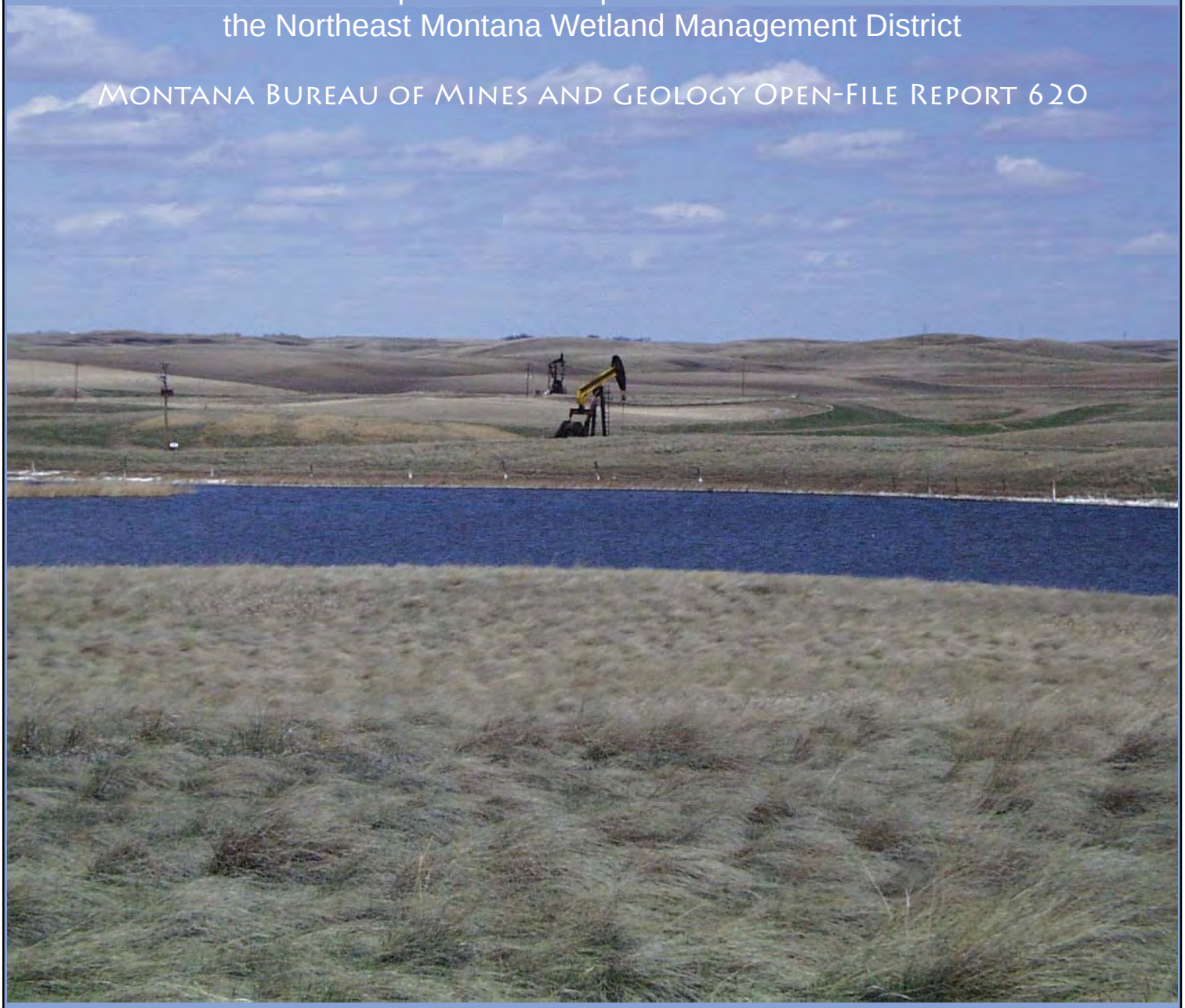
# U.S. FISH & WILDLIFE SERVICE
# REGION 6
# ENVIRONMENTAL CONTAMINANTS PROGRAM

## Montana—Impacts of Oil Exploration and Production to the Northeast Montana Wetland Management District

### Montana Bureau of Mines and Geology Open-File Report 620



by
David R. Rouse[1], Karen J. Nelson[1], and Jon C. Reiten[2]

DEC ID: 200460001
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# TABLE OF CONTENTS

## FIGURES

# TABLES

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# ABSTRACT

The Northeast Montana Wetland Management District provides habitat for numerous different species of breeding waterfowl and migrating shorebirds, including the threatened Piping Plover and endangered Whooping Crane. The management district is also located within the Williston Basin, which is often considered Montana's top oil-producing region, characterized by dense oil fields both currently operational and historic. The majority of the waterfowl production areas are located in the eastern half of Sheridan County, Montana, where very high densities of oil wells are also located. Produced water is the dominant waste product of the oil production process. Prior to the 1970s, it was often stored in unlined reserve pits or disposed of in infiltration pits. Produced waters of the Williston Basin are highly saline brines that often contain co-occurring contaminants that were either included as additives during the drilling process or derived from the deep oil-producing zones and brought to the surface during the extraction process. Improper disposal of produced water brines can degrade surface water and groundwater. This study was conducted to evaluate the extent of produced water contamination throughout the Northeast Montana Wetland Management District.

Numerous techniques were employed to assess produced water brine contamination throughout the Northeast Montana Wetland Management District. In the field, a contaminant index (i.e., chloride concentration/specific conductivity) was calculated for wetlands visited to initially quantify the extent of surface-water brine contamination. Water quality was assessed at 87 wetlands. Thirty-five of the visited wetlands had average contaminant index values indicating brine contamination. Impacted wetlands were found in 17 of the 29 waterfowl production areas and one refuge visited. The apparent terrain conductivity of sites where the contaminant index suggested produced water brine impacts was then characterized using soil electromagnetic conductivity (EM-31) surveys. Completed EM-31 surveys delineated the movement of brine from its original disposal location and indicated whether or not produced water and associated contaminants may have contaminated surface waters on the WPAs. Ionic compositions of groundwater monitoring well samples were quantified in areas with suspected contamination, and the calculated groundwater contaminant index value often verified the results of the EM-31 surveys. Furthermore, analyses for petroleum hydrocarbons on soil and groundwater samples and analyses for trace elements on groundwater and surface-water samples indicated that certain constituents from each group of co-occurring contaminants were present in the environment at potentially toxic levels as a result of the oil exploration and production processes. In an effort to quantify the impacts of co-occurring contaminants, an ion-toxicity model was applied in coordination with laboratory toxicity tests using site water.

The presence of historical infiltration disposal pits, coupled with underlying glacial outwash, represent scenarios in which the risk of environmental contamination is elevated due to the likelihood of drilling waste migrating offsite. Historic aerial maps could be used to identify historical brine pits and the application of the contaminant index could be used in coordination to identify other contaminated areas or to identify areas that are susceptible to contamination.

**Keywords:** DEC ID: 200460001, FFS: 61130- 6N51, Produced Water, Brines, Williston Basin, Northeast Montana Wetland Management District, EM-31

# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| Ag | Silver |
| Al | Aluminum |
| API | American Petroleum Institute |
| As | Arsenic |
| ASCII | American Standard Code for Information Interchange |
| B | Boron |
| Ba | Barium |
| Be | Beryllium |
| Br | Bromine |
| Ca | Calcium |
| Cd | Cadmium |
| CI | Contaminant index |
| Cl | Chloride |
| Co | Cobalt |
| $CO_3$ | Carbonate |
| Cr | Chromium |
| Cu | Copper |
| DEM | Digital elevation model |
| DO | Dissolved oxygen |
| DOC | Dissolved organic carbon |
| DW | Dry weight |
| EM-31 | Electromagnetic conductivity survey meter |
| EPA | Environmental Protection Agency |
| GPM | Gallons per minute |
| GWIC | Ground-Water Information Center |
| HAPET | Habit and Population Evaluation Team |
| $HCO_3$ | Bicarbonate |
| Hg | Mercury |
| ICP-MS | Inductively coupled plasma spectrometry |
| IDW | Inverse distance weighting |
| K | Potassium |
| Li | Lithium |
| MBMG | Montana Bureau of Mines and Geology |
| MBOGC | Montana Board of Oil and Gas Conservation |
| Mg | Magnesium |
| Mo | Molybdenum |
| Na | Sodium |
| NaCl | Sodium chloride |
| Ni | Nickel |
| $NO_3$ | Nitrate |
| NWR | National Wildlife Refuge |
| Pb | Lead |
| QA/QC | Quality assurance/quality control |
| RCRA | Resource Conservation and Recovery Act |
| SAR | Sodium adsorption ratio |
| SC | Specific conductivity |
| Se | Selenium |
| Service | United States Fish and Wildlife Service |
| $SO_4$ | Sulfate |
| Sr | Strontium |
| TDS | Total dissolved solids |
| TERL | Trace Element Research Laboratory |
| Ti | Titanium |
| TPH | Total petroleum hydrocarbons |
| U | Uranium |
| UWRBEBL | University of Wyoming Red Butte Environmental Biology Lab |
| V | Vanadium |
| WMD | Wetland Management District |
| WPA | Waterfowl Production Area |
| Zn | Zinc |
| Zr | Zirconium |

# INTRODUCTION

The Williston Basin, which extends into the northeastern corner of Montana, is Montana's top oil-producing region, accounting for 81% of all oil produced in the state (Montana Oil and Gas Conservation Division, 2000). The Northeast Montana Wetland Management District (WMD), found in Daniels, Sheridan, and Roosevelt Counties of Montana, contains a portion of the prairie pothole region, and also overlies numerous oil fields located in the Williston Basin. The majority of the waterfowl production areas (WPA) were purchased without underground mineral rights, and perpetual wetland and grassland easements do not prevent oil exploration or drilling activities. Consequently, oil field development in eastern Sheridan County, Montana has caused the transfer of highly concentrated sodium chloride brines from deep oil-producing zones to shallow aquifers, lakes, and wetlands. Therefore, the overlap of oil production activities has created concerns for the Northeast Montana WMD.

Oil was first discovered in the Williston Basin in North Dakota along the Nesson Anticline near the town of Tioga in 1951. The first oil boom in eastern Sheridan County, Montana did not occur until the early 1960s, when several large fields were developed. Two of the larger fields developed were the Goose Lake and Flat Lake fields. The primary targets for oil extraction were zones in the lower Charles Formation of the Mississippian Madison group. A second oil boom occurred in the 1970s when deeper oil formations were targeted, mainly in the Ordovician Red River Formation. Renewed oil exploration activity began in the mid-1990s with the advent of horizontal drilling and three-dimensional seismic technology (USFWS, 2000). Recent targets include the Bakken Shale and the underlying Three Forks Formation. Typical production from these units requires horizontal boreholes to be completed within the producing formation. To produce hydrocarbons, the formations surrounding the horizontal legs are hydrofractured using highly pressurized fluids developed to carry fine-sand-sized proppants into fractures induced by the high-pressure fluids. These induced fractures are propped open and stabilized by the sand grains, allowing hydrocarbons to flow toward the borehole, where they are extracted by surface pumps.

Environmental contaminants generated in conjunction with oil exploration and production that may cause adverse effects are drilling muds and production activity wastes, including produced water. Congress exempted these wastes from the more stringent requirements of the hazardous waste management provision of the Resource Conservation and Recovery Act (RCRA). Consequently, reserve pits, reinjection wells, and well site abandonment procedures are less stringent than would otherwise be required under RCRA, increasing the potential for contamination to remain in the environment (Kharaka and others, 1995).

Drilling fluids or muds are crucial production components for cooling and lubricating the drill bit, removing the drill cuttings from the drilling area, and transporting them to the surface. They counterbalance the geologic formation pressure to prevent formation fluids (i.e., oil, gas, and water) from entering the well prematurely and prevent the open uncased wellbore from caving in (EPA, 2000). Additives enhance the performance of the drilling fluids and typically contain weighting materials such as barium sulfate and various types of corrosion inhibitors such as iron oxide, aluminum bisulfate, zinc carbonate, and zinc chromate (EPA, 2000). In the Williston Basin, most drilling requires negotiating salt-bearing formations, which necessitates the use of special drilling muds. Muds used for these formations are either saltwater-based or oil-based. Saltwater-based muds typically contain 250,000 mg/L NaCl, while oil-based muds contain combinations of diesel fuel, crude oil, oxidized asphalt, fatty and organic acids, and stabilizing agents (Montana Office of the Governor and others, 1989). Other drilling additives employ dispersants such as iron lignosulfonates; flocculants such as acrylic polymers; surfactants; and biocides such as organic amines, chlorophenols, and formaldehydes, which are used to kill bacteria that may produce sulfide gas (EPA, 2000).

Drilling wastes range from 8 to 84 gallons for each foot drilled (EPA, 2000). In Sheridan County, where well depths vary between 6,520 and 12,000 ft (Montana Oil and Gas Conservation Division, 2000), drilling wastes may range from 52,000 to 1 million gallons per newly drilled well. Formation fluids, as well as rock cuttings from the drilling process, are also often found in the drilling wastes and may contribute to contaminant loads (EPA, 2000).

When brought to the surface through the extraction process, the formation fluid normally contains several constituents in addition to crude oil, such as natural gas, produced water, sand, silt, and various additives. In the Williston Basin, gas fraction hydrocarbons are typically burned off in a flare pit and the remaining formation fluid is piped to an onsite or nearby tank battery where initial oil/water separation occurs. The extraction process is turbulent, so the formation fluid usually is comprised of a high percentage of oil–water emulsion (EPA, 2000).

By volume, produced water is the largest waste product from the oil production process (EPA, 2000). The Montana portion of the Williston Basin has numerous older oil wells, defined as those wells drilled prior to the mid-1980s, and because the volume of produced water also increases with the age of the well, this basin likely produces saline water at far higher rates than oil. In fact, 90–98% of extracted fluid in older wells is produced water instead of oil (EPA, 2000). On a national scale, oil production in the U.S. resulted in the extraction of 2.5 billion barrels of crude oil and 25 billion barrels of produced water, a volume 10-fold greater than the crude oil produced (USGS, 1997).

Contaminant concentrations in produced water vary by region, depth to production zone, and age of the well (EPA, 2000). Frequently occurring produced water contaminants include hydrocarbons, trace elements, radionuclides, drilling mud additives, and salts (Stephenson, 1992). Trace element occurrence and concentration in produced waters can vary. Commonly occurring trace elements include barium, boron, cadmium, chromium, copper, lead, lithium, nickel, silver, strontium, and zinc (Stephenson, 1992; Jacobs and others, 1992). Some trace elements such as boron, lithium, and strontium are present in produced water because they are co-located within the oil-producing zones, while other trace elements such as silver, cadmium, lead, chromium, barium, aluminum, nickel, and zinc occur in produced water as drilling additive constituents (Reiten, 1991). Further, oil extracted from deep formations can be very corrosive, and can entrain high concentrations of trace elements added in the drilling process during extraction (Brian Cain, USFWS, written commun., 2009). Radionuclides are also a commonly occurring constituent in produced water. These radionuclides, often referred to as NORM (naturally occurring radioactive material), primarily consist of radium (226Ra and 228Ra; Stephenson, 1992), although uranium and radon can also be present (EPA, 2000). NORM can be found in high concentrations in the scale formation on the well casing. Scale forms as the salts in produced water precipitate out of solution as the formation fluid approaches the surface and cools. Scale and paraffin removal are regular maintenance activities completed with hydrochloric and hydrofluoric acid, organic acids, and phosphates (EPA, 2000). These maintenance activities can be continuous, and cleaning chemicals and associated scale material will likely become additional contaminant components in the produced water.

An additional concern associated with oil drilling is that co-produced water in the Williston Basin is some of the most saline produced water in the United States. In fact, the oil field brines produced from within the Williston Basin can be up to 10 times as salty as seawater. Migration of produced water brines to surface-water or groundwater has been characterized in many areas of the United States, and many of the contamination pathways are similar, such as leaching of brines from disposal pits, migrating from road spreading sites, and reinjection wells leaking into freshwater aquifers and contaminating drinking water and irrigation wells (Bair and Digel, 1990; Baker and Brendecke, 1983; Thamke and Craigg, 1997; Jones and Waite, 1988; Dutton and others, 1989).

Traditionally, infiltration pits and unlined reserve pits were excavated at the drill site and used to dispose of produced water, as well as other oil field wastes (Reiten, 1992). After the drilling was completed, the pits were left open to be used for additional produced water disposal, or they were backfilled (Reiten, 1991). Delivery of contaminated produced waters to these pits ranged from one half to 420 barrels (a standard oil barrel is 42 gallons) a day, and it was assumed that the contaminated produced water delivered to these unlined pits was evaporating (Murphy and others, 1988). Rather than evaporating, much of the produced water leached into the shallow groundwater system underlying the infiltration and reserve pits. Based on the average pit size and conservative chloride concentrations, an estimated 260 tons of sodium chloride salts was present in each pit (Reiten, 1992). Recharge events that allow moisture to infiltrate the soil layers above shallow aquifers have the potential to dissolve salts and cause downgradient migration, further increasing the mobile salt loads present in groundwater. Migration of salts from old infiltration pits has been documented numerous times, often resulting in lost productivity of crop ground and salinization of shallow groundwater and surface waters (Reiten and Tischmak, 1993). Prior to the mid-1970s, reserve pits were reclaimed by simply backfilling the pit.

While current reserve pit rules and regulations for the state of Montana require that all pits must now be lined, the liners used in these pits often become compromised during placement, or in time through use. Many of the liners observed at new drilling sites appear to be ripped, torn, or punctured (J. Reiten, Montana Bureau of Mines and Geology, and K. Nelson, USFWS, oral commun., 2009). Additionally, reserve pit liners were often breached as a means to reclaim the site, allowing salt-saturated mud to move to unlined trenches. Brines are extremely mobile, and only infiltrating snowmelt or rainfall dilutes the salt load. The rate of dilution is very slow, and high concentrations of salt can be found in both the soil and groundwater below a site for decades (Reiten, 1991).

Migration of brine results in salt contamination of soil and groundwater offsite. Recharge events have the potential to mobilize salts, contributing to downgradient migration. Additionally, upward migration of salt is common in areas with high water tables, resulting in the movement of salt into the soil, effectively sterilizing the soil to a point in which the system can no longer support vegetation. Produced water brines can kill vegetation, prevent germination of seeds, and cause increased erosion. The sodium in produced water can cause dispersion of clays, disruption of soil texture, and loss of soil cohesion (Otton and Zielinski, 2000). Additionally, produced water brines may cause damage to aquifers, contaminating water wells throughout the county. The cost of relocating and redrilling wells to avoid contaminated aquifers can be high. It may require drilling several test holes to find uncontaminated groundwater. Sampling in the 1990s indicated increased salt concentrations in and around parts of the Clear Lake aquifer near Dagmar. The Clear Lake aquifer eventually discharges to the many lakes and wetlands in Sheridan County that are protected as WPAs or are included in the Medicine Lake National Wildlife Refuge (NWR). Indirect costs include the loss of wildlife habitat caused by oilfield brine-contaminated wetlands and contaminated aquifers.
This investigation intends to determine to what extent

oilfield exploration and production wastes, principally through produced waters, have impacted WPAs administered by the Northeast Montana WMD and to promote the implementation of environmentally sound technology to new oil and gas drilling. Specifically, this investigation will determine the number of WPAs impacted by oil field waste and determine which wetlands contain potentially toxic concentrations of ions and co-occurring contaminants from oil exploration and production activities.

## STUDY AREA

The study area for this project, located in the northeastern corner of Montana, included Daniels, Sheridan, and Roosevelt Counties as well as the Medicine Lake NWR and the Northeast Montana WMD, which is administered by the Medicine Lake NWR complex (fig. 1). National Wildlife Refuge System lands within the WMD include 44 WPAs, totaling 12,507 acres; the two noncontiguous units of Medicine Lake NWR, totaling 31,660 acres; an additional 8,573 acres of wetlands protected under perpetual wetland easements; and perpetual grassland easements protecting 10,968 acres of grassland.

The Northeast Montana WMD provides habitat for approximately 200,000 waterfowl breeding pairs and in excess of 100,000 migrating shorebirds (M. Rabenberg, USFWS, oral commun., 2006). The area has been used by endangered Whooping Cranes (*Gus Americana*) and supports 85% of Montana's breeding population of the threatened Piping Plover (*Charadrius melodus*). Surveys completed in June 2000 indicated 144 adult plovers (66 breeding pairs) were using the WPAs as well as state and private lands in the area (USFWS, 2000).

Dry land farming and livestock grazing are the traditional land uses in Sheridan County. Irrigation development has increased in the past 29 years, occurring mainly in the southeastern part of the county where the Clear Lake aquifer is being tapped. Irrigable soils and sufficient water supplies for irrigation overlie several of the oil fields.

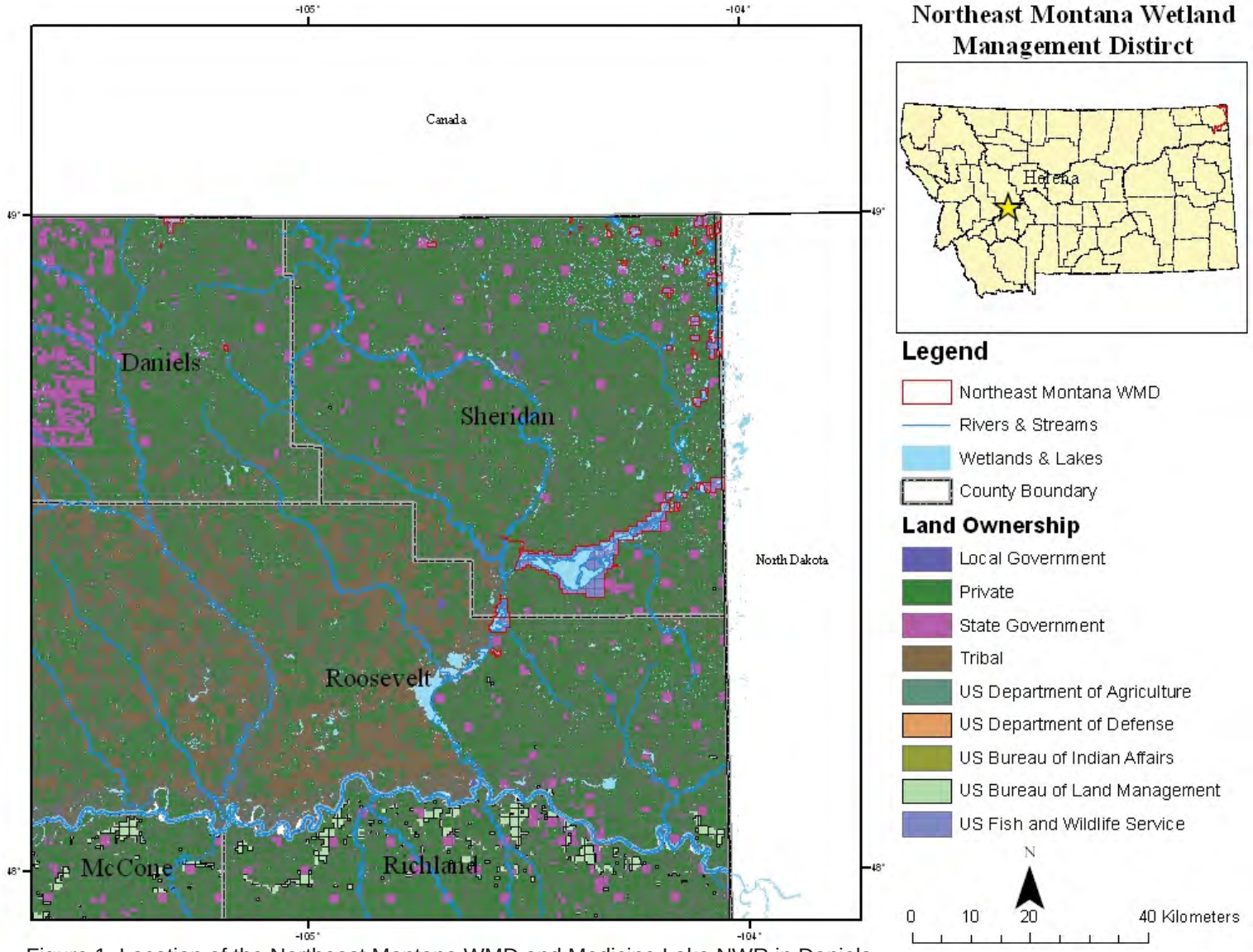


Figure 1. Location of the Northeast Montana WMD and Medicine Lake NWR in Daniels, Sheridan, and Roosevelt Counties.

Resource extraction industries that are present within Sheridan County include oil production, coal mining, and gravel mining. Reserves of lignite within the Fort Union Formation underlie the glacial and terrace deposits. Several abandoned coal mines are located near the town of Coalridge. Most of the glacial outwash deposits in this area are composed of sand and gravel, and are mined throughout eastern Sheridan County.

Hundreds of lakes and wetlands are located in eastern Sheridan County. These surface-water sources have a very diverse chemistry, with several-fold increases in dissolved solids possible between lakes separated by only a few hundred yards. The diverse chemistry implies the integration of complex groundwater flow systems including local, intermediate, and regional flow systems supplying water to the lakes and wetlands. The lakes are used by wildlife, livestock, and recreationists. Many of the lakes are important to the water balance of the region both as focused recharge sources and as buffers influencing groundwater levels.

## Climate

Eastern Sheridan County has a semiarid continental climate, characterized by cold, dry winters, moderately hot and dry summers, and cool, dry falls. Cold winters are often interrupted by warming trends, with summers dominated by hot days and cool nights. January is generally the coldest month and July the warmest. Based on the 29-year period of record from 1980 to 2009, the average precipitation at Westby is approximately 13.07 in/year with about 66 percent of the precipitation falling from May through August. June is typically the wettest month. Evaporation is typically much higher than precipitation in this area. The closest station with long-term Class A evaporation pan data is at Sidney. Long-term data from the Sidney site indicates that between 25 and 35 in of water evaporates annually. Evaporation data from a Class A pan of the U.S. Department of Agriculture research farm near Froid indicates significantly higher evaporation rates than at Sidney. The average evaporation at the Froid station was 52 in per year between 1984 and 1988. In contrast, the Sidney station reported 34 in of annual evaporation over the same period (Donovan, 1988). Wind and hot temperatures contribute to an average 6 to 12 in of monthly evaporation from May to August at the Froid site. The Froid climatic station appears to be more representative of conditions in eastern Sheridan County than the Sidney climatic station because of the proximity and more similar physiography.

Long-term climatic trends show a large range of monthly precipitation for individual months. This trend is most evident from April through September. A 10- to 20-year periodicity of below average precipitation is often accompanied by above average temperatures, indicating that cycles of drought are common in this region. The 1980s were drier than average, resulting in drought during much of the decade.

## Regional Hydrogeology

Eight major aquifer systems underlie eastern Sheridan County from the Paleozoic Madison Group to the Quaternary alluvium (table 1). Aquifers within 200 to 300 ft of ground surface include the Tongue River Member of the Tertiary Fort Union Formation, Tertiary/Quaternary terrace deposits, Quaternary glacial outwash deposits, and recent alluvial deposits. The lower Hell Creek–Fox Hills aquifer is the deepest source of potable water in this region. Depth to this aquifer ranges from 700 to 1100 ft. Deeper aquifers in rocks of Mesozoic and Paleozoic age contain nonpotable water, but are important aquifers because they are associated with oil reservoirs. Water from these aquifers is commonly pumped to the surface during oil production and can degrade potable supplies if allowed to infiltrate shallow aquifers.

The Prairie Pothole region of northeastern Montana consists of glaciated terrain that makes up parts of the Missouri Coteau and the Coteau Slope physiographic regions (Bluemle, 1991). Underlying the Quaternary glacial deposits are sediments and rocks that form a large regional structural feature known as the Williston Basin. The Basin is filled with Paleozoic to Recent Age sediments. Hydrocarbons were generated and trapped in several different Paleozoic age sediments. Depths of hydrocarbon targets range from about 6000 ft to more than 12,000 ft. Hydrocarbons accumulated in rocks of the Red River Formation, Three Forks Formation, Bakken Formation, and several formations within the Mississippian Group. Co-produced brines from this part of the Williston Basin are typically ten times more concentrated than sea water.

The Missouri Coteau and the Coteau Slope physiographic regions are clearly identifiable on aerial photographs, on satellite images, and on a variety of maps showing the topography. Plate 1 is a near-surface geologic map showing predominant lithologic units draped over a hillshade map of the area. The geologic map was developed using information from outcrops, drill holes, soil surveys (Richardson and Hanson, 1977), and open-file geologic maps (Bergantino, 1986). The Missouri Coteau is found in the two northern townships of this area. The Coteau Slope occupies the rest of the area. The topography of the Missouri Coteau is very hummocky with abundant potholes and sharp hills. The predominant near-surface deposits are glacial till with minor areas of lake sediment, outwash, and alluvium. The remnants of several ice-walled lakes are found in the Missouri Coteau region of Sheridan County. These are often slightly hummocky due to lake development over ice and subsequent differential melting of the stagnant ice. The topography of the Coteau slope is smoother, with gentler hills and fewer potholes. A relict swale trending southwest to northeast aligns with the ancestral valley of the Missouri River. The alluvial aquifer section of the Clear Lake Aquifer occupies the central part of the swale. Glacial till and glacial outwash are the predominant near-surface deposits. The glacial outwash section of the Clear Lake aquifer

underlies areas mapped as glacial outwash from Medicine Lake to Westby.

The distribution of surficial glacial deposits of till, outwash, and lake sediments are mapped throughout most of Sheridan County. These sediments were deposited during and after the advance of Late Wisconsinan glaciers into the region. Glacial till is the most widespread surficial geologic unit mapped in the study area. The glacial till consists of unbedded and unsorted gray to light olive brown, pebbly clay-loam, and is considered an aquitard. Pebbles, cobbles, and boulders of local and northern sources are common in this unit. Water in the till aquitards is generally under confined conditions. Secondary porosity caused by fractures in the till accounts for most of the groundwater flow.

Glacial outwash deposits are the second most widespread surficial geologic unit mapped in the study area. The outwash consists of light gray, brown, and reddish-brown silty sand, sand, and gravel. It is composed of a heterogeneous mixture of igneous, metamorphic, and sedimentary rock fragments. The outwash is typically composed of poorly sorted to moderately well-sorted sediments. Glacial outwash was deposited by meltwater streams draining the glaciers. Deposits of glacial outwash typically form aquifers, which if buried by glacial till or other fine-grained materials are commonly under confined or leaky confined conditions.

Glacial lake sediments cover the least area of the surficial geologic units mapped. These lake sediments consist of light brown to dark gray interbedded, fine-grained sand, silt, and clay. Lake sediments were deposited by interflow and underflow currents in glacially dammed lakes. All of the surficial lake deposits are restricted to the portion of Plate 1 north and west of McElroy. Due to its fine-grained nature, lake sediments typically form aquitards. As in glacial till, fractures cause secondary porosity, increasing the water-transmitting capabilities of this unit. Water in lake deposits is generally under confined conditions. For simplicity, recent deposits of alluvium, loess, colluvium, and slough sediment are not typically mapped. These deposits are usually thin (less than 3 ft thick) and where thicker are difficult to distinguish from the older glacial deposits.

Aquifers in Sheridan County range from non-potable water sources associated with deep hydrocarbon exploration and production to potable sources that are commonly used for stock, domestic, municipal, and irrigation supplies (Donovan, 1988). Water produced from aquifers stratigraphically below the Bearpaw Shale are typically unusable for most purposes and are generally considered a waste, often requiring injection into a properly engineered disposal well. These include aquifer zones within the Cretaceous Age Judith River Formation, Cretaceous Age Lakota and Dakota sandstone, Mississippian Age Madison Group limestone and dolomite, and deeper Paleozoic Age carbonate and sandstone. Waters from these aquifers are often co-produced with hydrocarbons and contain very high concentrations of dissolved minerals, sometimes greater than 300,000 mg/L total dissolved solids (TDS). Aquifer zones from the Dakota and deeper are often targeted for injection wells used for disposal of produced water from hydrocarbon production. Containment of this water is a significant concern to water users because of potential contamination from discharges into shallower potable supplies. Aquifers in the Madison Formation and deeper may have a potential for low-temperature geothermal exploitation because of high artesian pressures and water temperatures reaching 60ºC. These aquifers are believed to be part of a deep regional groundwater flow system with recharge areas located farther west in Montana and discharge areas in eastern North Dakota. As the groundwater flows from west to east, the dissolved minerals tend to increase significantly. Another significant component of the deep aquifer system is vertical leakage, where water leaks vertically to either overlying or underlying stratigraphic units dependent on differential hydrostatic pressures.

## Water Quality

Potable groundwater can be produced from several generally reliable aquifers underlying Sheridan County. Characteristics of these aquifers are summarized in table 1.

Groundwater occurring within sandstone units of the Fox Hills–Hell Creek aquifer system underlies Sheridan County at depths ranging from about 1000 to 1300 ft. This is the stratigraphically lowest aquifer that dependably yields potable water in this area. It is exposed or thinly covered by unconsolidated materials around the Poplar Dome located just west of Sheridan County. Water quality is summarized based on the results of five water analyses in Sheridan County. A Stiff diagram showing the dominant ions is shown in figure 2. Water from the Fox Hills–Hell Creek aquifer is dominated by ions of sodium and bicarbonate. The TDS ranged from 1187 to 1643 mg/L in samples from five wells in Sheridan County. The mean TDS was 1429 mg/L and mean sodium absorption ration (SAR) was 78. Fluoride concentrations ranged from 1.1 to 4.1 mg/L and are likely to be greater than drinking water standards. Based on regional studies in nearby areas it appears that groundwater from the Fox Hills–Hell Creek aquifer discharges to the deep incised trenches formed by the Big Muddy meltwater channel and ancestral Missouri River channel and eventually flows towards the Missouri River. Little is currently known about the volume of these discharges or how these discharges impact the water quality of surface-water bodies in Sheridan County.

The Fort Union Formation underlies Sheridan County and is about 1000 to 1500 ft thick. There are four Members of the Fort Union mapped in northeastern Montana. The Tullock Member is the oldest unit. It is largely yellow sandstone interbedded with grayish brown and black shale and thin beds of coal. This unit is overlain by the Lebo Member, which is composed of dark gray carbonaceous

Table 1. Water-yielding and water-quality characteristics of principal aquifers in Sheridan County.

| Stratigraphic Unit | Principal Aquifers | Aquifer Characteristics |
|---|---|---|
| Quaternary unconsolidated deposits 0–100 ft thick (110QAL) | Alluvial sand and gravel along and underlying the Big Muddy and its tributaries | Groundwater under unconfined and semi-confined conditions in alluvial sand and gravel along the Yellowstone River. Saturated thickness generally less than 40 ft. Well yields and quality adequate for domestic and stock uses. Water quality variable, mean TDS 1,470 mg/L. |
| Quaternary glacial aquifers unconsolidated deposits 0–250 ft thick (112OTSH, 112DRFT, 112TILL) | Minor low-yield aquifers in glacial till. High yield aquifers in glacial outwash deposits associated with buried channels | Groundwater is semi-confined or confined in buried channel aquifers. May directly overlie alluvial aquifer in buried channels, resulting in gravel deposits 100–250 ft thick. Well yields and quality commonly adequate for irrigation. Irrigation potential limited by high SAR, mean TDS 1,323. |
| Quaternary or Tertiary unconsolidated or poorly cemented deposits 0–300 ft thick (112ALVM, 112SNGR,112TRRC) | Minor upland sand and gravel associated with Flaxville Formation. More commonly in buried channels containing ancestral Missouri River (Wiota) sand and gravel deposits | Groundwater under unconfined conditions in isolated sand and gravel deposits underlying terraces on uplands above Big Muddy Creek valley. Groundwater is semi-confined or confined in buried channel aquifers. Saturated thickness ranges from 0 to 150 ft. Well yields and quality adequate for irrigation. Irrigation potential limited by high SAR, mean TDS 1,471 mg/L. |
| Fort Union Formation up to 1500 ft thick (125FRUN,125TGRV) | Fort Union Formation Sentinel Butte Member Tongue River Member Lebo Member Tullock Member | Sandstone up to 100 ft thick and coal beds up to 8 ft thick are water-yielding units. Groundwater generally unconfined in upper 200 ft, confined below. Yields typically average 10 gpm. Variable water quality, mean TDS 1,379 mg/L, may have high sulfate and iron concentrations. |
| Fox Hills/Hell Creek Formation 350–450 ft thick (211FHHC, 211 HLCK) | Fox Hills | Groundwater is generally under confined conditions in sandstones in the lower part of the Hell Creek Formation and upper part of the Fox Hills Sandstone (Colgate Member). Wells may flow in low-lying areas. Well yields as high as 100 gpm have been reported, but average about 20 gpm. Alkaline water, mean TDS 1,429 mg/L, sodium and bicarbonate are the dominant ions, may have high fluoride concentrations. |

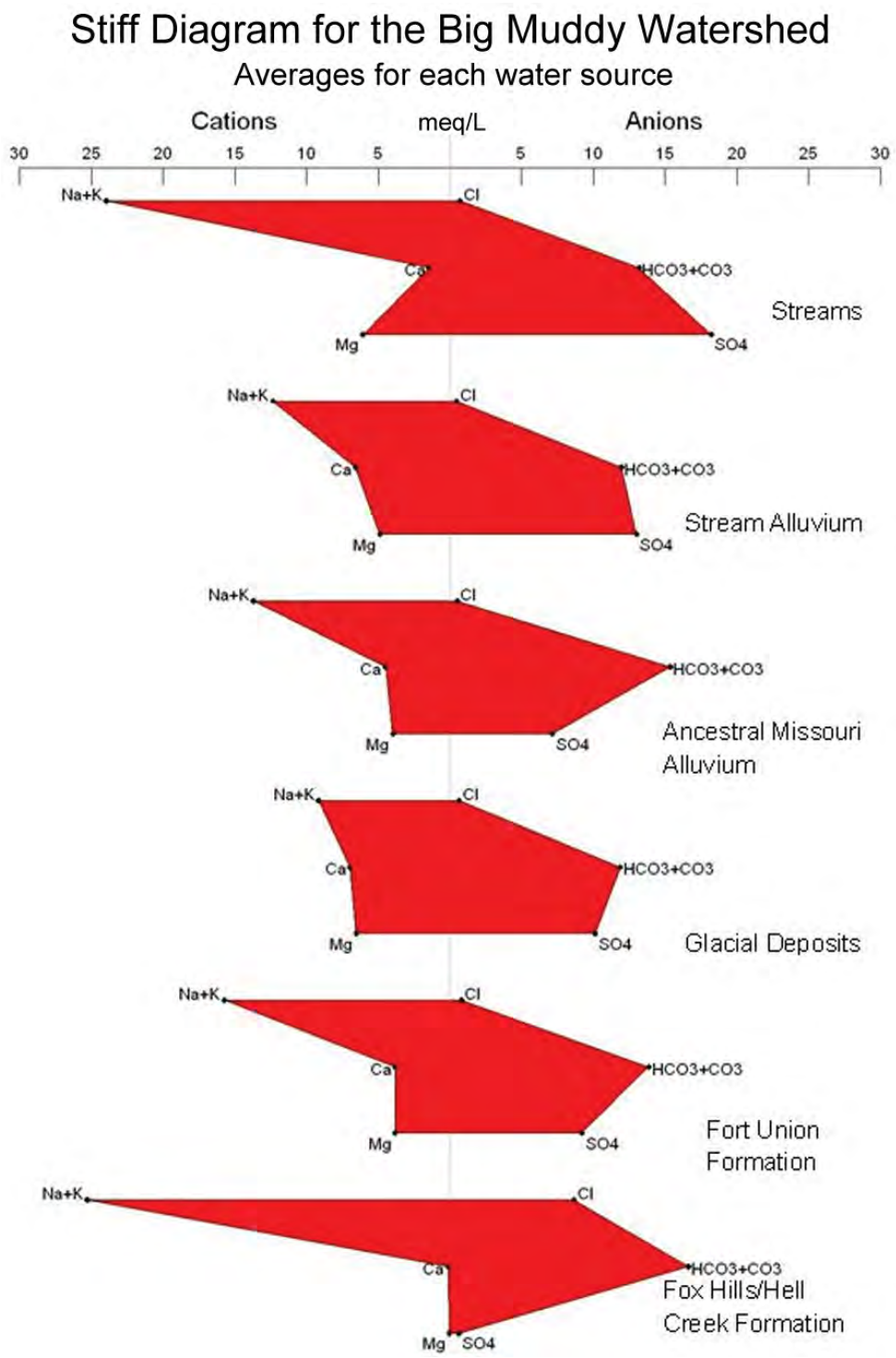


Figure 2. Stiff diagram based on the average values of major anions and cations in samples from Big Muddy Creek and wells completed in major geological sources in the Big Muddy watershed of Sheridan County.

shale, bentonitic claystone, sandstone, and coal. The next overlying unit is the Tongue River Member, composed of yellowish orange sandstone, sandy and silty carbonaceous shale, and coal. The uppermost unit is the Sentinel Butte Member, consisting of dark gray shale with interbedded lignite and gray sandstone. Groundwater production is typically limited to sandstone or coal lithologies. All of the members contain permeable zones that are aquifers, but the Lebo Member contains significantly more bentonitic claystone and shale. Wells completed in this unit are the least likely to produce significant amounts of water.

Well depths in the Fort Union aquifer range from 40 to 500 ft, and static water levels range from 10 to 350 ft depending on topographic position and regional flow conditions. Water quality is summarized based on the results of 38 water analyses in the Big Muddy watershed. A Stiff diagram showing the dominant ions is shown in figure 2. Water from the Fort Union aquifer is dominated by ions of sodium and bicarbonate. TDS ranged from 328 to 4009 mg/L in samples from 38 wells in the Big Muddy drainage. The mean TDS was 1379 mg/L and mean SAR was 86. The median value of TDS was 1229 and the median SAR was 8. While either the median or mean appear to be good predictors of TDS, the median of the SAR values is probably a better measurement of typical SAR values. Based on regional studies in nearby areas, it appears that groundwater discharges to the deep incised trench formed by the Big Muddy meltwater channel and eventually flows towards the Missouri River. Little is currently known about the volume of these discharges or how these discharges impact the water quality of the Big Muddy.

Deposits of the ancestral Missouri River in northeastern Montana are known as the Flaxville Formation and Wiota gravels. These units formed when the ancestral Missouri River flowed northeast towards Hudson Bay. The Flaxville Formation is a Tertiary Age gravel deposit that commonly forms unconfined aquifers typically less than 100 ft deep. It is restricted to upland alluvial gravel plateaus west of the Big Muddy, but is buried by glacial deposits in parts of eastern Sheridan County. Local rainfall and snowmelt provide abundant recharge and springs commonly form along the plateaus. The Wiota gravels are Quaternary age and contain fragments of Canadian Shield rocks, indicating association with glacial deposits. These gravels are overlain by 50 to 250 ft of glacial sediments. Aquifers developed in these gravels are typically semiconfined or confined. Water quality is summarized based on the results of 18 water

analyses in Sheridan County. A Stiff diagram showing the dominant ions is shown in figure 2. Water from the alluvial gravel aquifer is dominated by ions of sodium and bicarbonate. TDS ranged from 477 to 2068 mg/L in 18 samples from wells in the Big Muddy drainage. The mean TDS was 1282 mg/L and mean SAR was 8.

# METHODS

## Site Selection

Study site selection began by compiling spatial data in ArcView. Locations of oil wells drilled in Sheridan, Daniels, and Roosevelt Counties in Montana were obtained from the Montana Board of Oil and Gas Conservation (MBOGC). The Habitat and Population Evaluation Team (HAPET) of the U.S. Fish and Wildlife Service (Service) provided shapefiles for WPA and Refuge boundaries in these same counties; this included the Medicine Lake NWR and the Northeast Montana WMD. HAPET also provided wetland data and worked with MBOGC to create current information on the locations of all wells drilled in the Williston Basin. Wetlands were separated into basin classes when displayed in WPA maps. These classes, adopted from Niemuth and others (2010), include temporary, seasonal, semi-permanent, and lake classes. Digital elevation models (DEM), as well as hydrologic unit boundaries, soil types, landcover, and major roads were also added to the spatial data used. The created maps and the use of the associated attribute data allowed for desktop site selection. Site selection involved first compiling a list of all WPAs that have or have had oil exploration and production activities in their watershed. This subset of WPAs was then reviewed by examining the attribute data associated with the wells drilled on or nearby the selected WPA. Well information reviewed included date of drilling (wells drilled before the late 1970s will likely have unlined infiltration pits), type of well (i.e., oil, dry hole, injection well), and status (i.e., closed, temporarily abandoned, producing). All these factors were used to determine potential risks from a particular well. The Service also worked with the local inspector for MBOGC. The inspector was able to provide historical information about infiltration pits used in the area as well as provide access to tank batteries, or a group of tanks that are connected to receive product from a producing well, located off Service-owned lands. Previous research conducted in the area was also used for site selection. Some of this previous work included landowner interviews regarding improper oil field waste disposal.

## Produced Water in Wetlands

Sites selected for investigation were then visited to determine the Contaminant Index (CI), i.e., the ratio of field chloride concentration (mg/L) to field specific conductance (µS/cm; Reiten, 1992). This evaluation was conducted for all wetlands within each selected WPA. At each wetland, HACH Quantab titrators for chloride were employed to determine chloride concentrations. A small amount of wetland water was placed in a certified cleaned container with a chloride strip. Dilutions were completed with a graduated cylinder with distilled water if chloride concentrations exceeded the 613 mg/L maximum reading of the titration strips. Dilution water and site water in the graduated cylinder were mixed prior to measuring chlorides. Specific conductivity was determined using a Hydrolab MiniSonde 4a, while dissolved oxygen (DO), pH, and temperature were also recorded. Chloride concentrations were then divided by the specific conductance to determine the CI. Previous investigations completed in eastern Sheridan County determined an empirical lower limit for indicating produced water impacts at CI > 0.035 (Reiten, 1992). When possible, all wetlands within a WPA were sampled, although several wetlands were dry for the duration of this investigation. WPAs that were not necessarily under current risk from oil field exploration and production were also sampled as time allowed. This information would then be available to the WMD as baseline data if a new well was drilled in the area.

## Characterizing Oil Field Production Waste Migration

Sites where the CI showed produced water impacts were then characterized using soil electromagnetic conductivity (EM-31) surveys. EM-31 surveys document soil conductivity by measuring the electrical conductivity of pore water. This method was used to delineate the extent and/or movement of produced water from infiltration pits, reserve pits, or spills. The EM-31 was used in combination with a Trimble (Model GeoXT) global positioning system unit with sub-meter accuracy for accurate map production. Transects for each site were set up at each location and typically ran north to south, or east to west. Transects were located approximately 50 ft apart and crossed the location of an infiltration pit, reserve pit, or suspected location if no visual clues were evident. The transect length was determined by assessing background soil conductivity at each site. At the start of each survey, the EM-31 was monitored while walking in a presumed background area to determine soil conductivity of these areas. Once the background conductivity was noted, the length of each transect was determined by starting and ending in concentrations approximating background. The number of transects was also determined using the same method. However, mapping efforts were often stopped by property boundaries, wetlands, or roads.

Completed EM-31 surveys delineated the movement of brine from its original disposal location and indicated whether or not produced water and potentially associated contaminants have contaminated surface water on the WPAs (by looking at the extent of the mapped plume). The EM-31 surveys provided information on the movement of brines from reserve pits, as well as old infiltration pits. Information on the potential constituents in the ground water

was then determined at a subset of sites by installation of monitoring wells.

## Mapping EM-31 Surveys

Electrical conductivity data measured using an EM-31 and recorded in the field using a Trimble (Model GeoXT) global positioning system unit were imported to ArcGIS 9.3.1 as shapefiles. Several steps were involved to create maps that accurately displayed the electrical conductivity values collected. All of the proceeding analyses were done using ArcGIS 9.3.1. First, a single buffer was created around each set of measurement points at a distance of 85 ft, or until no gaps were left within the buffered zone. Next, the inverse distance weighted (IDW) function was used to interpolate the electrical conductivity to the same extent as the buffer layer. This creates a spatially interpolated surface that has the same rectangular extent as the buffer. We chose the IDW function as it is an exact interpolation method, meaning the surface produced is forced through all the data points, giving the exact value on the interpolated surface at the location of the corresponding data point. For this analysis we used a neighborhood of three points, which allows for finer resolution of rapidly changing values commonly encountered in these EM-31 surveys. Other interpolation methods, namely different krigging styles and splines, were also attempted. However, these methods are often used in studies that rely on fewer data points and cover much larger areas and commonly underestimate high values and overestimate low values. While these methods are more statistically robust, the interpolation surfaces created failed to honor the true electrical conductivity values collected in the field.

The IDW output produces a floating point raster, which is not supported by many other applications in ArcGIS 9.3.1. Therefore, these raster files where converted to ASCII text and then converted back to raster, which changes the format to an integer raster. These integer raster files were then converted to polygons. This conversion to polygon creates a separate polygon for each grid cell in the interpolated surface. To reduce the number of polygons, groups of neighboring polygons with the same electrical conductivity values were dissolved into single polygons. This polygon layer was then clipped to the buffer extent, thus restricting our interpolated surface to the area close to our data points. The accuracy of the spatially interpolated surface decreases moving away from the data points; therefore this clip allows us to only display data where we have appropriate control over electrical conductivity values and removes areas with strange artifacts of interpolation commonly seen on the edges of interpolated surfaces. Finally, the clipped spatially interpolated surface was classified as a quantity using a graduated color scheme with no outline and displayed with a 30% transparency.

## Monitoring Wells

Sites were selected for installation of monitoring wells near where produced water signatures were detected in wetlands and maps created with EM-31 survey information showed conditions greater than background levels. In total, 33 monitoring wells were drilled on six WPAs and two different locations on Medicine Lake NWR. In addition, 12 wells drilled by the Montana Bureau of Mines and Geology (MBMG) in an earlier investigation located on or adjacent to five WPAs were refurbished. Samples were collected from all wells for a total metals and major ions scan. Selected wells were also sampled for total petroleum hydrocarbon (TPH) based on well logs created during the drilling process. During the drilling of several monitoring wells, a hydrocarbon layer was encountered. In these cases, we added TPH to the analyte list.

The wells were drilled with an MBMG auger rig and were constructed through shallow-stem auger flights. All of the wells were completed using 2-inch PVC casing and PVC well screen. The annulus around each well screen was packed with 10/20 slot silica sand and sealed to the surface with bentonite chips, and in some cases, bentonitic well cuttings. The wells were flushed with water and developed by pumping and bailing until they produced water representative of ambient groundwater conditions, as determined by field water-quality parameters. Well logs and completion results are available through the MBMG's Groundwater Information Center website (http://mbmggwic.mtech.edu/). To access this data, go to the Groundwater Information Center (GWIC) homepage above, where you will be prompted to sign in and establish a password and data use prior to connecting to the database. Data can be accessed by project name, sample number, and location. The best way to view and download data associated with the Medicine Lake project is to navigate to Projects at the top of the page. Click on the General MBMG Program Data and scroll down to "OILFIELD BRINE IMPACTS ON USFWS WETLANDS IN SHERIDAN COUNTY, MT (USFWSBRINE)." For this project, there are data listed under Site Data, Site Visit Data, Water Quality Data, and Water Level Data. At this point, you can select the type of data you want to view. The Site Data table provides direct access to well logs, well completion reports, water-quality data, hydrographs, and a plot of the well locations. Unique GWIC identification numbers were included throughout the document for sites that have data accessible through the MBMG's Groundwater Information Center.

## Soil Salinity at Monitoring Well Drilling Locations and Salt Scald Areas

Soil samples were collected at selected monitoring well drilling sites and from two salt scars in 2005. Samples were collected at approximately 3 ft intervals (0–3, 3–5, 5–8, etc.) and were stored in wirl-pak plastic bags. The samples were placed in a cooler and then transported to the Service's Montana Field Office for processing.

Samples weighing approximately 200 grams were oven-dried at 50°C and then placed in a blender to disaggregate clay-cemented clumps formed during the drying process. Soil from the blender was then placed in a stainless steel sieve with a 2 mm aperture, and mesh number 10. Exactly 50 g of sieved soil was weighed into a polycarbonate centrifuge bottle and 50 ml of deionized water added. Each 1:1 (by weight) mixture was stirred vigorously, allowed to stand overnight at room temperature, and again stirred. The slurries were centrifuged at 4,000 revolutions per minute for 40 minutes to remove suspended particles larger than approximately 0.1 µm diameter. Clear solution was decanted and passed through a filter membrane of 0.45 µm pore size using a syringe. Specific conductance of each clear extract was measured immediately with an Oakton Con 510 Bench Conductivity/TDS meter, and chloride was measured using a HACH Quantab titrator for chloride.

## Invertebrate Community and Sampling

Light traps were deployed overnight in selected wetlands to determine the invertebrate community. Dr. Dan Gustafson from Montana State University agreed to identify all invertebrates collected from approximately 40 different wetlands. These data have not been provided to the Service at this time, but we hope to obtain the data in the future. Additionally, invertebrate sampling for 2006 at several wetlands for body burdens of contaminants could not be completed because the wetlands targeted for sampling were dry.

## Modeling Ion Toxicity and Toxicity Testing

In 2005, water was collected from 20 different wetlands in the study area. Samples were collected early in the morning and shipped overnight to the University of Wyoming's Red Buttes Environmental Biology Laboratory (UWRBEBL) to be used in toxicity tests. Toxicity tests were then started the next day to ensure test water did not exceed a 48 h holding time and followed the general guidance of the U.S. Environmental Protection Agency (EPA, 1991, 1993) for conducting acute whole effluent toxicity tests. All tests were conducted in 30 ml plastic beakers containing 10 ml of test solution and five organisms per chamber. Organisms used in these tests were *Ceriodaphnia dubia*. Tests were conducted under a 16 h:8 h light:dark photoperiod at 25°C. Each test was completed using four replicates of each control and site water. Exposure periods were 48 h with observations for mortality completed daily. The criteria for death were no visible movement and no response to prodding. During the tests, temperature, conductivity, pH, and DO were monitored at the beginning, at 28 h, and at 48 h.

Analyses completed on site waters included dissolved organic carbon (DOC), alkalinity, and major ions (Cl, NO3, SO4, Ca, K, Mg, and Na). Upon receiving results on the major ions present in water samples collected from selected wetlands, we used the statistical model developed by Mount and others (1997) to determine the predicted toxicity of the selected site waters to *C. dubia*. Predicted toxicity was then compared to the observed toxicity produced from the toxicity tests.

## Surface-Water and Groundwater Samples

Surface-water and groundwater samples were collected from monitoring wells, wetlands, and Medicine Lake and submitted for major ion analyses and/or a total metals scan. Water-quality parameters were recorded at locations of water samples using a Hydrolab MiniSonde 4a to determine pH, DO, specific conductivity (SC), and temperature. Surface-water samples were collected in a 5-gallon plastic bucket that was previously washed with an Alcanox-water solution and rinsed with 10% nitric acid and distilled water. Groundwater samples were collected at all wells capable of producing enough water for analysis. Samples were collected by pumping or bailing each well until three well casing volumes were removed or SC measured with a Hydrolab MiniSonde 4a stabilized. Groundwater was then pumped or bailed into a 5-gallon plastic bucket that was previously washed with an Alcanox-water solution and rinsed with 10% nitric acid and distilled water.

A Geopump Peristaltic Pump was then used to pump surface water or groundwater from the bucket to the certified chemically cleaned sample bottles. A Geotech Dipos-a-filter (0.45 µm) was used for samples requiring filtration. Filtered samples collected for trace element analyses were acidified with trace metal grade nitric acid to a pH <2. All samples were stored at 4°C until shipment to Trace Element Research Laboratory (TERL) or delivery to the MBMG. Analytical work was completed by two different laboratories, the MBMG Analytical Division and TERL. The MBMG completed analytical work for ions and trace elements, where metals including cations were determined using ICP and ICP-MS, and anions were determined using ion chromatography. Analytical work for a total metals scan was completed by TERL using atomic fluorescence spectroscopy for selenium, cold-vapor atomic absorption spectroscopy for mercury, graphite furnace atomic absorption spectroscopy for arsenic, and ICP for the rest of the trace elements. Quality assurance/quality control (QA/QC) for both laboratories consisted of procedural blanks, duplicate analyses, and spike recoveries. All reports of QA/QC completed by TERL were also reviewed by the Services Analytical Control Facility for acceptability before results are distributed. QA/QC for ion scans completed by the MBMG also included a mass balance.

A subset of monitoring wells was also sampled for TPH. If hydrocarbons were encountered during the monitoring well drilling process, TPH was sampled in those wells. Several soil samples were also collected in these areas. Additionally, if TPH were present in the wells, those wells were again sampled in the following year for aliphatic and aromatic hydrocarbons. All hydrocarbon samples were collected with a bailer, and decanted directly into certified cleaned amber

glass containers. These samples were shipped immediately to Mississippi State Chemical Laboratory where they were preserved prior to analysis.

The Kendall's tau statistic (Helsel and Hirsch, 1992), a nonparametric measure of the monotonic correlation between two continuous variables, was used to measure the strength of the relationship between the CI and trace element concentrations in groundwater and surface water. This statistic relies on ranks rather than actual values to calculate a correlation coefficient, so it is considered resistant to outliers and will perform on data with moderate censuring. Water-quality data are often not normally distributed and contain censored data values (data reported as being less than the analytical limit of detection). Ranging between -1 and 1, tau is dimensionless and calculates the relationship between two variables based on the direction of paired values. For example, when one variable increases as the second increases, tau is positive. Kendall's tau correlation coefficients were considered statistically significant when probabilities (p-values) were less than 0.05. Free Statistics Software (v1.1.23-r6) based on the R framework was used to calculated Kendall's tau correlation coefficients and resulting probabilities (p-values; Wessa, 2008).

### Quality Assurance/Quality Control

Contract laboratories performing analyses and the Service's Analytical Control Facility were responsible for adequate laboratory quality assurance and quality control. Precision and accuracy of laboratory analyses were confirmed with procedural blanks, duplicate analyses, test recoveries of spiked material, and reference material analyses when appropriate. Standard reference materials and spiked samples were analyzed to verify the accuracy of analytical techniques. Sample collection and storage followed standard operating procedures.

## RESULTS AND DISCUSSION

### Anderson WPA

Anderson WPA was established in August 1989 and is approximately 530 acres in area (fig. 3). Bird surveys have indicated that much of the WPA's habitat is suitable for breeding waterfowl during nesting season, with observations of 42–88 duck pairs per square mile in the northern portion of the WPA and 88–111 duck pairs per square mile in the southern portion of the WPA (Brian DeVries, USFWS, written commun., 2009). Much of the upland habitat is intact native prairie, so management practices, such as prescribed grazing and prescribed fire, are implemented to maintain and increase the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, there were four production wells and one tank battery located within the WPA. Using abbreviated American Petroleum Institute (API) well numbers, well 21351 is an approved plugged and abandoned dry hole that was completed in January 1981. Wells 05188 and 05191 are active enhanced oil recovery (EOR) injection wells that were completed in November 1964 and March 1965, respectively. Well 05184 is a shut-in oil well that was completed in February 1965. Additionally, many wells are located in close proximity to the WPA. For instance, well 05194 is a shut-in oil well completed in March 1965 that is located along the edge of the northwestern WPA boundary.

#### *Geology*

The surficial geology of this site is a mix of glacial outwash and glacial till (fig. 4). Nearby deeper drilling indicates that there is about 50 to 70 ft of glacial deposits overlying Fort Union bedrock. Lithologic logs indicate a mixture of glacial sediments, including: sand and gravel deposits (glacial outwash), pebbly clay loam deposits (glacial till), and fine-grained silt and clay deposits (glacial lake sediments).

#### *Groundwater Hydrology*

The water table altitude was estimated from water levels measured in the fall of 2005. Groundwater flow in the local flow system is shown in figure 5. The flow radiates away from the upland north and east of the site and in general mimics the topography (fig. 5). The cross section (fig. 6) indicates glacial outwash overlying glacial till except near the eastern wetland, where lake sediments directly underlie the outwash and eventually the outwash pinches out. The outwash forms a water table aquifer and the relatively high transmissivity of this glacial outwash aquifer creates a preferential pathway for contaminants moving offsite.

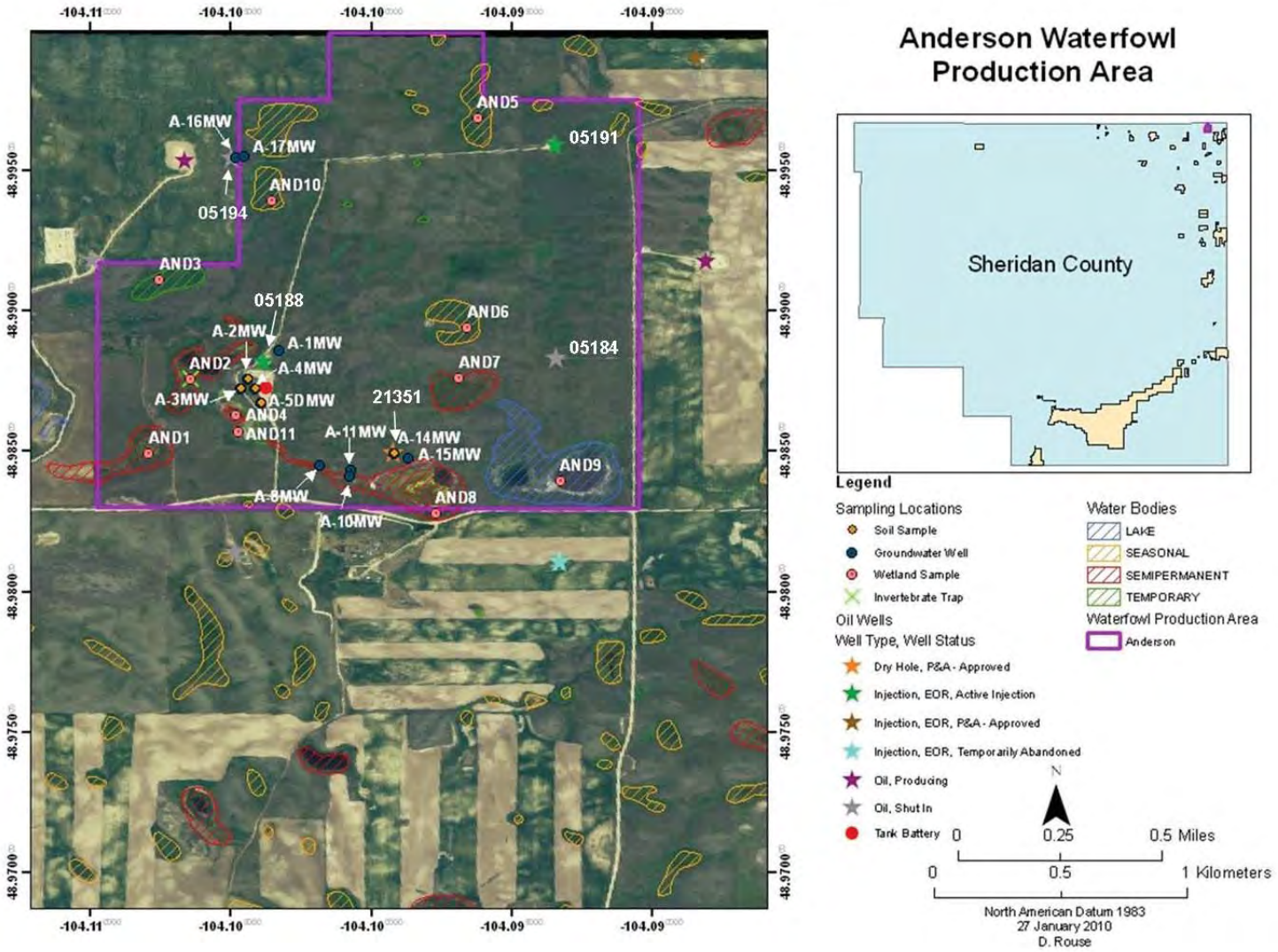


Figure 3. Map depicting locations of sampling sites, oil wells, and bodies of water for the Anderson WPA: T. 37 N., R. 58 E., sec. 4 & 5.

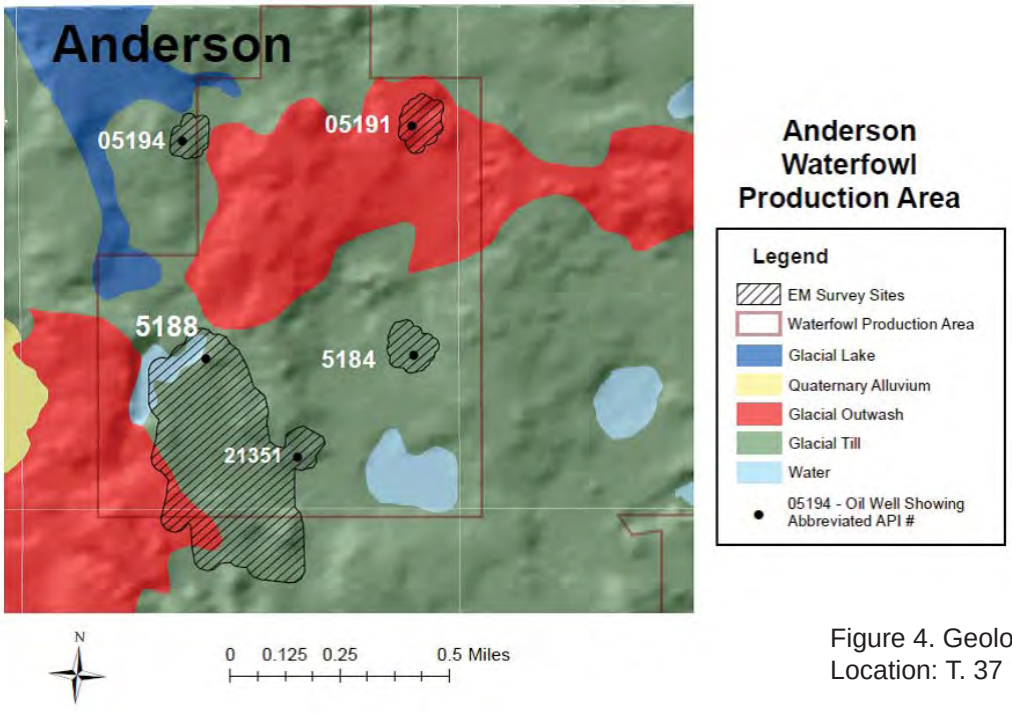


Figure 4. Geology of the Anderson WPA. Location: T. 37 N., R. 58 E., sec. 4 & 5.

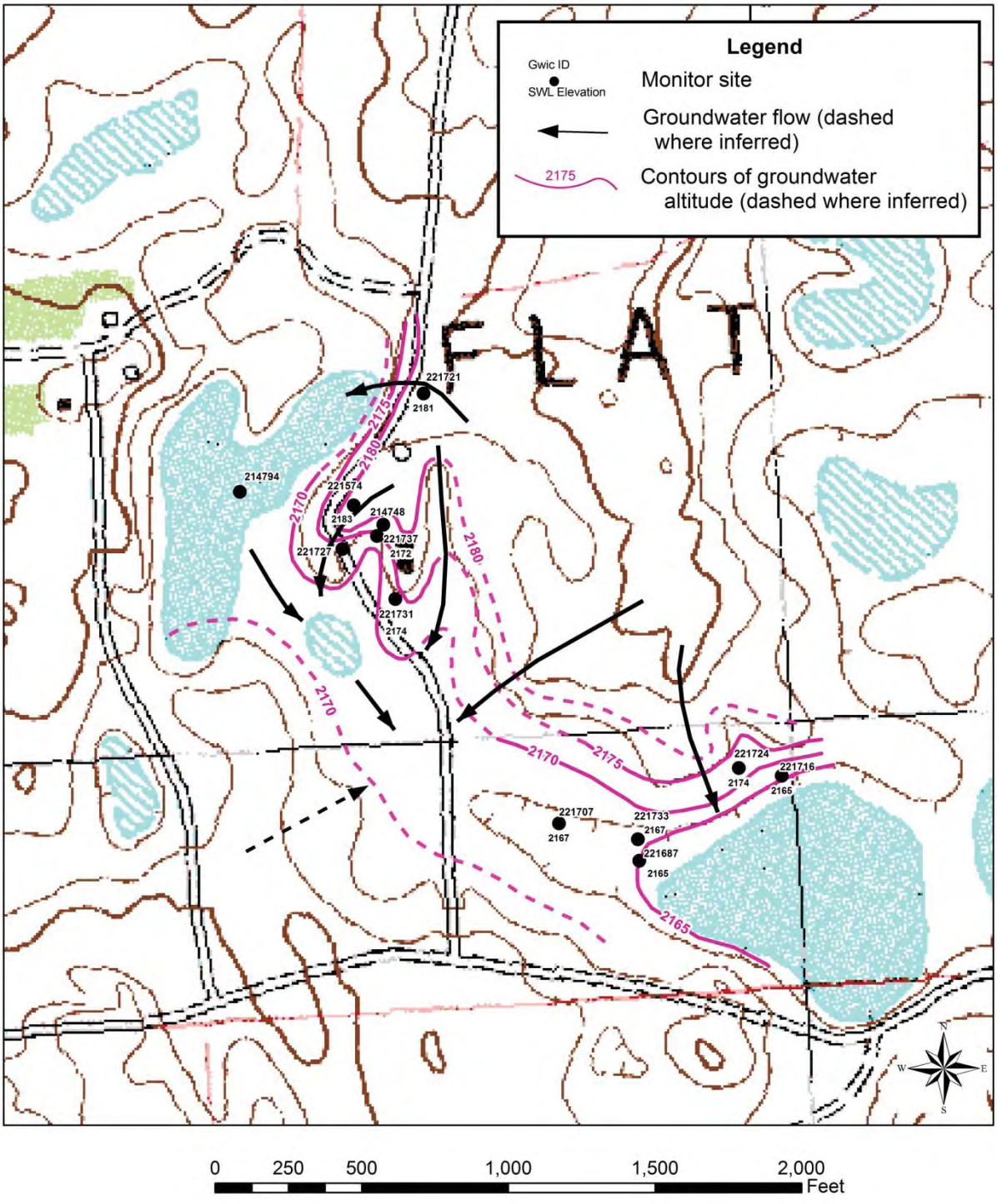


Figure 5. Groundwater flow map at the Anderson Tank battery and Site 4.

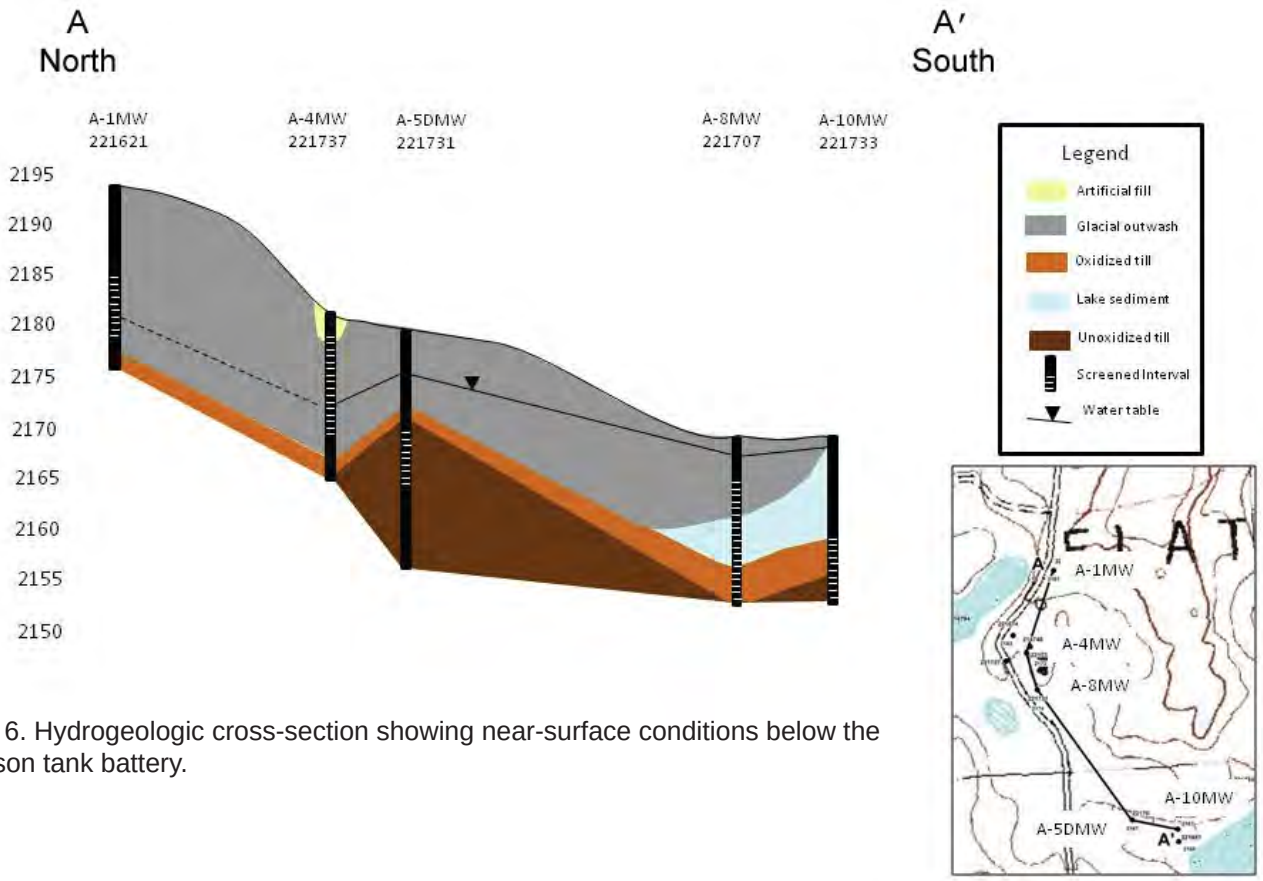


Figure 6. Hydrogeologic cross-section showing near-surface conditions below the Anderson tank battery.

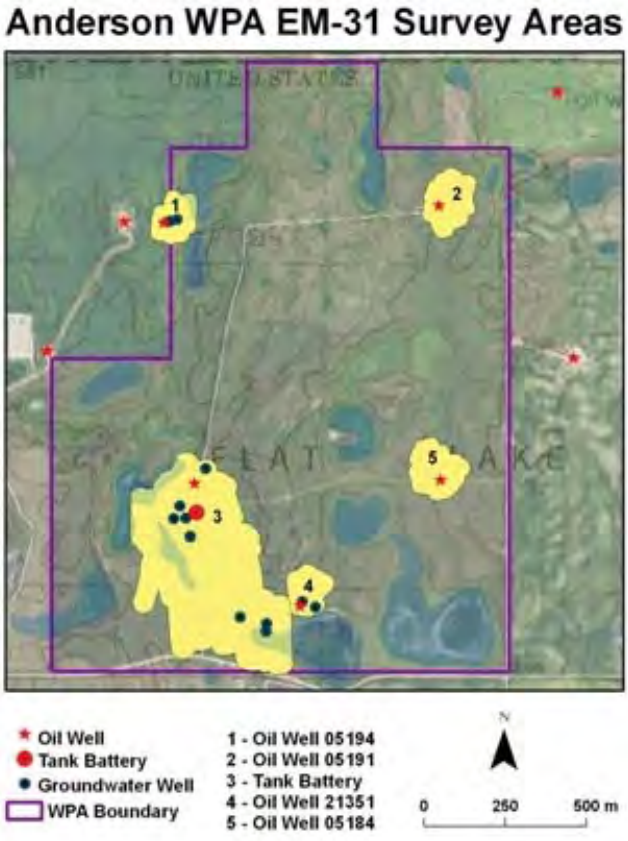


Figure 7. Location of the five EM-31 terrain-conductivity survey sites conducted at the Anderson WPA.

*Characterizing Oilfield Production Brine Migration*

EM-31 surveys identified five areas of high terrain conductivity associated with several of the oilfield locations on the Anderson WPA (fig. 7). Test drilling was conducted in and around these areas of high terrain conductivity in an effort to map plumes of brine-contaminated groundwater. Twelve monitoring wells were constructed at three of the Anderson sites in an effort to characterize brine plumes associated with oil wells 05194 and 21351, as well as the tank battery. One baseline well, well A-1MW (GWIC ID 221721), was also installed and 11 surface-water sites were visited to assess wetland condition.

Extensive areas of high conductivity associated with the Anderson tank battery, or Anderson WPA site 3 and Anderson WPA site 4, are shown in figures 9 and 10. For site 3, water-quality samples indicate that chloride concentrations and associated CI values diminish in groundwater downgradient of well A-8MW (GWIC ID 221707; fig. 11). Well A-1MW (GWIC ID 221721) is located outside the brine plume and is representative of a background ionic composition. Based on aerial photos taken in 1974, a large infiltration pit is clearly identifiable around the location of A-2MW (GWIC ID 221574). Not surprisingly, the wells A-2MW (GWIC ID 221574), A-3MW (GWIC ID 221727), A-4MW (GWIC ID 221737), A-5DMW (GWIC ID 221731), and A-8MW (GWIC ID 221707) reflect impacted groundwater conditions dominated by Cl- ions, while wells A-10MW (GWIC ID 221733) and A-11MW (GWIC ID 221687) reflect background condition (fig. 12). Similar results can be seen at site 4, where the ionic concentrations (fig. 13) and composition (fig. 14) of the sample collected from A-14MW (GWIC ID 221724) are indicative of brine impacts. However, well A-15MW (GWIC ID 221716), located near the suspected reserve pit location, did not show produced water impacts. This corresponds to the location where the outwash aquifer pinches out into fine-grained lake sediments.

Test holes were also drilled at the Anderson WPA site 1 based on measured high EM-terrain conductivities that appeared to relate to offsite migration of produced water (fig. 15). The surficial geologic map (fig. 4) indicates a narrow ridge of glacial till separating glacial lake deposits to the northwest and glacial outwash to the east. The well A-16 MW (GWIC ID 221715) was drilled on the slope directly east of the oilfield site. This well encountered a thin layer

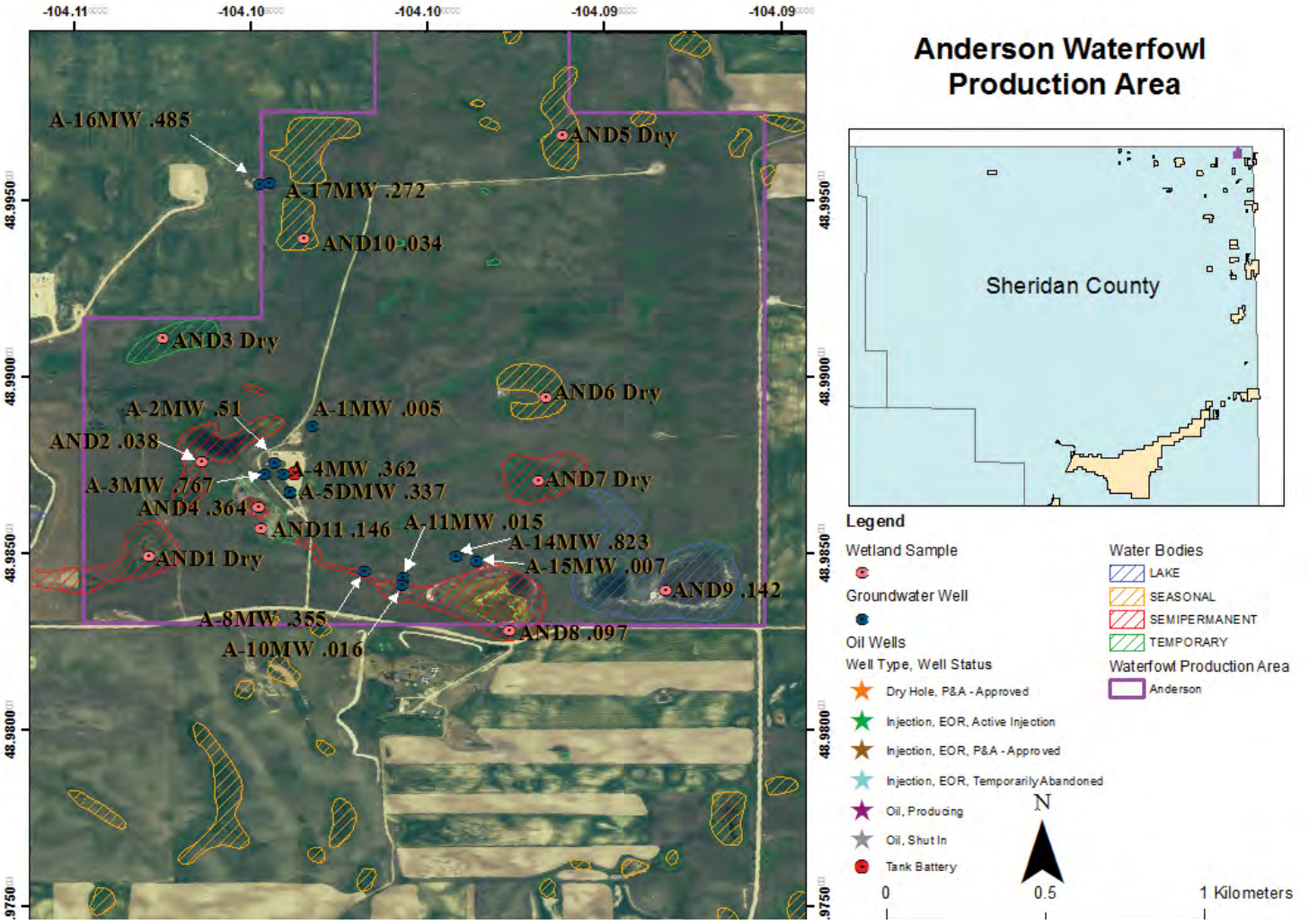


Figure 8. Distribution of the mean chloride contamination index measured in wells and wetlands at the Anderson WPA.

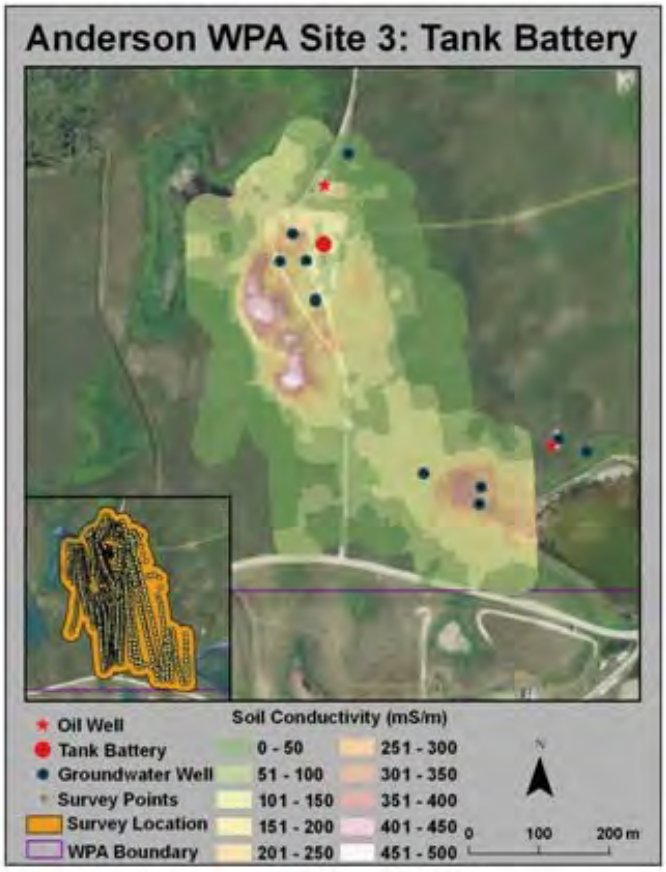


Figure 9. Apparent terrain-conductivity based on EM-31 surveys at Anderson WPA Site 3.

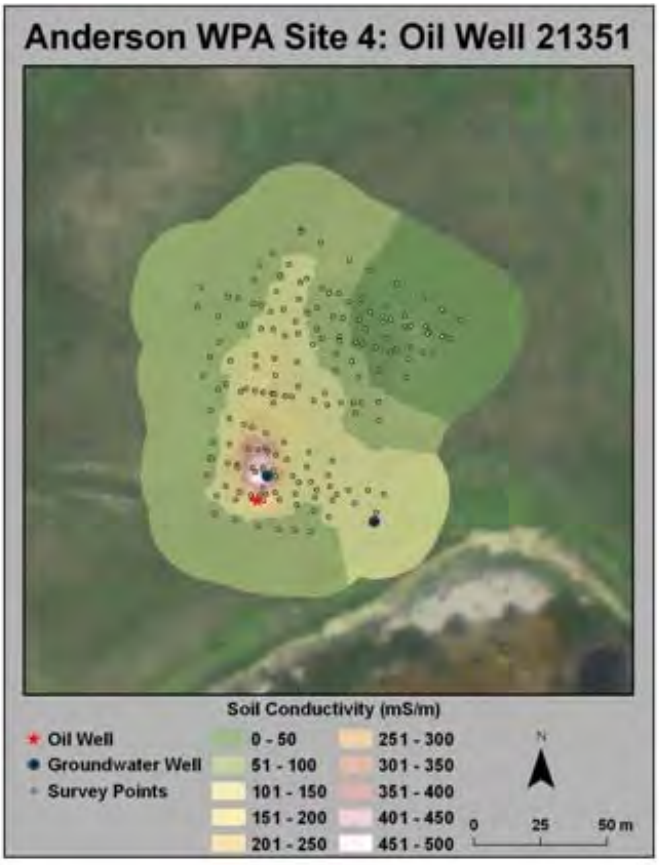


Figure 10. Apparent terrain-conductivity based on EM-31 surveys at Anderson WPA Site 4.

of artificial fill from the well pad overlying slightly oxidized glacial till to a depth of 38 ft. Unoxidized glacial till was encountered for the bottom 5 ft of the test hole. Another well, A-17MW (GWIC ID 221703), was constructed about 100 ft east of A-16 MW. This well encountered a thin layer of oxidized glacial till to a depth of 3 ft underlain by slightly oxidized till from 3 to 26 ft. Unoxidized glacial till was encountered for the bottom 10 ft of this test hole. Both wells confirm the presence of glacial till as the unit mapped at this site. A cross section constructed between these wells depicts the near-surface hydrogeologic conditions (fig. 16). Groundwater flow is generally towards the east.

Water-quality samples were collected at both of these wells. Sampling results indicate high concentrations of total dissolved solids and chloride concentrations. A high CI of 0.485 was identified at A-16MW (GWIC ID 221715) and 0.272 at A-17MW (GWIC ID 221703; fig. 17). Although very similar in ionic composition (fig. 18), the A-17MW (GWIC ID 221703) sample was more dilute with a slightly elevated SO42- concentration (fig. 17). These results verify a brine plume migrating away from the pad location with the groundwater flow direction. The ultimate fate of produced water moving off this site is unclear. Previous work around oilfield sites underlain by relatively thick glacial till have shown similar results, characterized by highly concentrated brine plumes migrating slowly because of the low transmissivity of the glacial till. The brines are slowly diluted and may ultimately flow into more productive aquifers.

High EM-31 terrain conductivities were mapped around Anderson site # 2 (fig. 19) and Anderson site # 5 (fig. 20), associated with oil wells 5191 and 5184, respectively, that show movement of brine out of the reserve pit location to the adjacent areas. Although groundwater wells were not constructed at these sites, movement of brine plumes is suspected based on the mapped terrain conductivities and near-surface materials. The near-surface geologic materials at site 2 consist of sand and gravel glacial outwash. The relatively high permeability at this site would promote a wider spread of a developing plume along with increased dilution. In contrast, the lower permeability associated with the glacial till underlying site 5 would typically result in a more localized, higher-concentrated brine plume. Plume geometry would require additional test drilling to verify these hypotheses.

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at selected monitoring well drilling sites and leachates were analyzed for specific conductivity and chlorides. When depths were compared, specific conductance and CI values were highly variable for all sites (table 2). This variability likely reflects the potential influence of contamination, geology, and the location of each site topographically. For instance, A-1MW, A-2MW, A-3MW, and A-5DMW share a similar increasing trend in specific conductance to a depth of 13–18 ft, while sites

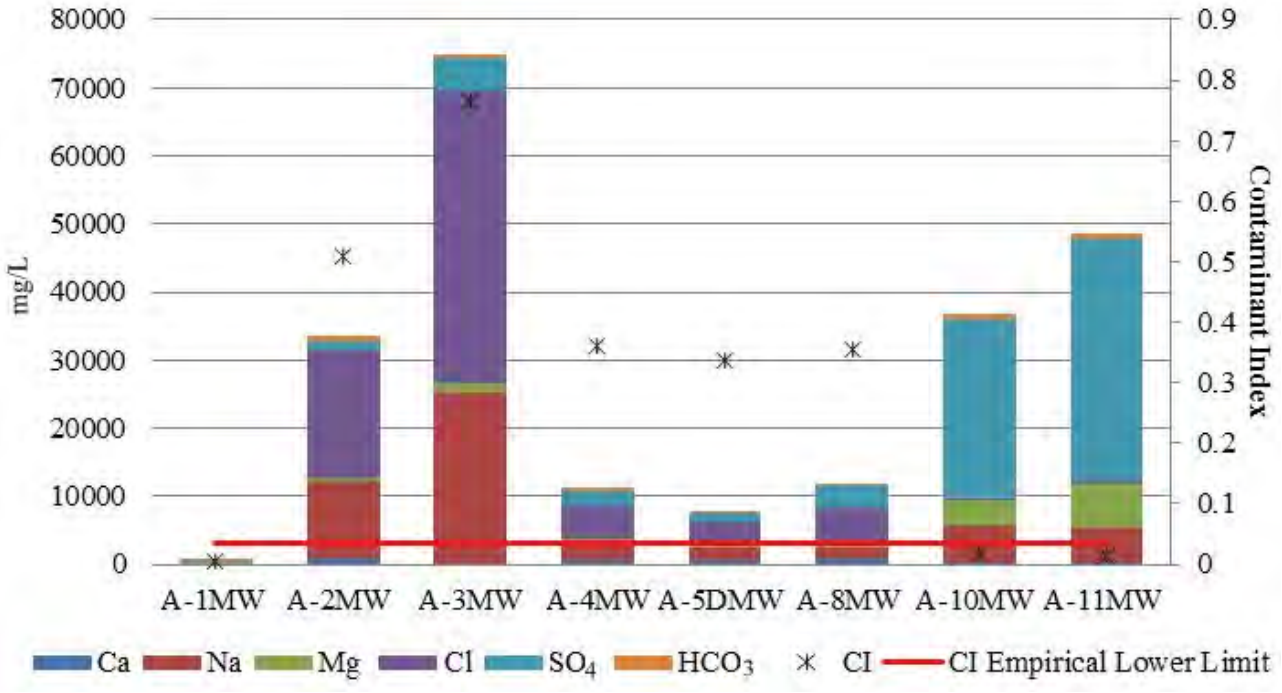


Figure 11. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within EM-31 survey site 3 of the Anderson WPA during 2005.

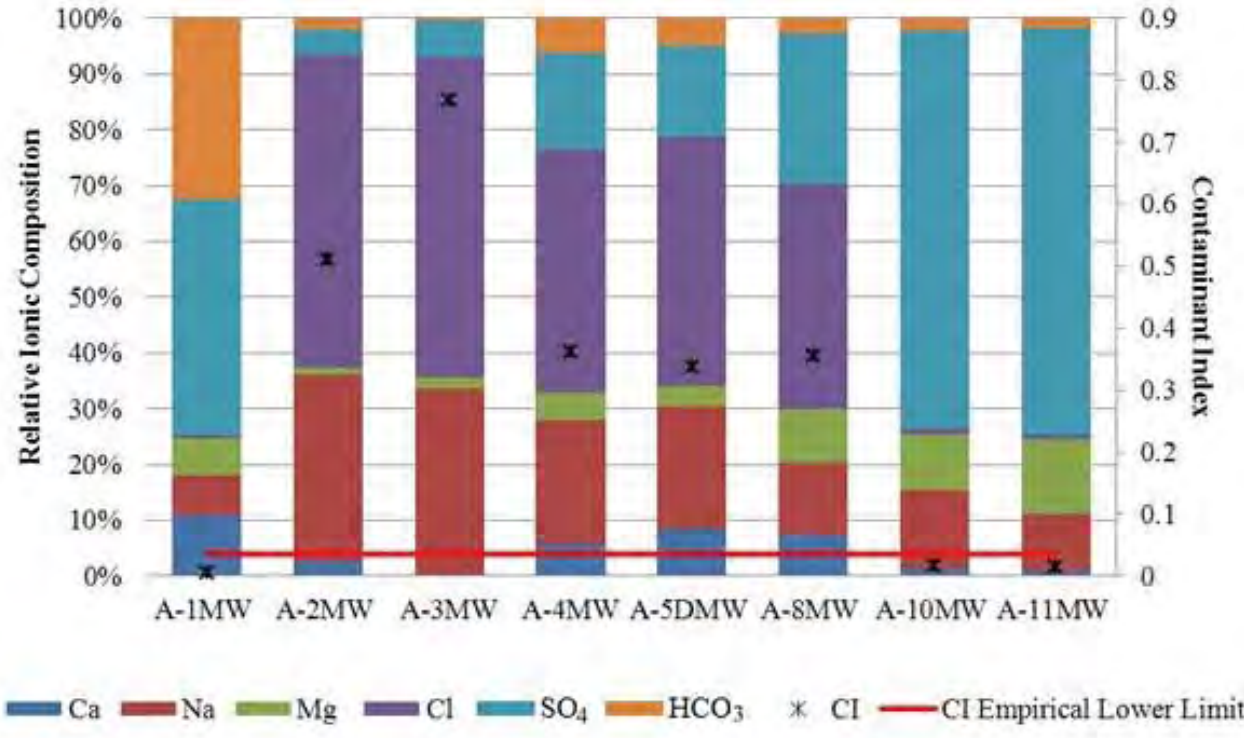


Figure 12. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within EM-31 survey site 3 of the Anderson WPA during 2005.

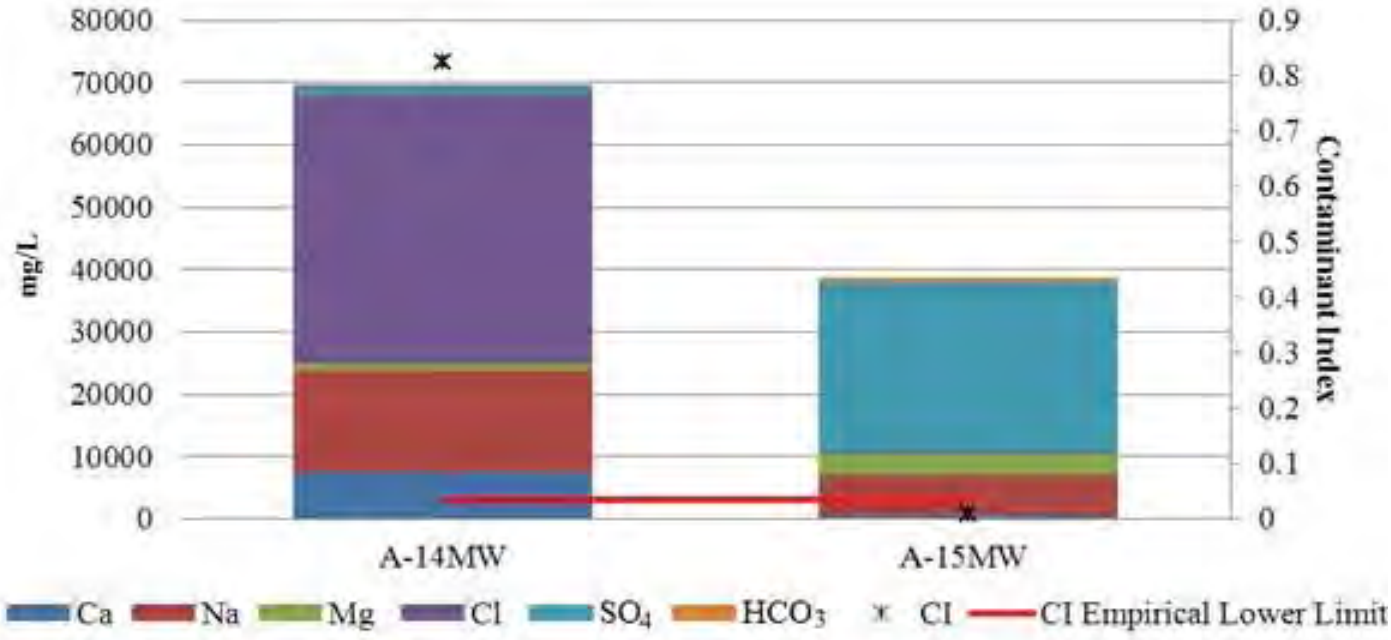


Figure 13. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within EM-31 survey site 4 of the Anderson WPA during 2005.

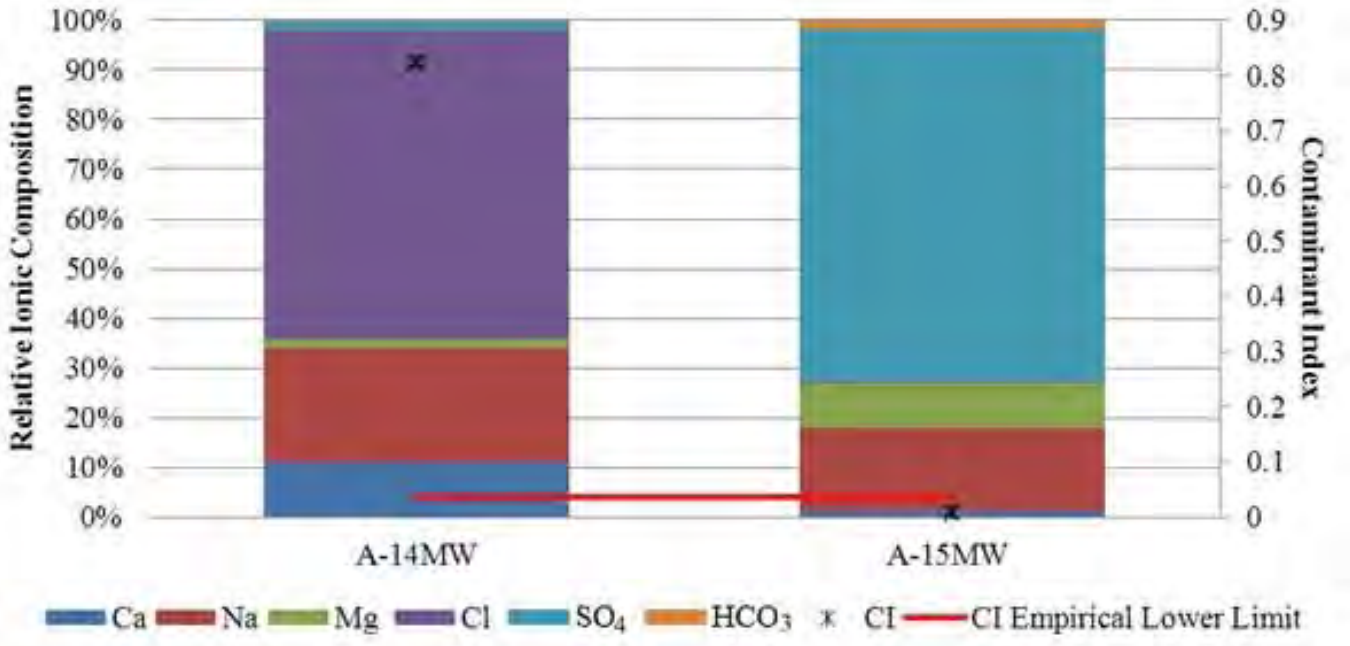


Figure 14. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within EM-31 survey site 4 of the Anderson WPA during 2005.

