy. These types of simulations work by making repeated random draws of model parameters from statistical distributions, and then using each randomly generated parameter combination to model phenomena of interest. These distributions were parameterized using expert information. The simulation only considered risks posed to wetlands by wells in terms of contamination from brine spills. Comparing the three locations required estimates of numerous uncertain factors, including the:

- Initial conditions (in terms of water chemistry) for each of the two wetlands;
- Probability of a brine spill, at each location and for each type of well pad considered;
- Size and chemistry of a brine spill, assuming such a spill occurs;
- Probability of the spill being detected, intercepted, and mitigated prior to affecting groundwater, and;
- Dispersion and flow rates of a brine spill over the surface, in the subsurface, and in groundwater.

These estimates, along with other assumptions, allow for the estimation of the Cl^- concentration in each wetland over time, assuming there is a well at each of the three locations. This illustrative modeling exercise also included consideration of effects on agriculture (for pad location “B” only) and some of the economic effects of a well at each location. Because this was an illustration, all the necessary model inputs and estimates were developed by using the expert judgment of the workshop participants. The components of the conceptual model that were quantified are represented by the yellow nodes in figure D–1. Very little is known about most of these factors, and these uncertainties are a primary concern throughout the region.

Based on previous experience, participants with knowledge of wetland chemistry provided initial estimates of Cl^- concentrations within each of the two wetlands. The small, fresh wetland (“West”) was estimated to have an initial Cl^- concentration between 10 and 60 milligrams per liter (mg/L). The large, saline wetland (“East”) was assumed to have an initial Cl^- concentration between 300 and 1,200 mg/L (fig. D–3).

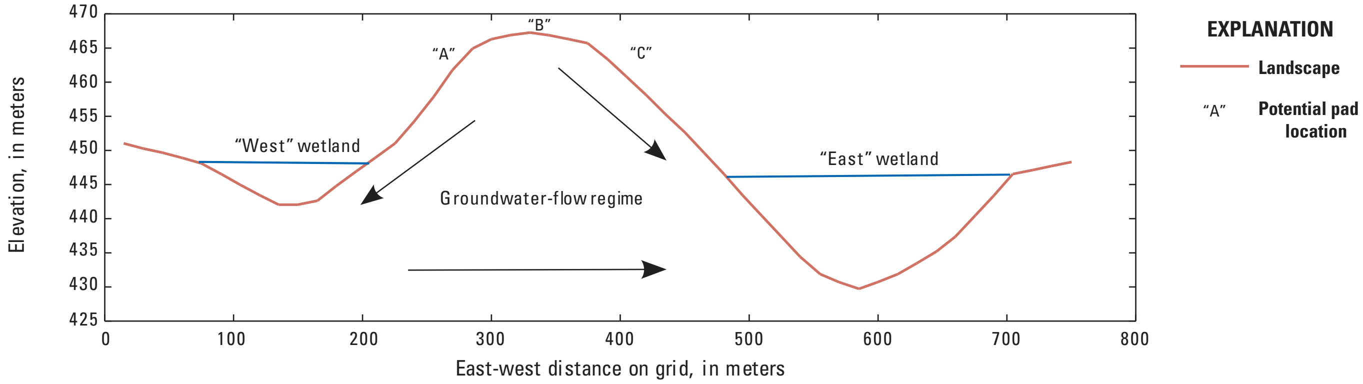

Figure D–2. Simulated landscape containing a small, fresh, seasonal wetland ("West") and a large, saline, year-round wetland ("East)".

Workshop participants first defined a brine spill as being over 4 liters (L), and then estimated that there was a 95-percent chance of a spill or leak of more than 4 L for each year a well was in operation. There was uncertainty about the total magnitude and the chemistry of spills, which were represented with subjective probability distributions (table D–3). The estimated total annual volume of brine spilled from a single well was between about 400 and 7,500 L, with a median estimate of 2,250 L. The Cl^- concentration of the spill was estimated to be between a minimum of 60,000 and a maximum of 255,000 mg/L, with a median estimate of 175,000 mg/L. This latter estimate was informed by the work described in chapter B of this report on the Cl^- concentrations in produced waters from the Bakken Formation.