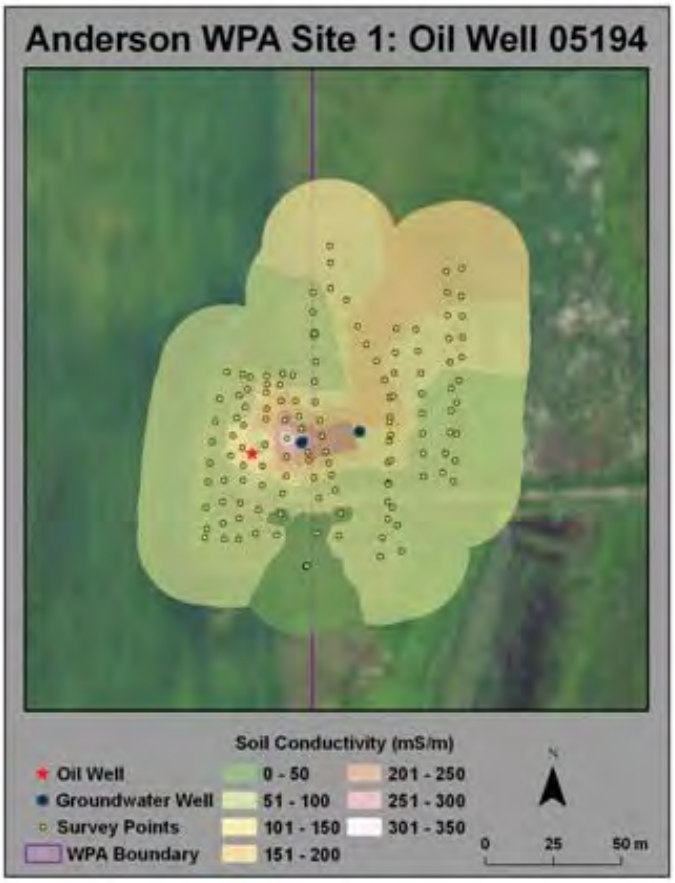


Figure 15. Apparent terrain-conductivity based on EM-31 surveys at Anderson WPA Site 1.

A-8MW, A-10MW, and A-11MW showed a general decreasing trend in specific conductance with depth.

These differences reflect the permeability and transmissivity of the glacial outwash found at sites A-1MW, A-2MW, A-3MW, and A-5DMW and evaporative concentration effects seen in the near-surface lake sediments of A-8MW, A-10MW, and A-11MW. Similarly, the distribution of chlorides appeared to be largely dependent upon proximity to the contaminant source and hydrogeology, with A-1MW upgradient of the historic infiltration pit and sites A-10MW and A-11MW below the extent of downgradient impacts. Trends were less apparent at sites A-14MW, A-15MW, A-16MW, and A-17MW, although the consistently low CI values seen at A-15MW suggest this area is not impacted. Otherwise, the rather variable specific conductance and CI values seen throughout these soil profiles may reflect a different hydrogelogic condition, one dominated by glacial till. The low permeability of glacial till concentrates and stores ions throughout the profile as opposed to the shifting concentrations seen in outwash.

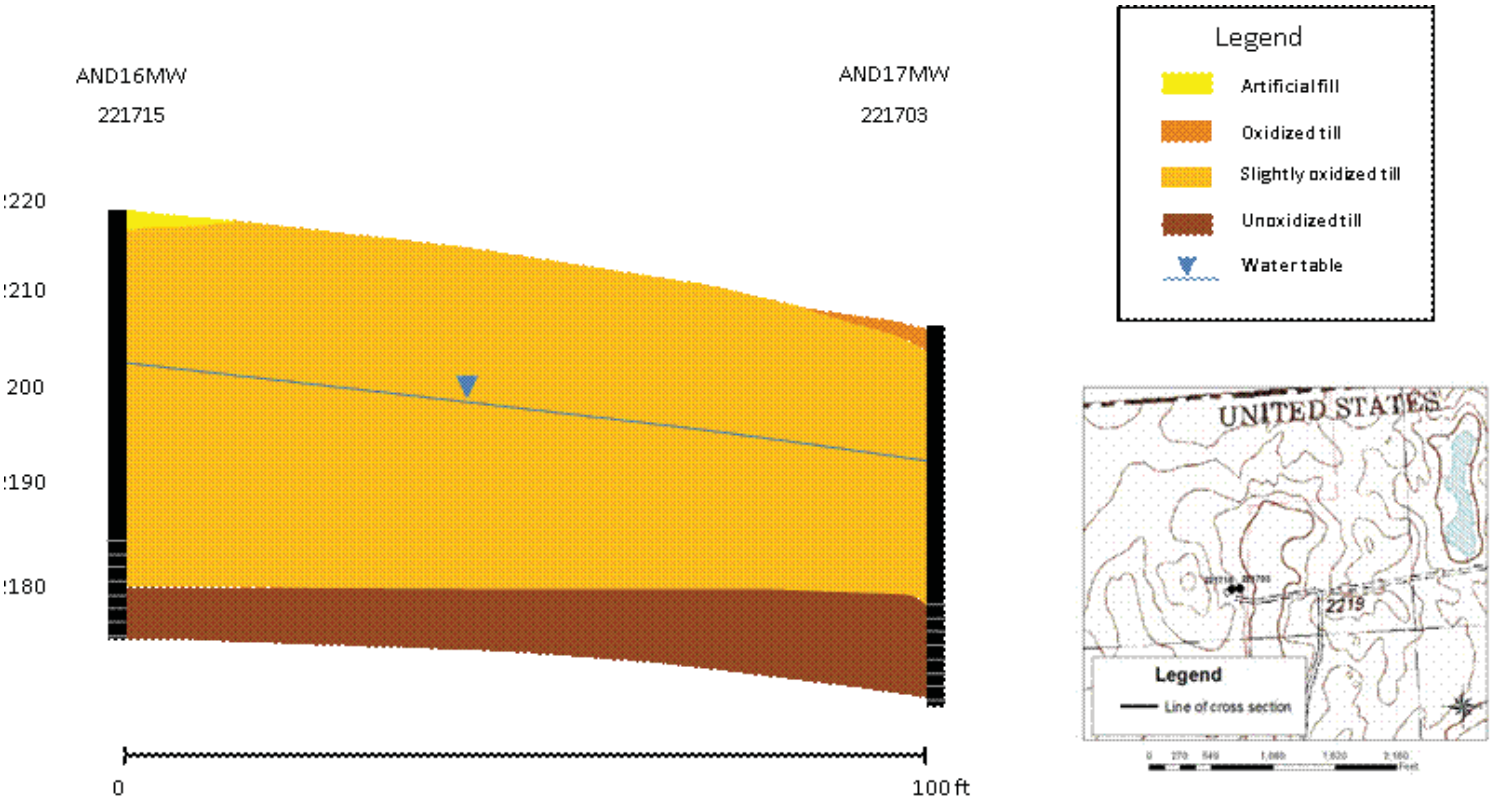


Figure 16. Hydrogeologic cross-section showing near-surface conditions below the Anderson site #1. Location: T. 37 N., R. 58 E., sec. 5.

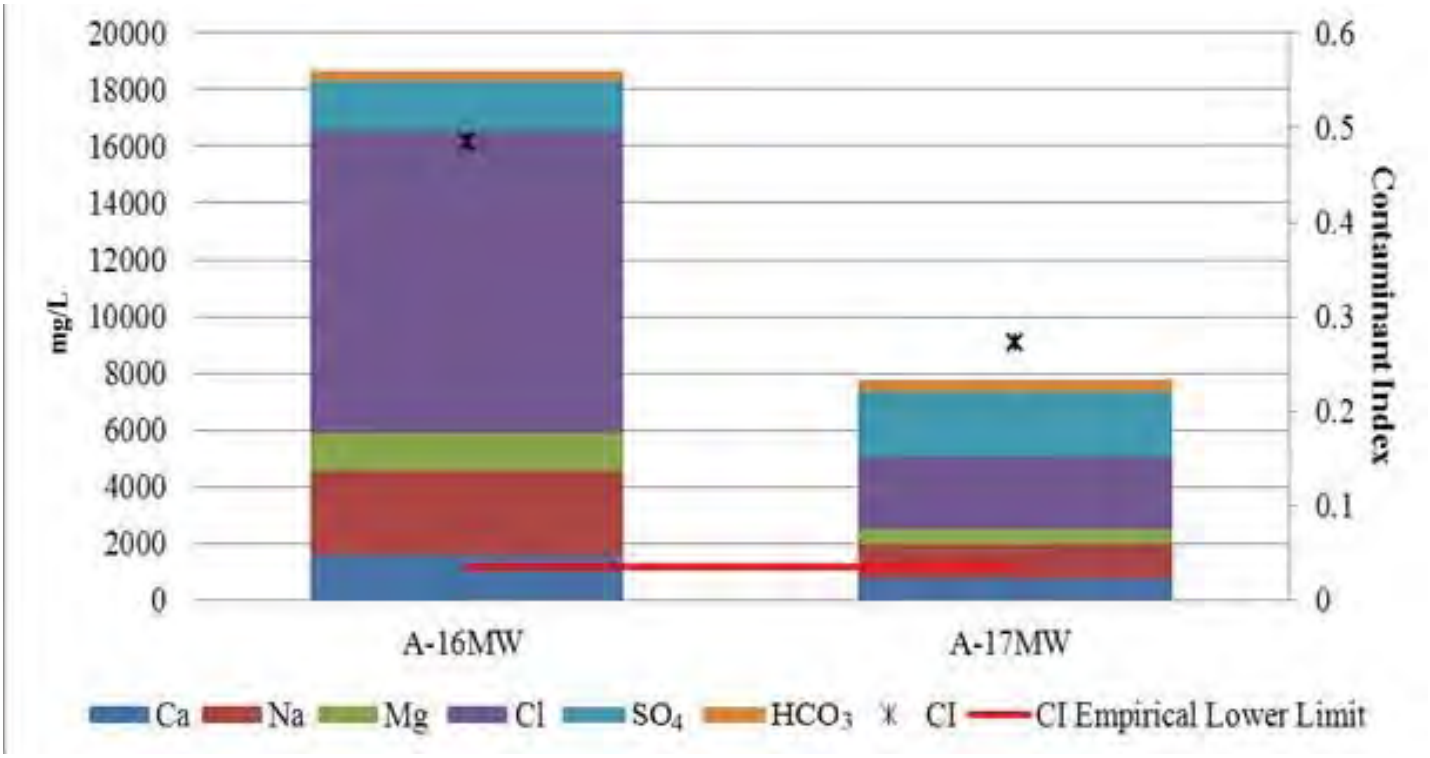


Figure 17. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within EM-31 survey site 1 of the Anderson WPA during 2005.

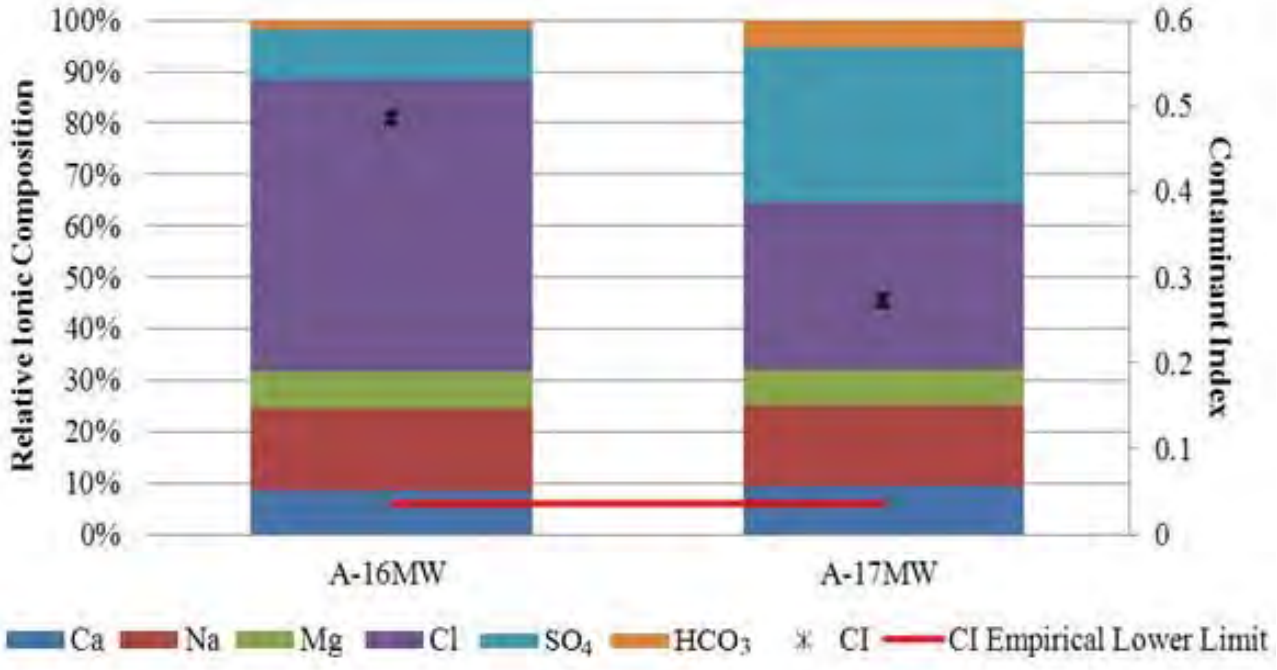


Figure 18. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within EM-31 survey site 1 of the Anderson WPA during 2005.

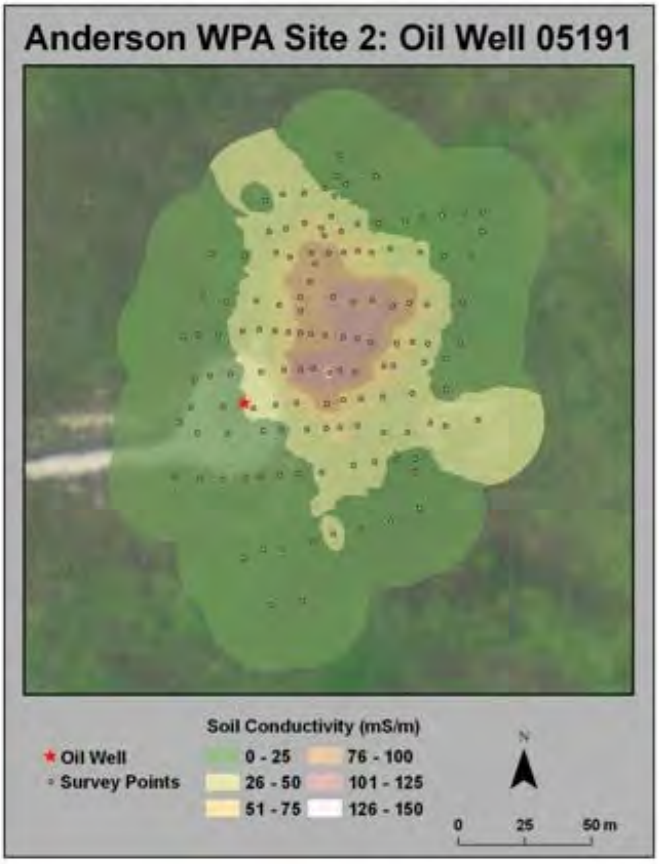


Figure 19. Apparent terrain-conductivity based on EM-31 surveys at Anderson WPA Site 2.

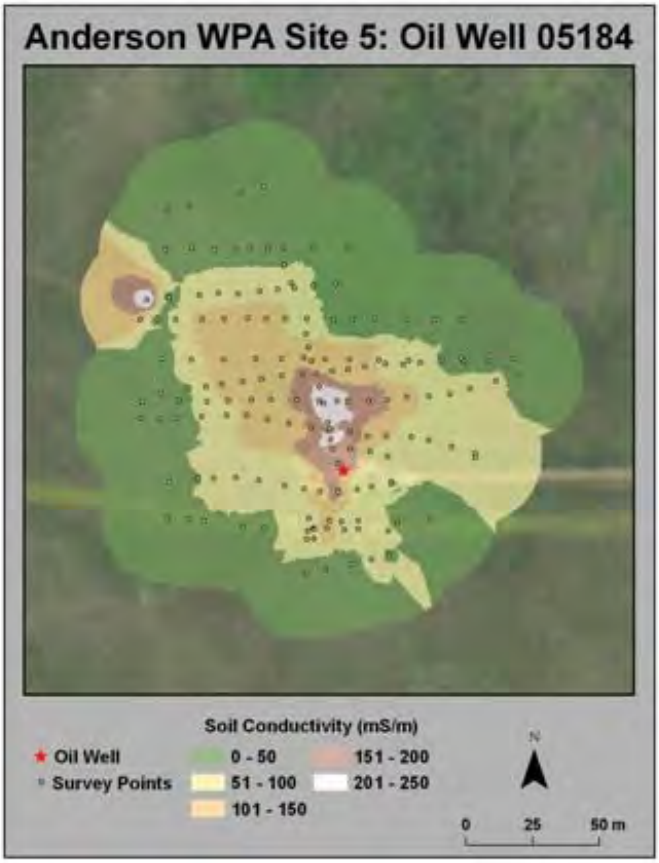


Figure 20. Apparent terrain-conductivity based on EM-31 surveys at Anderson WPA Site 5.

*Wetland Water Quality*

Specific conductance and chloride concentrations of the sampled wetlands of the Anderson WPA ranged from around 260 to 90,000 µS/cm and 9 to 32,000 mg/L, respectively (table 3). Based on the CI, brine impacts (CI > 0.035) were seen at 5 of the 11 sites—AND2, AND4, AND8, AND9, and AND11— but five of the other sites visited were dry. In fact, AND 2 and AND 10 were the only sites to produce CI values less than the CI empirical lower limit, though on average, AND 2 exceeded the lower limit. Based on EM-terrain conductivity surveys and groundwater monitoring, it appears that AND 10 is not impacted by produced water. This may be because the migrating produced water brine plume has yet to interact with the wetland, the migratory path of the plume is completely missing AND 10, consequently impacting the wetland directly north, or this wetland may serve as a point of groundwater recharge. Unfortunately, there are no data for the seasonal wetland directly north of AND10. Although the average CI for AND 2 exceeds the empirical lower limit, it only slightly exceeds this limit, and this site's CI values are lower than most of the other sites measured at the Anderson WPA. Even though AND 2 is in close proximity to an oil pad, it appears to have minimal interaction with the migrating brine plume. Conversely, AND 4 consistently produced the highest CI values, indicative of its location downgradient of the tank battery and historic infiltration pit. Similarly, AND 11 is also located within the migrating brine plume flow path, which is likely contributing to its elevated CI. Interestingly, AND 8 and AND9, both of which are located in the same groundwater flow path as AND4 and AND11, produced elevated CI values, but water-quality samples from the surrounding groundwater wells A-10MW (GWIC ID 221733), A-11MW (GWIC ID 221687), and A-15MW (GWIC ID 221716) suggest that AND8 and AND9 are beyond the extent of the brine plumes detected at EM-31 survey sites 3 and 4. Historic oil production waste disposal methods, including the direct release of produced water to the surface, leaking pipelines, and increased surface connectivity between wetlands during periods of deluge, are possible explanations for the impacts seen at these two wetlands.

*Co-occurring Contaminants*

Analyses were done to quantify elemental concentrations from samples taken from every monitoring well and the three wetlands AND2, AND4, and AND11. Numerous trace elements were detected from every groundwater sample, but concentrations exceeding Montana numerical water-quality standards for human health in groundwater were detected in the three wells A-3MW (GWIC ID 221727), A-14MW (GWIC ID 221724), and A-16MW (GWIC ID 221715) for cadmium, the well A-15MW (GWIC ID 221716) for selenium, and all wells except A-1MW (GWIC ID 221721) and A-5DMW (GWIC ID 221731) for strontium (table 4). Both cadmium and strontium have significant positive correlations with the CI, suggesting that the elevated levels detected at monitoring wells A-3MW

Table 2. Specific conductivity and Cl of 1:1 (by weight) aqeuous leachates of soil samples at different depths in the Anderson WPA.

| Depth (ft) | Soil Property | A-1MW | A-2MW | A-3MW | A-5DMW | A-8MW | A-10MW | A-11MW | A-14MW | A-15MW | A-16MW | A-17MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0–3 | SC (µS/cm) | 292 | 5,930 | 15,770 | 675 | 6,470 | 20,600 | 21,400 | 26,000 | 10,410 | 32,200 | 7,110 |
| | Cl | NA | 0.148 | 0.326 | 0.169 | 0.150 | 0.009 | 0.029 | 0.150 | 0.003 | 0.389 | 0.045 |
| 3–8 | SC (µS/cm) | 392 | 5,750 | 19,170 | 1,440 | 6,060 | 17,810 | 15,240 | 59,500 | 13,250 | 21,800 | 4,860 |
| | Cl | NA | 0.195 | 0.295 | 0.176 | 0.131 | 0.006 | 0.014 | 0.315 | 0.006 | 0.327 | 0.181 |
| **8–13** | **SC (µS/cm)** | **341** | **17,310** | **16,700** | **2,350** | **4,100** | **10,970** | **6,950** | **53,400** | **11,340** | **13,840** | **11,190** |
| | Cl | NA | 0.271 | 0.255 | 0.219 | 0.044 | 0.006 | 0.008 | 0.352 | 0.021 | 0.199 | 0.148 |
| 13–18 | SC (µS/cm) | 1,284 | 17,730 | 12,720 | 4,810 | NA | 7,390 | NA | 21,300 | 9,500 | 15,990 | 9,900 |
| | Cl | 0.065 | 0.290 | 0.216 | 0.120 | NA | 0.007 | NA | 0.294 | 0.009 | 0.321 | 0.167 |
| 18–23 | SC (µS/cm) | NA | 8,700 | 6,200 | 3,380 | NA | NA | NA | 49,000 | 5,290 | 19,500 | 8,610 |
| | Cl | NA | 0.174 | 0.064 | 0.008 | NA | NA | NA | 0.255 | 0.011 | 0.321 | 0.228 |
| 23–28 | SC (µS/cm) | NA | 5,910 | 4,850 | NA | NA | NA | NA | NA | NA | 19,900 | 6,910 |
| | Cl | NA | 0.098 | 0.066 | NA | NA | NA | NA | NA | NA | 0.314 | 0.140 |
| 28–33 | SC (µS/cm) | NA | NA | NA | NA | NA | NA | NA | NA | NA | 12,830 | 4,900 |
| | Cl | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.304 | 0.075 |
| 33–38 | SC (µS/cm) | NA | NA | NA | NA | NA | NA | NA | NA | NA | 7,930 | 4,510 |
| | Cl | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.191 | 0.048 |
| 38–43 | SC (µS/cm) | NA | NA | NA | NA | NA | NA | NA | NA | NA | 7,590 | NA |
| | Cl | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.200 | NA |

*Note.* NA, Data not available.

Table 3. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at Anderson WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| AND1 | 4/29/2004 | — | — | — | Dry |
| AND2 | 4/28/2004 | 4,351 | 145 | 0.033 | Oligosaline |
| AND2 | 7/27/2004 | 9,681 | 366 | 0.038 | Mesosaline |
| AND2 | 9/9/2004 | 14,160 | 590 | 0.042 | Mesosaline |
| AND2 | 7/8/2005 | 8,575 | 325 | 0.038 | Mesosaline |
| AND3 | 4/28/2004 | — | — | — | Dry |
| AND4 | 4/29/2004 | 82,463 | 27,293 | 0.331 | Hypersaline |
| AND4 | 5/16/2004 | 43,626 | 14,540 | 0.333 | Polysaline |
| AND4 | 7/27/2004 | 68,366 | 31,660 | 0.463 | Hypersaline |
| AND4 | 7/8/2005 | 46,350 | 15,220 | 0.328 | Eusaline |
| AND5 | 4/28/2004 | — | — | — | Dry |
| AND6 | 4/28/2004 | — | — | — | Dry |
| AND7 | 4/28/2004 | — | — | — | Dry |
| AND8 | 4/28/2004 | 12,647 | 1,198 | 0.095 | Mesosaline |
| AND8 | 7/27/2004 | 26,286 | 2,589 | 0.098 | Mesosaline |
| AND9 | 5/15/2004 | 19,657 | 2,748 | 0.140 | Mesosaline |
| AND9 | 7/27/2004 | 89,693 | 12,948 | 0.144 | Hypersaline |
| AND10 | 4/29/2004 | 260.1 | 9 | 0.034 | Fresh |
| AND11 | 5/16/2004 | 44,819 | 6,550 | 0.146 | Polysaline |

Table 4. Groundwater concentrations (µg/L) of trace elements present in groundwater samples from monitoring wells present within the Anderson WPA during 2005.

| | A-1MW | A-2MW | A-3MW | A-4MW | A-5DMW | A-8MW | A-10MW | A-11MW | A-14MW | A-15MW | A-16MW | A-17MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| As | 0.39 | 7.43 | 6.66 | <0.5 | 3.18 | 2.39 | 4.07 | <2.55 | 25.8 | 2.45 | 5.54 | 1.8 |
| B | 215 | 69,500 | 74,500 | 4,760 | 5,130 | 326 | 385 | 378 | 11,000 | 347 | 249 | 294 |
| Ba | 23 | 55 | 243 | 52 | 134 | 44 | 20 | 59 | 660 | 68 | 51 | 26 |
| Be | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Cd | 0.05 | 2.26 | 16.9* | <0.1 | 0.33 | 0.18 | 0.27 | <0.51 | 5.57* | 0.36 | 10.6* | 1.21 |
| Co | <5 | 5 | 6 | <5 | 8 | <5 | 11 | <5 | <5 | 10 | 12 | 13 |
| Cr | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Cu | <5 | 5 | 7 | <5 | <5 | <5 | 5 | 9 | 7 | 11 | 7 | <5 |
| Hg | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Mo | <10 | 40 | 10 | <10 | 10 | <10 | 20 | 30 | 10 | 20 | <10 | <10 |
| Ni | <5 | 53 | 59 | 5 | 14 | <5 | 24 | 45 | 68 | 30 | 82 | 38 |
| Pb | <0.01 | 0.58 | <0.51 | <0.1 | <0.05 | 0.13 | <0.2 | <0.51 | 0.59 | 0.69 | <0.1 | <0.05 |
| Se | 6.24 | 1.86 | 9.13 | 6.07 | 0.47 | 24.9 | 3.4 | 4.96 | 1.9 | 145* | 13.9 | 33.7 |
| Sr | 450 | 15,300* | 48,000* | 6,510* | 3,650 | 5,320* | 6,200* | 7,170* | 152,000* | 7,540* | 15,300* | 5,610* |
| Ti | <5 | 10 | 19 | 9 | 10 | 12 | 6 | <5 | 77 | 10 | 21 | 9 |
| V | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| Zn | 9 | 35 | 10 | <5 | 10 | 40 | 65 | <5 | 15 | 67 | 17 | 7 |

*Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

(GWIC ID 221727), A-14MW (GWIC ID 221724), A-15MW (GWIC ID 221716), and A-16MW (GWIC ID 221715) are a result of oil production activities (table 5). In fact, cadmium and strontium are two commonly detected elements in produced waters, and cadmium is often associated with drilling fluid additives (Stephenson, 1992; Jacobs and others, 1992; Neff, 1982). We failed to detect a significant correlation between groundwater selenium concentrations and the CI (table 5), although selenium has been detected in produced water samples collected from produced water reinjection sites in the Williston Basin before (Chen-Northern, 1994). Regardless, the well in which the elevated selenium concentration was detected, A-15MW (GWIC ID 221716), does appear to be located beyond the extent of the brine plume detected at A-14MW (GWIC ID 221724), suggesting that the elevated level of selenium is a result of some other process.

Two wetland sites, AND4 an AND11, had aluminum concentrations that exceeded established benchmark values (table 6). Due to the large number of sites with aluminum concentrations below the analytical limit of detection, the relationship between surface-water aluminum concentrations and the CI was not formally assessed (table 7). In spite of this, it is important to note that these two wetland sites consistently had the highest CI values, providing evidence that the elevated levels of aluminum may be a result of oil production activities.

The elevated concentrations of cadmium and strontium are at levels that would likely elicit a toxicological response, but their exposure pathways are largely confined to the groundwater systems in which they were detected. On the other hand, a significant positive relationship was detected between wetland strontium concentrations and the CI, inferring a surface water–groundwater interaction in which groundwater brine plumes are contributing strontium to surface-water systems. Although we failed to detect a significant relationship between wetland cadmium concentrations and the CI, potentially due to the large number of samples that were below the analytical limits of detection, cadmium concentrations were slightly elevated at sites AND4 and AND11.

Numerous processes affect the mobilization and attenuation of trace elements, and when coupled with dilution effects, it is not surprising that elements associated with groundwater that are likely interacting with surface-water systems are found at lower levels, especially when insoluble complexes are not considered (EPA, 2007). Nevertheless, aqueous aluminum concentrations exceeded water-quality standards in wetlands AND4 and AND11, environments in which numerous organisms may be exposed. In fact, toxic effects have been reported in algae, macroinverterbrates, and fish at concentrations below those detected at sites AND4 and

Table 5. Kendall's tau correlation coefficients and resulting probabilities (*p*-values) between groundwater trace element concentrations and the CI with associated sample size from samples collected across the Northeast MT WMD.

| Trace Element | Kendall's Tau Correlation Coefficient | *p*-value | Number of Samples |
|---|---|---|---|
| **Sr** | **0.59** | **<0.001** | 83 |
| **Li** | **0.56** | **<0.001** | 47 |
| **Cu** | **0.49** | **<0.001** | 81 |
| **B** | **0.49** | **<0.001** | 81 |
| **Cd** | **0.48** | **<0.001** | 80 |
| **Ba** | **0.42** | **<0.001** | 42 |
| **Ti** | **0.36** | **<0.001** | 81 |
| **V** | **0.31** | **<0.001** | 81 |
| **Zn** | **0.30** | **<0.001** | 80 |
| Se | 0.17 | 0.14 | 39 |
| As | 0.02 | 0.80 | 74 |
| Co | -0.04 | 0.67 | 75 |
| U | -0.05 | 0.72 | 40 |
| Be | NC | NC | 76 |
| Hg | NC | NC | 73 |
| Br | NC | NC | 46 |
| Al | NC | NC | 80 |
| Mo | NC | NC | 42 |
| Cr | NC | NC | 79 |
| Zr | NC | NC | 44 |
| Pb | NC | NC | 50 |
| V | NC | NC | 81 |
| Ni | NC | NC | 81 |
| Ag | NC | NC | 44 |

*Note.* NC, not calculated due to high number (>50%) of values below detection limit.
**Bolded text indicates *p*<0.05**.

AND11; however, aluminum toxicity is pH-dependent, with increasing toxicity as water becomes more acidic (Gensemer and Playle, 1999). The water-borne aluminum concentrations detected in this survey are likely highly complexed, diminishing their bioavailability, but varying conditions may alter the availability of aluminum to aquatic organisms as well as increase the risk to terrestrial organisms that may be exposed to elevated aluminum concentrations through dietary uptake (Gensemer and Playle, 1999; Rosseland and others, 1990).

Five soil samples were collected in 2005 for total petroleum hydrocarbon analysis. Concentrations ranged from 50 mg/kg to 22,600 mg/kg dry weight (DW). Sites A-2S and A-4S produced the highest concentrations, 8,210 mg/kg (DW) and 22,600 mg/kg (DW), respectively, with the next highest concentration, 382 mg/kg (DW), found at A-14S (fig. 21). Interestingly, A-4S was collected at the tank battery historic infiltration pit location and A-14S was collected at the suspected reserve pit location associated with oil well 21351.

In 2006, A-14S and A-2S were resampled and soil samples were analyzed for aliphatic and polynuclear aromatic hydrocarbons. These values were then compared to established toxic benchmark values to assess the relative toxicity at each site. For each hydrocarbon fraction assessed, concentrations detected at both sites, A-2S and A-14S, exceeded every benchmark value (table 8). Although both sites exceeded benchmark values, concentrations at site A-2S were consistently higher than those at A-14S. Although the toxicity criteria used in this assessment were developed to be protective of human health, values detected, specifically at A-2S, were at levels that have been reported as causing environmental impacts. For example, sublethal effects to plants, including reduced shoot and root length and reduced shoot and root biomass, and to invertebrates, including reduced reproductive success, as well as lethal effects, have been reported for values comparable to or less than the values detected at A-2S (Cermak and others, 2010). Additionally, impacts to microbial communities, including reduced microbial biomass and soil enzyme activity, have been reported for soils that possess hydrocarbon concentrations similar to those at A-2S (Megharaj and others, 2000). While the two soil samples taken at the Anderson WPA are not representative of large-scale hydrocarbon contamination to soil, they do illustrate that oil production practices

Table 6. Surface-water concentrations (µg/L) of trace elements present in the sampled wetland AND2 during 2004 and the wetlands AND4 and AND11 during 2005.

| | AND2 | AND4 | AND11 |
|---|---|---|---|
| Al | <50 | 328[#] | 252[#] |
| As | 6.76 | 11.6 | 17.4 |
| B | <500 | 19,800 | 1,610 |
| Ba | 56 | 106 | 126 |
| Be | <0.5 | 0.5 | <0.5 |
| Br | — | 1,340,000 | 1,030,000 |
| Cd | 0.1 | 0.17 | 0.26 |
| Co | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 |
| Cu | <5 | <5 | 6 |
| Hg | <0.1 | <0.1 | <0.1 |
| Mo | <10 | 40 | 30 |
| Ni | <5 | 7 | 5 |
| Pb | <0.05 | 0.14 | 0.11 |
| Se | 0.58 | 1.21 | 4.5 |
| Sr | 1,990 | 19,100 | 7,720 |
| Ti | 6 | — | — |
| V | <10 | <10 | <10 |
| Zn | 6 | 6 | 9 |

[#]Indicates value exceeded EPA's recommended national water quality criteria

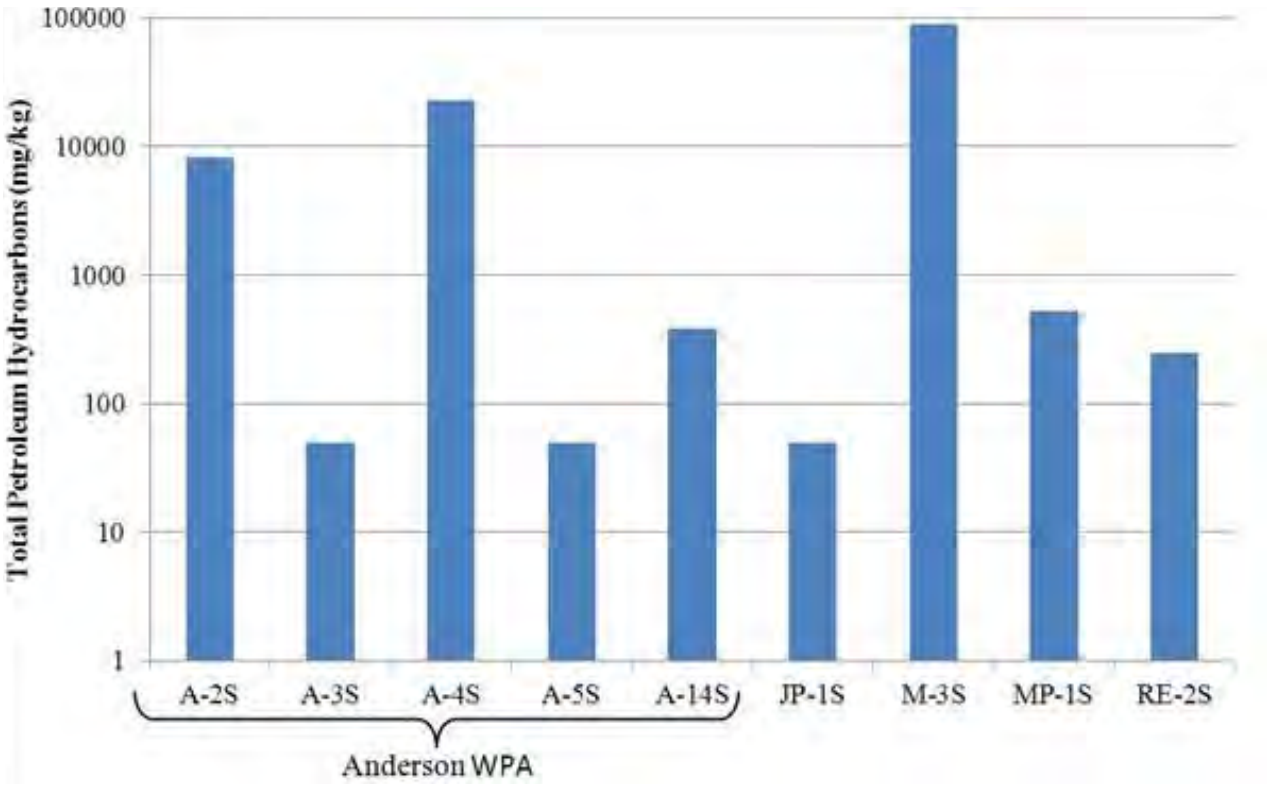


Figure 21. Concentrations (mg/kg DW) of total petroleum hydrocarbons from soil samples collected across the Northeast MTWMD in 2005 with the sites located in the Anderson WPA bracketed.

at the Anderson WPA are releasing petroleum hydrocarbons into the environment at potentially toxic levels.

In 2005, five groundwater samples were collected from five different wells and analyzed for total petroleum hydrocarbons. Hydrocarbons were detected at every well and concentrations ranged from 300 µg/l at A-2MW (GWIC ID 221574) to 810 µg/l at A-4MW (GWIC ID 221737; fig. 22). Out of the five wells, four were resampled in 2006 and analyzed for aliphatic and polynuclear aromatic hydrocarbons. Many compounds were below detection limits and no individual chemical or chemical group exceeded any benchmark value when compared to multiple toxicity criteria (table 9).

Table 7. Kendall's tau correlation coefficients and resulting probabilities (*p*-values) between surface-water trace element concentrations and the CI with associated sample size from samples taken across the Northeast MT WMD.

| Trace Element | Kendall's Tau Correlation Coefficient | *p*-value | Number of Samples |
|---|---|---|---|
| Li | 0.69 | 0.07 | 7 |
| **Ba** | **0.45** | **<0.01** | 28 |
| **Sr** | **0.44** | **<0.01** | 28 |
| **Se** | **0.37** | **0.01** | 28 |
| Br | 0.17 | 0.60 | 9 |
| Cd | 0.03 | 0.90 | 20 |
| Pb | 0.01 | 0.97 | 20 |
| As | -0.01 | 0.94 | 28 |
| B | -0.08 | 0.53 | 28 |
| Zn | NC | NC | 20 |
| Ni | NC | NC | 21 |
| Al | NC | NC | 28 |
| Ag | NC | NC | 9 |
| Ti | NC | NC | 20 |
| Be | NC | NC | 28 |
| Co | NC | NC | 28 |
| Cr | NC | NC | 28 |
| Cu | NC | NC | 28 |
| Hg | NC | NC | 21 |
| Mo | NC | NC | 28 |
| U | NC | NC | 28 |
| V | NC | NC | 28 |
| Zr | NC | NC | 7 |

*Note.* NC, not calculated due to high number (>50%) of values below detection limit. **Bolded text indicates *p*<0.05.**

Table 8. Concentrations (mg/kg DW) of hydrocarbon fractions from soil samples collected in 2006 within Anderson WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values | |
|---|---|---|---|---|
| Carbon Range | TPHCWG[1] (mg/kg/day) | MADEP[2] (mg/kg/day) | A-2S (mg/kg) | A-14S (mg/kg) |
| **Aliphatic** | | | | |
| C9-C18 | 0.10 | 0.10 | 8,005 | 9.57 |
| C19-C32 | 2.00 | 2.00 | 11,216 | 5.99 |
| **Aromatic** | | | | |
| C9-C16 | 0.04 | 0.03 | 137.16 | 0.27 |
| C17-C32 | 0.03 | 0.03 | 3.96 | 1.07 |

[1]Total Petroleum Hydrocarbon Criteria Working Group (Gustafson and others, 1997).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

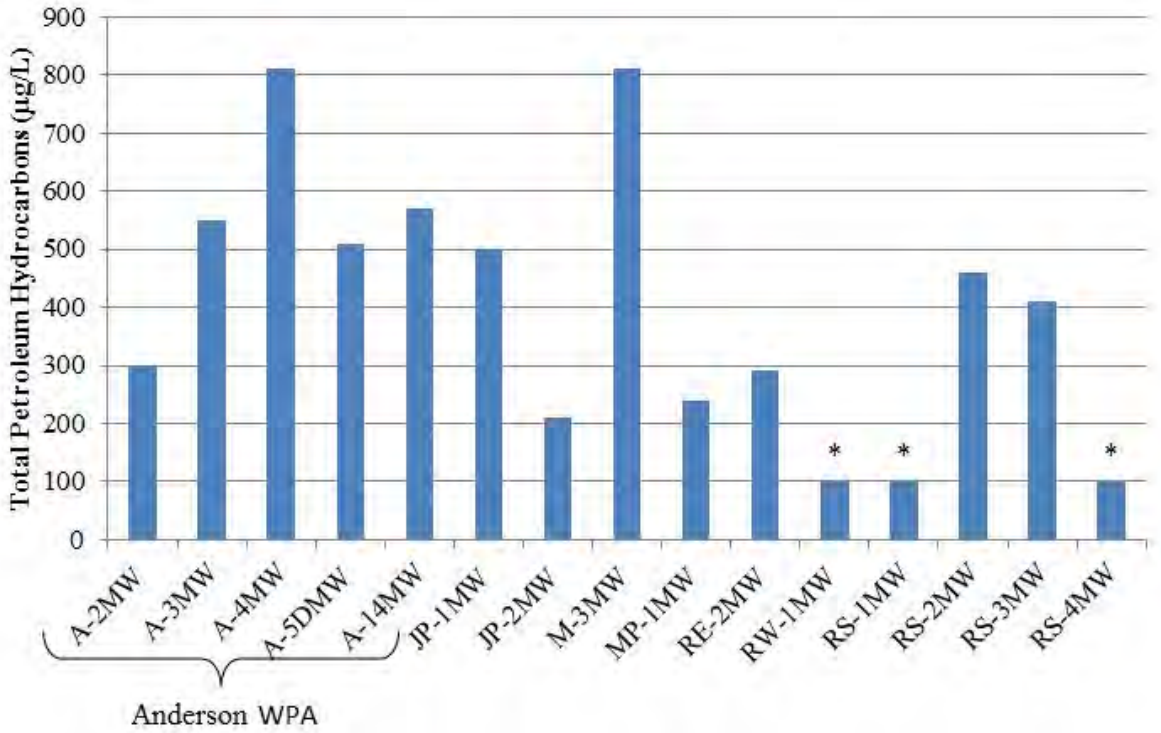


Figure 22. Concentrations (µg/L) of total petroleum hydrocarbons from groundwater samples collected across the Northeast Montana WMD in 2005 with sites from the Anderson WPA bracketed. *Indicates concentrations were below the analytical limit of detection of 100 µg/L.

Table 9. Concentrations (µg/L) of hydrocarbon fractions from groundwater samples collected in 2006 within Anderson WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values | | | |
|---|---|---|---|---|---|---|
| | MT RBSL[1] (µg/L) | MADEP[2] (µg/L) | A-2MW (µg/L) | A-3MW (µg/L) | A-4MW (µg/L) | A-14MW (µg/L) |
| **Aliphatics** | | | | | | |
| Carbon Range C9–C18 | 1,000 | 50,000 | 0 | 6 | 0 | 2.1 |
| Carbon Range C19–C36 | 1,000 | 50,000 | 5.7 | 19.4 | 3.6 | 34.5 |
| **Aromatics** | | | | | | |
| Carbon Range C9–C10 | — | 50,000 | <0.3 | <0.3 | <0.3 | <0.3 |
| Carbon Range C11–C22 | 1,000 | 5,000 | 0 | 0 | 0.5 | 0.3 |
| Acenaphthene | 670 | 6,000 | <0.3 | <0.3 | <0.3 | <0.3 |
| Anthracene | 2,100 | 30 | <0.3 | <0.3 | <0.3 | <0.3 |
| Benzo(a)pyrene | 0.05 | 500 | <0.3 | <0.3 | <0.3 | <0.3 |
| Benzo(b)fluoranthene | 0.5 | 400 | <0.3 | <0.3 | <0.3 | <0.3 |
| Benzo(k)fluoranthene | 5 | 100 | <0.3 | <0.3 | <0.3 | <0.3 |
| Chrysene | 50 | 70 | <0.3 | <0.3 | <0.3 | <0.3 |
| Dibenzo(a,h)anthracene | 0.05 | 40 | <0.3 | <0.3 | <0.3 | <0.3 |
| Fluoranthene | 130 | 200 | <0.3 | <0.3 | <0.3 | <0.3 |
| Flourene | 1,100 | 40 | <0.3 | <0.3 | <0.3 | <0.3 |
| Indeno(1,2,3-cd)pyrene | 0.5 | 100 | <0.3 | <0.3 | <0.3 | <0.3 |
| Naphthalene | 100 | 20,000 | <0.3 | <0.3 | <0.3 | <0.3 |
| Pyrene | 830 | 20 | <0.3 | <0.3 | <0.3 | <0.3 |

[1]Montana Tier 1 Risk-Based Corrective Action Guidance for Petroleum Release (MT DEQ, 2009).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

## Base Camp WPA

Base Camp WPA was established on 11/20/1968 with additional land purchases made on 6/18/1969, 8/11/1969, and 9/19/1969. The WPA encompasses an area of roughly 350 acres, with multiple wetlands located within or partially within its boundaries (fig. 23). Bird surveys have indicated that much of the WPA's habitat is suitable for breeding waterfowl during nesting season, with observations of 42–88 duck pairs per square mile (Brian DeVries, USFWS, written commun., 2009). Much of the upland habitat is intact native prairie, so management practices such as prescribed grazing and prescribed burning are implemented to maintain and increase the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, there were no production wells within the WPA. Using the abbreviated API well number, well 21337, located within 700 ft north of the WPA, is the closest well to the WPA. It is a producing oil well that was completed in January 1981.

### *Geology*

The surficial geology underlying the Base Camp WPA is depicted in figure 24. Most of the Base Camp WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft. A relatively long and narrow deposit of moderate to high permeability alluvium is mapped trending north to south through the central part of the Base Camp.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Base Camp WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes.

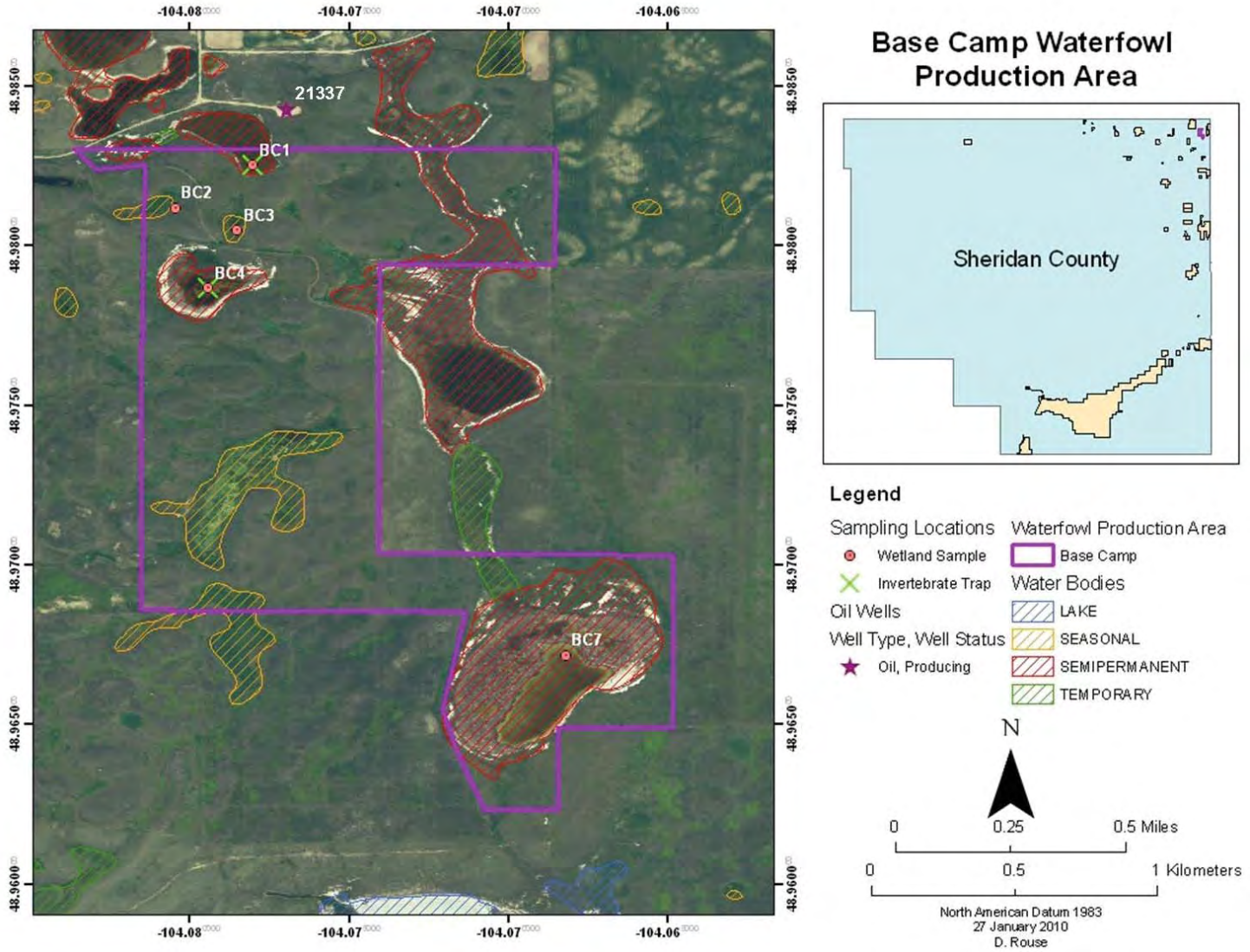


Figure 23. Map depicting locations of sampling sites, oil wells, and bodies of water for the Base Camp WPA: T. 37 N., R. 58 E., sec. 9, 10, 15 & 16.

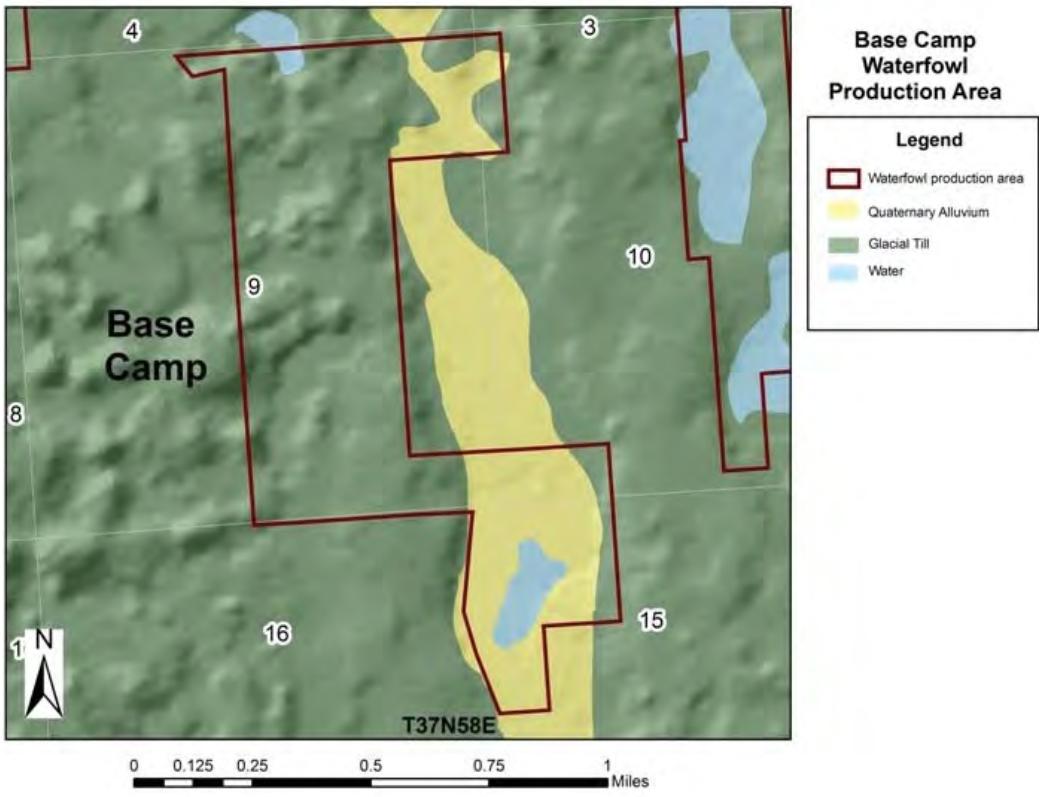


Figure 24. Near-surface geology of the Base Camp WPA: T. 37 N., R. 58 E., sec. 9, 10, 15 & 16.

### *Characterizing Oil Field Production Brine Migration*

EM surveys were not conducted at this site and there are no monitoring wells.

### *Wetland Water Quality*

Five wetlands were sampled to assess the potential influence from brine contamination on surface-water quality. Among the five surface-water sample locations at the Base Camp WPA, specific conductance, total dissolved solids, and chloride concentrations ranged from around 240 to 43,000 µS/cm, 0.15 to 27 g/L, and 6 to 1,147 mg/L, respectively (table 10). Based on the chloride index, brine impacts (CI > 0.035) were seen at BC1, although one of the sites visited, BC2, was dry. While it is likely that brine plumes are associated with oil wells near this site, predicting the extent of contamination is difficult because of the complex geologic setting.

### *Co-occurring Contaminants*

There were no additional analyses done for the Base Camp WPA.

## Chandler WPA

The Chandler WPA was established on 3/20/1969 and encompasses an area of approximately 45.5 acres. The southern extent of a lake extends into the WPA, covering much of its area (fig. 25). Bird surveys have documented the use of the Chandler WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA and the nearest well, an approved plugged and abandoned dry hole completed in October 1978, is located around 1,000 ft northwest of the WPA.

### *Geology*

The distribution of near-surface geologic materials is depicted in figure 26. As in many glaciated sites, glacial till, glacial lake sediments, and glacial outwash are all in

Table 10. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Base Camp WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| BC1 | 4/29/2004 | 14454 | 823 | 0.057 | Mesosaline |
| BC1 | 7/30/2004 | 17297 | 1147 | 0.066 | Mesosaline |
| BC2 | 4/29/2004 | | | | Dry |
| BC3 | 4/29/2004 | 240.1 | 7 | 0.027 | Fresh |
| BC4 | 4/29/2004 | 16872 | 141 | 0.008 | Mesosaline |
| BC4 | 7/30/2004 | 25796 | 233 | 0.009 | Mesosaline |
| BC7 | 9/11/2004 | 42264 | 954 | 0.023 | Polysaline |

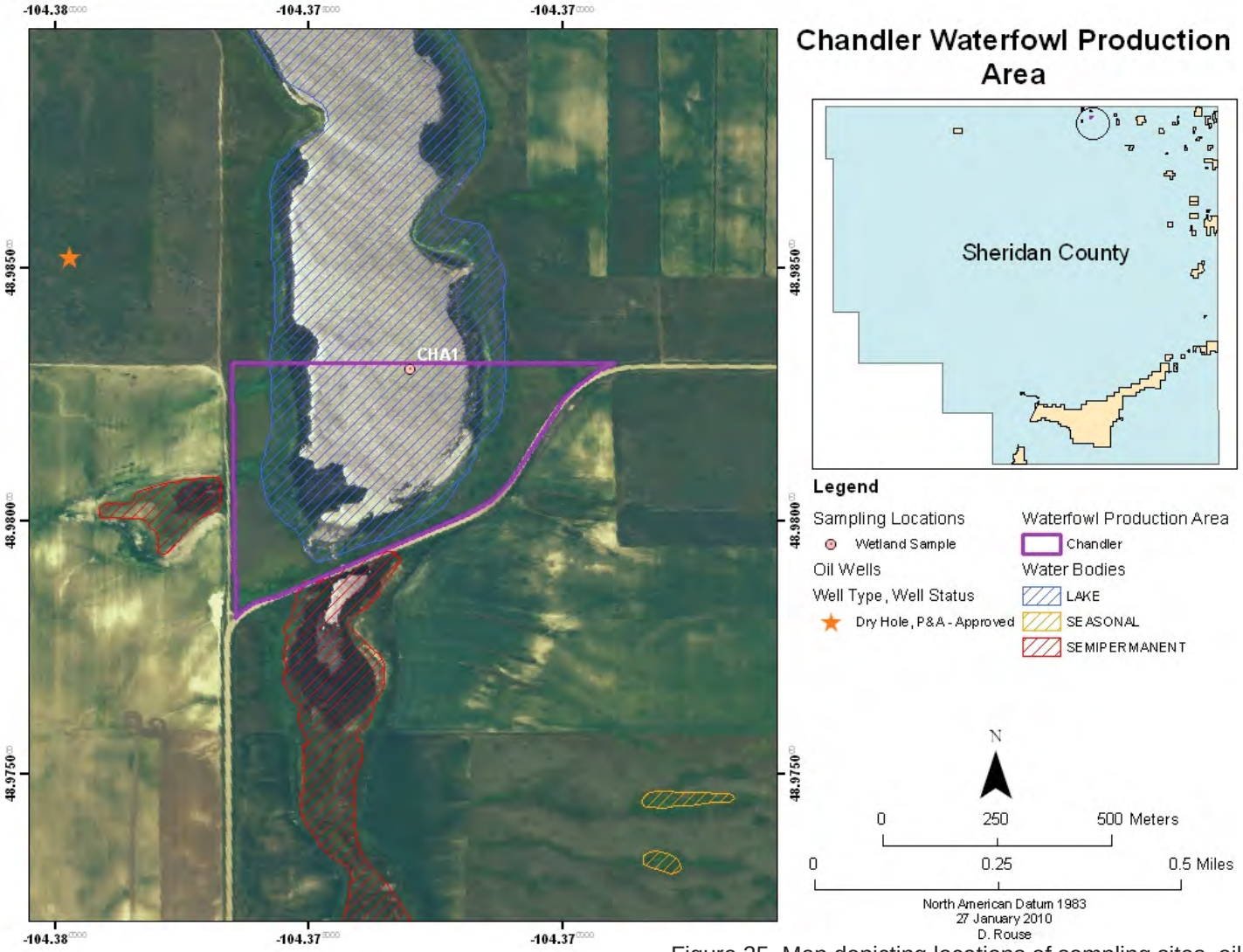


Figure 25. Map depicting locations of sampling sites, oil wells, and bodies of water for the Chandler WPA: T. 37 N., R. 56 E., sec. 8.

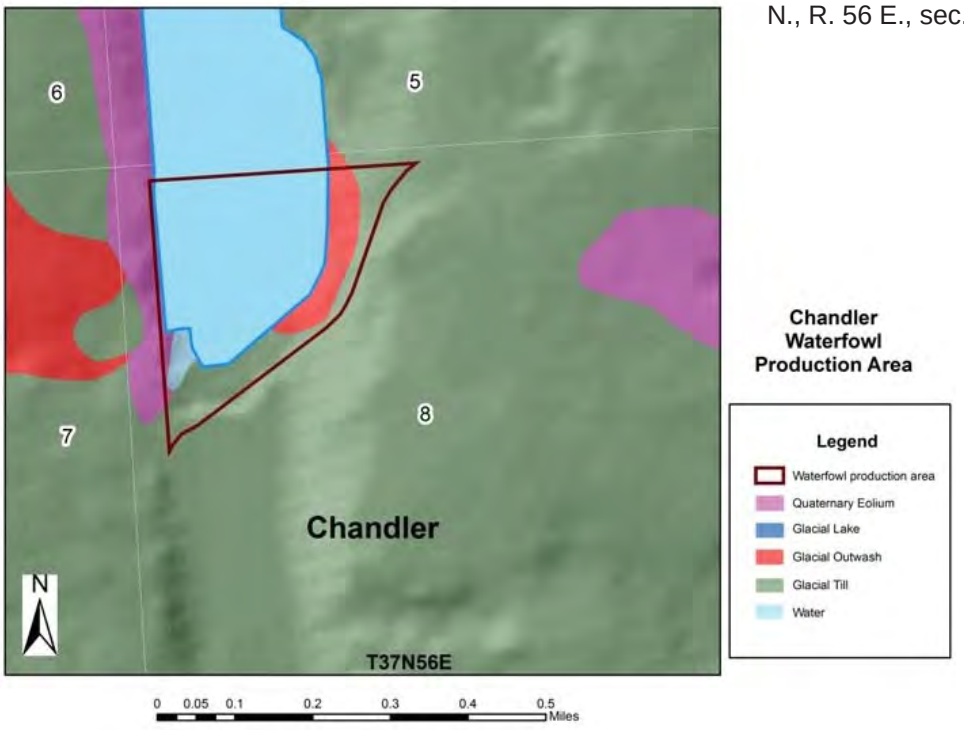


Figure 26. Geology of the Chandler WPA: T. 37 N., R. 56 E., sec. 8.

Table 11. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Chandler WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| CHA1 | 6/14/2005 | 13,520 | 360 | 0.027 | Mesosaline |

close proximity at this site. Most of the Chandler WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Chandler WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes.

### *Characterizing Oil Field Production Brine Migration*

EM-31 terrain conductivity surveys were not conducted on the Chandler WPA and there are no monitoring wells.

### *Wetland Water Quality*

There was a single sample, CHA1, taken from the lake in the WPA. The specific conductivity was around 13,000 µS/cm and the chloride concentration was 360 mg/L (table 11). The CI for this site was 0.027, suggesting minimal brine impacts.

### *Co-occurring Contaminants*

There were no additional analyses done for Chandler WPA.

## Long Lake WPA

The Long Lake WPA was established on 10/13/69. It encompasses approximately 210 acres with multiple wetlands located within its boundary (fig. 27). The WPA also borders Long Lake. Bird surveys have documented the use of the Long Lake WPA by breeding waterfowl during nesting season, with observations of 42–88 duck pairs per square mile (Brian DeVries, USFWS, written commun., 2009). Much of the upland habitat is intact native prairie, so management practices, such as prescribed grazing and prescribed fire, are implemented to maintain and improve the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, well 21457, an approved plugged and abandoned dry hole completed in December 1981, is the only production well located within the Long Lake WPA.

### *Geology*

Glacial deposits underlie the Long Lake WPA (fig. 28). Most of the WPA is underlain by collapsed glacial outwash with lesser amounts of glacial till in the southeastern part of the area. The glacial deposits probably range from 100 to 200 ft thick in this area and the site overlies deeper outwash of the Clear Lake aquifer. Based on completions records from a nearby irrigation well, the most productive interval of the Clear Lake aquifer is at depths ranging from 50 to 150 ft.

### *Groundwater Hydrology*

No monitoring wells were constructed to verify brine migration at this site. Groundwater of the Clear Lake aquifer underlies this site and, in general, flows to the southwest at this location.

### *Characterizing Oil Field Production Brine Migration*

Only a few small areas of higher than background terrain conductivity were identified from the EM-31 survey of the Long Lake WPA (fig. 29). Based on the date of completion for well 21457, the area of high terrain conductivity to the east of the well may reflect the presence of a lined reserve pit that has since been reclaimed. There are no monitoring wells at this site.

### *Wetland Water Quality*

Among the three wetlands sampled at the Long Lake WPA, specific conductance and chloride concentrations ranged from around 2,000 to 9,000 µS/cm and 61 to 279 mg/L, respectively (table 12). The highest specific conductivity was seen at LL3, while LL2 (GWIC ID 214789) had the highest chloride concentrations. In fact, LL2 (GWIC ID 214789) was the only site that exceeded a CI value of 0.035. However, CI values were slightly lower for LL2 (GWIC ID 214789) during 2005. The slight reduction in chlorides, coupled with the increase in sulfates, contributed to the diminished CI. Fluctuating water volumes or flushing and dilution by rainfall may have contributed to the differences seen in ionic composition between years (Reiten, 1992).

### *Co-occurring Contaminants*

Among trace element concentrations, the selenium concentration from the 2004 LL2 (GWIC ID 214789) sample and the nickel concentration from the 2005 LL2 (GWIC ID

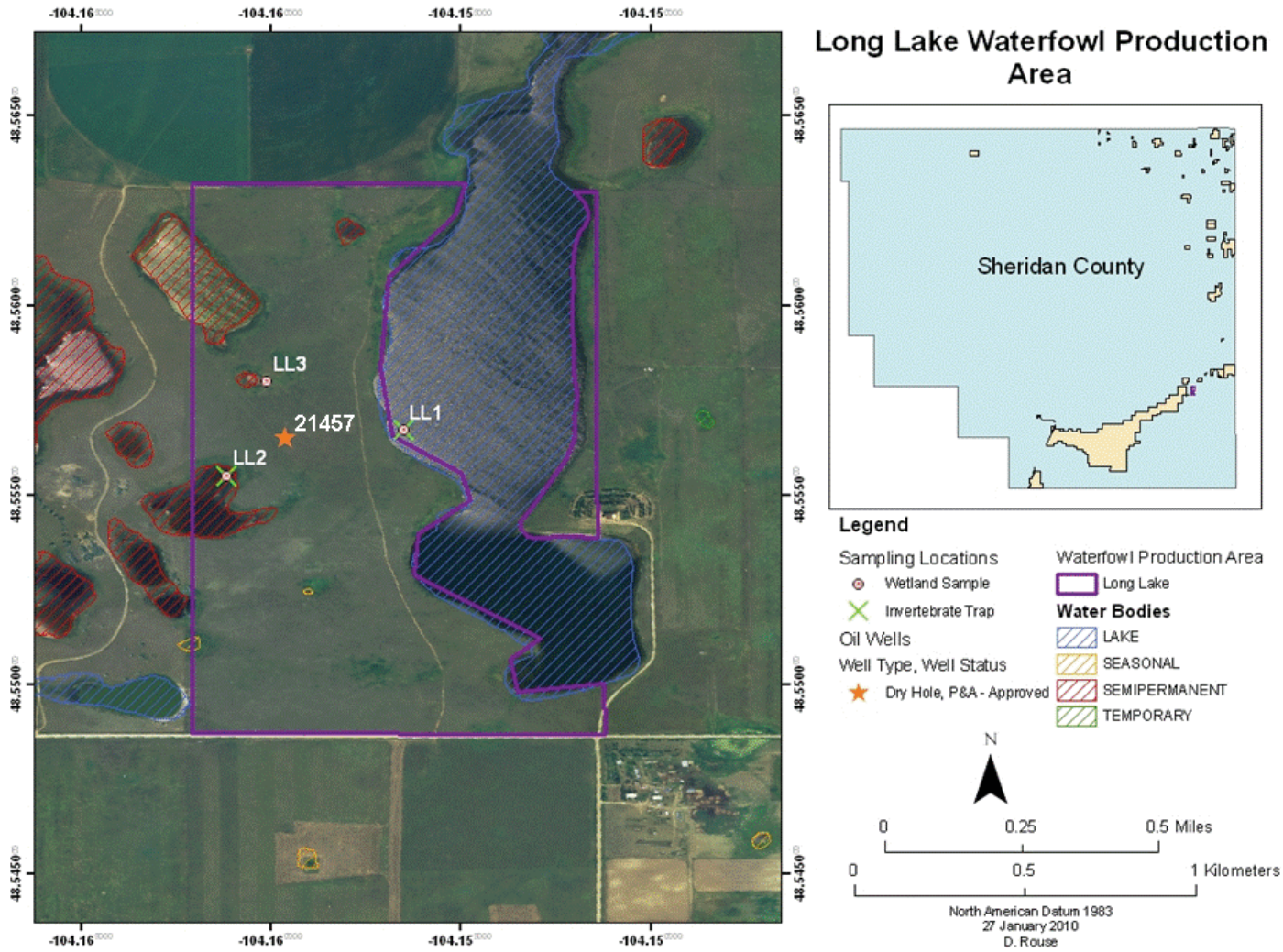


Figure 27. Map depicting locations of sampling sites, oil wells, and bodies of water for the Long Lake WPA: T. 32 N., R. 58 E., sec. 3.

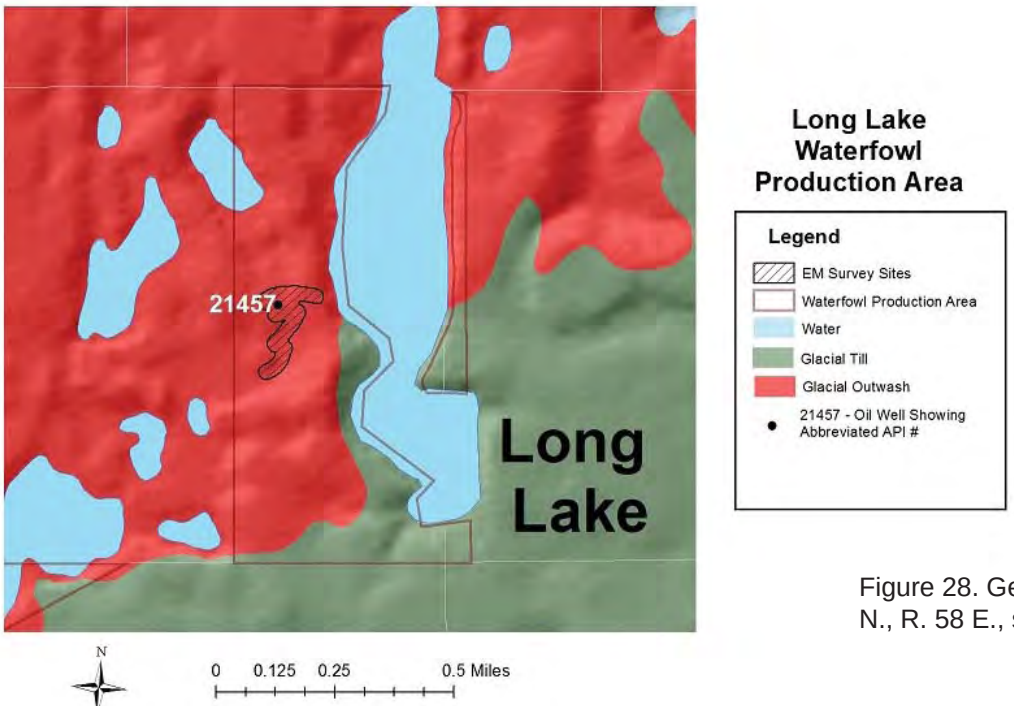


Figure 28. Geology of the Long Lake WPA: T. 32 N., R. 58 E., sec. 3.

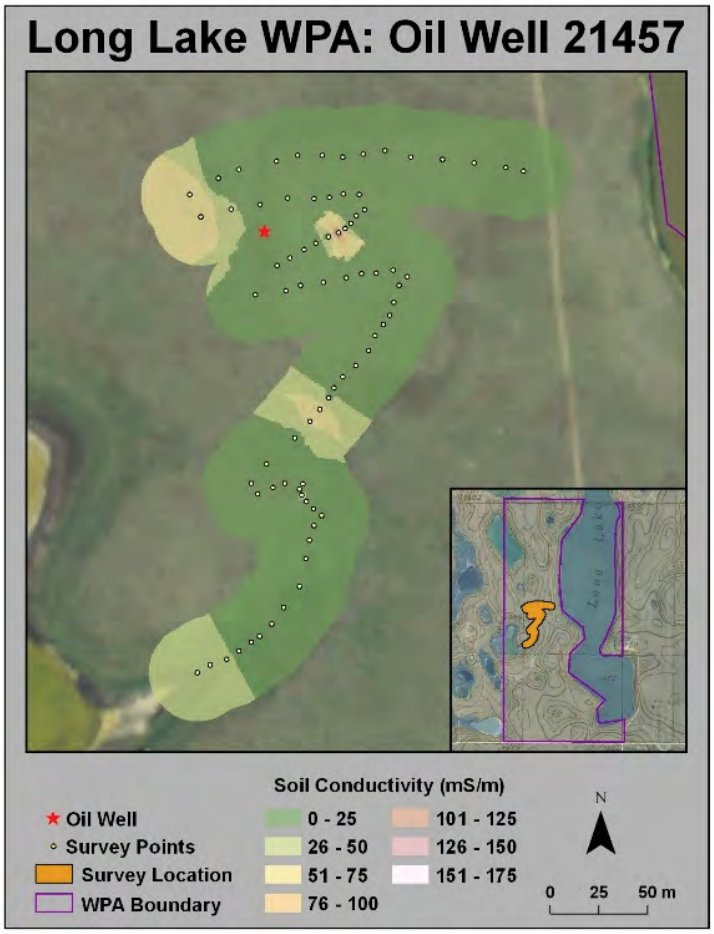


Figure 29. Location of EM-31 terrain-conductivity surveys conducted at the Long Lake WPA: T. 32 N., R. 58 E., sec. 3.

214789) sample were the only elements to exceed EPA's recommended national water-quality criteria (table 13). Although slight, a significant positive relationship was detected between surface-water selenium concentrations and the CI (table 7). Selenium has been detected in produced water samples collected from produced water reinjection sites in the Williston Basin before (Chen-Northern, 1994). Food chain bioaccumulation and reproductive failure in certain fish and wildlife species has been reported for aqueous selenium concentration as low as 2 µg/l. Therefore, the concentration detected at LL2 (GWIC ID 214789) in 2004 of 62.6 µg/L posed a great risk to many wildlife species, particularly sensitive species like aquatic birds. Reproductive failure has been reported in birds exposed to dietary concentrations of selenium as low as 4 µg/kg (Heinz and others, 1989). Interestingly, selenium concentrations, along with other elemental concentrations including chromium and strontium, were greatly reduced during the 2005 sampling event. Fluctuating water volumes or flushing and dilution by rainfall may have contributed to the differences seen in trace element concentrations between years (Reiten, 1992).

Due to differences in analytical methodologies between 2004 and 2005, the lower limit of detection for the 2004 sample was greater than the value detected in 2005. Therefore, we are unable to accurately describe the temporal trend for nickel concentrations in LL2 (GWIC ID 214789). In spite of this, if nickel is behaving similarly in this wetland as other elements such as arsenic, chromium, selenium, and strontium, we would expect nickel to be slightly greater in 2004 than the value detected in 2005. Nickel is a naturally occurring element and is considered an essential element for certain organisms (Chau and Kulikovsky-Cordeiro, 1995; Phipps and others, 2002). It is present in the environment due to natural processes, as well as anthropogenic activities such as mining, smelting, fuel combustion, and waste incineration (Chau and Kulikovsky-Cordeiro, 1995). Moreover, nickel has been detected in produced water samples (EPA, 1981). Aquatic nickel toxicity is typically inhibited by the presence of competing ions, so a site-specific hardness factor is incorporated into the benchmark concentration. LL2 (GWIC ID 214789) has a relatively low hardness value, which lowers the benchmark concentration. Consequently, the 2005 nickel concentration, albeit a concentration exceeding EPA's hardness-dependent benchmark concentration, is not particularly elevated when compared to values from other sites across the Northeast Montana WMD. Regardless, nickel toxicity has been reported for aquatic and terrestrial organisms, including birds, but at concentrations greater than those detected at LL2 (Phipps and others, 1995; Outridge and Scheuhammer, 1993). Whereas oil production activities may be contributing nickel to the environment, it is difficult to determine if those activities are contributing significantly to the concentrations detected at LL2 (GWIC ID 214789).

Table 12. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Long Lake WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| LL1 | 4/27/2004 | 2,481 | 61 | 0.025 | Oligosaline |
| LL1 | 9/10/2004 | 3,631 | 68 | 0.019 | Oligosaline |
| LL2 | 7/21/2004 | 5,966 | 216 | 0.036 | Oligosaline |
| LL2 | 9/10/2004 | 6,900 | 279 | 0.040 | Oligosaline |
| LL2 | 7/11/2005 | 7,280 | 168 | 0.023 | Oligosaline |
| LL2 | 7/8/2005 | 7,834 | 228 | 0.029 | Oligosaline |
| LL3 | 7/21/2004 | 8,950 | 184 | 0.021 | Mesosaline |

Table 13. Surface-water concentrations (µg/L) of trace elements present in the sampled wetland LL2 during 2004 and 2005.

| | LL2 (9/10/2004) | LL2 (7/11/2005) |
|---|---|---|
| Al | <100 | <50 |
| As | 33.3 | 17.3 |
| B | 1471 | 1510 |
| Ba | <20 | 7 |
| Be | <20 | <0.5 |
| Br | 7710 | |
| Cd | <10 | <0.05 |
| Co | <20 | <5 |
| Cr | 33.5 | <5 |
| Cu | <20 | <5 |
| Hg | | <0.1 |
| Li | 221 | |
| Mo | <100 | <10 |
| Ni | <20 | 6[#] |
| Pb | <20 | <0.05 |
| Se | 62.6[#] | 0.13 |
| Sr | 153 | 85 |
| Ti | <10 | <5 |
| U | <5 | |
| V | <50 | <10 |
| Zn | <20 | <5 |

[#]Indicates value exceeded EPA's recommended national water-quality criteria.

## Berger Pond WPA

The Berger Pond WPA was established on 3/14/1968 and encompasses an area of 12.79 acres. Much of the WPA is the southeastern portion of a lake (fig. 30). Bird surveys have documented the use of the Berger Pond WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within, or in close proximity to, the WPA.

### *Geology*

Glacial deposits underlie the Berger Pond WPA (fig. 31). Most of the WPA is underlain by collapsed glacial outwash, with limited glacial till in the southeastern part of the area. The glacial deposits are up to 200 ft thick in this area and the site overlies several permeable zones of the Clear Lake aquifer. The glacial materials overlie sandstone and mudstone of the Fort Union Formation.

### *Groundwater Hydrology*

No shallow monitoring wells were constructed at this site. Groundwater of the Clear Lake aquifer underlies this site and, in general, flows to the southwest at this location.

### *Characterizing Oil Field Production Brine Migration*

No oil wells or other oil field activities are located on or near the Berger Pond WPA. No EM-31 surveys were conducted on the Berger Pond WPA and no test wells were constructed.

### *Wetland Water Quality*

One wetland was sampled over three sampling events. Specific conductance and chloride concentrations ranged from around 10,600 to 11,300 µS/cm and 198 to 357 mg/L, respectively. There were no apparent brine impacts based on the CI.

### *Co-occurring Contaminants*

There were no additional analyses done for the Berger Pond WPA.

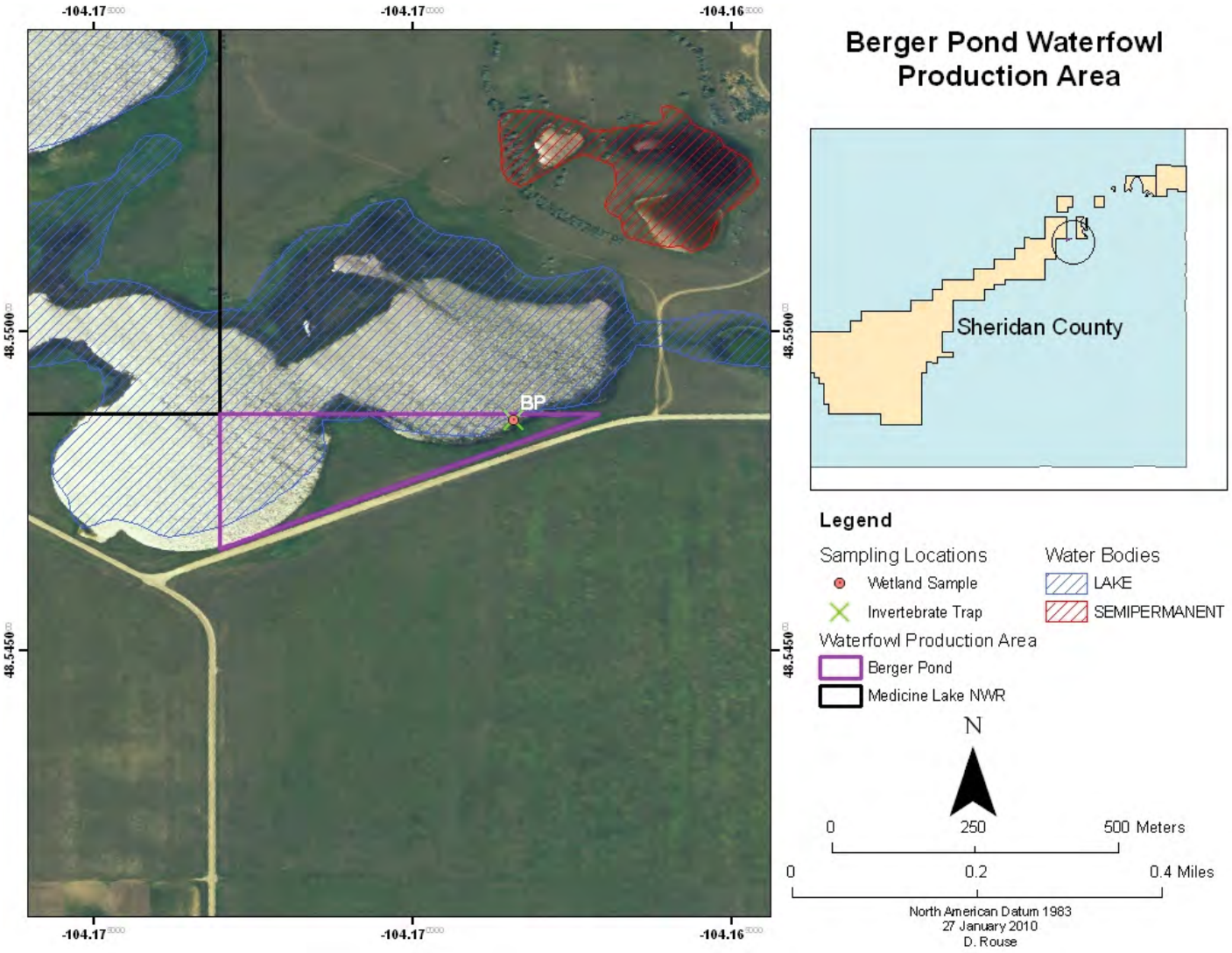


Figure 30. Map depicting locations of sampling sites, oil wells, and bodies of water for the Berger Pond WPA: T. 32 N., R. 58 E., sec. 10.

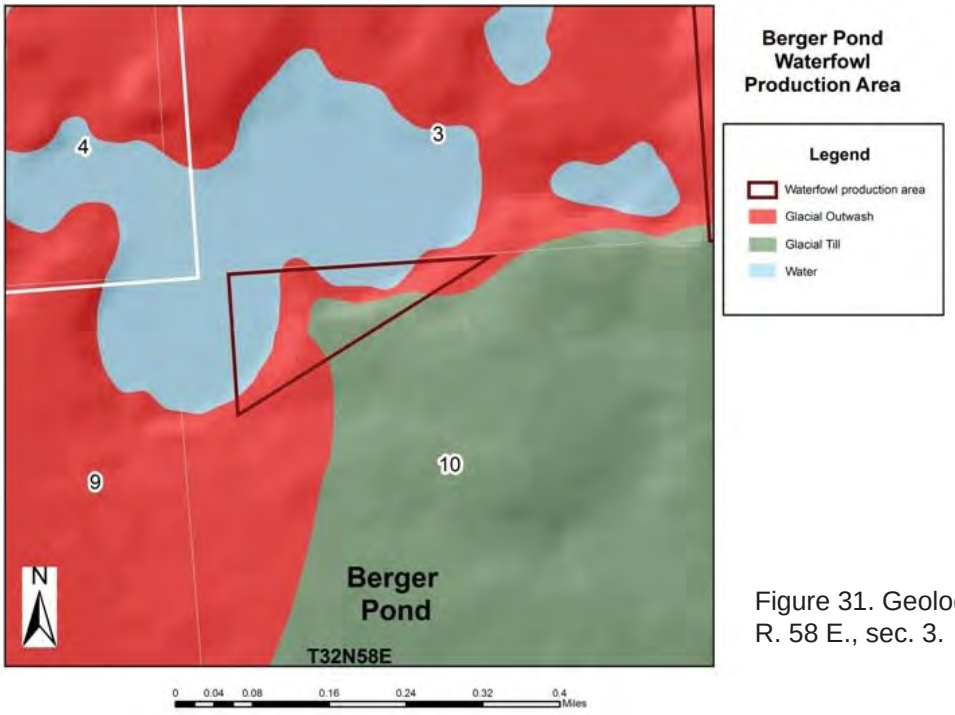


Figure 31. Geology of the Berger Pond WPA: T. 32 N., R. 58 E., sec. 3.

## Melby WPA

The Melby WPA was established on 7/17/1968 and encompasses an area of 20.08 acres. Portions of one seasonal wetland and one lake extend into the WPA (fig. 32). Bird surveys have documented the use of the Melby WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA, but one approved plugged and abandoned oil well is located approximately 100 ft from the southwestern boundary. This well, API well 21102, was completed in October 1987. Furthermore, an adjacent landowner allowed reserve pit waste to be land-farmed on land located just southeast of the WPA.

### *Geology*

The Melby WPA is underlain by glacial till deposits (fig. 33). These deposits are estimated to be from 50 to 100 ft thick based on nearby test drilling. Fort Union Sandstone and mudstone underlies the glacial materials. Glacial outwash deposits are located east of the Melby WPA. These sand and gravel deposits may be associated with tributaries to the Clear Lake aquifer.

### *Groundwater Hydrology*

Shallow groundwater flow in the Melby WPA is northwest towards the lake based on fall 2005 water-level measurements (figs. 34, 35). The general flow of the tributaries to the Clear Lake aquifer is to the southwest at this location (figs. 34, 35).

### *Characterizing Oil Field Production Brine Migration*

EM-31 terrain conductivity surveys identified higher than background conditions near the abandoned oil well site and downgradient of the site towards the north and west (fig. 36). These areas of high terrain conductivity appear to be associated with brine plumes migrating offsite. Additionally, small patches of elevated conductivity along the southeastern boundary of the WPA likely reflect the land-farming of pit wastes that once occurred (fig. 36). Among the five groundwater sampling sites, specific conductivity ranged from around 1,300 to 21,000 µS/cm and chloride concentrations ranged from 16.5 to 7087

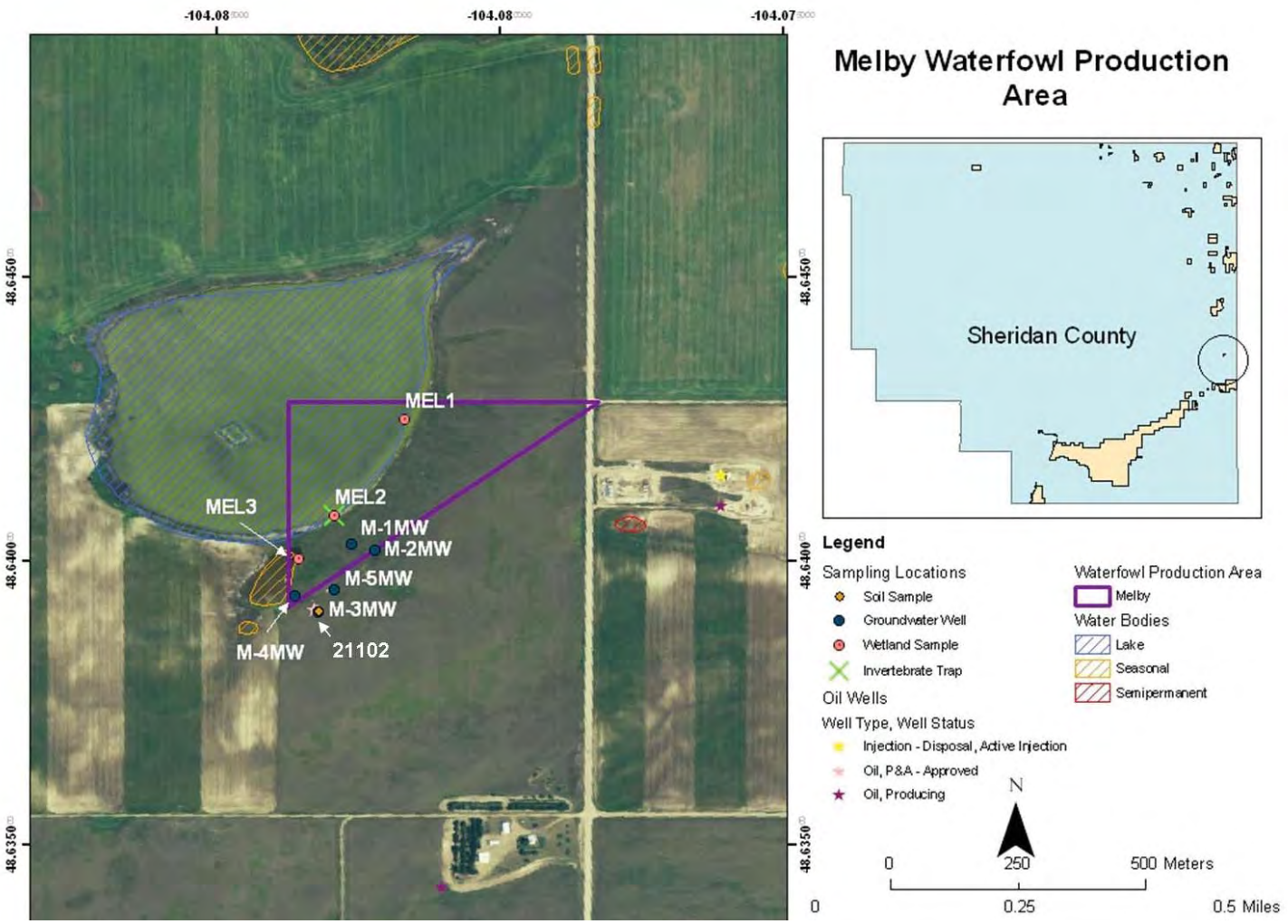


Figure 32. Map depicting locations of sampling sites, oil wells, and bodies of water for the Melby WPA: T. 33 N., R. 58 E., sec. 2.

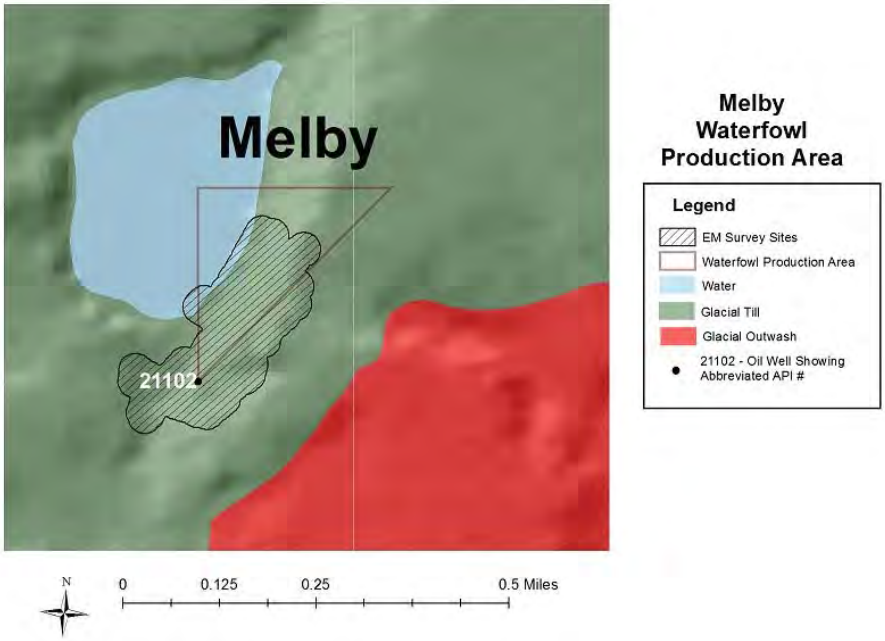


Figure 33. Geology of the Melby WPA: T. 33 N., R. 58 E., sec. 2.

mg/L. Based on the CI, brine impacts (CI > 0.035) were seen at two of the five monitoring wells: M-3MW (GWIC ID 221714) and M-4MW (GWIC ID 221595). Additionally, the ionic concentrations (fig. 37) and compositions (fig. 38) of samples collected from M-3MW (GWIC ID 221714) and M-4MW (GWIC ID 221595) are indicative of brine-impacted systems, dominated by Cl-, whereas M-5MW (GWIC ID 221725), M-1MW (GWIC ID 221690), and M-2MW (GWIC ID 221712) reflect a more naturally mineralized shallow aquifer dominated by $SO_4^{2-}$. In summary, groundwater impacts were evident where a reserve pit once existed but not where land framing of pit waste took place. The distribution of average CI values measured across the Melby WPA is shown in figure 39.

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at all of the monitoring well drilling sites and leachates were analyzed for specific conductivity and chlorides. Generally, specific conductance increased to a depth of 3–8 ft, then began to decrease at depth at most sites except M-4MW (table 14). Chlorides followed a similar trend, as indicated by stable CI values across varying depths, although the elevated CI values at sites M-3MW and M-4MW suggest these sites have chloride contamination to depths of 23 and 13 ft, respectively (table 14). This contamination reflects the residual impacts of the past use of a reserve pit at this site. While all of the sites are largely comprised of glacial till, indicative of the conserved patterns across different sites, artificial fill was identified at M-4MW, which may explain the different patterns seen at this site.

*Wetland Water Quality*

Three surface-water sites were sampled, two of which, MEL1 and MEL2 (GWIC ID 221718), were sampled from different locations within the same lake. Among the sampling locations, specific conductivity ranged from around 13,000 to 63,000 µS/cm and chloride concentrations ranged from 405 to 6,053 mg/L (table 15). Sites MEL1 and MEL2 (GWIC ID 221718) had CI values at or just below 0.035 in 2004, but a sample in 2005 at MEL2 (GWIC ID 221718) indicated there was a substantial increase in chlorides, characterized by a three-fold increase in the chloride concentration and a CI value over double what it was a year earlier. Furthermore, MEL3, a smaller seasonal wetland just south of the lake, showed clear signs of brine impacts based on the elevated CI. Based on EM-31 surveying and groundwater monitoring, it appears that M-5MW (GWIC ID 221725), M-1MW (GWIC ID 221690), and M-2MW (GWIC ID 221712) are beyond the extent of the brine plume's flow path, which suggests that impacts seen at sites MEL1 and MEL2 (GWIC ID 221718) are from some other source. Conversely, it appears quite evident that MEL3 is receiving contaminated water via groundwater transport based on the elevated CI associated with wells M-3MW (GWIC ID 221714) and M-4MW (GWIC ID 221595). Furthermore, it is likely that MEL3 is a potential source of contamination to MEL1 and MEL2 (GWIC ID 221718), either through surface-water interactions, groundwater interactions, or both.

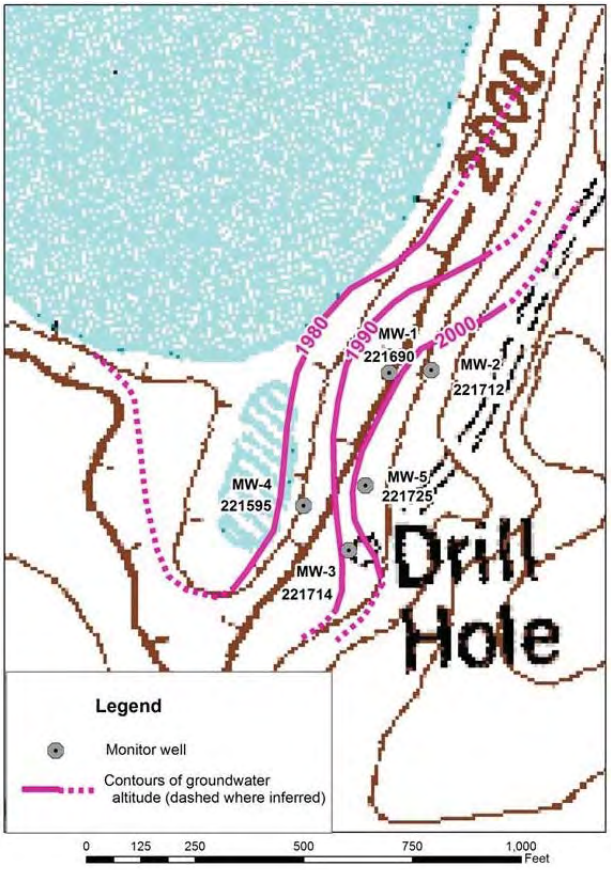


Figure 34. Groundwater flow at the Melby WPA: T. 33 N., R. 58 E., sec. 2.

Table 14. Specific conductivity and CI of 1:1 (by weight) aqueous leachates of soil samples at different depths in the Melby WPA.

| Depth (ft) | Soil Property | M-1MW | M-2MW | M-3MW | M-4MW | M-5MW |
|---|---|---|---|---|---|---|
| 0–3 | SC (µS/cm) | 644 | 4,580 | 20,275 | 639 | 11,990 |
| | CI | NA | 0.007 | 0.273 | 0.169 | 0.008 |
| 3–8 | SC (µS/cm) | 12,050 | 10,800 | 77,700 | 1,708 | 12,480 |
| | CI | 0.005 | 0.004 | 0.386 | 0.086 | 0.007 |
| 8–13 | SC (µS/cm) | 8,830 | 8,270 | 64,500 | 9,740 | 6,370 |
| | CI | 0.005 | 0.004 | 0.388 | 0.170 | 0.007 |
| 13–18 | SC (µS/cm) | 5,560 | 3,330 | 10,410 | 9,100 | 4,420 |
| | CI | 0.005 | NA | 0.205 | 0.041 | 0.007 |
| 18–23 | SC (µS/cm) | 5,160 | 3,420 | 6,950 | NA | 2,940 |
| | CI | 0.006 | NA | 0.153 | NA | NA |
| 23–28 | SC (µS/cm) | 2,890 | 2,700 | 3,310 | NA | 1,721 |
| | CI | NA | NA | 0.028 | NA | NA |

*Note.* NA, data not available.

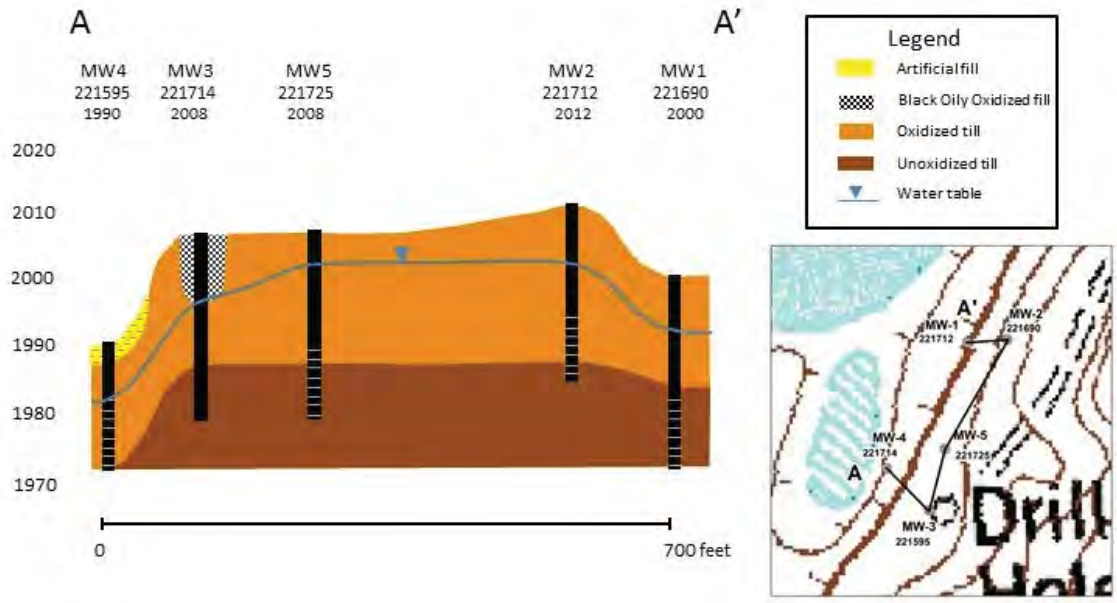


Figure 35. Hydrogeologic cross-sec. at the Melby WPA oil well site: T. 33 N., R. 58 E., sec. 2.

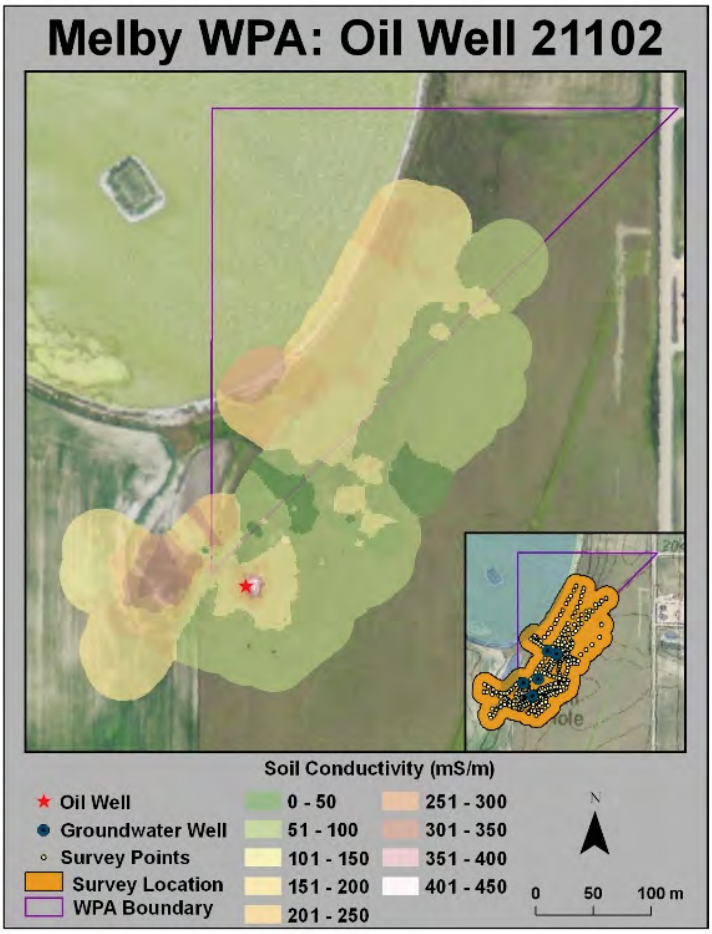


Figure 36. Location of EM-31 terrain-conductivity surveys conducted at the Melby WPA: T. 33 N., R. 58 E., sec. 2.

### *Co-occurring Contaminants*

One sample from MEL2 (GWIC ID 221718) was analyzed for metals (table 16). Based on those data, aluminum was the only element to exceed EPA's national recommended water-quality criteria. Due to the large number of sites with aluminum concentrations below the analytical limit of detection, the relationship between surface-water aluminum concentrations and the CI was not formally assessed (table 7). Therefore, it is difficult to determine the effect of oil production activities on aluminum concentrations in neighboring water bodies. Nevertheless, the concentration of aluminum at MEL2 (GWIC ID 221718) was at a level in which toxic effects have been reported in algae, macroinverterbrates, and fish (Gensemer and Playle, 1999). Aluminum toxicity is considered pH-dependent, with increasing toxicity as water becomes more acidified (Gensemer and Playle, 1999). With a pH around 9 at MEL2 (GWIC ID 221718), the water-borne aluminum concentrations detected in this survey are likely highly complexed, diminishing its bioavailability. In spite of this, varying conditions may alter the availability of aluminum to aquatic organisms, as well as increase the risk to terrestrial organisms, like birds, that may be exposed to elevated aluminum concentrations through dietary uptake (Gensemer and Playle, 1999; Rosseland and others, 1990).

When compared to the Montana numerical water-quality standards for human health in groundwater, two sites, M-4MW (GWIC ID 221595) and M-5MW (GWIC ID 221725), had exceedances for strontium and arsenic, respectively (table 16). There does not appear to be a relationship between arsenic and the CI suggestion that the elevated arsenic concentration detected at M-5MW (GWIC ID 221725) is from some other source (table 5). Conversely, there is a significant positive relationship between the CI and groundwater strontium concentrations (table 5). Strontium is a commonly detected element in produced waters (Stephenson, 1992) and has been shown to be a useful indicator of produced water impacts through the use of isotopic fractions (Peterman and others, 2010).

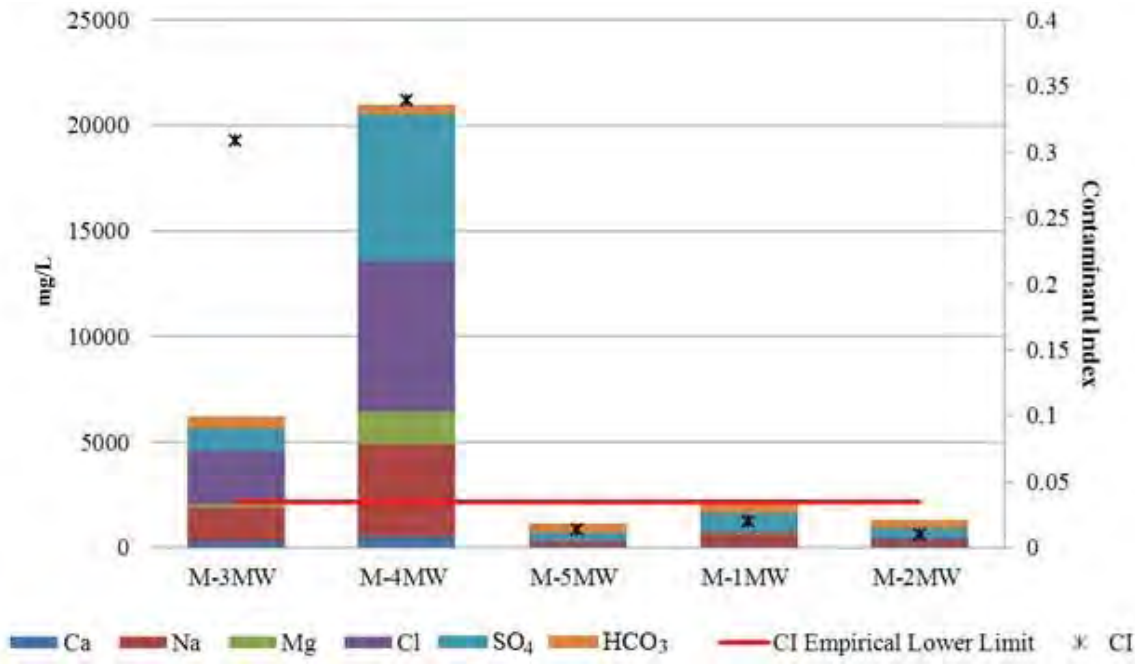


Figure 37. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within the Melby WPA during 2005.

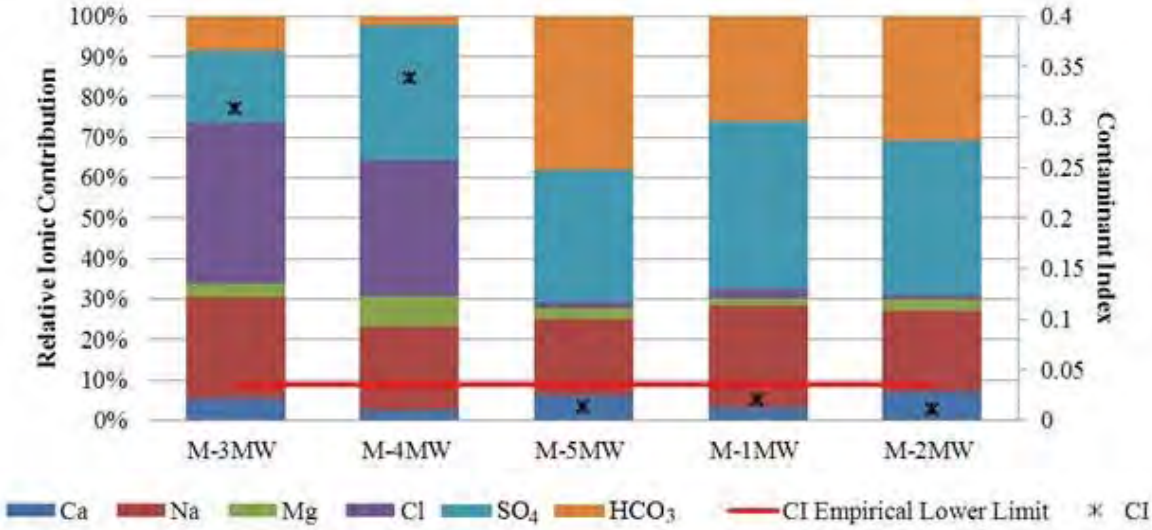


Figure 38. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within the Melby WPA during 2005.

Table 15. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Melby WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| MEL1 | 5/14/2004 | 13,233 | 405 | 0.031 | Mesosaline |
| MEL2 | 5/14/2004 | 13,207 | 464 | 0.035 | Mesosaline |
| MEL2 | 7/21/2004 | 15,637 | 414 | 0.026 | Mesosaline |
| MEL2 | 9/16/2005 | 22,800 | 1,338 | 0.059 | Mesosaline |
| MEL3 | 7/21/2004 | 62,540 | 6,053 | 0.097 | Hypersaline |

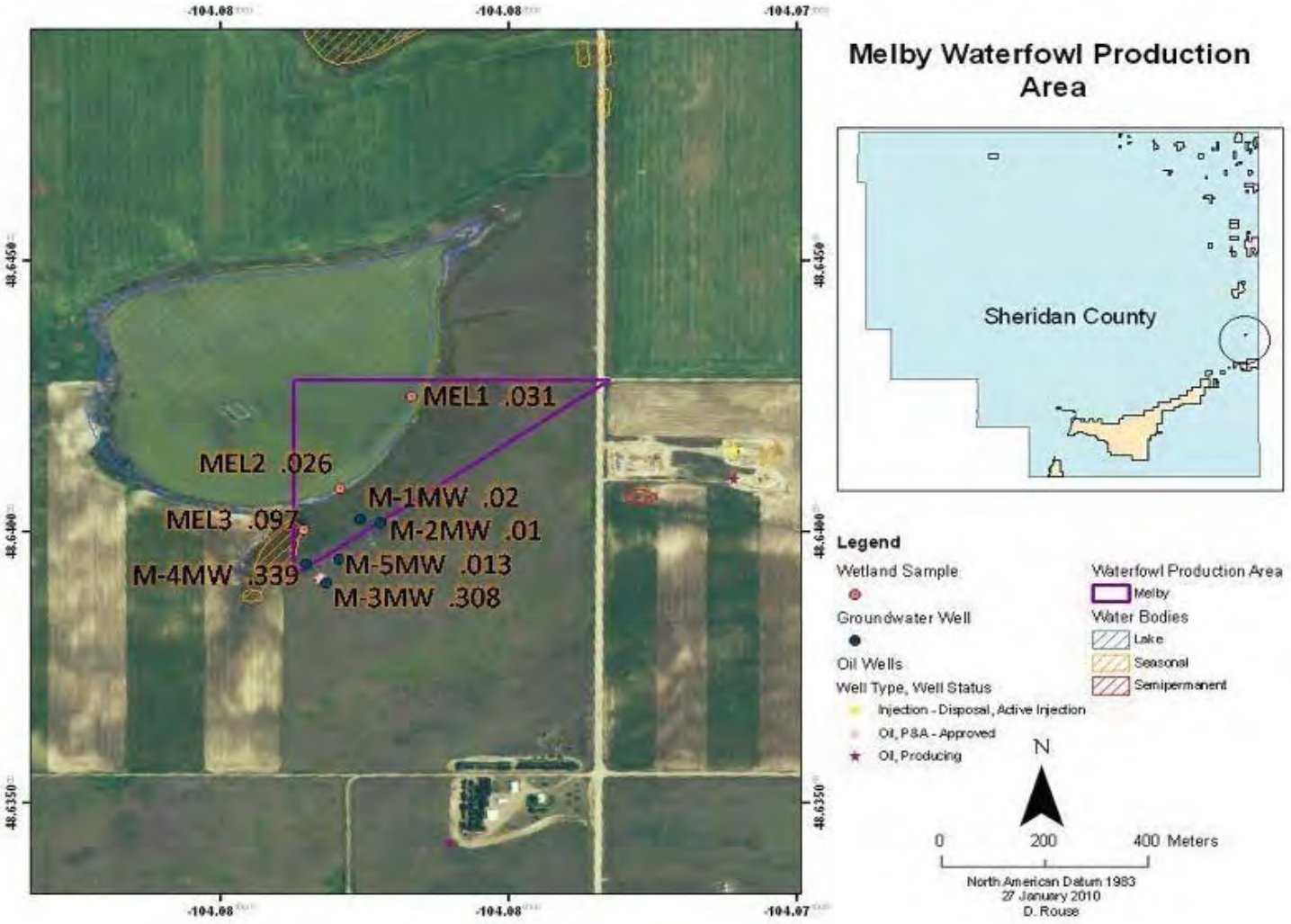


Figure 39. Distribution of the mean chloride contamination index measured in wells and wetlands associated with the Melby WPA: T. 33 N., R. 58 E., sec. 2.

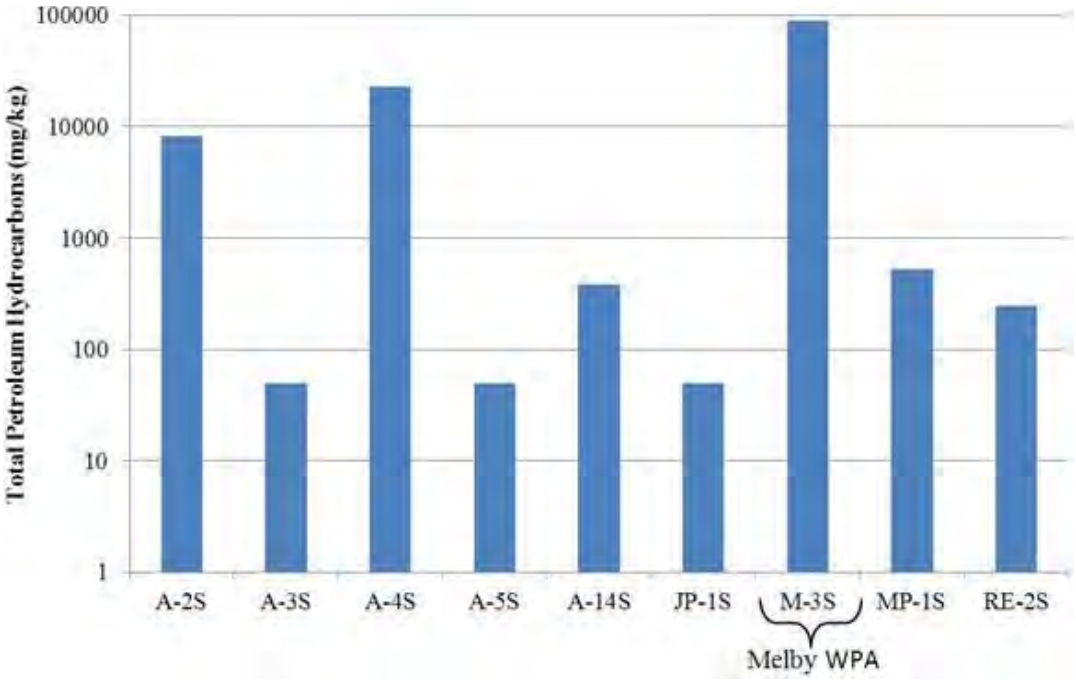


Figure 40. Concentrations (mg/kg) of total petroleum hydrocarbons from soil samples collected across the Northeast Montana WMD in 2005 with the site located in the Melby WPA bracketed.

Table 16. Surface-water and groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells and wetland of the Melby WPA in 2005.

| | Groundwater | | | | | Surface Water |
|---|---|---|---|---|---|---|
| | M-1MW | M-2MW | M-3MW | M-4MW | M-5MW | MEL2 |
| Al | <50 | <50 | <50 | <50 | <50 | 215[#] |
| As | 5.06 | 4.47 | 5.16 | 2.79 | 13.8[*] | 46.5 |
| B | 273 | 228 | 288 | 671 | 230 | 5,800 |
| Ba | 42 | 27 | 76 | 79 | 36 | 26 |
| Be | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Cd | 0.11 | 0.04 | 0.18 | 0.18 | 0.04 | <0.2 |
| Co | <5 | <5 | <5 | <5 | <5 | <5.00 |
| Cr | <5 | <5 | <5 | <5 | <5 | <5.00 |
| Cu | <5 | <5 | <5 | 6 | <5 | <5.00 |
| Hg | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Mo | 20 | <10 | 10 | 10 | <10 | 20 |
| Ni | <5 | <5 | 8 | <5 | <5 | 5 |
| Pb | 0.1 | 0.02 | <0.05 | <0.1 | <0.01 | 0.82 |
| Se | 1.76 | <0.1 | 0.88 | 32.7 | <0.1 | 0.81 |
| Sr | 435 | 590 | 2,570 | 7,630[*] | 435 | 220 |
| Ti | <5 | <5 | <5 | 7 | <5 | 10 |
| V | <10 | <10 | <10 | <10 | <10 | <10 |
| Zn | <5 | 12 | <5 | 14 | <5 | |

[*]Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

[#]Indicates value exceeded EPA's recommended national water-quality criteria.

While elevated strontium concentrations have been linked to reduced eggshell thickness in birds (Matz and Rocque, 2007), the elevated concentrations at the Melby WPA are confined to groundwater, and therefor unavailable to most organisms.

One soil sample, M-3S, was collected in 2005 for total petroleum hydrocarbon analysis (fig. 40). With a concentration of 89,200 mg/kg (DW), this sample had the highest concentration of total petroleum hydrocarbons of all of the soil samples taken at the Northeast Montana WMD. In 2006, two grab samples were taken at M-3S and were analyzed for aliphatic and polynuclear aromatic hydrocarbons. Average hydrocarbon values from 2006 were compared to established toxic benchmark values to assess the relative toxicity at each site. For each hydrocarbon fraction assessed, average concentrations detected exceeded every benchmark value (table 17).

Although the toxicity criteria used in this assessment were developed to be protective of human health, values detected were at levels that have been reported as causing environmental impacts. For example, sublethal effects to plants and invertebrates as well as lethal effects to invertebrates have been reported for values comparable to those detected at M-3S (Cermak and others, 2010). Additionally, impacts to microbial communities, including reduced microbial biomass and soil enzyme activity, have been reported for soils that possess hydrocarbon levels comparable to those at M-3S (Megharaj and others, 2000). While the two soils samples taken at the Melby WPA are not representative of large-scale soil contamination, they do illustrate that oil production practices at this WPA are releasing petroleum hydrocarbons into the environment at potentially toxic levels.

In 2005, one groundwater sample was collected from M-3MW and analyzed for total petroleum hydrocarbons. Total petroleum hydrocarbons were present at a concentration of 810 µg/L, which was one of the highest concentrations detected (fig. 41). M-3MW was resampled in 2006 and analyzed for aliphatic and polynuclear aromatic hydrocarbons. Numerous compounds were present at concentrations greater than the analytical detection limits, with one individual compound, dibenz(a,h)anthracene, exceeding toxicity criteria (table 18). Dibenz(a,h)anthracene is classified

Table 17. Concentrations (mg/kg DW) of hydrocarbon fractions from soil samples collected in 2006 within the Melby WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| Carbon Range | TPHCWG[1] (mg/kg/day) | MADEP[2] (mg/kg/day) | M-3S (mg/kg) |
| **Aliphatic** | | | |
| C9–C18 | 0.10 | 0.10 | 11,311 |
| C19–C32 | 2.00 | 2.00 | 1,665.45 |
| **Aromatic** | | | |
| C9–C16 | 0.04 | 0.03 | 90 |
| C17–C32 | 0.03 | 0.03 | 6.81 |

[1]Total Petroleum Hydrocarbon Criteria Working Group (Gustafson and others, 1997).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

by EPA as a probable human carcinogen and is considered toxic to many wildlife species. However, groundwater is largely unavailable to most organisms, and if dibenz(a,h) anthracene was transported to a surface-water body, it would likely be associated with the sediments. MacDonald and others (2000) proposed a consensus-based toxic effect concentration of 33 µg/kg, below which harmful effects are unlikely to occur. Groundwater may contribute trace levels of dibenz(a,h)anthracene to wetlands through groundwater–surface-water interactions, but runoff from contaminated soils will more likely contribute concentrations of dibenz(a,h)anthracene or other soil-bound hydrocarbons at toxic levels. No other individual compound or chemical group exceeded toxicity benchmarks, but many of these values were consistently higher than other samples taken throughout the Northeast Montana WMD. For instance, the lighter aliphatic fraction (C9–C18) concentration for M-3MW was greater than 18 times the concentration found at A-3MW, the site with the next highest lighter aliphatic (C9–C18) fraction concentration. The concentration of the lighter aromatic fraction (C9–C10) was at least twice that of the next highest concentration, although all other sites had concentrations below detection limits. Both of the heavier fractions of aliphatic (C19–C36) and aromatic (C11–C22) hydrocarbons were slightly less than two times the values found at A-14MW and A-4MW, the sites with the next highest concentrations of the heavier fractions of aliphatic (C19–C36) and aromatic (C11–C22) hydrocarbons, respectively.

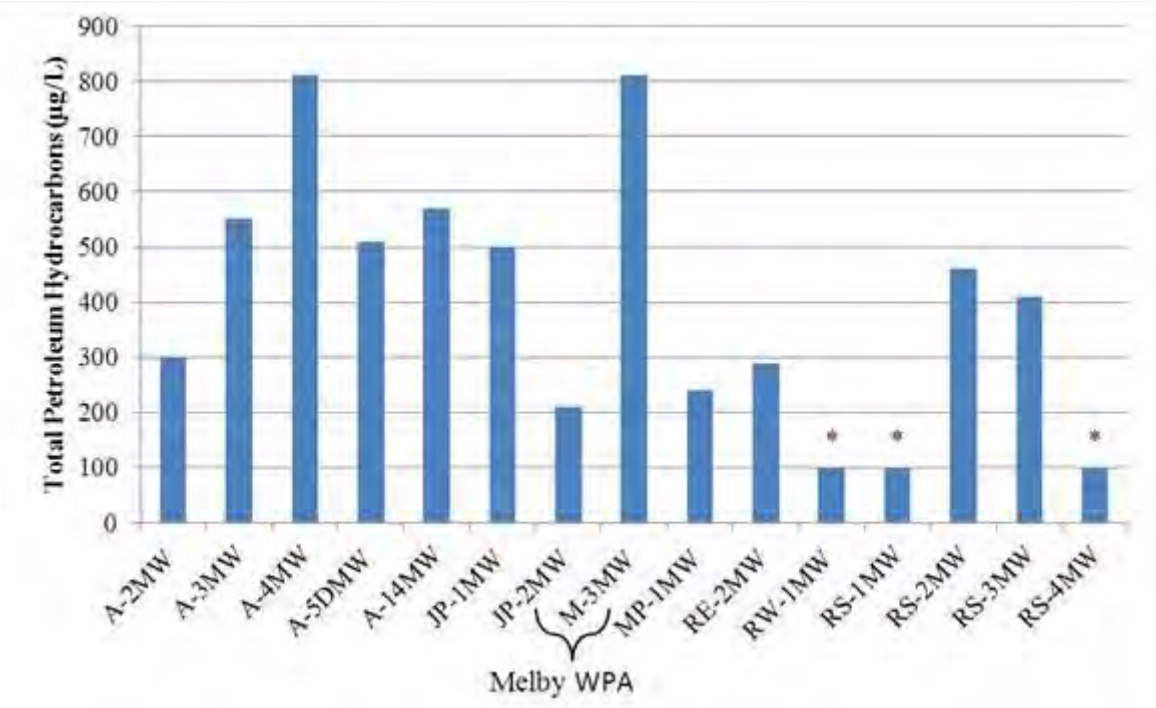


Figure 41. Concentrations (µg/L) of total petroleum hydrocarbons from groundwater samples collected across the Northeast Montana WMD in 2005 with the site located in the Melby WPA bracketed. *Indicates concentration is below the analytical detection limit of 100 µg/L.

Table 18. Concentrations (µg/L) of hydrocarbon fractions from groundwater samples collected in 2006 within the Melby WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| | MT RBSL[1] (µg/L) | MADEP[2] (µg/L) | M-3MW (µg/L) |
| **Aliphatics** | | | |
| Carbon range C9–C18 | 1,000 | 50,000 | 108.9 |
| Carbon range C19–C36 | 1,000 | 50,000 | 57.1 |
| **Aromatics** | | | |
| Carbon range C9–C10 | — | 50,000 | 0.7 |
| Carbon range C11–C22 | 1,000 | 5,000 | 0.8 |
| Acenaphthene | 670 | 6,000 | <0.3 |
| Anthracene | 2,100 | 30 | <0.3 |
| Benzo(a)pyrene | 0.05 | 500 | <0.3 |
| Benzo(b)fluoranthene | 0.5 | 400 | <0.3 |
| Benzo(k)fluoranthene | 5 | 100 | <0.3 |
| Chrysene | 50 | 70 | <0.3 |
| Dibenzo(a,h)anthracene | 0.05 | 40 | 0.3† |
| Fluoranthene | 130 | 200 | <0.3 |
| Flourene | 1,100 | 40 | <0.3 |
| Indeno(1,2,3-cd)pyrene | 0.5 | 100 | <0.3 |
| Napthalene | 100 | 20,000 | 0.7 |
| Pyrene | 830 | 20 | <0.3 |

[1]Montana Tier 1 Risk-Based Corrective Action Guidance for Petroleum Release (MT DEQ, 2009).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).
†Indicates value exceeds a toxicity benchmark.

## Mallard Pond WPA

The Mallard Pond WPA was established on 3/14/1968 and encompasses an area of approximately 160 acres with multiple bodies of water extending on to the property (fig. 42). Bird surveys have documented the use of the Mallard Pond WPA by breeding waterfowl during nesting season, with observations of 42–88 duck pairs per square mile (Brian DeVries, USFWS, written commun., 2009). Much of the upland habitat is intact native prairie, so management practices, such as prescribed grazing and prescribed fire, are implemented to maintain and improve the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, well 21236, an approved plugged and abandoned oil well, was the only production well found within the WPA. The closest production well outside of the WPA was a producing oil well located within 800 ft of the northern WPA boundary (fig. 42). Well 21236 was completed in June 1979. Historical aerial photos reveal that a tank battery was present at the location of well 21236, as well as a salt scar located just to the east.

### *Geology*

The Mallard Pond WPA is underlain by glacial outwash deposits (fig. 43). These deposits are estimated to be from 50 to 150 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlies the glacial materials. Quaternary alluvial deposits are located underlying the western part of the Mallard Pond WPA and are associated with swales and lowlands along Lake Creek and its tributaries. The sand and gravel glacial outwash deposits are associated with the upper permeable zone of the Clear Lake aquifer.

### *Groundwater Hydrology*

The Mallard Pond site overlies the Clear Lake aquifer. Water levels at Mallard Pond and other wetlands in this area approximate the water table of the Clear Lake aquifer. Flow in the aquifer is generally towards the west or southwest. The cross section shown in figure 44 depicts the outwash overlying the aquifer and the similar water levels in monitoring wells constructed at the Mallard Pond WPA and Mallard Pond.

### *Characterizing Oil Field Production Brine Migration*

EM terrain conductivity surveys indicated higher than background readings in an area east of the abandoned oil well (fig. 45). These appear to be related to well construction activities where brine or brine-saturated materials were either spilled or buried. These could also reflect the salt scars identified in the historical aerial photos. Among the three monitoring well samples, specific conductance ranged from around 680 to 16,300 µS/cm and chloride concentrations ranged from 4.57 to 8581 mg/L. Based on the CI, brine impacts (CI > 0.035) were seen at two of the three monitoring wells: MP-1MW (GWIC ID 221735) and MP-2MW (GWIC ID 221704). The ionic concentrations (fig. 46) and compositions (fig. 47) of groundwater samples

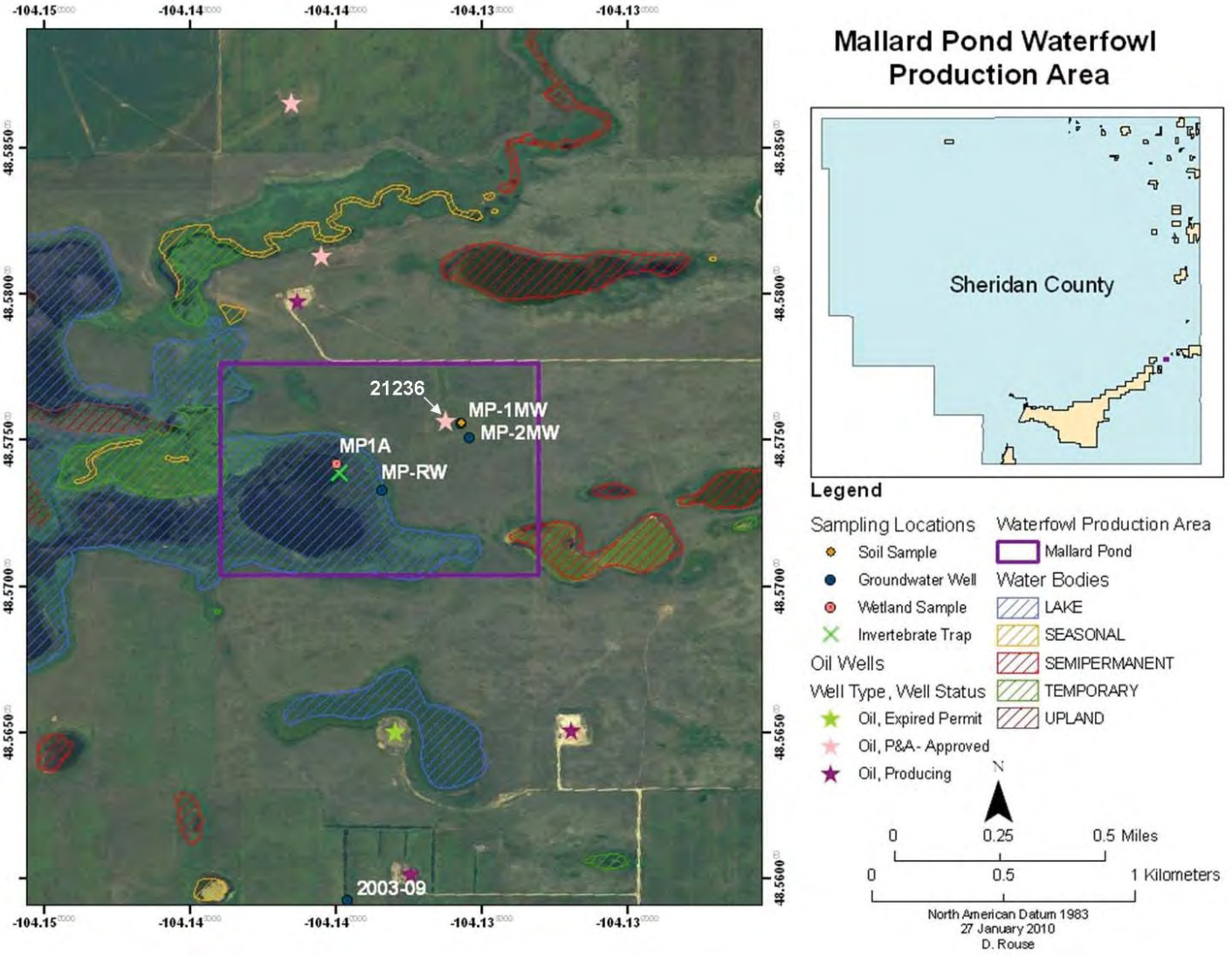


Figure 42. Map depicting locations of sampling sites, oil wells, and bodies of water for the Mallard Pond WPA: T. 33 N., R. 58 E., sec. 33.

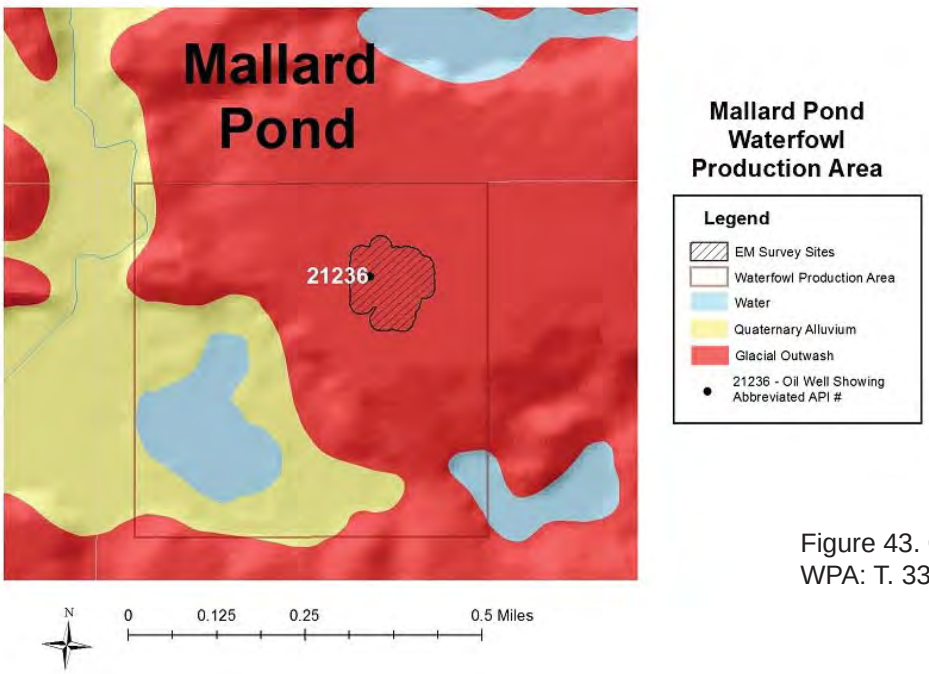


Figure 43. Geology of the Mallard Pond WPA: T. 33 N., R. 58 E., sec. 33.

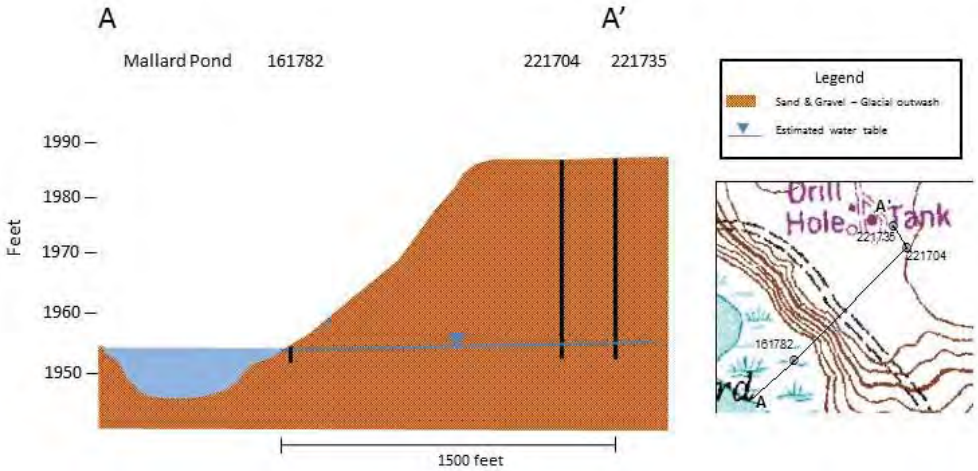


Figure 44. Cross section showing hydrogeologic conditions in the vicinity of the of the Mallard Pond WPA.

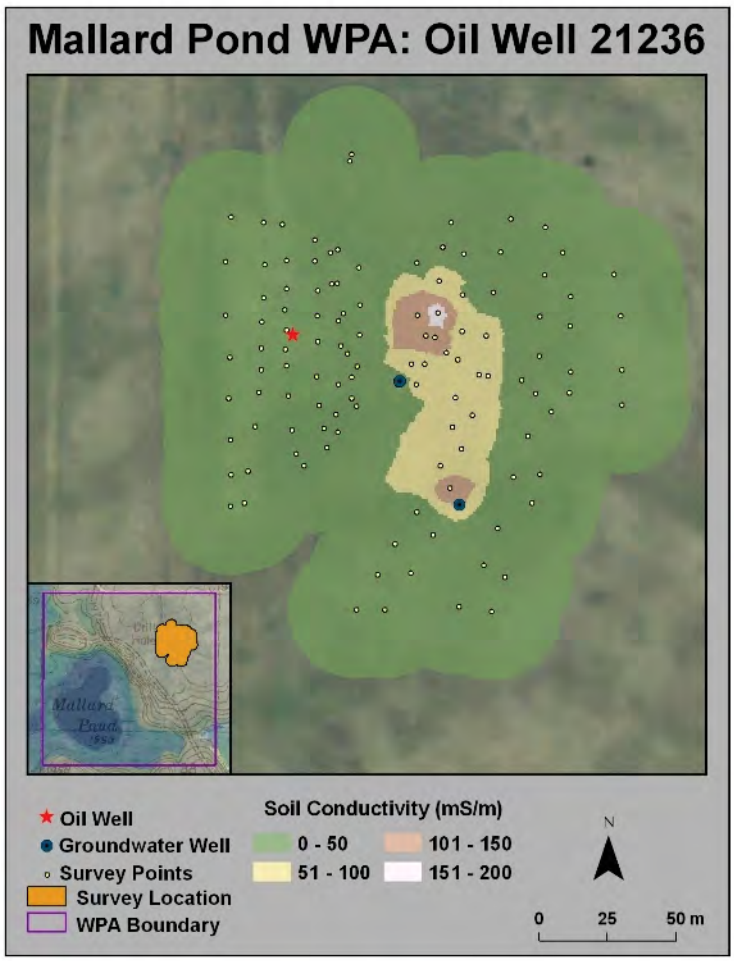


Figure 45. Location of EM-31 terrain-conductivity surveys conducted at the Mallard Pond WPA: T. 33 N., R. 58 E., sec. 33.

taken from wells MP-1MW (GWIC ID 221735) and MP-2MW (GWIC ID 221704) are indicative of brine impacts, dominated by Cl- ions, whereas well MP-RW (GWIC ID 161782) lacks that Cl- dominance. The distribution of mean CI values associated with the Mallard Pond WPA is shown in figure 48.

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at the monitoring well drilling sites of MP-1MW and MP-2MW, and leachates were analyzed for specific conductivity and chlorides (table 19). MP-1MW consistently had high specific conductivity and CI values throughout the various sampled depths, while MP-2MW had a clearer increasing trend in values with depth. The differences between the two sites may reflect proximity to the contaminant source. For example, MP-1MW may have been the location of a chronic leak or waste site associated with oil well 21236, and the permeable outwash in which both sites are located have allowed chloride contamination to migrate to a point in which subsurface impacts are seen at MP-2MW.

### *Wetland Water Quality*

One wetland, Mallard Pond, was sampled four times between 1990 and 2005 (table 20). Results from the 1990 sample were reflective of the drought conditions that existed during the 1980s that had evapoconcentrated water in the pond, resulting in an elevated specific conductivity value of 2,590 µS/cm. However, the chloride concentration of 25.7 mg/L and the CI value of 0.01 were similar to the values seen during the 2004 sampling event. The specific conductivity in 2004, though, reflected the wetter conditions that existed after 1980 that improved the overall water quality. Much like the 2004 samples, the 2006 specific conductivity value reflected the wetter conditions that existed after 1980, although the chloride concentration increased to 54.9 mg/L with a resultant CI of 0.03, approaching the lower limit indicative of brine contamination. The variation in chloride concentrations seen at Mallard Pond is likely the result of regional influences.

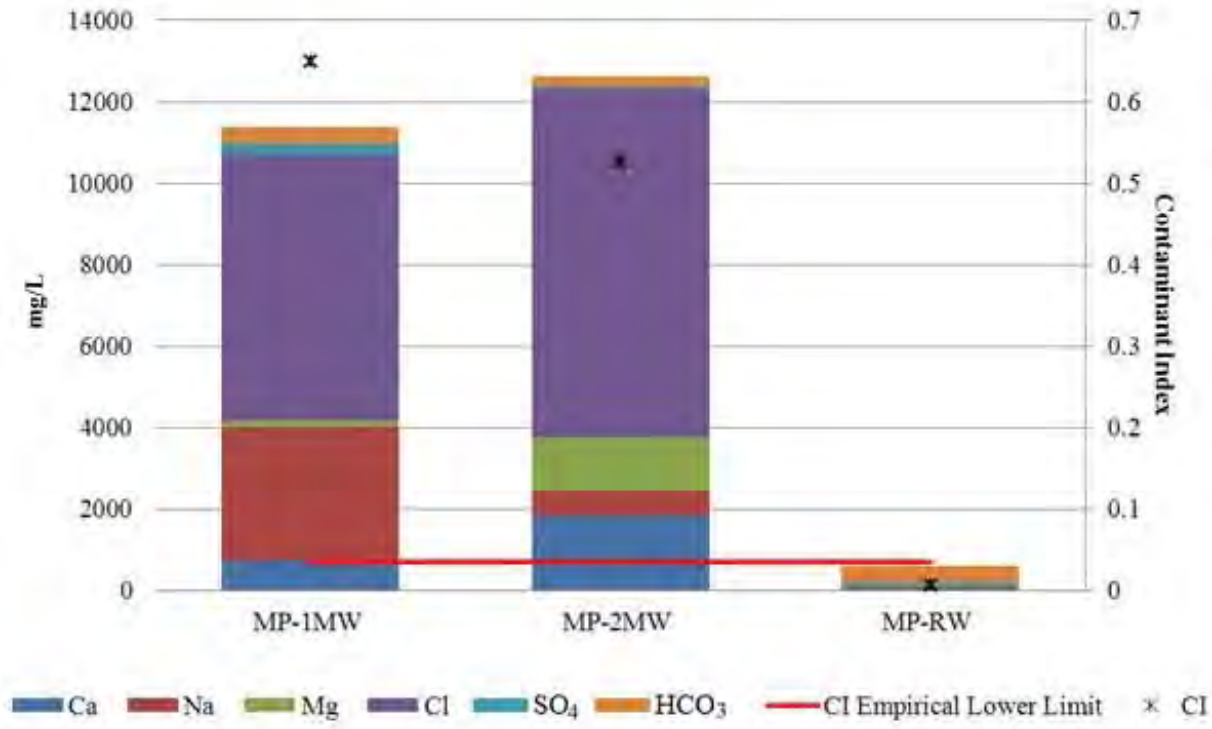


Figure 46. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within the Mallard Pond WPA during 2005.

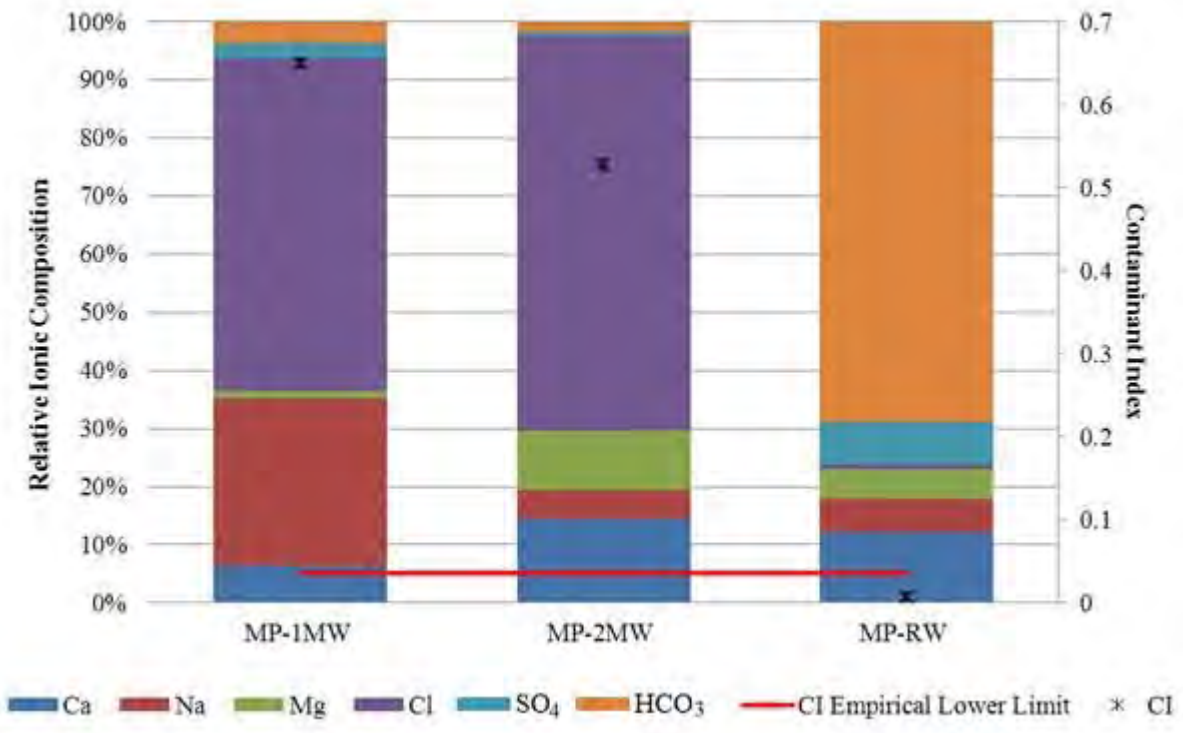


Figure 47. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within the Mallard Pond WPA during 2005.

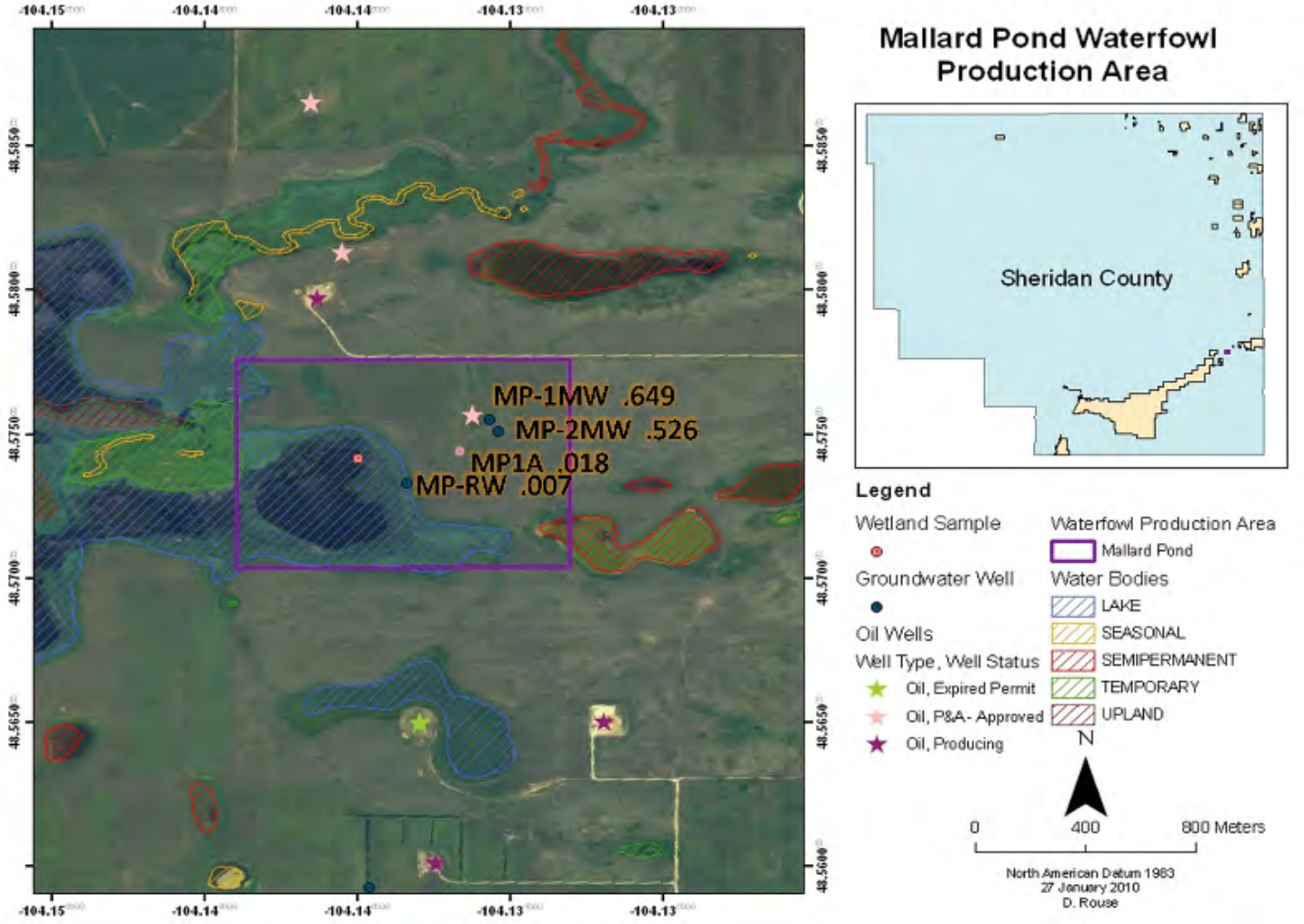


Figure 48. Distribution of the mean chloride contamination index measured in wells and wetlands associated with the Mallard Pond WPA: T. 33 N., R. 58 E., sec. 33.

*Co-occurring Contaminants*

Inorganic analyses were completed on samples taken from the wetland MP1A and the three monitoring wells MP-1MW (GWIC ID 221735), MP-2MW (GWIC ID 221704), and MP-RW (GWIC ID 161782). Numerous trace elements were detected in the wetland sample, as well as the groundwater samples. For surface water, zinc exceeded EPA's national recommended water-quality criteria (table 21). The relationship between surface-water zinc concentrations and the CI was not formally assessed due to the large number of values below the analytical detection level (table 7), but there does appear to be a slight positive relationship with groundwater zinc concentrations and the CI (table 5). Regardless, EM-31 surveys and groundwater surveys provide evidence that there is little to no interaction between the MP1A wetland sample and the brine plume present within the WPA. This does not account for other interactions that occur between the lake and neighboring surface-water bodies that may be intermittently connected. Nevertheless, it is difficult to determine the influence that oil production activities may have had on the present zinc concentration detected at MP1A, but zinc is often considered a commonly occurring trace element in produced waters (Stephenson, 1992; Jacobs and others, 1992). Many species respond differently to elevated zinc levels and there are numerous interactions that may influence zinc toxicity, but effects have been reported for various species including some plants, macroinvertebrates, and amphibians at concentrations less than the concentration detected at MP1A (Eisler, 1993).

When groundwater concentrations were compared to the Montana numerical water-quality standards for human health in groundwater, sites MP-2MW (GWIC ID 221704) and MR-RW (GWIC ID 161782) had exceedances for arsenic, and sites MP-1MW (GWIC ID 221735) and MP-2MW (GWIC ID 221704) had exceedances for strontium (table 21). There does not appear to be a relationship between arsenic and the CI, suggesting that the elevated arsenic concentrations detected at MP-RW (GWIC ID 161782) and MP-2MW (GWIC ID 221704) are from some other source (table 5). Conversely, there is a significant positive

Table 19. Specific conductivity and CI of 1:1 (by weight) aqueous leachates of soil samples at different depths in the Mallard Pond WPA.

| Depth (ft.) | Soil Property | MP-1MW | MP-2MW |
|---|---|---|---|
| 0–3 | SC (µS/cm) | 7,270 | 265 |
| | CI | 0.209 | NA |
| 3–8 | SC (µS/cm) | 4,460 | 261 |
| | CI | 0.238 | NA |
| 8–13 | SC (µS/cm) | 8,720 | 638 |
| | CI | 0.316 | 0.174 |
| 13–18 | SC (µS/cm) | 7,130 | 2,220 |
| | CI | 0.294 | 0.284 |
| 18–23 | SC (µS/cm) | 7,420 | 8,970 |
| | CI | 0.306 | 0.350 |
| 23–28 | SC (µS/cm) | 3,240 | 5,010 |
| | CI | 0.310 | 0.330 |
| 28–33 | SC (µS/cm) | 787 | 2,410 |
| | CI | 0.241 | 0.317 |
| 33–38 | SC (µS/cm) | 4,530 | 3,820 |
| | CI | 0.310 | 0.287 |

*Note.* NA, data not available.

Table 20. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Mallard Pond WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| MP1A | 8/25/1990 | 2,590 | 26 | 0.010 | Oligosaline |
| MP1A | 4/27/2004 | 1,049 | 24 | 0.023 | Oligosaline |
| MP1A | 9/12/2004 | 1,194 | 16 | 0.014 | Oligosaline |
| MP1A | 9/16/2005 | 1,650 | 55 | 0.033 | Oligosaline |

Table 21. Surface-water and groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells and wetland of the Mallard Pond WPA in 2005.

| | Groundwater | | | Surface Water |
|---|---|---|---|---|
| | MP-1MW | MP-2MW | MP-RW | MP1A |
| Al | <50 | <50 | <50 | <50 |
| As | 3.21 | 13.3* | 13.8* | 4.39 |
| B | 8,560 | 90 | 106 | 562 |
| Ba | 640 | 3,440 | 545 | 12 |
| Be | <0.5 | <0.5 | <0.5 | <0.5 |
| Cd | 2.16 | 1.79 | 0.08 | 0.03 |
| Co | <5 | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 | <0.1 |
| Mo | <10 | <10 | 10 | <10 |
| Ni | 17 | <5 | <5 | <5 |
| Pb | <0.05 | <0.05 | 0.12 | 0.05 |
| Se | 2.26 | 2.8 | 0.14 | 0.16 |
| Sr | 15,000* | 6,930* | 240 | 95 |
| Ti | 9 | 24 | <5.00 | <5 |
| V | <10 | <10 | <10 | <10 |
| Zn | <5 | 7 | <5 | 11# |

*Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

#Indicates value exceeded EPA's recommended national water-quality criteria.

Table 22. Concentrations (mg/kg DW) of hydrocarbon fractions from the soil sample collected in 2006 within the Mallard Pond WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| Carbon Range | TPHCWG[1] (mg/kg/day) | MADEP[2] (mg/kg/day) | MP-1S (mg/kg) |
| **Aliphatic** | | | |
| C9–C18 | 0.10 | 0.10 | 0.248 |
| C19–C32 | 2.00 | 2.00 | 0.518 |
| **Aromatic** | | | |
| C9–C16 | 0.04 | 0.03 | 0 |
| C17–C32 | 0.03 | 0.03 | 0.003 |

[1]Total Petroleum Hydrocarbon Criteria Working Group (Gustafson and others, 1997).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

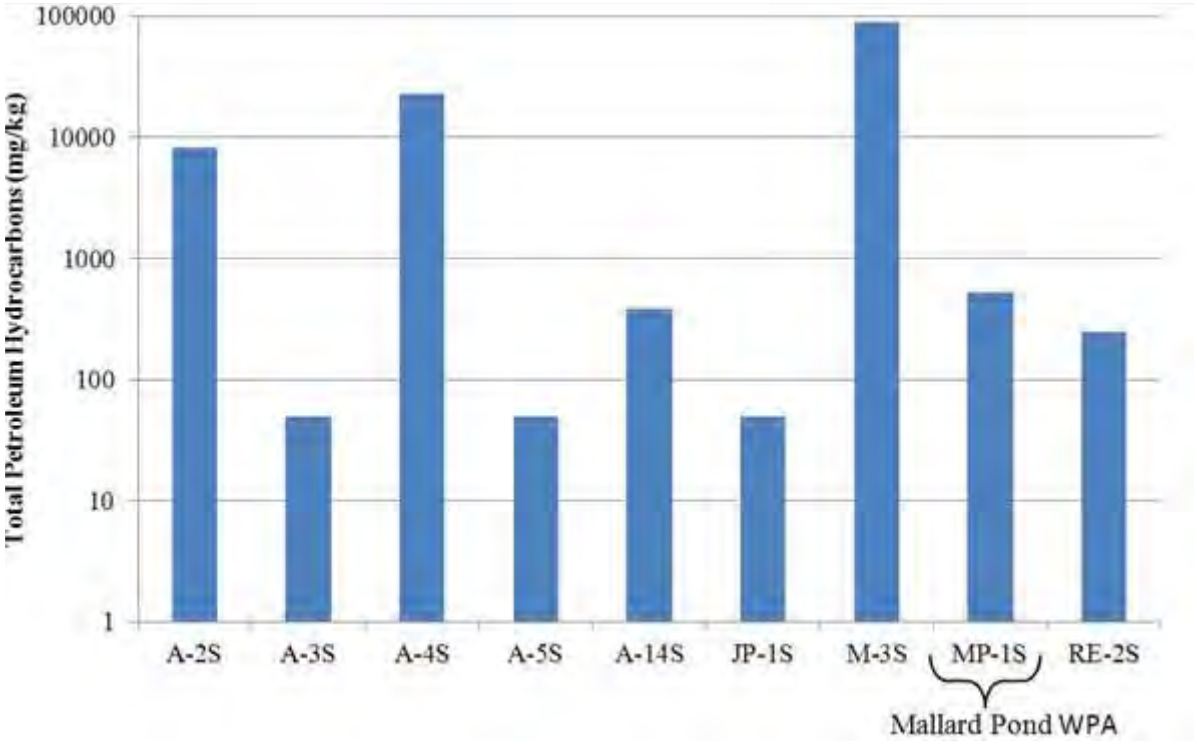


Figure 49. Concentrations (mg/kg DW) of total petroleum hydrocarbons from soil samples collected across the Northeast Montana WMD in 2005 with the site located in the Mallard Pond WPA bracketed.

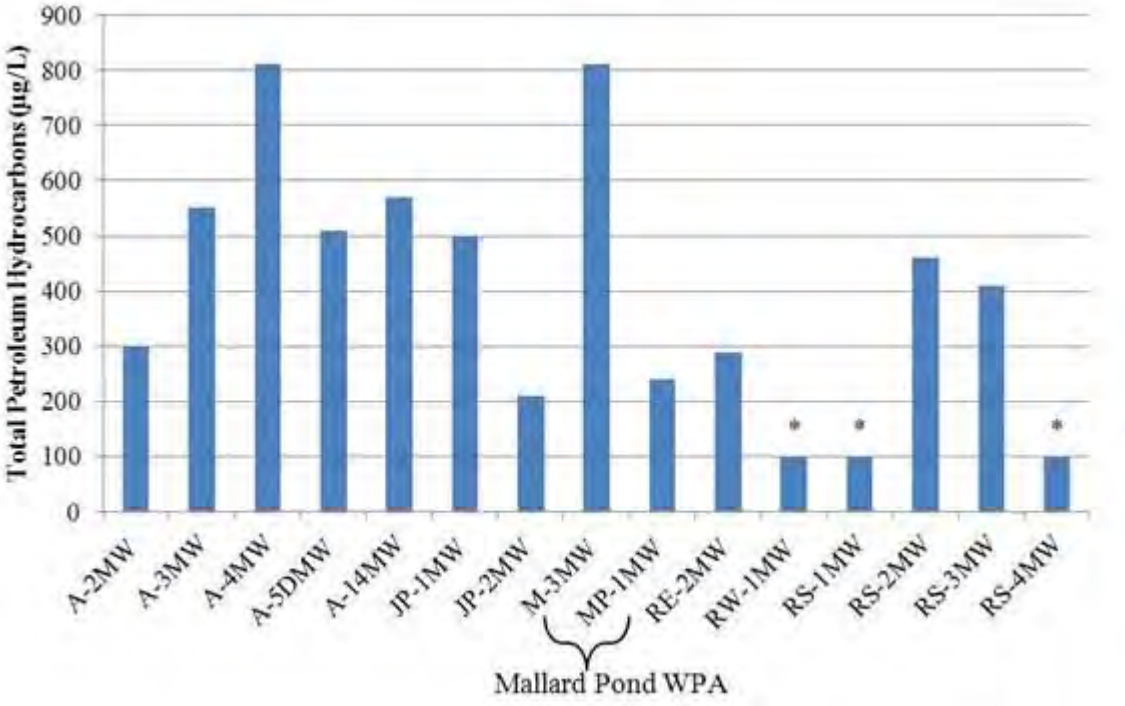


Figure 50. Concentrations (µg/L) of total petroleum hydrocarbons from groundwater samples collected across the Northeast Montana WMD in 2005 with the site located in the Mallard Pond WPA bracketed. *Indicates concentration is below the analytical detection limit of 100 µg/L.

relationship between the CI and groundwater strontium concentrations (table 5). Strontium is a commonly detected element in produced waters (Stephenson, 1992). The concentrations detected in MP-1MW (GWIC ID 221735) and MP-2MW (GWIC ID 221704) are at levels that could elicit a toxicological response (Matz and Rocque, 1997), but the exposure pathway is largely confined to the groundwater systems in which it was detected, rendering this element unavailable to many organisms.

One soil sample, MP-1S, was collected in 2005 for total petroleum hydrocarbon analysis. This sample had a total petroleum hydrocarbon concentration of 524 mg/kg (DW) (fig. 49). In 2006, another grab sample were taken at MP-1S and was analyzed for aliphatic and polynuclear aromatic hydrocarbons. Hydrocarbon fractions from 2006 were then compared to established toxic benchmark values. Only the C9–C18 aliphatic fraction exceeded a benchmark value (table 22). The toxicity criteria used to assess toxicity were developed to be protective of human health, and as they do serve as a useful frame of reference, the concentrations present in the soil at MP-1S will have little impact on wildlife. In 2005, one groundwater sample was collected from MP-1MW (GWIC ID 221735) and analyzed for total petroleum hydrocarbons. Total petroleum hydrocarbons were present at a concentration of 240 µg/l (fig. 50). There were no further organic analyses done for MP-1MW (GWIC ID 221735). It appears that oil production activities have contaminated groundwater with petroleum hydrocarbons, but at levels that will unlikely produce a significant toxicological impact to wildlife.

## Northeast WPA

The Northeast WPA was established on 7/17/1968, although additional land purchases were made until 8/11/1969. Currently, the Northeast WPA includes an area of 218.5 acres with multiple wetlands (fig. 51). Bird surveys have documented the use of the Northeast WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no oil wells present within the WPA, but four are located in close proximity. Wells 05173 and

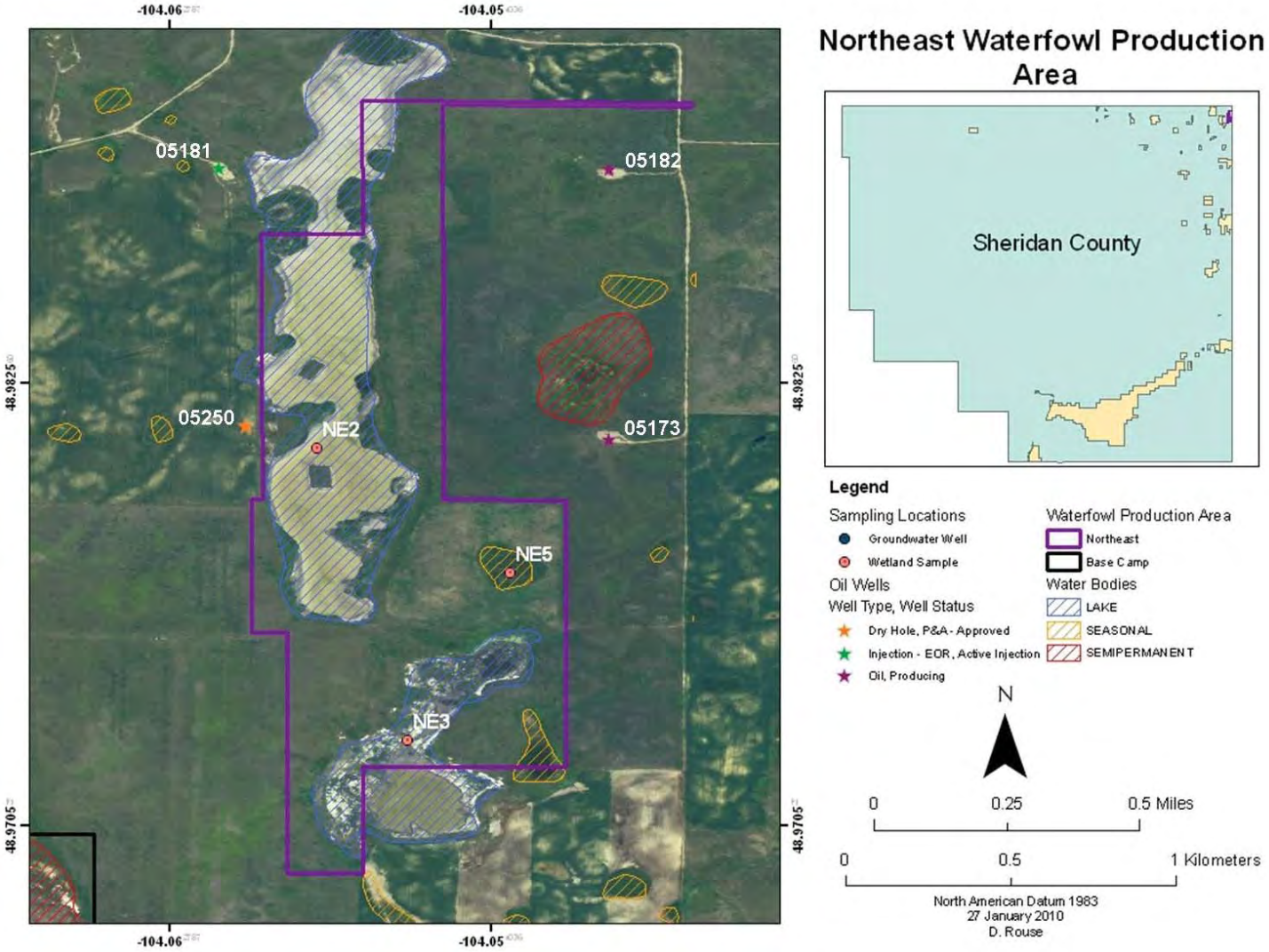


Figure 51. Map depicting locations of sampling sites, oil wells, and bodies of water for the Northeast WPA: T. 37 N., R. 58 E., sec. 3 & 10.

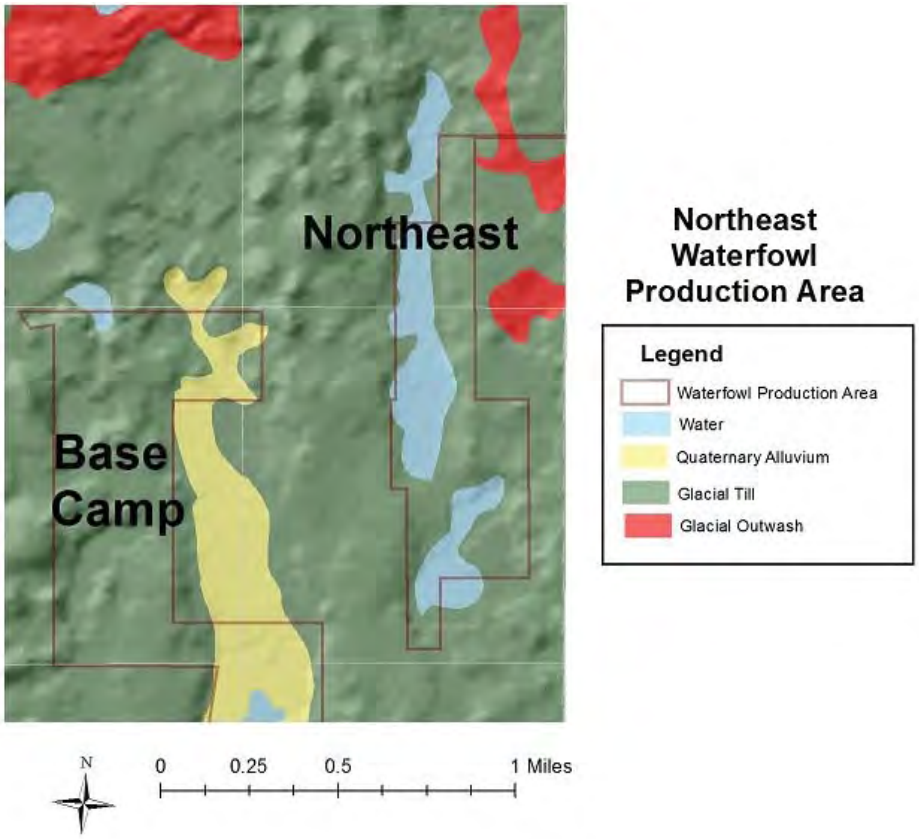


Figure 52. Geology of the Northeast WPA: T. 37 N., R. 58 E., sec. 3 & 10.

05182 are both oil-producing wells that were completed in November 1965 and August 1965, respectively. Well 05250 is an approved plugged and abandoned dry hole that was completed in December 1965 and well 05181 is an active injection EOR well that was completed in July 1965.

### *Geology*

The surficial geology underlying the Northeast WPA is depicted in figure 52. Most of the Northeast WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft. A relatively long and narrow deposit of moderate to high-permeability alluvium is mapped trending north to south through the central part of the Northeast WPA.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Northeast WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. No regional glacial outwash aquifers have been identified in this area.

### *Characterizing Oil Field Production Brine Migration*

EM surveys were not conducted at this site and no monitoring wells were established.

### *Wetland Water Quality*

Three wetlands were sampled, two of which, NE3 and NE5, were dry. For NE2, the specific conductivity was around 94,000 µS/cm and the chloride concentration was 5,179 mg/L (table 21). Based on the CI value for NE2, chloride impacts (CI >0.035) were evident. Further investigations, such as EM-31 surveys and groundwater monitoring, would be required to determine the source of contamination for NE2.

### *Co-occurring Contaminants*

There were no additional analyses done for the Northeast WPA.

## North Root WPA

The North Root WPA was established on 6/19/1988 and contains an area of 320 acres (fig. 53). Bird surveys have documented the use of the North Root WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile in the eastern half of the WPA and 20–42 duck pairs per square mile in the western half during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, well 05101, an active injection EOR well completed in February 1965, was the only well present within the WPA. Well 05091, an approved plugged and abandoned dry hole completed in March 1965, is located just south of the WPA (fig. 53).

### *Geology*

The surficial geology underlying the North Root WPA is depicted in figure 54. Most of the North Root WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft. A deposit of moderate to high-permeability glacial outwash underlies the western part of this WPA in the vicinity of mapped oil field location 05101.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the North Root WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetland to the west of the site. No regional glacial outwash aquifers have been identified in this area.

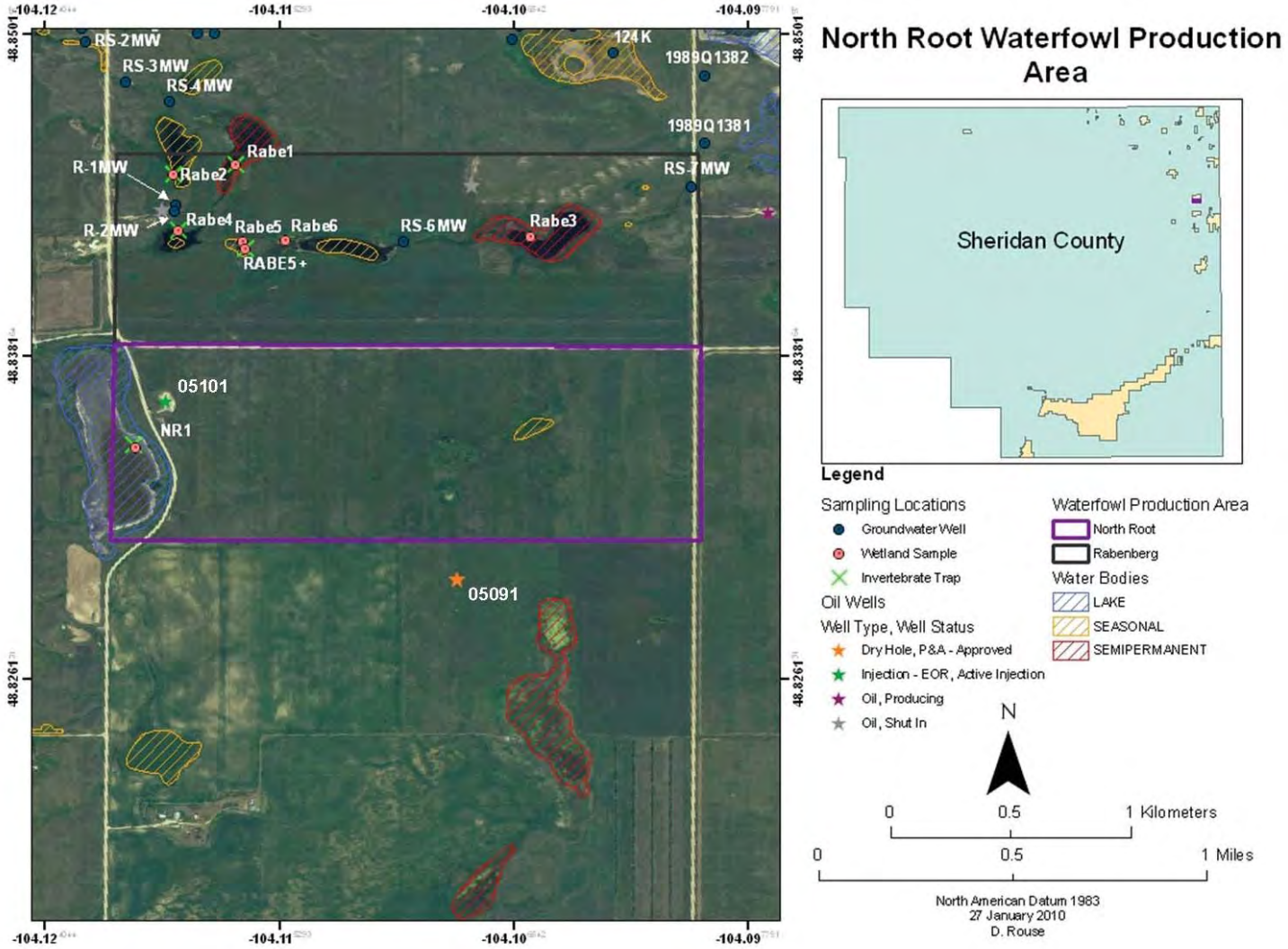


Figure 53. Map depicting locations of sampling sites, oil wells, and bodies of water for the North Root WPA: T. 36 N., R. 58 E., sec. 34.

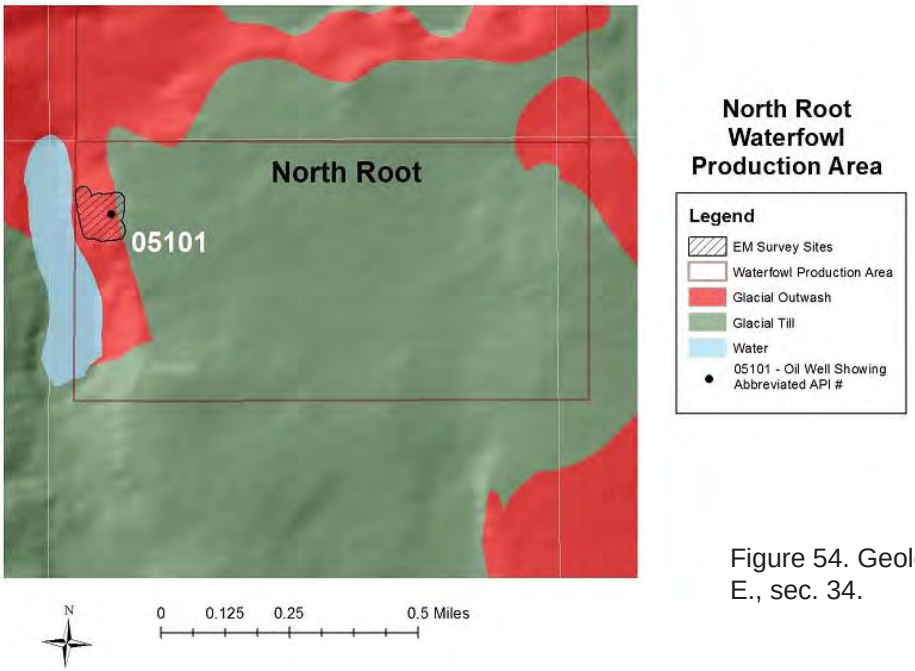


Figure 54. Geology of the North Root WPA: T. 36 N., R. 58 E., sec. 34.


Figure 55. Location of EM-31 terrain-conductivity surveys conducted at the North Root WPA: T. 36 N., R. 58 E., sec. 34.

### *Characterizing Oil Field Production Brine Migration*

EM terrain conductivity surveys indicated higher than background readings in an area west of oil well location 05101 (fig. 55). The area of high conductivity closest to the well is likely the location of a reserve pit, while the other elevated areas show a plume migrating downslope ending along the county road. There are no groundwater wells associated with this site to characterize groundwater chemistry.

### *Wetland Water Quality*

One surface-water location, NR1, was sampled and had an average specific conductivity of 24,731.5 µS/cm and an average chloride concentration of 3067.5 mg/L. Based on the average CI value for NR1, 0.121, chloride impacts (CI >0.035) were evident. Based on the EM-31 survey, it appears that a brine plume is moving offsite and is impacting NR1. Additionally, several flow lines and produced water lines have been observed along the shoreline of the NR1 wetland. These may serve, or have served, as a contaminant source to the wetland through leaks or spills that may have occurred over time.

### *Co-occurring Contaminants*

There were no additional analyses done for the North Root WPA.

## Big Slough WPA

The Big Slough WPA was established on 12/20/1968, with additional land acquired on 12/30/1968 and 4/16/1969, ultimately encompassing an area of approximately 850 acres. Multiple water bodies are located within the WPA, including lakes, semi-permanent, seasonal, and temporary wetlands (fig. 56). Bird surveys have documented the use of the Big Slough WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, there is designated Piping Plover critical habitat located in the Big Slough WPA. Much of the upland habitat is managed as dense nesting cover through selective planting, prescribed haying, prescribed fire, and limited grazing. As of January 2010, well 05056, an approved plugged and abandoned dry hole completed in September 1964, was the only well within the WPA. However, numerous wells, including an unapproved plugged and abandoned dry hole, approved plugged and abandoned dry wells, and a producing oil well were all located in close proximity to the WPA boundary (fig. 56).

### *Geology*

The Big Slough WPA is located near the western edge of a major glacial outwash deposit (fig. 57). The entire WPA is underlain by glacial outwash deposits. These deposits are estimated to be from 50 to 150 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlies the glacial materials. Quaternary alluvial and lacustrine deposits are located underlying relatively small areas of the Big Slough WPA and are associated with swales and lowlands along wetlands and lakes.

### *Groundwater Hydrology*

The Big Slough WPA overlies the Clear Lake aquifer. Several highly productive irrigation wells are located within 1 mile to the south and east of the WPA. Flow in the aquifer is generally towards the south or southwest. There is a good potential for groundwater flow to be from oil well location 05056 towards nearby wetlands.

### *Characterizing Oil Field Production Brine Migration*

EM-31 terrain conductivity surveys indicated higher than background readings in an area north of oil well location 05056 (fig. 58). These appear to be related to well construction activities, and based on the date of well construction, may reflect the location of a historic unlined reserve pit. Among the four monitoring wells sampled, specific conductance ranged from around 1,600 to 8320 µS/cm and chloride concentrations ranged from 14.7 to 2,094 mg/L.

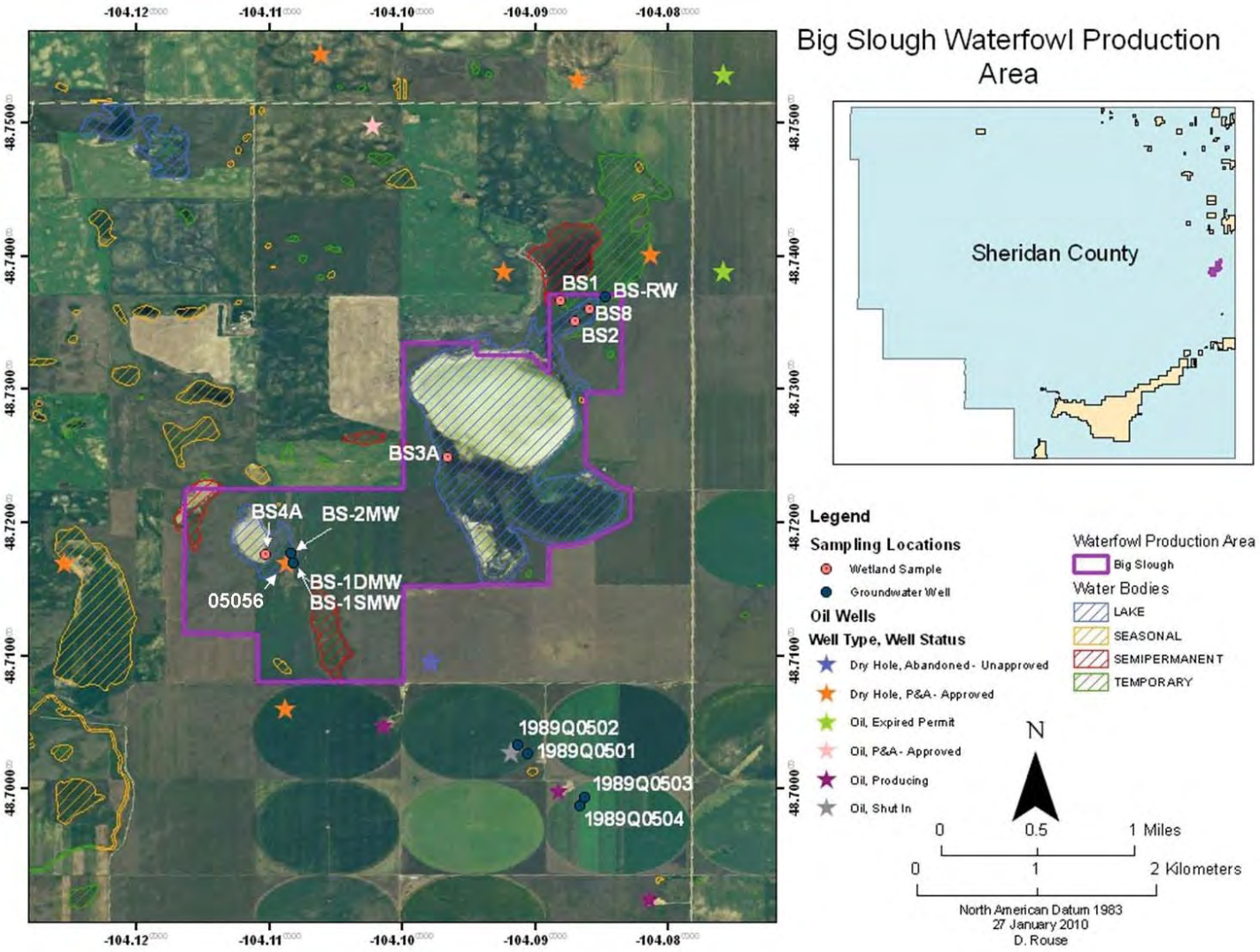


Figure 56. Map depicting locations of sampling sites, oil wells, and bodies of water for the Big Slough WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

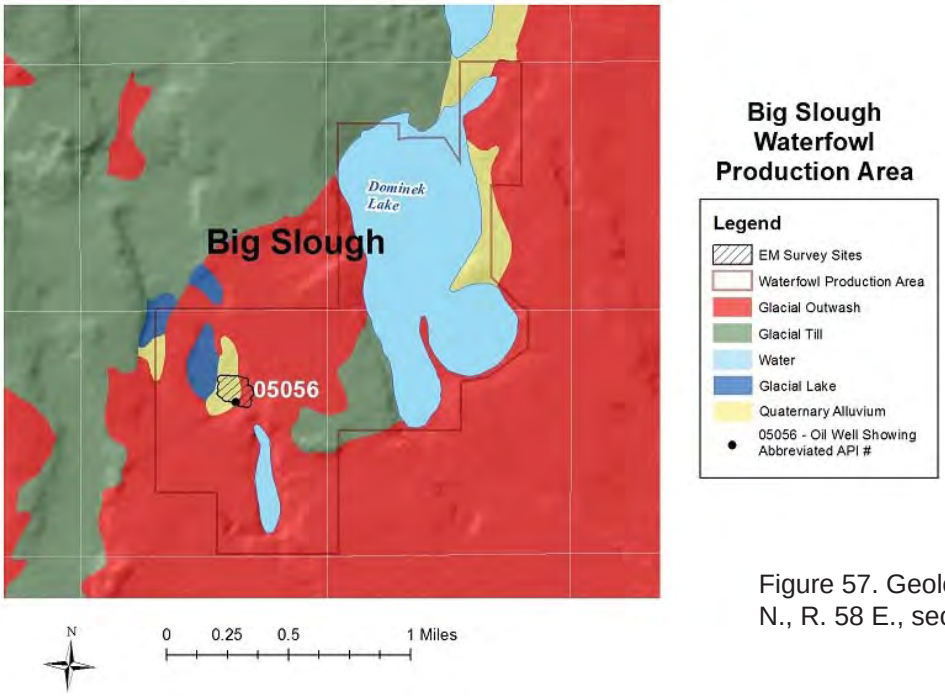


Figure 57. Geology of the Big Slough WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

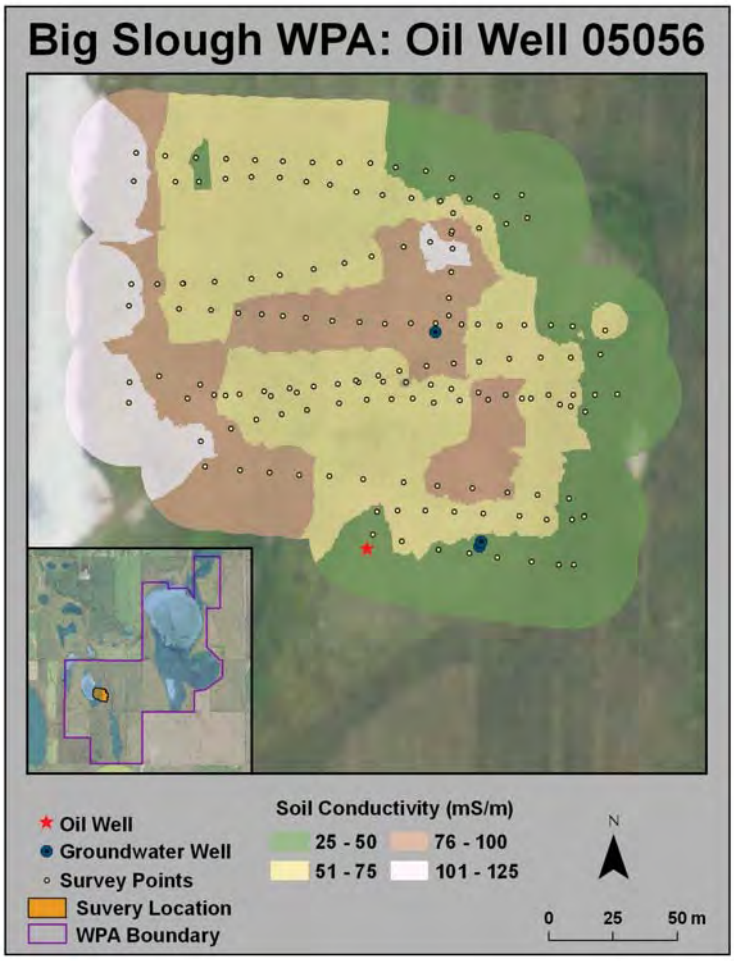


Figure 58. Location of EM-31 terrain-conductivity surveys conducted at the Big Slough WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

As indicated by the calculated CI values from the well samples, produced water impacts were evident at sites BS-1DMW (GWIC ID 221706), BS-1SMW (GWIC ID 221736), and BS-2MW (GWIC ID 221689). The ionic concentrations (fig. 59) and compositions (fig. 60) of groundwater samples taken from wells BS-1DMW (GWIC ID 221706), BS-1SMW (GWIC ID 221736), and BS-2MW (GWIC ID 221689) are less indicative of brine impacts than other groundwater sites sampled in the Northeast Montana WMD, which are typically more clearly dominated by Cl- ions. Rather, impacted well sites in the Big Slough WPA show only a slight displacement of naturally dominant ions, like HCO3-, by Cl- ions, although impacts are more clearly seen in BS-2MW (GWIC ID 221689). In agreement with the EM-31 survey, it appears that wells BS-1DMW (GWIC ID 221706) and BS-1SMW (GWIC ID 221736) are along the edge of the brine plume, while BS-2MW (GWIC ID 221689) is situated in a more concentrated, highly impacted area. Although no EM-31 surveys were conducted surrounding BS-RW (GWIC ID161785), this site appears to reflect background groundwater conditions.

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at the monitoring well drilling sites of BS-1DMW and BS-2MW, and leachates were analyzed for specific conductance and chlorides (table 23). Impacts are evident at both sites based on the elevated CI values, although the distribution of ions between the soil profiles differs. For instance, specific conductance, including the contribution of chlorides, was more pronounced at depths greater than 8 ft at BS-1DMW, while surficial impacts were evident at BS-2MW. Hyrdogeologic differences between the two sites, as well as proximity to

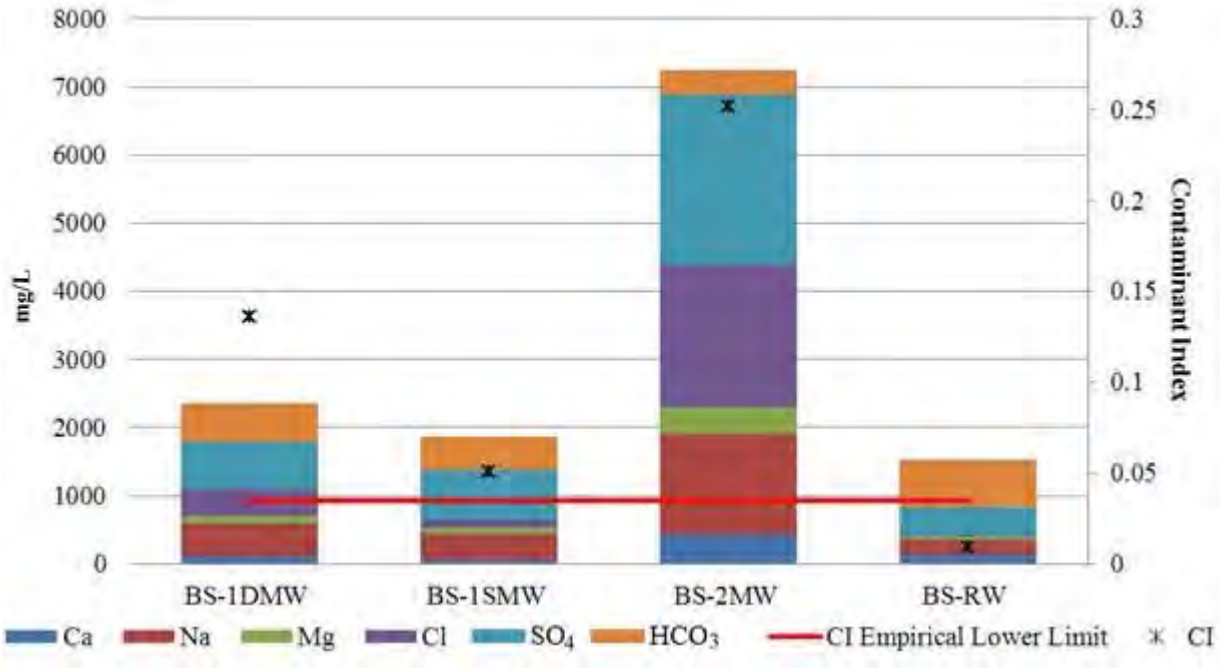


Figure 59. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within the Big Slough WPA during 2005.

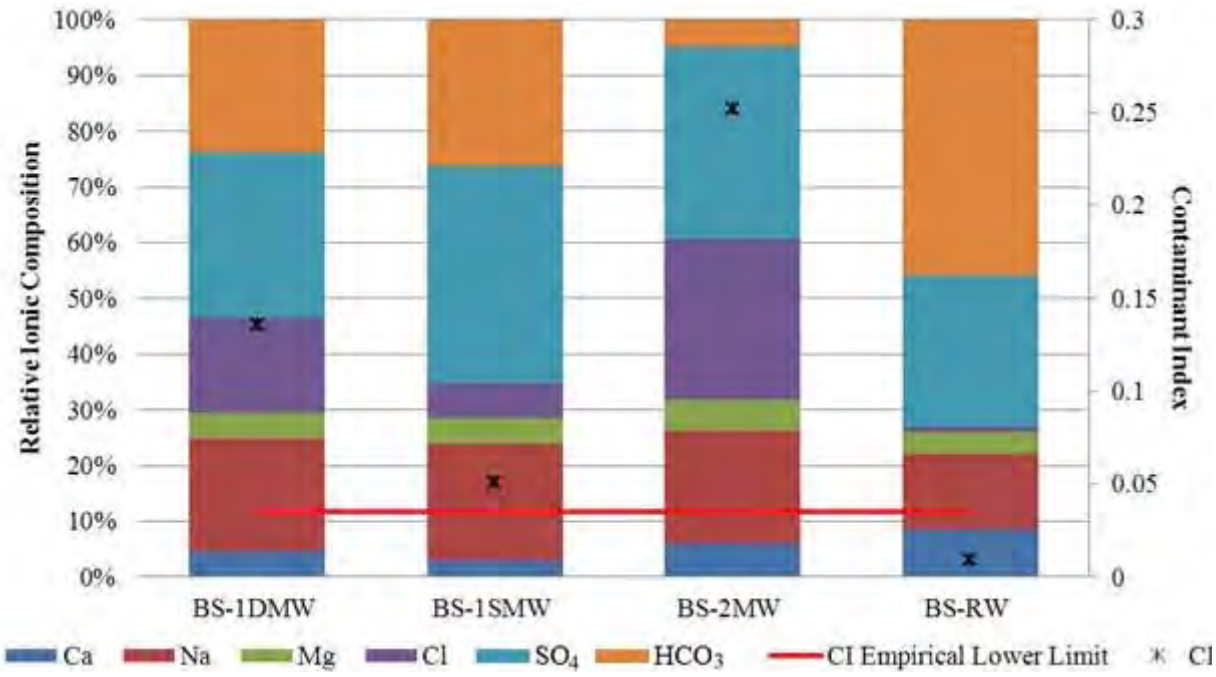


Figure 60. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within Big Slough WPA during 2005.

the contaminant source, may explain the differences seen between these two sites. For example, BS-1DMW is more representative of glacial outwash, with unequal distributions of ions reflecting the permeability and transmissivity of these deposits, while BS-2MW, located in alluvium, is exhibiting elevated near-surface concentrations due to evaporative concentration effects. Furthermore, EM-31 surveys show areas of high terrain conductivity closer to BS-2MW, where brine or brine-saturated materials were either spilled or buried.

### *Wetland Water Quality*

Among the five wetlands sampled, specific conductance ranged from around 1,700 to 34,000 µS/cm and chloride concentrations ranged from 16 to 1,198 mg/L (table 24). Based on the CI values for the Big Slough WPA, there was only one site, BS4A, displaying chloride impacts. The results from the EM-31 surveys conducted onsite and the groundwater analyses suggest that past oil production and exploration activities are likely impacting BS4A though brine contamination.

### *Co-occurring Contaminants*

Analyses for co-occurring contaminants were not conducted for wetlands, but were completed on samples taken from every groundwater monitoring well. When compared to the Montana numerical water-quality standards for human health in groundwater, there were no constituents that exceeded any benchmark value (table 25).

Table 23. Specific conductivity and CI of 1:1 (by weight) aqueous leachates of soil samples at different depths in the Big Slough WPA.

| Depth (ft) | Soil Property | BS-1DMW | BS-2MW |
|---|---|---|---|
| 0-3 | SC (µS/cm) | 479 | 7,750 |
| | CI | NA | 0.113 |
| 3-8 | SC (µS/cm) | 630 | 3,300 |
| | CI | 0.044 | 0.138 |
| 8-13 | SC (µS/cm) | 3,040 | NA |
| | CI | 0.185 | NA |
| 13-18 | SC (µS/cm) | 1,147 | NA |
| | CI | 0.121 | NA |

*Note.* NA, data not available.

Table 24. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Big Slough WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| BS1 | 5/15/2004 | 2,216 | 32 | 0.014 | Oligosaline |
| BS2 | 5/15/2004 | 1,768 | 16 | 0.009 | Oligosaline |
| BS3A | 5/15/2004 | 8,834 | 222 | 0.025 | Mesosaline |
| BS4A | 5/15/2004 | 34,017 | 1,198 | 0.035 | Polysaline |
| BS8 | 5/15/2004 | 4,616 | 109 | 0.024 | Oligosaline |

Table 25. Groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Big Slough WPA in 2005.

| | Groundwater | | | |
|---|---|---|---|---|
| | BS-1DMW | BS-1SMW | BS-2MW | BS-RW |
| Al | <50 | <50 | <50 | <50 |
| As | 1.06 | 1.03 | 1.57 | 11.3 |
| B | 284 | 272 | 1450 | 439 |
| Ba | 91 | 12 | 77 | 35 |
| Be | <0.5 | <0.5 | <0.5 | <0.5 |
| Cd | 0.06 | 0.12 | 0.14 | 0.02 |
| Co | <5 | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 | <0.1 |
| Mo | <10 | 10 | <10 | <10 |
| Ni | <5 | <5 | <5 | <5 |
| Pb | <0.01 | 0.02 | <0.05 | <0.01 |
| Se | 2.72 | 3.6 | 0.49 | <0.1 |
| Sr | 670 | 445 | 3,240 | 1,140 |
| Ti | <5 | <5 | 6 | <5 |
| V | <10 | <10 | <10 | <10 |
| Zn | <5 | <5 | 8 | <5 |

## Rabenberg WPA

The Rabenberg WPA encompasses an area of approximately 320 acres. Multiple bodies of water are located in, or partially located in, the WPA, including seasonal and semi-permanent wetlands (fig. 61). Bird surveys have documented the use of the Rabenberg WPA by breeding bird pairs, with observations of 42–88 duck pairs per square mile in the eastern half of the WPA and 20–42 duck pairs per square mile in the western half during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, API wells 05105 and 21056, two shut-in oil wells completed in September 1965 and November 1968, respectively, were located within the WPA. Furthermore, one producing oil well was located within 700 ft east of the WPA, a shut-in oil well was located within 1,000 ft of the western WPA boundary, and a tank battery and producing oil well were located just over a quarter of a mile north of the northwestern corner of Rabenberg WPA (fig. 61). A slough located downslope of the tank battery creates a surface-water pathway for contaminants from the tank battery to the refuge. An expanded report detailing oil and gas impacts identified at the Goose Lake Oil Field, including Rabenberg WPA, is found in appendix A.