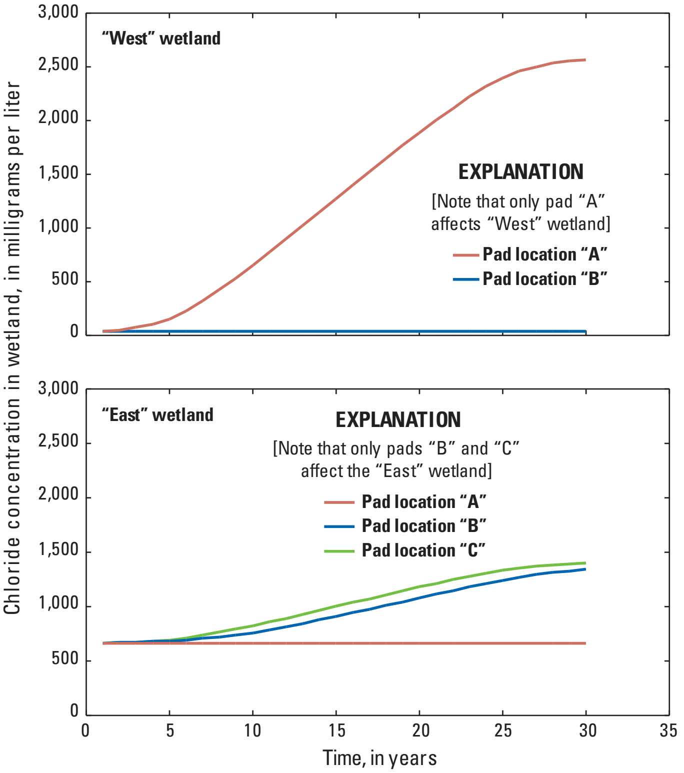

Figure D–3. Mean estimates of the effects of well development on wetland water chemistry (chloride concentration) for two simulated wetlands ("West" and "East") and three well sites, assuming outwash geology.

Not all spills or leaks will necessarily lead to brine contamination of wetlands; some will be detected and intercepted when they occur. Participants assumed that between 5 percent and 95 percent of spills could actually be intercepted, which reflects a high degree of uncertainty. For brine spills that reach the shallow groundwater, both the groundwater-flow rate and the rate at which the brine contamination disperses within the groundwater affect the timing and degree of effect on the wetlands. Groundwater-flow rates in the region differ considerably based on the near-surface geologic deposits, with much lower flow rates in glacial till than in outwash. This illustration included till and outwash as potential scenarios and included uncertainty in the groundwater-flow rates for each (table D–3). Lastly, a simple approximation for dispersion of the Cl^- plume at the wetland was used along with an assumption that Cl^- concentrations would increase over the first 5 years after the initial arrival at the wetland and then would decline over the following 10 years.

Using these estimates and assumptions, the effects of contamination to the two wetlands were calculated for each of the three well locations. A well at pad "A" affected only the "West" wetland, while wells at pads "B" or "C" affected the "East" wetland (fig. D–2). The calculations show that the effect of a well at pad "A" on the "West" wetland was much greater than the effect of a well at pads "B" or "C" on the "East" wetland (fig. D–3). This was because of the smaller size and lower initial Cl^- concentration of the "West" wetland, which means a spill of similar size and chemistry from well pad "A" would have a greater effect on wetland water chemistry than from well pads "B" or "C". Figure D–4 shows the influence of site geology on the resulting wetland water chemistry, with till soils greatly slowing the rate at which the Cl^- plume contaminates the wetland.

Figures D–3 and D–4 show only mean values; the degree of uncertainty regarding the effects of these hypothetical wells on wetland water chemistry is of equal interest. Figure D–5

Table D–3. Model parameters and assumptions for Monte Carlo decision model.