### *Geology*

The Rabenberg WPA is underlain by collapsed glacial

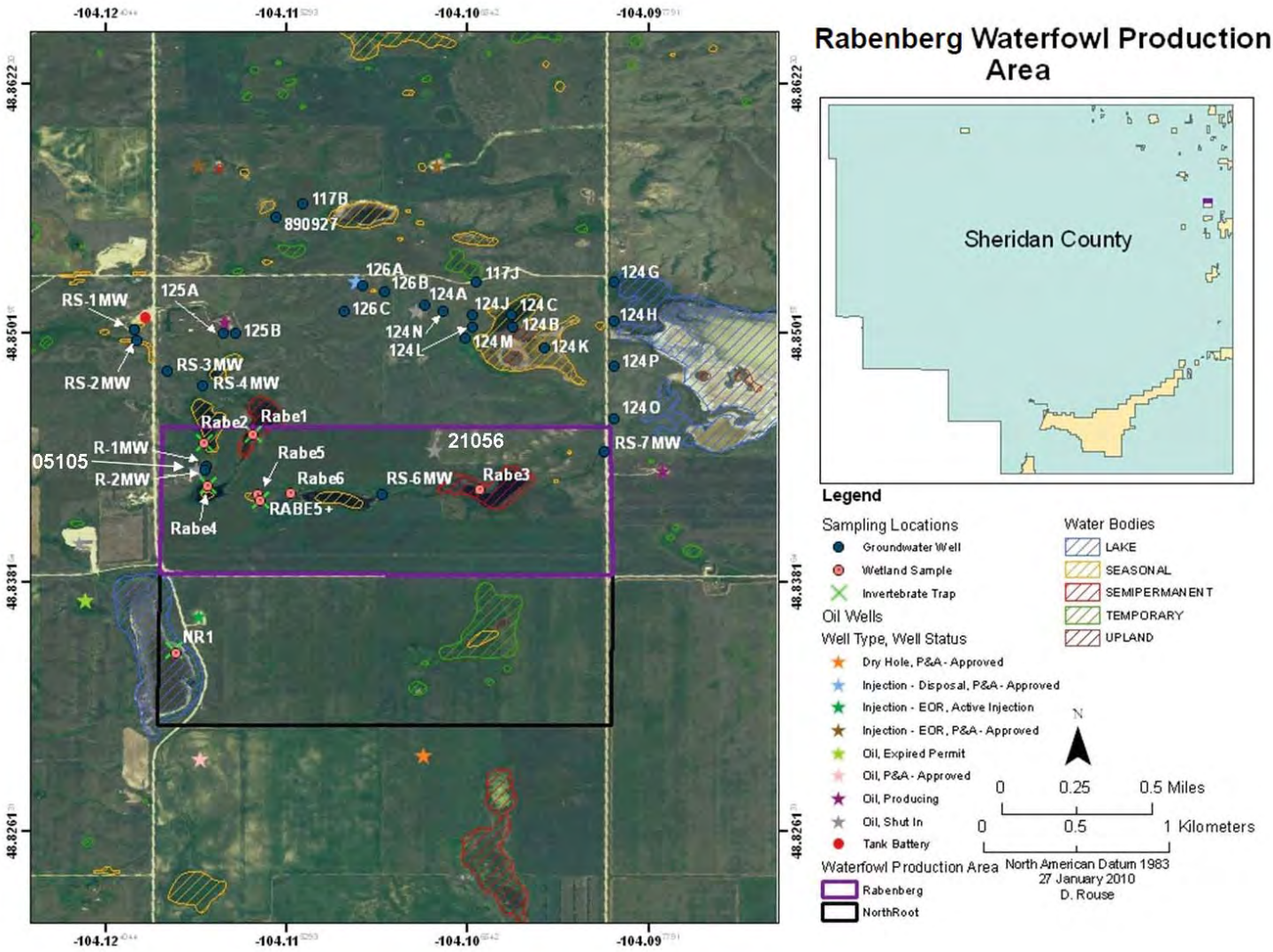


Figure 61. Map depicting locations of sampling sites, oil wells, and bodies of water for the Rabenberg WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

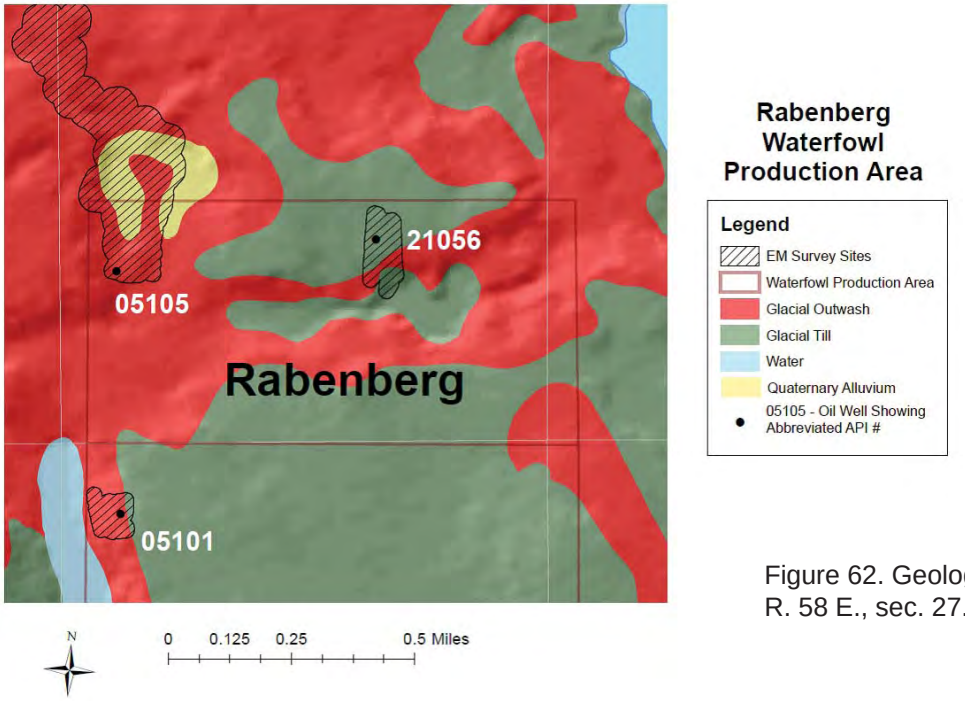


Figure 62. Geology of the Rabenberg WPA: T. 36 N., R. 58 E., sec. 27.

outwash overlying glacial till (fig. 62). These sediments overlie sandstone and mudstone of the Fort Union Formation. The depth to bedrock has not been clearly defined, but is estimated at 50 to 100 ft below land surface. Details of the near-surface geology are expanded in Appendix A.

### *Groundwater Hydrology*

The Rabenberg WPA overlies a tributary to the Clear Lake aquifer. Flow in the aquifer is generally towards the east or southeast. Groundwater flows towards a western extension of Goose Lake near the eastern boundary of the WPA. Details of groundwater flow are expanded in the Goose Lake report in Appendix A that also compares results of the 1989 sampling to samples collected from the same wells in 2006.

### *Characterizing Oilfield Production Brine Migration*

EM surveys were conducted in three separate locations within and directly outside of the WPA boundaries (fig. 63). For instance, surveys conducted at site 1 characterized an area of elevated apparent terrain conductivity associated with the tank battery just north of the northwest corner of the WPA (fig. 64). Surface salt scars from historic improper disposal of produced water are apparent along the slough on the west side of the road, and historic photos show the presence of a produced water pit just upslope of the slough. Surveys conducted at site 2 characterized another area of elevated apparent terrain conductivity associated with the oil well 05105 that appears to extend northward into the slough area (fig. 65). Based on the drilling date for well 05105, the reserve pit associated with this well would have been unlined. Last, surveys conducted at site 3 identified areas of elevated apparent terrain conductivity associated with oil well 21056 (fig. 66), but less extensive than at sites 1 and 2. This well would have also had an unlined reserve pit associated with it based on its drilling date.

Four monitoring wells are located within the WPA, but numerous wells are located in close proximity to the WPA as well. However, only six wells outside the WPA have been sampled within the past 10 years. These include those wells located in Rabenberg Slough—RS-1MW (GWIC ID 890940), RS-2MW (GWIC ID 890445), RS-3MW (GWIC ID 890446), and RS-4MW (GWIC ID 890939), which are northwest and upslope of the WPA—as well as two MBMG research wells, 124K (GWIC ID 220937) and 124B (GWIC ID 220932), located north of the eastern portion of the WPA. Of the wells sampled within 10 years, including

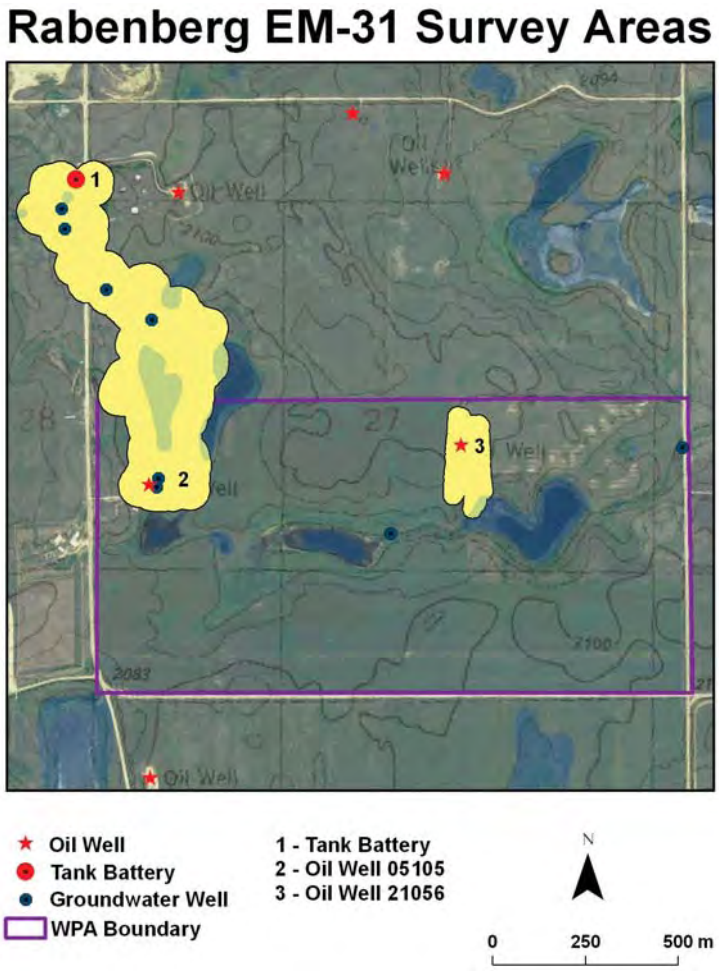


Figure 63. Location of EM-31 terrain-conductivity surveys conducted at the Rabenberg WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

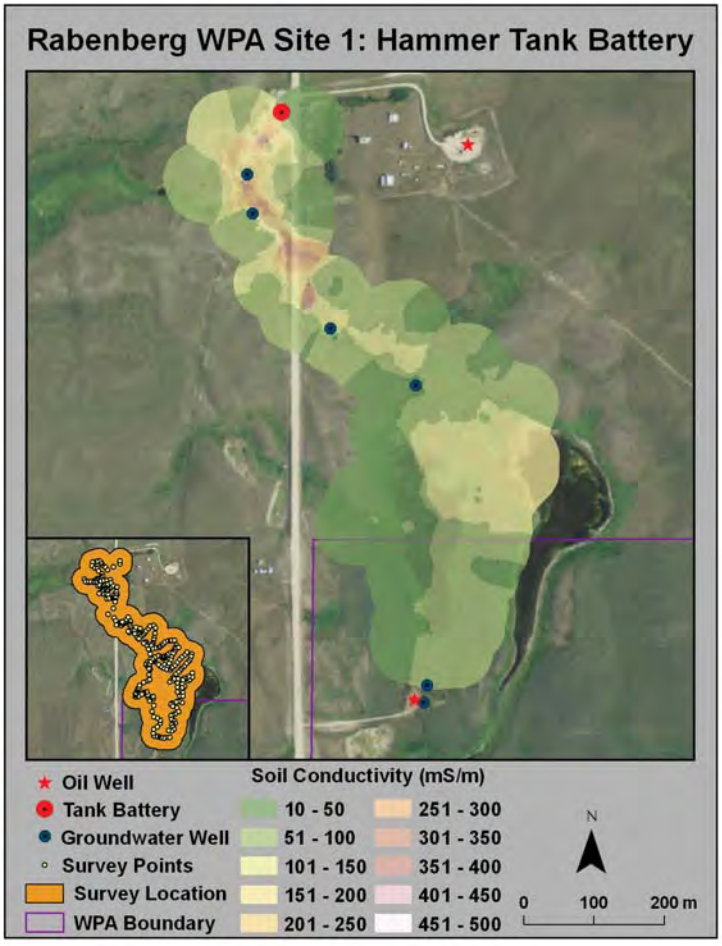


Figure 64. Location of EM-31 terrain-conductivity survey conducted at Site 1 of the Rabenberg WPA.

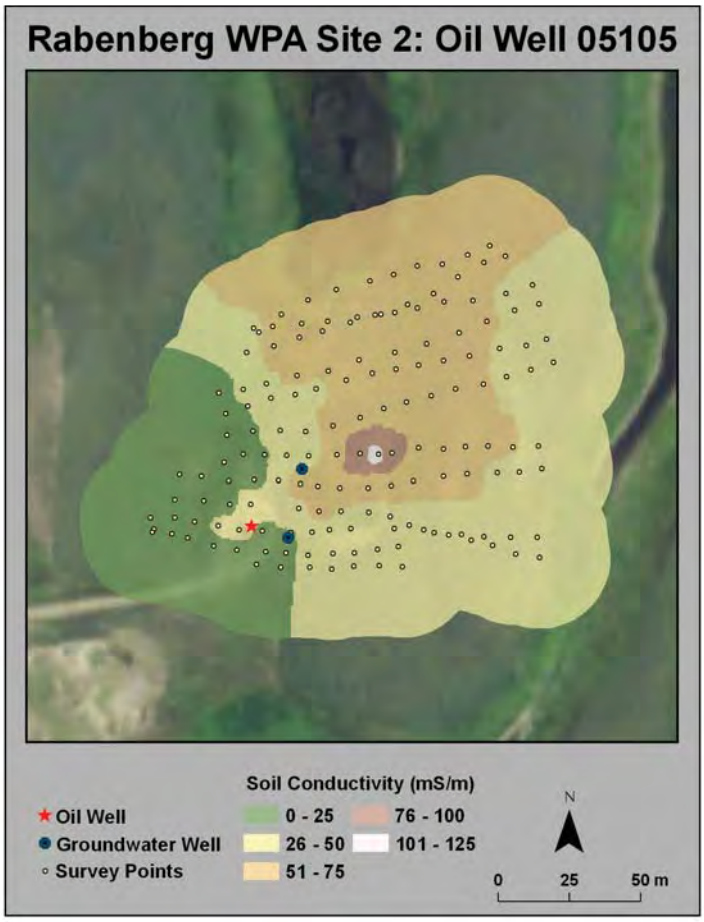


Figure 65. Location of EM-31 terrain-conductivity survey conducted at Site 2 of the Rabenberg WPA.

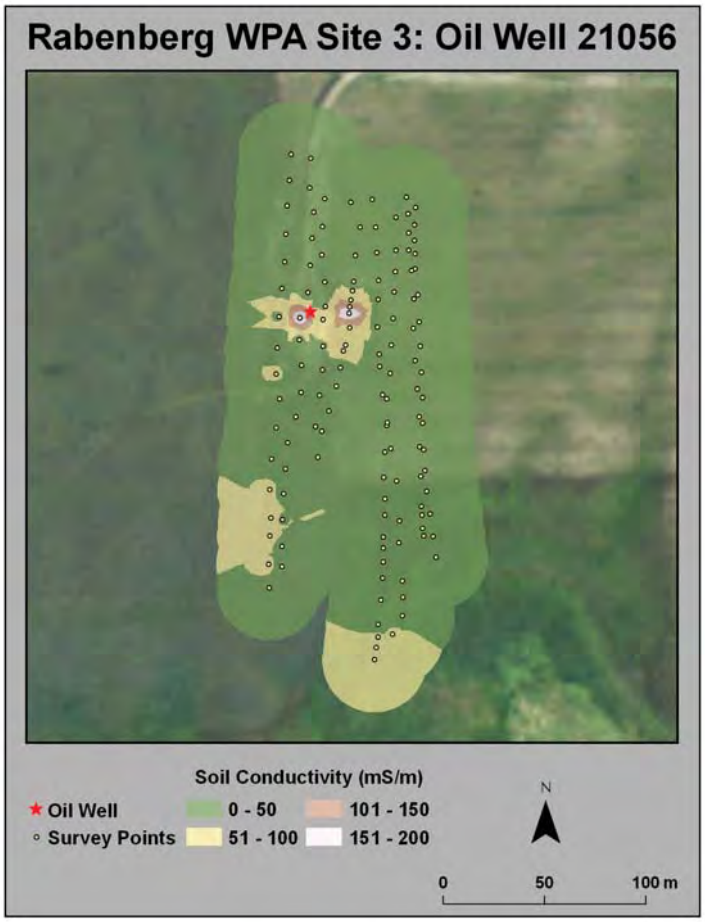


Figure 66. Location of EM-31 terrain-conductivity survey conducted at Site 3 of the Rabenberg WPA.

those located within the WPA, specific conductance ranged from around 760 to 807,299 µS/cm, and chloride concentrations ranged from 12.31 to 66,900 mg/L. According to the CI values calculated for the groundwater samples, produced water impacts were evident at every site, except RS-7MW (GWIC ID 890937), which is located along the eastern WPA boundary. A decreasing trend in chloride contamination is obvious following the Rabenberg Slough downslope from the tank battery south and to the east. Based on the concentrations (fig. 67) and compositions (fig. 68) of the dominant ions in the shallow groundwater samples, it appears that the brine plume is largely present between RS-1MW (GWIC ID 890940) and RS-6MW (GWIC ID 890936). When data were reviewed from 1989 for samples from wells located in the upper part of the slough, RS-1MW (GWIC ID 890940), RS-2MW (GWIC ID 890445), RS-3MW (GWIC ID 890446), and RS-4MW (GWIC ID 890939), the overall concentrations were generally higher (fig. 69), while compositionally most of the wells were very similar (fig. 70). However, the 2005 RS-1MW (GWIC ID 890940) sample begun to reflect a more background composition, with an increasing presence of SO4- and HCO3-, although chloride impacts were still evident based on the CI. Based on these observations, similar trends of groundwater improvement over time at sites in the upper slough would be expected, while areas located downslope like RS-6MW (GWIC ID 890936) and RS-7MW (GWIC ID 890937) might continue to reflect impairment as the brine continues to migrate downslope. However, precipitation and unimpacted recharge waters will also continue to dilute the plume over time, slowly improving groundwater quality. A more detailed report of oil production impacts to the Goose Lake Oilfield, including the Rabenberg WPA, is located in Appendix A.

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at the monitoring well drilling sites of R-1MW and R-2MW, and leachates were analyzed

Table 26. Specific conductivity and CI of 1:1 (by weight) aqeuous leachates of soil samples at different depths in the Rabenberg WPA.

| Depth (ft) | Soil Property | R-1MW | R-2MW |
|---|---|---|---|
| 0–3 | SC (µS/cm) | 833 | 1,904 |
| | CI | 0.108 | 0.113 |
| 3–8 | SC (µS/cm) | 1,021 | 1,177 |
| | CI | 0.202 | 0.155 |
| 8–13 | SC (µS/cm) | 2,890 | 902 |
| | CI | 0.290 | 0.184 |

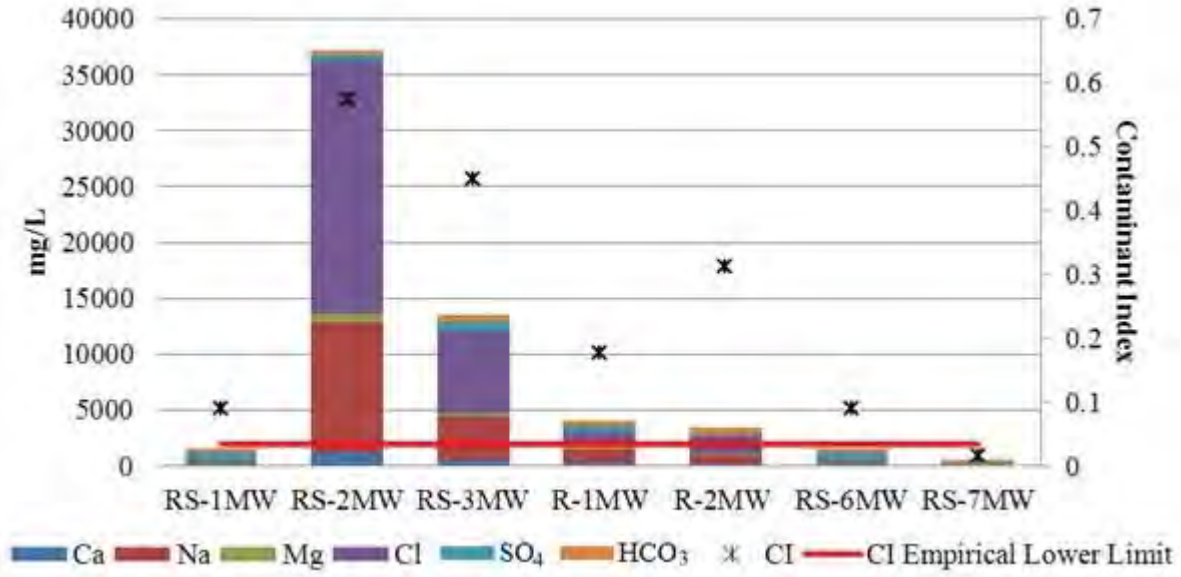


Figure 67. Major groundwater ionic concentrations and associated contaminant index for monitoring wells present within and around the Rabenberg WPA during 2005.

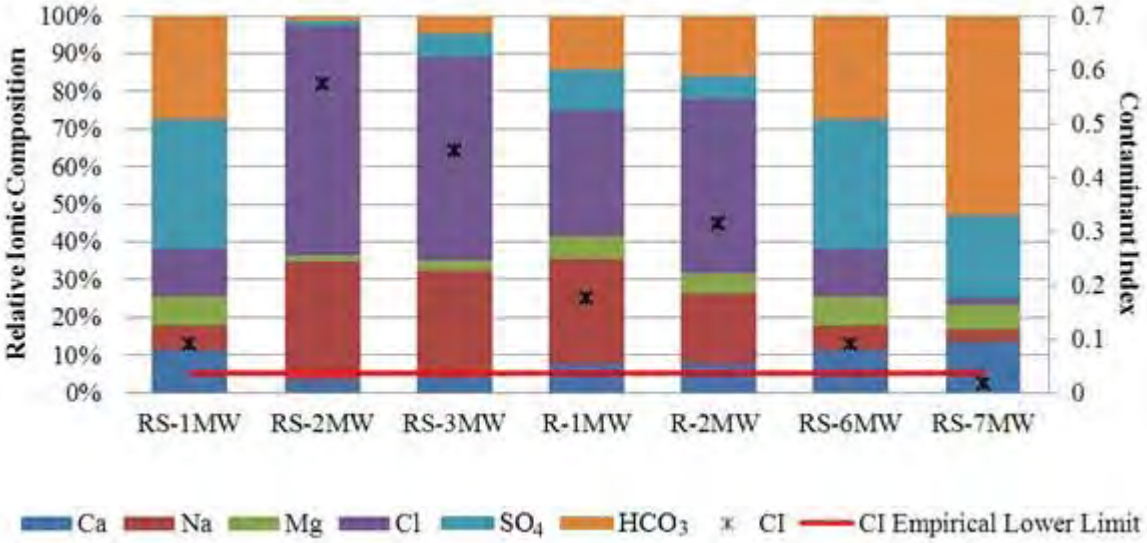


Figure 68. Major groundwater ionic compositions and associated contaminant index for monitoring wells present within and around the Rabenberg WPA during 2005.

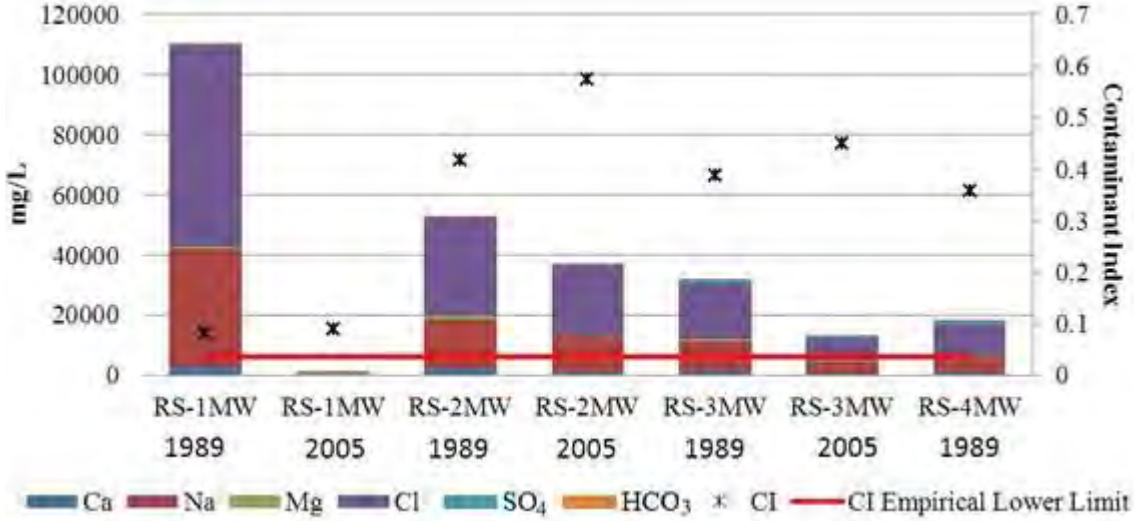


Figure 69. Comparison of major groundwater ionic concentrations and associated contaminant indices for selected monitoring wells present within and around the Rabenberg WPA during 1989 and 2005.

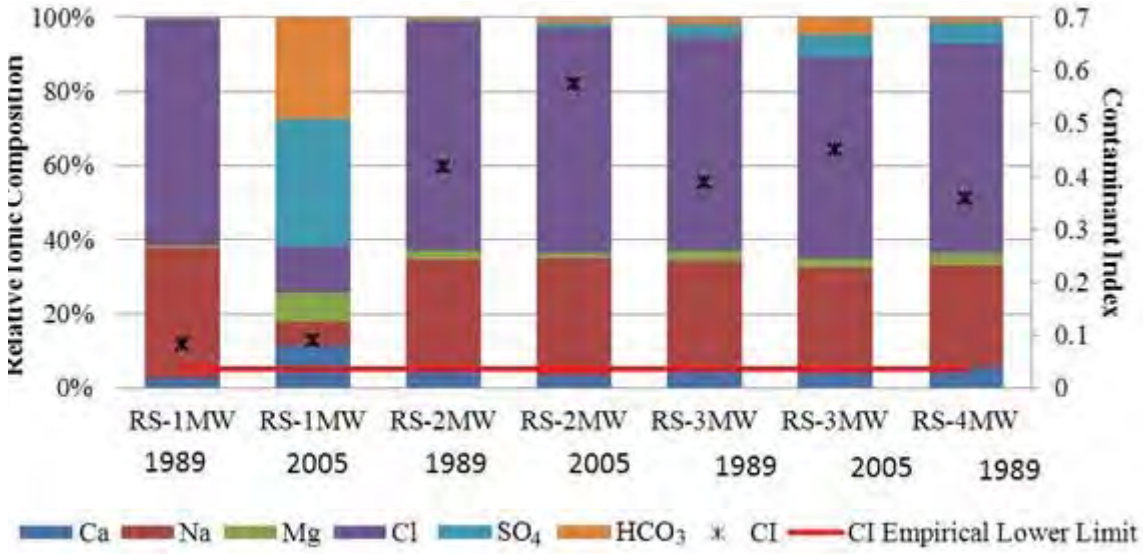


Figure 70. Comparison of major groundwater ionic compositions and associated contaminant indices for selected monitoring wells present within and around the Rabenberg WPA during 1989 and 2005.

for specific conductance and chlorides (table 26). Based on the elevated CI values, chloride impacts are likely at both sites across all sampled depths, with values slightly increasing with depth. However, specific conductivity increases with depth at R-1MW, while there is a decreasing trend with depth at R-2MW. The differences seen between the two sites likely reflect the influence of multiple contaminant sources. For instance, R-2MW reflects impacts from oil well 05105, while R-2MW may reflect both well 05105 influences and upgradient contaminant sources such as the tank battery.

### *Wetland Water Quality*

Among the seven sites visited for surface-water samples, specific conductance ranged from around 2,700 to 22,500 µS/cm and chloride concentrations ranged from 633.91 to 8,362 mg/L (table 27). Based on the calculated CI for each site, produced water impacts were seen at each sampled wetland. It is quite apparent from EM-31 surveys and groundwater analyses that migrating brine plumes are likely contributing to the chloride impacts identified across the wetlands sampled. However, the influence from seasonal surface-water connectivity cannot be discounted due the likelihood that constituents from one wetland may be transported during periods of runoff to another wetland.

### *Co-occurring Contaminants*

Metals analyses were done on all but four of the sampled wetland sites. The results from these analyses indicate that only selenium concentrations exceeded EPA's national recommended water-quality criteria in four samples across four sites, including RABE1 (GWIC ID 214791), RABE2 (GWIC ID 214792), RABE4 (GWIC ID 214790), and RABE5+ (GWIC ID 214788) (table 28). Although slight, a significant positive relationship was detected between surface-water selenium concentrations and the CI (table 7). Selenium has been detected in produced water samples collected from produced water reinjection sites in the Williston Basin before (Chen-Northern, 1994). Food chain bioaccumulation and reproductive failure in certain fish and wildlife species have been reported for aqueous selenium concentrations as low as 2 µg/L. Therefore, the concentrations detected at RABE1 (GWIC ID 214791), RABE2 (GWIC ID 214792), RABE4 (GWIC ID 214790), and RABE5+ (GWIC ID 214788) posed a great risk to many wildlife species, particularly sensitive species like aquatic birds. Reproductive failure has been reported in birds exposed to dietary concentrations of selenium as low as 4 µg/kg (Heinz and others, 1989). Interestingly, selenium concentrations, along with other elemental concentrations including chromium and strontium, were greatly reduced during the 2005 sampling event. Fluctuating water volumes or flushing and dilution by rainfall may have contributed to the differences seen in trace element concentrations between years (Reiten, 1992).

For groundwater, there were only three different elements in 2005 with concentrations that exceeded Montana numerical water-quality standards for human health in groundwater (table 29). Specifically, there was one exceedance for cadmium at site RS-2MW (GWIC ID 890445), two total exceedances for strontium at sites RS-2MW (GWIC ID 8904445) and RS-3MW (GWIC ID 890446), and two exceedances for aluminum at RS-4MW (GWIC ID 890939) and RS-6MW (GWIC ID 890936). However, when data from 1989 were reviewed, there were additional historical exceedances, including aluminum at wells RS-1MW (GWIC ID 890940) and RS-4MW (GWIC ID 890939); cadmium at wells RS-1MW (GWIC ID 890940), RS-2MW (GWIC ID 890445), RS-3MW (GWIC ID 890446), and RS-4MW (GWIC ID 890939); nickel at well RS-2MW (GWIC ID 890445); lead at wells RS-1MW (GWIC ID 890940) and RS-4MW (GWIC ID 890939); and strontium

Table 27. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetlands visited at the Rabenberg WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| RABE1 | 5/13/2004 | 22,480 | 8,362 | 0.372 | Mesosaline |
| RABE1 | 7/25/2004 | 12,002 | 4,181 | 0.348 | Mesosaline |
| RABE1 | 9/14/2004 | 19,131 | 7,380 | 0.386 | Mesosaline |
| RABE1 | 6/13/2005 | 13,360 | 3,349 | 0.251 | Mesosaline |
| RABE2 | 5/13/2004 | 4,130 | 953 | 0.231 | Oligosaline |
| RABE2 | 7/20/2004 | 3,942 | 961 | 0.244 | Oligosaline |
| RABE2 | 9/14/2004 | 5,150 | 1,485 | 0.288 | Oligosaline |
| RABE2 | 6/13/2005 | 3,530 | 634 | 0.180 | Oligosaline |
| RABE3 | 4/27/2004 | 2,731 | 650 | 0.238 | Oligosaline |
| RABE3 | 7/23/2004 | 4,011 | 908 | 0.226 | Oligosaline |
| RABE3 | 6/13/2005 | 5,650 | 1,172 | 0.207 | Oligosaline |
| RABE4 | 5/13/2004 | 4,788 | 1,198 | 0.250 | Oligosaline |
| RABE4 | 7/27/2004 | 3120 | 705 | 0.226 | Oligosaline |
| RABE4 | 9/14/2004 | 8,658 | 3,145 | 0.363 | Mesosaline |
| RABE4 | 6/13/2005 | 6,550 | 1,794 | 0.274 | Oligosaline |
| RABE5 | 7/27/2004 | 7,509 | 2,420 | 0.322 | Oligosaline |
| RABE5 | 8/31/2004 | 8,126 | 2,690 | 0.331 | Mesosaline |
| RABE5+ | 8/31/2004 | 8,437 | 2,908 | 0.345 | Mesosaline |
| RABE5+ | 9/14/2004 | 8,613 | 3,405 | 0.395 | Mesosaline |
| RABE5+ | 6/13/2005 | 7,270 | 2,687 | 0.370 | Oligosaline |
| RABE6 | 7/27/2004 | 8,812 | 2,614 | 0.297 | Mesosaline |

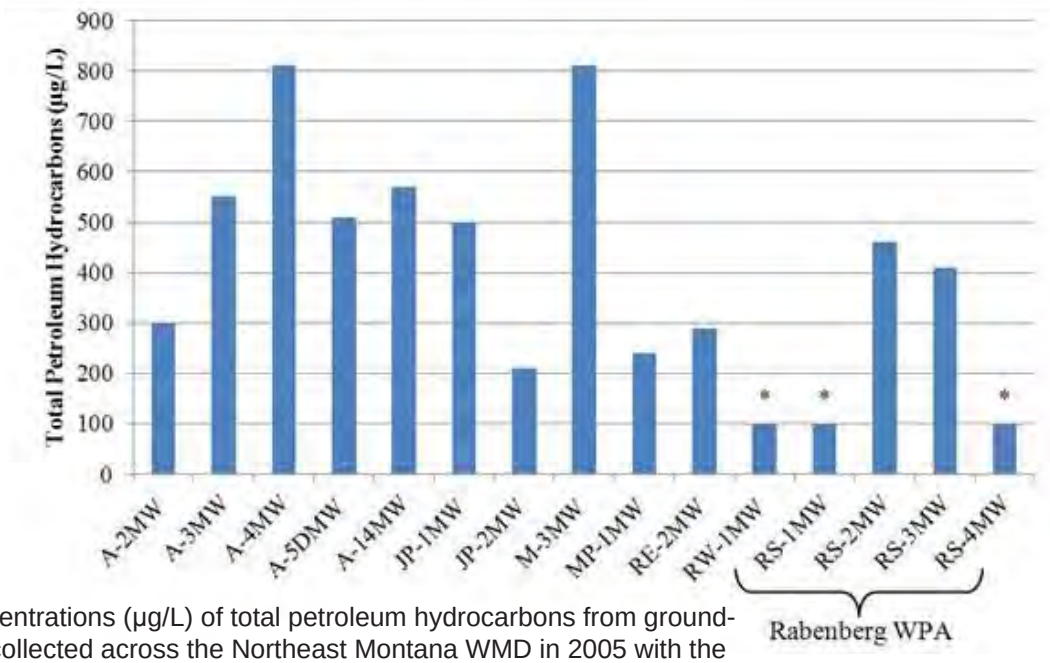


Figure 71. Concentrations (µg/L) of total petroleum hydrocarbons from ground-water samples collected across the Northeast Montana WMD in 2005 with the sites located in or near the Rabenberg WPA bracketed. *Indicates concentration is below the analytical detection limit of 100 µg/L.

Table 28. Surface-water concentrations (µg/L) of trace elements present in the sampled wetlands of the Rabenberg WPA in 2004 and 2005.

| | Surface Water | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2004 Samples | | | 2005 Samples | | | | |
| | RABE1 | RABE2 | RABE4 | RABE1 | RABE2 | RABE3 | RABE4 | RABE5+ |
| Ag | <20 | <10 | <10 | | | | | <10 |
| Al | <200 | <100 | <100 | <50 | <50 | <50 | <50 | <100 |
| As | 43.4 | 10.5 | 14.7 | 8.4 | 3.93 | 9.89 | 5.57 | 16.3 |
| B | 1,704 | 1,186 | 368 | 1,180 | 1,140 | 453 | 446 | 826 |
| Ba | 536 | 233 | 239 | 300 | 102 | 150 | 325 | 236 |
| Be | <40 | <20 | <20 | <0.5 | <0.5 | <0.5 | <0.5 | <20 |
| Br | 10,400 | 1,640 | 3,780 | | | | | 2880 |
| Cd | <20 | <10 | <10 | <0.05 | <0.01 | 0.02 | <0.02 | <10 |
| Co | <40 | <20 | <20 | <5 | <5 | <5 | <5 | <20 |
| Cr | <40 | <20 | <20 | <5 | <5 | <5 | <5 | <20 |
| Cu | <40 | <20 | <20 | <5 | <5 | <5 | <5 | <20 |
| Hg | | | | <0.1 | <0.1 | <0.1 | <0.1 | |
| Li | 863 | 298 | 317 | | | | | 349 |
| Mo | <200 | <100 | <100 | <10 | <10 | <10 | <10 | <100 |
| Ni | <40 | <20 | <20 | <5 | <5 | <5 | <5 | <20 |
| Pb | <40 | <20 | <20 | <0.05 | 0.04 | 0.06 | 0.06 | <20 |
| Se | 112[#] | 24.6[#] | 48.1[#] | 0.22 | 0.22 | 0.35 | 0.21 | 45.3[#] |
| Sr | 4,203 | 1,261 | 1,586 | 2,350 | 720 | 995 | 1,020 | 1,635 |
| Ti | <20 | <10 | <10 | 7 | <5 | <5 | <5 | <10 |
| U | <10 | <5 | <5 | | | | | <5 |
| V | <100 | <50 | <50 | <10 | <10 | <10 | <10 | <50 |
| Zn | <40 | <20 | <20 | <5 | <5 | <5 | <5 | <20 |
| Zr | <30 | <20 | <20 | | | | | <20 |

[#]Indicates value exceeded EPA's recommended national water-quality criteria.

at wells RS-1MW (GWIC ID 890940), RS-2MW (GWIC ID 890445), RS-3MW (GWIC ID 890446), and RS-4MW (GWIC ID 890939) (table 30). Of the elements that exceeded water-quality standards, cadmium and strontium both had significant positive relationships with the CI (table 5). Unfortunately, the relationships between aluminum, nickel, and lead and the CI were not formally assessed due to the large number of values below the limit of detection.

In 2005, groundwater samples were collected from wells RS-1MW (GWIC ID 890940), RS-2MW (GWIC ID 890445), RS-3MW (GWIC ID 890446), and RS-4MW (GWIC ID 890939) and analyzed for total petroleum hydrocarbons. Total petroleum hydrocarbons were below the detection limit for the samples taken from wells RS-1MW (GWIC ID 890940) and RS-4MW (GWIC ID 890939), while concentrations of 460 and 410 µg/L were detected at RS-2MW (GWIC ID 890445) and RS-3MW (GWIC ID 890446), respectively (fig. 71). Wells RS-2MW (GWIC ID 890445) and RS-3MW (GWIC ID 890446) are in close proximity to the shut-in oil well 05105, suggesting that the hydrocarbon contamination detected in these samples are a result of activities associated with this well. Analyses for aliphatic and polynuclear aromatic hydrocarbons were not done for this site.

Table 29. Groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Rabenberg WPA in 2005.

| | Groundwater | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | R-1MW | R-2MW | RS-1MW | RS-2MW | RS-3MW | RS-4MW | RS-6MW | RS-7MW |
| Al | <50 | <50 | 70 | <50 | <50 | 1,840* | 178* | <50 |
| As | 1.45 | 1.76 | | 5.04 | 1.85 | 4.44 | 9.93 | 7.5 |
| B | 1,510 | 764 | 156 | 36,200 | 10,300 | 3,700 | 252 | 170 |
| Ba | 204 | 146 | | 620 | 97 | 163 | 370 | 96 |
| Be | <0.5 | <0.5 | | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Br | | | 200 | | | | | |
| Cd | 0.44 | 0.06 | <5 | 14.7* | 0.64 | 0.7 | <0.05 | 0.1 |
| Co | <5 | <5 | | <5 | <5 | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 | <5 | 8 | 13 | <5 | <5 |
| Cu | 6 | <5 | 6 | 7 | 7 | 10 | <5 | <5 |
| Hg | <0.1 | <0.1 | | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Li | | | 81 | | | | | |
| Mo | <10 | <10 | <40 | <10 | 10 | <10 | <10 | <10 |
| Ni | 12 | <5 | <20 | 55 | 28 | 14 | <5 | <5 |
| Pb | <0.05 | <0.01 | | <0.2 | 1.1 | 3.82 | 0.43 | <0.01 |
| Se | 0.26 | 1.35 | | 8.58 | 0.43 | 0.32 | 0.29 | <0.1 |
| Sr | 1930 | 1020 | 590 | 21,800* | 7,000* | 3,120 | 1,570 | 990 |
| Ti | <5 | <5 | 4 | 16 | 7 | 48 | 12 | <5 |
| U | | | | | | | | |
| V | <10 | <10 | 7 | <10 | <10 | <10 | <10 | <10 |
| Zn | 40 | <5 | <7 | 6 | 16 | 126 | 7 | <5 |
| Zr | | | <6 | | | | | |

*Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

Table 30. Groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Rabenberg WPA in 1989.

| | Groundwater | | | | | |
|---|---|---|---|---|---|---|
| | RS-1MW | RS-2MW | RS-3MW | RS-4MW | RS-6MW | RS-7MW |
| Ag | 18 | 15 | 3 | 10 | <4 | <4 |
| Al | 100* | 40 | <30 | 120* | 70 | 43 |
| B | 89,700 | 20,600 | 12,200 | 6,200 | 156 | 114 |
| Ba | 803 | | | | | |
| Br | 2,200 | <100 | <100 | 7,100 | 200 | <100 |
| Cd | 25* | 71* | 11* | 12* | <5 | <5 |
| Cr | 9 | 24 | 10 | 5 | <5 | <5 |
| Cu | 39 | 77 | 47 | 15 | 6 | <4 |
| Li | 22,200 | 6,280 | 3,280 | 2,030 | 81 | 28 |
| Mo | <40 | 30 | <20 | <40 | <40. | <40 |
| Ni | 40 | 120* | 80 | 40 | <20 | <20 |
| Pb | 680* | | | 180* | | |
| Sr | 80,100* | 25,400* | 16,600* | 7,750* | 590 | 230 |
| Ti | <4 | <1 | <1 | 17 | 4 | 4 |
| V | 30 | 51 | 29 | 19 | 7 | 6 |
| Zn | 11 | 17 | 14 | 16 | <7 | 7 |
| Zr | 25 | 29 | <4. | 9 | <6 | <6 |

*Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

## Hansen WPA

The Hansen WPA was established on 7/16/1968 and encompasses an area of approximately 54.4 acres. One lake is located within the WPA (fig. 72). Bird surveys have documented the use of Hansen WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Much of the upland habitat is managed as dense nesting cover through selective planting, prescribed haying, prescribed fire, and limited grazing. As of January 2010, there were no production wells present within the WPA, but three wells, one approved plugged and abandoned EOR injection well, one permitted injection oil well, and one shut-in oil well, were all located within 700 ft of the WPA (fig. 72) . API well 21350, the permitted injection oil well, is the closest of the wells to the WPA and was completed in January 1981.

### *Geology*

The Hansen WPA is underlain by a complex mix of glacial and post-glacial deposits (fig. 73). It is near the east edge of an ice-walled glacial lake plain deposited as the stagnant ice melted. Glacial till is the predominant geologic unit at the site and, based on nearby well logs, ranges from about 100 to 150 ft thick. Glacial outwash and glacial lake deposits make up a relatively minor portion of the glacial deposits. Although no regional glacial outwash aquifers have been identified in this area, smaller discontinuous outwash sand and gravel deposits often overlie and are interbedded within the glacial till. These outwash deposits form locally significant aquifers supplying landowners and wetlands. The Quaternary alluvial deposits are probably relatively thin layers of fine sand and silt associated with swales forming modern wetlands. The Quaternary eolium is composed of windblown silt and fine sand associated with the shoreline of the ice-walled lake. This material is likely only 2 to 3 ft thick.

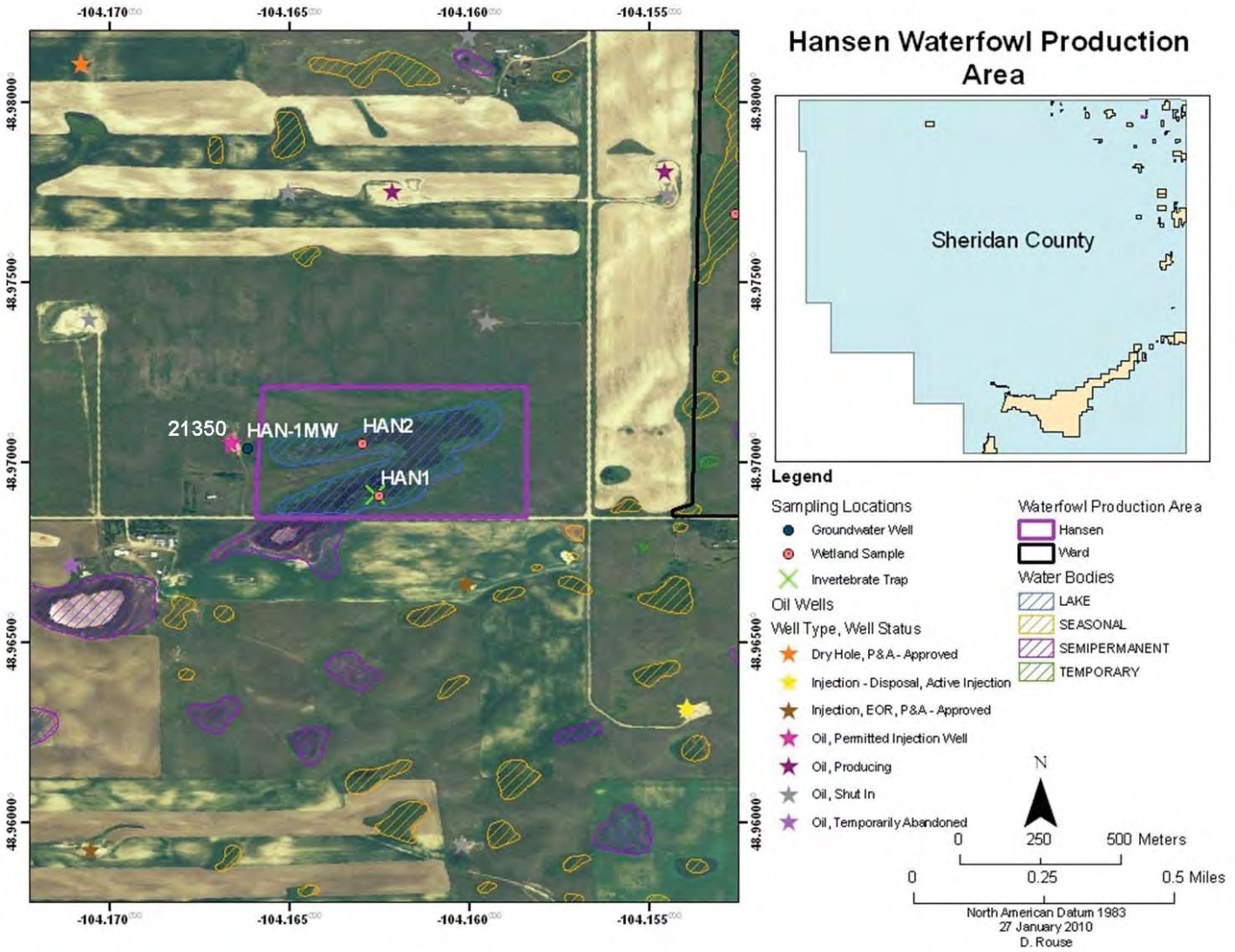


Figure 72. Map depicting locations of sampling sites, oil wells, and bodies of water for the Hansen WPA: T. 34 N., R. 58 E., sec. 2, 10 & 11.

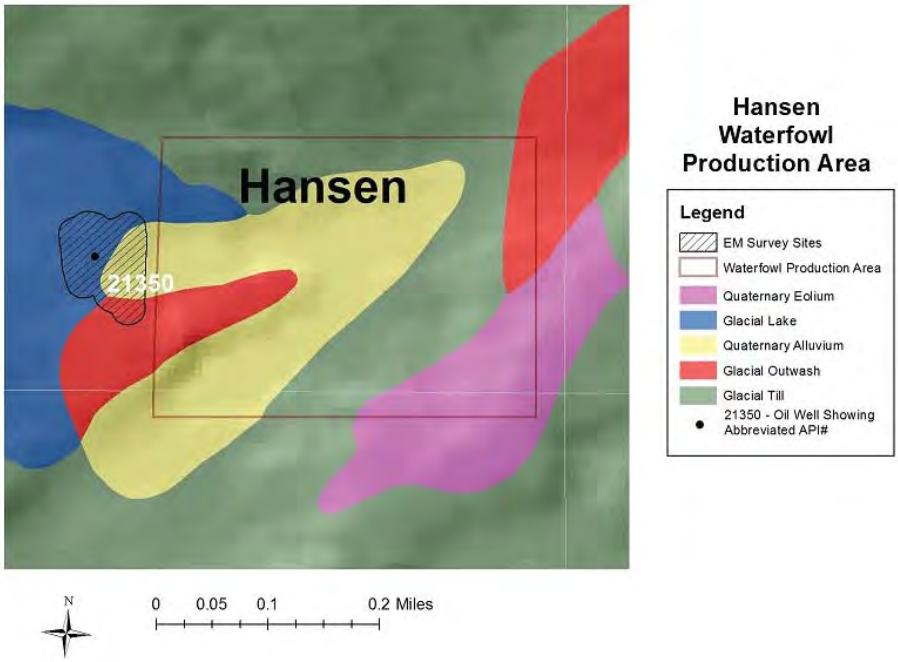


Figure 73. Geology of the Hansen WPA: T. 37 N., R. 57 E., sec. 11.

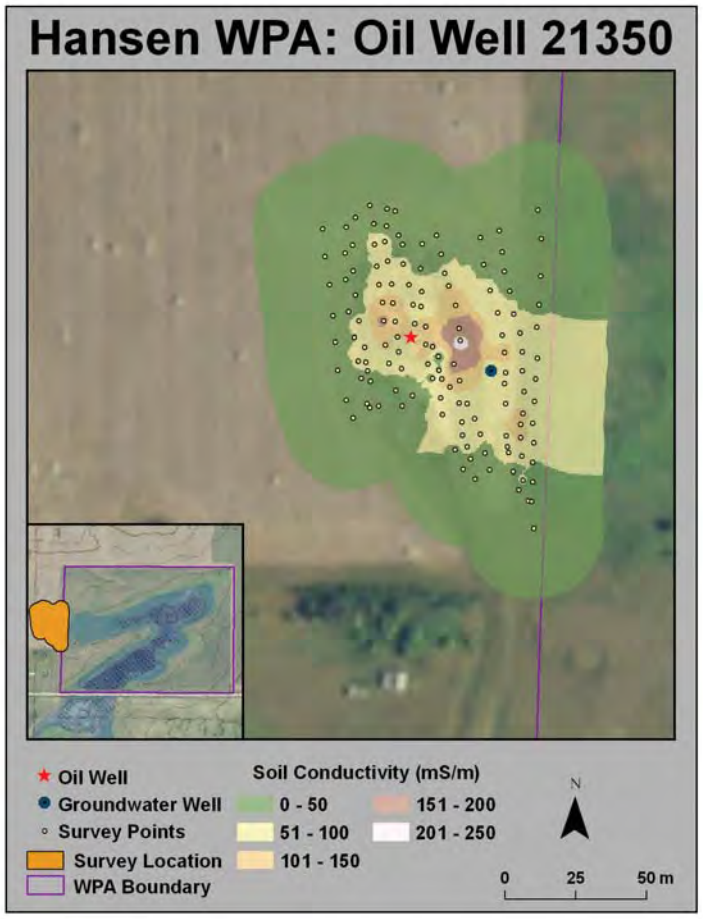


Figure 74. Location of EM-31 terrain-conductivity surveys conducted at the Hansen WPA: T. 37 N., R. 57 E., sec. 11.

### *Groundwater Hydrology*

In 1989, monitoring well HAN-1MW (GWIC ID 890447) was completed in interbedded glacial till and glacial outwash. Based on the change in water quality at this well from 1989 to 2005, local groundwater flow is towards the east. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes.

### *Characterizing Oilfield Production Brine Migration*

EM-31 terrain conductivity surveys identified higher than background conditions near the abandoned oil well site and downgradient of the site towards the east (fig. 74). Although a reserve pit associated with well 21350 would have been lined based on its date of completion, these areas of high terrain conductivity appear to be associated with brine plumes migrating downgradient towards the east. There is one monitoring well present within the Hansen WPA that was sampled on 4/22/1989 (GWIC Sample 1989Q0510) and again on 9/14/2005 (GWIC Sample 2006Q0305). In 1989, the specific conductivity was around 1,900 µS/cm, and in 2005, the specific conductivity was close to 8,000 µS/cm. In 1989, the chloride concentration was 138 mg/L, and in 2005, the chloride concentration was 2,781 mg/L. During both sampling events, produced water impacts were evident based on their respective CI values, but the 2005 value was greater than 20 times the value in 1989. Brine impacts have increased from 1989 to 2005 at HAN-1MW (GWIC ID 890447), characterized by increased ion concentrations (fig. 75) and a shift towards an ionic composition dominated by Cl- ions (fig. 76). This is due to the migration of brine waste offsite from where it was originally released.

### *Wetland Water Quality*

Two locations, HAN1 (GWIC ID 214749) and HAN2, were visited to collect surface-water samples, but are likely both part of the same lake system. At these sites, specific conductance ranged from around 2,300 to 3,200 µS/cm and chloride concentrations ranged from 200 to 250 mg/L (table 31). Both sites had CI values indicating produced water impacts. It is clear from the EM-31 survey and groundwater monitoring efforts that activities associated with oil well 21350 have contributed to the impacts observed at HAN1 (GWIC ID 214749) and HAN2.

### *Co-occurring Contaminants*

Metals analyses were done on samples taken from HAN1 (GWIC ID 214749) and HAN-1MW (GWIC ID 890447).

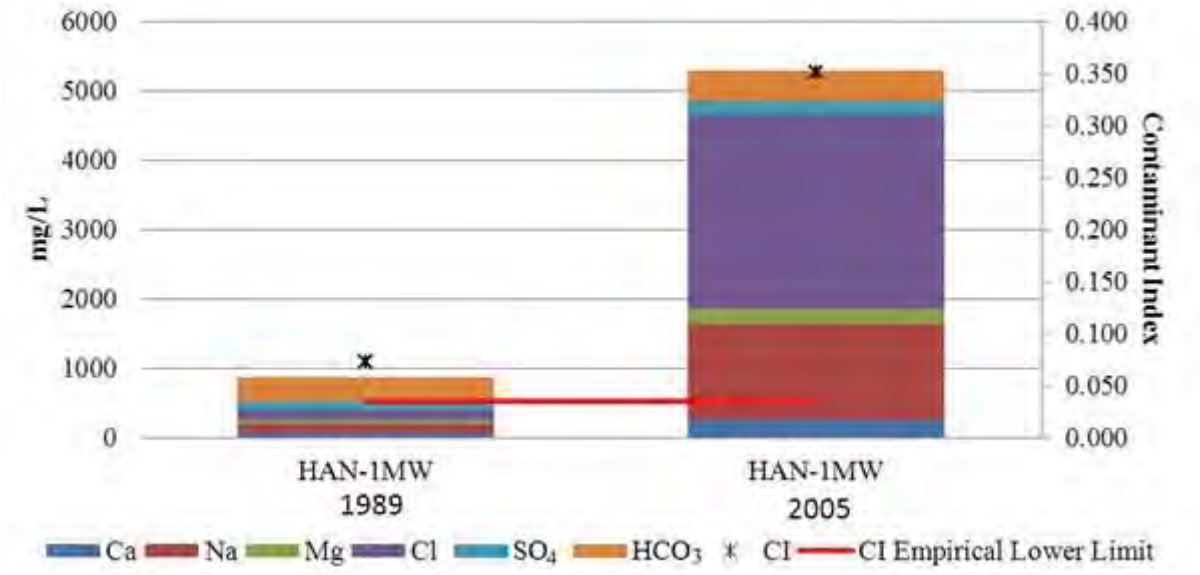


Figure 75. Comparison of major groundwater ionic concentrations and associated contaminant indices between 1989 and 2005 for the groundwater well HAN-1MW.

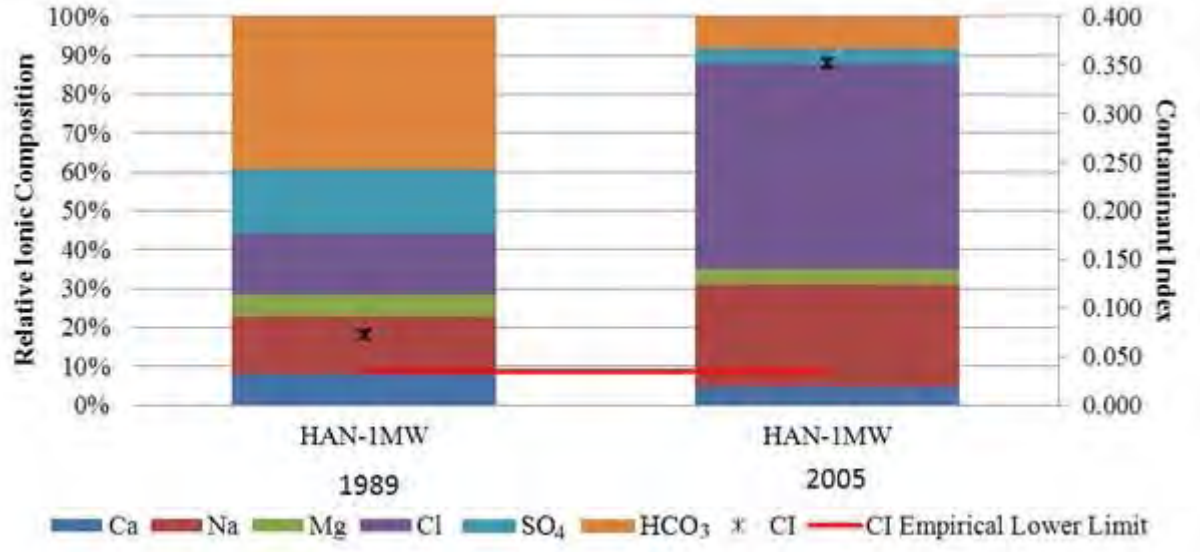


Figure 76. Comparison of major groundwater ionic compositions and associated contaminant indices between 1989 and 2005 for the groundwater well HAN-1MW.

Table 31. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Hansen WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| HAN1 | 4/28/2004 | 2,313 | 205 | 0.089 | Oligosaline |
| HAN1 | 7/24/2004 | 3,160 | 250 | 0.079 | Oligosaline |
| HAN1 | 6/13/2005 | 2,950 | 200 | 0.068 | Oligosaline |
| HAN2 | 4/28/2004 | 2,368 | 231 | 0.098 | Oligosaline |

The results from these analyses indicate that many elements are present within these samples, but are often found in trace amounts (table 32). There were no concentrations that exceeded either EPA's national recommended water-quality criteria or Montana numerical water-quality standards for human health in groundwater.

Table 32. Surface-water concentrations (µg/L) of trace elements from HAN1 in 2005 and groundwater concentrations (µg/L) of trace elements present in the sampled monitoring well HAN-1MW in 1989 and 2005.

| | Groundwater | | Surface Water |
|---|---|---|---|
| | 1989 Sample | 2005 Sample | 2005 Sample |
| | HAN-1MW | HAN-1MW | HAN1 |
| Ag | <2 | | |
| Al | <30 | <50 | <50 |
| As | | 1.58 | 4.03 |
| B | 480 | 2,420 | 149 |
| Ba | | 228 | 74 |
| Be | | <0.5 | <0.5 |
| Br | <100 | | |
| Cd | <2 | <0.05 | 0.02 |
| Co | | <5 | <5 |
| Cr | <2 | <5 | <5 |
| Cu | <2 | <5 | <5 |
| Hg | | <0.1 | <0.1 |
| Li | 100 | | |
| Mo | <20 | <10 | <10 |
| Ni | <10 | <5 | <5 |
| Pb | | <0.05 | 0.06 |
| Se | | 12.2 | 0.25 |
| Sr | 290 | 2,150 | 600 |
| Ti | <1 | <5 | <5 |
| V | <1 | <10 | <10 |
| Zn | <3 | 5 | <5 |

## Ward WPA

The Ward WPA was established on 6/18/1969 and encompasses an area of approximately 86 acres. Multiple bodies of water are located in, or partially located in, the WPA, including seasonal and semi-permanent wetlands (fig. 77). Bird surveys have documented the use of the Ward WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA, but five existed within 1,000 ft of the boundary. This included one oil-producing well; one approved, plugged, and abandoned EOR injection well; one approved, plugged, and abandoned dry hole; and two shut-in oil wells.

### *Geology*

The Ward WPA is underlain by glacial till deposits (fig. 78). These deposits are estimated to be from 50 to 100 ft thick based on nearby test drilling. Fort Union Sandstone and mudstone underlies the glacial materials. Previous test drilling identified an outwash channel underlying the Ward WPA. A long narrow south- to north-trending swale spans the WPA and appears to be a remnant of a glacial meltwater channel. The soils did not indicate these materials as outwash, but drilling in 1989 encountered a thin outwash aquifer. A private well referred to asWD-3MW (GWIC ID 48284) appears to be constructed in glacial outwash.

### *Groundwater Hydrology*

Monitoring wells completed in 1989 were completed in interbedded glacial till and glacial outwash. Most of the groundwater flows through the outwash aquifer towards the north. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes.

### *Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at the Ward WPA. There are four monitoring wells present within the WPA. One well, 167B (GWIC ID 890436), is a Sheridan County Conservation District well that was sampled on 4/22/1989. The other three wells, WD-1MW (GWIC ID 220958), WD-2MW (GWIC ID 221688), and WD-3MW (GWIC ID 48284), were sampled on 9/14/2005, although chloride and specific conductivity data were not collected for WD-1MW (GWIC ID 220958). For those wells with specific conductivity and chloride values available, specific conductance ranged from around 500 to 11,930 µS/cm and chloride concentrations ranged from 35.1 to 4,751 mg/L. The calculated CI value for each groundwater sample indicated produced water impacts at each well. Well 167B (GWIC ID 890436) was the least impacted, but without recent data to compare it to, it is difficult to determine whether the differences in concentrations (fig. 79) and compositions (fig. 80) seen between this well and others are due to a temporal factor, a spatial factor, or a combination of the two. Furthermore, Reiten and Tischmak (1993) have reported vertical density gradients in outwash aquifer sites such as 167B (GWIC ID 890436), in which the concentrations of salts vary depending on where in the water column the sample is collected. Regardless, the 2005 data indicate that WD-3MW (GWIC ID 48284) is the most impacted, which is most likely due to its location in the outwash channel. Reiten and Tischmak (1993) identified historic infiltration pits to the east of Ward WPA as significant sources of contamination to this area.

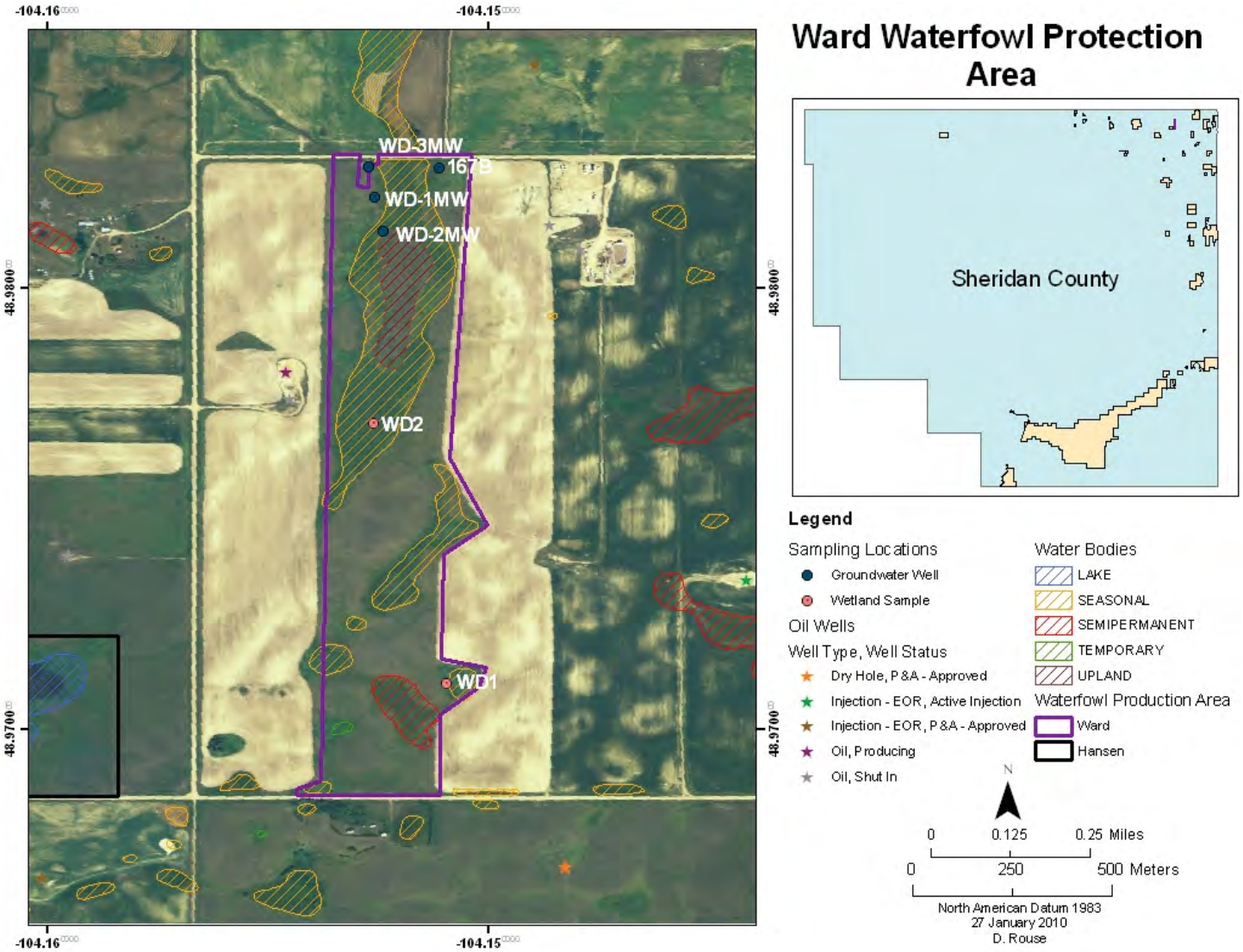


Figure 77. Map depicting locations of sampling sites, oil wells, and bodies of water for the Ward WPA: T. 37 N., R. 57 E., sec. 12.

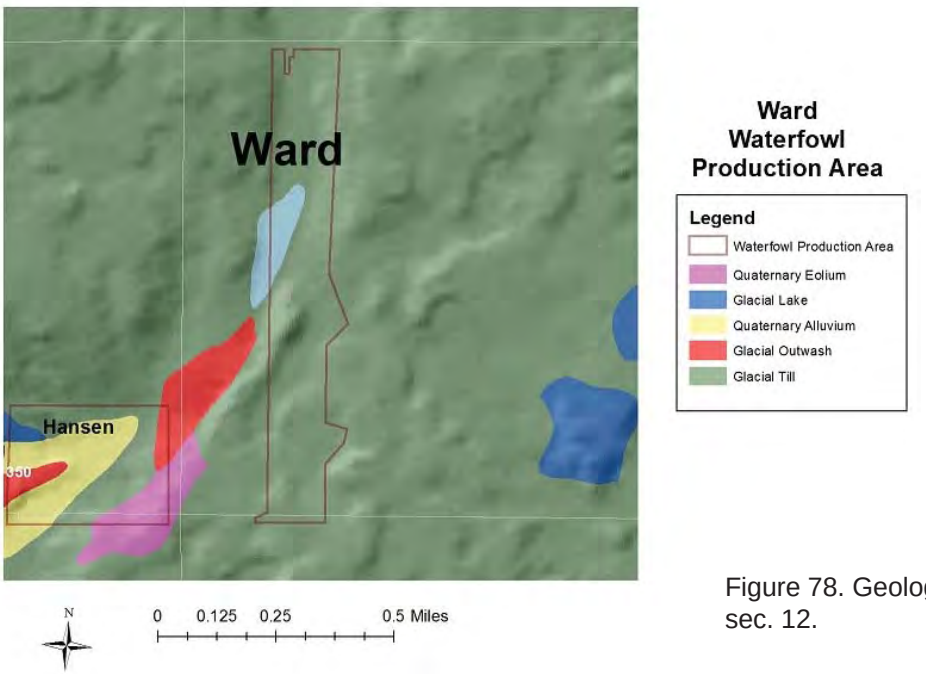


Figure 78. Geology of the Ward WPA: T. 37 N., R. 57 E., sec. 12.

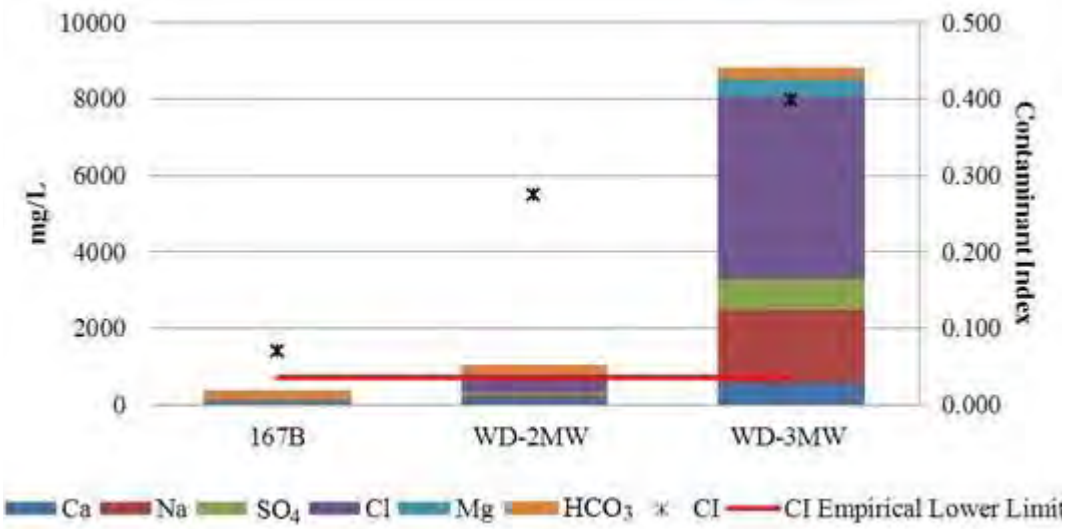


Figure 79. Major groundwater ionic concentrations and associated contaminant index values for the monitoring well 167B in 1989 and the wells WD-2MW and WD-3MW in 2005 present within the Ward WPA.

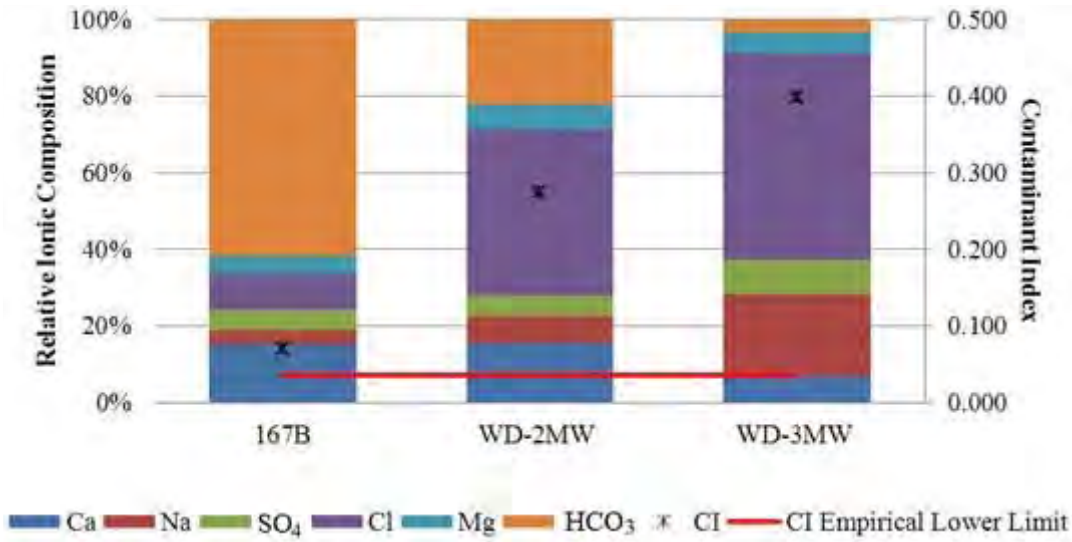


Figure 80. Major groundwater ionic compositions and associated contaminant index values for the monitoring well 167B in 1989 and the wells WD-2MW and WD-3MW in 2005 present within the Ward WPA.

### *Wetland Water Quality*

Two wetlands were visited to collect surface-water samples, but one of those sites was dry. The sampled wetland, WD1, had a specific conductivity value close to 182 µS/cm and a chloride concentration of 5.3 mg/L (table 33). The CI value for this site, 0.029, suggests that there are no produced water impacts. However, based on the measured specific conductivity, WD1 is a freshwater system, and although the CI index does not exceed 0.035, the calculated CI is elevated compared to that of other sites within the Northeast Montana WMD. This suggests that this site is either just beginning to reflect brine impacts, that there is a significant freshwater source diluting contaminants migrating to this system, or certain geologic features are reducing the connectivity between contaminated groundwater plumes and the surface water.

### *Co-occurring Contaminants*

Metals analyses were done on groundwater samples taken from WD-1MW (GWIC ID 220958), WD-2MW (GWIC ID 221688), and WD-3MW (GWIC ID 48284). Numerous elements were present in the samples at varying concentrations (table 34). Typically, WD-3MW (GWIC ID 48284) possessed some of the higher concentrations, although there were no concentrations from any well sample that exceeded Montana numerical water-quality standards for human health in groundwater.

Table 33. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Ward WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| WD1 | 4/28/2004 | 181.2 | 5 | 0.029 | Fresh |
| WD2 | 4/28/2004 | | | | Dry |

Table 34. Groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Ward WPA in 2005.

| | Groundwater | | |
|---|---|---|---|
| | WD-1MW | WD-2MW | WD-3MW |
| Al | <50 | <50 | <50 |
| As | 0.57 | 1.33 | 2.38 |
| B | 30 | 40 | 184 |
| Ba | 197 | 560 | 105 |
| Be | <0.5 | <0.5 | <0.5 |
| Cd | 0.02 | 0.04 | 0.2 |
| Co | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 |
| Mo | <10 | <10 | <10 |
| Ni | <5 | <5 | <5 |
| Pb | 0.02 | <0.01 | <0.05 |
| Se | 1.79 | 0.1 | 1.14 |
| Sr | 180 | 245 | 3,000 |
| Ti | <5 | <5 | 8 |
| V | <10 | <10 | <10 |
| Zn | 10 | 9 | 264 |

## Jerde WPA

The Jerde WPA was established on 5/16/1968 and encompasses an area of 187 acres. It is largely covered by a single lake, but two smaller wetlands are also present (fig. 81). Bird surveys have documented the use of the Jerde WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, API well 05262, an oil-producing well completed in May 1966, was the only well present within the WPA. Numerous other wells are located in close proximity to the WPA, including two oil-producing wells, two shut-in oil wells, one completed water source, and one expired oil well (fig. 81). A tank battery that used an infiltration pit to dispose of produced water was located near the southwestern border of the WPA.

### *Geology*

The Jerde WPA is underlain by a complex mix of glacial and post-glacial deposits (fig. 82). Glacial till is the predominant geologic unit at the site and, based on nearby well logs, ranges from about 100 to 150 ft thick. Glacial outwash and glacial lake deposits make up a relatively minor portion of the glacial deposits. Although no regional glacial outwash aquifers have been identified in this area, smaller discontinuous outwash sand and gravel deposits often overlie and are interbedded within the glacial till. These outwash deposits form locally significant aquifers supplying landowners and wetlands. The lake at this site is mapped as Larson Slough on USGS 7.5-minute topographic maps. It appears to be located near the east edge of a former ice-walled glacial lake. The cross section in figure 83 shows the stratigraphic relationships between the glacial till and the lake sediment. The glacial lake sediments overlie glacial till and pinch out between wells JP2 and JP1. The upper till unit is yellow or yellowish-brown with bright red–red ochre fragments, indicating strongly oxidizing conditions. Below this unit is a light brown till that forms a transitional zone to the basal dark blue till, indicating unoxidized or reduced conditions.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Jerde WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetland to the west of the site. No regional glacial outwash aquifers have been identified in this area. The cross section in figure 80 shows the water table dropping towards Larson Slough, indicating flow to the west.

### *Characterizing Oilfield Production Brine Migration*

EM-31 surveys were conducted at two sites (fig. 84). Site 1 surveys identified an area of terrain conductivity higher than background conditions surrounding oil well 05262 (fig. 85). Based on the date of completion for well 05262,

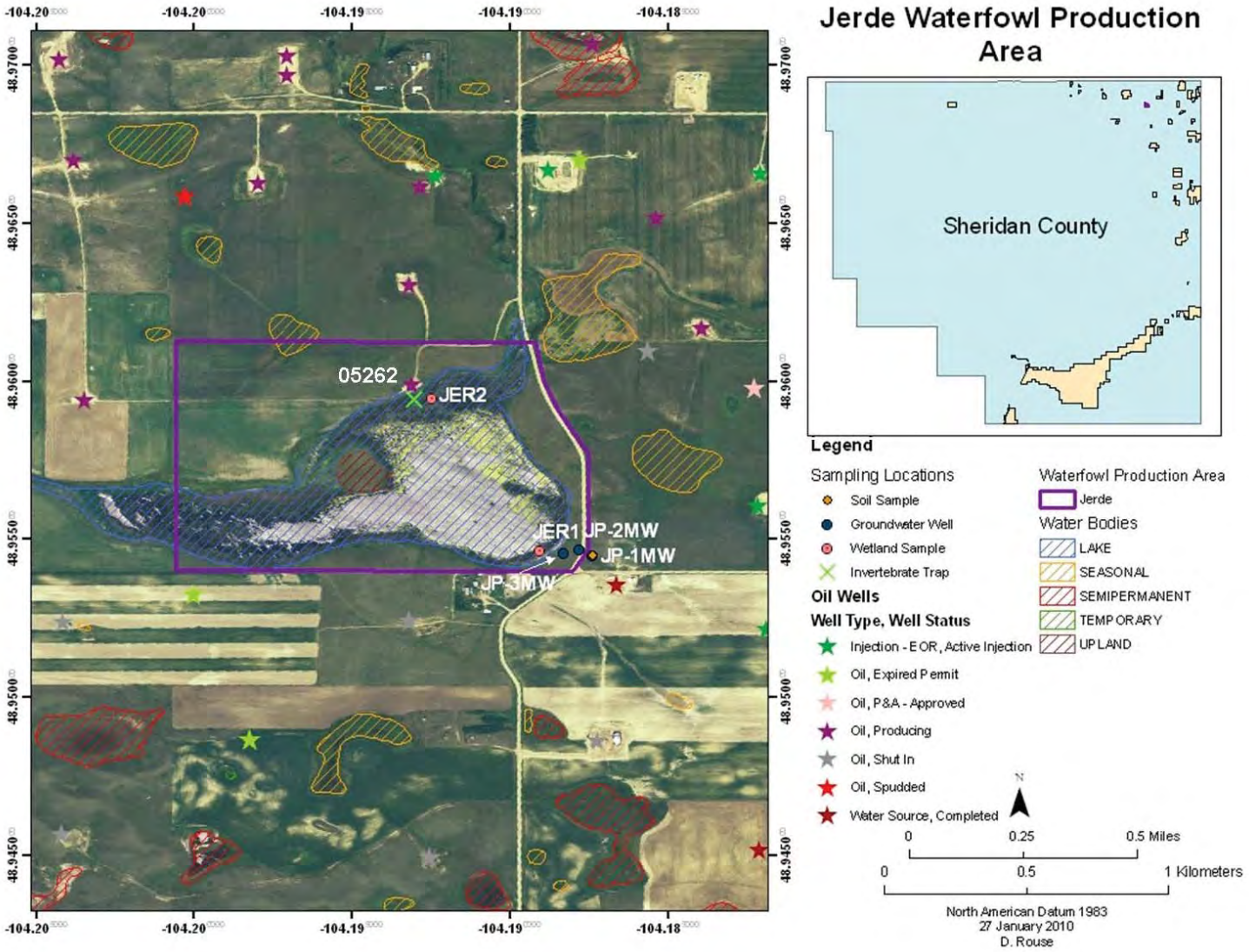


Figure 81. Map depicting locations of sampling sites, oil wells, and bodies of water for the Jerde WPA: T. 37 N., R. 57 E., sec. 15.

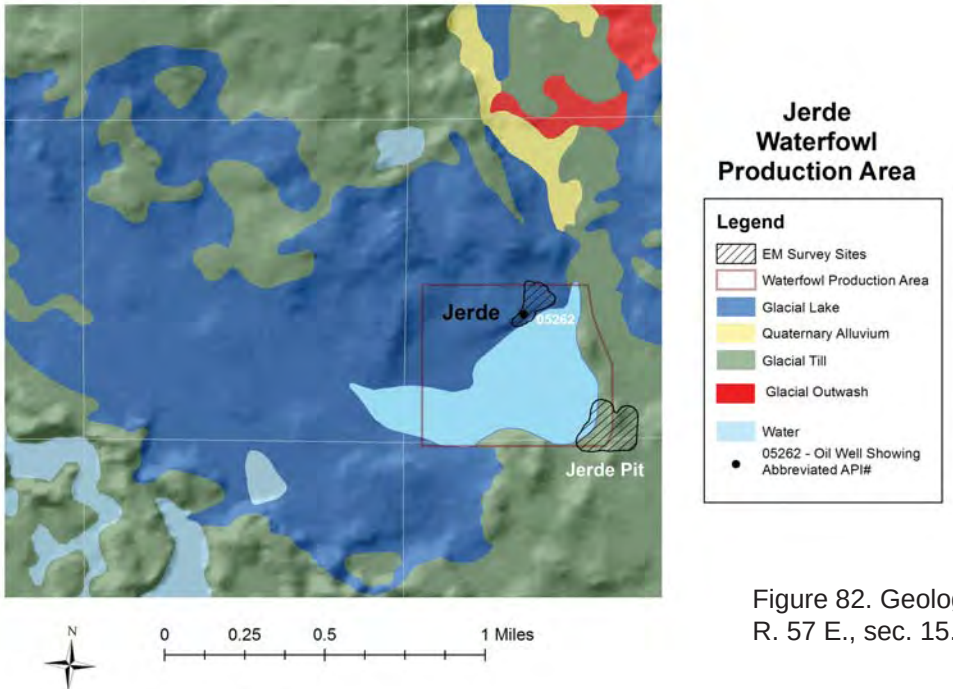


Figure 82. Geology of the Jerde WPA. Location: T. 37 N., R. 57 E., sec. 15.

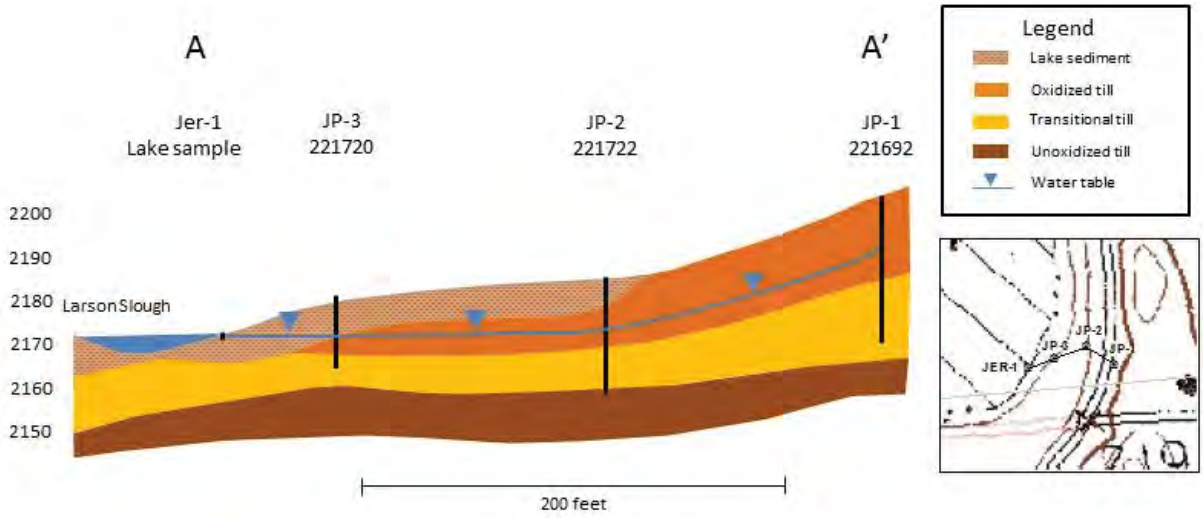


Figure 83. Cross section showing hydrogeologic conditions at the Jerde WPA. Location: T. 37 N., R. 57 E., sec. 15.

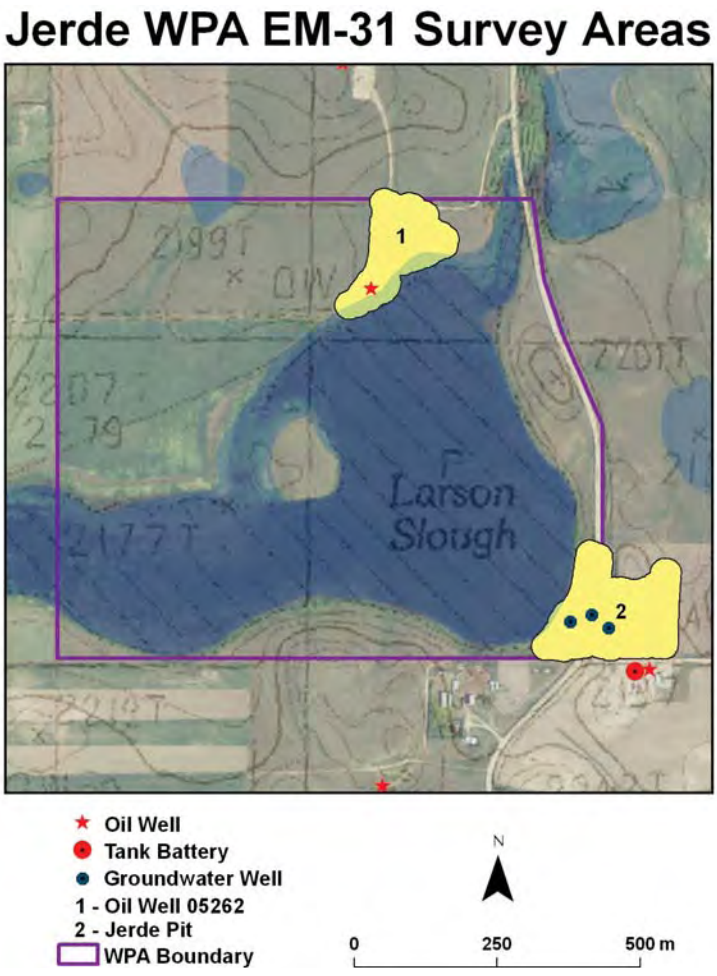


Figure 84. Location of EM-31 terrain-conductivity surveys conducted at the Jerde WPA: T. 37 N., R. 57 E., sec. 15.

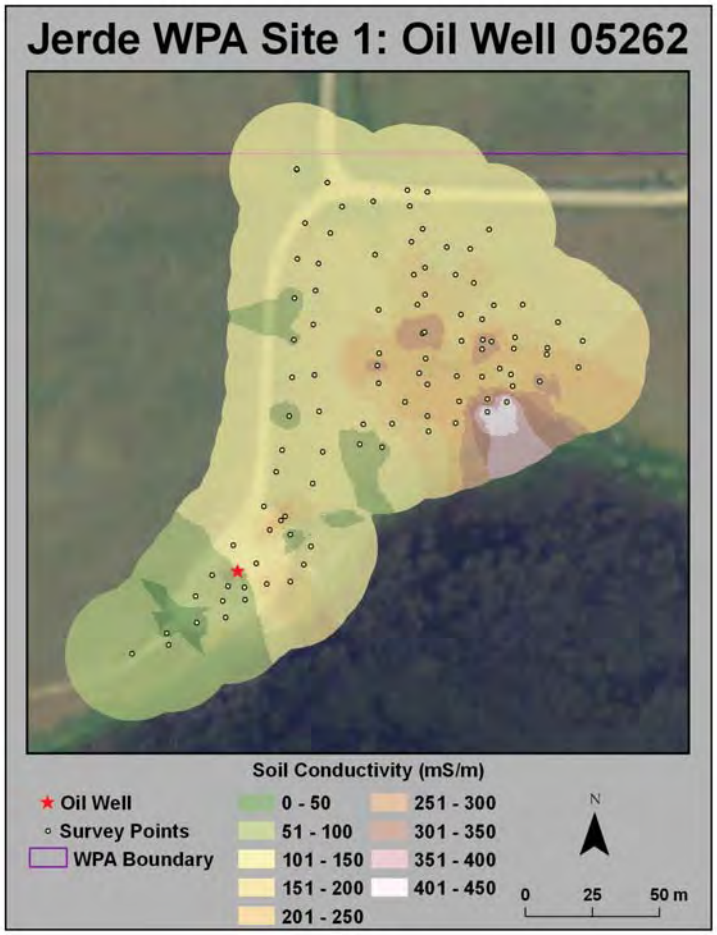


Figure 85. Location of EM-31 terrain-conductivity site 1 surveys conducted at the Jerde WPA: T. 37 N., R. 57 E., sec. 15.

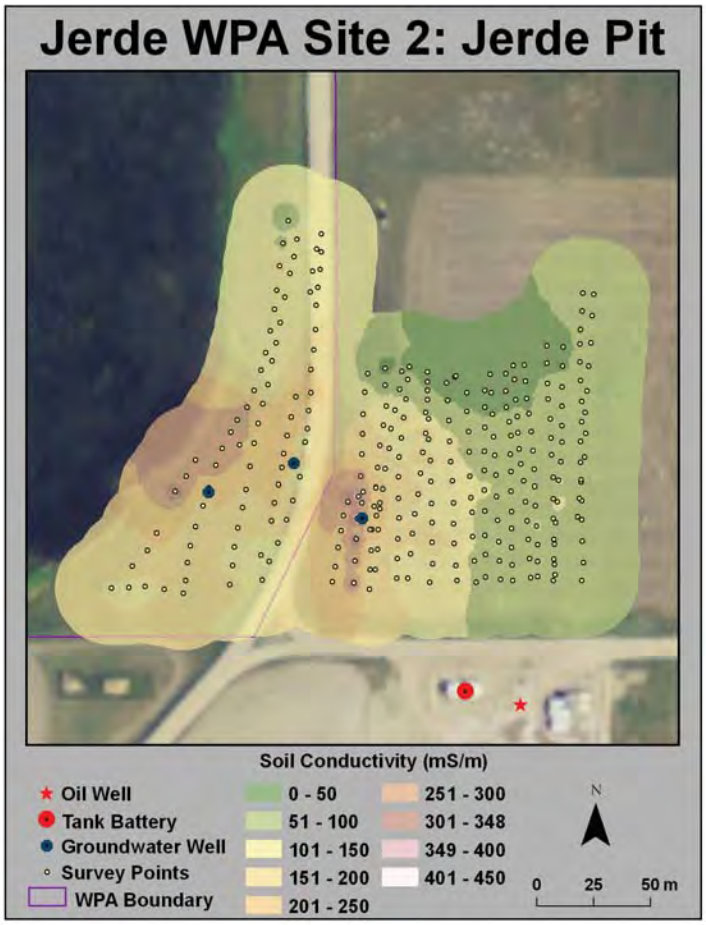


Figure 86. Location of EM-31 terrain-conductivity site 2 surveys conducted at the Jerde WPA: T. 37 N., R. 57 E., sec. 15.

the reserve pit associated with this well would have been unlined. Site 2 surveys identified another area of terrain conductivity higher than background conditions surrounding the Jerde Pit and tank battery located close to the southeast corner of Jerde WPA (fig. 86). These areas of high terrain conductivity appear to be associated with brine plumes migrating downgradient towards Larson Slough. Three monitoring wells located within the EM-31 survey site 2 were sampled in 2005. Among the three monitoring wells sampled, specific conductance ranged from around 32,700 to 43,200 µS/cm and chloride concentrations ranged from 15,549 to 27,655 mg/L. As indicated by the calculated CI values for the well samples, produced water impacts were evident at each well site. In fact, the ionic compositions of the three wells are very similar (fig. 87), with concentrations slightly varying (fig. 88).

JP-1MW (GWIC ID 221692) is located close to the site of the infiltration pit. The chloride concentrations at this site are 15,549 mg/L. Down the flow path to the west, the concentration increases to 27,655 mg/L at JP-2MW (GWIC ID 221722) and then decreases slightly to 22,888 mg/L at JP-3MW (GWIC ID 221720).

In addition to EM-31 surveys and groundwater analyses, soil samples were collected at the monitoring well drilling sites of JP-1MW, JP-2MW, and JP-3MW, and leachates were analyzed for specific conductance and chlorides (table 35). Impacts are evident at all sites based on the elevated CI values, with impacts seen relatively evenly distributed to depths of 18 ft at JP-1MW, while impacts are more pronounced between 3 and 13 ft at sites JP-2MW and JP-3MW. This likely reflects the capacity for glacial till to hold and concentrate ions as well as proximity to the historical infiltration pit.

### *Wetland Water Quality*

Two wetland samples were taken from opposite ends of a single lake system. One of the samples at JER1 (GWIC ID 120874) was taken in 1990; all other samples were taken either in 2004 or 2005. On average, JER1 (GWIC ID 120874) and JER2 had specific conductivity values

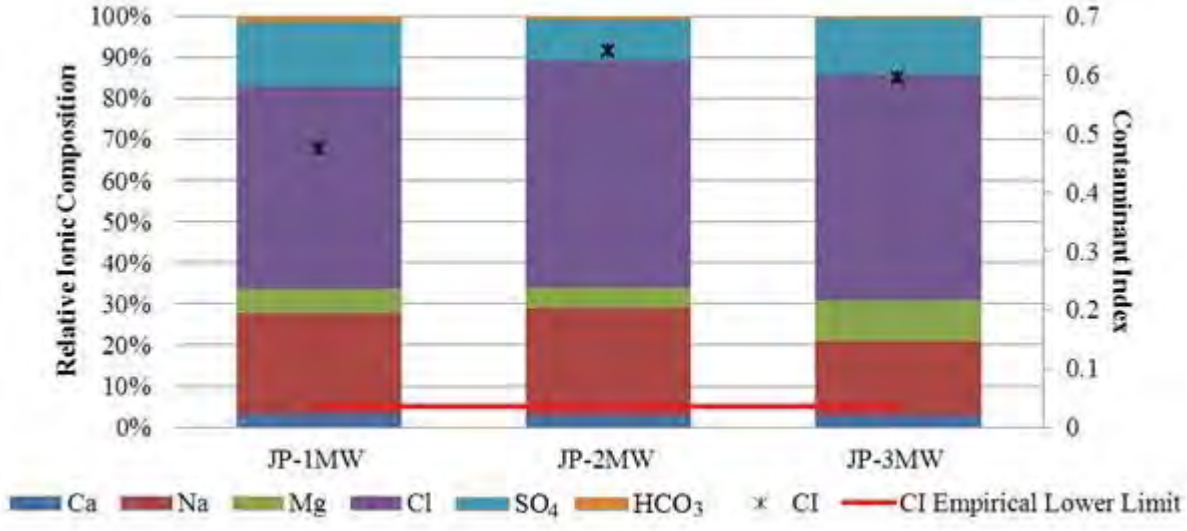


Figure 87. Major groundwater ionic compositions and associated contaminant index values for monitoring wells present within the Ward WPA during 2005.