Parameters	Assumptions
Size of spill, in liters per year	Log-normal distribution with median = 2,250 and standard deviation = 2
Chemistry of spill, in milligrams per liter	Log-normal distribution with median = 175,000 and standard deviation = 2
Groundwater-flow rate in outwash sites, in meters per year	Triangular distribution with minimum = 3 , mode = 30 , maximum = 150
Groundwater-flow rate in till sites, in meters per year	Triangular distribution with minimum = 0.03, mode = 0.6, maximum = 5.7
Local communities	Decisions about how to manage the “boom”

demonstrates the uncertainty in the water chemistry of the “West” wetland given a well at pad location “A” when it is located in a glacial outwash deposit. Each line in figure D–5 represents a probability band; the top line represents the 95th percentile estimate and the bottom line represents the 5th percentile estimate. This graph suggests that given all of the uncertainties in the input parameters, there is a 90-percent confidence that the Cl^- concentration in the “West” wetland in 30 years will be between 500 and 5,700 mg/L, given a well at pad “A” with near-surface outwash deposits.

One of the benefits of this modeling approach is that it provides the ability to show the relative importance of each of the uncertainties in the model inputs on the uncertainty in output. The relation between uncertain inputs and outputs for the workshop simulations is represented with an “importance diagram” (fig. D–6). Each of the inputs is shown on the vertical axis, and the length of the bar shows the correlation between the uncertainty in that value and the resulting uncertainty in the Cl^- concentration in the “West” wetland. The highest correlation is for the proportion of the spill volume that is intercepted, which was also the most uncertain value. While that factor is an important contributor to the uncertainty in the Cl^- concentration in the “West” wetland, the importance of the other factors varies over time. Uncertainty about the groundwater-flow rate and about the baseline chemistry of the wetland, for example, are important determinants of wetland water chemistry in year 5 (the fifth year after well installation); however, by year 30, both are much less important.

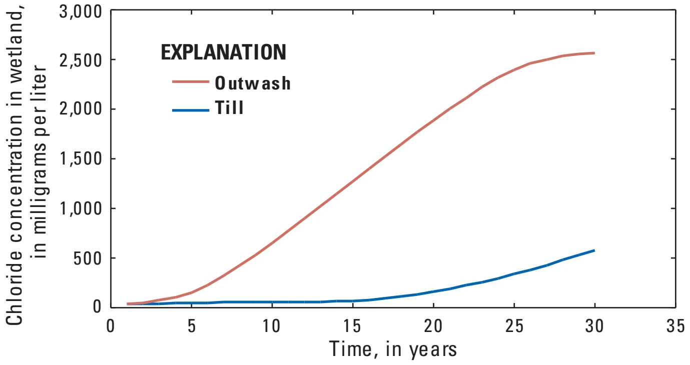

Figure D–4. Effect of site geology on the mean migration rate of a brine plume originating from well pad “A” and affecting the “West” wetland.

This type of analysis can be used to help prioritize research areas, if the goal is to have a better understanding of particular outputs of interest. With regard to the workshop exercise, improved understanding of (or better control over) the ability to detect and intercept spills before they reach groundwater would greatly decrease the expected magnitude and the uncertainty about wetland contamination from a well at a particular location. Additionally, improved understanding of brine chemistry and the size of the wetlands potentially affected would improve understanding of the magnitude of wetland contamination more than reducing uncertainty about the size of the spills or the baseline water chemistry of the potentially affected wetlands.

Participants considered additional effects of well development on some of the other objectives identified during the workshop as a final step in this illustrative modeling exercise. Specifically, estimates were made of expected State tax revenues based on simple assumptions about well production and tax rates over time. The potential higher costs for installing a well pad on a slope (locations “A” or “C”) compared to a flat location (location “B”) and estimated possible effects on farm profits also were considered. All of these simple estimates were made without consideration of uncertainty in order to illustrate the tradeoffs that could be considered in the recommendation of well pad locations.

Table D–4 contains the results of the modeling exercise and illustrates these tradeoffs. Pad “A” clearly has the largest negative effect on the “West” wetland, while pad “B” had a comparatively lower effect in terms of brine spills and similar tax revenues when compared with “A”; pad “B” had a negative effect on farm income because the well was sited on agricultural land. Pad “C” was similar to pad “B” in terms of effects on water chemistry, was a more expensive location, but had no effect on farm income. While the workshop did not explicitly illustrate methods for assessing tradeoffs in a multiobjective DA, this last comparison shows how adding more components to the problem can make the analysis more complex and informative.

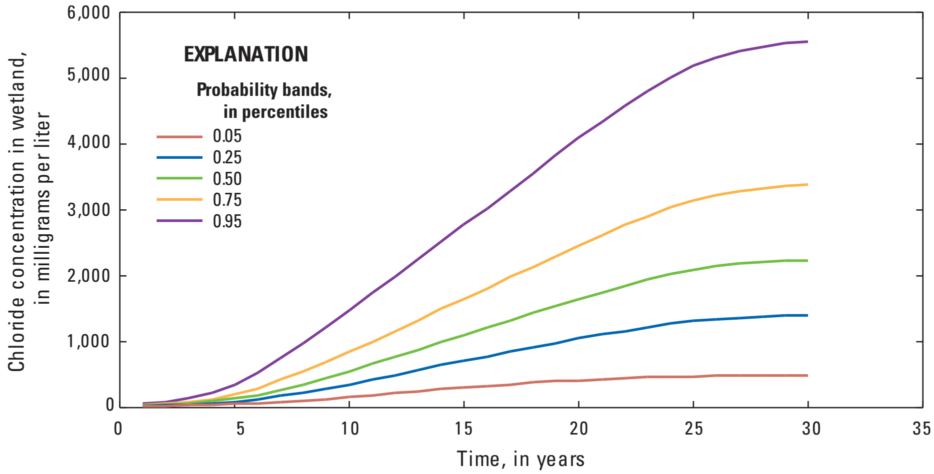

Figure D–5. Uncertainty in the concentration of chlorides in the "West" wetland over time, assuming a well located at pad "A" and outwash geology.