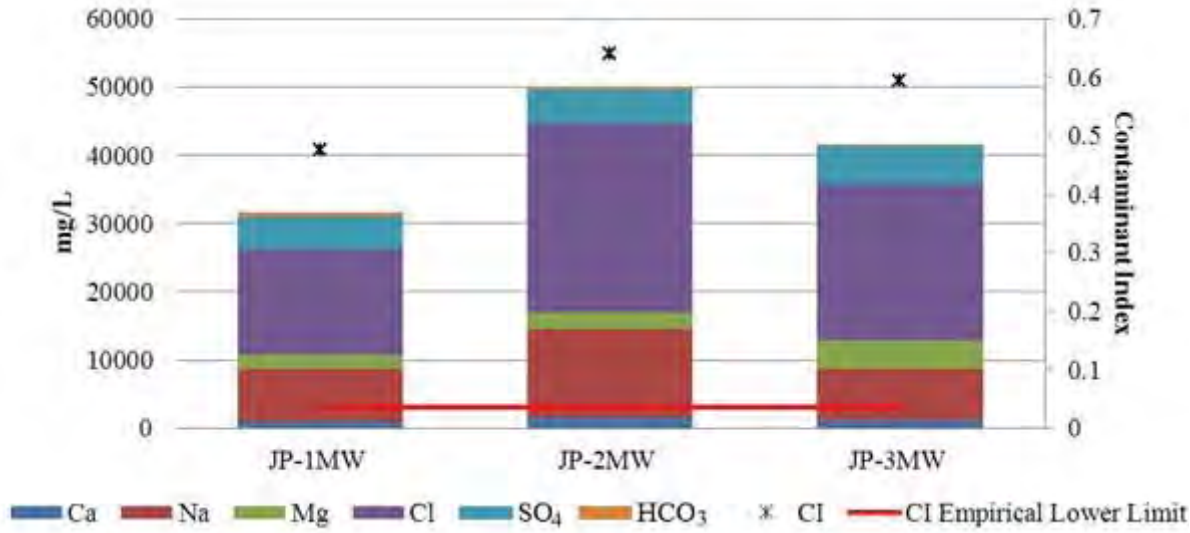


Figure 88. Major groundwater ionic concentrations and associated contaminant index values for monitoring wells present within the Ward WPA during 2005.

Table 35. Specific conductivity and CI of 1:1 (by weight) aqeuous leachates of soil samples at different depths in the Jerde WPA.

| Depth (ft) | Soil Property | JP-1MW | JP-2MW | JP-3MW |
|---|---|---|---|---|
| 0–3 | SC (µS/cm) | 14770 | 12780 | 8760 |
| | CI | 0.348 | 0.141 | 0.189 |
| 3–8 | SC (µS/cm) | 9330 | 16840 | 16240 |
| | CI | 0.229 | 0.278 | 0.317 |
| 8–13 | SC (µS/cm) | 15460 | 16890 | 16350 |
| | CI | 0.231 | 0.277 | 0.286 |
| 13–18 | SC (µS/cm) | 15290 | 6010 | NA |
| | CI | 0.255 | 0.076 | NA |
| 18–23 | SC (µS/cm) | NA | 7920 | NA |
| | CI | NA | 0.080 | NA |
| 23–28 | SC (µS/cm) | 5150 | 6130 | NA |
| | CI | 0.088 | 0.036 | NA |

*Note.* NA, data not available.

Table 36. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Jerde WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| JER1 | 8/27/1990 | 1,746 | 50 | 0.028 | Oligosaline |
| JER1 | 4/28/2004 | 1,223 | 78 | 0.064 | Oligosaline |
| JER1 | 7/23/2004 | 2,035 | 118 | 0.058 | Oligosaline |
| JER1 | 6/13/2005 | 2,140 | 99 | 0.046 | Oligosaline |
| JER2 | 4/28/2004 | 1,212 | 83 | 0.068 | Oligosaline |
| JER2 | 9/14/2004 | 2,341 | 136 | 0.058 | Oligosaline |

of around 1668 and 1777 µS/cm and chloride concentrations of 86.2 and 109.3 mg/L, respectively (table 36). The average CI values for each site, 0.049 for JER1 (GWIC ID 120874) and 0.063 for JER2, indicate that produced waters are likely impacting this system. Interestingly, the CI value for JER1 (GWIC ID 120874) in 1990 was less than 0.035, but samples taken in 2004 and 2005 had CI values that were all above 0.035. Most likely, impacts have increased at JER1 (GWIC ID 120874) from 1990 due to the migrating plume of brine waste on to the WPA and subsequent interaction with surface water. Although large volumes of fresh groundwater and surface water are diluting brines that are entering into the wetland, signs of oilfield contamination are increasing and should be monitored in the future to evaluate water-quality degradation.

*Co-occurring Contaminants*

Metals analyses were done on the wetland site JER1 (GWIC ID 120874) and all three of the monitoring wells groundwater samples taken from JP-1MW (GWIC ID 221692), JP-2MW (GWIC ID 221722), and JP-3MW (GWIC ID 221720) (table 37). The results for JER1 (GWIC ID 120874) from 1990 indicated that the concentration for aluminum exceeded EPA's national recommended water-quality criteria; otherwise, no other benchmark concentration was exceeded. Interestingly, aluminum concentrations were well below EPA's national recommended water-quality criteria for aluminum in 2005 at a concentration less than 50 µg/L. This, however, was not a common trend for all of the other elemental concentrations. In fact, many concentrations increased in 2005 compared to 1990 values.

Due to the large number of sites across the Northeast Montana WMD with aluminum concentrations below the analytical limit of detection, the relationship between surface-water aluminum concentrations and the CI was not formally assessed (table 7). Therefore, it is difficult to

Table 37. Surface-water concentrations (µg/L) of trace elements from JER1 in 1990 and 2005 and groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Jerde WPA in 2005.

| | Surface Water | | Groundwater | | |
|---|---|---|---|---|---|
| | 1990 Sample | 2005 Sample | 2005 Samples | | |
| | JER1 | JER1 | JP-1MW | JP-2MW | JP-3MW |
| Ag | 26 | | | | |
| Al | 222[#] | <50 | <50 | <50 | <50 |
| As | 14 | 16.1 | 4.23 | 5.08 | 5.39 |
| B | 50 | 117 | 22,600 | 31,400 | 2,700 |
| Ba | 54 | 110 | 179 | 270 | 167 |
| Be | | <0.5 | <0.5 | <0.5 | <0.5 |
| Br | 100 | | | | |
| Cd | <5 | 0.06 | 2.47 | 2.4 | 0.38 |
| Co | | <5 | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 | <5 | <5 |
| Cu | <4 | <5 | 7 | 6 | 8 |
| Hg | | <0.1 | <0.1 | <0.1 | <0.1 |
| Li | 50 | | | | |
| Mo | <40 | <10 | 10 | 10 | 10 |
| Ni | <20 | <5 | 14 | 22 | <5 |
| Pb | <50 | 0.09 | <0.2 | <0.31 | <0.2 |
| Se | 0.6 | 0.38 | 4.57 | 74.5[*] | 248[*] |
| Sr | 401 | 565 | 19,800 | 29,900 | 23,200 |
| Ti | <5 | <5 | 12 | 17 | 18 |
| V | <5 | <10 | <10 | <10 | <10 |
| Zn | <6 | <5 | 10 | <5 | 80 |

[#]Indicates value exceeded EPA's recommended national water-quality criteria.
[*]Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

determine the effect of oil production activities on aluminum concentrations in neighboring water bodies. Nevertheless, aqueous aluminum concentrations exceeded water-quality standards in JER1 (GWIC ID 120874) in 1990, impacting environments in which numerous organisms may be exposed. In fact, toxic effects have been reported in algae, macroinverterbrates, and fish at concentrations below those detected at JER1 (GWIC ID 120874), although aluminum toxicity is often considered pH-dependent, with increasing toxicity as water becomes more acidified (Gensemer and Playle, 1999). The water-borne aluminum concentrations detected in this survey are likely highly complexed, diminishing their bioavailability, but varying conditions may alter the availability of aluminum to aquatic organisms as well as increase the risk to terrestrial organisms, like birds, that may be exposed to elevated aluminum concentrations through dietary uptake (Gensemer and Playle, 1999; Rosseland and others, 1990).

Numerous elements were present in the groundwater samples at varying concentrations (table 37). Selenium concentrations from wells JP-2MW (GWIC ID 221722) and JP-3MW (GWIC ID 221720) were the only values to exceed Montana numerical water-quality standards for human health in groundwater. Although JP-2MW (GWIC ID 221722) and JP-3MW (GWIC ID 221720) were impacted by brine contamination as indicated by the CI, when groundwater data from across the entire Northeast Montana WMD was used to compare the relationship between the CI and groundwater selenium concentrations, we failed to detect a significant correlation (table 5). In spite of this, selenium has been detected in produced water samples collected from produced water reinjection sites in the Williston Basin before (Chen-Northern, 1994). Regardless, selenium concentrations are elevated at these sites, but appear to have little influence on surface-water selenium concentrations (table 37).

One soil sample, JP-1S, was collected in 2005 for total petroleum hydrocarbon analysis. With a concentration of 50 mg/kg (DW), this sample had one of the lowest concentrations of total petroleum hydrocarbons of all the soil samples taken across the Northeast Montana WMD (fig. 89). This site was resampled in 2006 and analyzed for aliphatic and polynuclear aromatic hydrocarbons. When multiple hydrocarbon fractions were compared to toxicity criteria, this sample failed to exceed any benchmark category (table 38).

In 2005, one groundwater sample was collected from each of the wells JP-1MW and JP-2MW and analyzed for total petroleum hydrocarbons. Total petroleum hydrocarbons were present at concentrations of 500 and 210 µg/L in the samples collected from JP-1MW and JP-2MW, respectively (fig. 90). JP-2MW was resampled in 2006 and analyzed for aliphatic and polynuclear aromatic hydrocarbons. The majority of the compounds screened for were below the limits of detection, although a few compounds, mostly aliphatic, were present at levels above the analytical detection limit. There were no compounds that exceeded the selected toxicity criteria (table 39).

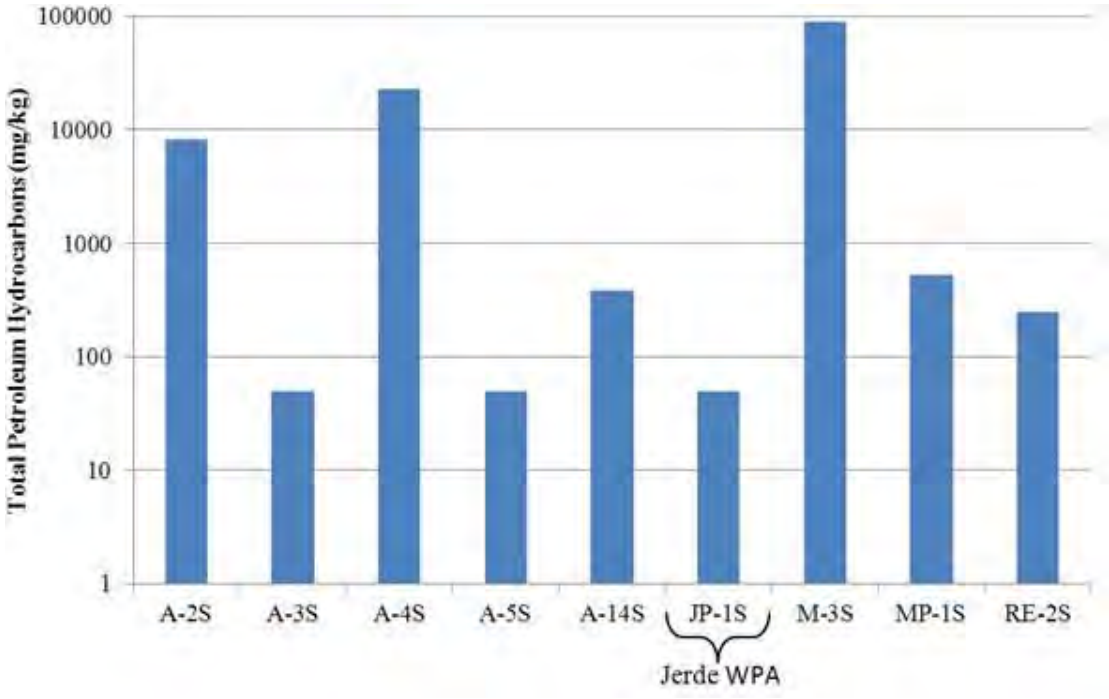


Figure 89. Concentrations (mg/kg DW) of total petroleum hydrocarbons from soil samples collected across the Northeast Montana WMD in 2005 with the site located in Jerde WPA bracketed.

Table 38. Concentrations (mg/kg DW) of hydrocarbon fractions from soil samples collected in 2006 within the Jerde WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| Carbon Range | TPHCWG[1] (mg/kg/day) | MADEP[2] (mg/kg/day) | JP-1S (mg/kg) |
| **Aliphatic** | | | |
| C9–C18 | 0.10 | 0.10 | 0.029 |
| C19–C32 | 2.00 | 2.00 | 0.034 |
| **Aromatic** | | | |
| C9–C16 | 0.04 | 0.03 | 0 |
| C17–C32 | 0.03 | 0.03 | 0.016 |

[1]Total Petroleum Hydrocarbon Criteria Working Group (Gustafson and others, 1997).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

Table 39. Concentrations (µg/L) of hydrocarbon fractions from the groundwater sample collected in 2006 within the Jerde WPA with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| | MT RBSL[1] (µg/L) | MADEP[2] (µg/L) | JP-2MW (µg/L) |
| **Aliphatics** | | | |
| Carbon Range C9–C18 | 1,000 | 50,000 | 0 |
| Carbon Range C19–C36 | 1,000 | 50,000 | 6.9 |
| **Aromatics** | | | |
| Carbon Range C9–C10 | - | 50,000 | <0.3 |
| Carbon Range C11–C22 | 1,000 | 5,000 | 0.4 |
| Acenaphthene | 670 | 6,000 | <0.3 |
| Anthracene | 2,100 | 30 | <0.3 |
| Benzo(a)pyrene | 0.05 | 500 | <0.3 |
| Benzo(b)fluoranthene | 0.5 | 400 | <0.3 |
| Benzo(k)fluoranthene | 5 | 100 | <0.3 |
| Chrysene | 50 | 70 | <0.3 |
| Dibenzo(a,h)anthracene | 0.05 | 40 | <0.3 |
| Fluoranthene | 130 | 200 | <0.3 |
| Flourene | 1,100 | 40 | <0.3 |
| Indeno(1,2,3-cd)pyrene | 0.5 | 100 | <0.3 |
| Napthalene | 100 | 20,000 | <0.3 |
| Pyrene | 830 | 20 | <0.3 |

[1]Montana Tier 1 Risk-Based Corrective Action Guidance for Petroleum Release (MT DEQ, 2009).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

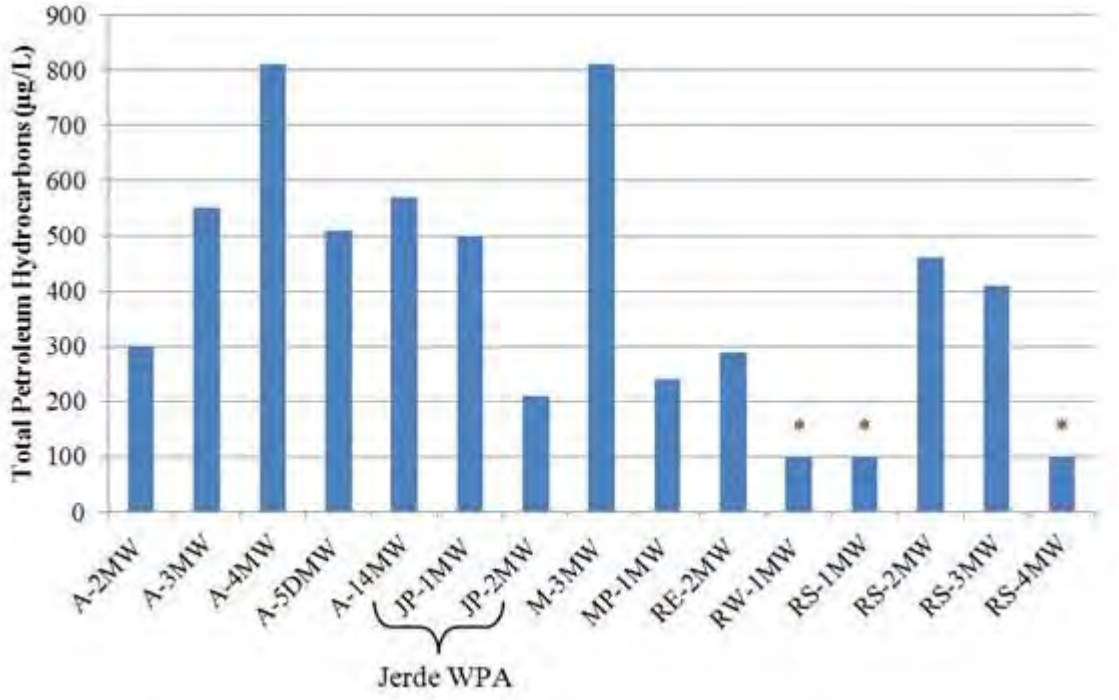


Figure 90. Concentrations (µg/L) of total petroleum hydrocarbons from groundwater samples collected across the Northeast Montana WMD in 2005 with the sites located in the Jerde WPA bracketed. *Indicates concentration is below the analytical detection limit of 100 µg/L.

## Erickson WPA

The Erickson WPA was established on 10/02/1974 and encompasses an area of 1,097 acres. Various water bodies exist throughout the WPA, including lakes, plus seasonal, temporary, and semi-permanent wetlands (fig. 91). Bird surveys have documented the use of the Erickson WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, there is designated Piping Plover critical habitat located in this area. Much of the upland habitat is managed as dense nesting cover through selective planting, prescribed haying, prescribed fire, and limited grazing. As of January 2010, well 05050, an approved plugged and abandoned dry hole completed in March 1961, was the only well located within the WPA. The next closest well is over a quarter of a mile north of the WPA.

### *Geology*

The Erickson WPA is underlain by glacial outwash deposits (fig. 92). These deposits are estimated to be from 50 to 300 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlies the glacial materials. Quaternary alluvial deposits are located underlying the western part of the Erickson WPA and are associated with swales and lowlands along streams. The sand and gravel glacial outwash deposits are associated with the upper permeable zone of the Clear Lake aquifer.

### *Groundwater Hydrology*

The Erickson WPA overlies the Clear Lake aquifer. Based on nearby lithologic logs, several permeable zones of the Clear Lake aquifer underlie this site. The shallowest zone is 10 to 31 ft below land surface and the deepest is at depths of 300 to 350 ft. Both the deep ancestral Missouri River alluvium and glacial outwash of Late Wisconsinan meltwater channels make up the aquifer zones. The log for GWIC ID 3867 indicated that Fort Union bedrock was encountered at depths of 335 ft. This well was completed in the ancestral Missouri River zone of the Clear Lake aquifer. The depth of this zone is 318 to 335 ft below land surface. Flow in the aquifer is generally towards the west or southwest.

### *Characterizing Oilfield Production Brine Migration*

EM-31 terrain conductivity surveys indicated higher than background readings in an area east of abandoned oil well 05050 (fig. 93). These likely reflect a migrating brine plume that originated from an associated reserve pit that, based on the date of the well completion, was unlined. There are no monitoring wells associated with this site.

### *Wetland Water Quality*

Among the seven wetlands sampled at the Erickson WPA, specific conductance ranged from around 500 to 52,700 µS/cm and chloride concentration ranged from 20 to 2,303 mg/L (table 40). Four sites, ERK2, ERK4, ERK5, and ERK7, showed signs of produced water impacts based on their calculated CI values. ERK5 is located in Horseshoe

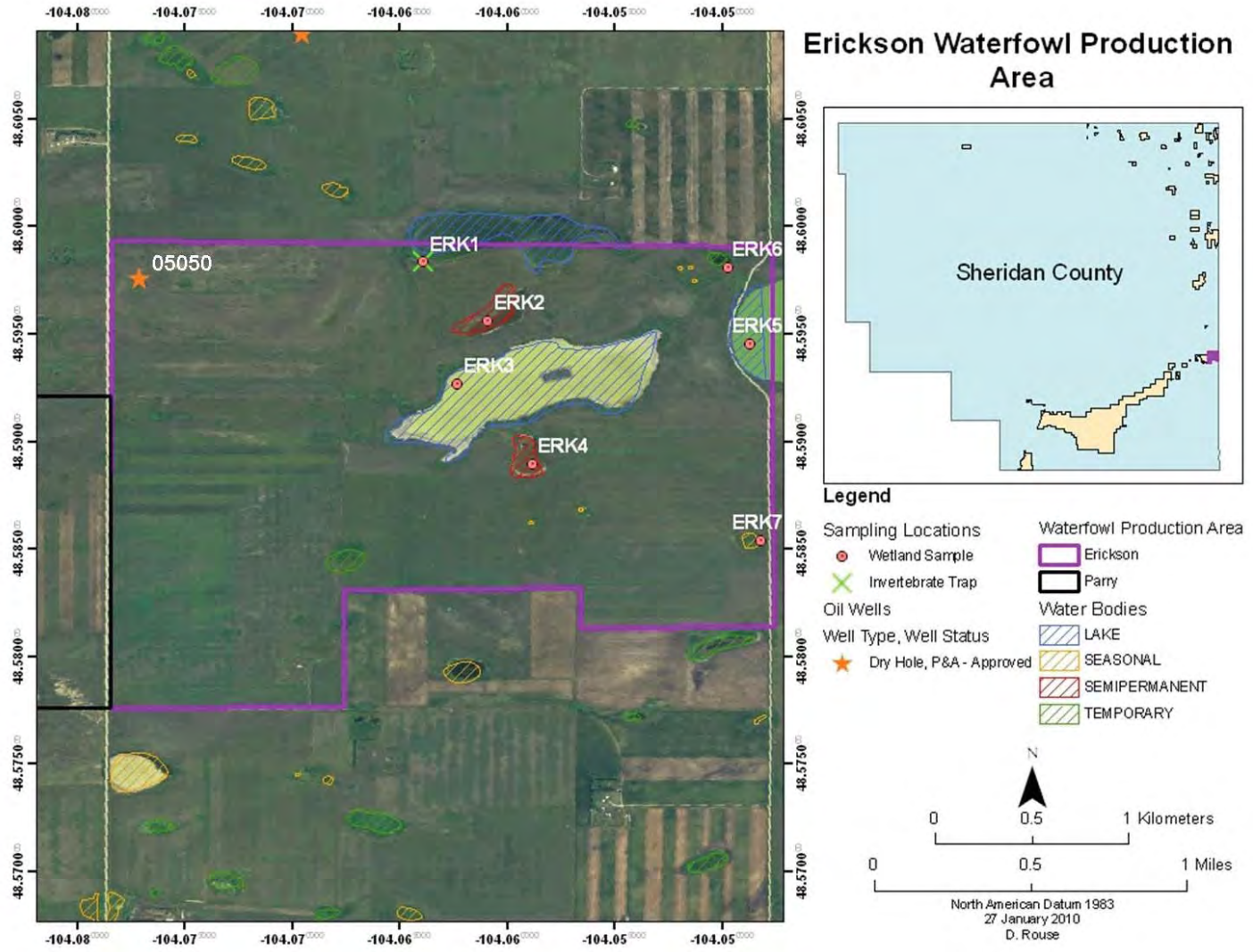


Figure 91. Map depicting locations of sampling sites, oil wells, and bodies of water for the Erickson WPA: T. 33 N., R. 58 E., sec. 24 & 25.

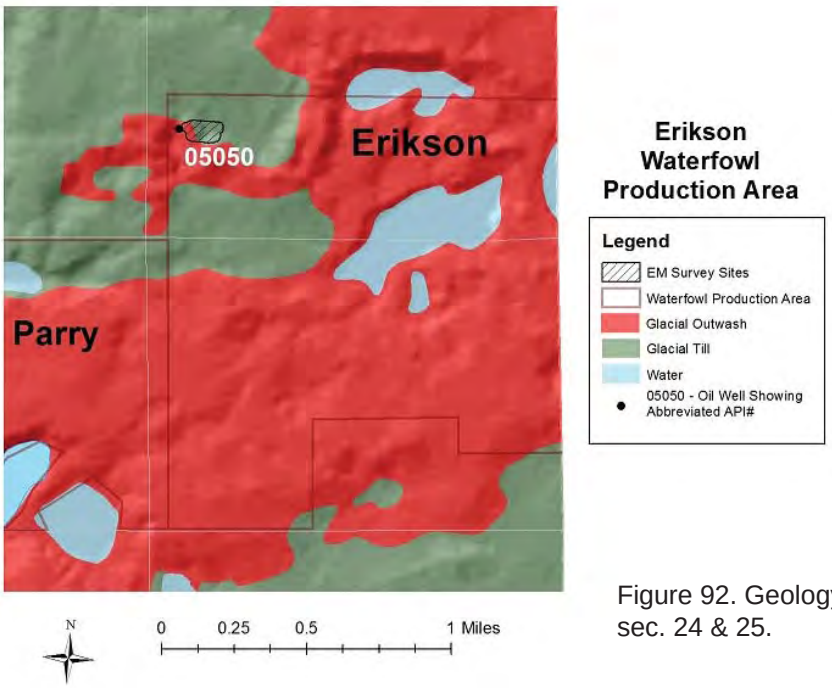


Figure 92. Geology of the Erikson WPA: T. 33 N., R. 58 E., sec. 24 & 25.

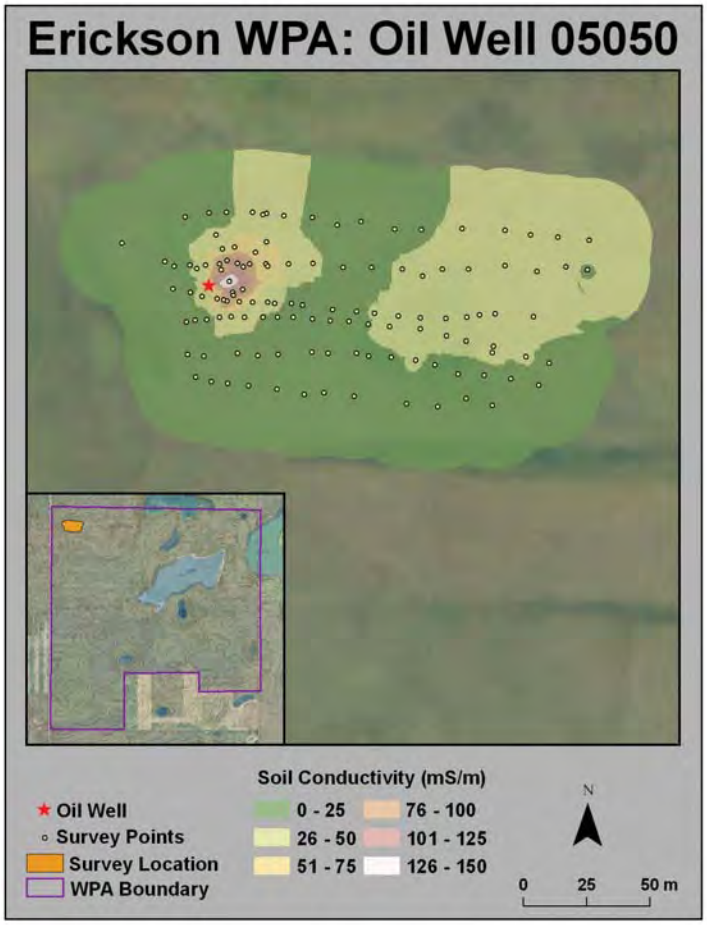


Figure 93. Location of EM-31 terrain-conductivity surveys conducted at the Erickson WPA: T. 33 N., R. 58 E., sec. 24 & 25.

Lake, which was sampled in 1990 (GWIC ID 120885). The chloride concentration was 7690 mg/L in 1990 and the calculated CI from that sample was 0.08. Although ERK5 is still impacted from brine contamination, the most recent surveys indicate that water quality has improved, most likely due to the influx of non-contaminated water since the 1990s.

### *Co-occurring Contaminants*

There were no additional analyses done for the Erickson WPA.

## Ferguson WPA

The Ferguson WPA was established on 5/17/1968 and encompasses and area of 105.1 acres. Much of the area is covered by a lake, but two seasonal wetlands are located in, or partially located in, the WPA as well (fig. 94). Bird surveys have documented the use of the Ferguson WPA by breeding waterfowl, with observations of 88–111 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA, but an approved plugged and abandoned dry hole and an approved plugged and abandoned oil well are located in close proximity to the WPA. There is also a tank battery that is located in the same watershed as this WPA.

### *Geology*

The Ferguson WPA is underlain by glacial deposits (fig. 95). The surficial materials are largely glacial till. These deposits are estimated to be from 50 to 200 ft thick based on limited test drilling. Glacial outwash deposits are located at depths between 100 and 160 ft. Fort Union sandstone and mudstone underlies the glacial materials. The sand and gravel glacial outwash deposits are associated with the upper permeable zone of the Clear Lake aquifer.

### *Groundwater Hydrology*

Limited drilling data and interpretations indicate that a buried channel reaching depths up to 150 ft underlies this WPA. This aquifer appears to be a northern extension of the Clear Lake aquifer. Groundwater flow is towards the south.

### *Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at this site and there are no established groundwater monitoring wells within the Ferguson WPA.

Table 40. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Erickson WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| ERK1 | 5/14/2004 | 9,680 | 259 | 0.027 | Mesosaline |
| ERK1 | 7/21/2004 | 10,400 | 291 | 0.028 | Mesosaline |
| ERK2 | 5/14/2004 | 36,789 | 1,749 | 0.048 | Polysaline |
| ERK3 | 5/14/2004 | 52,686 | 1,547 | 0.029 | Eusaline |
| ERK4 | 5/14/2004 | 25,072 | 2,303 | 0.092 | Mesosaline |
| ERK5 | 5/14/2004 | 45,169 | 1,678 | 0.037 | Eusaline |
| ERK6 | 5/14/2004 | 3,013 | 53 | 0.018 | Oligosaline |
| ERK7 | 5/14/2004 | 520.2 | 20 | 0.038 | Fresh |

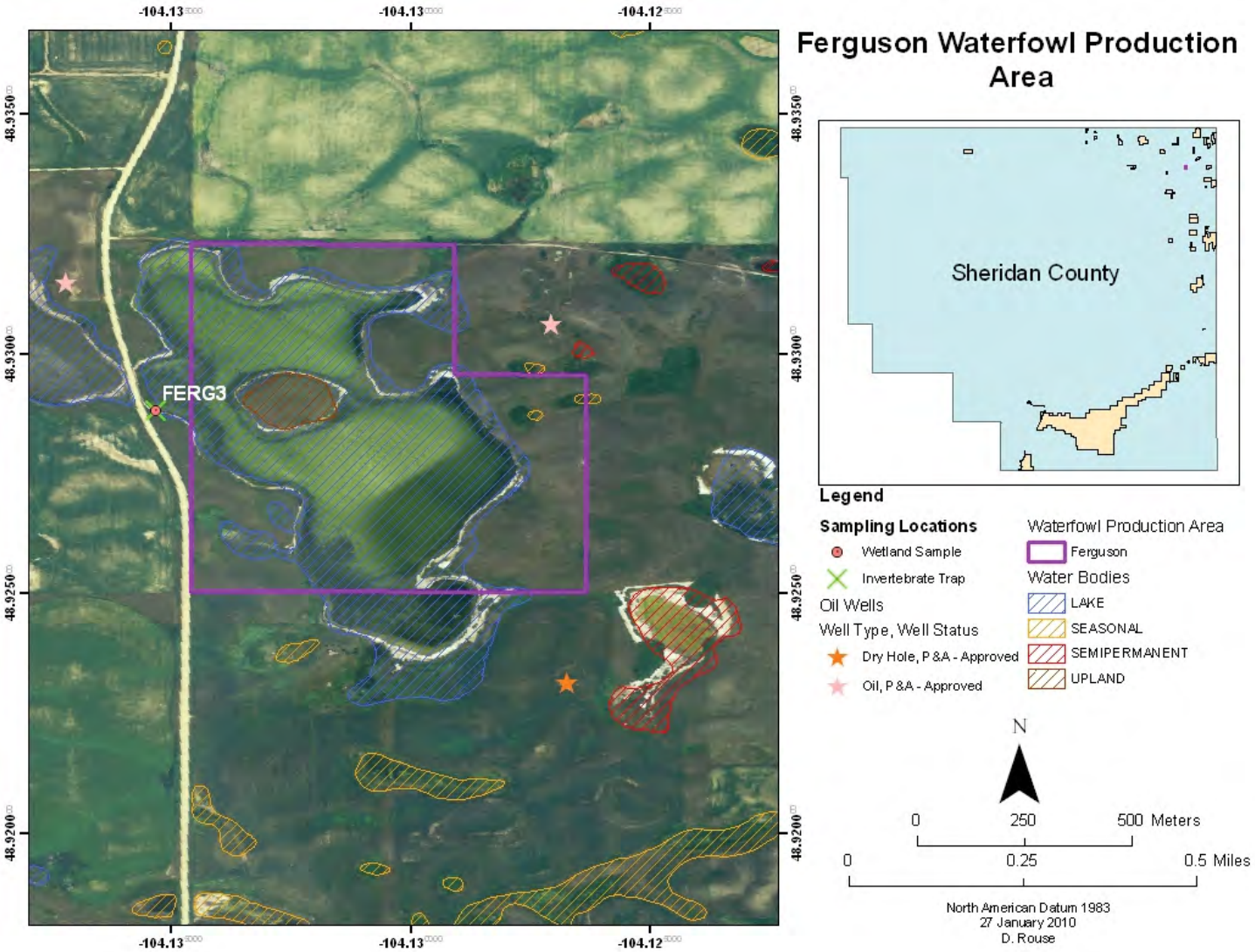


Figure 94. Map depicting locations of sampling sites, oil wells, and bodies of water for the Redhead Retreat WPA: T. 35 N., R. 58 E., sec. 10 & 15.

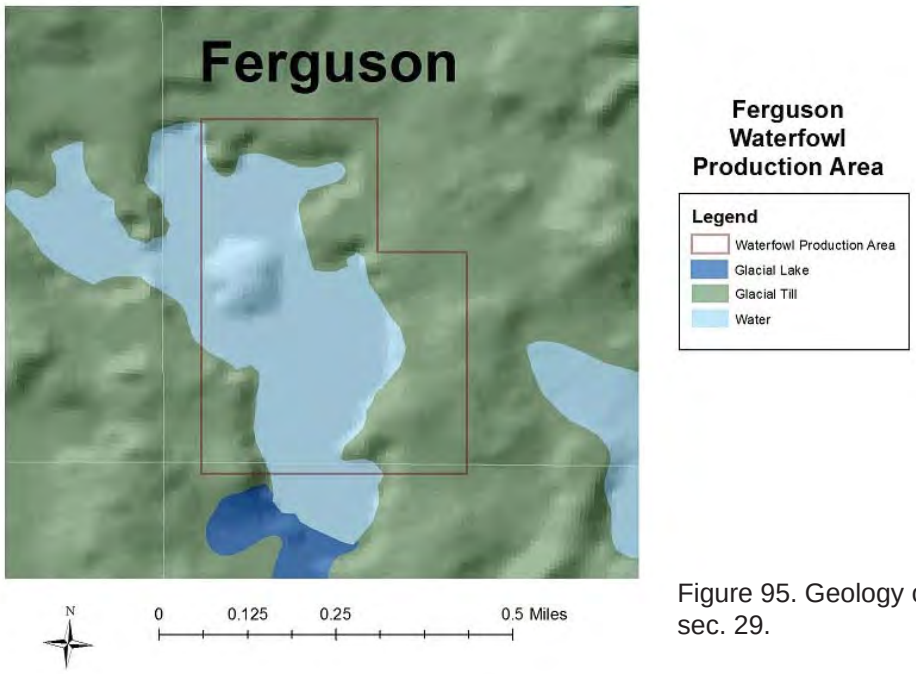


Figure 95. Geology of the Ferguson WPA: T. 37 N., R. 58 E., sec. 29.

Table 41. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Ferguson WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| FERG3 | 5/13/2004 | 21,881 | 527 | 0.024 | Mesosaline |

*Wetland Water Quality*

One wetland site, FERG3, was visited that had a specific conductivity value close to 22,000 µS/cm and a chloride concentration of 527 mg/L (table 41). The CI value for this wetland, 0.024, indicates that there were no produced water impacts at this site at the time of sampling. In comparison, a previous sample collected in 1990 at this location (GWIC ID 120875) had a specific conductivity value close to 28,000 µS/cm and a chloride concentration of 865 mg/L. The CI value of 0.031 is just below the value indicating brine contamination.

*Co-occurring Contaminants*

There were no additional analyses done for the Ferguson WPA.

## Gjesdal East WPA

The Gjesdal East WPA was established on 6/18/1974 and spans an area of 121.69 acres. Two lakes are present in the western half of the WPA (fig. 96). Bird surveys have documented the use of the Gjesdal East WPA by breeding bird pairs during nesting season, with observations of 42–88

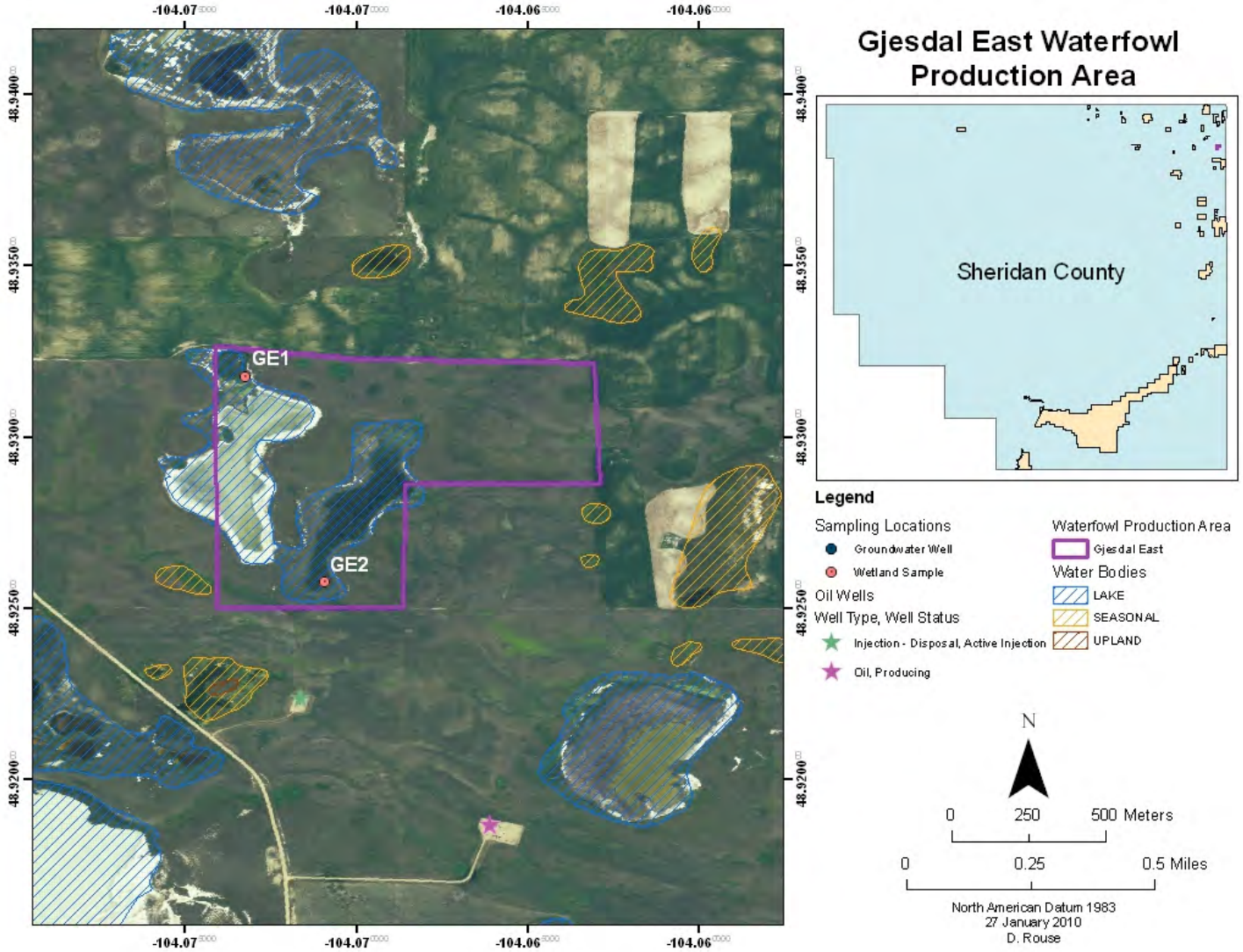


Figure 96. Map depicting locations of sampling sites, oil wells, and bodies of water for the Gjesdal East WPA: T. 37 N., R. 58 E., sec. 26 & 27.

duck pairs per square mile over much of the WPA, although 88–111 duck pairs per square mile have been documented in the southern extent of the WPA (Brian DeVries, USFWS, written commun., 2009). Additionally, there is designated Piping Plover critical habitat. As of January 2010, there were no production wells present within the WPA and the closest well, an active injection-disposal well, was located within 1,000 ft south of the WPA.

### *Geology*

The surficial geology underlying the Gjesdal East WPA is depicted in figure 97. Most of the Gjesdal East WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft. A relatively long and narrow deposit of moderate to high-permeability glacial outwash is mapped south of the area covered by the Base Camp geologic map (fig. 24). This appears to be an extension of the Clear Lake aquifer.

### *Groundwater Hydrology*

Limited drilling data and interpretations from mapping in North Dakota (North Dakota State Water Commission file data) indicate that a buried channel reaching depths up to 150 ft underlies this WPA. This appears to be a tributary of the Clear Lake aquifer. Groundwater flow is towards the south.

### *Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at this site and there are no groundwater monitoring wells located within this WPA.

### *Wetland Water Quality*

The two lakes present within the Gjesdal East WPA were visited for surface-water sampling on 5/17/2004. These sites, GE1 and GE2, had specific conductance values of around 8,000 and 3,000 µS/cm and chloride concentrations of 405.5 and 49.5 mg/L, respectively (table 42). Based on the calculated CI values for each site, GE1, which had a CI value of 0.05, showed signs of produced water impacts, but GE2, which had a CI value of 0.018, did not (table 42). The source of contamination to GE1 is unknown and would require further investigation.

### *Co-occurring Contaminants*

There were no additional analyses done for the Gjesdal East WPA.

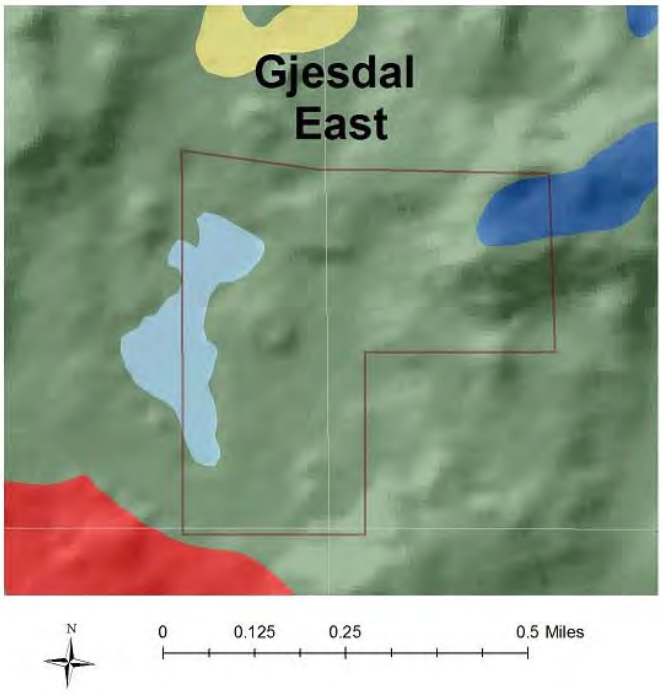


Figure 97. Geology of the Gjesdal East WPA: T. 37 N., R. 58 E., sec. 26 & 27.

Table 42. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Gjesdal East WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| GE1 | 5/17/2004 | 8,150 | 406 | 0.050 | Mesosaline |
| GE2 | 5/17/2004 | 2,740 | 50 | 0.018 | Oligosaline |

## Redhead Retreat WPA

The Redhead Retreat WPA was established on 2/17/1970, but additional land was acquired on 4/23/1970. This WPA encompasses an area of approximately 206.26 acres, including parts of three separate water bodies (fig. 98). Bird surveys have documented the use of the Redhead Retreat WPA by breeding waterfowl, with observations of 20–42 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells located within the WPA, but two wells, both approved plugged and abandoned dry holes, are located within a quarter of a mile to the southeast of the WPA. Additionally, one approved plugged and abandoned disposal-injection well is located just over a quarter of mile northwest of the WPA.

### *Geology*

The Redhead Retreat WPA is underlain largely by glacial deposits (fig. 99). Glacial till makes up most of this and relatively thin deposits of Quaternary alluvium are associated with the wetlands. These alluvial deposits are probably composed of organic silts and clays. A borehole located in the NE quarter section of Section 10 (GWIC ID 154227) penetrated about 40 ft of glacial till before encountering Fort Union bedrock.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Redhead Retreat WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetland to the west of the site. No regional glacial outwash aquifers have been identified in this area.

### *Characterizing Oilfield Production Brine Migration*

No EM-31 surveys were conducted at this site, and there are no groundwater monitoring wells associated with this WPA.

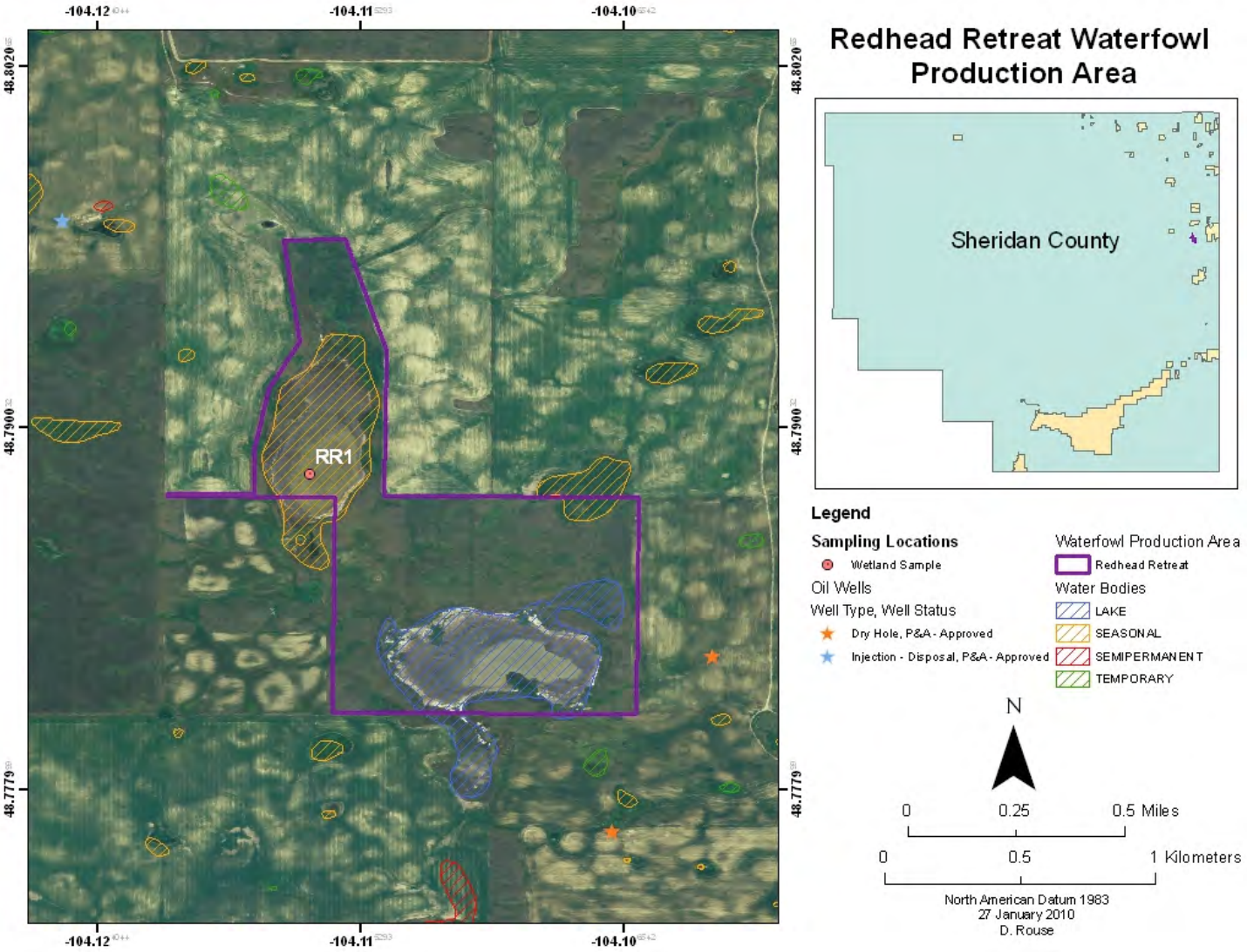


Figure 98. Map depicting locations of sampling sites, oil wells, and bodies of water for the Redhead Retreat WPA: T. 35 N., R. 58 E., sec. 10 & 15.

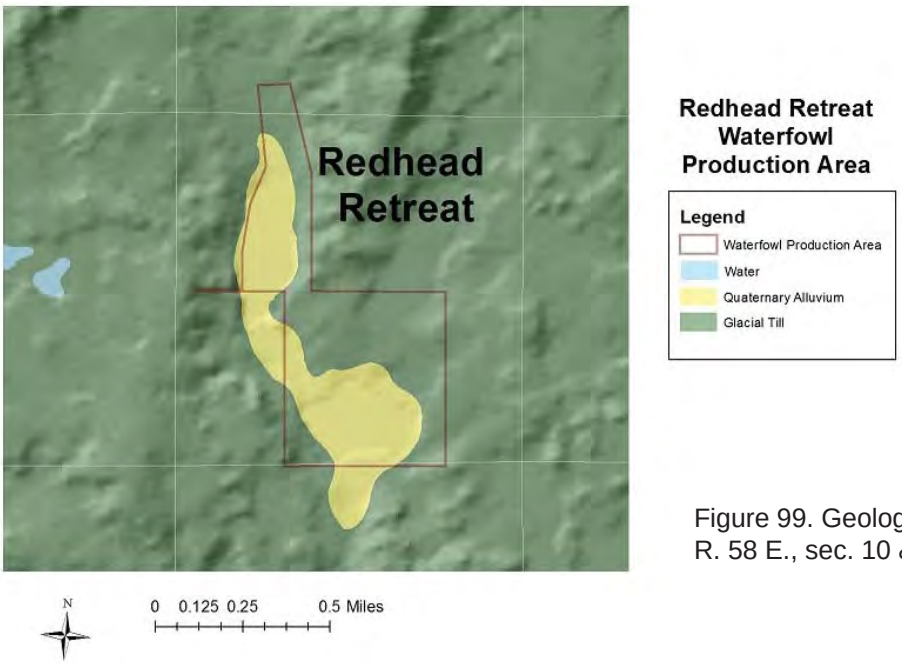


Figure 99. Geology of the Redhead Retreat WPA: T. 35 N., R. 58 E., sec. 10 & 15.

*Wetland Water Quality*

One seasonal wetland was visited to assess surface-water condition. The specific conductivity at this site was around 16,000 µS/cm and the chloride concentration was 560.5 mg/L (table 43). The CI for this site is just below the empirical lower limit of contamination, indicating that this site may be receiving contaminated water from some source. Since EM-31 surveys were not conducted and monitoring wells are not established, identifying that source would require future monitoring efforts.

*Co-occurring Contaminants*

There were no additional analyses done for the Redhead Retreat WPA.

## Westgard WPA

The Westgard WPA was established on 5/21/1968 and encompasses an area of approximately 120 acres. Multiple water bodies are located in, or partially located in, the WPA, including lakes, plus seasonal and semi-permanent wetlands (fig. 100). Bird surveys have documented the use of the Westgard WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA, but three wells, two approved plugged and abandoned dry holes and one producing oil well, are located within a quarter of a mile of the WPA.

*Geology*

The surficial geology underlying the Westgard WPA is depicted in figure 101. Most of this WPA is underlain by glacial sediments. The thickness of the relatively low-permeability glacial till is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 100 to 200 ft. A deeper outwash aquifer was encountered about 1 mile west of this site. A relatively long and narrow deposit of moderate to high-permeability glacial outwash is mapped trending north to south through the central part of the Westgard WPA geologic map. A small area of relatively thin Quaternary eolium overlies the till along the eastern and northeastern part of this WPA.

*Groundwater Hydrology*

Little information is available on groundwater flow underlying the Westgard WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. Although some deep glacial outwash wells have

Table 43. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Redhead Retreat WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| RR1 | 5/13/2004 | 21,881 | 527 | 0.024 | Mesosaline |

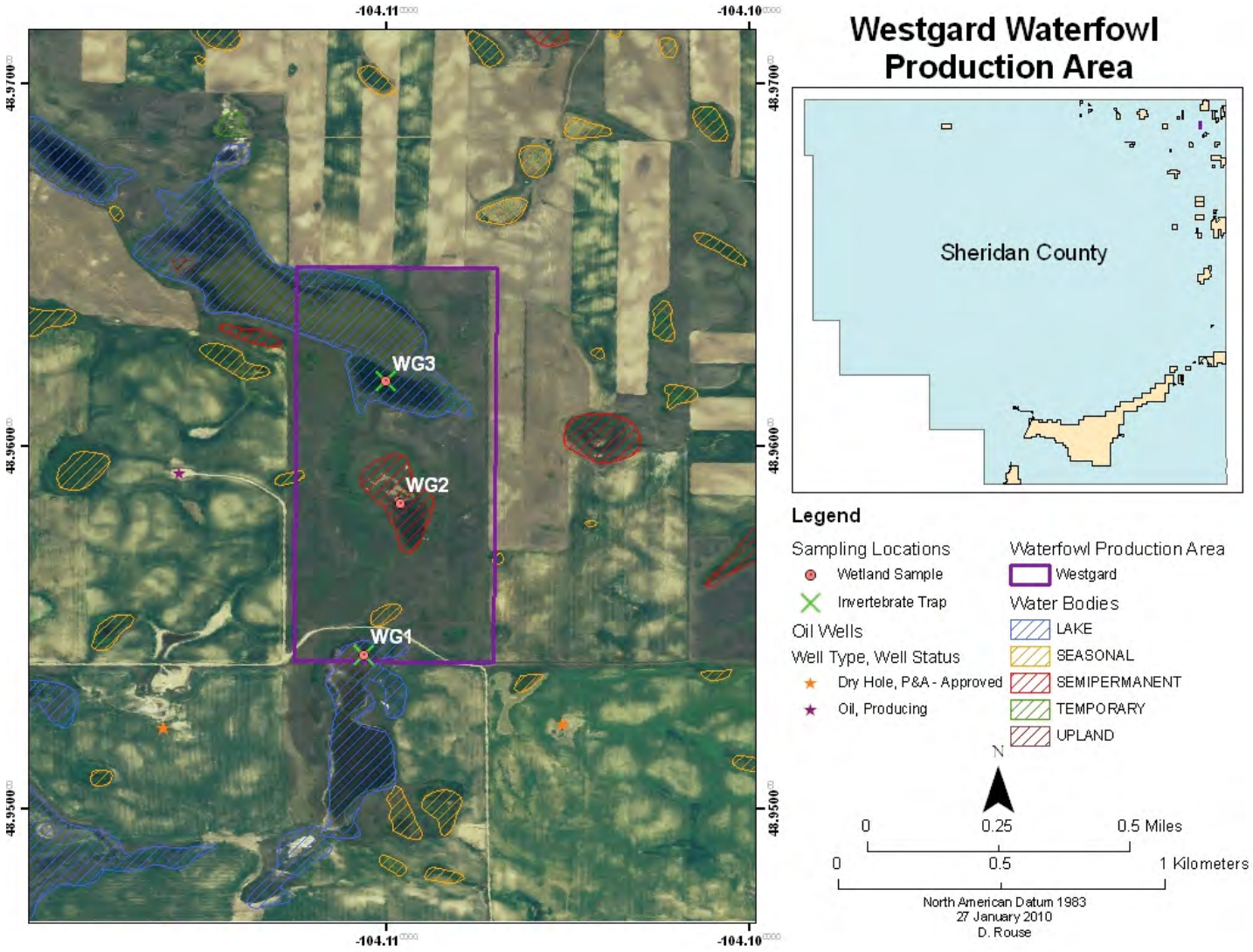


Figure 100. Map depicting locations of sampling sites, oil wells, and bodies of water for the Westgard WPA: T. 37 N., R. 58 E., sec. 17.

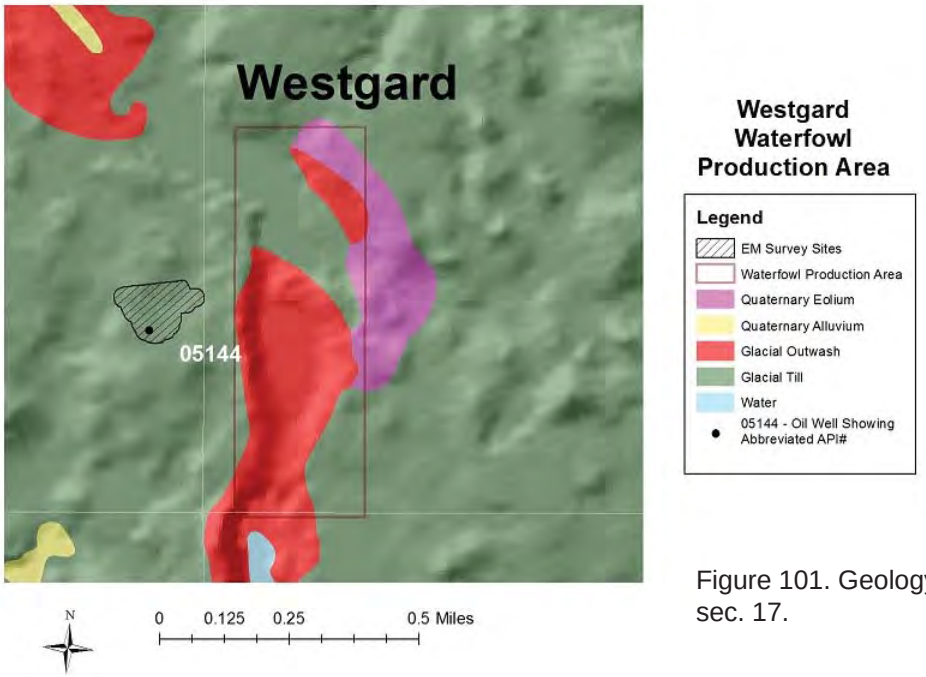


Figure 101. Geology of the Westgard WPA: T. 37 N., R. 58 E., sec. 17.

Table 44. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Westgard WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| WG1 | 5/16/2004 | 25,955 | 433 | 0.017 | Mesosaline |
| WG1 | 7/23/2004 | 31,520 | 444 | 0.014 | Polysaline |
| WG2 | 5/16/2004 | 15,530 | 405 | 0.026 | Mesosaline |
| WG3 | 5/16/2004 | 11,863 | 377 | 0.032 | Mesosaline |
| WG3 | 9/9/2004 | 19,041 | 1,423 | 0.075 | Mesosaline |

been constructed in this area, no regional glacial outwash aquifers have been identified, and these permeable zones appear to be isolated.

### *Characterizing Oilfield Production Brine Migration*

EM-31 terrain conductivity surveys indicated higher than background readings in an area north of oil well location 05144 (fig. 102). Well 05144 was completed in 1965; therefore, the elevated conductivity may reflect buried brine-saturated material in an unlined reserve pit. There are no groundwater monitoring wells associated with this WPA, so the groundwater chemistry was not characterized for this site.

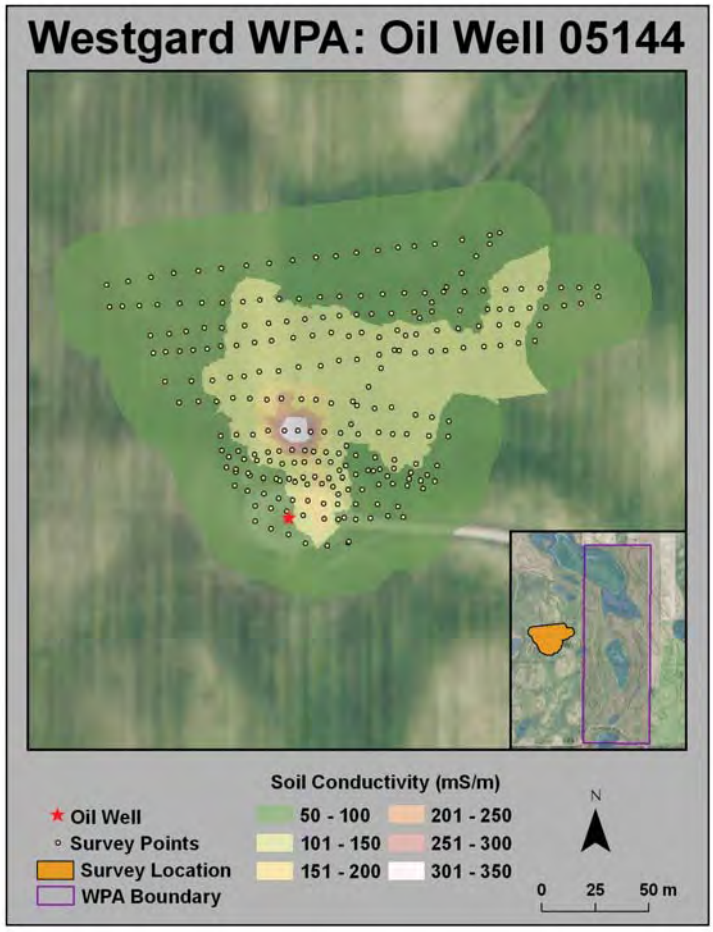


Figure 102. Location of EM-31 terrain-conductivity surveys conducted at the Westgard WPA: T. 37 N., R. 58 E., sec. 17.

### *Wetland Water Quality*

Three sites, WG1, WG2, and WG3 (GWIC ID 214793), were visited for surface-water analyses. Specific conductance and chloride concentrations for these sites ranged from around 11,900 to 31,500 µS/cm and 377 to 1,423 mg/L, respectively (table 44). With the exception of one site, site WG3 (GWIC ID 214793), produced water impacts were not evident based on CI values. On 5/16/2004, the CI for WG3 (GWIC ID 214793) was actually below 0.035, but was elevated during the 9/9/2004 sampling event (table 44). This result may be a result of seasonal variation within a wetland. For instance, a similar trend is seen in WG1 for specific conductivity in that conductance increased from May to July, although the CI remained relatively stable. On the other hand, the large increase in the CI for WG3 (GWIC ID 214793) indicates that the Cl- ions are accumulating disproportionately to other ions, suggesting WG3 (GWIC ID 214793) is receiving contaminated water.

### *Co-occurring Contaminants*

Metals data are available for WG3 (GWIC ID 214793) from the 9/9/2004 sampling event (table 45). Various elements were present in the sample, although many were below the limits of detection. When compared to EPA's national recommended water-quality criteria, the only concentration that exceeded any established benchmark was selenium. Although slight, a significant positive relationship was detected between surface-water selenium concentrations and the CI (table 7). Selenium has been detected in produced water samples collected from produced water reinjection sites in the Williston Basin before (Chen-Northern, 1994). Food chain bioaccumulation and reproductive failure in certain fish and wildlife species has been reported for aqueous selenium concentrations as low as 2 µg/L. Therefore, the concentration detected at WG3 (GWIC ID 214793) in 2004, 81 µg/L, posed a great risk to many wildlife species, particularly sensitive species like aquatic birds.

Table 45. Surface-water concentrations (µg/L) of trace elements present in the sampled wetland WG3 in 2004.

| | WG3 |
|---|---|
| Ag | <20 |
| Al | <200 |
| As | 26.4 |
| B | 3472 |
| Ba | <49 |
| Be | <40 |
| Br | 5,860 |
| Cd | <20 |
| Co | <40 |
| Cr | <40 |
| Cu | <40 |
| Li | 1,438 |
| Mo | <200 |
| Ni | <40 |
| Pb | <40 |
| Se | 81[#] |
| Sr | 461 |
| Ti | <20 |
| U | <10 |
| V | <100 |
| Zn | <40 |
| Zr | <40 |

[#]Indicates value exceeded EPA's recommended national water-quality criteria.

## Dog Leg WPA

The Dog Leg WPA was established on 5/17/1968 and encompasses an area of approximately 70 acres. The WPA is largely covered by two bodies of water, a lake and a semi-permanent wetland (fig. 103). Bird surveys have documented the use of the Dog Leg WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, this area contains designated Piping Plover critical habitat. As of January 2010, there were no production wells present within the WPA, but there are three wells located within a quarter of a miles of the WPA. These include API wells 21075, a shut-in oil well completed in August 1969; 21074, an approved plugged and abandoned oil well completed in July 1969; and 21101, a shut-in oil well completed in June 1970. A tank battery is associated with well 21101, but it appears to not be currently operational.

### *Geology*

The surficial geology underlying the Dog Leg WPA is depicted in figure 104. Most of this WPA is underlain by glacial deposits. A nearby stock well (GWIC ID 190801) encountered about 15 ft of outwash sand and gravel overlying soft gray clay (either clayey till or lake deposits) before completing the well in a coalbed of the Fort Union bedrock at a depth of 110 ft. The glacial outwash shown on the geologic map probably makes up the thin deposit of moderate to high-permeability glacial outwash underlying most of this WPA.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Dog Leg WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well sites to migrate towards the wetland east of well 21075 and northwest of well 21101. No regional glacial outwash aquifers have been identified in this area.

### *Characterizing Oilfield Production Brine Migration*

EM surveys were conducted at three sites close to oil wells that are near the Dog Leg WPA (fig. 105). Terrain conductivity surveys identified higher than background conditions near and downgradient from the three oil well sites (figs. 106–108). The largest plume is associated with the tank battery, while the other areas likely reflect buried brine-saturated waste in unlined reserve pits. These areas of high terrain conductivity appear to be associated with brine plumes migrating downgradient towards nearby wetlands. There are no groundwater monitoring wells associated with this WPA to characterize groundwater chemistry.

### *Wetland Water Quality*

The two bodies of water located in the Dog Leg WPA were visited for surface-water analyses. Specific conductance ranged from around 3,000 to 38,200 µS/cm and chloride concentrations ranged from 49.5 to 1,547 mg/L (table 46). Based on the calculated CI values for each site, DL1 (GWIC ID 214746), which had an average CI value of 0.015, had no produced water impacts, but DL2, which had a CI value of 0.041, did (table 46). Although these two wetlands are in close proximity to each other, DL1 (GWIC ID 214746) was clearly unimpacted, suggesting that there is little to no connectivity between the two water bodies. The EM-31 survey at site 2 reflects extensive brine contamination that may be one source of contamination to DL2.

### *Co-occurring Contaminants*

There were no additional analyses done for the Dog Leg WPA.

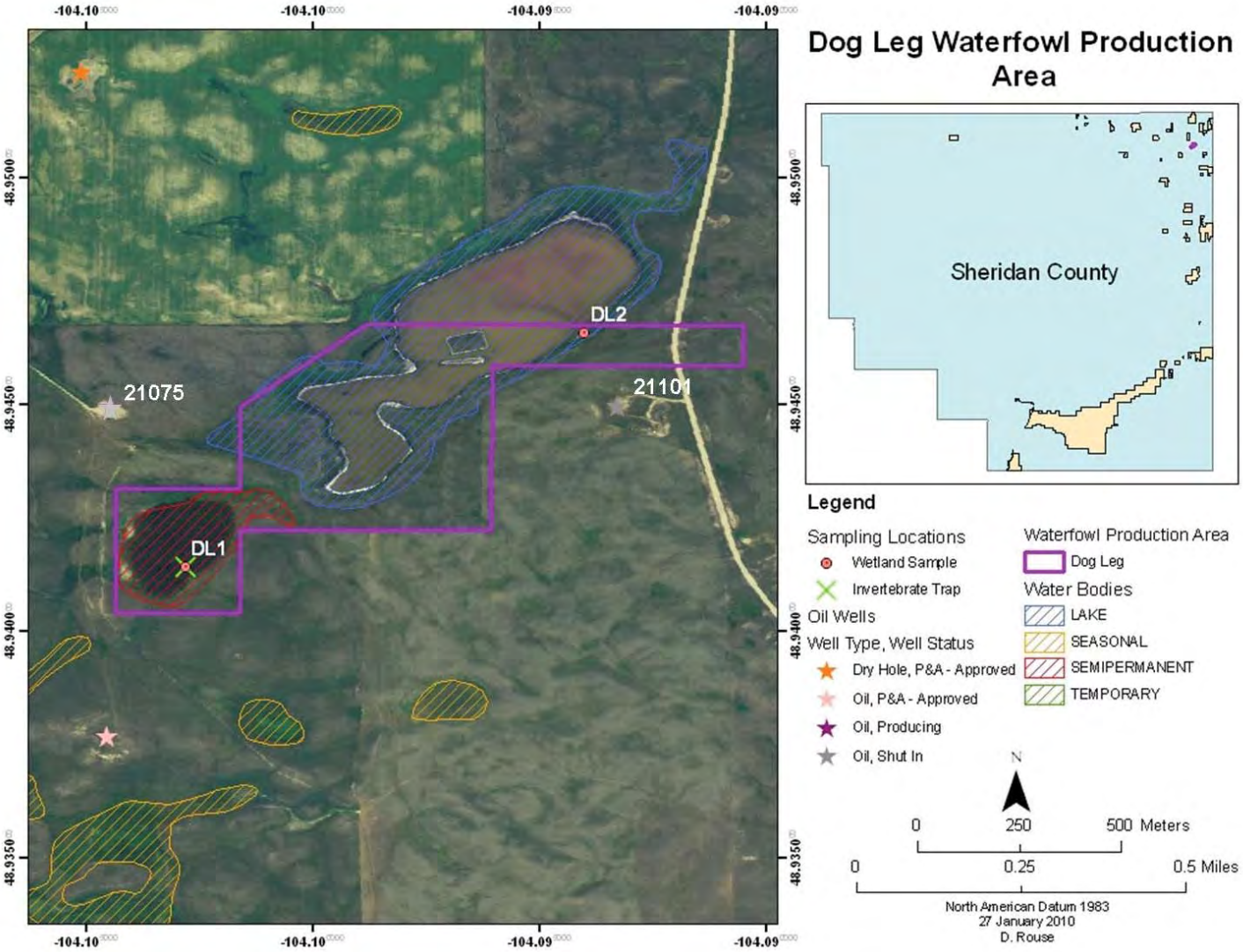


Figure 103. Map depicting locations of sampling sites, oil wells, and bodies of water for the Dog Leg WPA: T. 37 N., R. 58 E., sec. 20.

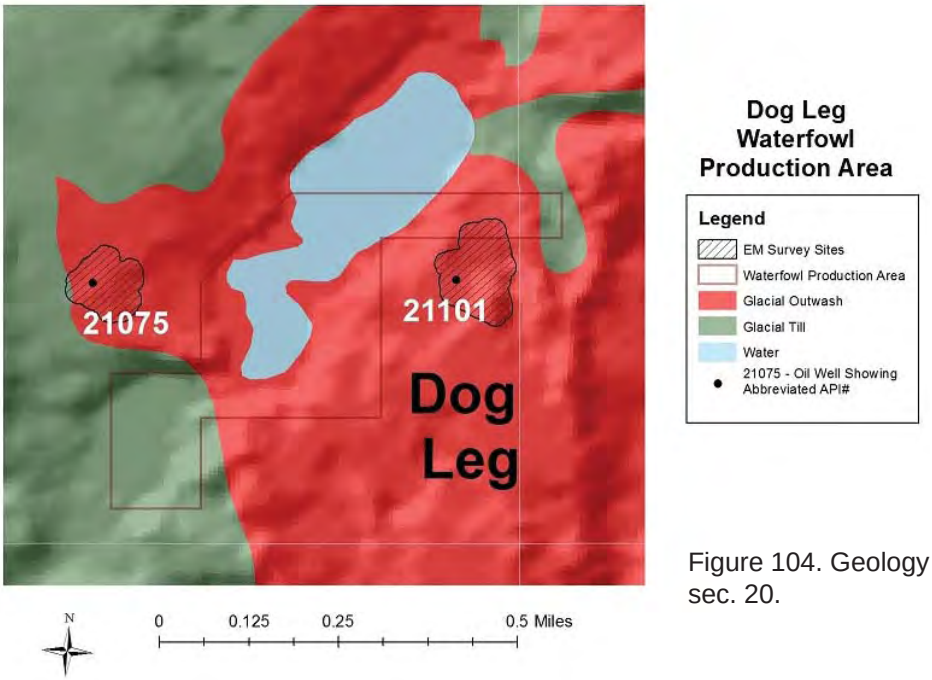


Figure 104. Geology of the Dog Leg WPA: T. 37 N., R. 58 E., sec. 20.

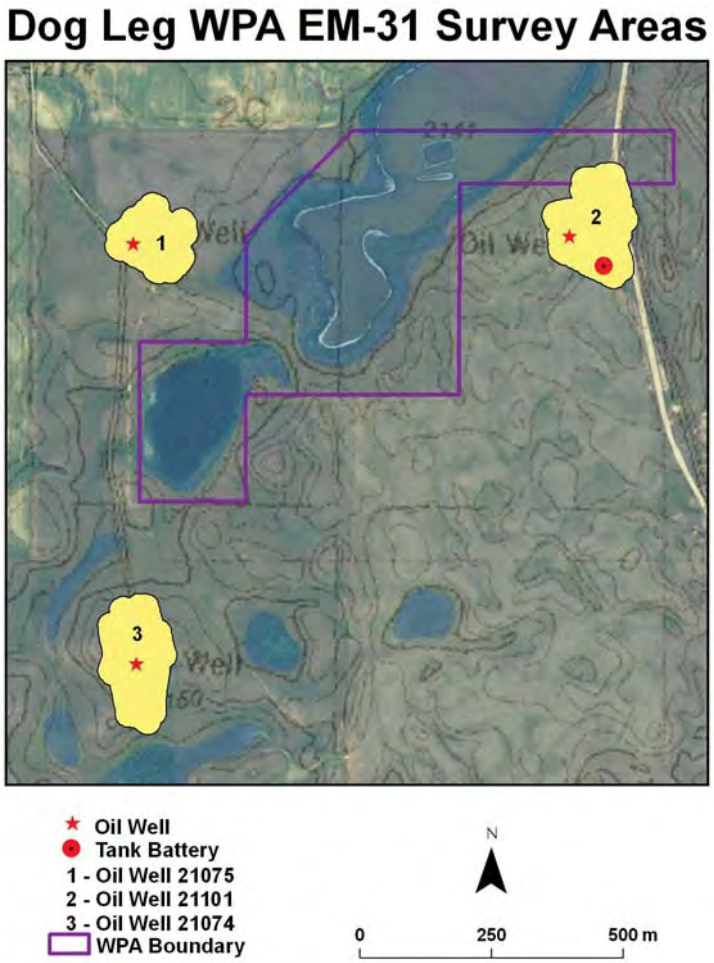


Figure 105. Location of EM-31 terrain-conductivity surveys conducted at the Dog Leg WPA: T. 37 N., R. 58 E., sec. 20.

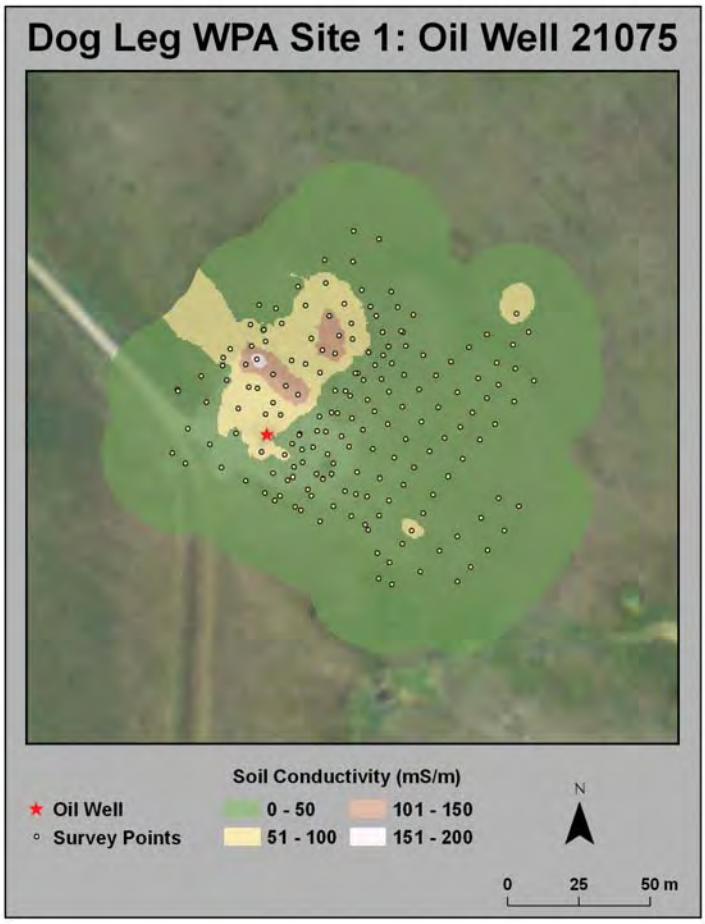


Figure 106. Location of EM-31 terrain-conductivity survey conducted at Site 1 of the Dog Leg WPA.

Table 46. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Dog Leg WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| DL1 | 5/16/2004 | 3,067 | 50 | 0.016 | Oligosaline |
| DL1 | 7/23/2004 | 3,850 | 56 | 0.015 | Oligosaline |
| DL2 | 4/29/2004 | 38,152 | 1,547 | 0.041 | Polysaline |

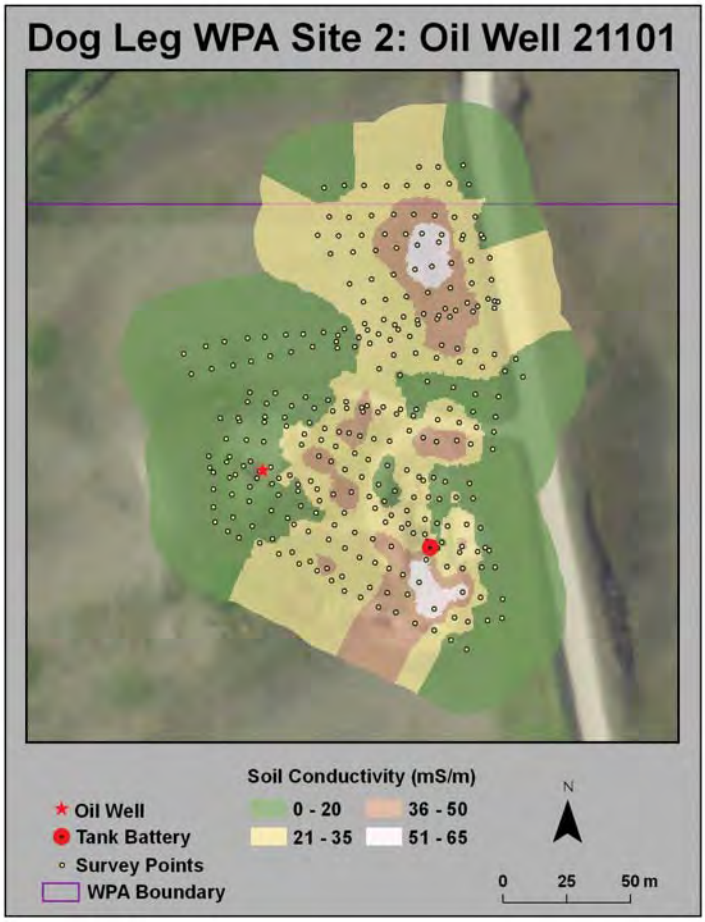


Figure 107. Location of EM-31 terrain-conductivity survey conducted at Site 2 of the Dog Leg WPA.

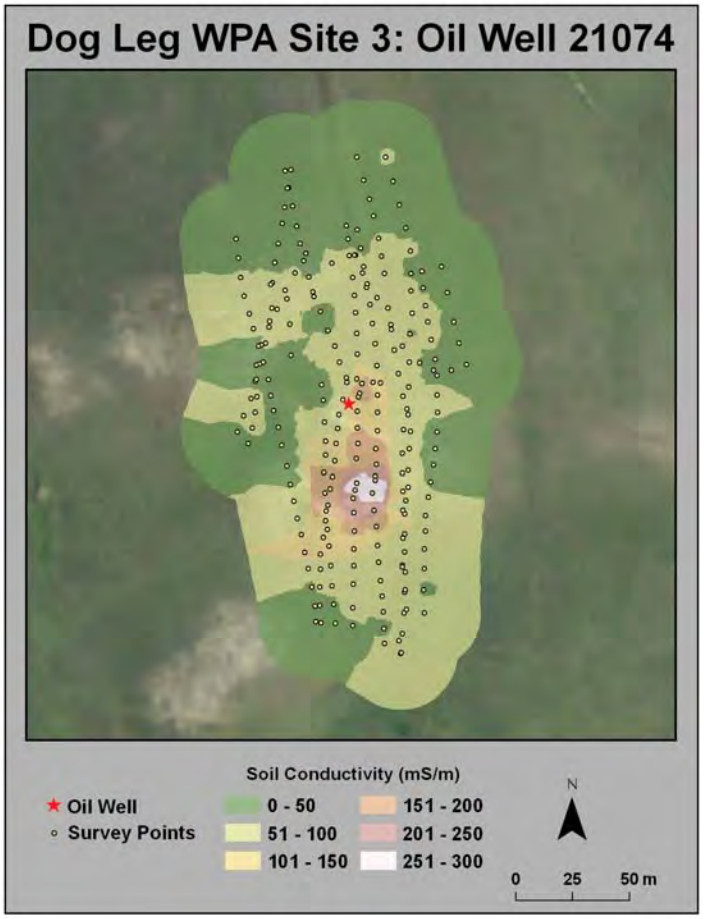


Figure 108. Location of EM-31 terrain-conductivity survey conducted at Site 3 of the Dog Leg WPA.

## Goose Lake WPA

The Goose Lake WPA was established on 7/24/1968, but additional land purchases continued until 7/30/1980. Ultimately, around 1,665 acres were acquired for the Goose Lake WPA. Numerous water bodies are located within this WPA, including lakes, plus seasonal and semi-permanent wetlands (fig. 109). Bird surveys have documented the use of Goose Lake WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, this area contains designated Piping Plover critical habitat. As of January 2010, there was one approved plugged and abandoned dry hole (well 05082) located within the WPA; there were no other production wells located within the Goose Lake WPA. There are, however, three approved plugged and abandoned dry holes located within 700 ft of the WPA. Most of the reserve pits associated with these wells would have been unlined based on their dates of completion. A produced water disposal facility could result in contamination of wetland GL12.

### *Geology*

The Goose Lake WPA overlies a major glacial outwash deposit that makes up the Clear Lake aquifer (fig. 110). The entire WPA is underlain by glacial outwash deposits. These deposits are estimated to be from 50 to 150 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlie the glacial materials. Quaternary alluvial and lacustrine deposits are located underlying relatively small areas of the Goose Lake WPA and are associated with swales and lowlands along wetlands and lakes.

### *Groundwater Hydrology*

The Goose Lake WPA overlies the Clear Lake aquifer. Several highly productive irrigation wells are located east of the WPA. Regional groundwater flow in the aquifer is generally towards the south or southwest. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes.

### *Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at this WPA, and there are no groundwater monitoring wells associated with this site. Appendix A contains a supplemental report that contains a detailed investigation and assessment of brine contamination across the Goose Lake Oilfield.

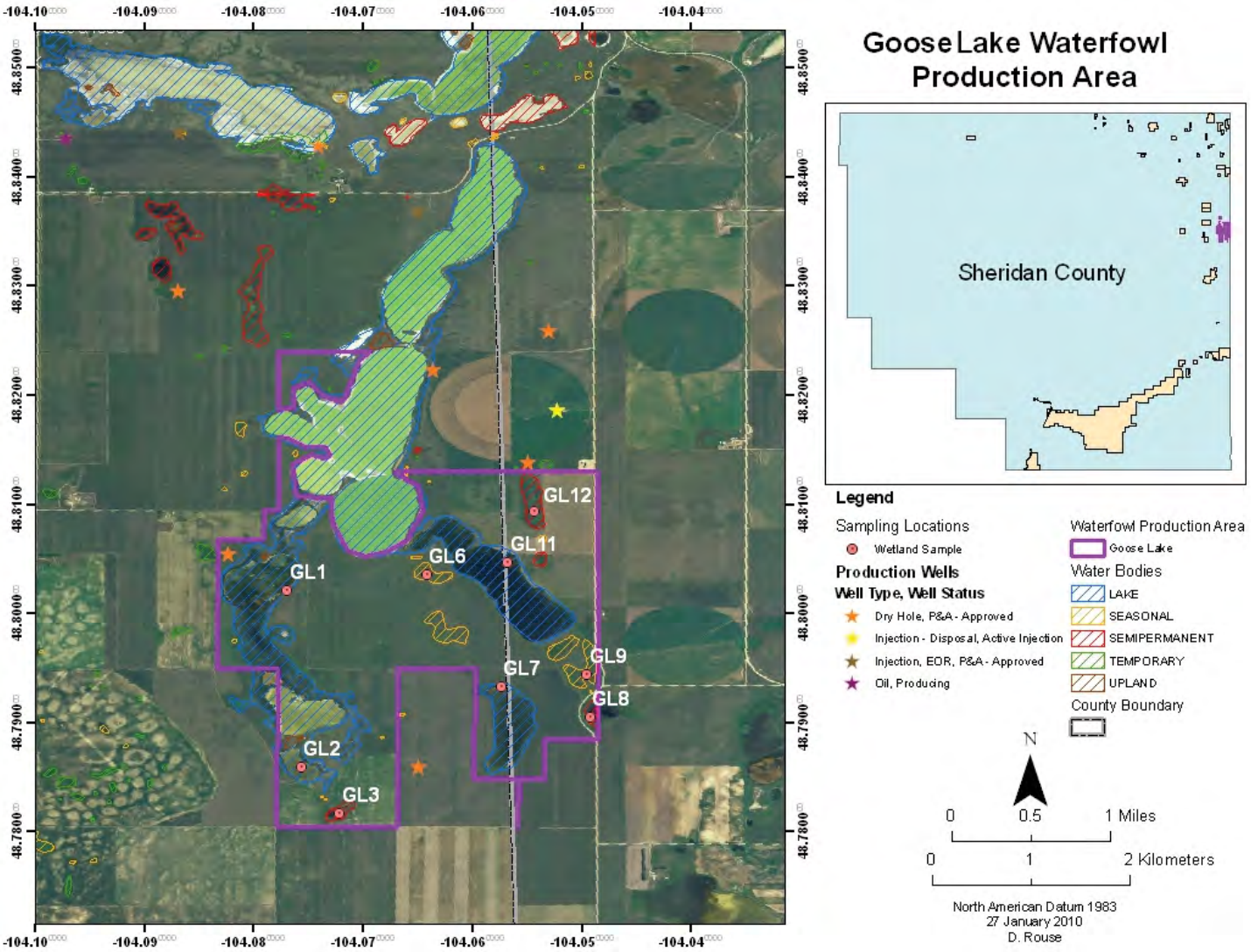


Figure 109. Map depicting locations of sampling sites, oil wells, and bodies of water for the Goose Lake WPA: T. 35 N., R. 58 E., sec. 1, 11, 12 & 13.

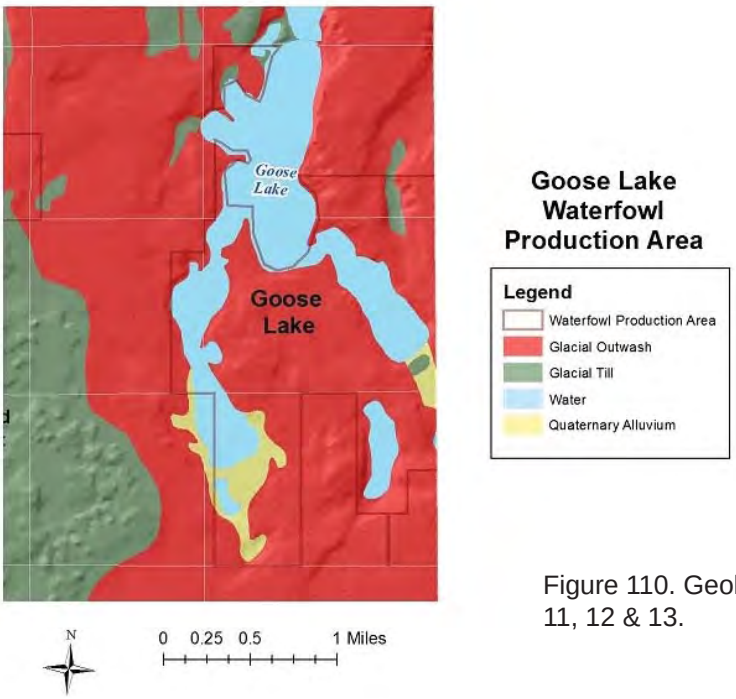


Figure 110. Geology of the Goose Lake WPA: T. 35 N., R. 58 E., sec. 1, 11, 12 & 13.

Table 47. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Goose Lake WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| GL1 | 5/13/2004 | 3,859 | 53 | 0.014 | Oligosaline |
| GL1 | 7/8/2005 | 3,702 | 39 | 0.011 | Oligosaline |
| GL2 | 5/14/2004 | 9,655 | 222 | 0.023 | Mesosaline |
| GL3 | 5/14/2004 | 5,209 | 46 | 0.009 | Oligosaline |
| GL3 | 7/9/2004 | 4,198 | 52 | 0.012 | Oligosaline |
| GL6 | 5/13/2004 | 278 | 5 | 0.019 | Freshwater |
| GL7 | 5/13/2004 | 6,610 | 120 | 0.018 | Oligosaline |
| GL7 | 7/8/2005 | 8,370 | 137 | 0.016 | Mesosaline |
| GL8 | 5/13/2004 | 2,145 | 39 | 0.018 | Oligosaline |
| GL8 | 7/8/2005 | 2,532 | 52 | 0.021 | Oligosaline |
| GL9 | 5/13/2004 | 1,887 | 23 | 0.012 | Oligosaline |
| GL11 | 5/13/2004 | 1,829 | 61 | 0.033 | Oligosaline |
| GL12 | 5/13/2004 | 3,024 | 78 | 0.026 | Oligosaline |

*Wetland Water Quality*

Nine surface-water sites were visited that had specific conductance ranging from around 300 to 10,000 µS/cm and chloride concentrations ranging from around 5 to 200 mg/L (table 47). There were no sites that showed signs of produced water impacts based on their calculated CI values (table 47). However, a water sample was collected in 1990 along the southeast shore of Goose Lake at GWIC ID 120850. At that time, there appeared to be an indication of brine contamination with a specific conductance of 28,790 µS/cm, chloride concentration of 1070 mg/L, and calculated CI of 0.037.

*Co-occurring Contaminants*

Metals data are available for sites GL1, GL3, anTad GL7 from the 7/11/2005 sampling event. Based on that data, GL1 had cadmium and nickel concentrations that exceeded established water-quality benchmarks, while GL3 had cadmium and lead concentrations that exceeded established water quality benchmarks (table 48). Due to the lack of brine impacts at these sites, oil production and exploration activities appear to have little influence on the surface-water concentrations of cadmiuTablem, nickel, and lead at these sites. There are no monitoring wells associated with this WPA.

Table 48. Surface-water concentrations (µg/L) of trace elements present in select wetlands of the Goose Lake WPA in 2005.

| | GL1 | GL3 | GL7 |
|---|---|---|---|
| Al | <50 | <50 | <50 |
| As | 143 | 92.9 | 19.3 |
| B | 23,100 | 2,540 | 1,490 |
| Ba | 14 | 109 | 7 |
| Be | <0.5 | <0.5 | <0.5 |
| Cd | 1.35# | 0.22# | 0.05 |
| Co | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 |
| Mo | <10 | <10 | <10 |
| Ni | 16# | 11 | <5 |
| Pb | <0.51 | 0.58# | <0.05 |
| Se | 0.31 | 0.43 | <0.1 |
| Sr | 40 | 410 | <25 |
| Ti | <5 | <5 | <5 |
| V | <10 | <10 | <10 |
| Zn | <5 | <5 | <5 |

# Indicates value exceeded EPA's recommended national water-quality criteria.

## Gjesdal West WPA

The Gjesdal West WPA was established on 6/18/1974 and encompasses an area of approximately 400 acres. There are numerous seasonal wetlands scattered throughout the WPA, and as of January 2010, there was one approved plugged and abandoned well (21171) within the WPA, cpmpleted in 1976 (fig. 111). Based on its date of completion, there was likely a lined reserve pit associated with this well for waste storage and disposal. There are no other wells within the WPA, but the next closest well is an approved plugged and abandoned dry hole located within 700 ft northwest of the WPA. Bird surveys have documented the use of the Gjesdal West WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile throughout much of the WPA during the nesting season (Brian DeVries, USFWS, written commun., 2009).

### *Geology*

The surficial geology underlying the Gjesdal West WPA is depicted in figure 112. Most of the Northeast WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 150 ft. Nearby well logs indicate layers of glacial outwash within the thicker till deposits. The glacial till or outwash deposits directly overlie Fort Union bedrock.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Gjesdal West WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. No regional glacial outwash aquifers have been identified in this area, although in several cases productive zones of glacial outwash have been identified. For example, in the NE quarter of Section 8 at GWIC ID 206182, water is produced from an outwash aquifer at a depth of 132 to 141 ft.

### *Characterizing Oilfield Production Brine Migration*

EM-31 surveys were conducted at one site surrounding oil well 21171. These terrain conductivity surveys indicated

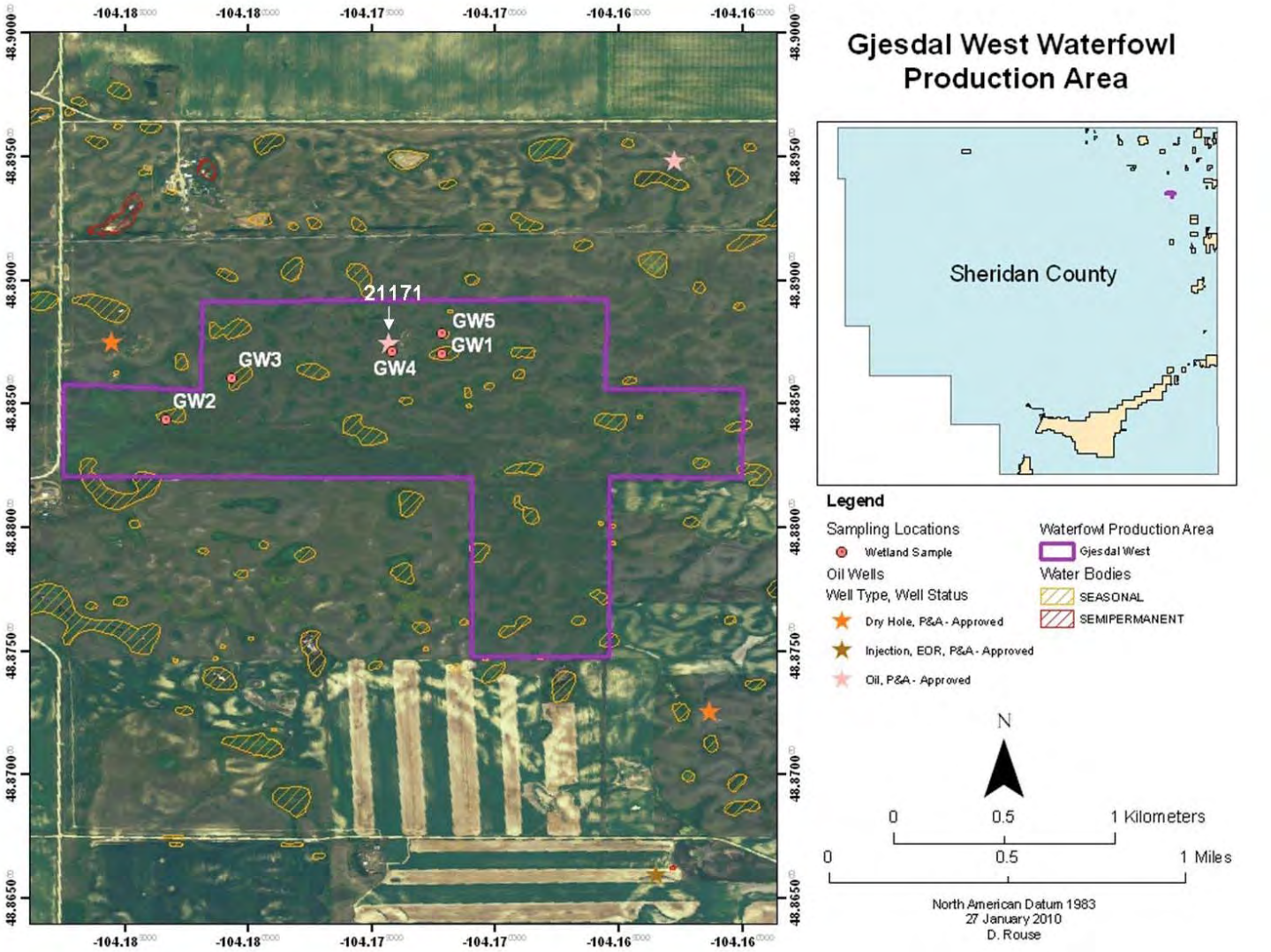


Figure 111. Map depicting locations of sampling sites, oil wells, and bodies of water for the Gjesdal West WPA: T. 35 N., R. 58 E., sec. 1, 11, 12 & 13.

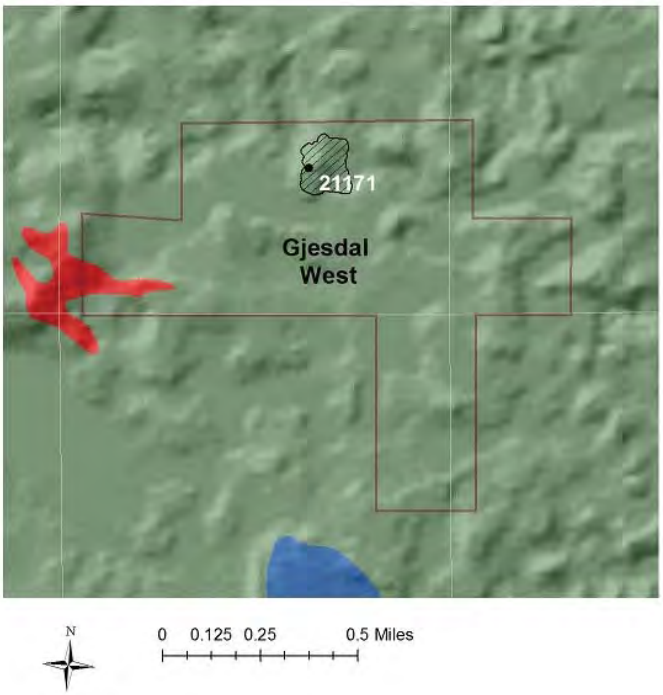


Figure 112. Geology of the Gjesdal West WPA: T. 36 N., R. 58 E., sec. 7, 8, 17 & 18.