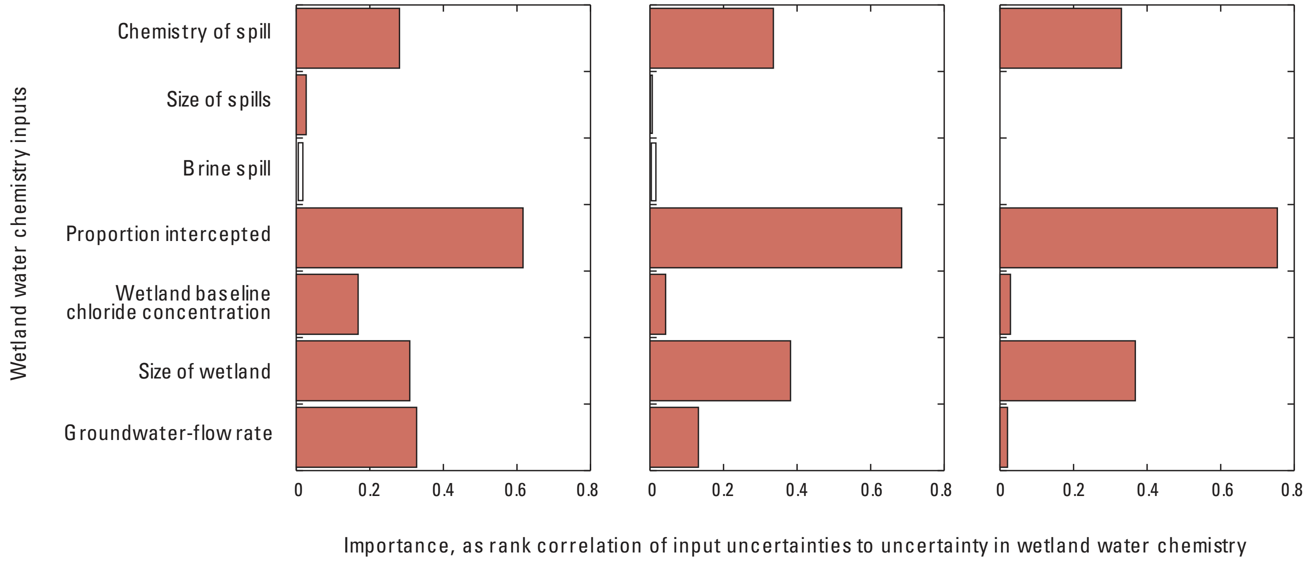

Figure D–6. Effect of uncertainty in each input variable on uncertainty in the resulting water chemistry in the "West" wetland at three different times, assuming outwash geology.

Steps for Moving Forward

The main focus of the analysis presented in this chapter was simplified to only include two of the stakeholders (USFWS managers and the oil and gas industry) and well-by-well effects on two individual wetlands. It may be useful to expand this framework so that it can be used by multiple stakeholders to evaluate a broader array of decisions and identify key areas of research that would be most valuable across a range of decisions. The end goal is to build a model that can be used by stakeholders to assess alternative development decisions within a broader geographic area. Additionally, this model would account for the cumulative effects of oil and gas well development in the area and provide a basis for identifying and prioritizing applied science activities. A list of possible next steps was developed to accomplish this goal, and challenges were identified that could arise as the framework and model are extended.

1. Include perspectives from other relevant stakeholders. While the workshop participants and facilitators made an effort to include the perspective of the oil and gas industry, more needs to be done to work more directly with industry to accurately represent that perspective. Likewise, the perspectives of local communities and private landowners need to be added to the framework. The current model structure will need to be reviewed with these additional stakeholders to identify missing elements as well as future patterns of oil and gas development. However, drawing these stakeholders together may prove difficult and require discussions with individual groups instead of larger workshops.

2. Define the geographic scope. A challenge for extending this modeling effort is to define a useful geographic scope as the example focused only on a single well pad and its effects on a single wetland. A scale needs to be chosen

Table D–4. Results of modeling exercise showing the mean impact of well development after 20 years (assuming outwash geology).

[mg/L, milligrams per liter; $, United States dollars]

Output	Pad "A" "West" wetland	Pad "B" "East" wetland	Pad "C" "East" wetland
Chloride concentration, mg/L	1,910	1,079	1,179
Change in chloride concentration, mg/L	+1,876	+412	+512
Industry added cost, $	3,300	0	3,300
Lost farm income, $	0	20,000	0
Added tax revenue, $	1.6 million	1.6 million	1.6 million
Jobs created, in man-years	23	23	23

that is large enough to allow for comparisons between alternative development scenarios but small enough to model potential effects with relevant detail to maximize the utility of the modeling framework.

3. Define the scale of oil and gas development. The relevant scale of oil and gas development needs to be considered in addition to defining a geographic scope for the model. For example, it may be more useful to focus effort on the cumulative effects of multiple wells rather than well-by-well effects throughout the region. However, it is possible that the most important factors to stakeholders regarding cumulative effects of different development patterns may be less than the environmental factors considered and more than socioeconomic responses to development.

4. Consider alternative strategies. The main scope of this workshop was analyzing decisions about best management practices and their effects on nearby wetlands. This focus was targeting the oil and gas well development process. But another set of strategies to consider are decisions about remediation postdevelopment. This would not be as focused on the immediate effects of development, but rather on what the best strategies are for addressing postdevelopment problems. Considering immediate effects, potential spill effects, and remediation options would allow one to look at tradeoffs between lessening immediate effects to a site during well installation relative to future remediation of the site after the well is shut in, or some combination of the two.

5. Assess the value of information. The ultimate goal of this exercise is to provide decisionmakers with a framework that can be used to prioritize management actions and identify science and information needed to improve management. Therefore, there is a need to identify the current state of information related to this problem and be efficient in acquiring new information. A more robust value-of-information analysis (Clemen and Reilly, 2001) than illustrated above could be useful in identifying the most significant uncertainties and where decisionmakers stand to gain the most from new studies associated with this problem.

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