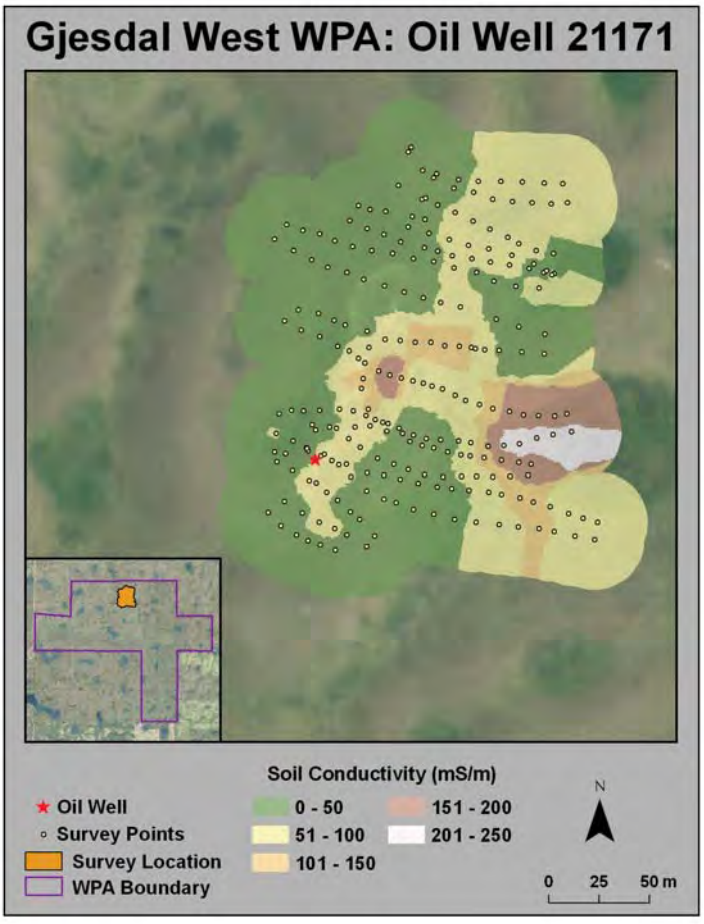


Figure 113. Location of EM-31 terrain-conductivity surveys conducted at the Gjesdal West WPA: T. 36 N., R. 58 E., sec. 7, 8, 17 & 18.

higher than background readings in an area east and north of oil well location 21171 (fig. 113). These appear to be related to well construction activities where brine or brine-saturated materials were either spilled or buried. There are no groundwater monitoring wells associated with this site to characterize groundwater chemistry.

### *Wetland Water Quality*

Five sites were visited at the Gjesdal West WPA to assess surface-water conditions. Specific conductance ranged from around 100 to 800 µS/cm and chloride concentrations ranged from 0 to 123 mg/L (table 49). Chloride concentrations were below detection in the field for GW4. Its position upslope of the migrating plume provides protection from contaminant influences. Conversely, sites GW1 and GW5 appear to be more vulnerable to brine impacts and are receiving contaminant impacts from oil well 21171. The source of contamination for GW3 is unclear. With the exception of sites GW4 and GW2 (missing chloride data), every site had an average CI value that exceeded 0.035, indicating produced water impacts.

### *Co-occurring Contaminants*

When compared to EPA's recommended national water-quality criteria, GW1 and GW5 had exceedances for cadmium, while GW5 also exhibited lead and zinc concentrations that exceeded benchmark values (table 50). The influence of oil production and exploration activities on wetland cadmium, lead, and zinc concentrations is unclear. There were no significant relationships detected between the CI and surface-water cadmium and lead concentrations, while the relationship between surface-water zinc concentrations and the CI was not assessed due the large number of zinc values below the analytical detection limit (table 7). Regardless, all three elements have been detected in produced water samples collected from produced water reinjection sites in the Williston Basin (Chen-Northern, 1994), and coupled with the fact that both groundwater cadmium and zinc concentrations have positive significant relationships with the CI suggests that oil production activities may have had some influence on the elevated element concentrations detected at GW1 and GW5 (table 5).

Table 49. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Gjesdal West WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| GW1 | 5/17/2004 | 754 | 123 | 0.163 | Freshwater |
| GW1 | 6/13/2005 | 521 | 78 | 0.150 | Freshwater |
| GW2 | 5/17/2004 | 179.3 | No Data | No Data | Freshwater |
| GW3 | 5/17/2004 | 120.9 | 4 | 0.036 | Freshwater |
| GW4 | 5/17/2004 | 166 | 0 | 0 | Freshwater |
| GW5 | 5/17/2004 | 94.4 | 4 | 0.047 | Freshwater |
| GW5 | 6/13/2005 | 156 | 4 | 0.025 | Freshwater |

Table 50. Surface-water concentrations (µg/L) of trace elements present in select wetlands of the Gjesdal West WPA in 2005.

| | GW1 | GW5 |
|---|---|---|
| Al | <50 | 60 |
| As | 2.53 | 1.29 |
| B | 403 | 90 |
| Ba | 65 | 54 |
| Be | <0.5 | <0.5 |
| Cd | 0.51# | 0.15# |
| Co | <5 | <5 |
| Cr | <5 | <5 |
| Cu | <5 | <5 |
| Hg | <0.1 | <0.1 |
| Mo | <10 | <10 |
| Ni | <5 | <5 |
| Pb | 0.21 | 0.31# |
| Se | 0.28 | 0.83 |
| Sr | 190 | 30 |
| Ti | <5 | <5 |
| V | <10 | <10 |
| Zn | 12 | 26# |

# Indicates value exceeded EPA's national recommended water-quality criteria.

## Olson WPA

The Olson WPA was established on 5/1/1969 and encompasses approximately 16 acres. There is one lake system that partially extends into the WPA (fig. 114). Bird surveys have documented the use of the Olson WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009 . As of January 2010, there were no production wells present within or in close proximity to the WPA. In fact, the closest well was located greater than half a mile away.

### *Geology*

The Olson WPA is underlain by glacial outwash deposits and pre-glacial alluvial deposits (fig. 115). These deposits are estimated to be from 250 to 350 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlies the glacial materials. These sand and gravel deposits form the regionally important Clear Lake aquifer.

### *Groundwater Hydrology*

The Olson WPA site overlies the Clear Lake aquifer. Based on nearby well logs, both permeable zones of the Clear Lake aquifer underlie this WPA, with the shallow glacial outwash zone at depths of about 100 to 200 ft and the deeper ancestral Missouri River alluvial zone from 250 to 350 ft. Flow in the aquifer is generally towards the west or southwest.

### *Characterizing Oilfield Production Brine Migration*

EM surveys were not conducted at this site and there are no monitoring wells associated with this WPA.

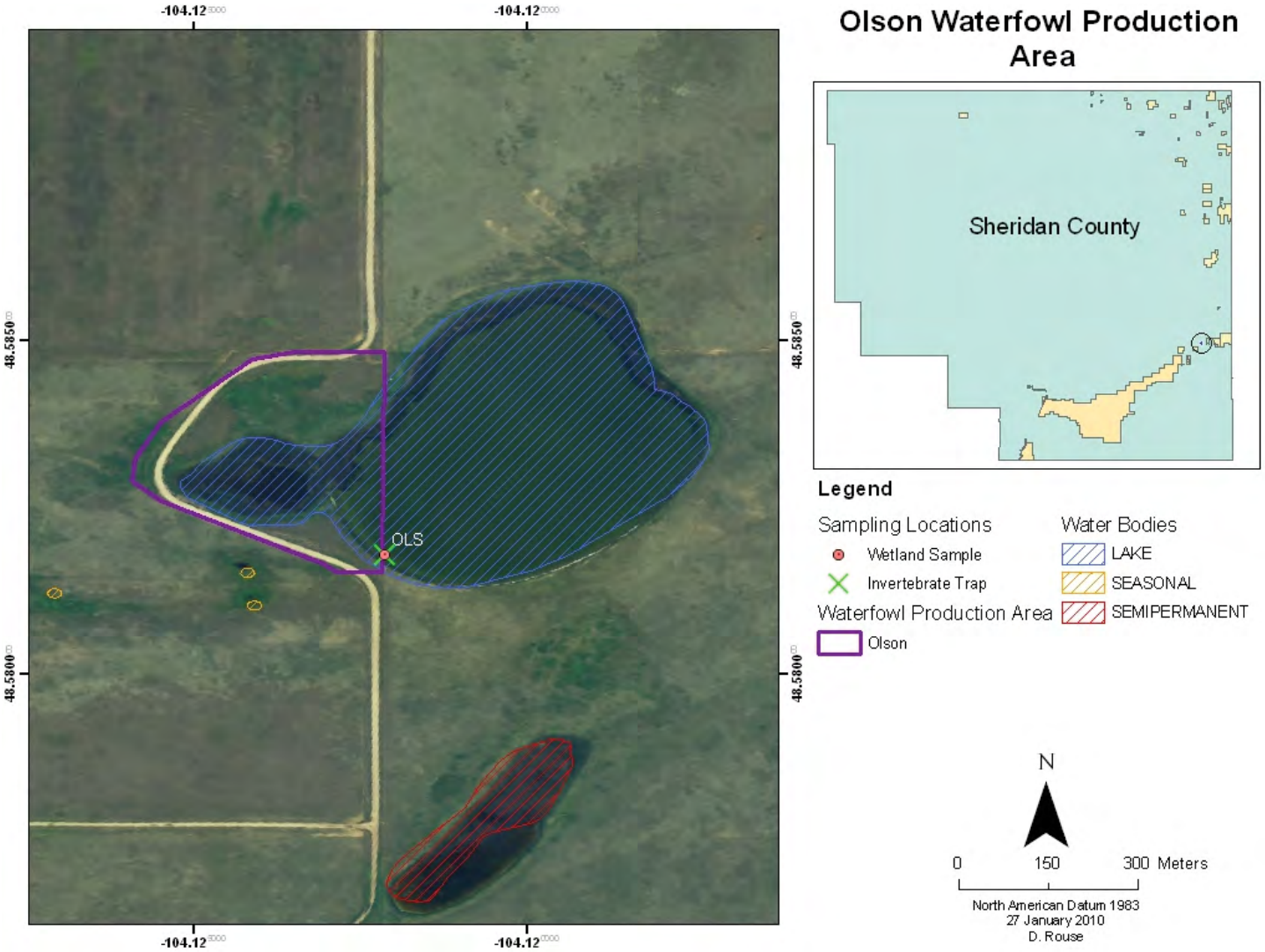


Figure 114. Map depicting locations of sampling sites, oil wells, and bodies of water for the Olson WPA: T. 33 N., R. 58 E., sec. 26 & 27.

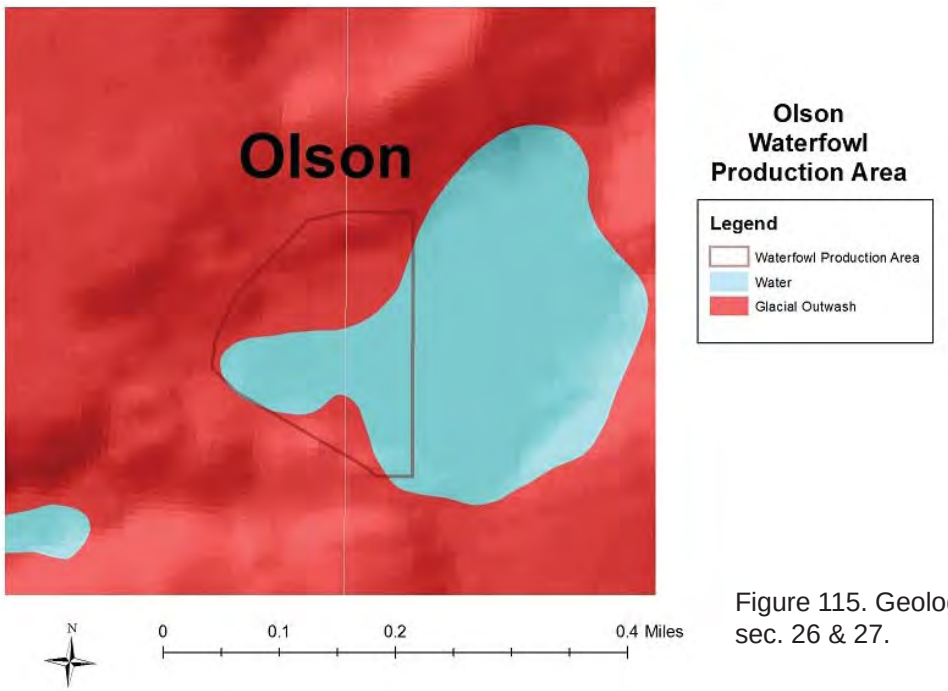


Figure 115. Geology of the Olson WPA: T. 33 N., R. 58 E., sec. 26 & 27.

Table 51. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Olson WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| OLS | 8/24/1990 | 9,409 | 75 | 0.008 | Mesosaline |
| OLS | 7/21/2004 | 4,314 | 30 | 0.007 | Oligosaline |
| OLS | 9/12/2004 | 4,772 | 33 | 0.007 | Oligosaline |
| OLS | 7/9/2005 | 4,602 | 33 | 0.007 | Oligosaline |

*Wetland Water Quality*

For site OLS, specific conductance ranged from around 4,300 to 4,800 µS/cm and chloride concentrations ranged from 30 to 33 mg/L (table 51). Based on the CI, there are no apparent produced water impacts. Additionally, this wetland was sampled in a previous in 1990 (GWIC ID 120886). Although specific conductance and the chloride concentration were higher in 1990, the CI was similar to current conditions, indicating that this system has remained free of brine contamination and that the differences seen in conductivity and chlorides are likely reflecting the natural variation of drought and non-drought conditions (table 51).

Table 52. Surface-water concentrations (µg/L) of trace elements present in the OLS site at the Olson WPA in 2005.

| | OLS |
|---|---|
| Al | <50 |
| As | 18.7 |
| B | 2,250 |
| Ba | 4 |
| Be | <0.5 |
| Cd | 0.06[#] |
| Co | <5 |
| Cr | <5 |
| Cu | <5 |
| Hg | <0.1 |
| Mo | <10 |
| Ni | <5 |
| Pb | <0.02 |
| Se | <0.1 |
| Sr | <25 |
| Ti | <5 |
| V | <10 |
| Zn | <5 |

[#]Indicates value exceeded EPA's national recommended water-quality criteria.

*Co-occurring Contaminants*

One sample from 2005 was analyzed for metals (table 52). Based on those data, the only constituent that exceeded any of EPA's national recommended water-quality criteria was cadmium. EPA's national recommended water-quality criteria for cadmium is corrected for hardness, in that organisms inhabiting a system with reduced hardness will be more vulnerable to cadmium toxicity. So while cadmium exceeds the hardness-corrected toxicity value at OLS, the actual concentration detected, 0.06 µg/L, is relatively low compared to other values detected in surface-water sites across the Northeast Montana WMD and is not associated with brine contamination. More importantly, since cadmium does appear to be associated with brine contamination for much of the Northeast Montana WMD (table 5), it becomes apparent that systems similar to OLS are more vulnerable to trace element toxicity due to reduced hardness and should be protected from future contamination.

## Rivers WPA

The Rivers WPA was established on 5/21/1984 and encompasses an area of approximately 160 acres. Seasonal and semi-permanent wetlands partially extend into the WPA (fig. 116). Bird surveys have documented the use of the Rivers WPA by breeding waterfowl, with observations of 20–42 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells present within the WPA, with the closest well, an oil-producing well, located greater than a quarter of a mile northeast of the WPA.

*Geology*

The surficial geology underlying the Rivers WPA is depicted in figure 117. Most of the Rivers WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 50 to 100 ft. A deposit of moderate to high-permeability glacial outwash underlies parts of this WPA. These outwash deposits appear to be thin veneers overlying glacial till. Lithologic logs from nearby wells indicate isolated outwash deposits at depths as great as 100 ft.

*Groundwater Hydrology*

Little information is available on groundwater flow underlying the Rivers WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. Although isolated glacial aquifers have been encountered and in many cases produce significant volumes of water, no regional glacial outwash aquifers have been identified in this area.

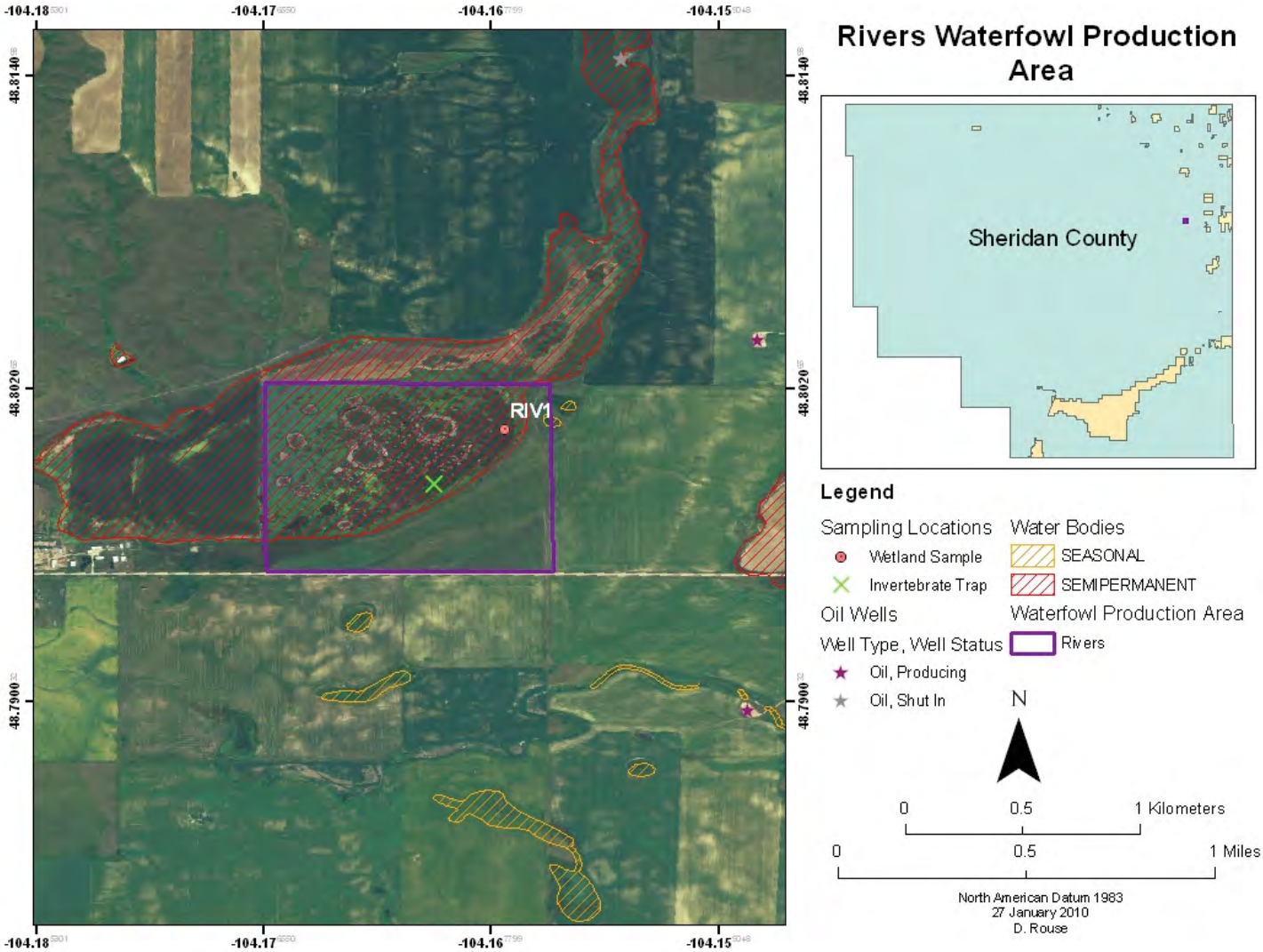


Figure 116. Map depicting locations of sampling sites, oil wells, and bodies of water for the Rivers WPA: T. 35 N., R. 58 E., sec. 7 & 8.

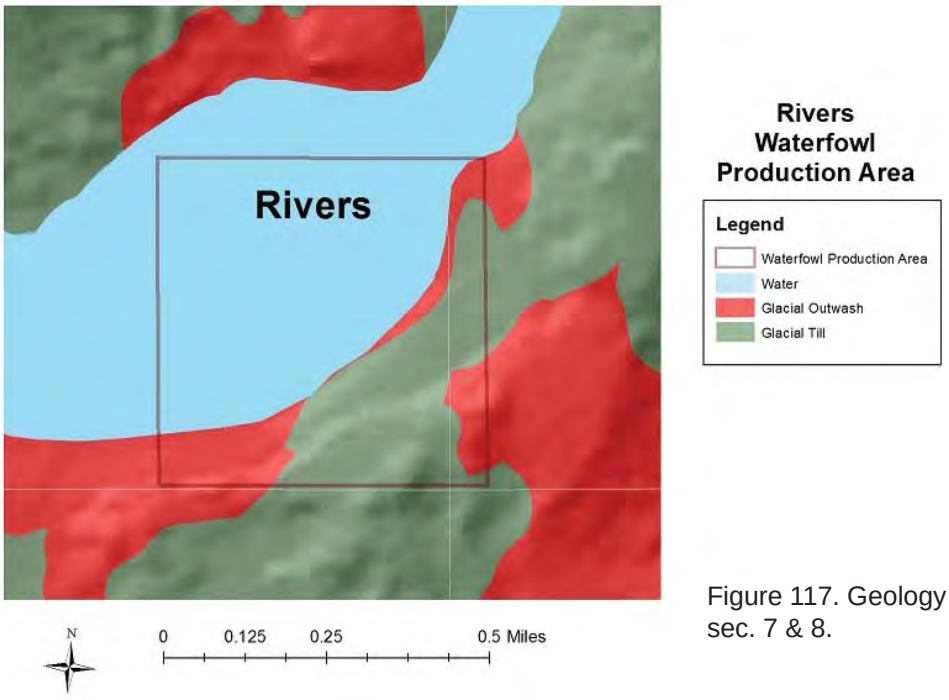


Figure 117. Geology of the Rivers WPA: T. 35 N., R. 58 E., sec. 7 & 8.

Table 53. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the wetland visited at the Rivers WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| RIV1 | 4/27/2004 | 326 | 15 | 0.046 | Freshwater |
| RIV1 | 6/13/2005 | 1,090 | 24 | 0.022 | Oligosaline |

*Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at this WPA, and there are no groundwater monitoring wells associated with this site.

*Wetland Water Quality*

One surface-water site, RIV1, was visited for water-quality assessment. Based on laboratory and field measurements taken during two separate sampling events for RIV1, specific conductance ranged from around 300 to 1100 µS/cm and chloride concentrations ranged from 15 to 24 mg/L (table 53). Using data collected from the field measurements taken on the 4/17/2004 sampling event, the CI indicated that there were produced water impacts at this site. Conversely, the CI value calculated using laboratory data from the 6/13/2005 sampling event suggests there were no produced water impacts. On average, the CI value for RIV1 is just below the 0.035 threshold value for produced water impacts (table 53).

Table 54. Surface-water concentrations (µg/L) of trace elements present in the RIV1 site at the Rivers WPA in 2005.

| | RIV1 |
|---|---|
| Al | <50 |
| As | 8.06 |
| B | 101 |
| Ba | 168 |
| Be | <0.5 |
| Cd | 0.21[#] |
| Co | <5 |
| Cr | <5 |
| Cu | <5 |
| Hg | <0.1 |
| Mo | <10.0 |
| Ni | <5 |
| Pb | 0.13 |
| Se | 0.23 |
| Sr | 165 |
| Ti | <5 |
| V | <10 |
| Zn | <5 |

[#]Indicates value exceeded EPA's national recommended water-quality criteria.

*Co-occurring Contaminants*

One sample was collected for metals analysis, and based on lab results, cadmium was the only element that exceeded EPA's national recommended water-quality criteria (table 54). This sample was collected in 2005 when brine contamination was not evident based on the CI, so it appears that its presence is not a result of produced water encroachment.

## Rich Johnson WPA

The Rich Johnson WPA was established on 5/23/1995 and encompasses an area of 320 acres. Many smaller wetlands are located in, or partially located in, this WPA (fig. 118). Much of the upland habitat is managed as dense nesting cover through selective planting, prescribed haying, prescribed fire, and limited grazing. Additionally, one approved plugged and abandoned dry hole, API well 21554, was located within the WPA as of January 2010. This well was completed in September 1985, and any reserve pit associated with this well would have been lined.

*Geology*

The surficial geology underlying the Rich Johnson WPA is depicted in figure 119. Most of the Rich Johnson WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 10 to 50 ft.

*Groundwater Hydrology*

Little information is available on groundwater flow underlying the Rich Johnson WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetland to the west of the site. No regional glacial outwash aquifers have been identified in this area.

*Characterizing Oilfield Production Brine Migration*

There were no EM-31 surveys conducted at this WPA and there are no groundwater monitoring wells associated with this site.

*Wetland Water Quality*

Three wetland sites were visited during 6/15/2005. The specific conductivity for these sites ranged from around 3,200 to 3,600 µS/cm and chloride concentrations ranged from 39 to 68 mg/L (table 55). The CI values for all three sites showed no indication of brine contamination.

*Co-occurring Contaminants*

There were no additional analyses done for the Rich Johnson WPA.

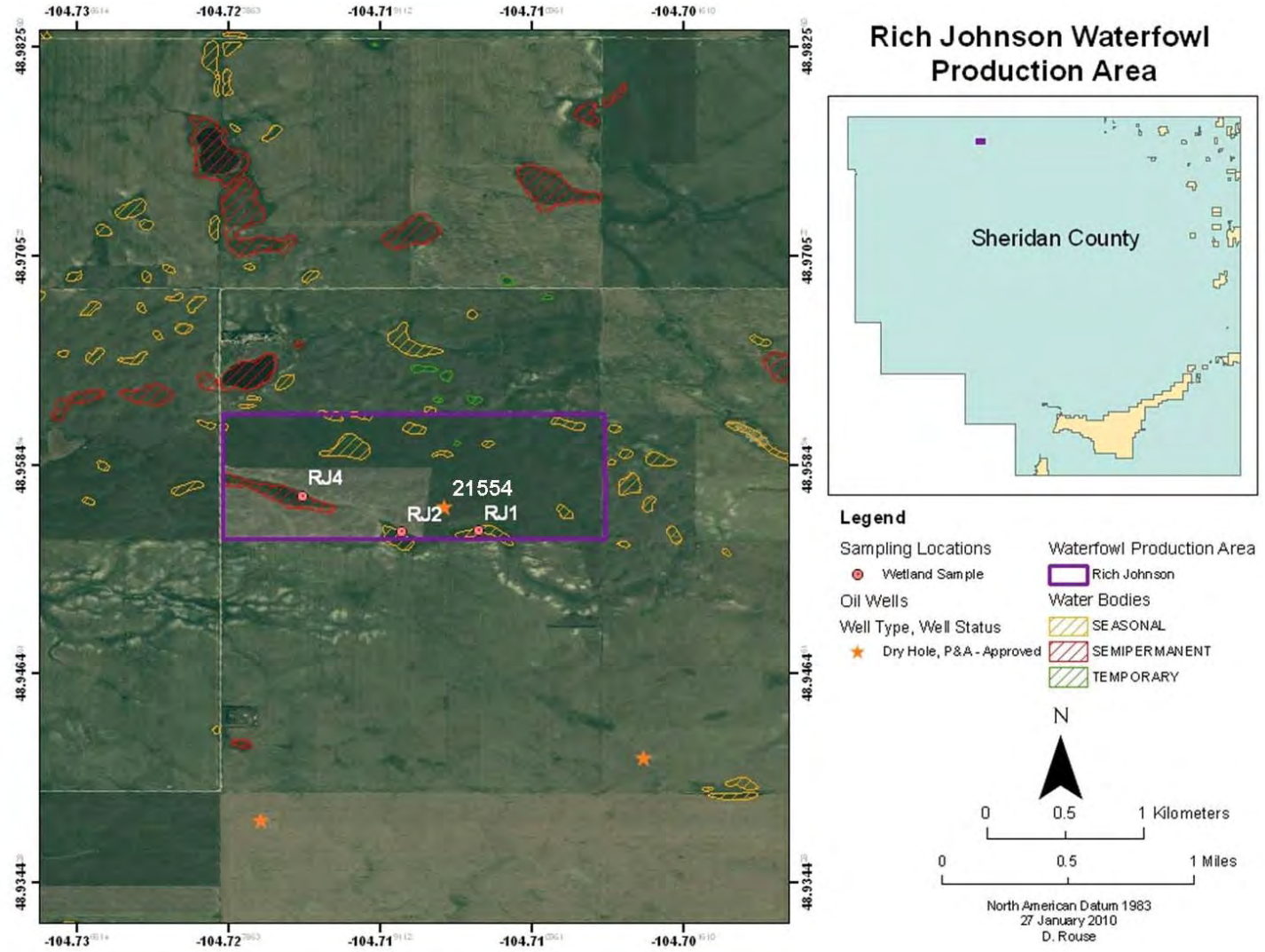


Figure 118. Map depicting locations of sampling sites, oil wells, and bodies of water for the Rich Johnson WPA: T. 37 N., R. 53 E., sec. 14 & 15.

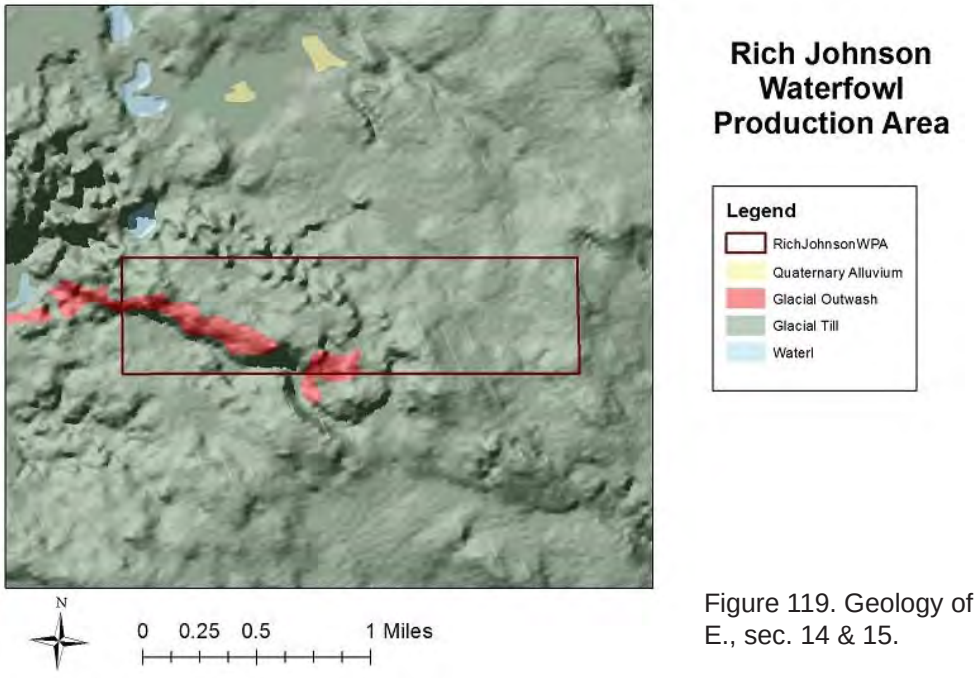


Figure 119. Geology of the Rich Johnson WPA: T. 37 N., R. 53 E., sec. 14 & 15.

Table 55. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Rich Johnson WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| RJ1 | 6/15/2005 | 3593 | 45 | 0.013 | Oligosaline |
| RJ2 | 6/15/2005 | 3298 | 39 | 0.012 | Oligosaline |
| RJ4 | 6/15/2005 | 3244 | 68 | 0.021 | Oligosaline |

## Parry WPA

The Parry WPA was established on 7/16/1968 and covers an area of 566.68 acres. There are five bodies of water located in, or partially located in, this WPA, including one lake and four semi-permanent wetlands (fig. 120). Bird surveys have documented the use of the Parry WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, there is designated Piping Plover critical habitat and intact native prairie. Management practices, such as prescribed grazing and prescribed fire, are implemented to maintain and improve the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, there were no production wells located within the WPA and the closest well, an expired oil well, is located greater than a quarter of mile away northwest of the WPA.

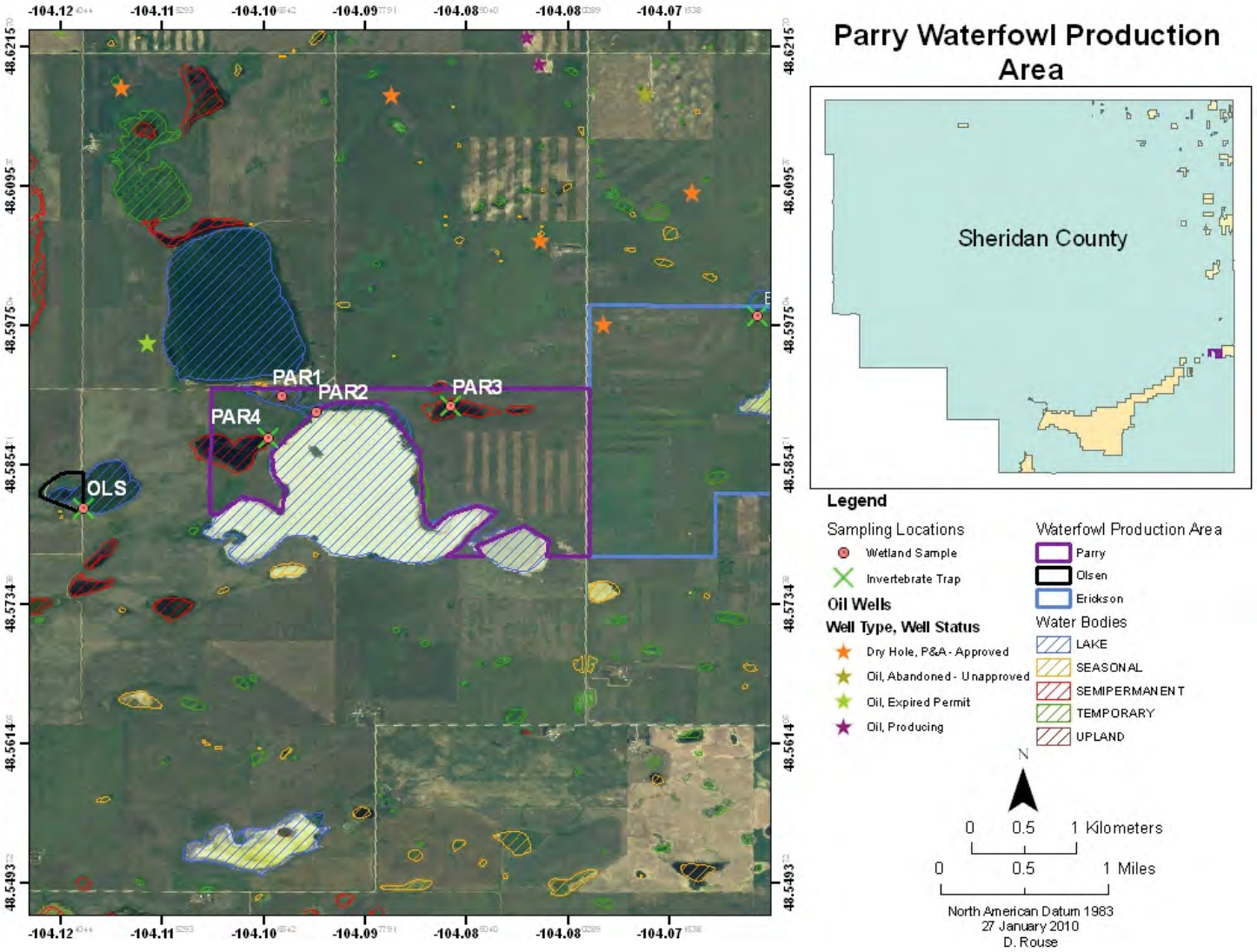


Figure 120. Map depicting locations of sampling sites, oil wells, and bodies of water for the Parry WPA: T. 33 N., R. 58 E., sec. 26 & 27.

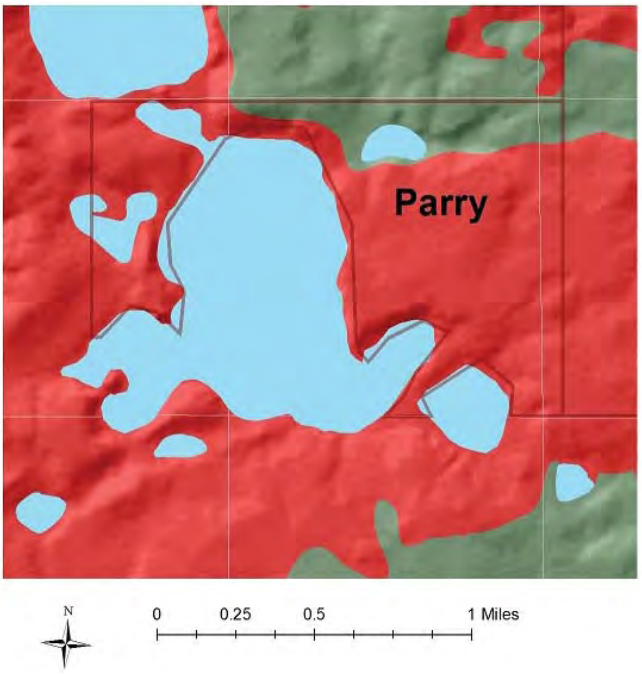


Figure 121. Geology of the Parry WPA: T. 33 N., R. 58 E., sec. 26 & 27.

## *Geology*

The Parry WPA is underlain by glacial outwash deposits (fig. 121). These deposits are estimated to be from 50 to 300 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlie the glacial materials. The sand and gravel glacial outwash deposits are associated with both the upper permeable glacial outwash zone and the deeper ancestral Missouri River alluvial zone of the Clear Lake aquifer.

## *Groundwater Hydrology*

The Parry WPA overlies the Clear Lake aquifer. Based on nearby lithologic logs, several permeable zones of the Clear lake aquifer underlie this site. The shallowest zone is 10 to 31 ft below land surface and the deepest is at depths of 300 to 350 ft. Both the deep ancestral Missouri River alluvium and glacial outwash of Late Wisconsinan meltwater channels make up the aquifer zones. The log for GWIC ID 3867 indicated Fort Union bedrock was encountered at depths of 335 ft. This well was completed in the Ancestral Missouri River zone of the Clear Lake aquifer. The depth of this zone is 318 to 335 ft below land surface. Flow in the regional aquifer is generally towards the west or southwest. It is likely that the shallow localized flow is dominated by topography with groundwater flowing from upland hummocks to the low-lying wetlands and lakes.

## *Characterizing Oil Field Production Brine Migration*

There were no EM-31 surveys conducted at this WPA, and there are no groundwater monitoring wells associated with this site.

## *Wetland Water Quality*

Four wetland sites were visited during the months of May and September 2004. Among the wetlands assessed, the specific conductivity ranged from around 2,700 to 55,200 µS/cm and the chloride concentrations ranged from 27 to 1,547 mg/L (table 56). From a previous investigation, samples were collected and analyzed from PAR1 (GWIC

Table 56. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Parry WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| PAR1 | 8/24/1990 | 24,490 | 365 | 0.015 | Mesosaline |
| PAR1 | 5/14/2004 | 4,902 | 53 | 0.011 | Oligosaline |
| PAR1 | 5/14/2004 | 4,680 | 53 | 0.011 | Oligosaline |
| PAR2 | 5/14/2004 | 55,185 | 1,547 | 0.028 | Eusaline |
| PAR3 | 8/31/1990 | 14,846 | 258 | 0.017 | Mesosaline |
| PAR3 | 5/14/2004 | 4,351 | 61 | 0.014 | Oligosaline |
| PAR3 | 9/2/2004 | 5,928 | 84 | 0.014 | Oligosaline |
| PAR4 | 9/31/1990 | 17,952 | 262 | 0.015 | Mesosaline |
| PAR4 | 5/14/2004 | 2,669 | 27 | 0.010 | Oligosaline |
| PAR4 | 9/2/2004 | 3,396 | 30 | 0.009 | Oligosaline |

ID 120847), PAR3 (GWIC ID 120887), and PAR4 (GWIC ID 120866) in 1990. Although specific conductance and chloride concentrations were substantially higher, the CI remained stable, suggesting that the observed elevated parameters were due to natural variation, rather than historic brine impacts (table 56). The CI values for all of the sampled wetlands suggest that there were no produced water impacts.

### *Co-occurring Contaminants*

There were no additional analyses done for the Parry WPA.

## Shoveler Puddle WPA

The Shoveler Puddle WPA was established on 10/24/1968 and encompasses an area of approximately 30 acres. A semi-permanent wetland extends into much of the WPA (fig. 122). Bird surveys have documented the use of the Shoveler Puddle WPA by breeding waterfowl, with observations of 42–88 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). As of January 2010, there were no production wells within, or in close proximity to, the WPA. The wetland present within the Shoveler Puddle WPA was visited on 6/14/2004 for water-quality assessment, but the site was dry. There are no metals data available and no monitoring wells established for this WPA.

### *Geology*

The Shoveler Puddle WPA is underlain by a complex mix of glacial deposits (fig. 123). It is near the southwest edge of an ice-walled glacial lake plain deposited as the stagnant ice melted. Glacial till is the predominant geologic unit at the site and, based on limited nearby well logs, ranges from about 50 to 100 ft thick. Glacial outwash and glacial lake deposits make up a relatively minor portion of the glacial deposits. Although no regional glacial outwash aquifers have been identified in this area, smaller discontinuous outwash sand and gravel deposits often overlie and are interbedded within the glacial till. These outwash deposits

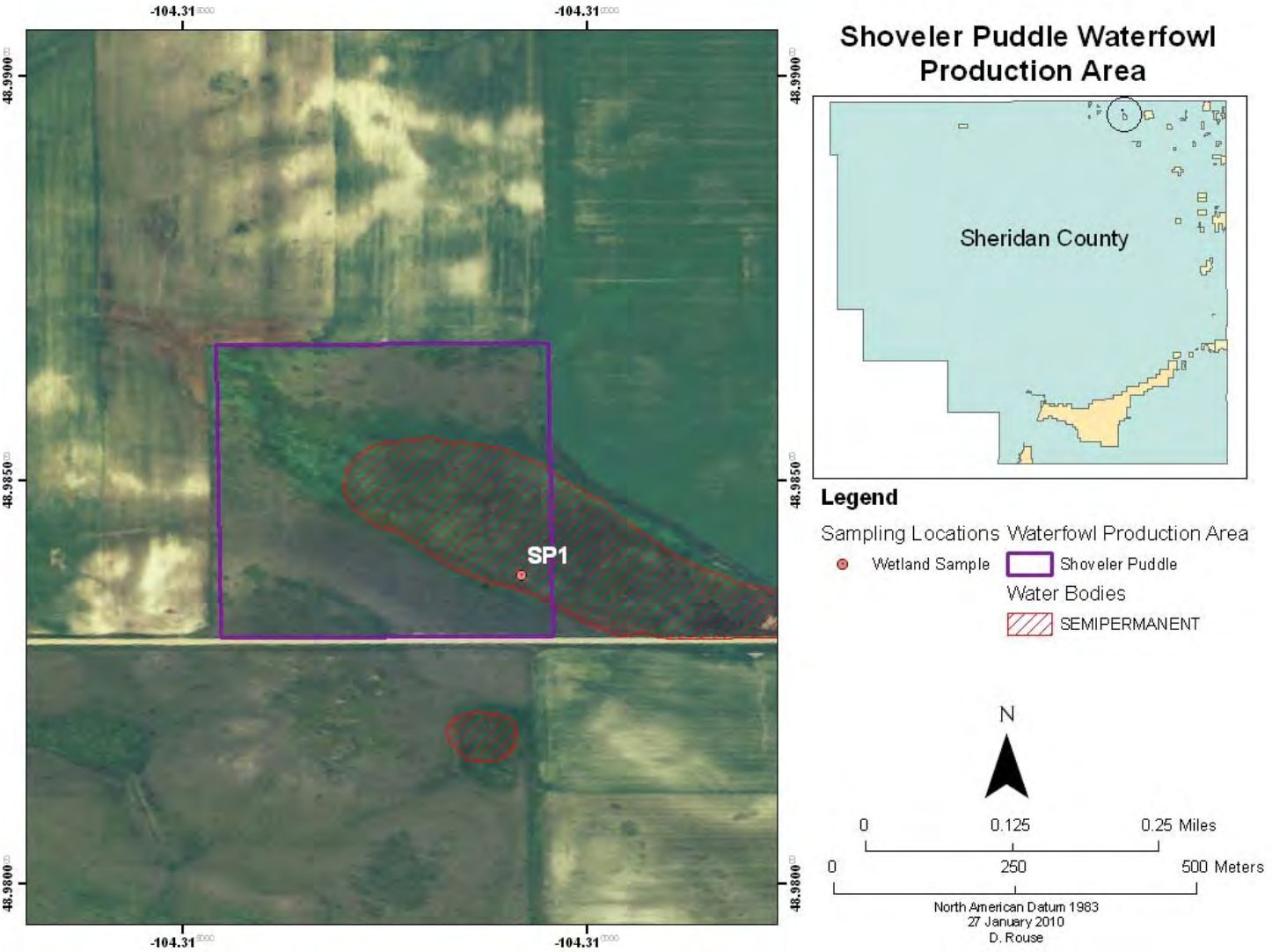


Figure 122. Map depicting locations of sampling sites, oil wells, and bodies of water for the Shoveler Puddle WPA: T. 37 N., R. 56 E., sec. 3.

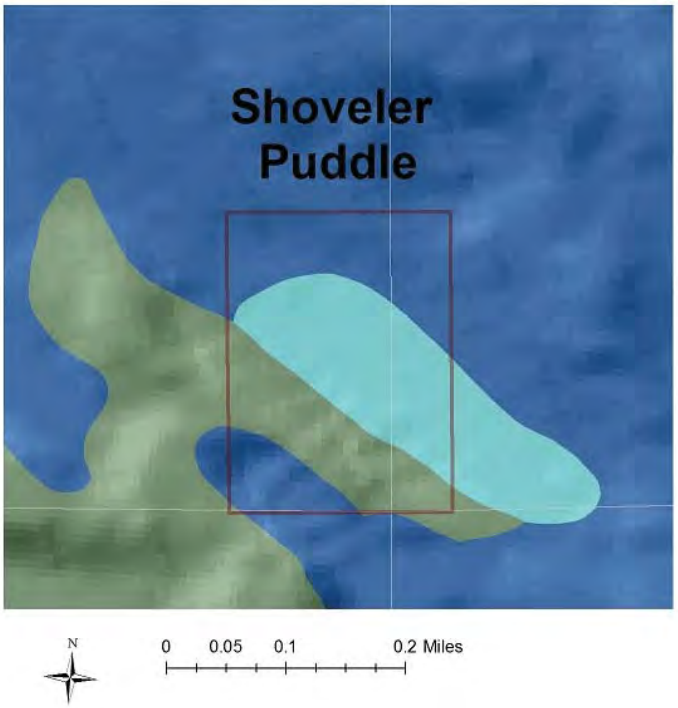


Figure 123. Geology of the Shoveler Puddle WPA: T. 37 N., R. 56 E., sec. 3.

form locally significant aquifers supplying landowners and wetlands.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Shoveler Puddle WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetland to the west of the site. No regional glacial outwash aquifers have been identified in this area.

### *Characterizing Oil Field Production Brine Migration*

EM surveys were not conducted at this site, and there are no monitoring wells associated with the Shoveler Puddle WPA.

### *Wetland Water Quality*

One site, SP1, was visited on 6/14/2005, but it was dry.

### *Co-occurring Contaminants*

There were no samples collected at this WPA.

## State Line WPA

The State Line WPA was established on 6/19/1969 and covers an area of approximately 607 acres. Numerous wetlands are located in, or partially located in, the WPA (fig. 124). Bird surveys have documented the use of the State Line WPA by breeding waterfowl, with observations of 88–111 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, the State Line WPA is located within the Westby Prairie-Wetland Complex, a globally significant important bird area designated by the Audubon Society. As of January 2010, there were no production wells present within the WPA, but the closest well, an approved plugged and abandoned dry hole, is located within 700 ft of the WPA.

### *Geology*

The surficial geology underlying the State Line WPA is depicted in figure 125. Most of the State Line WPA is underlain by glacial till. The thickness of this relatively low-permeability unit is unknown, but based on nearby test holes and wells, the till thickness probably ranges from 200 to 300 ft. Interbedded within the till are fine-grained glacial lake deposits and coarse-grained glacial outwash deposits. The glacial outwash is part of the Clear Lake aquifer (referred to as the Skjermo Lake aquifer in North Dakota). A relatively long and narrow deposit of alluvium is mapped trending east to west through the central part of the State Line geologic map. This appears to underlie low-lying areas. Deposits of glacial lake clays ring modern lakes and lowlands near the lakes. Surficial glacial outwash deposits underlie an area along the east edge of the WPA.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the State Line WPA. It is likely that the localized flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. Flow in the Clear Lake (Skjermo Lake aquifer) is towards the south. The northern limit of this aquifer is near Skjermo Lake located a few miles northeast of this WPA, close to the North Dakota–Saskatchewan border.

### *Characterizing Oil Field Production Brine Migration*

There were no EM-31 surveys conducted at this WPA, and there are no groundwater monitoring wells associated with this site.

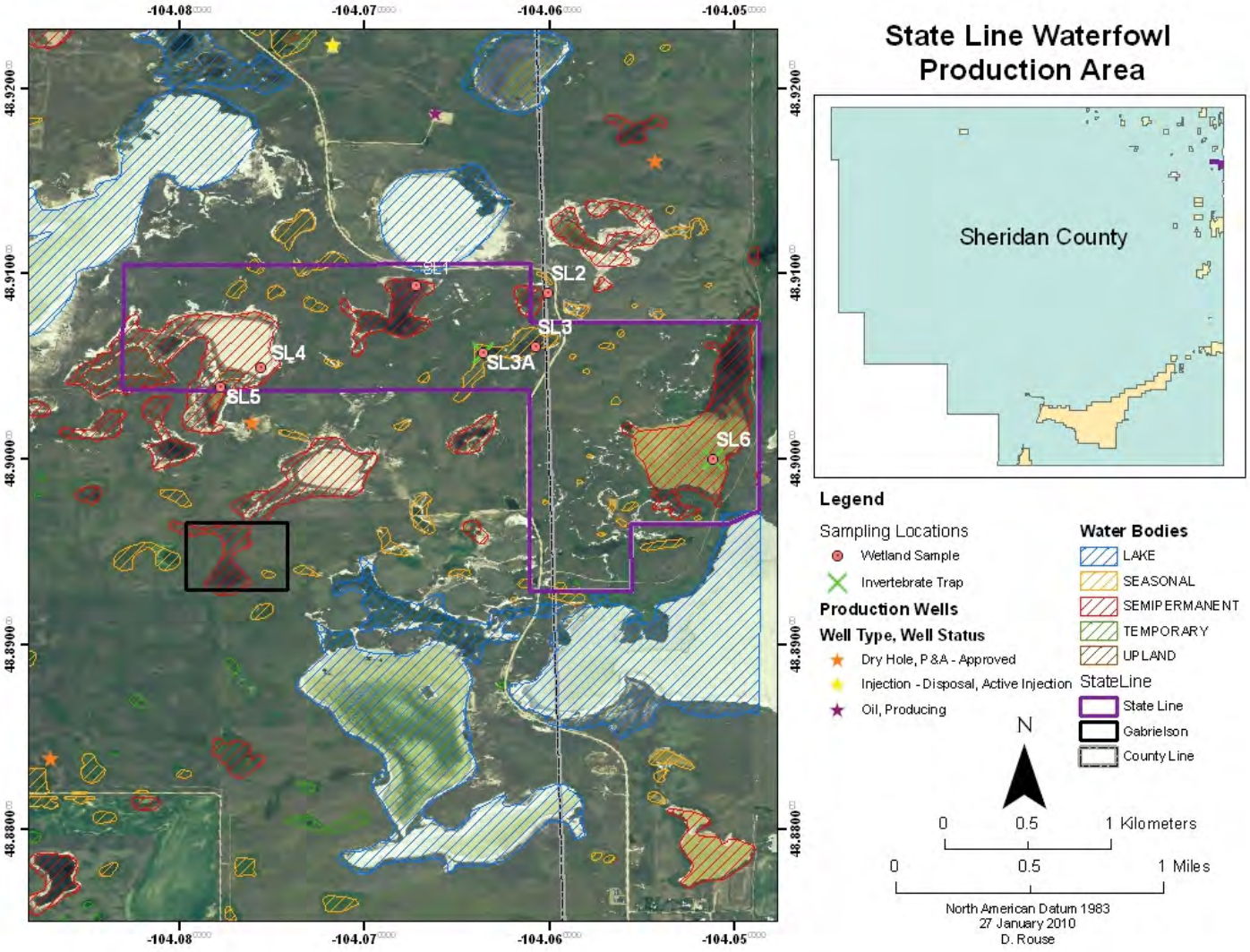


Figure 124. Map depicting locations of sampling sites, oil wells, and bodies of water for the State Line WPA: T. 36 N., R. 58 E., sec. 1, 2 & 12.

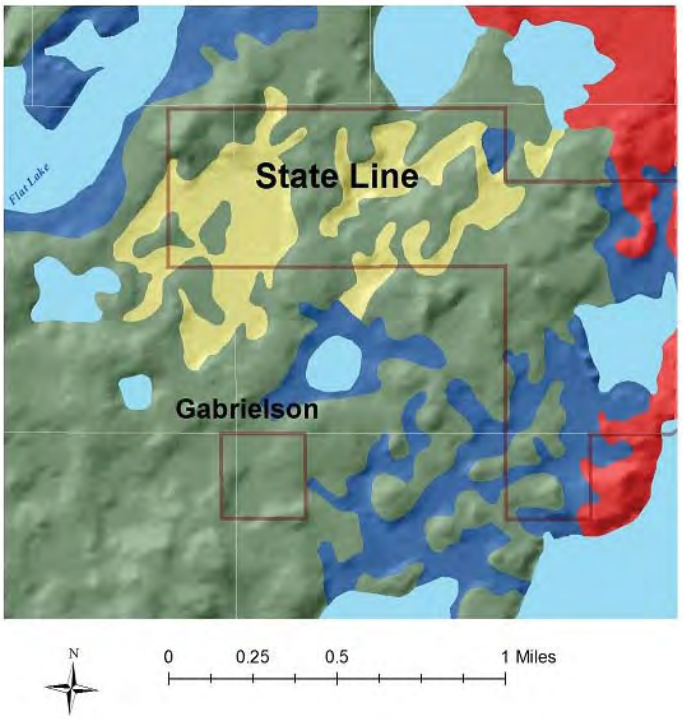


Figure 125. Geology of the State Line WPA: T. 36 N., R. 58 E., sec. 1, 2 & 12.

Table 57. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the State Line WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| SL1 | 5/13/2004 | 9,228 | 222 | 0.024 | Mesosaline |
| SL1 | 7/8/2005 | 21,460 | 1,336 | 0.062 | Mesosaline |
| SL2 | 7/11/2005 | 7,040 | 102 | 0.014 | Oligosaline |
| SL3 | 5/13/2004 | 2,988 | 39 | 0.013 | Oligosaline |
| SL3 | 7/8/2005 | 5,846 | 77 | 0.013 | Oligosaline |
| SL3 | 7/11/2005 | 5,710 | 68 | 0.012 | Oligosaline |
| SL3A | 9/10/2004 | 6,260 | 68 | 0.011 | Oligosaline |
| SL4 | 9/10/2004 | 22,648 | 1,678 | 0.074 | Mesosaline |
| SL5 | 9/10/2004 | 23,569 | 1,547 | 0.066 | Mesosaline |
| SL6 | 8/26/1990 | 7,291 | 80 | 0.011 | Oligosaline |
| SL6 | 7/25/2004 | 7,155 | 77 | 0.011 | Oligosaline |
| SL6 | 9/11/2004 | 8,713 | 86 | 0.010 | Mesosaline |
| SL6 | 7/8/2005 | 7,371 | 73 | 0.010 | Oligosaline |
| SL6 | 7/11/2005 | 6,890 | 57 | 0.008 | Oligosaline |

### *Wetland Water Quality*

Seven locations were visited to assess surface-water condition. Of the wetlands sampled, specific conductance ranged from around 3,000 to 23,600 µS/cm and chloride concentrations ranged from 39 to 1,678 mg/L (table 57). Two sites, SL4 and SL5, had CI values that exceeded the benchmark CI value indicating produced water impacts (table 57). Both of these sites are in close proximity to oil well 21746, which was completed in 1999. Based on its date of completion, any associated reserve pit would have been lined. However, the contamination detected in SL4 and SL5 are likely associated with oil well 21746 and may be the result of a reserve pit that was trenched prior to burying. Additionally, SL1 had an average CI value, 0.043, that exceeded the benchmark CI value indicating produced water impacts, but the 2004 CI value for SL1 was below 0.035 (table 57). From a previous investigation, a sample (GWIC ID 120852) was collected in 1990 from the same water body as SL6. Specific conductance, chloride concentration, and the resultant CI for SL6 are all similar to values observed in 2004 and 2005.

### *Co-occurring Contaminants*

Three sites, SL2, SL3, and SL6, had samples analyzed for metals. Based on these analyses, there were no sites that exceeded established water-quality benchmarks for metals (table 58).

Table 58. Surface-water concentrations (µg/L) of trace elements present in select wetland sites at the State Line WPA in 2005.

| | SL2 | SL3 | SL6 |
|---|---|---|---|
| Al | <50 | <50 | <50 |
| As | 15.5 | 4.12 | 12.5 |
| B | 1,760 | 670 | 1,770 |
| Ba | 105 | 72 | 8 |
| Be | <0.5 | <0.5 | <0.5 |
| Cd | 0.09 | <0.05 | 0.06 |
| Co | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 |
| Mo | <10 | <10 | <10 |
| Ni | <5 | <5 | <5 |
| Pb | 0.52 | 0.13 | <0.05 |
| Se | 1.16 | 0.47 | 0.13 |
| Sr | 1,000 | 1,300 | 245 |
| Ti | <5 | <5 | <5 |
| V | <10 | <10 | <10 |
| Zn | 5 | 12 | <5 |

## Wigeon Slough WPA

The Wigeon Slough WPA was established on 3/07/1968 and encompasses an area of approximately 552 acres. Numerous water bodies are present within the WPA, including lakes, plus temporary, semi-permanent, and seasonal wetlands (fig. 126). Bird surveys have documented the use of the Wigeon Slough WPA by breeding waterfowl, with density observations ranging from 42–88 duck pairs per square mile to 88–111 duck pairs per square mile during the nesting season (Brian DeVries, USFWS, written commun., 2009). Additionally, there is designated Piping Plover critical habitat and intact native prairie. Management practices, such as prescribed grazing and prescribed fire, are implemented to maintain and improve the diversity of native prairie plants and the wildlife species that rely on that native prairie habitat. As of January 2010, API well 21383, an approved plugged and abandoned dry hole, was located within the WPA. Just to the east outside the WPA is API well 05165, an oil-producing well. Wells 21383 and 05165 were completed in August 1981 and April 2003, respectively, and any reserve pits associated with these wells would be lined.

### *Geology*

The Wigeon Slough WPA is underlain by a complex mix of glacial deposits (fig. 127). It is near the northeast edge of an ice-walled glacial lake plain deposited as the stagnant ice melted. Glacial till is the predominant geologic unit at the site and, based on limited nearby well logs, ranges from about 100 to 200 ft thick. Glacial outwash and glacial lake deposits make up a relatively minor portion of the glacial deposits. Although no regional glacial outwash aquifers have been identified in this area, smaller discontinuous outwash sand and gravel deposits often overlie and are interbedded within the glacial till. These outwash deposits form locally significant aquifers supplying landowners and wetlands.

### *Groundwater Hydrology*

Little information is available on groundwater flow underlying the Wigeon Slough WPA. It is likely that the localized

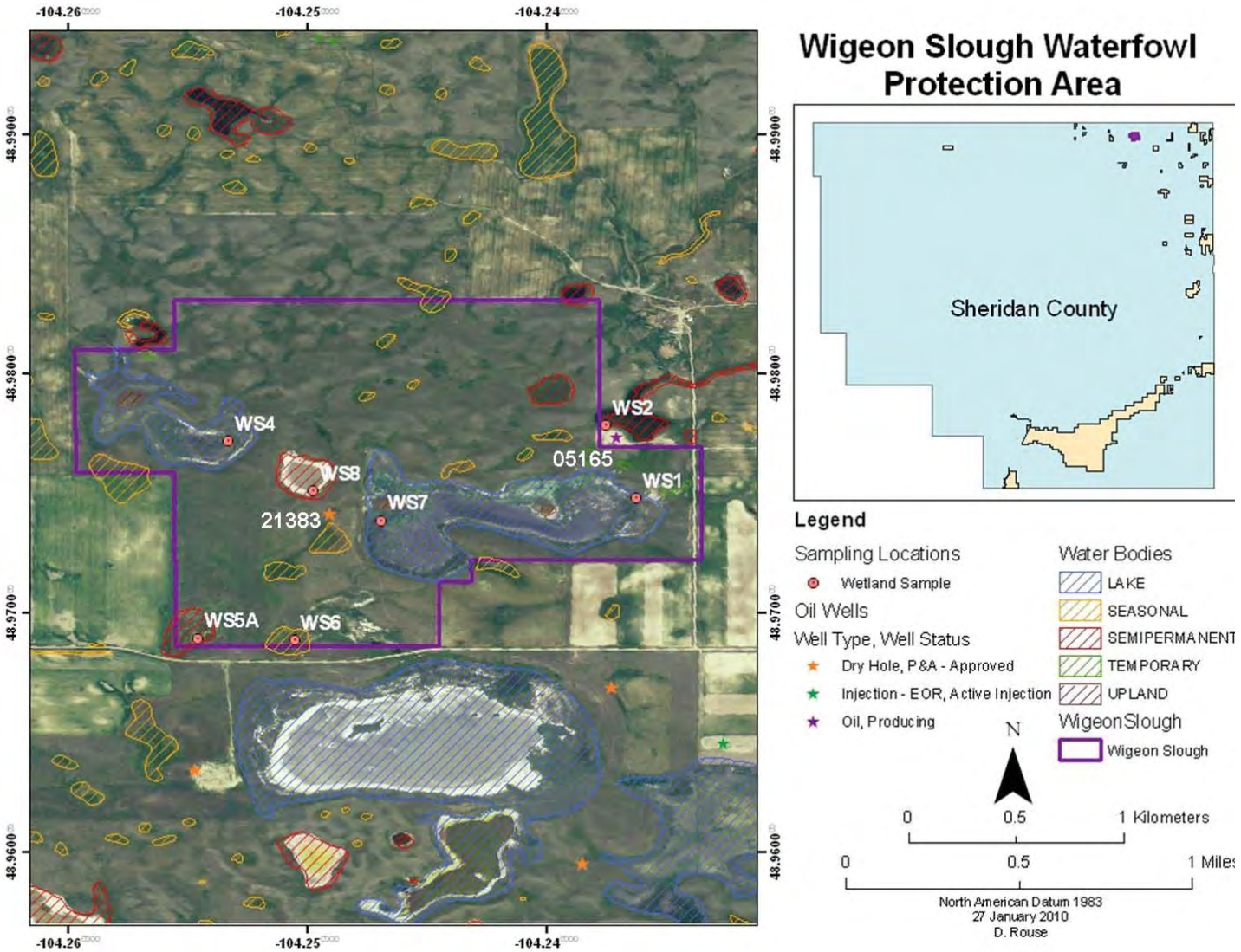


Figure 126. Map depicting locations of sampling sites, oil wells, and bodies of water for the Wigeon Slough WPA: T. 37 N., R. 57 E., sec. 7 & 8.

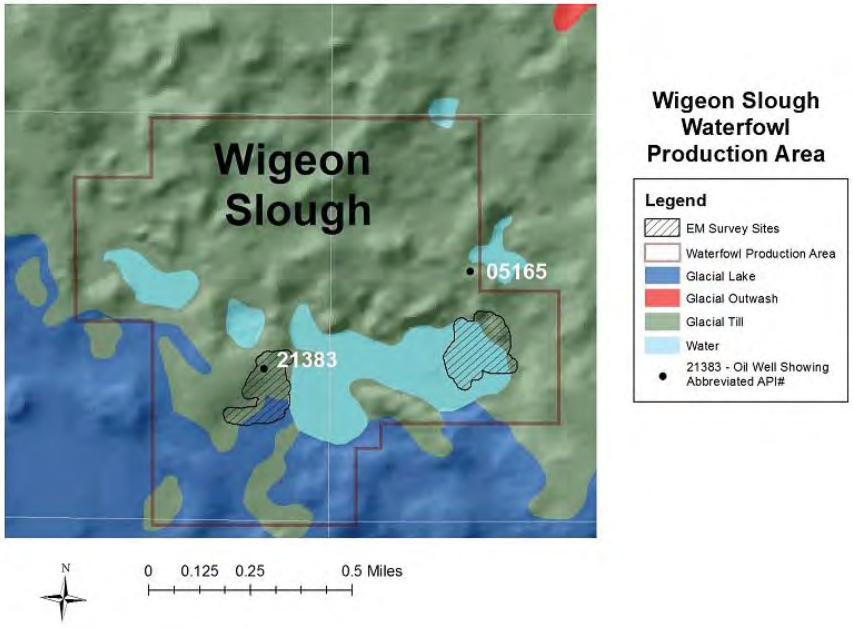


Figure 127. Geology of the Wigeon Slough WPA: T. 37 N., R. 57 E., sec. 7 & 8.

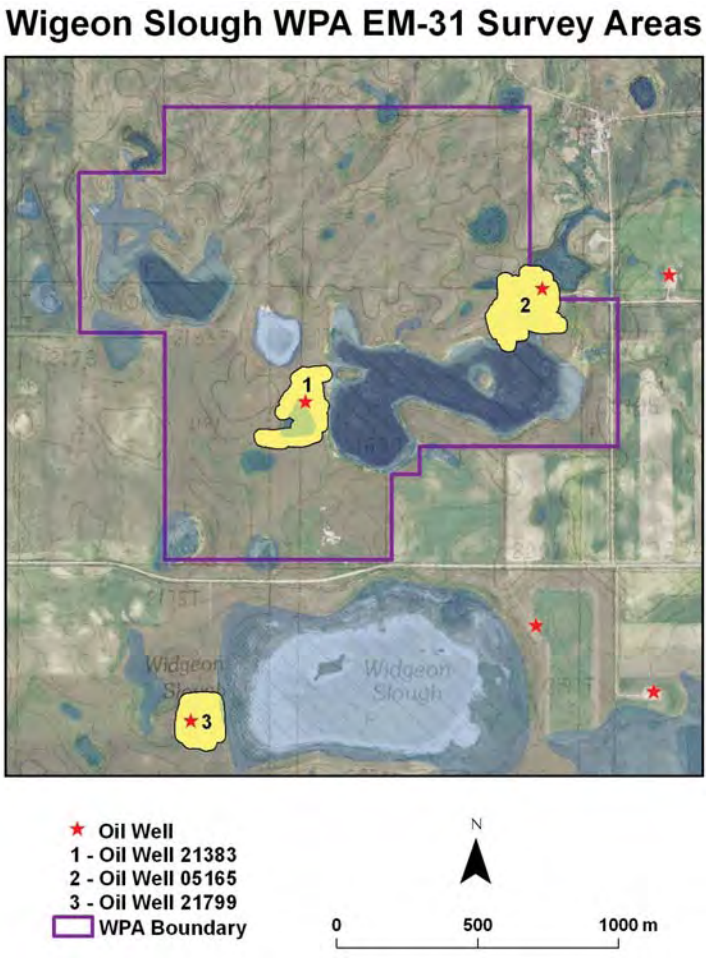


Figure 128. Location of EM-31 terrain-conductivity surveys conducted at the Wigeon Slough WPA: T. 37 N., R. 57 E., sec. 7 & 8.

flow is dominated by topography and groundwater flows from upland hummocks to the low-lying wetlands and lakes. At this location there is a strong potential for a brine plume associated with the oil well site to migrate towards the wetlands east of oil-well sites 21383 and 05165. Although isolated glacial aquifers have been encountered and in many cases produce significant volumes of water, no regional glacial outwash aquifers have been identified in this area.

### *Characterizing Oil Field Production Brine Migration*

A total of three EM-31 surveys were completed on or adjacent to Wigeon Slough WPA. Two EM-31 terrain conductivity surveys were conducted within the WPA surrounding two separate oil-wells, wells 21383 and 05165, while one other survey was conducted just south of the WPA surrounding API well 21799, an approved plugged and abandoned dry hole that was completed in November 2003 (fig. 128). Terrain conductivity surveys identified higher than background conditions near the three sites (figs. 129–131). The EM-31 survey completed on well 21383 showed elevated conductivity that is likely associated with the reserve pit adjacent to the well and a plume moving out of this reserve pit and migrating to the southwest. This plume could be degrading water quality in the wetland, as indicated by monitoring completed at site WS-7. The other EM-31 survey conducted surrounding well 05165 identified a reserve pit that appears to be located on the south side of the well; based on the water monitoring completed on the adjacent wetlands, oilfield exploration and production activities at this site appear to have impacted adjacent wetlands (WS-1 and WS-2). The last well surveyed, API well 21799, was completed a year after the well was first spudded. This survey shows a very distinct location of the reserve pit. This pit should be lined, and would be a good site to monitor again in the future to determine if reserve pit wastes are migrated outside of the existing boundary. No groundwater monitoring wells were installed at this WPA to characterize groundwater chemistry.

### *Wetland Water Quality*

There are no monitoring wells located in this WPA; however, seven wetlands were visited to assess surface-water condition. Of the wetlands sampled, specific conductance ranged from around 2,600 to 25,100 µS/cm and chloride concentrations ranged from 30 to 349 mg/L (table 59). Sites WS1 and WS2 were the only sites that had CI values indicating brine impacts. Both of these are most likely impacted due to past activities, or present activities associated with the oil well 05165. The WS2 terrain conductivity survey appears to reflect areas of high conductivity that flow southwest, towards WS1. However, since WS2 is located much closer to the oil well than WS1, impacts seen there

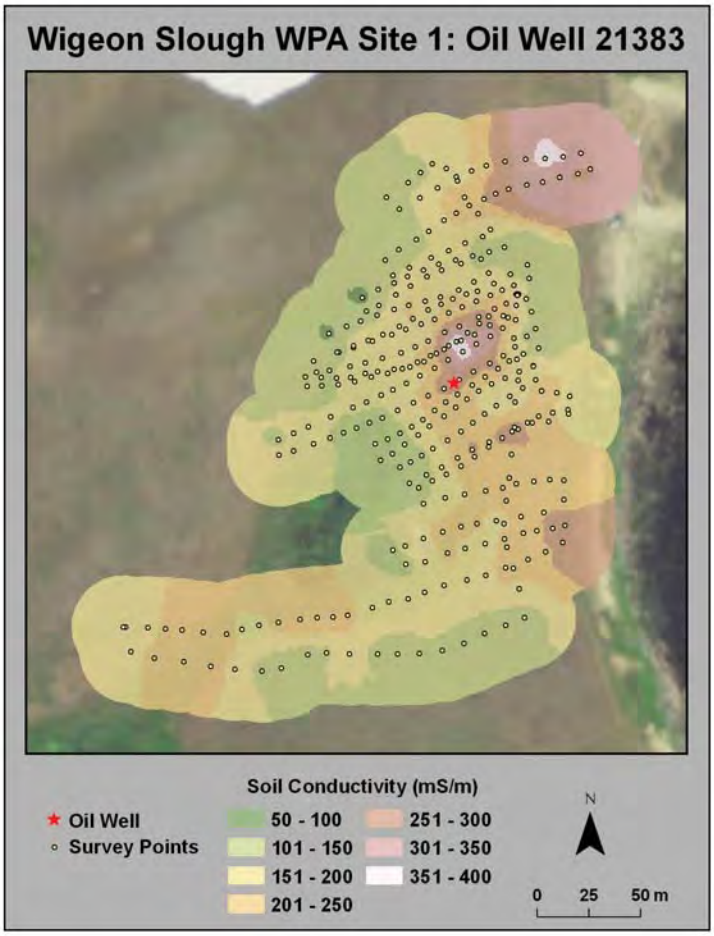


Figure 129. Location of EM-31 terrain-conductivity survey conducted at Site 1 of the Wigeon Slough WPA.

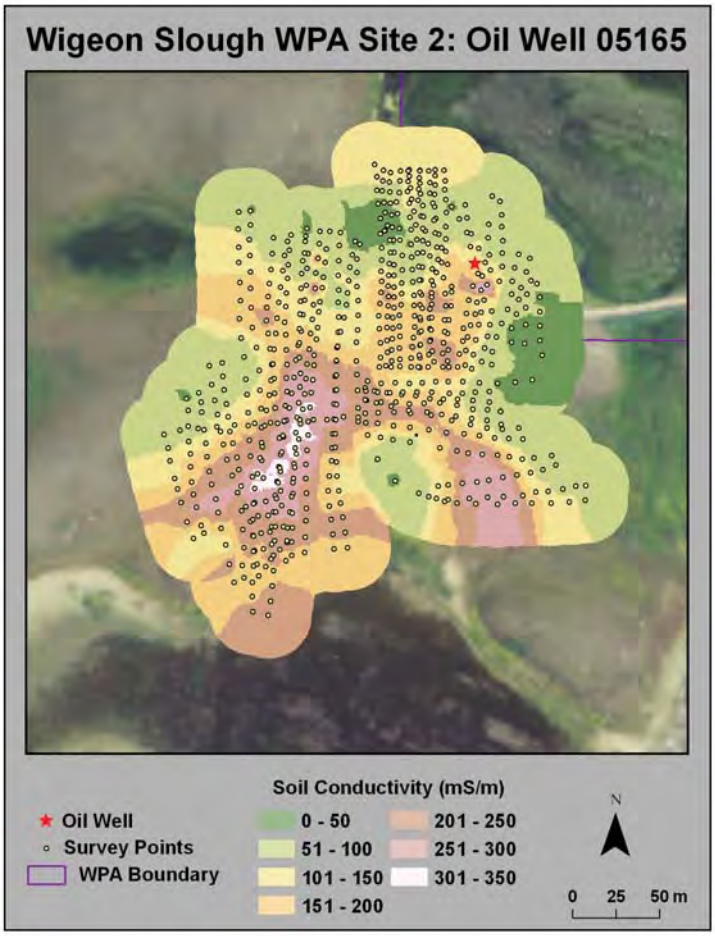


Figure 130. Location of EM-31 terrain-conductivity survey conducted at Site 2 of the Wigeon Slough WPA.

Table 59. Wetland sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for wetlands visited at the Wigeon Slough WPA.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| WS1 | 4/28/2004 | 6,145 | 205 | 0.033 | Oligosaline |
| WS1 | 6/13/2005 | 14,160 | 537 | 0.038 | Mesosaline |
| WS2 | 9/14/2004 | 2,191 | 106 | 0.048 | Oligosaline |
| WS4 | 4/28/2004 | 4,251 | 109 | 0.026 | Oligosaline |
| WS5A | 4/28/2004 | 2,607 | 39 | 0.015 | Oligosaline |
| WS6 | 4/28/2004 | 2,972 | 30 | 0.010 | Oligosaline |
| WS7 | 4/28/2004 | 5,895 | 189 | 0.032 | Oligosaline |
| WS8 | 5/16/2004 | 25,072 | 349 | 0.014 | Mesosaline |

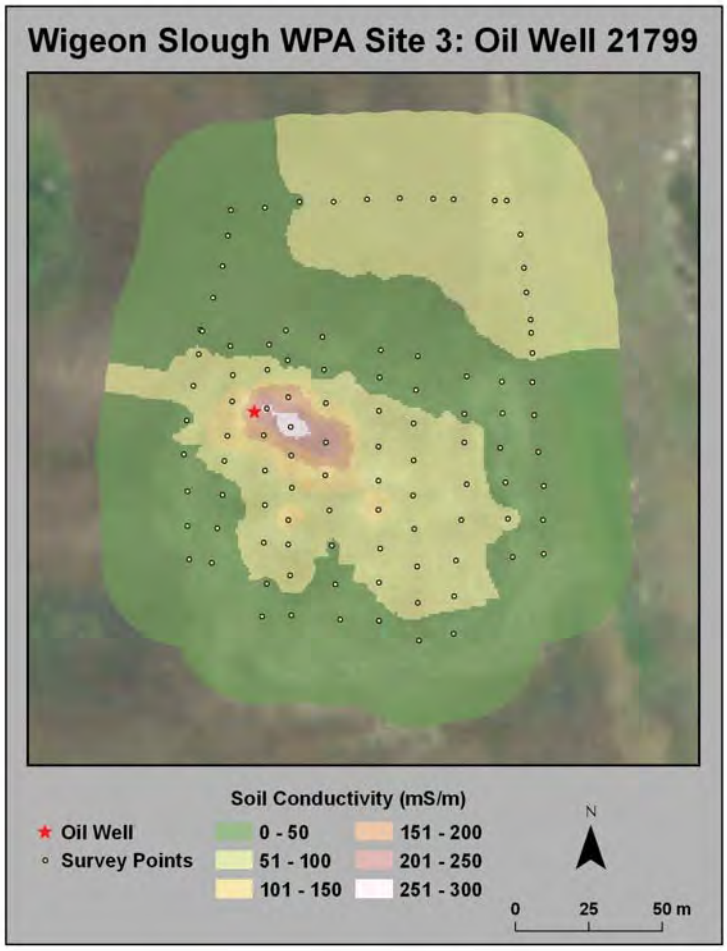


Figure 131. Location of EM-31 terrain-conductivity survey conducted at Site 3 of the Wigeon Slough WPA.

may be the result of spills, leaks, or chronic discharges that are directly entering the wetland. Additionally, site WS7 had a CI value that was approaching the empirical lower limit of 0.035. The WS1 terrain conductivity survey appears to have identified a flow path characterized by higher conductivity levels that leads to WS7. The surface-water impacts may not be as evident as one would expect due to the relatively low permeability of glacial till, reducing the amount of brine contamination reaching the wetland.

### *Co-occurring Contaminants*

There were no additional analyses done for the Wigeon Slough WPA.

## Medicine Lake National Wildlife Refuge

The Medicine Lake NWR was established on 08/19/1935 by Executive Order No. 7148 signed by Franklin D. Roosevelt. The refuge is made up of two contiguous areas, a 28,396-acre main unit consisting of the 8,218-acre Medicine Lake and 17 smaller bodies of water and adjacent grasslands, and the 3,264-acre Homestead Unit that includes additional wetland and grassland habitat. Originally, the Medicine Lake NWR was "reserved and set apart… as a refuge and breeding ground for migratory birds and other wildlife." Today, the refuge is recognized as a Globally Important Bird Area by the Audubon Society. Much of the work for this project was located in the eastern half of the refuge (fig. 132). Specifically, work was focused on the two oil wells 21600 and 21599, which are located within the refuge. Wells 21600 and 21599 are both oil-producing wells that were completed in April 1986 and March 1986, respectively. These wells were drilled with reserve pits used to store fluids and well cuttings during oil well drilling and testing. These pits and associated wastes appear to have been buried as a final reclamation method. This method of reclamation has been the most common method used in the Montana portion of the Williston Basin. Currently, other waste disposal methods are being used, such as pitless drilling, where most of the fluids are recycled and pits are solidified.

### *Geology*

The Medicine Lake NWR is underlain by glacial outwash deposits (fig. 133). These deposits are estimated to be from 100 to 200 ft thick based on nearby test drilling. Fort Union sandstone and mudstone underlie the glacial materials. The sand and gravel glacial outwash deposits are associated with the upper permeable glacial outwash zone. The deeper ancestral Missouri River alluvial zone of the Clear Lake aquifer underlies the refuge further to the south.

### *Groundwater Hydrology*

The area surrounding wells 21600 and 21599 located within Medicine Lake NWR overlies the Clear Lake aquifer. Based on nearby lithologic logs, two permeable zones of the Clear Lake aquifer underlie this site. The shallowest zone is 0 to 40 ft below land surface and the deepest is at depths of 100 to 150 ft. Flow in the regional aquifer is generally towards the west or southwest. It is likely that the shallow localized flow is dominated by topography with groundwater flowing from upland hummocks to the low-lying wetlands and lakes. Water level measurements on 9/11/2005 were used to construct a water table map (fig. 134). Groundwater flow is towards the south from the oilfield sites towards the lake. Hydrogeologic stratigraphic relationships in the vicinity of these oil wells are shown in figure 135. Brines associated with reserve pits at these locations are likely to move down into the main part of the Clear Lake aquifer and migrate south towards the lake.

### *Characterizing Oil Field Production Brine Migration*

EM-31 terrain conductivity surveys were conducted surrounding the two oil wells, 21600 (fig. 136) and 21599 (fig. 137). Additionally, a vertical conductivity survey was conducted surrounding oil well 21599 (fig. 138). These surveys indicated higher than background readings in areas associated with these oil well locations. These appear to be related to the reclaimed reserve pits associated with the wells. Among the five monitoring wells sampled, specific

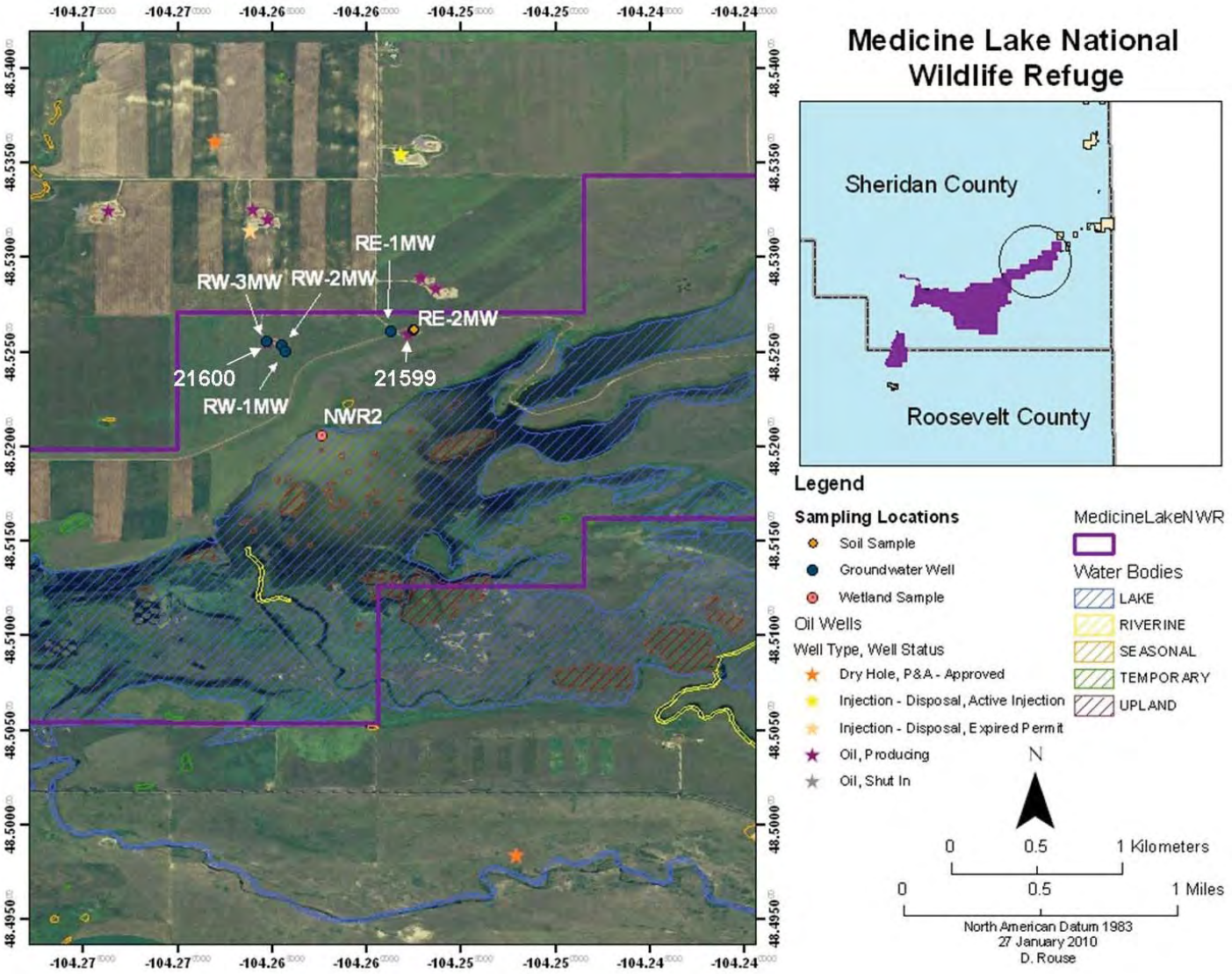


Figure 132. Map depicting locations of sampling sites, oil wells, and bodies of water for the Medicine Lake NWR: T. 32 N., R. 57 E., sec. 13 & 14.

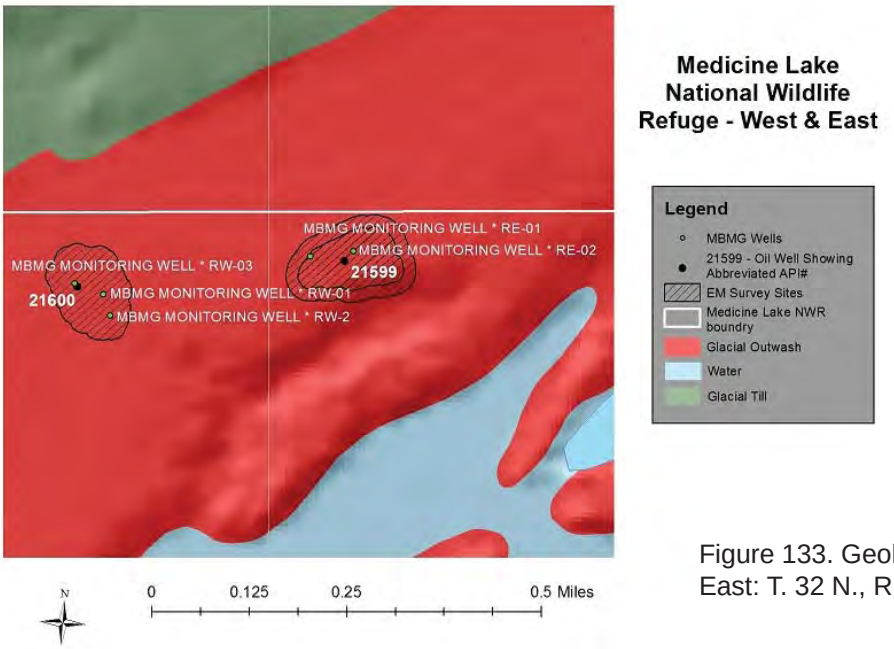


Figure 133. Geology of the Medicine Lake NWR—West & East: T. 32 N., R. 57 E., sec. 13 & 14.

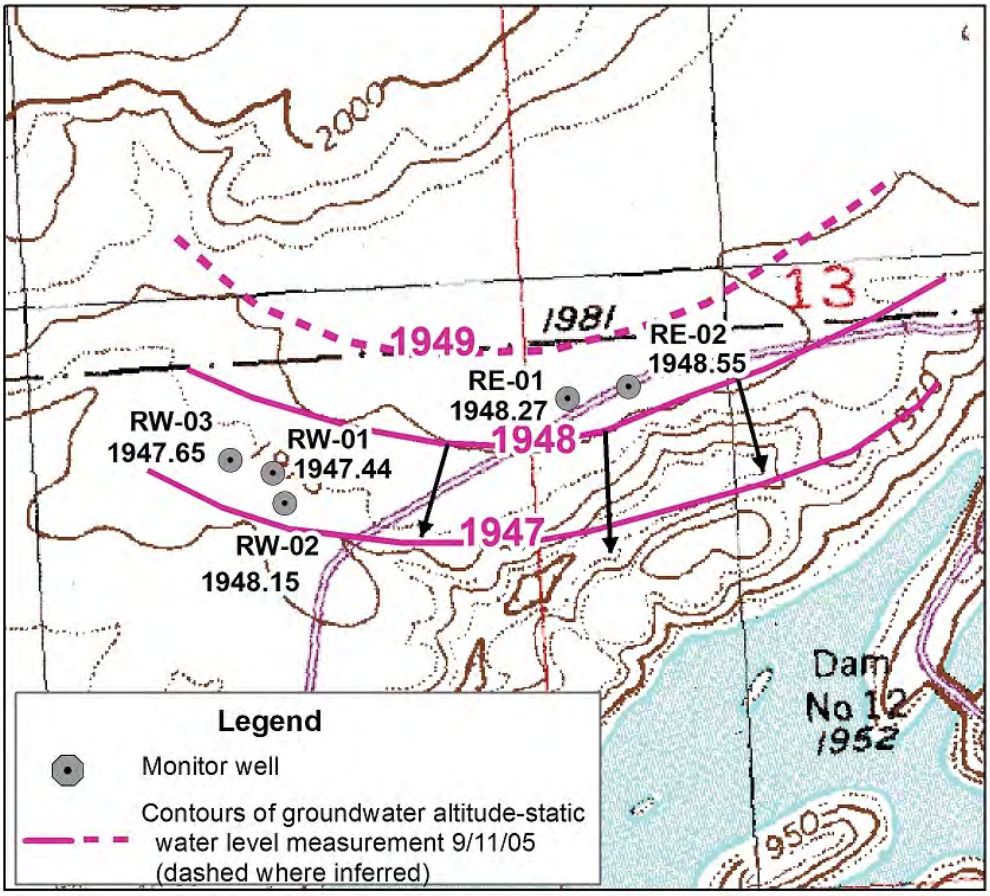


Figure 134. Geology of Medicine Lake NWR—West & East: T. 32 N., R. 57 E., sec. 13 & 14.

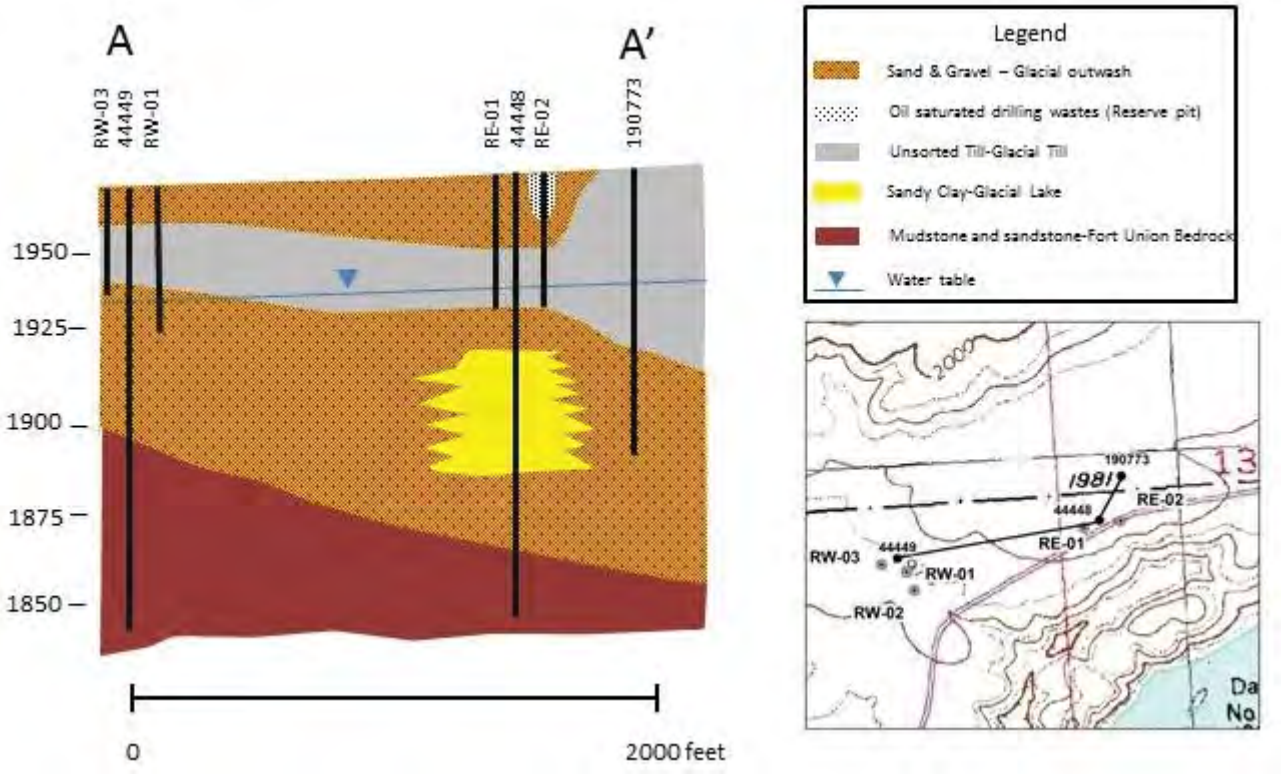


Figure 135. Cross-section A-A' at Medicine Lake NWR – West & East: T. 32N, R. 57E, sec. 13 & 14.

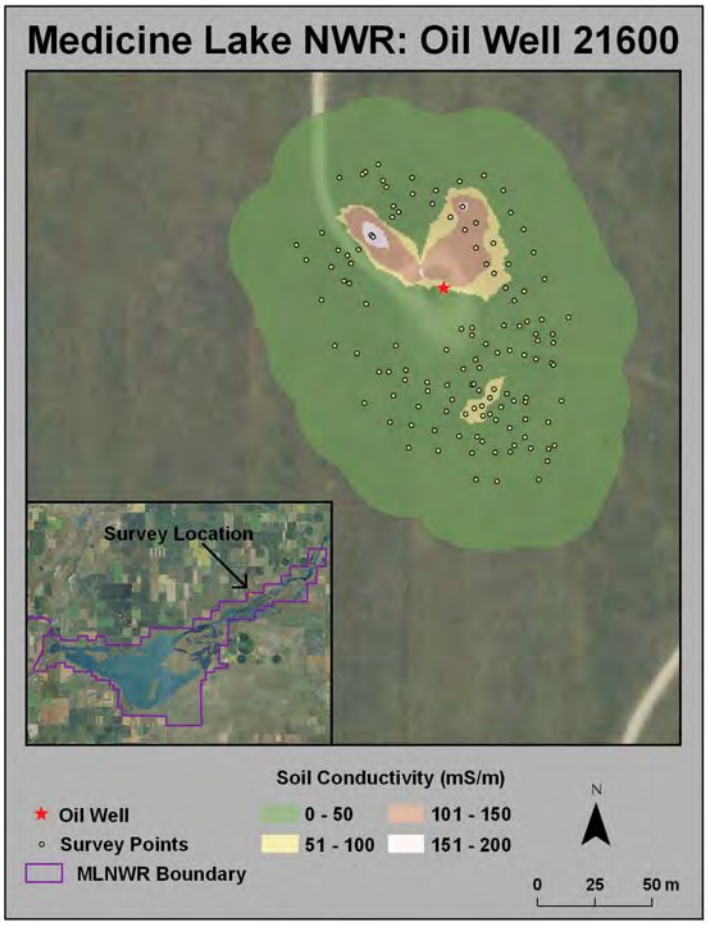


Figure 136. Location of EM-31 terrain-conductivity survey conducted at the Medicine Lake NWR surrounding oil well 21600: T. 37 N., R. 57 E., sec. 7 & 8.

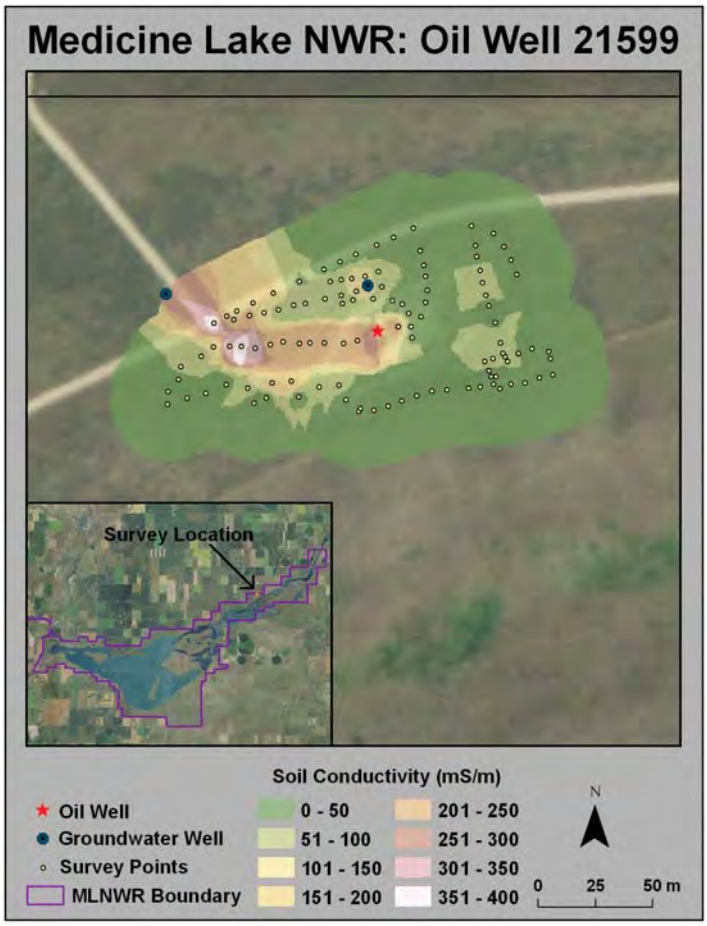


Figure 137. Location of EM-31 terrain-conductivity survey conducted at the Medicine Lake NWR surrounding oil well 21599: T. 37 N., R. 57 E., sec. 7 & 8.

Table 60. Surface-water sampling date, specific conductivity, chloride concentration, contaminant index, and salinity classification based on inland salinity modifiers developed by Cowardin and others (1979) for the Medicine Lake NWR.

| Site | Sampling Date | Specific Conductivity (µS/cm) | Chloride Concentration (mg/L) | Contaminant Index | Salinity Classification |
|---|---|---|---|---|---|
| NWR2 | 4/27/2004 | 1,702 | 30 | 0.018 | Oligosaline |

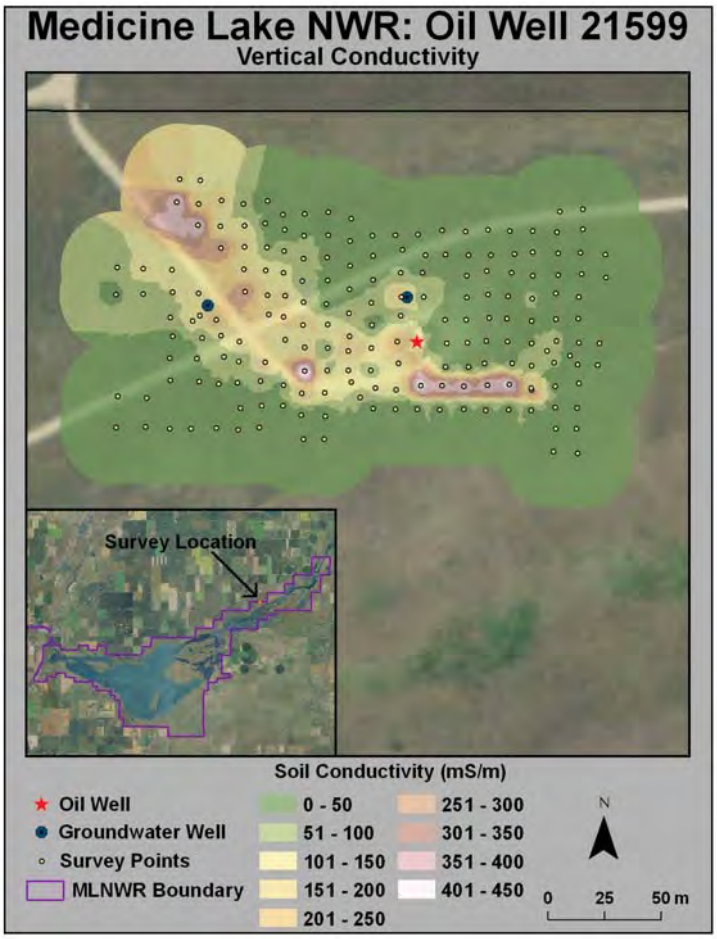


Figure 138. Location of vertical EM-31 terrain-conductivity survey conducted at the Medicine Lake NWR surrounding oil well 21599: T. 37 N., R. 57 E., sec. 7 & 8.

conductance ranged from around 725 to 24,300 µS/cm and chloride concentrations ranged from around to 11,538 mg/L. As indicated by the calculated CI values from the well samples, produced water impacts were evident at sites RW-1MW (GWIC ID 221728) and RE-2MW (GWIC ID 221691). The ionic concentrations (fig. 139) and compositions (fig. 140) of groundwater samples taken from wells RW-1MW (GWIC ID 221728) and RE-2MW (GWIC ID 221691) are indicative of brine-impacted systems, although impacts are more evident at RE-2MW (GWIC ID 221691) based on the dominant Cl- presence. In fact, the drill cuttings for RE-2MW indicated that this well was installed below the reserve pit. Further, no liner appeared in the drill cuttings, which should have appeared if the reserve pit was lined. RW-2MW (GWIC ID 221596), RW-3MW (GWIC ID 221726), and RE-1MW (GWIC ID 221719) appear to be outside of the extent of contamination during this sampling event. Although brine contamination appears to be relatively localized at this point, it is likely that brines will continue to move offsite. These sites will require future cleanup to prevent brines from migrating into nearby wetlands of the Medicine Lake Wildlife Refuge.

### *Wetland Water Quality*

One site was visited in 2004 to assess surface-water quality. This site, NWR2, had a specific conductivity of 1,702 µS/cm, a chloride concentration of 30 mg/L, and a CI indicating no current brine contamination (table 60).

### *Co-occurring Contaminants*

Samples were collected from each of the five groundwater monitoring wells within the Medicine Lake NWR in 2005 and analyzed for trace elements (table 61). Exceedances based on Montana's numerical water-quality standards for

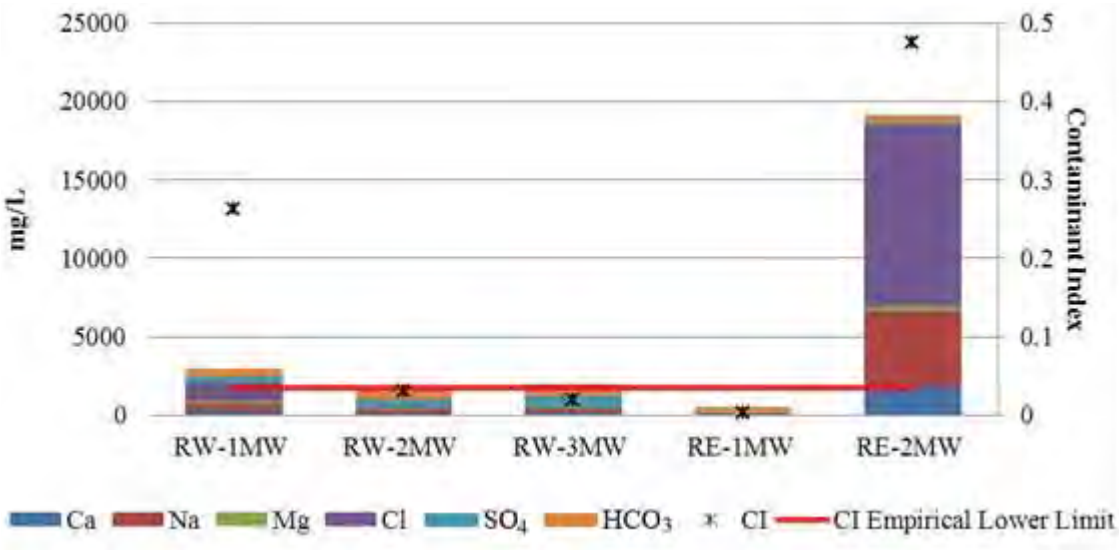


Figure 139. Major groundwater ionic concentrations and associated contaminant index values for monitoring wells present within the Medicine Lake NWR during 2005.

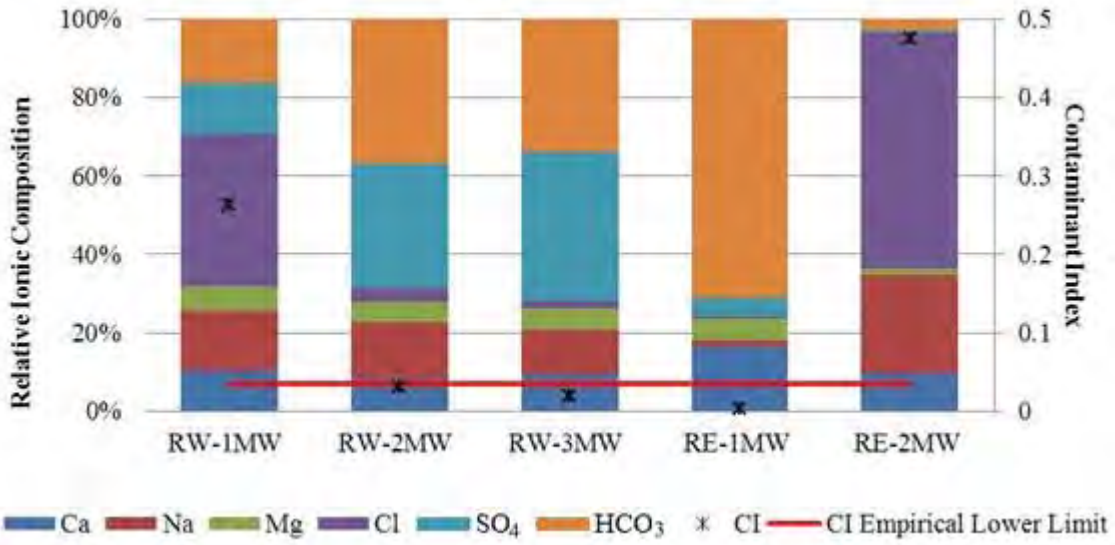


Figure 140. Major groundwater ionic compositions and associated contaminant index values for monitoring wells present within the Medicine Lake NWR during 2005.

Table 61. Surface-water concentrations (µg/L) of trace elements from ML-SW in 2005 and groundwater concentrations (µg/L) of trace elements present in the sampled monitoring wells of the Medicine Lake NWR in 2005.

| | Surface Water | Groundwater | | | | |
|---|---|---|---|---|---|---|
| | ML-SW | RW-1MW | RW-2MW | RW-3MW | RE-1MW | RE-2MW |
| Al | 50 | <50 | <50 | <50 | <50 | <50 |
| As | 33.9 | 0.63 | 0.23 | 0.33 | 0.19 | 6.28 |
| B | 1,400 | 289 | 253 | 223 | 60 | 5,430 |
| Ba | 48 | 60 | 21 | 29 | 150 | 1,350 |
| Be | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Cd | 0.2# | <0.05 | 0.02 | 0.02 | 0.03 | 2.08* |
| Co | <5 | <5 | <5 | <5 | <5 | <5 |
| Cr | <5 | <5 | <5 | <5 | <5 | <5 |
| Cu | <5 | <5 | <5 | <5 | <5 | <5 |
| Hg | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Mo | <10 | <10 | <10 | <10 | <10 | <10 |
| Ni | <5 | <5 | <5 | <5 | <5 | <5 |
| Pb | 0.09 | <0.05 | <0.01 | <0.01 | <0.01 | <0.1 |
| Se | 0.53 | 31.7 | 32.4 | 143* | 1.39 | 3.88 |
| Sr | 465 | 1,910 | 1,330 | 1,450 | 320 | 48,100* |
| Ti | <5 | <5 | <5 | <5 | <5 | 20 |
| V | <10 | <10 | <10 | <10 | <10 | <10 |
| Zn | <5 | <5 | <5 | <5 | <5 | <5 |

#Indicates value exceeded EPA's recommended national water-quality criteria.

*Indicates value exceeded Montana numerical water-quality standards for human health in groundwater.

human health in groundwater were observed within wells RW-3MW (GWIC ID 221726) and RE-2MW (GWIC ID 221691). Selenium exceeded water-quality guidelines at RW-3MW (GWIC ID 221726) but appears to be unrelated to brine contamination based on the low CI value. In contrast, cadmium and strontium concentrations exceeded water-quality guidelines at well RE-2MW (GWIC ID 221691) and are likely a result of brine contamination based on the CI value, as well as the general relationship observed between the CI and trace element concentrations across the Northeast Montana WMD (table 5). In spite of this, trace elements are largely confined to the shallow aquifers from which they were collected, greatly limiting the exposure to wildlife. Nevertheless, surface water–groundwater interactions may be a pathway for trace element exposures in wildlife.

In 2005, one sample was collected from the surface-water site ML-SW, a site located just south of refuge headquarters on Medicine Lake. Based on EPA's recommended water-quality criteria, there was one exceedance for cadmium (table 61). Although not at the same location as ML-SW, the water quality of Medicine Lake was assessed at NWR2 in 2004. Based on that assessment, it appears that Medicine Lake was not impacted by brine contamination. Therefore, the elevated cadmium concentration is likely due to some other process or source. Medicine Lake receives water from a relatively large drainage, so it will be difficult to discern the source, or sources, contributing to the observed cadmium concentration.

One soil sample, ME-2S, was collected in 2005 for total petroleum hydrocarbon analysis. This sample had a total petroleum hydrocarbon concentration of 246 mg/kg (DW) (fig. 141). Aliphatic and aromatic fractions were not determined for this site. In 2005, two groundwater samples were collected from RE-2MW (GWIC ID 221691) and RW-1MW (GWIC ID 221728) and were then analyzed for total petroleum hydrocarbons. Total petroleum hydrocarbons were present in the samples from RE-2MW (GWIC ID 221691) and RW-1MW (GWIC ID 221728) at concentrations of 290 and <100 µg/L, respectively (fig. 142). In 2006, a groundwater sample from RE-2MW (GWIC ID 221691) was analyzed for aliphatic and aromatic hydrocarbons (table 62). The heavy hydrocarbon fractions were elevated in this sample suggesting that that oil production activities have contaminated groundwater with petroleum hydrocarbons, but at levels that will unlikely produce a significant toxicological response in wildlife.

### *Ion Toxicity*

Ion toxicity models have been developed based on ion specific toxicity tests conducted on organisms such as *C. dubia*. For example, Mount and others (1997) developed a statistical model to predict the relative toxicity of varying concentrations and compositions of major ions in freshwater. This model has been used successfully to quantify major ion toxicity associated with produced waters from across the United States (Tietge and others, 1997). Furthermore, statistical ion toxicity models have also proven useful in identifying impacts from co-occurring contaminants by investigating discrepancies that occur between the observed and predicted toxic outcomes. Since a suite of co-occurring contaminants are often associated with produced waters, it was our intent to assess the applicability of applying this model in coordination with site-specific toxicity tests as a means to quantify impacts from

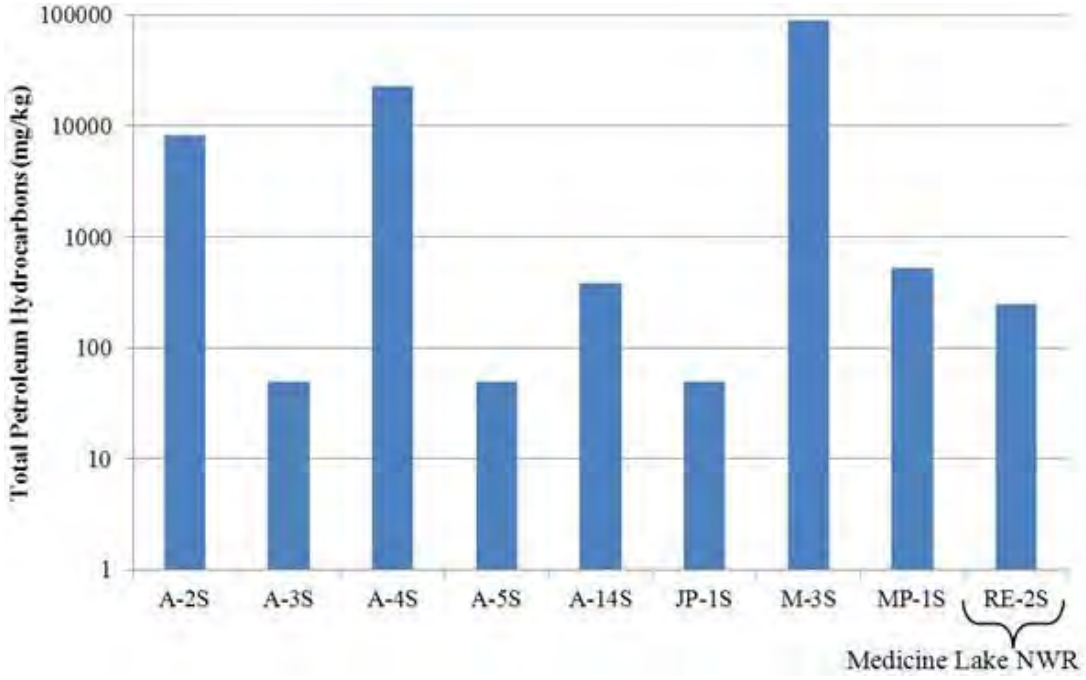


Figure 141. Concentrations (mg/kg DW) of total petroleum hydrocarbons from soil samples collected across the Northeast MTWMD in 2005 with the site located in the Medicine Lake NWR bracketed.

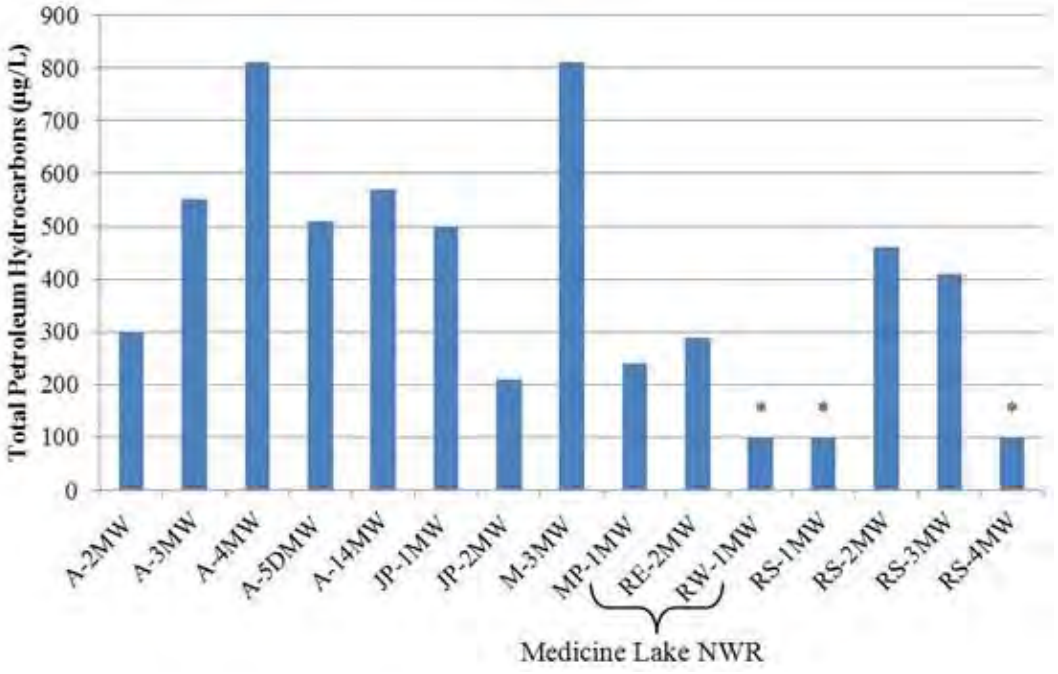


Figure 142. Concentrations (µg/L) of total petroleum hydrocarbons from groundwater samples collected across the Northeast MTWMD in 2005 with the site located in the Medicine Lake NWR bracketed. *Indicates concentration is below the analytical detection limit of 100 µg/L.

Table 62. Concentrations (µg/L) of hydrocarbon fractions from the groundwater sample collected in 2006 within the Medicine Lake NWR with associated toxicity criteria.

| | Toxicity Criteria | | Site Values |
|---|---|---|---|
| | MT RBSL[1] (µg/L) | MADEP[2] (µg/L) | RE-2MW (µg/L) |
| **Aliphatics** | | | |
| Carbon Range C9–C18 | 1,000 | 50,000 | 0 |
| Carbon Range C19–C36 | 1,000 | 50,000 | 19.2 |
| **Aromatics** | | | |
| Carbon Range C9–C10 | — | 50,000 | <0.3 |
| Carbon Range C11–C22 | 1,000 | 5,000 | 0.5 |
| Acenaphthene | 670 | 6,000 | <0.3 |
| Anthracene | 2,100 | 30 | <0.3 |
| Benzo(a)pyrene | 0.05 | 500 | <0.3 |
| Benzo(b)fluoranthene | 0.5 | 400 | <0.3 |
| Benzo(k)fluoranthene | 5 | 100 | <0.3 |
| Chrysene | 50 | 70 | <0.3 |
| Dibenzo(a,h)anthracene | 0.05 | 40 | <0.3 |
| Fluoranthene | 130 | 200 | <0.3 |
| Flourene | 1,100 | 40 | <0.3 |
| Indeno(1,2,3-cd)pyrene | 0.5 | 100 | <0.3 |
| Napthalene | 100 | 20,000 | <0.3 |
| Pyrene | 830 | 20 | <0.3 |

[1]Montana Tier 1 Risk-Based Corrective Action Guidance for Petroleum Release (MT DEQ, 2009).
[2]Massachusetts Department of Environmental Protection (MADEP, 2003).

co-occurring contaminants. Laboratory toxicity tests using *C. dubia* were implemented using site water from 20 different locations found within 12 separate WPAs, and results were then compared to the predicted outcomes produced by the Mount and others (1997) model based on site-specific water chemistry data.

When the variability in the toxicity tests was considered, the Mount and others (1997) model accurately predicted survival in 75% of the samples, over-predicted toxicity (predicted lower % survival than was observed) for 15% of the samples, and under-predicted toxicity (predicted higher % survival than was observed) in 10% of the samples tested (fig. 133). It is important to note that 11 of the 15 samples in which the model accurately predicted toxicity were samples that resulted in a 0% survival rate in test species. If those samples are not considered, the Mount and others (1997) model accurately predicted survival in 44% of the samples, over-predicted toxicity (predicted lower % survival than was observed) for 22% of the samples, and under-predicted toxicity (predicted higher % survival than was observed) in 33% of the samples tested. From these results, it is quite clear that the concentrations of major ions present at these sites create an environment unsuitable for a species such as *C. dubia*, but impacts from co-occurring contaminants are difficult to discern.

For sites RIV1, HAN1, and SL3, the model over-predicted toxicity (fig. 143). One possible explanation for this is that there may be some other constituent, or constituents, that are reducing the toxic effects of the major ions present due to their direct competition or ability to form complexes with various ions (Schamphelaere and Janssen, 2003). Another possibility is that these unidentified constituents may cause some physiological response in the test organisms that reduces the uptake rates of the major ions present (Soucek and others, 2011). Last, the model could simply be predicting poorly given the specific ion concentrations.

The model under-predicted toxicity for the two sites GW5 and RABE4 (fig. 143). Numerous factors may have contributed to this discrepancy, including but not limited to the presence of co-occurring contaminants or a failure in the model to predict accurately given the specific ion concentrations. When reviewing co-occurring contaminant data for GW5, it appears that elevated trace element concentrations, specifically those concentrations of cadmium, lead, and zinc that exceeded water-quality criteria, could have contributed to the differences seen in observed and predicted survival. The degree of toxicity of trace elements is directly related to their bioavailability. There are many properties that affect the bioavailability of metals, but complexation with dissolved organic matter and competition between other dissolved ions often reduces the toxic potential (Di Toro and others, 2001). GW5 is one of the freshest wetlands observed across the Northeast MT WMD; therefore, competition between ions is reduced compared to other sites and it is likely that cadmium, lead, and zinc are contributing to the increased toxicity observed at this site. On the other hand, there were no clear co-occurring contaminants for RABE4 at levels that may elicit a toxicological response. There may, however, be interactions occurring between measured constituents that are producing toxicity, but these interactions are difficult to quantity without further investigation. Additionally, there may be other co-occurring contaminants that we failed to measure, such as pesticides or other oilfield exploration and production wastes that were not on our analyte list, that may be producing toxicity.

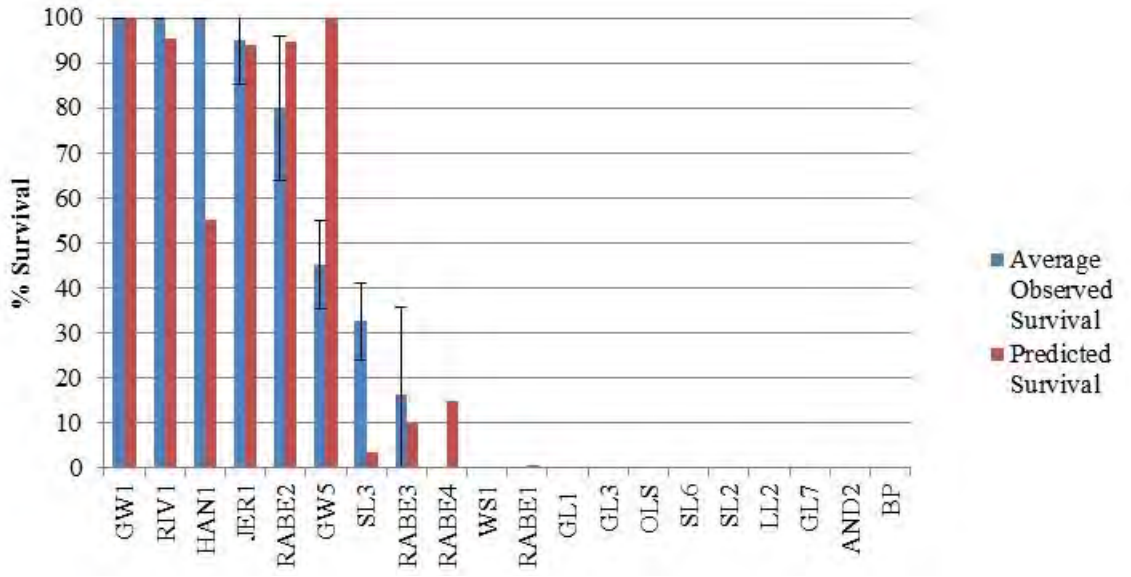


Figure 143. Average observed survival (%) of *C. dubia* with 95% confidence intervals (n=4) when exposed to site water from 20 locations across the Northeast MTWMD with predicted survival (%) based on Mount and others (1997) ion toxicity model using site-water chemistry.

## CONCLUSIONS

It is clear that oil production activities can alter wetland ion chemistry through groundwater migration and surface-water transport of produced waters. This has been characterized through the use of EM-31 surveys, field and analytical assessments of surface-water and groundwater chemical compositions, and the application of a contaminant index to detect brine impacts among a suite of chemically diverse aquatic systems, ranging from fresh to hypersaline. Additionally, certain trace elements have been identified as co-occurring contaminants, as these are often found at elevated levels in areas that are experiencing brine impacts, although the correlation between trace elements and the CI is stronger in groundwater than in surface water. A summary of produced water impacts, including chloride impacts and water-quality exceedances for surface-water and groundwater samples collected across the Northeast Montana WMD, is provided in table 63. Petroleum hydrocarbons have also been detected at potentially toxic levels at the soil surface, while concentrations in the groundwater, although present, are at levels that are typically below toxic thresholds and will likely have minimal impact if they reach surface-water systems. Nevertheless, when the potential transport of soil-bound petroleum hydrocarbons by processes such as a high rainfall event is considered, hydrocarbons may reach surface-water bodies at levels potentially toxic to aquatic and terrestrial organisms. A potential strategy to distinguish the impacts of co-occurring contaminants from salinization was investigated; its merit is discussed in more detail below.

Glacial till, glacial outwash, and glacial lake sediments typically have complex stratigraphic and areal inter-relationships. Aquifers developed in glacial deposits can rarely be classified as isotropic, homogeneous, and infinite. Consequently, defining the aquifers formed in glacial deposits and defining the properties of these aquifers, such as transmissivity, storativity, and boundary conditions, are difficult tasks, subject to a wide margin of errors. Because of these complex relationships, impacts from produced water spills and other discharges are very difficult to identify, map their extent, and predict contamination impacts. However, the relatively high permeability of glacial outwash would promote a wider spread of a developing plume along with increased dilution, while the lower permeability associated with the glacial till would typically result in a more localized, higher-concentrated brine plume. The geologic map depicted in plate 1 displays the surficial geology of the project area, distribution of oil well sites, WPA boundaries, and impacts of oilfield brine releases at selected sites. Special care should be taken in glacial deposits regarding oil well site location, produced water handling, and oil field waste disposal. Glaciated areas are generally poor areas for onsite disposal of oil field wastes. Other disposal methods are critical, and a monitoring program should be developed to assess impacts. For instance, the CI proved to be a useful indicator of brine pollution in this area and can be a relatively simple tool to assess contamination. EM-31 surveys are also very useful tools in identifying brine plumes. Geologic mapping provides a framework for understanding brine movement and dispersion. These methods can help identify both the location and magnitude of contamination underlying a site.

Although wetland chemistry of northeastern Montana is quite diverse and often characterized as naturally saline, the application of the CI has been useful in identifying those wetlands that have been impacted by produced waters. In fact, 40% of the wetlands assessed were classified as impacted based on their average CI values (fig. 144). These impacted wetlands were present in 18 WPAs of the Northeast Montana WMD. Some of the more pronounced impacts were seen at the Anderson and Rabenberg WPAs. Both of these sites have tank batteries and historic produced water infiltration pits associated with them.

While the CI is a useful tool in identifying chemical

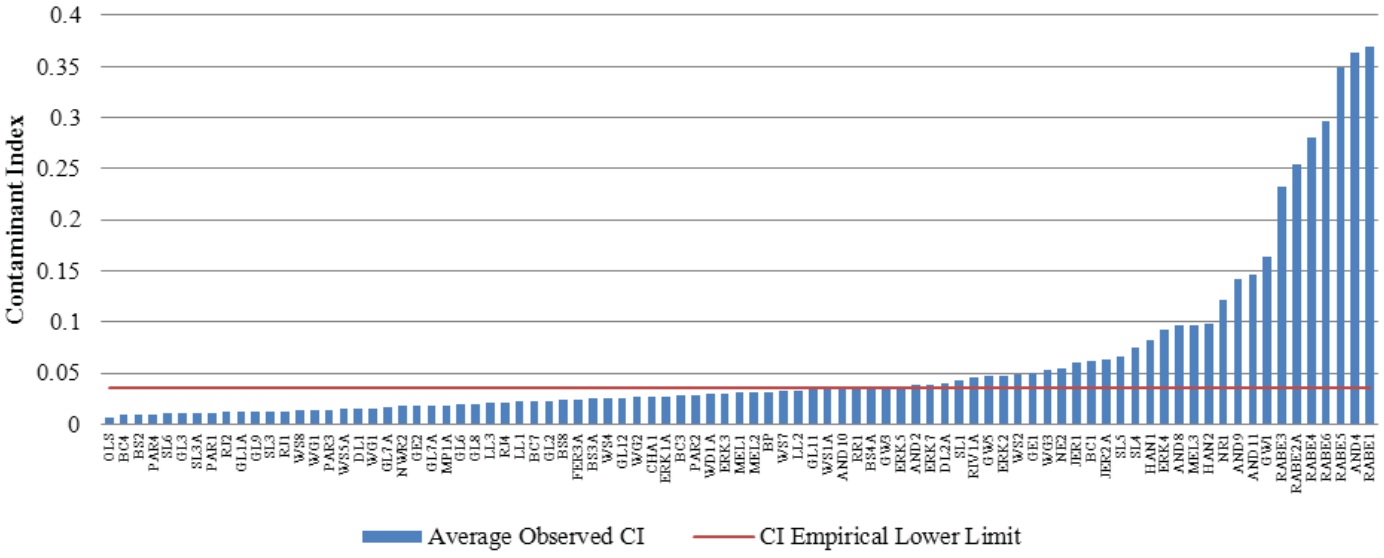


Figure 144. Average CI value for wetland sites visited across the Northeast Montana Wetland Management District.

Table 63. Summary of chloride impacts and water-quality exceedances for surface-water and groundwater samples collected across the Northeast Montana WMD.

| | Chloride Impacts[1] | | Co-occuring Contaminants | |
|---|---|---|---|---|
| | Surface Water | Groundwater | Surface Water[2] | Groundwater[3] |
| Anderson WPA | Yes | Yes | Yes | Yes |
| Base Camp WPA | Yes | N/A | N/A | N/A |
| Chandler WPA | No | N/A | N/A | N/A |
| Long Lake WPA | Yes | N/A | Yes | N/A |
| Berger Pond WPA | No | N/A | N/A | N/A |
| Melby WPA | Yes | Yes | Yes | Yes |
| Mallard Pond WPA | No | Yes | Yes | Yes |
| Northeast WPA | Yes | N/A | N/A | N/A |
| North Root WPA | Yes | N/A | N/A | N/A |
| Big Slough WPA | Yes | Yes | N/A | No |
| Rabenberg WPA | Yes | Yes | Yes | Yes |
| Hansen WPA | Yes | Yes | No | No |
| Ward WPA | No | Yes | N/A | No |
| Jerde WPA | Yes | Yes | Yes | Yes |
| Erickson WPA | Yes | N/A | N/A | N/A |
| Ferguson WPA | No | N/A | N/A | N/A |
| Gjesdal East WPA | Yes | N/A | N/A | N/A |
| Redhead Retreat WPA | No | N/A | N/A | N/A |
| Westgard WPA | Yes | N/A | Yes | N/A |
| Dog Leg WPA | Yes | N/A | N/A | N/A |
| Goose Lake WPA | No | N/A | Yes | N/A |
| Gjesdal West WPA | Yes | N/A | Yes | N/A |
| Olson WPA | No | N/A | Yes | N/A |
| Rivers WPA | Yes | N/A | Yes | N/A |
| Rich Johnson WPA | No | N/A | N/A | N/A |
| Parry WPA | No | N/A | N/A | N/A |
| Shoveler Puddle WPA | N/A | N/A | N/A | N/A |
| State Line WPA | Yes | N/A | No | N/A |
| Wigeon Slough WPA | Yes | N/A | N/A | N/A |
| Medicine Lake NWR | No | Yes | Yes | Yes |

[1]Based on CI values in exceedance of 0.035.

[2]Based on EPA's recommended national water-quality criteria.

[3]Based on Montana's numerical water-quality standards for human health in groundwater.

*Note:* N/A, data not available.

impacts from brine contamination, the biological impacts are still unclear. Salinization, whether naturally or anthropogenically derived, can impact both abiotic and biotic entities. Increased salinity in uplands can cause increased erosion through the dispersion of clays, disruption of soil texture, and loss of soil cohesion (Otton and Zielinski, 2000). Additionally, increasing salinity levels typically result in a loss of plant diversity (Kantrud and others, 1989), as salts may indirectly stress plant tissues by reducing water availability or directly stress plant tissues through ion-specific toxicity (Munns and Tester, 2008). Similarly, elevated salinity levels have also been shown to impact seed germination of certain plant species (Galinato and Van Der Valk, 1986). In aquatic environments, invertebrate and vertebrate organisms may also be impacted by salinization. For instance, reduced survival of sensitive invertebrate species such as *C. dubia* has been attributed to major inorganic ions associated with produced water discharges (Boelter

and others, 1992). Furthermore, macroinverterbrate richness may decrease in response to increasing salinity levels (Waterkeyn and others, 2008), although invertebrate biomass is typically maintained with increasing salinity due to the elevated abundance of one or two salt-tolerant species (Wollheim and Lovvern, 1995; Rubega and Robinson, 1997). The shifting invertebrate community structure may alter the avian composition due to differing feeding strategies, but the physiological stressors induced by elevated salt concentrations appear to have greater impacts to avian health than the homogenization of the prey community (Gordus and others, 2002; Rubega and Robinson, 1997).

Salt has been reported to affect birds in numerous ways. For instance, surface tension is reduced with increasing dissolved solutes, which in turn can negatively impact a feathers' thermoregulatory and buoyancy function, ultimately causing hypothermia or an increased incidence of drowning (Rubega and Robinson, 1997; Ramirez, 2009). Similarly, salt encrustation can occur, especially during periods of cooler weather that promote salt precipitation, which effectively immobilizes birds (Nelson and Reiten, 2009). Through preening, drinking, and eating, salt can be ingested at potentially toxic levels. Specifically, it has been suggested that around 4 grams of sodium chloride can cause mortality in certain waterfowl species (Meteyer and others, 1997). Although waterfowl have mechanisms to deal with internal salt concentrations, primarily through supraorbital salt glands and to a lesser extent renal excretion and intestinal absorptive mechanisms (Wobeser, 1981), high levels of ingested salts can overwhelm their coping mechanisms, leading to toxicosis. Additionally, ducklings and goslings typically do not develop salt glands until 4 to 6 days after hatching (Mitcham and Wobeser, 1988b; Stolley and others, 1999).

Impacts have been reported in birds across varying degrees of salinization. Based on specific conductivity, Mitcham and Wobeser (1988a) observed a 10% reduction in growth when 1-day-old mallard ducklings were provided drinking water from a saline wetland with specific conductance as low as 4,000 µS/cm. Furthermore, increased incidence of mortality was observed when ducklings were provided water with a specific conductivity of 20,000 µS/cm and mortality was observed within 30 hours for ducklings provided water with a specific conductivity of 67,000 µS/cm (Mitcham and Wobeser, 1988a). Die-offs in adult waterfowl using hypersaline wetlands have also been attributed to salt toxicosis (Meteyer and others, 1997; Windingstad and others, 1987; Nelson and Reiten, 2009). The increased sensitivity for young birds, observed impacts of hypersaline environments, and the preference for freshwater environments makes it increasingly clear that freshwater resources need to be protected in this area (Swanson and others, 1984).

Brine-impacted waters are generally characterized by a shift in the composition of anions, resulting in a Cl- dominated system as opposed to the naturally elevated SO4- and HCO3- ions. Ion-specific toxicities have been evaluated in the laboratory using common test organisms such as *C. dubia*. In general, the relative ion toxicity was HCO3->Cl->SO42- for both chronic and acute exposures (Lasier and Hardin, 2010; Mount and others, 1997). However, hardness strongly influenced ion toxicity, with reduced Cl- and SO42- toxicity as hardness increased (Lasier and Hardin, 2010). Conversely, hardness had little effect on HCO3- toxicity. Based on these observations, Cl- dominated brines will unlikely elicit toxicological responses in organisms inhabiting areas with moderate to high water hardness and alkalinity. On the other hand, if produced water brine were to encroach upon a system dominated by the SO42- ion, toxicological responses would be more likely, particularly in systems with diminished water hardness.
Numerous contaminants co-occur in produced waters, but the compositions and concentrations often vary. Elements that commonly occur in produced water, such as barium, boron, cadmium, copper, lithium, strontium, and zinc (Stephenson, 1992; Jacobs and others,1992), were often elevated in groundwater samples that were impacted by brine contamination. On the other hand, the relationship between surface-water trace element concentrations and brine contamination was much less apparent. In many cases, elements such as aluminum, selenium, and nickel appeared to be elevated in sites where brine contamination was evident, but the source of contamination is difficult to identify. The differences in trace element speciation and behavior between a groundwater environment and a surface-water environment may confound our ability to detect trends between surface-water and groundwater trace element concentrations. However, elevated co-occurring contaminants in wetlands may be present due to surface spills and other undesirable practices and events that may have directly released produced water to that system. Regardless, wetlands generally favor the immobilization of trace elements through the formation of insoluble complexes (Gambrell, 1994). Essentially, various elements may be reaching wetland systems, but analyses of dissolved surface-water samples will not reflect the complete composition of elements present when insoluble complexes are considered. Thus, analyses on sediment samples may reveal higher levels of trace elements associated with brine contamination. While the immobilization of trace elements from the water column may reduce the toxic potential for organisms inhabiting that environment (Starodub and others, 1987), sediment-dwelling organisms may still be impacted (Wentsel and others, 1978). Furthermore, sediment-dwelling organisms may remobilize accumulated metals during certain periods of their life histories such as emergence, ultimately impacting other aquatic organisms, as well as terrestrial organisms in the case of insectivores (Currie and others, 1997).

Although not covered in this investigation, the loss of habitat and increased level of human activity associated with well pad development and operation should also be considered, as mule deer have been observed altering their

normal winter ranges to avoid these areas (Sawyer and others, 2009). Similarly, sensitive species such as the Piping Plover should continue to be monitored to determine if these activities are impacting their behavior and survival. Furthermore, the presence of nuisance weed species will likely increase, as plants such as *Kochia sp.* will grow on salt-damaged soil. Not only will pesticide use increase during preliminary exploratory periods to clear oil pad locations, but weed infestations due to oil production activities will require additional pesticide applications as well.

Hundreds of miles of flow lines and produced water pipelines traverse Sheridan County (Reiten and Tischmak, 1993), and a smaller number of oil pipelines transport oil through 6- and 12-inch lines. Oil and associated produced water pumped at each oil well pump jack are most commonly sent to a tank battery on site or to a nearby location through a flow line, where the initial separation of oil and water occurs. This produced water is then transferred to an injection well via produced water pipelines. These produced water pipelines are generally laid on the ground surface, and most are made of fiberglass or PVC pipe. At present, produced water pipelines are not mapped, and unlike many other types of pipelines and disposal wells, are not monitored for integrity (Reiten and Tischmak, 1993). The history of uncontained brine discharges is based on informal reports from local residents and documented investigations by several state agencies (MBMG, file data). Concern over contamination of water supplies was a major reason for organizing the Northeast Montana Land and Mineral Owners Association, Inc. Most of the reports of contamination were originally from members of the association. Several members reported improper disposal of brines into existing wetlands, brine and oil pipeline and flow line leaks, brine spills, and overflowing evaporation pits. Investigations by state agencies documented several cases of surface-water and groundwater contamination during the early 1970s.

Monetarily, produced water damages to land are likely high, although quantifying those costs would be a difficult task. Many of the impacts do not appear until many years after the sites have been abandoned. Surface damages range in area from ½ acre to more than 5 acres. Direct costs or impacts include soil damage that ranges from completely sterilized soils to marginally productive soils where plant growth is stunted. In many cases, only nuisance weeds will grow on salt-damaged soils. Soil damage will increase costs of growing crops on and around the damaged area and weed infestations will cause an increase in the use of chemicals to control the problem.

## MANAGEMENT RECOMMENDATIONS

The application of the CI has been a useful tool in identifying wetlands that have been impacted by produced waters. Using a chloride titrator kit and handheld water-quality probe, chloride concentrations and specific conductivity measurements can be collected with relative ease in the field. Based on the ease of calculation and the ability to detect produced water impacts, the CI could be incorporated into a monitoring plan to track the degree of impacts through time, or it could be applied in land preacquisition surveys as a quick and easy method to determine the level of impacts present within a piece of property and therefore avoid the acquisition of a highly contaminated site. For instance, if development were to occur near a site that has been characterized as unimpacted, a monitoring plan could be designed to track CI values as development ensues to ensure that impacts are not occurring, or to immediately track the point at which water quality begins to degrade. For preacquisition surveys, CI values could quickly be measured during initial surveys to detect produced water impacts that would normally be difficult to recognize.

Additional techniques have been applied to assess produced water impacts to wetlands, such as the use of strontium isotopes. Although this method requires more in-depth chemical analyses, strontium isotope fractionation has proven to be a highly effective tool not only to detect produced water impacts to surface and groundwater resources of the prairie pothole region, but also to quantify the degree of impact (Peterman and others, 2010).

As some of the more pronounced impacts were seen at locations in close proximity to tank batteries and historic brine disposal pits, these practices, both current and historical, could be useful indicators of potential contamination during land preacquisition surveys. Past aerial photos could be used to identify where historic brine disposal pits were implemented and to potentially determine for how long. This, in coordination with the CI, could aid in the decision-making process of whether or not a site should be preserved through easement or purchase.

The use of ion toxicity models in coordination with laboratory toxicity tests using site water was assessed in this investigation as a potential management tool to quantify impacts of co-occurring contaminants. This effort produced mixed results by proving to be helpful in identifying potential impacts of co-occurring contaminants at site GW5, while creating more uncertainties for sites such as RIV1, HAN1, and SL3. Unfortunately, much of the utility of this method may have been lost in the number of sites that resulted in 0% survival. If a series of dilutions were made for these sites, a gradient of responses could then be captured based on varying concentrations, and potentially, effects of co-occurring contaminants might then become apparent. Although this technique did not provide overwhelmingly clear results, it could serve as a useful tool to track changes in major ion chemistry, as well as a means to assess potential impacts of co-occurring contaminants from oil production activities. If determining the effects of co-occurring elements in highly saline waters is the objective, implementing a series of dilutions to a site water sample would allow one to calculate an observed LC50 (lethal

concentration for 50% of test population) and then compare that to a calculated LC50 based on predicted survival estimates produced by the ion toxicity model. Significant differences between those LC50 values would suggest that co-occurring contaminants may be eliciting a toxicological response.

As indicated in the Montana Code Annotated 2009, oil and gas developers are responsible for paying the surface owner a sum of money or other compensation equal to the amount of damages sustained by the surface owner, including lost land value due to oil and gas operations (Mont. Code Ann. § 82-10-504, et seq,). In response to a produced water spill, the Montana Board of Oil and Gas is one point of contact that can assist in initiating remediation activities (their contact number is (406) 656-0040; Steve Sasaki, Montana Board of Oil and Gas, oral commun., 2011). Reclamation and remediation strategies are often negotiated between the surface owner and the oil and gas developer. One strategy that is often implemented in response to produced water spills is to apply soil amendments in order to increase the leaching of produced water constituents to depths below the root zone (Steve Sasaki, Montana Board of Oil and Gas, oral communication, 2011). While this practice may be protective for certain plants, the results of this study suggest that this practice would not be advisable. The contamination of aquifers derived in glacial deposits can lead to the increased transport of brines, impacting a much larger area, and create a persistent source of produced water with a fate that is difficult to predict and characterize. Alternatives to this method should be considered, including the physical removal of soils impacted by produced water, followed by the restoration of the impacted ecosystem.

An encouraging point is the fact that many of the largest oil field operators in the region are transitioning to pitless drilling practices that are commonly used in other areas but have had limited use in this area. Pitless drilling uses large tanks to store and circulate drilling fluids. Upon well completion the fluids are recycled and the drill cuttings are dried and hauled to a landfill. This type of disposal reduces the volume of wastes and removes the waste from glacial deposits that often have unpredictable waste storage properties.

In summary, multiple tools and trends have been identified that can aid in the management of oil and gas development on Service land. For example, the CI for eastern Montana is a useful indicator of brine contamination that can be measured with relative ease with little equipment. Strontium isotope fractionation has also proven to be a highly effective tool in detecting and quantifying the degree of impact of produced water to surface water and groundwater resources of the prairie pothole region (Peterman and others, 2010), but requires more time for samples to be analyzed and interpreted. The use of past aerial photos may be advantageous in the land acquisition process, as certain historical practices such as brine disposal pits appear to be responsible for some of the higher levels of impacts seen in this investigation. Furthermore, certain geological features such as the relatively high permeability of glacial outwash should be considered, as these areas are more susceptible to brine migration. Due to the development of reliable ion toxicity models (Mount and others, 1997), the observed toxic responses from laboratory toxicity tests using site water can be compared to predicted outcomes to assess the impacts from co-occurring contaminants. Although this technique has proven to be useful in other investigations similar to this one (Tietge and others, 1997), the results from this study were not as clear. Although technologies have improved, such as the development of closed-looped systems, and past practices such as the use of unlined reserve pits are no longer allowed, spills, leaks, compromised reserve pit linings, and reserve pit overflow may continue to contribute produced water to the environment.

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# APPENDIX A

**Oilfield Brine Plumes in Shallow Groundwater,
Goose Lake Field, Sheridan County, Montana:
Documenting Water-Quality Changes over 16 Years**

## HYDROGEOLOGIC BACKGROUND

Previous work in the late 1980s identified a large salt plume associated with several oilfield sites in the Goose Lake field (Reiten and Tischmak, 1993). Several maps and figures were constructed characterizing the hydrogeology and extent of this area. To understand the water-quality changes identified by comparing samples from 1989 to 2006, the hydrogeologic background must be reviewed. Nine oilfield sites appear to be related to brine contamination in parts of sections 22, 26, 27, and 28 in T. 36 N., R. 58 E. Figure A1 is a hydrogeologic map identifying oilfield sites, monitoring wells, EM-31 conductivity anomalies, and cross-section locations in part of the Goose Lake Field.

The topography within the detailed study area is expressed by gently rolling hills, with the land surface sloping towards the east (fig. A2). A broad hill covers the central and northern parts of sec. 27. Surface drainages surround this hill, with all coulees emptying into the unnamed lake on the east edge of the study area. Several small ephemeral sloughs are located within the drainages.

Figure A1 depicts the distribution of three hydrogeologic units: glacial till, dry glacial outwash, and saturated glacial outwash. A contact between surficial deposits of glacial till and surficial deposits of outwash is located in the northern one-third of the study area. South of the contact, glacial outwash mantles the underlying glacial till with a relatively

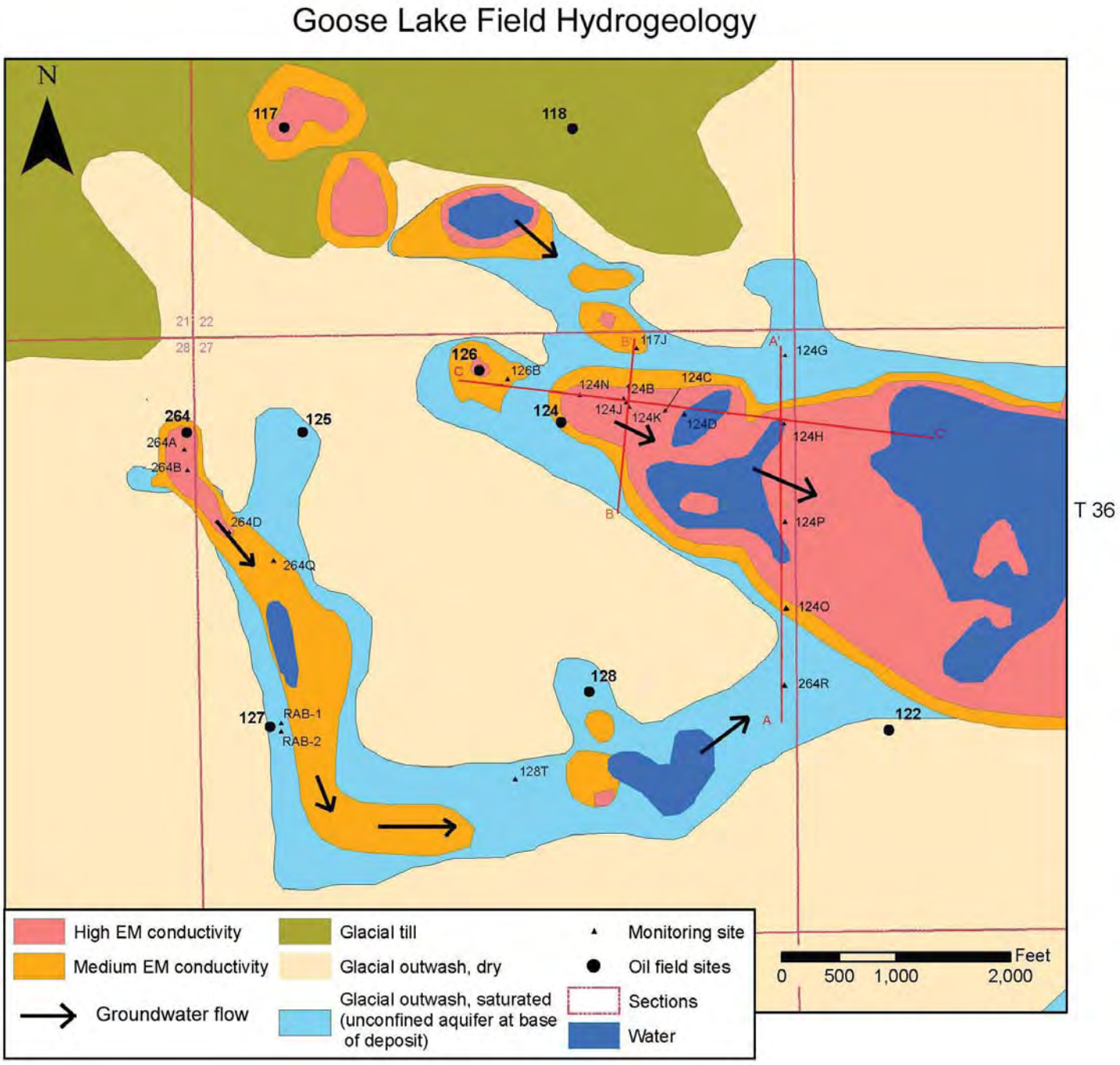


Figure A1. Hydrogeologic map of part of the Goose Lake Field.

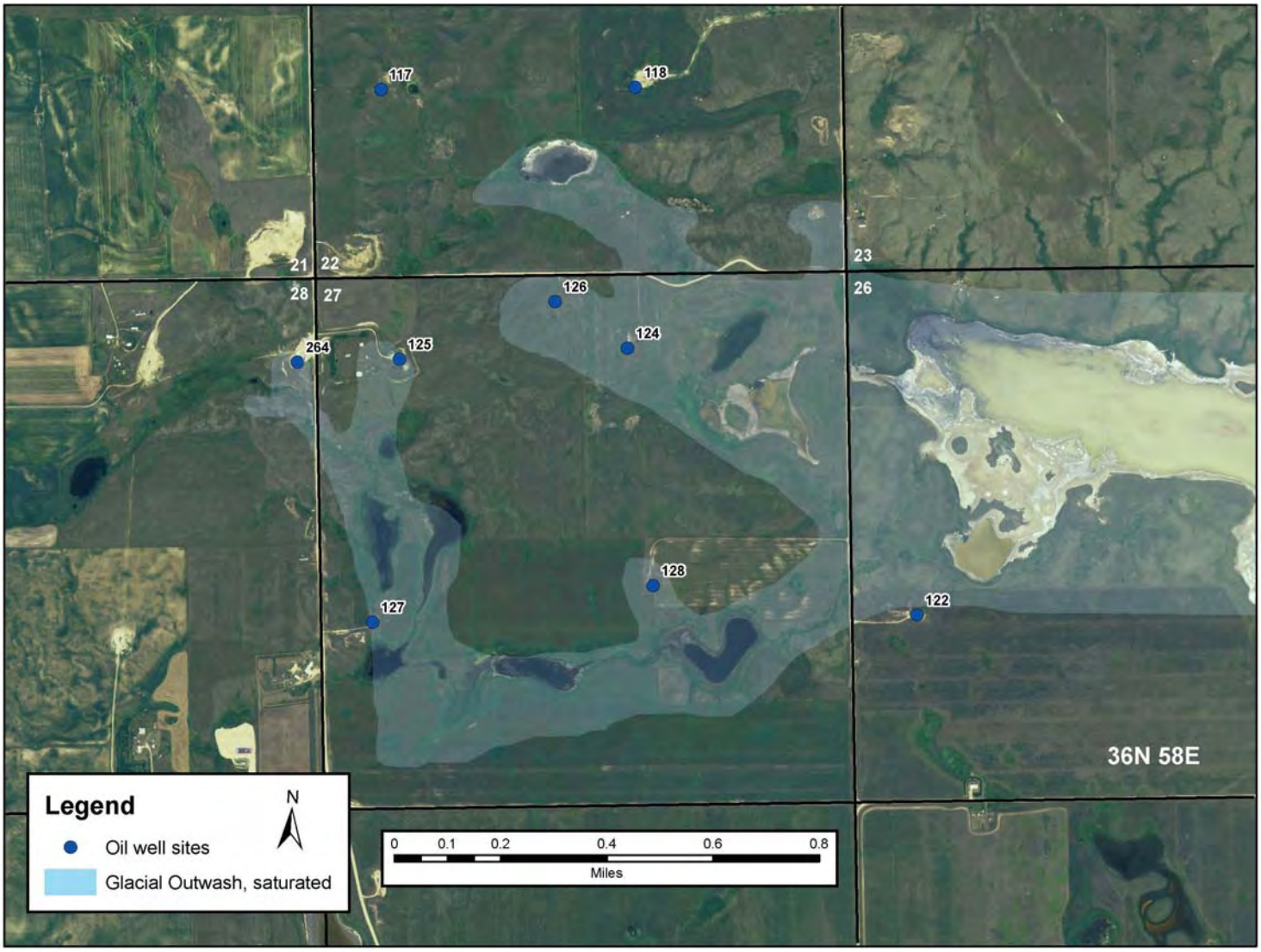


Figure A2. Aerial orthophotograph of part of the Goose Lake oilfield.

uniform thickness of sand and gravel averaging about 15 ft thick. The glacial outwash is composed of moderately well-sorted to very poorly sorted silty sand and gravel. The basal confining layer is composed of relatively impermeable pebbly clay loam (glacial till). These outwash deposits are unsaturated beneath the hills. Under low-lying areas associated with the drainages, the outwash deposits are saturated, forming an unconfined aquifer.

Cross sections constructed through this area are shown in figures A3 and A4, depicting the major hydrogeologic relationships. Cross sections A–A´ and B–B´ are constructed perpendicular to the drainage located in the northeast part of sec. 27 (fig. A3). Cross section C–C´ is constructed along the axis of this drainage (fig. A4). As previously mentioned, a relatively uniform thickness of outwash sand and gravel mantles the underlying till. As a result, the saturated thickness of the unconfined outwash aquifer is controlled by topography of both the land surface and the till surface. Examples of variations in saturated thickness of the aquifer are shown on cross section A–A´ (fig. A3). At monitor well 124P, near the center of the cross section, a knob of till produces a very thin saturated zone; while at monitor well 124G, in the northern part of the cross section, a depression in the till surface produces a much thicker saturated zone.

Apparent conductivity anomalies could be caused by a variety of conditions, including: highly mineralized ground water; fine-grained soils; saline seeps; and a high water table. The close association of the conductivity anomalies with the oil-field sites supported the interpretation that near-surface materials had been contaminated by brine discharges. Brine plumes were identified adjacent to and down slope of all of the oil-field sites shown in figures A1 and A2. The results of water sampling confirmed that the conductivity anomalies were caused by sodium chloride salts. The only local sources of these salts are from oilfield brines.

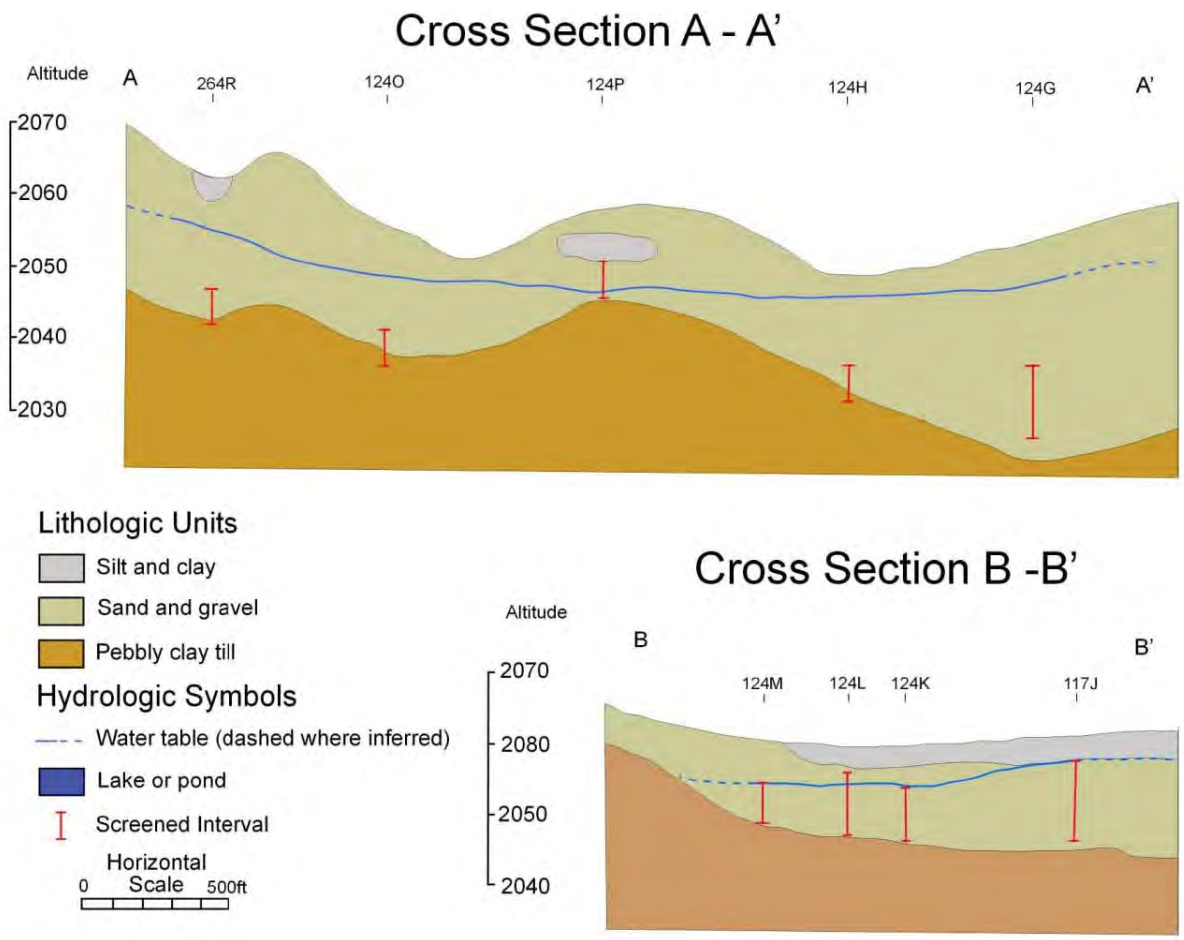


Figure A3. Cross-sections A–A´ and B–B´ showing the hydrogeology of near-surface sediments in the Goose Lake oilfield. See Figure 29 for lines of the cross sections.

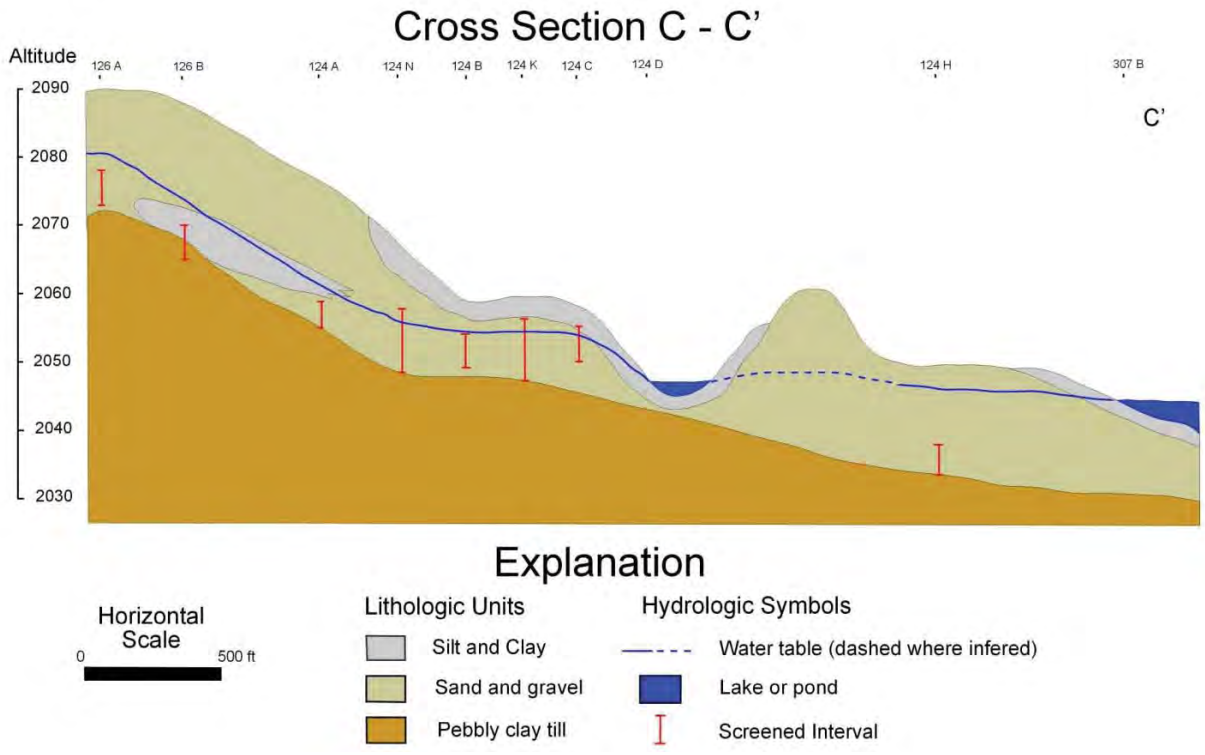


Figure A4. Cross-section C–C´ showing hydrogeology of near-surface sediments in the Goose Lake oilfield. See figure 52 for the line of the cross section.

Some of the complexities associated with groundwater transport of contaminants in glacial terrains are evident in the Goose Lake field. An area of high apparent conductivity at oilfield site 117 covers several acres surrounding the abandoned oil well (fig. A1). Water tests from shallow wells underlying this area of high apparent conductivity and a high-conductivity area immediately south of the site had very low chloride concentrations. The source of these anomalies appear to be from a combination of surface brine spills, reclaimed infiltration pits, pipeline leaks, a small containment dam, high water table, and saline seeps. The combined effect of relatively low hydraulic conductivity of the glacial till and the water table near or above the ground surface have prevented downward infiltration of oilfield brines. As a result, surface brine leaks and spills moved overland downslope and did not infiltrate until reaching the more permeable glacial outwash having a lower water table and downward flow gradients.

An abundance of very soluble sodium sulfate salts are associated with glacial deposits in this region. These have resulted in saline seeps and lakes with naturally high salinity. As a result, contamination from produced-water brines cannot be positively identified by specific conductance alone. A chloride index (CI) was devised to determine the magnitude of brine impacts to any surface-water or groundwater sample (Reiten, 1991). The index is calculated by the ratio of the chloride concentration to specific conductance. The chloride concentration is determined using test strips that provide a direct reading and the specific conductance is determined by a field meter. Empirical data based on hundreds of measurements indicate that the lower limit of brine contamination is a CI of about 0.035 (Reiten and Tischmak, 1993). Heavily impacted waters have CI values of 0.50 or greater. The CI is a valuable tool to identify the source and magnitude of salinity impacts to water resources. It clearly distinguishes between oilfield and non-oilfield impacts and has been used by researchers, regulators, landowners, and conservation districts to identify contamination sources.

Another common feature of brine plumes are vertical-density gradients. Density gradients are the result of the more concentrated solutions sinking to the base of an aquifer. These are most apparent in relatively permeable glacial outwash deposits. The hydraulic conductivity was estimated at 100 ft/day based on the interpretation of an aquifer test conducted in 1989 (Reiten and Tischmak, 1993). Several examples of density gradients have been identified in the Goose Lake field. Figure A5 shows the density gradient that developed in the shallow outwash aquifer at well 124J. Vertical-density gradients form as the denser, highly concentrated solutions sink to the base of the aquifer. The density gradients at 124J were originally measured in 1989 by collecting field-water samples at several vertical positions within the well and testing for chloride concentration using test strips. The SC was measured directly by a field meter while stabilizing the probe at known vertical positions. The CI (ratio of CL/SC) was calculated at 0.40 and

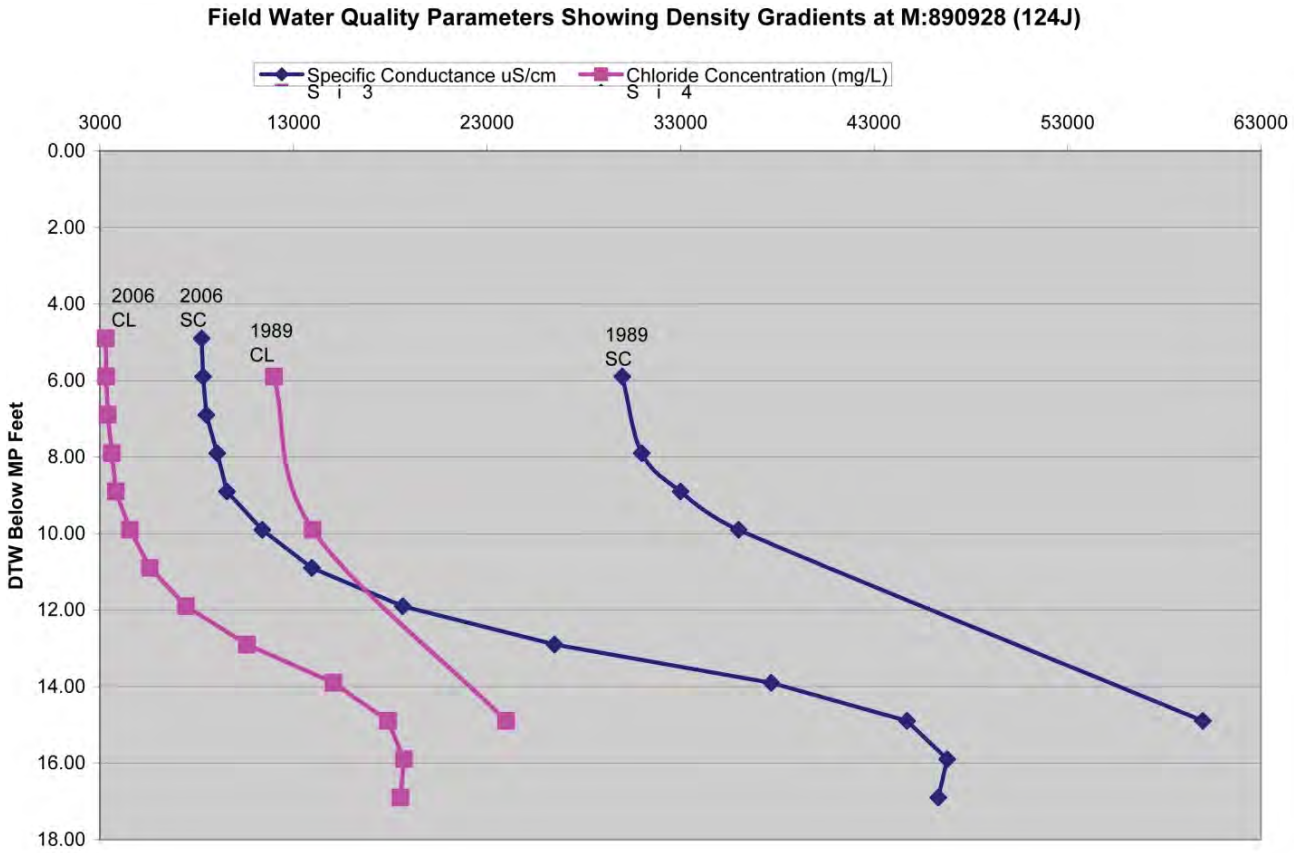


Figure A5. Plot showing increase of specific conductance and chloride concentration with depth caused by density gradients in the outwash aquifer. Note decrease in concentrations from 1989 to 2006.

remained relatively stable at the differing concentrations. SC was measured directly for the 2006 sampling, as the probe was dropped and stabilized at 1 ft increments. As an estimate, the 2006 chloride concentration was calculated by multiplying the SC value by the CI (0.40). The concentration of brine has declined significantly at this well from 1989 to 2006, but the vertical-density gradients remain very similar. Vertical-density gradients complicate any description of contaminant movement, because defining the vertical position within a plume is of equal importance to defining the horizontal position. As a result of these complications, a map view of a chloride plume must also refer to a third dimension perpendicular to the plane of the map.

The sampling points in the Goose Lake field available for mapping brine plumes include wells screened from the water table to the base of the aquifer as well as surface-water bodies. Fortunately, as demonstrated in figure A5, the CI is relatively uniform across vertical-density gradients, normalizing the effect of differing well depths. This allows using the CI to map the extent of brine plumes regardless of well depth.

Highly concentrated saltwater has traveled from the source at site 117 towards the northeast part of sec. 27 near well 117J, located about 3500 ft downslope from the source. The saltwater moved overland across low permeable glacial till with upward flow gradients until reaching the more permeable glacial outwash with downward flow gradients, where it infiltrated and formed a groundwater brine plume. Several hundred feet south of well 117J this plume coalesced with plumes flowing from oilfield sites 126 and 124. As saltwater from these three sources mix, a large area of high apparent conductivity develops along the east side of sec. 27. Very high CI values indicate groundwater degradation is highest underlying small wetlands east of site 124 (Reiten and Tischmak, 1993). The shorelines of these wetlands are sterilized, devoid of vegetation, or dominated by salt-tolerant plants (Salicornia rubra, saltwort) or salt-tolerant weeds (koshia).

Brine plumes flowing from several sites to the west and southwest have moved through groundwater below an intermittent drainage and combined with the larger plume (fig. A1). The south half of sec. 27 was purchased by the Service as a waterfowl production area, where several wetlands have been restored and enhanced. Fortunately, the brine contamination is not as severe in this drainage as it is in the northeast quarter of sec. 27. Work in this area is being evaluated by an ongoing Service project.

## WATER-QUALITY CHANGES 1989– 2006

At the start of this project it was realized that many of the wells constructed in the late 1980s were still in place. The TAC discussed this and determined that sampling some of these wells would provide a chance to evaluate the persistence of brine contamination. This is an important consideration for evaluating future impacts. Wells were cleaned out and water samples were collected during the spring of 2006 from several wells initially sampled in 1989. The results of these analyses can be viewed on the MBMG website http://mbmggwic@mtech.edu, under project name SCDBRINE.

Changes in total dissolved solids (TDS, mg/L), chloride concentrations (CL, mg/L), and chloride index (CI) are summarized in figures A6, A7, and A8. Eleven of twelve samples were from the Goose Lake field. TDS (fig. A6) decreased in samples from nine sites and increased in only two sites from the Goose Lake field. The TDS changes ranged from a decline of 83% at 124C to an increase of 32% at 117J. The average TDS concentration was about 44% less in 2007 than in 1989. The largest absolute change in TDS was measured at 264A, where the TDS declined from about 111,000 mg/L to 51,000 mg/L. Chloride concentrations (fig. 58) also decreased in all but the same two samples. The change in chloride ranged from a decline of 84% at 124C to an increase of 34% at117J. The average chloride concentration was about 44% less in 2007 than in 1989. The largest absolute change in chloride concentrations was measured at 264A, where the TDS declined from about 67,000,000 mg/L to 31,000 mg/L. The CI changes were not as large as the other parameters and ranged from a decline of 49% at 126A to an increase of 4% at 117J (fig. A8). The CI declined the most at wells 264A (41%) and 126B (49%). Overall the CI declined an average of about 20% within this group of wells. These decreases imply dilution of the brine plumes from recharge of rainfall and snowmelt. The fact that the dilution effects are not uniform may indicate the variability of recharge across the landscape and changes in the concentration of the sodium chloride sources.

Figure A9 provides a map view showing changes in TDS from resampled wells. The bar graphs in this and subsequent maps are uniformly scaled from figures A6, A7, and A8. The greatest dilution effects represented by TDS are associated with samples from two wells (124H and 264A). Overall, the concentration of the TDS plume has declined 44% in the past 17 years. While the overall trend is towards declining TDS, the plume is dynamic, with TDS increasing at 117J and 124P. Figure A10 provides a map view showing changes in the CI in water from resampled wells. The largest changes are in monitoring wells close to suspected brine sources. These changes suggest a reduction in the concentration at the sources. The fact that these changes show an overall dilution is somewhat encouraging and suggests that natural processes will eventually dilute the brine plumes. Unfortunately, the concentrations are extremely high, especially in areas where several plumes have coalesced.

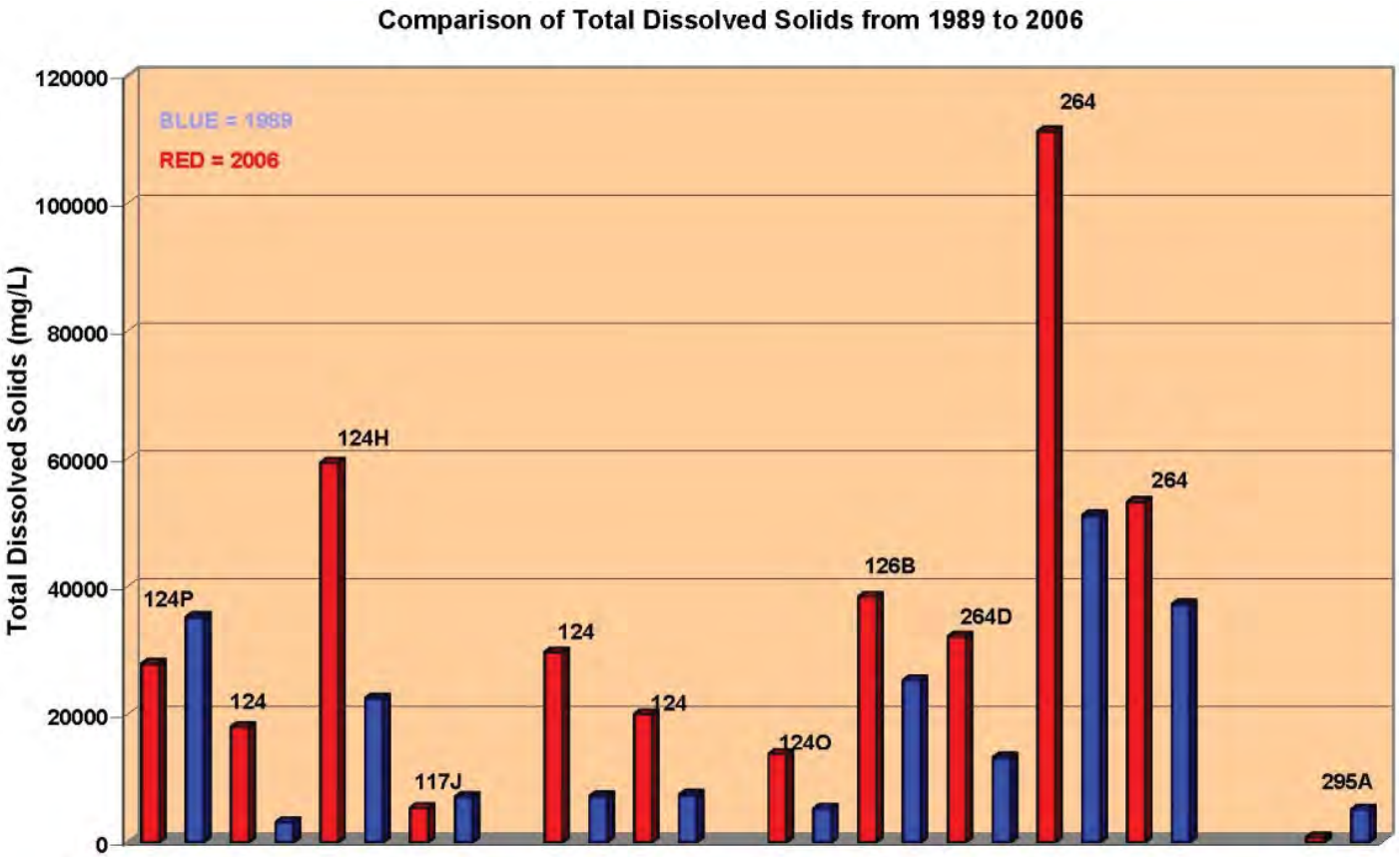


Figure A6. Change in Total Dissolved Solids in selected wells from1989 to 2006. All sites with the exception of well 295A are from the Goose Lake oilfield.

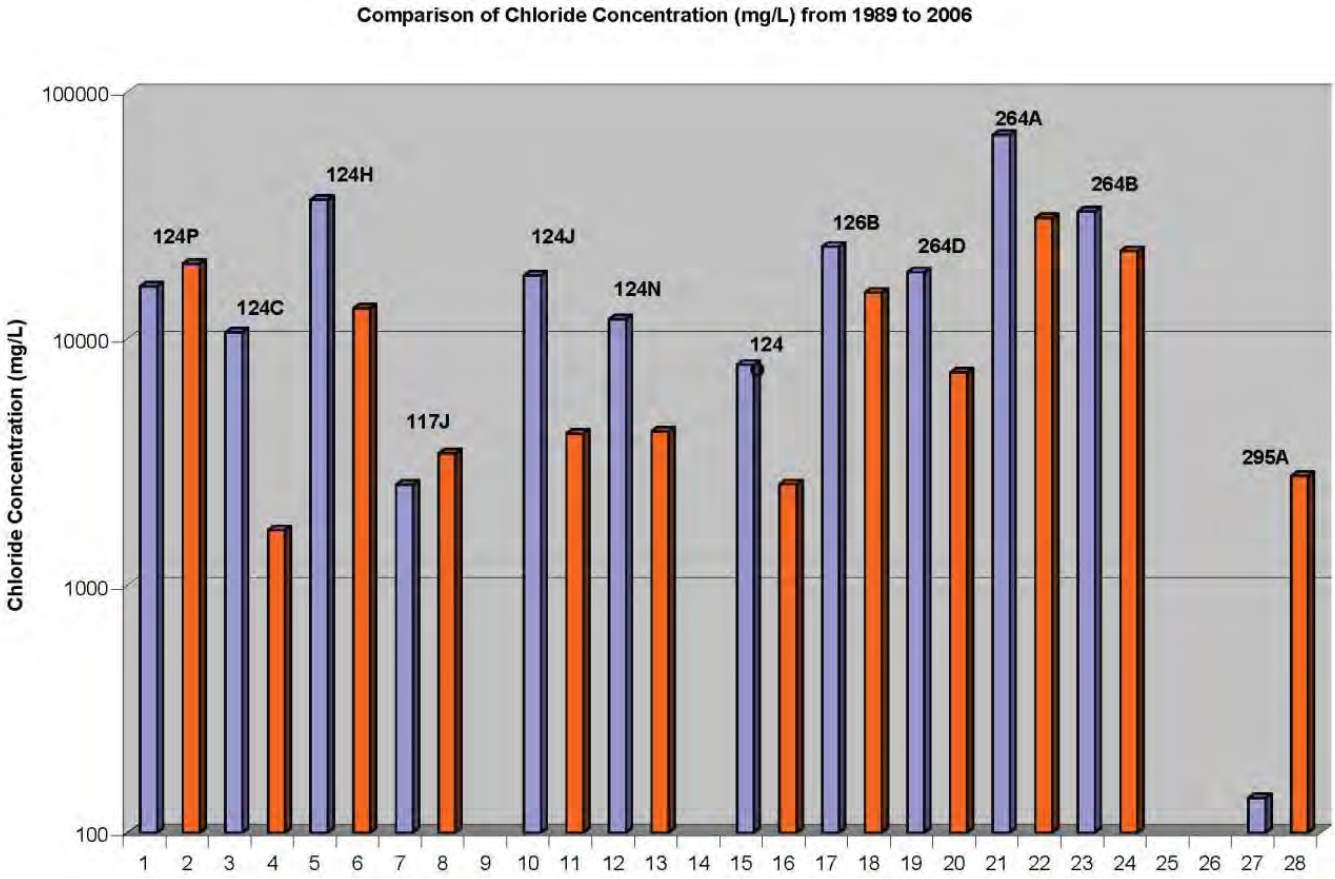


Figure A7. Change in chloride concentration in selected wells from1989 to 2006. All sites with the exception of well 295A are from the Goose Lake oilfield.

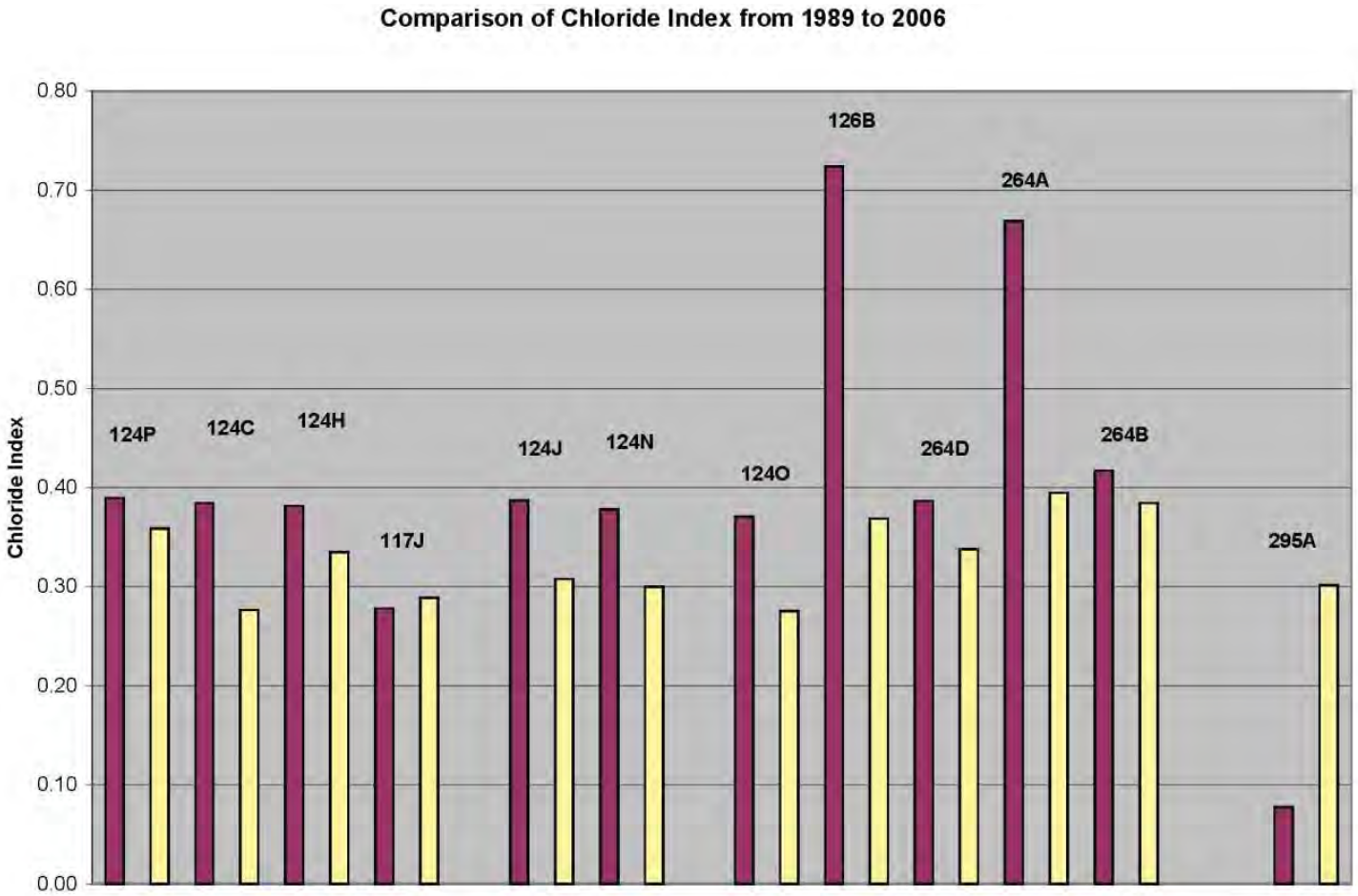


Figure A8. Change in chloride contamination index (CI) in selected wells from1989 to 2006. All sites with the exception of well 295A are from the Goose Lake oilfield.

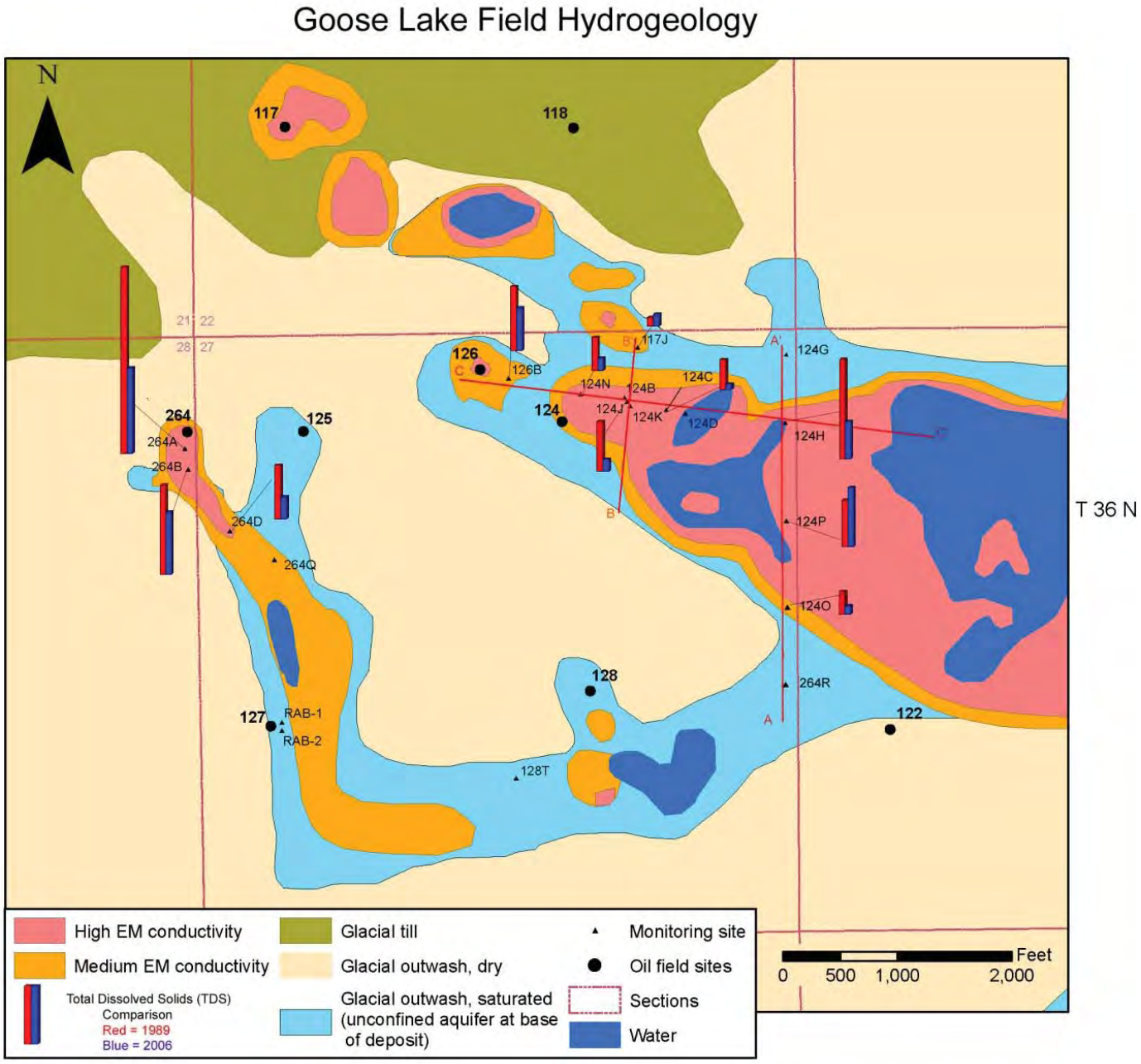


Figure A9. Map showing change in TDS (1989–2006) from samples collected from wells completed in glacial outwash and glacial till in part of the Goose Lake oilfield.

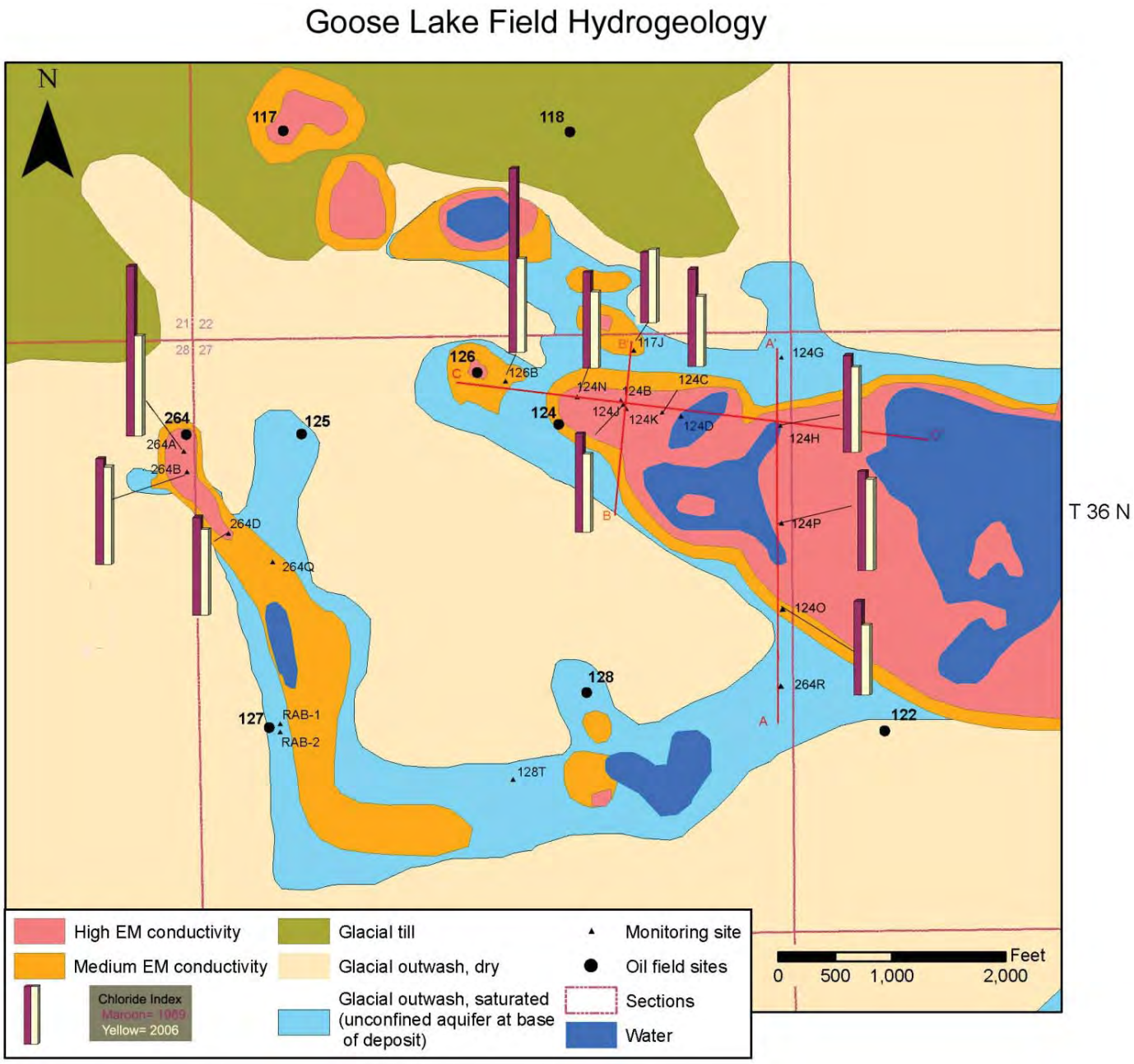


Figure A10. Map showing change in chloride contamination index (CI) (1989–2006) from samples collected from wells completed in glacial outwash and glacial till in part of the Goose Lake oilfield.

# APPENDIX B

## Analytical Results of Inorganic Analyses for Surface and Groundwater Samples

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | | | | |
| | | NWR2 | 48.5206 | -104.2623 | | Lake | | USFWS | 4/27/2004 | 16.03 | 8.53 |
| | | ML-SW | 48.4820 | -104.4510 | | Lake | | USFWS | 9/17/2005 | | |
| | 221728 | RW-1MW | 48.5254 | -104.2645 | 32N57E14DA | Well | 45 | USFWS | 9/17/2005 | 8.7 | |
| | 221728 | RW-1MW | 48.5254 | -104.2645 | 32N57E14DA | Well | 45 | USFWS | 9/17/2005 | | |
| | 221596 | RW-2MW | 48.5250 | -104.2643 | 32N57E14DA | Well | 34 | USFWS | 9/17/2005 | 8.3 | |
| | 221596 | RW-2MW | 48.5250 | -104.2643 | 32N57E14DA | Well | 34 | USFWS | 9/17/2005 | | |
| | 221726 | RW-3MW | 48.5256 | -104.2653 | 32N57E14DA | Well | 38 | USFWS | 9/17/2005 | 8.8 | |
| | 221726 | RW-3MW | 48.5256 | -104.2653 | 32N57E14DA | Well | 38 | USFWS | 9/17/2005 | | |
| | 221719 | RE-1MW | 48.5261 | -104.2587 | 32N57E13 | Well | 38 | USFWS | 9/17/2005 | 8.7 | |
| | 221719 | RE-1MW | 48.5261 | -104.2587 | 32N57E13 | Well | 38 | USFWS | 9/17/2005 | | |
| | 221691 | RE-2MW | 48.5262 | -104.2575 | 32N57E13 | Well | 38 | USFWS | 9/17/2005 | 9.9 | |
| | 221691 | RE-2MW | 48.5262 | -104.2575 | 32N57E13 | Well | 38 | USFWS | 9/17/2005 | | |
| *Anderson WPA* | | | | | | | | | | | |
| | | AND1 | 48.9849 | -104.1079 | | Wetland | | USFWS | 4/29/2004 | | |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 7/27/2004 | 24.99 | 7.65 |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 4/28/2004 | 7.02 | 7.28 |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 9/9/2004 | 21.72 | 8.1 |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 7/8/2005 | 26.98 | 7.46 |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 7/11/2005 | | |
| | | AND2 | 48.9876 | -104.1064 | | Wetland | | USFWS | 7/11/2005 | | |
| | | AND3 | 48.9911 | -104.1075 | | Wetland | | USFWS | 4/28/2004 | | |
| | | AND4 | 48.9863 | -104.1048 | | Wetland | | USFWS | 4/29/2004 | 10.36 | 6.92 |
| | | AND4 | 48.9863 | -104.1048 | | Wetland | | USFWS | 5/16/2004 | 22.16 | 8.13 |
| | | AND4 | 48.9863 | -104.1048 | | Wetland | | USFWS | 7/27/2004 | 24.74 | 8.01 |
| | | AND4 | 48.9863 | -104.1048 | | Wetland | | USFWS | 7/8/2005 | 31.57 | 8.44 |
| | | AND4 | 48.9863 | -104.1048 | | Wetland | | USFWS | 5/18/2004 | | |
| | | AND5 | 48.9969 | -104.0962 | | Wetland | | USFWS | 4/28/2004 | | |
| | | AND6 | 48.9894 | -104.0965 | | Wetland | | USFWS | 4/28/2004 | | |
| | | AND7 | 48.9911 | -104.0968 | | Wetland | | USFWS | 4/28/2004 | | |
| | | AND8 | 48.9828 | -104.0977 | | Wetland | | USFWS | 7/27/2004 | 25.44 | 9.24 |
| | | AND8 | 48.9828 | -104.0977 | | Wetland | | USFWS | 4/28/2004 | 5.8 | 8.38 |
| | | AND9 | 48.9840 | -104.0933 | | Wetland | | USFWS | 5/15/2004 | 16.41 | 9.35 |
| | | AND9 | 48.9840 | -104.0933 | | Wetland | | USFWS | 7/27/2004 | 25.89 | 8.22 |
| | | AND10 | 48.9939 | -104.1035 | | Wetland | | USFWS | 4/29/2004 | 14.94 | 8.03 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | | | | | |
| | | NWR2 | 1,702 | 8.04 | 1.09 | 30 | | | | | | |
| | | ML-SW | | | | | TERL | | | 20.2 | 92.1 | 651 |
| | 221728 | RW-1MW | | | | | MBMG | 7.41 | 4,430 | 309 | 188 | 453 |
| | 221728 | RW-1MW | | | | | TERL | | | | | |
| | 221596 | RW-2MW | | | | | MBMG | 7.45 | 1,810 | 136 | 84.3 | 231 |
| | 221596 | RW-2MW | | | | | TERL | | | | | |
| | 221726 | RW-3MW | | | | | MBMG | 7.46 | 2,150 | 185 | 109 | 223 |
| | 221726 | RW-3MW | | | | | TERL | | | | | |
| | 221719 | RE-1MW | | | | | MBMG | 7.51 | 725 | 84.3 | 29.9 | 8.57 |
| | 221719 | RE-1MW | | | | | TERL | | | | | |
| | 221691 | RE-2MW | | | | | MBMG | 7.36 | 24,300 | 1,848 | 305 | 4,822 |
| | 221691 | RE-2MW | | | | | TERL | | | | | |
| *Anderson WPA* | | | | | | | | | | | | |
| | | AND1 | | | | | | | | | | |
| | | AND2 | 9,681 | 7.27 | 6.20 | 366 | | | | | | |
| | | AND2 | 4,351 | 7.54 | 2.79 | 145 | | | | | | |
| | | AND2 | 14,160 | 11.5 | | 590 | | | | | | |
| | | AND2 | 8,575 | 3.62 | 5.49 | 324.5 | | | | | | |
| | | AND2 | | | | | TERL | | | 358 | 697 | 1,030 |
| | | AND2 | | | | | UWRBEBL | 7.81 | 7,990 | 380.0 | 714.3 | 1,117 |
| | | AND3 | | | | | | | | | | |
| | | AND4 | 82,463 | 7.07 | 52.78 | 27,292.5 | | | | | | |
| | | AND4 | 43,626 | 10.68 | 27.94 | 14,540 | | | | | | |
| | | AND4 | 68,366 | 6.62 | 43.74 | 31,660 | | | | | | |
| | | AND4 | 46,350 | 7.54 | 29.68 | 15,220 | | | | | | |
| | | AND4 | | | | | TERL | | | 1,340 | 766 | 6,430 |
| | | AND5 | | | | | | | | | | |
| | | AND6 | | | | | | | | | | |
| | | AND7 | | | | | | | | | | |
| | | AND8 | 26,286 | 13.91 | 16.82 | 2,589 | | | | | | |
| | | AND8 | 12,647 | 11.78 | 8.09 | 1,198 | | | | | | |
| | | AND9 | 19,657 | 10.23 | 12.58 | 2,748 | | | | | | |
| | | AND9 | 89,693 | 4.78 | 57.40 | 12,948 | | | | | | |
| | | AND10 | 260.1 | 14.77 | 0.17 | 8.8 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | | | | | |
| | | NWR2 | | | | | | | | | | |
| | | ML-SW | 34.1 | 0.12 | 0.01 | 2 | | | | | | |
| | 221728 | RW-1MW | 11.2 | | | | 484.3 | 0 | 392 | 1,162 | | |
| | 221728 | RW-1MW | | <0.01 | <0.002 | 11 | | | | | | |
| | 221596 | RW-2MW | 6.18 | | | | 596.6 | 0 | 514 | 57.2 | | |
| | 221596 | RW-2MW | | <0.01 | 0.22 | 10.7 | | | | | | |
| | 221726 | RW-3MW | 8.1 | | | | 669.4 | 0 | 740 | 40.2 | | |
| | 221726 | RW-3MW | | <0.01 | 0.46 | 10.2 | | | | | | |
| | 221719 | RE-1MW | 2.93 | | | | 367.2 | 0 | 24.6 | 1.96 | | |
| | 221719 | RE-1MW | | <0.01 | 0.95 | 9.2 | | | | | | |
| | 221691 | RE-2MW | 116 | | | | 552.7 | 0 | 99.9 | 11,538 | | |
| | 221691 | RE-2MW | | <0.01 | 3.86 | 8.6 | | | | | | |
| *Anderson WPA* | | | | | | | | | | | | |
| | | AND1 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | 107 | 0.144 | 0.02 | 1.5 | | | | | | |
| | | AND2 | 110 | | | | | | 2,370 | 152 | 10.10 | |
| | | AND3 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | 270 | <0.01 | 0.09 | | 156 | | 3,250 | 17,900 | | |
| | | AND5 | | | | | | | | | | |
| | | AND6 | | | | | | | | | | |
| | | AND7 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND10 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | | | | | |
| | | NWR2 | | | | | | | | | | |
| | | ML-SW | | | 50 | 33.9 | 1,400 | 48 | <0.5 | | 0.2 | <5 |
| | 221728 | RW-1MW | | | | | | | | | | |
| | 221728 | RW-1MW | | | <50 | 0.63 | 289 | 60 | <0.5 | | <0.05 | <5 |
| | 221596 | RW-2MW | | | | | | | | | | |
| | 221596 | RW-2MW | | | <50 | 0.23 | 253 | 21 | <0.5 | | 0.02 | <5 |
| | 221726 | RW-3MW | | | | | | | | | | |
| | 221726 | RW-3MW | | | <50 | 0.33 | 223 | 29 | <0.5 | | 0.02 | <5 |
| | 221719 | RE-1MW | | | | | | | | | | |
| | 221719 | RE-1MW | | | <50 | 0.19 | 60 | 150 | <0.5 | | 0.03 | <5 |
| | 221691 | RE-2MW | | | | | | | | | | |
| | 221691 | RE-2MW | | | <50 | 6.28 | 5,430 | 1350 | <0.5 | | 2.08 | <5 |
| *Anderson WPA* | | | | | | | | | | | | |
| | | AND1 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | <50 | 6.76 | <500 | 56 | <0.5 | | 0.1 | <5 |
| | | AND2 | | | | | | | | | | |
| | | AND3 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | <10 | 328 | 11.6 | 19,800 | 106 | 0.5 | 1,340,000 | 0.17 | <5 |
| | | AND5 | | | | | | | | | | |
| | | AND6 | | | | | | | | | | |
| | | AND7 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND10 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | | | | | |
| | | NWR2 | | | | | | | | | | |
| | | ML-SW | <5 | <5 | <0.1 | | <10 | <5 | 0.09 | 0.53 | 465 | <5 |
| | 221728 | RW-1MW | | | | | | | | | | |
| | 221728 | RW-1MW | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 31.7 | 1,910 | <5 |
| | 221596 | RW-2MW | | | | | | | | | | |
| | 221596 | RW-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 32.4 | 1,330 | <5 |
| | 221726 | RW-3MW | | | | | | | | | | |
| | 221726 | RW-3MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 143 | 1,450 | <5 |
| | 221719 | RE-1MW | | | | | | | | | | |
| | 221719 | RE-1MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 1.39 | 320 | <5 |
| | 221691 | RE-2MW | | | | | | | | | | |
| | 221691 | RE-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.1 | 3.88 | 48,100 | 20 |
| *Anderson WPA* | | | | | | | | | | | | |
| | | AND1 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | | | | | | | | | | |
| | | AND2 | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 0.58 | 1,990 | 6 |
| | | AND2 | | | | | | | | | | |
| | | AND3 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | | | | | | | | | | |
| | | AND4 | <5 | <5 | <0.1 | | 40 | 7 | 0.14 | 1.21 | 19,100 | |
| | | AND5 | | | | | | | | | | |
| | | AND6 | | | | | | | | | | |
| | | AND7 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND8 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND9 | | | | | | | | | | |
| | | AND10 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| *Medicine Lake NWR* | | | | | | | | |
| | | NWR2 | | | | | 0.018 | |
| | | ML-SW | | <10 | <5 | | | |
| | 221728 | RW-1MW | | | | | 0.262 | |
| | 221728 | RW-1MW | | <10 | <5 | | | |
| | 221596 | RW-2MW | | | | | 0.032 | |
| | 221596 | RW-2MW | | <10 | <5 | | | |
| | 221726 | RW-3MW | | | | | 0.019 | |
| | 221726 | RW-3MW | | <10 | <5 | | | |
| | 221719 | RE-1MW | | | | | 0.003 | |
| | 221719 | RE-1MW | | <10 | <5 | | | |
| | 221691 | RE-2MW | | | | | 0.475 | |
| | 221691 | RE-2MW | | <10 | <5 | | | |
| *Anderson WPA* | | | | | | | | |
| | | AND1 | | | | | | dry |
| | | AND2 | | | | | 0.038 | |
| | | AND2 | | | | | 0.033 | |
| | | AND2 | | | | | 0.042 | |
| | | AND2 | | | | | 0.038 | |
| | | AND2 | | <10 | 6 | | | |
| | | AND2 | | | | | 0.019 | |
| | | AND3 | | | | | | dry |
| | | AND4 | | | | | 0.331 | |
| | | AND4 | | | | | 0.333 | |
| | | AND4 | | | | | 0.463 | |
| | | AND4 | | | | | 0.328 | |
| | | AND4 | | <10 | 6 | | | |
| | | AND5 | | | | | | dry |
| | | AND6 | | | | | | dry |
| | | AND7 | | | | | | dry |
| | | AND8 | | | | | 0.098 | |
| | | AND8 | | | | | 0.095 | |
| | | AND9 | | | | | 0.140 | |
| | | AND9 | | | | | 0.144 | |
| | | AND10 | | | | | 0.034 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AND11 | 48.9857 | -104.1047 | | Wetland | | USFWS | 5/16/2004 | 26.68 | 7.33 |
| | | AND11 | 48.9857 | -104.1047 | | Wetland | | USFWS | 5/18/2004 | | |
| | 221721 | A-1MW | 48.9886 | -104.1033 | 37N58E5 | Well | 18 | USFWS | 9/13/2005 | 12.4 | |
| | 221721 | A-1MW | 48.9886 | -104.1033 | 37N58E5 | Well | 18 | USFWS | 9/13/2005 | | |
| | 221574 | A-2MW | 48.9876 | -104.1044 | 37N58E5CA | Well | 28 | USFWS | 9/13/2005 | 10 | |
| | 221574 | A-2MW | 48.9876 | -104.1044 | 37N58E5CA | Well | 28 | USFWS | 9/13/2005 | | |
| | 221727 | A-3MW | 48.9872 | -104.1046 | 37N58E5 | Well | 28 | USFWS | 9/13/2005 | 9.8 | |
| | 221727 | A-3MW | 48.9872 | -104.1046 | 37N58E5 | Well | 28 | USFWS | 9/13/2005 | | |
| | 221737 | A-4MW | 48.9873 | -104.1041 | 37N58E5CA | Well | 18 | USFWS | 9/13/2005 | 12 | |
| | 221737 | A-4MW | 48.9873 | -104.1041 | 37N58E5CA | Well | 18 | USFWS | 9/13/2005 | | |
| | 221731 | A-5DMW | 48.9867 | -104.1039 | 37N58E5 | Well | 23 | USFWS | 9/13/2005 | 10.26 | |
| | 221731 | A-5DMW | 48.9867 | -104.1039 | 37N58E5 | Well | 23 | USFWS | 9/13/2005 | | |
| | 221707 | A-8MW | 48.9845 | -104.1018 | 37N58E4 | Well | 18 | USFWS | 9/14/2005 | 10.4 | |
| | 221707 | A-8MW | 48.9845 | -104.1018 | 37N58E4 | Well | 18 | USFWS | 9/14/2005 | | |
| | 221733 | A-10MW | 48.9843 | -104.1007 | 37N58E5 | Well | 18 | USFWS | 9/14/2005 | 10.3 | |
| | 221733 | A-10MW | 48.9843 | -104.1007 | 37N58E5 | Well | 18 | USFWS | 9/14/2005 | | |
| | 221687 | A-11MW | 48.9841 | -104.1007 | 37N58E5 | Well | 13 | USFWS | 9/14/2005 | 13.3 | |
| | 221687 | A-11MW | 48.9841 | -104.1007 | 37N58E5 | Well | 13 | USFWS | 9/14/2005 | | |
| | 221724 | A-14MW | 48.9849 | -104.0992 | 37N58E5 | Well | 18 | USFWS | 9/14/2005 | 14.9 | |
| | 221724 | A-14MW | 48.9849 | -104.0992 | 37N58E5 | Well | 18 | USFWS | 9/14/2005 | | |
| | 221716 | A-15MW | 48.9848 | -104.0986 | 37N58E5BA | Well | 23 | USFWS | 9/17/2005 | 8 | |
| | 221716 | A-15MW | 48.9848 | -104.0986 | 37N58E5BA | Well | 23 | USFWS | 9/17/2005 | | |
| | 221715 | A-16MW | 48.9955 | -104.1048 | 37N58E5BA | Well | 43 | USFWS | 9/13/2005 | 10.6 | |
| | 221715 | A-16MW | 48.9955 | -104.1048 | 37N58E5BA | Well | 43 | USFWS | 9/13/2005 | | |
| | 221703 | A-17MW | 48.9955 | -104.1045 | 37N58E5BA | Well | 38 | USFWS | 9/13/2005 | 7.7 | |
| | 221703 | A-17MW | 48.9955 | -104.1045 | 37N58E5BA | Well | 38 | USFWS | 9/13/2005 | | |
| *Base Camp WPA* | | | | | | | | | | | |
| | | BC1 | 48.9825 | -104.0780 | | Wetland | | USFWS | 4/29/2004 | 11.52 | 8.87 |
| | | BC1 | 48.9825 | -104.0780 | | Wetland | | USFWS | 7/30/2004 | 21.35 | 10.18 |
| | | BC2 | 48.9812 | -104.0804 | | Wetland | | USFWS | 4/29/2004 | | |
| | | BC3 | 48.9805 | -104.0785 | | Wetland | | USFWS | 4/29/2004 | 15.24 | 6.96 |
| | | BC4 | 48.9787 | -104.0794 | | Wetland | | USFWS | 4/29/2004 | 13.67 | 8.61 |
| | | BC4 | 48.9787 | -104.0794 | | Wetland | | USFWS | 7/30/2004 | 22.1 | 10.11 |
| | | BC7 | 48.9672 | -104.0682 | | Wetland | | USFWS | 9/11/2004 | 19.19 | 9.03 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AND11 | 44819 | 5.73 | 28.05 | 6550 | | | | | | |
| | | AND11 | | | | | TERL | | | 1,030 | 1,230 | 2540 |
| | 221721 | A-1MW | | | | | MBMG | 7.51 | 902 | 76.1 | 46.6 | 49.7 |
| | 221721 | A-1MW | | | | | TERL | | | | | |
| | 221574 | A-2MW | | | | | MBMG | 7.34 | 36,800 | 930 | 452 | 11,154 |
| | 221574 | A-2MW | | | | | TERL | | | | | |
| | 221727 | A-3MW | | | | | MBMG | 7.05 | 56,000 | 162 | 1,462 | 25,054 |
| | 221727 | A-3MW | | | | | TERL | | | | | |
| | 221737 | A-4MW | | | | | MBMG | 7.34 | 13,670 | 642 | 566 | 2,543 |
| | 221737 | A-4MW | | | | | TERL | | | | | |
| | 221731 | A-5DMW | | | | | MBMG | 7.55 | 10,410 | 664 | 302 | 1,723 |
| | 221731 | A-5DMW | | | | | TERL | | | | | |
| | 221707 | A-8MW | | | | | MBMG | 7.26 | 13,480 | 880 | 1,145 | 1,504 |
| | 221707 | A-8MW | | | | | TERL | | | | | |
| | 221733 | A-10MW | | | | | MBMG | 7.63 | 22,000 | 417 | 3,784 | 5,207 |
| | 221733 | A-10MW | | | | | TERL | | | | | |
| | 221687 | A-11MW | | | | | MBMG | 7.57 | 24,800 | 433 | 6,529 | 4,982 |
| | 221687 | A-11MW | | | | | TERL | | | | | |
| | 221724 | A-14MW | | | | | MBMG | 6.94 | 52,500 | 7,559 | 1,163 | 16,134 |
| | 221724 | A-14MW | | | | | TERL | | | | | |
| | 221716 | A-15MW | | | | | MBMG | 7.7 | 23,600 | 473 | 3,552 | 6,423 |
| | 221716 | A-15MW | | | | | TERL | | | | | |
| | 221715 | A-16MW | | | | | MBMG | 7.04 | 21,900 | 1,563 | 1,348 | 2,997 |
| | 221715 | A-16MW | | | | | TERL | | | | | |
| | 221703 | A-17MW | | | | | MBMG | 7.21 | 9,340 | 732 | 534 | 1,212 |
| | 221703 | A-17MW | | | | | TERL | | | | | |
| *Base Camp WPA* | | | | | | | | | | | | |
| | | BC1 | 14,454 | 10.77 | 9.25 | 823 | | | | | | |
| | | BC1 | 17,297 | 7.68 | 11.07 | 1147 | | | | | | |
| | | BC2 | | | | | | | | | | |
| | | BC3 | 240.1 | 10.14 | 0.15 | 6.6 | | | | | | |
| | | BC4 | 16,872 | 10.8 | 10.80 | 141 | | | | | | |
| | | BC4 | 25,796 | 7.05 | 16.51 | 233 | | | | | | |
| | | BC7 | 42,264 | 9.65 | 27.04 | 953.5 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AND11 | | | | | | | | | | |
| | | AND11 | 96.2 | 0.01 | 0.21 | | 122 | | 207 | 6,170 | | |
| | 221721 | A-1MW | 5.46 | | | | 226.5 | 0 | 296 | 4.59 | | |
| | 221721 | A-1MW | | <0.01 | 5.57 | 9.3 | | | | | | |
| | 221574 | A-2MW | 189 | | | | 662.5 | 0 | 1,507 | 18,770 | | |
| | 221574 | A-2MW | | <0.01 | 0.255 | 7.4 | | | | | | |
| | 221727 | A-3MW | 381 | | | | 340.4 | 0 | 4,808 | 42,955 | | |
| | 221727 | A-3MW | | <0.01 | 10.2 | 8 | | | | | | |
| | 221737 | A-4MW | 38.6 | | | | 714.9 | 0 | 1,971 | 4,954 | | |
| | 221737 | A-4MW | | <0.01 | 0.162 | 14.3 | | | | | | |
| | 221731 | A-5DMW | 40.4 | | | | 398.9 | 0 | 1,276 | 3,513 | | |
| | 221731 | A-5DMW | | 0.03 | 0.306 | 10.4 | | | | | | |
| | 221707 | A-8MW | 26.7 | | | | 325.7 | 0 | 3,202 | 4,789 | | |
| | 221707 | A-8MW | | <0.01 | 0.004 | 9.9 | | | | | | |
| | 221733 | A-10MW | 72.1 | | | | 871.1 | 0 | 26,252 | 341 | | |
| | 221733 | A-10MW | | 0.01 | 14.9 | 6.9 | | | | | | |
| | 221687 | A-11MW | 114 | | | | 884.5 | 0 | 35,418 | 360 | | |
| | 221687 | A-11MW | | <0.01 | 1.01 | 9.9 | | | | | | |
| | 221724 | A-14MW | 340 | | | | 167.1 | 0 | 1,264 | 43,213 | | |
| | 221724 | A-14MW | | <0.01 | 8.49 | 6.2 | | | | | | |
| | 221716 | A-15MW | 55.3 | | | | 713.7 | 0 | 27,426 | 163 | | |
| | 221716 | A-15MW | | 0.02 | 9.44 | 6.6 | | | | | | |
| | 221715 | A-16MW | 62.2 | | | | 357.5 | 0 | 1,772 | 10,612 | | |
| | 221715 | A-16MW | | 0.01 | 0.04 | 9.4 | | | | | | |
| | 221703 | A-17MW | 31 | | | | 407.5 | 0 | 2,332 | 2,542 | | |
| | 221703 | A-17MW | | <0.01 | 2.86 | 10.3 | | | | | | |
| *Base Camp WPA* | | | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC2 | | | | | | | | | | |
| | | BC3 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC7 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AND11 | | | | | | | | | | |
| | | AND11 | | <10 | 252 | 17.4 | 1,610 | 126 | <0.5 | 1,030,000 | 0.26 | <5 |
| | 221721 | A-1MW | | | | | | | | | | |
| | 221721 | A-1MW | | | <50 | 0.39 | 215 | 23 | <0.5 | | 0.05 | <5 |
| | 221574 | A-2MW | | | | | | | | | | |
| | 221574 | A-2MW | | | <50 | 7.43 | 69,500 | 55 | <0.5 | | 2.26 | 5 |
| | 221727 | A-3MW | | | | | | | | | | |
| | 221727 | A-3MW | | | <50 | 6.66 | 74,500 | 243 | <0.5 | | 16.9 | 6 |
| | 221737 | A-4MW | | | | | | | | | | |
| | 221737 | A-4MW | | | <50 | <0.5 | 4,760 | 52 | <0.5 | | <0.1 | <5 |
| | 221731 | A-5DMW | | | | | | | | | | |
| | 221731 | A-5DMW | | | <50 | 3.18 | 5,130 | 134 | <0.5 | | 0.33 | 8 |
| | 221707 | A-8MW | | | | | | | | | | |
| | 221707 | A-8MW | | | <50 | 2.39 | 326 | 44 | <0.5 | | 0.18 | <5 |
| | 221733 | A-10MW | | | | | | | | | | |
| | 221733 | A-10MW | | | <50 | 4.07 | 385 | 20 | <0.5 | | 0.27 | 11 |
| | 221687 | A-11MW | | | | | | | | | | |
| | 221687 | A-11MW | | | <50 | <2.55 | 378 | 59 | <0.5 | | <0.51 | <5 |
| | 221724 | A-14MW | | | | | | | | | | |
| | 221724 | A-14MW | | | <50 | 25.8 | 11,000 | 660 | <0.5 | | 5.57 | <5 |
| | 221716 | A-15MW | | | | | | | | | | |
| | 221716 | A-15MW | | | <50 | 2.45 | 347 | 68 | <0.5 | | 0.36 | 10 |
| | 221715 | A-16MW | | | | | | | | | | |
| | 221715 | A-16MW | | | <50 | 5.54 | 249 | 51 | <0.5 | | 10.6 | 12 |
| | 221703 | A-17MW | | | | | | | | | | |
| | 221703 | A-17MW | | | <50 | 1.8 | 294 | 26 | <0.5 | | 1.21 | 13 |
| *Base Camp WPA* | | | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC2 | | | | | | | | | | |
| | | BC3 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC7 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AND11 | | | | | | | | | | |
| | | AND11 | <5 | 6 | <0.1 | | 30 | 5 | 0.11 | 4.5 | 7,720 | |
| | 221721 | A-1MW | | | | | | | | | | |
| | 221721 | A-1MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 6.24 | 450 | <5 |
| | 221574 | A-2MW | | | | | | | | | | |
| | 221574 | A-2MW | <5 | 5 | <0.1 | | 40 | 53 | 0.58 | 1.86 | 15,300 | 10 |
| | 221727 | A-3MW | | | | | | | | | | |
| | 221727 | A-3MW | <5 | 7 | <0.1 | | 10 | 59 | <0.51 | 9.13 | 48,000 | 19 |
| | 221737 | A-4MW | | | | | | | | | | |
| | 221737 | A-4MW | <5 | <5 | <0.1 | | <10 | 5 | <0.1 | 6.07 | 6,510 | 9 |
| | 221731 | A-5DMW | | | | | | | | | | |
| | 221731 | A-5DMW | <5 | <5 | <0.1 | | 10 | 14 | <0.05 | 0.47 | 3,650 | 10 |
| | 221707 | A-8MW | | | | | | | | | | |
| | 221707 | A-8MW | <5 | <5 | <0.1 | | <10 | <5 | 0.13 | 24.9 | 5,320 | 12 |
| | 221733 | A-10MW | | | | | | | | | | |
| | 221733 | A-10MW | <5 | 5 | <0.1 | | 20 | 24 | <0.2 | 3.4 | 6,200 | 6 |
| | 221687 | A-11MW | | | | | | | | | | |
| | 221687 | A-11MW | <5 | 9 | <0.1 | | 30 | 45 | <0.51 | 4.96 | 7,170 | <5 |
| | 221724 | A-14MW | | | | | | | | | | |
| | 221724 | A-14MW | <5 | 7 | <0.1 | | 10 | 68 | 0.59 | 1.9 | 152,000 | 77 |
| | 221716 | A-15MW | | | | | | | | | | |
| | 221716 | A-15MW | <5 | 11 | <0.1 | | 20 | 30 | 0.69 | 145 | 7,540 | 10 |
| | 221715 | A-16MW | | | | | | | | | | |
| | 221715 | A-16MW | <5 | 7 | <0.1 | | <10 | 82 | <0.1 | 13.9 | 15,300 | 21 |
| | 221703 | A-17MW | | | | | | | | | | |
| | 221703 | A-17MW | <5 | <5 | <0.1 | | <10 | 38 | <0.05 | 33.7 | 5,610 | 9 |
| *Base Camp WPA* | | | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC1 | | | | | | | | | | |
| | | BC2 | | | | | | | | | | |
| | | BC3 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC4 | | | | | | | | | | |
| | | BC7 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | | AND11 | | | | | 0.146 | |
| | | AND11 | | <10 | 9 | | | |
| | 221721 | A-1MW | | | | | 0.005 | |
| | 221721 | A-1MW | | <10 | 9 | | | |
| | 221574 | A-2MW | | | | | 0.510 | |
| | 221574 | A-2MW | | <10 | 35 | | | |
| | 221727 | A-3MW | | | | | 0.767 | |
| | 221727 | A-3MW | | <10 | 10 | | | |
| | 221737 | A-4MW | | | | | 0.362 | |
| | 221737 | A-4MW | | <10 | <5 | | | |
| | 221731 | A-5DMW | | | | | 0.337 | |
| | 221731 | A-5DMW | | <10 | 10 | | | |
| | 221707 | A-8MW | | | | | 0.355 | |
| | 221707 | A-8MW | | <10 | 40 | | | |
| | 221733 | A-10MW | | | | | 0.016 | |
| | 221733 | A-10MW | | <10 | 65 | | | |
| | 221687 | A-11MW | | | | | 0.015 | |
| | 221687 | A-11MW | | <10 | <5 | | | |
| | 221724 | A-14MW | | | | | 0.823 | |
| | 221724 | A-14MW | | <10 | 15 | | | |
| | 221716 | A-15MW | | | | | 0.007 | |
| | 221716 | A-15MW | | <10 | 67 | | | |
| | 221715 | A-16MW | | | | | 0.485 | |
| | 221715 | A-16MW | | <10 | 17 | | | |
| | 221703 | A-17MW | | | | | 0.272 | |
| | 221703 | A-17MW | | <10 | 7 | | | |
| *Base Camp WPA* | | | | | | | | |
| | | BC1 | | | | | 0.057 | |
| | | BC1 | | | | | 0.066 | |
| | | BC2 | | | | | | dry |
| | | BC3 | | | | | 0.027 | |
| | | BC4 | | | | | 0.008 | |
| | | BC4 | | | | | 0.009 | |
| | | BC7 | | | | | 0.023 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | | | | |
| | | CHA1 | 48.9830 | -104.3730 | | Wetland | | USFWS | 6/14/2005 | 25.19 | 8.5 |
| *Long Lake WPA* | | | | | | | | | | | |
| | | LL1 | 48.5567 | -104.1565 | | Wetland | | USFWS | 4/27/2004 | 14 | 8.69 |
| | | LL1 | 48.5567 | -104.1565 | | Wetland | | USFWS | 9/10/2004 | 14.73 | 9.62 |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 7/21/2004 | 24.5 | 8.89 |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 9/10/2004 | 16 | |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 7/11/2005 | | |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 7/11/2005 | | |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 9/10/2004 | 16.45 | 9.25 |
| | 214789 | LL2 | 48.5555 | -104.1612 | 32N58E3 | Wetland | | USFWS | 7/8/2005 | 30.33 | 9.36 |
| | | LL3 | 48.5580 | -104.1601 | | Wetland | | USFWS | 7/21/2004 | 24.86 | 9.23 |
| *Berger Pond WPA* | | | | | | | | | | | |
| | | BP | 48.5486 | -104.1684 | | Wetland | | USFWS | 7/11/2005 | | |
| | | BP | 48.5486 | -104.1684 | | Wetland | | USFWS | 7/11/2005 | | |
| | | BP | 48.5486 | -104.1684 | | Wetland | | USFWS | 9/10/2004 | 17.31 | 9.25 |
| | | BP | 48.5486 | -104.1684 | | Wetland | | USFWS | 7/9/2004 | 26.97 | 9.13 |
| *Melby WPA* | | | | | | | | | | | |
| | | MEL1 | 48.6425 | -104.0817 | | Wetland | | USFWS | 5/14/2004 | 12.6 | 8.41 |
| | 221718 | MEL2 | 48.6408 | -104.0829 | 33N58E2 | Wetland | | USFWS | 5/14/2004 | 11.46 | 8.41 |
| | 221718 | MEL2 | 48.6408 | -104.0829 | 33N58E2 | Wetland | | USFWS | 7/21/2004 | 25.05 | 8.99 |
| | 221718 | MEL2 | 48.6408 | -104.0829 | 33N58E2 | Wetland | | USFWS | 9/16/2005 | 20 | |
| | 221718 | MEL2 | 48.6408 | -104.0829 | 33N58E2 | Wetland | | USFWS | 9/16/2005 | | |
| | | MEL3 | 48.6400 | -104.0836 | | Wetland | | USFWS | 7/21/2004 | 23.43 | 8.5 |
| | 221690 | M-1MW | 48.6403 | -104.0826 | 33N58E2 | Well | 28 | USFWS | 9/17/2005 | | |
| | 221690 | M-1MW | 48.6403 | -104.0826 | 33N58E2 | Well | 28 | USFWS | 9/17/2005 | | |
| | 221712 | M-2MW | 48.6402 | -104.0822 | 33N58E2 | Well | 28 | USFWS | 9/16/2005 | 9.6 | |
| | 221712 | M-2MW | 48.6402 | -104.0822 | 33N58E2 | Well | 28 | USFWS | 9/16/2005 | | |
| | 221714 | M-3MW | 48.6391 | -104.0832 | 33N58E2 | Well | 28 | USFWS | 9/16/2005 | 19.8 | |
| | 221714 | M-3MW | 48.6391 | -104.0832 | 33N58E2 | Well | 28 | USFWS | 9/16/2005 | | |
| | 221595 | M-4MW | 48.6394 | -104.0836 | 33N58E2 | Well | 18 | USFWS | 9/16/2005 | 14 | |
| | 221595 | M-4MW | 48.6394 | -104.0836 | 33N58E2 | Well | 18 | USFWS | 9/16/2005 | | |
| | 221725 | M-5MW | 48.6395 | -104.0829 | 33N58E2 | Well | 28 | USFWS | 9/16/2005 | 12 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | | | | | |
| | | CHA1 | 13,520 | 8.38 | 8.66 | 360 | | | | | | |
| *Long Lake WPA* | | | | | | | | | | | | |
| | | LL1 | 2,481 | 9.3 | 1.59 | 61 | | | | | | |
| | | LL1 | 3,631 | 9.58 | 2.32 | 68 | | | | | | |
| | 214789 | LL2 | 5,966 | 1.46 | 3.82 | 216 | | | | | | |
| | 214789 | LL2 | | | | | MBMG | 9.27 | 6,900 | 8.8 | 72.6 | 2,094 |
| | 214789 | LL2 | | | | | TERL | | | 6.05 | 75.9 | 1,900 |
| | 214789 | LL2 | | | | | UWRBEBL | 9.57 | 7,280 | 5.31 | 77.5 | 2,054 |
| | 214789 | LL2 | 7,633 | 9.7 | 4.89 | 251 | | | | | | |
| | 214789 | LL2 | 7,834 | 10.79 | 5.01 | 228 | | | | | | |
| | | LL3 | 8,950 | 6.26 | 5.73 | 184 | | | | | | |
| *Berger Pond WPA* | | | | | | | | | | | | |
| | | BP | | | | | TERL | | | 5.21 | 87.2 | 2,890 |
| | | BP | | | | | UWRBEBL | 9.39 | 10,600 | 4.61 | 89.9 | 3,066 |
| | | BP | 10,737 | 5.15 | 6.87 | 336 | | | | | | |
| | | BP | 11,300 | 8.13 | 7.23 | 357 | | | | | | |
| *Melby WPA* | | | | | | | | | | | | |
| | | MEL1 | 13,233 | 8.97 | 8.47 | 405 | | | | | | |
| | 221718 | MEL2 | 13,207 | 9.68 | 8.45 | 464 | | | | | | |
| | 221718 | MEL2 | 15,637 | 8.33 | 10.01 | 414 | | | | | | |
| | 221718 | MEL2 | | | | | MBMG | 9.17 | 22,800 | 27.7 | 898 | 8,307 |
| | 221718 | MEL2 | | | | | TERL | | | | | |
| | | MEL3 | 62,540 | 7.66 | 40.03 | 6053 | | | | | | |
| | 221690 | M-1MW | | | | | MBMG | 7.9 | 2,790 | 71.3 | 37 | 575 |
| | 221690 | M-1MW | | | | | TERL | | | | | |
| | 221712 | M-2MW | | | | | MBMG | 7.33 | 1,641 | 93.5 | 34.3 | 267 |
| | 221712 | M-2MW | | | | | TERL | | | | | |
| | 221714 | M-3MW | | | | | MBMG | 7.76 | 8,050 | 322 | 202 | 1,561 |
| | 221714 | M-3MW | | | | | TERL | | | | | |
| | 221595 | M-4MW | | | | | MBMG | 7.89 | 20,900 | 554 | 1,596 | 4,297 |
| | 221595 | M-4MW | | | | | TERL | | | | | |
| | 221725 | M-5MW | | | | | MBMG | 7.59 | 1,372 | 68.6 | 30.1 | 219 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | | | | | |
| | | CHA1 | | | | | | | | | | |
| *Long Lake WPA* | | | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | 58.3 | 0.14 | <0.01 | 1.61 | 2,316.8 | 504 | 1,738 | 279 | <2.5 | <2.5 |
| | 214789 | LL2 | 59.1 | <0.01 | 0.48 | 1 | | | | | | |
| | 214789 | LL2 | 66 | | | | | | 3,205 | 168 | ND | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | | LL3 | | | | | | | | | | |
| *Berger Pond WPA* | | | | | | | | | | | | |
| | | BP | 120 | 0.01 | 0.07 | 4.4 | | | | | | |
| | | BP | 134 | | | | | | 1,128.0565 | 198 | ND | |
| | | BP | | | | | | | | | | |
| | | BP | | | | | | | | | | |
| *Melby WPA* | | | | | | | | | | | | |
| | | MEL1 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | 176 | | | | 1,150.46 | 300 | 16,887 | 1,338 | | |
| | 221718 | MEL2 | | 0.77 | 0.85 | 2.6 | | | | | | |
| | | MEL3 | | | | | | | | | | |
| | 221690 | M-1MW | 8.15 | | | | 593.7 | 0 | 946 | 55.4 | | |
| | 221690 | M-1MW | | 0.11 | 2.39 | 6.7 | | | | | | |
| | 221712 | M-2MW | 6.29 | | | | 408 | 0 | 504 | 16.5 | | |
| | 221712 | M-2MW | | 2.38 | 0.03 | 10.4 | | | | | | |
| | 221714 | M-3MW | 21.9 | | | | 533.5 | 0 | 1103 | 2,483 | | |
| | 221714 | M-3MW | | 0.02 | 0.31 | 7.7 | | | | | | |
| | 221595 | M-4MW | 25.3 | | | | 463.6 | 0 | 7011 | 7,087 | | |
| | 221595 | M-4MW | | 0.03 | 0.003 | 10.7 | | | | | | |
| | 221725 | M-5MW | 6.34 | | | | 436.8 | 0 | 377 | 18.1 | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | | | | | |
| | | CHA1 | | | | | | | | | | |
| *Long Lake WPA* | | | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | <2.5 | <10 | <100 | 33.3 | 1,471 | <20 | <20 | 7,710 | <10 | <20 |
| | 214789 | LL2 | | | <50 | 17.3 | 1,510 | 7 | <0.5 | | <0.05 | <5 |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | | LL3 | | | | | | | | | | |
| *Berger Pond WPA* | | | | | | | | | | | | |
| | | BP | | | <50 | 17.3 | 2,660 | 13 | <0.5 | | 0.06 | <5 |
| | | BP | | | | | | | | | | |
| | | BP | | | | | | | | | | |
| | | BP | | | | | | | | | | |
| *Melby WPA* | | | | | | | | | | | | |
| | | MEL1 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | 215 | 46.5 | 5,800 | 26 | <0.5 | | <0.2 | <5 |
| | | MEL3 | | | | | | | | | | |
| | 221690 | M-1MW | | | | | | | | | | |
| | 221690 | M-1MW | | | <50 | 5.06 | 273 | 42 | <0.5 | | 0.11 | <5 |
| | 221712 | M-2MW | | | | | | | | | | |
| | 221712 | M-2MW | | | <50 | 4.47 | 228 | 27 | <0.5 | | 0.04 | <5 |
| | 221714 | M-3MW | | | | | | | | | | |
| | 221714 | M-3MW | | | <50 | 5.16 | 288 | 76 | <0.5 | | 0.18 | <5 |
| | 221595 | M-4MW | | | | | | | | | | |
| | 221595 | M-4MW | | | <50 | 2.79 | 671 | 79 | <0.5 | | 0.18 | <5 |
| | 221725 | M-5MW | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | | | | | |
| | | CHA1 | | | | | | | | | | |
| *Long Lake WPA* | | | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | | LL1 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | 33.5 | <20 | | 221 | <100 | <20 | <20 | 62.6 | 153 | <10 |
| | 214789 | LL2 | <5 | <5 | <0.1 | | <10 | 6 | <0.05 | 0.13 | 85 | <5 |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | 214789 | LL2 | | | | | | | | | | |
| | | LL3 | | | | | | | | | | |
| *Berger Pond WPA* | | | | | | | | | | | | |
| | | BP | <5 | <5 | <0.1 | | <10 | 10 | 0.09 | 0.12 | 110 | <5 |
| | | BP | | | | | | | | | | |
| | | BP | | | | | | | | | | |
| | | BP | | | | | | | | | | |
| *Melby WPA* | | | | | | | | | | | | |
| | | MEL1 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | | | | | | | | | | |
| | 221718 | MEL2 | <5 | <5 | <0.1 | | 20 | 5 | 0.82 | 0.81 | 220 | 10 |
| | | MEL3 | | | | | | | | | | |
| | 221690 | M-1MW | | | | | | | | | | |
| | 221690 | M-1MW | <5 | <5 | <0.1 | | 20 | <5 | 0.1 | 1.76 | 435 | <5 |
| | 221712 | M-2MW | | | | | | | | | | |
| | 221712 | M-2MW | <5 | <5 | <0.1 | | <10 | <5 | 0.02 | <0.1 | 590 | <5 |
| | 221714 | M-3MW | | | | | | | | | | |
| | 221714 | M-3MW | <5 | <5 | <0.1 | | 10 | 8 | <0.05 | 0.88 | 2570 | <5 |
| | 221595 | M-4MW | | | | | | | | | | |
| | 221595 | M-4MW | <5 | 6 | <0.1 | | 10 | <5 | <0.1 | 32.7 | 7630 | 7 |
| | 221725 | M-5MW | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| *Chandler WPA* | | | | | | | | |
| | | CHA1 | | | | | 0.027 | |
| *Long Lake WPA* | | | | | | | | |
| | | LL1 | | | | | 0.025 | |
| | | LL1 | | | | | 0.019 | |
| | 214789 | LL2 | | | | | 0.036 | |
| | 214789 | LL2 | <5 | <50 | <20 | <20 | 0.040 | |
| | 214789 | LL2 | | <10 | <5 | | | |
| | 214789 | LL2 | | | | | 0.023 | |
| | 214789 | LL2 | | | | | 0.033 | |
| | 214789 | LL2 | | | | | 0.029 | |
| | | LL3 | | | | | 0.021 | |
| *Berger Pond WPA* | | | | | | | | |
| | | BP | | <10 | <5 | | | |
| | | BP | | | | | 0.019 | |
| | | BP | | | | | 0.031 | |
| | | BP | | | | | 0.032 | |
| *Melby WPA* | | | | | | | | |
| | | MEL1 | | | | | 0.031 | |
| | 221718 | MEL2 | | | | | 0.035 | |
| | 221718 | MEL2 | | | | | 0.026 | |
| | 221718 | MEL2 | | | | | 0.059 | |
| | 221718 | MEL2 | | <10 | | | | |
| | | MEL3 | | | | | 0.097 | |
| | 221690 | M-1MW | | | | | 0.020 | |
| | 221690 | M-1MW | | <10 | <5 | | | |
| | 221712 | M-2MW | | | | | 0.010 | |
| | 221712 | M-2MW | | <10 | 12 | | | |
| | 221714 | M-3MW | | | | | 0.308 | |
| | 221714 | M-3MW | | <10 | <5 | | | |
| | 221595 | M-4MW | | | | | 0.339 | |
| | 221595 | M-4MW | | <10 | 14 | | | |
| | 221725 | M-5MW | | | | | 0.013 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | 48.6395 | -104.0829 | | Well | 28 | USFWS | 9/16/2005 | | |
| *Mallard Pond WPA* | | | | | | | | | | | |
| | | MP1A | 48.5742 | -104.1399 | | Wetland | | USFWS | 9/16/2005 | | |
| | | MP1A | 48.5742 | -104.1399 | | Wetland | | USFWS | 4/27/2004 | 15.3 | 8.33 |
| | | MP1A | 48.5742 | -104.1399 | | Wetland | | USFWS | 9/12/2004 | 14.98 | 7.81 |
| | 221735 | MP-1MW | 48.5756 | -104.1357 | 33N58E33 | Well | 38 | USFWS | 9/16/2005 | 11.2 | |
| | 221735 | MP-1MW | 48.5756 | -104.1357 | 33N58E33 | Well | 38 | USFWS | 9/16/2005 | | |
| | 221704 | MP-2MW | 48.5751 | -104.1354 | 33N58E33 | Well | 38 | USFWS | 9/16/2005 | | |
| | 221704 | MP-2MW | 48.5751 | -104.1354 | 33N58E33 | Well | 38 | USFWS | 9/16/2005 | | |
| | 161782 | MP-RW | 48.5733 | -104.1384 | 33N58E33BDBC | Well | 10 | USFWS | 9/16/2005 | 14.49 | |
| | 161782 | MP-RW | 48.5733 | -104.1384 | 33N58E33BDBC | Well | 10 | USFWS | 9/16/2005 | | |
| *Northeast WPA* | | | | | | | | | | | |
| | | NE2 | 48.9808 | -104.0588 | | Wetland | | USFWS | 9/1/2004 | 36 | 8.64 |
| | | NE3 | 48.9729 | -104.0563 | | Wetland | | USFWS | 9/1/2004 | | |
| | | NE5 | 48.9774 | -104.0535 | | Wetland | | | 9/1/2004 | | |
| *North Root WPA* | | | | | | | | | | | |
| | | NR1 | 48.8348 | -104.1206 | | Wetland | | USFWS | 4/29/2004 | 14.97 | 8.25 |
| | | NR1 | 48.8348 | -104.1206 | | Wetland | | USFWS | 7/25/2004 | 25.88 | 9.35 |
| *Big Slough WPA* | | | | | | | | | | | |
| | | BS1 | 48.7366 | -104.0881 | | Wetland | | USFWS | 5/15/2004 | 13.38 | 7.25 |
| | | BS2 | 48.7351 | -104.0870 | | Wetland | | USFWS | 5/15/2004 | 12.04 | 7.69 |
| | | BS3A | 48.7249 | -104.0966 | | Wetland | | USFWS | 5/15/2004 | 13.75 | 7.92 |
| | | BS4A | 48.7176 | -104.1102 | | Wetland | | USFWS | 5/15/2004 | 16.1 | 8.14 |
| | | BS8 | 48.7360 | -104.0859 | | Wetland | | USFWS | 5/15/2004 | 11.81 | 7.49 |
| | 221706 | BS-1DMW | 48.7170 | -104.1081 | 34N58E10 | Well | 17 | USFWS | 9/16/2005 | 11.4 | |
| | 221706 | BS-1DMW | 48.7170 | -104.1081 | 34N58E10 | Well | 17 | USFWS | 9/16/2005 | | |
| | 221736 | BS-1SMW | 48.7170 | -104.1081 | 34N58E10 | Well | 8 | USFWS | 9/16/2005 | 13.7 | |
| | 221736 | BS-1SMW | 48.7170 | -104.1081 | 34N58E10 | Well | 8 | USFWS | 9/16/2005 | | |
| | 221689 | BS-2MW | 48.7177 | -104.1083 | 34N58E10 | Well | 8 | USFWS | 9/16/2005 | 11 | |
| | 221689 | BS-2MW | 48.7177 | -104.1083 | 34N58E10 | Well | 8 | USFWS | 9/16/2005 | | |
| | 161785 | BS-RW | 48.7369 | -104.0847 | 34N58E1ABAA | Well | 7.8 | USFWS | 9/15/2005 | 10.1 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | | | | | TERL | | | | | |
| *Mallard Pond WPA* | | | | | | | | | | | | |
| | | MP1A | | | | | TERL | | | 14.3 | 88.9 | 242 |
| | | MP1A | 1,049 | 8.57 | 0.67 | 24 | | | | | | |
| | | MP1A | 1,194 | 3.89 | 0.77 | 16.2 | | | | | | |
| | 221735 | MP-1MW | | | | | MBMG | 7.41 | 10,050 | 727 | 150 | 3,279 |
| | 221735 | MP-1MW | | | | | TERL | | | | | |
| | 221704 | MP-2MW | | | | | MBMG | 7.08 | 16,300 | 1,827 | 1,297 | 623 |
| | 221704 | MP-2MW | | | | | TERL | | | | | |
| | 161782 | MP-RW | | | | | MBMG | 7.69 | 682 | 72.1 | 30.2 | 33.9 |
| | 161782 | MP-RW | | | | | TERL | | | | | |
| *Northeast WPA* | | | | | | | | | | | | |
| | | NE2 | 94,000 | 3.91 | | 5,179 | | | | | | |
| | | NE3 | | | | | | | | | | |
| | | NE5 | | | | | | | | | | |
| *North Root WPA* | | | | | | | | | | | | |
| | | NR1 | 21,296 | 9.49 | 13.63 | 2,130 | | | | | | |
| | | NR1 | 28,167 | 8.22 | 18.03 | 4,005 | | | | | | |
| *Big Slough WPA* | | | | | | | | | | | | |
| | | BS1 | 2,216 | 4.21 | 1.42 | 32 | | | | | | |
| | | BS2 | 1,768 | 7.85 | 1.13 | 16 | | | | | | |
| | | BS3A | 8,834 | 8.33 | 5.68 | 222 | | | | | | |
| | | BS4A | 34,017 | 6.16 | 21.78 | 1,198 | | | | | | |
| | | BS8 | 4,616 | 6.54 | 2.95 | 109 | | | | | | |
| | 221706 | BS-1DMW | | | | | MBMG | 7.89 | 2,940 | 110 | 112 | 474 |
| | 221706 | BS-1DMW | | | | | TERL | | | | | |
| | 221736 | BS-1SMW | | | | | MBMG | 7.89 | 2,300 | 54.1 | 88.4 | 389 |
| | 221736 | BS-1SMW | | | | | TERL | | | | | |
| | 221689 | BS-2MW | | | | | MBMG | 7.49 | 8,320 | 435 | 393 | 1,465 |
| | 221689 | BS-2MW | | | | | TERL | | | | | |
| | 161785 | BS-RW | | | | | MBMG | 7.22 | 1615 | 129 | 58.7 | 206 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | | 0.23 | 1.33 | 10.8 | | | | | | |
| *Mallard Pond WPA* | | | | | | | | | | | | |
| | | MP1A | 19.4 | 0.01 | 0.012 | 0.7 | | | | | | |
| | | MP1A | | | | | | | | | | |
| | | MP1A | | | | | | | | | | |
| | 221735 | MP-1MW | 107 | | | | 411.1 | 0 | 296 | 6,525 | | |
| | 221735 | MP-1MW | | <0.01 | 1.03 | 10.7 | | | | | | |
| | 221704 | MP-2MW | 17.9 | | | | 239.1 | 0 | 60.1 | 8,581 | | |
| | 221704 | MP-2MW | | <0.01 | 0.01 | 10.4 | | | | | | |
| | 161782 | MP-RW | 4.76 | | | | 407.8 | 0 | 44.1 | 4.57 | | |
| | 161782 | MP-RW | | 0.47 | 0.06 | 9.4 | | | | | | |
| *Northeast WPA* | | | | | | | | | | | | |
| | | NE2 | | | | | | | | | | |
| | | NE3 | | | | | | | | | | |
| | | NE5 | | | | | | | | | | |
| *North Root WPA* | | | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| *Big Slough WPA* | | | | | | | | | | | | |
| | | BS1 | | | | | | | | | | |
| | | BS2 | | | | | | | | | | |
| | | BS3A | | | | | | | | | | |
| | | BS4A | | | | | | | | | | |
| | | BS8 | | | | | | | | | | |
| | 221706 | BS-1DMW | 8.81 | | | | 562.01 | 0 | 697 | 400 | | |
| | 221706 | BS-1DMW | | <0.01 | 0.12 | 11.1 | | | | | | |
| | 221736 | BS-1SMW | 6.91 | | | | 487.2 | 0 | 724 | 117 | | |
| | 221736 | BS-1SMW | | 0.02 | 0.38 | 11.4 | | | | | | |
| | 221689 | BS-2MW | 20.8 | | | | 358.7 | 0 | 2,493 | 2,094 | | |
| | 221689 | BS-2MW | | <0.01 | <0.002 | 11 | | | | | | |
| | 161785 | BS-RW | 7.12 | | | | 698.3 | 0 | 414 | 14.7 | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | | | <50 | 13.8 | 230 | 36 | <0.5 | | 0.04 | <5 |
| *Mallard Pond WPA* | | | | | | | | | | | | |
| | | MP1A | | | <50 | 4.39 | 562 | 12 | <0.5 | | 0.03 | <5 |
| | | MP1A | | | | | | | | | | |
| | | MP1A | | | | | | | | | | |
| | 221735 | MP-1MW | | | | | | | | | | |
| | 221735 | MP-1MW | | | <50 | 3.21 | 8,560 | 640 | <0.5 | | 2.16 | <5 |
| | 221704 | MP-2MW | | | | | | | | | | |
| | 221704 | MP-2MW | | | <50 | 13.3 | 90 | 3,440 | <0.5 | | 1.79 | <5 |
| | 161782 | MP-RW | | | | | | | | | | |
| | 161782 | MP-RW | | | <50 | 13.8 | 106 | 545 | <0.5 | | 0.08 | <5 |
| *Northeast WPA* | | | | | | | | | | | | |
| | | NE2 | | | | | | | | | | |
| | | NE3 | | | | | | | | | | |
| | | NE5 | | | | | | | | | | |
| *North Root WPA* | | | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| *Big Slough WPA* | | | | | | | | | | | | |
| | | BS1 | | | | | | | | | | |
| | | BS2 | | | | | | | | | | |
| | | BS3A | | | | | | | | | | |
| | | BS4A | | | | | | | | | | |
| | | BS8 | | | | | | | | | | |
| | 221706 | BS-1DMW | | | | | | | | | | |
| | 221706 | BS-1DMW | | | <50 | 1.06 | 284 | 91 | <0.5 | | 0.06 | <5 |
| | 221736 | BS-1SMW | | | | | | | | | | |
| | 221736 | BS-1SMW | | | <50 | 1.03 | 272 | 12 | <0.5 | | 0.12 | <5 |
| | 221689 | BS-2MW | | | | | | | | | | |
| | 221689 | BS-2MW | | | <50 | 1.57 | 1,450 | 77 | <0.5 | | 0.14 | <5 |
| | 161785 | BS-RW | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | <0.100 | 435 | <5 |
| *Mallard Pond WPA* | | | | | | | | | | | | |
| | | MP1A | <5 | <5 | <0.1 | | <10 | <5 | 0.05 | 0.16 | 95 | <5 |
| | | MP1A | | | | | | | | | | |
| | | MP1A | | | | | | | | | | |
| | 221735 | MP-1MW | | | | | | | | | | |
| | 221735 | MP-1MW | <5 | <5 | <0.1 | | <10 | 17 | <0.05 | 2.26 | 15,000 | 9 |
| | 221704 | MP-2MW | | | | | | | | | | |
| | 221704 | MP-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 2.8 | 6,930 | 24 |
| | 161782 | MP-RW | | | | | | | | | | |
| | 161782 | MP-RW | <5 | <5 | <0.1 | | 10 | <5 | 0.12 | 0.14 | 240 | <5 |
| *Northeast WPA* | | | | | | | | | | | | |
| | | NE2 | | | | | | | | | | |
| | | NE3 | | | | | | | | | | |
| | | NE5 | | | | | | | | | | |
| *North Root WPA* | | | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| | | NR1 | | | | | | | | | | |
| *Big Slough WPA* | | | | | | | | | | | | |
| | | BS1 | | | | | | | | | | |
| | | BS2 | | | | | | | | | | |
| | | BS3A | | | | | | | | | | |
| | | BS4A | | | | | | | | | | |
| | | BS8 | | | | | | | | | | |
| | 221706 | BS-1DMW | | | | | | | | | | |
| | 221706 | BS-1DMW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 2.72 | 670 | <5 |
| | 221736 | BS-1SMW | | | | | | | | | | |
| | 221736 | BS-1SMW | <5 | <5 | <0.1 | | 10 | <5 | 0.02 | 3.6 | 445 | <5 |
| | 221689 | BS-2MW | | | | | | | | | | |
| | 221689 | BS-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 0.49 | 3,240 | 6 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | 221725 | M-5MW | | <10 | <5 | | | |
| *Mallard Pond WPA* | | | | | | | | |
| | | MP1A | | <10 | 11 | | | |
| | | MP1A | | | | | 0.023 | |
| | | MP1A | | | | | 0.014 | |
| | 221735 | MP-1MW | | | | | 0.649 | |
| | 221735 | MP-1MW | | <10 | <5 | | | |
| | 221704 | MP-2MW | | | | | 0.526 | |
| | 221704 | MP-2MW | | <10 | 7 | | | |
| | 161782 | MP-RW | | | | | 0.007 | |
| | 161782 | MP-RW | | <10 | <5 | | | |
| *Northeast WPA* | | | | | | | | |
| | | NE2 | | | | | 0.000 | |
| | | NE3 | | | | | | dry |
| | | NE5 | | | | | | dry |
| *North Root WPA* | | | | | | | | |
| | | NR1 | | | | | 0.100 | |
| | | NR1 | | | | | 0.142 | |
| *Big Slough WPA* | | | | | | | | |
| | | BS1 | | | | | 0.014 | |
| | | BS2 | | | | | 0.009 | |
| | | BS3A | | | | | 0.025 | |
| | | BS4A | | | | | 0.035 | |
| | | BS8 | | | | | 0.024 | |
| | 221706 | BS-1DMW | | | | | 0.136 | |
| | 221706 | BS-1DMW | | <10 | <5 | | | |
| | 221736 | BS-1SMW | | | | | 0.051 | |
| | 221736 | BS-1SMW | | <10 | <5 | | | |
| | 221689 | BS-2MW | | | | | 0.252 | |
| | 221689 | BS-2MW | | <10 | 8 | | | |
| | 161785 | BS-RW | | | | | 0.009 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | 48.7369 | -104.0847 | 34N58E1ABAA | Well | 7.8 | USFWS | 9/15/2005 | | |
| *Rabenburg WPA* | | | | | | | | | | | |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13 | |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 5/13/2004 | 6.32 | 7.42 |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 7/25/2004 | 26.09 | 8.8 |
| | 214791 | RABE1 | 48.8453 | -104.1169 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13.06 | 7.47 |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 5/13/2004 | 5.97 | 7.05 |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 7/20/2004 | 24.03 | 7.26 |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13.19 | 7.63 |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13 | |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214792 | RABE2 | 48.8449 | -104.1192 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214747 | RABE3 | 48.8426 | -104.1059 | 36N58E27 | Wetland | | USFWS | 7/23/2004 | 21.22 | 7.41 |
| | 214747 | RABE3 | 48.8426 | -104.1059 | 36N58E27 | Wetland | | USFWS | 4/27/2004 | 12.51 | 7.98 |
| | 214747 | RABE3 | 48.8426 | -104.1059 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214747 | RABE3 | 48.8426 | -104.1059 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 5/13/2004 | 6.08 | 7.37 |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 7/27/2004 | 25.08 | 7.56 |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13.94 | 7.57 |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 13 | |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | 214790 | RABE4 | 48.8428 | -104.1191 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | | |
| | | RABE5 | 48.8424 | -104.1167 | 36N58E27 | Wetland | | USFWS | 7/27/2004 | 18.07 | 7.17 |
| | | RABE5 | 48.8424 | -104.1167 | 36N58E27 | Wetland | | USFWS | 8/31/2004 | 24.43 | 7.91 |
| | 214788 | RABE5+ | 48.8421 | -104.1166 | 36N58E27 | Wetland | | USFWS | 8/31/2004 | 19.7 | 7.9 |
| | 214788 | RABE5+ | 48.8421 | -104.1166 | 36N58E27 | Wetland | | USFWS | 9/14/2004 | 16.23 | 7.89 |
| | 214788 | RABE5+ | 48.8421 | -104.1166 | 36N58E27 | Wetland | | USFWS | 6/13/2005 | 16 | |
| | | RABE6 | 48.8424 | -104.1151 | | Wetland | | USFWS | 7/27/2004 | 27.2 | 9.04 |
| | 221734 | R-1MW | 48.8438 | -104.1191 | 36N58E27CBBD | Well | 13 | USFWS | 9/15/2005 | | |
| | 221734 | R-1MW | 48.8438 | -104.1191 | 36N58E27CBBD | Well | 13 | USFWS | 9/15/2005 | | |
| | 221723 | R-2MW | 48.8436 | -104.1192 | 36N58E27CBBD | Well | 13 | USFWS | 9/15/2005 | | |
| | 221723 | R-2MW | 48.8436 | -104.1192 | 36N58E27CBBD | Well | 13 | USFWS | 9/15/2005 | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | | | | | TERL | | | | | |
| *Rabenburg WPA* | | | | | | | | | | | | |
| | 214791 | RABE1 | | | | | TERL | | | 500 | 531 | 1640 |
| | 214791 | RABE1 | | | | | UWRBEBL | 8 | 13,360 | 523.74 | 554.06 | 1,840.05 |
| | 214791 | RABE1 | | | | | MBMG | 7.37 | 15,370 | 699 | 752 | 2492 |
| | 214791 | RABE1 | 22,480 | 9.11 | 14.39 | 8,362 | | | | | | |
| | 214791 | RABE1 | 12,002 | 13.91 | 7.68 | 4,181 | | | | | | |
| | 214791 | RABE1 | 19,131 | 4.98 | 12.24 | 7,380 | | | | | | |
| | 214792 | RABE2 | 4,130 | 9.29 | 2.64 | 953 | | | | | | |
| | 214792 | RABE2 | 3,942 | 4.7 | | 961 | | | | | | |
| | 214792 | RABE2 | 5,150 | 6.23 | 3.30 | 1,485 | | | | | | |
| | 214792 | RABE2 | | | | | MBMG | 7.84 | 5,210 | 148 | 163 | 723 |
| | 214792 | RABE2 | | | | | TERL | | | 102 | 104 | 457 |
| | 214792 | RABE2 | | | | | UWRBEBL | 7.97 | 3,530 | 105.45 | 105.08 | 492.43 |
| | 214747 | RABE3 | 4,011 | 8.92 | 2.57 | 908 | | | | | | |
| | 214747 | RABE3 | 2,731 | 8 | 1.75 | 650 | | | | | | |
| | 214747 | RABE3 | | | | | TERL | | | 150 | 398 | 501 |
| | 214747 | RABE3 | | | | | UWRBEBL | 8.31 | 5,650 | 155.17 | 399.86 | 530.45 |
| | 214790 | RABE4 | 4,788 | 7.4 | 3.07 | 1,198 | | | | | | |
| | 214790 | RABE4 | 3,120 | 6.31 | 2.00 | 705 | | | | | | |
| | 214790 | RABE4 | 8,658 | 4.84 | 5.54 | 3,145 | | | | | | |
| | 214790 | RABE4 | | | | | MBMG | 8.05 | 7,510 | 321 | 358 | 1,025 |
| | 214790 | RABE4 | | | | | TERL | | | 223 | 267 | 768 |
| | 214790 | RABE4 | | | | | UWRBEBL | 8.06 | 6,550 | 230.87 | 279.34 | 825.96 |
| | | RABE5 | 7,509 | 5.99 | 4.81 | 2,420 | | | | | | |
| | | RABE5 | 8,126 | 15.69 | 5.20 | 2,690 | | | | | | |
| | 214788 | RABE5+ | 8,437 | 10.68 | 5.40 | 2,908 | | | | | | |
| | 214788 | RABE5+ | 8,613 | 8.23 | 5.51 | 3,405 | | | | | | |
| | 214788 | RABE5+ | | | | | MBMG | 7.23 | 7,270 | 267 | 337 | 1,063 |
| | | RABE6 | 8,812 | 16.33 | 5.60 | 2,614 | | | | | | |
| | 221734 | R-1MW | | | | | MBMG | 7.68 | 7,770 | 311 | 243 | 1,139 |
| | 221734 | R-1MW | | | | | TERL | | | | | |
| | 221723 | R-2MW | | | | | MBMG | 7.41 | 5,050 | 255 | 188 | 634 |
| | 221723 | R-2MW | | | | | TERL | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | | 7.52 | 0.05 | 13.3 | | | | | | |
| *Rabenburg WPA* | | | | | | | | | | | | |
| | 214791 | RABE1 | 43.2 | 0.09 | 0.26 | 1.9 | | | | | | |
| | 214791 | RABE1 | 50.16 | | | | | | 408 | 3,349 | ND | |
| | 214791 | RABE1 | 67.8 | 0.87 | 0.78 | 15 | 479.05 | 0 | 763 | 6,770 | 0.83 | <0.5 |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | 34.1 | 0.24 | 0.38 | 10.7 | 530.7 | 0 | 310 | 1,287 | <0.5 | <0.5 |
| | 214792 | RABE2 | 32.4 | 0.05 | 0.16 | 1.5 | | | | | | |
| | 214792 | RABE2 | 33.75 | | | | | | 179 | 633.91 | ND | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | 74 | 0.06 | 0.04 | 5 | | | | | | |
| | 214747 | RABE3 | 74.71 | | | | | | 791 | 1,172 | ND | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | 25.7 | 0.47 | 0.22 | 26.1 | 696.6 | 0 | 257 | 2,639 | <0.5 | <0.5 |
| | 214790 | RABE4 | 23 | 0.2 | 0.1 | 4.6 | | | | | | |
| | 214790 | RABE4 | 25.71 | | | | | | 146 | 1,794 | ND | |
| | | RABE5 | | | | | | | | | | |
| | | RABE5 | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | 29.8 | 0.49 | 0.11 | 12.5 | 303.8 | 0 | 339 | 2,687 | <0.5 | <0.5 |
| | | RABE6 | | | | | | | | | | |
| | 221734 | R-1MW | 28.1 | | | | 584 | 0 | 443 | 1,366 | 425 | |
| | 221734 | R-1MW | | <0.01 | 0.28 | 12.5 | | | | | | |
| | 221723 | R-2MW | 15.4 | | | | 540.1 | 0 | 216 | 1,578 | | |
| | 221723 | R-2MW | | <0.01 | 0.51 | 11.8 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | | | <50 | 11.3 | 439 | 35 | <0.5 | | 0.02 | <5 |
| *Rabenburg WPA* | | | | | | | | | | | | |
| | 214791 | RABE1 | | | <50 | 8.4 | 1,180 | 300 | <0.5 | | <0.05 | <5 |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | <0.5 | <20 | <200 | 43.4 | 1,704 | 536 | <40 | 10,400 | <20 | <40 |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | <0.5 | <10 | <100 | 10.5 | 1,186 | 233 | <20 | 1,640 | <10 | <20 |
| | 214792 | RABE2 | | | <50 | 3.93 | 1,140 | 102 | <0.5 | | <0.01 | <5 |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | | | <50 | 9.89 | 453 | 150 | <0.5 | | 0.02 | <5 |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | <0.5 | <10 | <100 | 14.7 | 368 | 239 | <20 | 3,780 | <10 | <20 |
| | 214790 | RABE4 | | | <50 | 5.57 | 446 | 325 | <0.5 | | <0.02 | <5 |
| | 214790 | RABE4 | | | | | | | | | | |
| | | RABE5 | | | | | | | | | | |
| | | RABE5 | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | <0.5 | <10 | <100 | 16.3 | 826 | 236 | <20 | 2,880 | <10 | <20 |
| | | RABE6 | | | | | | | | | | |
| | 221734 | R-1MW | | | | | | | | | | |
| | 221734 | R-1MW | | | <50 | 1.45 | 1,510 | 204 | <0.5 | | 0.44 | <5 |
| | 221723 | R-2MW | | | | | | | | | | |
| | 221723 | R-2MW | | | <50 | 1.76 | 764 | 146 | <0.5 | | 0.06 | <5 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | <0.1 | 1,140 | <5 |
| *Rabenburg WPA* | | | | | | | | | | | | |
| | 214791 | RABE1 | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 0.22 | 2,350 | 7 |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | <40 | <40 | | 863 | <200 | <40 | <40 | 112 | 4,203 | <20 |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214791 | RABE1 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214792 | RABE2 | <20 | <20 | | 298 | <100 | <20 | <20 | 24.6 | 1,261 | <10 |
| | 214792 | RABE2 | <5 | <5 | <0.1 | | <10 | <5 | 0.04 | 0.22 | 720 | <5 |
| | 214792 | RABE2 | | | | | | | | | | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214747 | RABE3 | <5 | <5 | <0.1 | | <10 | <5 | 0.06 | 0.35 | 995 | <5 |
| | 214747 | RABE3 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | | | | | | | | | | |
| | 214790 | RABE4 | <20 | <20 | | 317 | <100 | <20 | <20 | 48.1 | 1,586 | <10 |
| | 214790 | RABE4 | <5 | <5 | <0.1 | | <10 | <5 | 0.06 | 0.21 | 1,020 | <5 |
| | 214790 | RABE4 | | | | | | | | | | |
| | | RABE5 | | | | | | | | | | |
| | | RABE5 | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | | | | | | | | | | |
| | 214788 | RABE5+ | <20 | <20 | | 349 | <100 | <20 | <20 | 45.3 | 1,635 | <10 |
| | | RABE6 | | | | | | | | | | |
| | 221734 | R-1MW | | | | | | | | | | |
| | 221734 | R-1MW | <5 | 6 | <0.1 | | <10 | 12 | <0.05 | 0.26 | 1,930 | <5 |
| | 221723 | R-2MW | | | | | | | | | | |
| | 221723 | R-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 1.35 | 1,020 | <5 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | 161785 | BS-RW | | <10 | <5 | | | |
| *Rabenburg WPA* | | | | | | | | |
| | 214791 | RABE1 | | <10 | <5 | | | |
| | 214791 | RABE1 | | | | | 0.251 | |
| | 214791 | RABE1 | <10 | <100 | <40 | <30 | 0.440 | |
| | 214791 | RABE1 | | | | | 0.372 | |
| | 214791 | RABE1 | | | | | 0.348 | |
| | 214791 | RABE1 | | | | | 0.386 | |
| | 214792 | RABE2 | | | | | 0.231 | |
| | 214792 | RABE2 | | | | | 0.244 | |
| | 214792 | RABE2 | | | | | 0.288 | |
| | 214792 | RABE2 | <5 | <50 | <20 | <20 | 0.247 | |
| | 214792 | RABE2 | | <10 | <5 | | | |
| | 214792 | RABE2 | | | | | 0.180 | |
| | 214747 | RABE3 | | | | | 0.226 | |
| | 214747 | RABE3 | | | | | 0.238 | |
| | 214747 | RABE3 | | <10 | <5 | | | |
| | 214747 | RABE3 | | | | | 0.207 | |
| | 214790 | RABE4 | | | | | 0.250 | |
| | 214790 | RABE4 | | | | | 0.226 | |
| | 214790 | RABE4 | | | | | 0.363 | |
| | 214790 | RABE4 | <5 | <50 | <20 | <20 | 0.351 | |
| | 214790 | RABE4 | | <10 | <5 | | | |
| | 214790 | RABE4 | | | | | 0.274 | |
| | | RABE5 | | | | | 0.322 | |
| | | RABE5 | | | | | 0.331 | |
| | 214788 | RABE5+ | | | | | 0.345 | |
| | 214788 | RABE5+ | | | | | 0.395 | |
| | 214788 | RABE5+ | <5 | <50 | <20 | <20 | 0.370 | |
| | | RABE6 | | | | | 0.297 | |
| | 221734 | R-1MW | | | | | 0.176 | |
| | 221734 | R-1MW | | <10 | 40 | | | |
| | 221723 | R-2MW | | | | | 0.312 | |
| | 221723 | R-2MW | | <10 | <5 | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | 48.8504 | -104.1226 | 36N58E28AADA | Well | 23 | USFWS | 10/13/1989 | 8.8 | |
| | 890940 | RS-1MW | 48.8504 | -104.1226 | 36N58E28AADA | Well | 23 | USFWS | 9/15/2005 | 13.7 | |
| | 890940 | RS-1MW | 48.8504 | -104.1226 | 36N58E28AADA | Well | 23 | USFWS | 9/15/2005 | 13.7 | |
| | 890445 | RS-2MW | 48.8499 | -104.1225 | 36N58E28AADD | Well | 8 | USFWS | 9/15/2005 | 18.1 | |
| | 890445 | RS-2MW | 48.8499 | -104.1225 | 36N58E28AADD | Well | 8 | USFWS | 9/15/2005 | | |
| | 890445 | RS-2MW | 48.8499 | -104.1225 | 36N58E27BCBC | Well | 8 | USFWS | 4/20/1989 | 6 | |
| | 890446 | RS-3MW | 48.8484 | -104.1210 | 36N58E28AADD | Well | 13 | USFWS | 9/15/2005 | 16.4 | |
| | 890446 | RS-3MW | 48.8484 | -104.1210 | 36N58E28AADD | Well | 13 | USFWS | 9/15/2005 | | |
| | 890446 | RS-3MW | 48.8484 | -104.1210 | 36N58E28BCBD | Well | 13 | USFWS | 4/20/1989 | 5 | |
| | 890939 | RS-4MW | 48.8477 | -104.1193 | 36N58E28AADD | Well | 23 | USFWS | 9/15/2005 | | |
| | 890939 | RS-4MW | 48.8477 | -104.1193 | 36N58E28AADD | Well | 23 | USFWS | 10/13/1989 | 13.7 | |
| | 890936 | RS-6MW | 48.8424 | -104.1106 | 36N58E27DAAD | Well | 22 | USFWS | 9/15/2005 | | |
| | 890936 | RS-6MW | 48.8424 | -104.1106 | 36N58E27DAAD | Well | 22 | USFWS | 10/13/1989 | 10.7 | |
| | 890937 | RS-7MW | 48.8445 | -104.0999 | 36N58E27DBCC | Well | 27 | USFWS | 9/15/2005 | | |
| | 890937 | RS-7MW | 48.8445 | -104.0999 | 36N58E27DBCC | Well | 27 | USFWS | 10/13/1989 | 11.7 | |
| | 220932 | 124B | 48.8505 | -104.1043 | 36N58E27ABAC | Well | 8 | MBMG | 4/10/2006 | 3.35 | |
| | 220937 | 124K | 48.8495 | -104.1028 | 36N58E27ABDA | Well | 14 | SCCD | 4/10/2006 | 3.54 | |
| *Hansen WPA* | | | | | | | | | | | |
| | 214749 | HAN1 | 48.9691 | -104.1625 | 37N57E11 | Wetland | | USFWS | 7/24/2004 | 22 | |
| | 214749 | HAN1 | 48.9691 | -104.1625 | 37N57E11 | Wetland | | USFWS | 6/13/2005 | | |
| | 214749 | HAN1 | 48.9691 | -104.1625 | 37N57E11 | Wetland | | USFWS | 6/13/2005 | | |
| | 214749 | HAN1 | 48.9691 | -104.1625 | 37N57E11 | Wetland | | USFWS | 4/28/2004 | 9.2 | 7.65 |
| | 214749 | HAN1 | 48.9691 | -104.1625 | 37N57E11 | Wetland | | USFWS | 7/24/2004 | 22.25 | 7.51 |
| | | HAN2 | 48.9705 | -104.1630 | | Wetland | | USFWS | 4/28/2004 | 6.37 | 6.96 |
| | 890447 | HAN-1MW | 48.9704 | -104.1661 | 37N57E11DCAC | Well | 13 | USFWS | 9/14/2005 | 12.4 | |
| | 890447 | HAN-1MW | 48.9704 | -104.1661 | 37N57E11DCAC | Well | 13 | USFWS | 9/14/2005 | 12.4 | |
| | 890447 | HAN-1MW | 48.9704 | -104.1661 | 37N57E11DCAC | Well | 13 | MBMG | 4/22/1989 | 7.7 | |
| *Ward WPA* | | | | | | | | | | | |
| | | WD1 | 48.9711 | -104.1509 | | Wetland | | USFWS | 4/28/2004 | 7.03 | 7.5 |
| | | WD2 | 48.9769 | -104.1526 | | Wetland | | USFWS | | | |
| | 220958 | WD-1MW | 48.9820 | -104.1526 | 37N57E12BBAA | Well | 13 | USFWS | 9/14/2005 | | |
| | 221688 | WD-2MW | 48.9813 | -104.1524 | 37N47E12BBA | Well | 16 | USFWS | 9/14/2005 | 11.4 | |
| | 221688 | WD-2MW | 48.9813 | -104.1524 | 37N47E12BBA | Well | 16 | USFWS | 9/14/2005 | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | | | | | MBMG | 7.18 | 807,299 | 2,770 | 859 | 39,000 |
| | 890940 | RS-1MW | | | | | MBMG | 7.67 | 2,181.5 | 178 | 122 | 99.98 |
| | 890940 | RS-1MW | | | | | TERL | | | | | |
| | 890445 | RS-2MW | | | | | MBMG | 7.05 | 39,500 | 1,227 | 630 | 11,739 |
| | 890445 | RS-2MW | | | | | TERL | | | | | |
| | 890445 | RS-2MW | | | | | MBMG | 6.95 | 78,625.5 | 2,420 | 1,420 | 15,900 |
| | 890446 | RS-3MW | | | | | MBMG | 7.31 | 16,220 | 560 | 343 | 3,817 |
| | 890446 | RS-3MW | | | | | TERL | | | | | |
| | 890446 | RS-3MW | | | | | MBMG | 6.7 | 48,105 | 1,500 | 853 | 9,590 |
| | 890939 | RS-4MW | | | | | TERL | | | 352 | 239 | 1,660 |
| | 890939 | RS-4MW | | | | | MBMG | 7.03 | 28,810 | 1,010 | 596 | 5,060 |
| | 890936 | RS-6MW | | | | | TERL | | | 372 | 302 | 545 |
| | 890936 | RS-6MW | | | | | MBMG | 7.67 | 2,181.5 | 178 | 122 | 99.98 |
| | 890937 | RS-7MW | | | | | TERL | | | 267 | 206 | 199 |
| | 890937 | RS-7MW | | | | | MBMG | 7.7 | 760.5 | 80.8 | 39.44 | 20.39 |
| | 220932 | 124B | | | | | MBMG | 7.01 | 6,030 | 114 | 65.1 | 972 |
| | 220937 | 124K | | | | | MBMG | 7.46 | 12,830 | 371 | 152 | 2,670 |
| *Hansen WPA* | | | | | | | | | | | | |
| | 214749 | HAN1 | | | | | MBMG | 8.19 | 3,160 | 104 | 265 | 209 |
| | 214749 | HAN1 | | | | | TERL | | | 95.5 | 236 | 165 |
| | 214749 | HAN1 | | | | | UWRBEBL | 7.74 | 2,950 | 105.14 | 260.48 | 188.04 |
| | 214749 | HAN1 | 2,313 | 9.82 | 1.48 | 205 | | | | | | |
| | 214749 | HAN1 | 3,240 | 2.44 | 2.08 | 242 | | | | | | |
| | | HAN2 | 2,368 | 8.85 | 1.52 | 231 | | | | | | |
| | 890447 | HAN-1MW | | | | | MBMG | 7.44 | 7,920 | 249 | 218 | 1,391 |
| | 890447 | HAN-1MW | | | | | TERL | | | | | |
| | 890447 | HAN-1MW | | | | | MBMG | 7.89 | 1,898.9 | 68.2 | 47.8 | 131 |
| *Ward WPA* | | | | | | | | | | | | |
| | | WD1 | 181.2 | 11.94 | 0.12 | 5.3 | | | | | | |
| | | WD2 | | | | | | | | | | |
| | 220958 | WD-1MW | | | | | TERL | | | 72.7 | 23.9 | <100 |
| | 221688 | WD-2MW | | | | | MBMG | 7.56 | 1,644 | 163 | 70.4 | 73.1 |
| | 221688 | WD-2MW | | | | | TERL | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | 860 | 0.96 | 11.32 | 10.1 | 320 | 0 | 669 | 66,900 | 34.6 | 0.3 |
| | 890940 | RS-1MW | 19.15 | | | | 427 | 0 | 538 | 195 | <.007 | 0.1 |
| | 890940 | RS-1MW | | <.004 | 0.64 | 22.9 | | | | | | |
| | 890445 | RS-2MW | 223 | | | | 488 | 0 | 537 | 22,638 | | |
| | 890445 | RS-2MW | | 0.04 | 0.86 | 8.9 | | | | | | |
| | 890445 | RS-2MW | 272 | 0.003 | 6.08 | 9.2 | 320 | 0 | 250 | 32,800 | 24 | <5 |
| | 890446 | RS-3MW | 61.8 | | | | 623.4 | 0 | 838 | 7,302 | | |
| | 890446 | RS-3MW | | <0.01 | 2.93 | 8.4 | | | | | | |
| | 890446 | RS-3MW | 110 | 0.073 | 9.52 | 11.9 | 547 | 0 | 1210 | 18,600 | 7 | <1 |
| | 890939 | RS-4MW | 29.6 | 5.22 | 0.73 | 13.2 | | | | | | |
| | 890939 | RS-4MW | 56.9 | <.004 | 3.11 | 15.7 | 273 | 0 | 1060 | 10,300 | 5.02 | 0.1 |
| | 890936 | RS-6MW | 26.6 | 18.5 | <0.002 | 11.2 | | | | | | |
| | 890936 | RS-6MW | 19.15 | <.004 | 0.64 | 22.9 | 427 | 0 | 538 | 195 | <.007 | 0.1 |
| | 890937 | RS-7MW | 27.7 | 0.69 | <0.002 | 9.9 | | | | | | |
| | 890937 | RS-7MW | 5.86 | 1.35 | 0.69 | 23 | 321 | 0 | 130 | 12.31 | 0.06 | 0.35 |
| | 220932 | 124B | 26.4 | <0.005 | 0.03 | 19 | 306.22 | 0 | <125 | 1,628 | 3.17 | <2.5 |
| | 220937 | 124K | 61 | <0.05 | 1.18 | 18 | 239.1 | 0 | <250 | 4,886 | 6.08 | <5 |
| *Hansen WPA* | | | | | | | | | | | | |
| | 214749 | HAN1 | 147 | | | | 669.8 | 0 | 991 | 250 | | |
| | 214749 | HAN1 | 122 | 0.09 | 0.15 | 3.5 | | | | | | |
| | 214749 | HAN1 | 129.58 | | | | | | 910 | 199.66 | 54.99 | |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | | HAN2 | | | | | | | | | | |
| | 890447 | HAN-1MW | 21.2 | | | | | 0 | 212 | 2,781 | | |
| | 890447 | HAN-1MW | | 0.18 | 0.03 | 10.8 | 440.8 | | | | | |
| | 890447 | HAN-1MW | 4.5 | <.002 | <.001 | 20.3 | 341 | 0 | 142 | 138 | 11.9 | 0.4 |
| *Ward WPA* | | | | | | | | | | | | |
| | | WD1 | | | | | | | | | | |
| | | WD2 | | | | | | | | | | |
| | 220958 | WD-1MW | 8.89 | 0.02 | 3.19 | 7.1 | | | | | | |
| | 221688 | WD-2MW | 12.1 | | | | 231.8 | 0 | 56.3 | 451 | | |
| | 221688 | WD-2MW | | 0.73 | 0.32 | 4.8 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | | 18 | 100 | | 89,700 | 803 | | 2,200 | 25 | |
| | 890940 | RS-1MW | | <4 | | | | | | | | |
| | 890940 | RS-1MW | | | 70 | | 156 | | | 200 | <5 | |
| | 890445 | RS-2MW | | | | | | | | | | |
| | 890445 | RS-2MW | | | <50 | 5.04 | 36,200 | 620 | <0.5 | | 14.7 | <5 |
| | 890445 | RS-2MW | <1 | 15 | 40 | | 20,600 | | | <100 | 71 | |
| | 890446 | RS-3MW | | | | | | | | | | |
| | 890446 | RS-3MW | | | <50 | 1.85 | 10,300 | 97 | <0.5 | | 0.64 | <5 |
| | 890446 | RS-3MW | <.1 | 3 | <30 | | 12,200 | | | <100 | 11 | |
| | 890939 | RS-4MW | | | 1,840 | 4.44 | 3,700 | 163 | <0.5 | | 0.7 | <5 |
| | 890939 | RS-4MW | | 10 | 120 | | 6,200 | | | 7,100 | 12 | |
| | 890936 | RS-6MW | | | 178 | 9.93 | 252 | 370 | <0.5 | | <0.05 | <5 |
| | 890936 | RS-6MW | | <4 | 70 | | 156 | | | 200 | <5 | |
| | 890937 | RS-7MW | | | <50 | 7.5 | 170 | 96 | <0.5 | | 0.1 | <5 |
| | 890937 | RS-7MW | | <4 | 43 | | 114 | | | <100 | <5 | |
| | 220932 | 124B | <2.5 | <1 | <10 | 7.04 | 2,326 | 119 | <2 | 3,270 | <1 | <2 |
| | 220937 | 124K | <5 | <10 | <100 | 16.5 | 6,387 | 202 | <20 | 9,220 | <10 | <20 |
| *Hansen WPA* | | | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | <50 | 4.03 | 149 | 74 | <0.5 | | 0.02 | <5 |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | | HAN2 | | | | | | | | | | |
| | 890447 | HAN-1MW | | | | | | | | | | |
| | 890447 | HAN-1MW | | | <50 | 1.58 | 2,420 | 228 | <0.5 | | <0.05 | <5 |
| | 890447 | HAN-1MW | <.1 | <2 | <30 | | 480 | | | <100 | <2 | |
| *Ward WPA* | | | | | | | | | | | | |
| | | WD1 | | | | | | | | | | |
| | | WD2 | | | | | | | | | | |
| | 220958 | WD-1MW | | | <50 | 0.57 | 30 | 197 | <0.5 | | 0.02 | <5 |
| | 221688 | WD-2MW | | | | | | | | | | |
| | 221688 | WD-2MW | | | <50 | 1.33 | 40 | 560 | <0.5 | | 0.04 | <5 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | 9 | 39 | | 22,200 | <40 | 40 | 680 | | 80,100 | <4 |
| | 890940 | RS-1MW | | | | | | | | | | |
| | 890940 | RS-1MW | <5 | 6 | | 81 | <40 | <20 | | | 590 | 4 |
| | 890445 | RS-2MW | | | | | | | | | | |
| | 890445 | RS-2MW | <5 | 7 | <0.1 | | <10 | 55 | <0.2 | 8.58 | 21,800 | 16 |
| | 890445 | RS-2MW | 24 | 77 | | 6,280 | 30 | 120 | | | 25,400 | <1 |
| | 890446 | RS-3MW | | | | | | | | | | |
| | 890446 | RS-3MW | 8 | 7 | <0.1 | | 10 | 28 | 1.1 | 0.43 | 7,000 | 7 |
| | 890446 | RS-3MW | 10 | 47 | | 3,280 | <20 | 80 | | | 16,600 | <1. |
| | 890939 | RS-4MW | 13 | 10 | <0.1 | | <10 | 14 | 3.82 | 0.32 | 3,120 | 48 |
| | 890939 | RS-4MW | 5 | 15 | | 2,030 | <40 | 40 | 180 | | 7,750 | 17 |
| | 890936 | RS-6MW | <5 | <5 | <0.1 | | <10 | <5 | 0.43 | 0.29 | 1,570 | 12 |
| | 890936 | RS-6MW | <5 | 6 | | 81 | <40 | <20 | | | 590 | 4 |
| | 890937 | RS-7MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | <0.1 | 990 | <5 |
| | 890937 | RS-7MW | <5 | <4 | | 28 | <40 | <20 | | | 230 | 4 |
| | 220932 | 124B | 3.93 | 12.5 | | 363 | <10 | <2 | 2.67 | 27.2 | 2,095 | <1 |
| | 220937 | 124K | <20 | 26.7 | | 1,116 | <100 | <20 | <20 | 67.3 | 7,380 | <10 |
| *Hansen WPA* | | | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | <5 | <5 | <0.1 | | <10 | <5 | 0.06 | 0.25 | 600 | <5.00 |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | 214749 | HAN1 | | | | | | | | | | |
| | | HAN2 | | | | | | | | | | |
| | 890447 | HAN-1MW | | | | | | | | | | |
| | 890447 | HAN-1MW | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 12.2 | 2,150 | <5 |
| | 890447 | HAN-1MW | <2 | <2 | | 100 | <20 | <10 | | | 290 | <1. |
| *Ward WPA* | | | | | | | | | | | | |
| | | WD1 | | | | | | | | | | |
| | | WD2 | | | | | | | | | | |
| | 220958 | WD-1MW | <5 | <5 | <0.1 | | <10 | <5 | 0.02 | 1.79 | 180 | <5 |
| | 221688 | WD-2MW | | | | | | | | | | |
| | 221688 | WD-2MW | <5 | <5 | <0.1 | | <10 | <5 | <0.01 | 0.1 | 245 | <5 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | 890940 | RS-1MW | | 30 | 11 | 25 | 0.083 | |
| | 890940 | RS-1MW | | | | | 0.089 | |
| | 890940 | RS-1MW | | 7 | <7 | <6 | | |
| | 890445 | RS-2MW | | | | | 0.573 | |
| | 890445 | RS-2MW | | <10 | 6 | | | |
| | 890445 | RS-2MW | | 51 | 17 | 29 | 0.417 | |
| | 890446 | RS-3MW | | | | | 0.450 | |
| | 890446 | RS-3MW | | <10 | 16 | | | |
| | 890446 | RS-3MW | | 29 | 14 | <4 | 0.387 | |
| | 890939 | RS-4MW | | <10 | 126 | | | |
| | 890939 | RS-4MW | | 19 | 16 | 9 | 0.358 | |
| | 890936 | RS-6MW | | <10 | 7 | | | |
| | 890936 | RS-6MW | | 7 | <7 | <6 | 0.089 | |
| | 890937 | RS-7MW | | <10 | <5 | | | |
| | 890937 | RS-7MW | | 6 | 7 | <6 | 0.016 | |
| | 220932 | 124B | 6.92 | <5 | <2 | <2 | 0.270 | |
| | 220937 | 124K | <5 | <50 | <20 | <20 | 0.381 | |
| *Hansen WPA* | | | | | | | | |
| | 214749 | HAN1 | | | | | 0.079 | |
| | 214749 | HAN1 | | <10 | <5 | | | |
| | 214749 | HAN1 | | | | | 0.068 | |
| | 214749 | HAN1 | | | | | 0.089 | |
| | 214749 | HAN1 | | | | | 0.075 | |
| | | HAN2 | | | | | 0.098 | |
| | 890447 | HAN-1MW | | | | | 0.351 | |
| | 890447 | HAN-1MW | | <10 | 5 | | | |
| | 890447 | HAN-1MW | | <1 | <3 | <4 | 0.073 | |
| *Ward WPA* | | | | | | | | |
| | | WD1 | | | | | 0.029 | |
| | | WD2 | | | | | | dry |
| | 220958 | WD-1MW | | <10 | 10 | | | |
| | 221688 | WD-2MW | | | | | 0.274 | |
| | 221688 | WD-2MW | | <10 | 9 | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | 48.9828 | -104.1527 | 37N47E12BBAD | Well | 21 | USFWS | 9/14/2005 | 12.7 | |
| | 48284 | WD-3MW | 48.9828 | -104.1527 | 37N47E12BBAD | Well | 21 | USFWS | 9/14/2005 | | |
| | 890436 | 890436 | 48.9827 | -104.1511 | 37N57E12BBAA | Well | 13 | MBMG | 4/22/1989 | 7.6 | |
| *Jerde WPA* | | | | | | | | | | | |
| | 120874 | JER1 | 48.9546 | -104.1891 | 37N57E15DCBC | Wetland | | MBMG | 8/27/1990 | 22.5 | |
| | 120874 | JER1 | 48.9546 | -104.1891 | 37N57E15DCBC | Wetland | | USFWS | 6/13/2005 | | |
| | 120874 | JER1 | 48.9546 | -104.1891 | 37N57E15DCBC | Wetland | | USFWS | 7/23/2004 | 23.57 | 7.77 |
| | 120874 | JER1 | 48.9546 | -104.1891 | 37N57E15DCBC | Wetland | | USFWS | 4/28/2004 | 8.87 | 8.19 |
| | 120874 | JER1 | 48.9546 | -104.1891 | 37N57E15DCBC | Wetland | | USFWS | 6/13/2005 | | |
| | | JER2 | 48.9595 | -104.1925 | | Wetland | | USFWS | 4/28/2004 | 9.64 | 8.05 |
| | | JER2 | 48.9595 | -104.1925 | | Wetland | | USFWS | 9/14/2004 | 16.44 | 8.36 |
| | 221692 | JP-1MW | 48.9545 | -104.1874 | 37N57E15 | Well | 33 | USFWS | 9/15/2005 | 8.23 | |
| | 221692 | JP-1MW | 48.9545 | -104.1874 | 37N57E15 | Well | 33 | USFWS | 9/15/2005 | | |
| | 221722 | JP-2MW | 48.9547 | -104.1878 | 37N57E15 | Well | 28 | USFWS | 9/15/2005 | | |
| | 221722 | JP-2MW | 48.9547 | -104.1878 | 37N57E15 | Well | 28 | USFWS | 9/15/2005 | | |
| | 221720 | JP-3MW | 48.9546 | -104.1883 | 37N57E15 | Well | 13 | USFWS | 9/15/2005 | 10.3 | |
| | 221720 | JP-3MW | 48.9546 | -104.1883 | 37N57E15 | Well | 13 | USFWS | 9/15/2005 | | |
| *Erikson WPA* | | | | | | | | | | | |
| | 214744 | ERK1 | 48.5984 | -104.0639 | 33N58E24 | Wetland | | USFWS | 7/21/2004 | 26 | |
| | 214744 | ERK1 | 48.5984 | -104.0639 | 33N58E24 | Wetland | | USFWS | 5/14/2004 | 7.45 | 8.65 |
| | 214744 | ERK1 | 48.5984 | -104.0639 | 33N58E24 | Wetland | | USFWS | 7/21/2004 | 26.4 | 8.88 |
| | | ERK2 | 48.5956 | -104.0609 | | Wetland | | USFWS | 5/14/2004 | 14.5 | 9.52 |
| | | ERK3 | 48.5927 | -104.0623 | | Wetland | | USFWS | 5/14/2004 | 16.07 | 9.4 |
| | | ERK4 | 48.5890 | -104.0588 | | Wetland | | USFWS | 5/14/2004 | 14.71 | 9.2 |
| | | ERK5 | 48.5945 | -104.0487 | | Wetland | | USFWS | 5/14/2004 | 7.81 | 9.53 |
| | | ERK6 | 48.5981 | -104.0497 | | Wetland | | USFWS | 5/14/2004 | 15.17 | 8.2 |
| | | ERK6 | 48.5981 | -104.0497 | | Wetland | | USFWS | 5/14/2004 | 15.1 | 8.21 |
| | | ERK7 | 48.5854 | -104.0482 | | Wetland | | USFWS | 5/14/2004 | 16.03 | 7.84 |
| *Ferguson WPA* | | | | | | | | | | | |
| | | FERG3 | 48.9288 | -104.1353 | | Wetland | | USFWS | 5/13/2004 | 8.17 | 8.71 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | | | | | MBMG | 7.23 | 11,930 | 582 | 485 | 1,903 |
| | 48284 | WD-3MW | | | | | TERL | | | | | |
| | 890436 | 890436 | | | | | MBMG | 7.81 | 500.8 | 58.6 | 18.8 | 14.3 |
| *Jerde WPA* | | | | | | | | | | | | |
| | 120874 | JER1 | | | | | MBMG | 8.89 | 1,745.9 | 94.6 | 59.7 | 219 |
| | 120874 | JER1 | | | | | TERL | | | 114 | 123 | 155 |
| | 120874 | JER1 | 2,035 | 3.62 | 1.30 | 118 | | | | | | |
| | 120874 | JER1 | 1,223 | 8.14 | 0.78 | 78 | | | | | | |
| | 120874 | JER1 | | | | | UWRBEBL | 8.61 | 2,140 | 115.28 | 124.3 | 198.21 |
| | | JER2 | 1,212 | 4.39 | 0.78 | 83 | | | | | | |
| | | JER2 | 2,341 | 6.47 | 1.50 | 135.5 | | | | | | |
| | 221692 | JP-1MW | | | | | MBMG | 7.34 | 32,700 | 997 | 1,920 | 7,770 |
| | 221692 | JP-1MW | | | | | TERL | | | | | |
| | 221722 | JP-2MW | | | | | MBMG | 7.33 | 43,200 | 1,482 | 2,574 | 12,997 |
| | 221722 | JP-2MW | | | | | TERL | | | | | |
| | 221720 | JP-3MW | | | | | MBMG | 7.3 | 38,500 | 1,219 | 4,041 | 7,555 |
| | 221720 | JP-3MW | | | | | TERL | | | | | |
| *Erikson WPA* | | | | | | | | | | | | |
| | 214744 | ERK1 | | | | | MBMG | 9.63 | 9,220 | 5.07 | 209 | 2,304 |
| | 214744 | ERK1 | 9,680 | 8.99 | 6.20 | 259 | | | | | | |
| | 214744 | ERK1 | 10,400 | 10.08 | 6.66 | 291 | | | | | | |
| | | ERK2 | 36,789 | 9.02 | 23.57 | 1,748.5 | | | | | | |
| | | ERK3 | 52,686 | 5.98 | 33.72 | 1,547 | | | | | | |
| | | ERK4 | 25,072 | 10.35 | 16.05 | 2,303 | | | | | | |
| | | ERK5 | 45,169 | 4.67 | 28.91 | 1,678 | | | | | | |
| | | ERK6 | 3,013 | 8.79 | 1.93 | 53 | | | | | | |
| | | ERK6 | 3,066 | 9.02 | 1.96 | 53 | | | | | | |
| | | ERK7 | 520.2 | 6.96 | 0.33 | 20 | | | | | | |
| *Ferguson WPA* | | | | | | | | | | | | |
| | | FERG3 | 21,881 | 9.91 | 14.00 | 527 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | 21.3 | | | | 286.7 | 0 | 810 | 4,751 | | |
| | 48284 | WD-3MW | | 2.04 | 3,190 | 4.4 | | | | | | |
| | 890436 | 890436 | 8.3 | <.002 | 0.004 | 8.5 | 237.2 | 0 | 20.5 | 35.1 | 0.87 | 0.2 |
| *Jerde WPA* | | | | | | | | | | | | |
| | 120874 | JER1 | 35 | 0.09 | 0.05 | 24.2 | 349 | 28.8 | 591 | 49.6 | <.07 | 0.21 |
| | 120874 | JER1 | 54.5 | 0.01 | 0.89 | 1.4 | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | 53.74 | | | | | | 491 | 99.35 | 22.66 | |
| | | JER2 | | | | | | | | | | |
| | | JER2 | | | | | | | | | | |
| | 221692 | JP-1MW | 96.7 | | | | 489.2 | 0 | 4,931 | 15,549 | | |
| | 221692 | JP-1MW | | <0.01 | 0.01 | 8.7 | | | | | | |
| | 221722 | JP-2MW | 120 | | | | 387.9 | 0 | 4,967 | 27,655 | | |
| | 221722 | JP-2MW | | <0.01 | <0.002 | 7 | | | | | | |
| | 221720 | JP-3MW | 32.3 | | | | 251.3 | 0 | 5,710 | 22,888 | | |
| | 221720 | JP-3MW | | <0.01 | 0.14 | 9.2 | | | | | | |
| *Erikson WPA* | | | | | | | | | | | | |
| | 214744 | ERK1 | 86 | | | | 1,423.7 | 349.2 | 4,100 | 298 | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | | ERK2 | | | | | | | | | | |
| | | ERK3 | | | | | | | | | | |
| | | ERK4 | | | | | | | | | | |
| | | ERK5 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK7 | | | | | | | | | | |
| *Ferguson WPA* | | | | | | | | | | | | |
| | | FERG3 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | | | | | | | | | | |
| | 48284 | WD-3MW | | | <50 | 2.38 | 184 | 105 | <0.5 | | 0.2 | <5 |
| | 890436 | 890436 | <.1 | <2 | <30 | 0 | <20 | | 0 | <100 | <2 | 0 |
| *Jerde WPA* | | | | | | | | | | | | |
| | 120874 | JER1 | | 26 | 222 | 14 | 50 | 54 | | 100 | <5 | |
| | 120874 | JER1 | | | <50 | 16.1 | 117 | 110 | <0.5 | | 0.06 | <5 |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | | JER2 | | | | | | | | | | |
| | | JER2 | | | | | | | | | | |
| | 221692 | JP-1MW | | | | | | | | | | |
| | 221692 | JP-1MW | | | <50 | 4.23 | 22,600 | 179 | <0.5 | | 2.47 | <5 |
| | 221722 | JP-2MW | | | | | | | | | | |
| | 221722 | JP-2MW | | | <50 | 5.08 | 31,400 | 270 | <0.5 | | 2.4 | <5 |
| | 221720 | JP-3MW | | | | | | | | | | |
| | 221720 | JP-3MW | | | <50 | 5.39 | 2,700 | 167 | <0.5 | | 0.38 | <5 |
| *Erikson WPA* | | | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | | ERK2 | | | | | | | | | | |
| | | ERK3 | | | | | | | | | | |
| | | ERK4 | | | | | | | | | | |
| | | ERK5 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK7 | | | | | | | | | | |
| *Ferguson WPA* | | | | | | | | | | | | |
| | | FERG3 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | | | | | | | | | | |
| | 48284 | WD-3MW | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 1.14 | 3,000 | 8 |
| | 890436 | 890436 | <2 | <2 | 0 9 | | <20 | <10 | | | 110 | <2. |
| *Jerde WPA* | | | | | | | | | | | | |
| | 120874 | JER1 | <5 | <4 | | 50 | <40 | <20 | <50 | 0.6 | 401 | <5 |
| | 120874 | JER1 | <5 | <5 | <0.1 | | <10 | <5 | 0.09 | 0.38 | 565 | <5 |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | 120874 | JER1 | | | | | | | | | | |
| | | JER2 | | | | | | | | | | |
| | | JER2 | | | | | | | | | | |
| | 221692 | JP-1MW | | | | | | | | | | |
| | 221692 | JP-1MW | <5 | 7 | <0.1 | | 10 | 14 | <0.2 | 4.57 | 19,800 | 12 |
| | 221722 | JP-2MW | | | | | | | | | | |
| | 221722 | JP-2MW | <5 | 6 | <0.1 | | 10 | 22 | <0.31 | 74.5 | 29,900 | 17 |
| | 221720 | JP-3MW | | | | | | | | | | |
| | 221720 | JP-3MW | <5 | 8 | <0.1 | | 10 | <5 | <0.2 | 248 | 23,200 | 18 |
| *Erikson WPA* | | | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | 214744 | ERK1 | | | | | | | | | | |
| | | ERK2 | | | | | | | | | | |
| | | ERK3 | | | | | | | | | | |
| | | ERK4 | | | | | | | | | | |
| | | ERK5 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK6 | | | | | | | | | | |
| | | ERK7 | | | | | | | | | | |
| *Ferguson WPA* | | | | | | | | | | | | |
| | | FERG3 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | 48284 | WD-3MW | | | | | 0.398 | |
| | 48284 | WD-3MW | | <10 | 264 | | | |
| | 890436 | 890436 | 0 | <1 | 3 | <4 | 0.070 | |
| *Jerde WPA* | | | | | | | | |
| | 120874 | JER1 | | <5 | <6 | <6 | 0.028 | |
| | 120874 | JER1 | | <10 | <5 | | | |
| | 120874 | JER1 | | | | | 0.058 | |
| | 120874 | JER1 | | | | | 0.064 | |
| | 120874 | JER1 | | | | | 0.046 | |
| | | JER2 | | | | | 0.068 | |
| | | JER2 | | | | | 0.058 | |
| | 221692 | JP-1MW | | | | | 0.476 | |
| | 221692 | JP-1MW | | <10 | 10 | | | |
| | 221722 | JP-2MW | | | | | 0.640 | |
| | 221722 | JP-2MW | | <10 | <5 | | | |
| | 221720 | JP-3MW | | | | | 0.594 | |
| | 221720 | JP-3MW | | <10 | 80 | | | |
| *Erikson WPA* | | | | | | | | |
| | 214744 | ERK1 | | | | | 0.032 | |
| | 214744 | ERK1 | | | | | 0.027 | |
| | 214744 | ERK1 | | | | | 0.028 | |
| | | ERK2 | | | | | 0.048 | |
| | | ERK3 | | | | | 0.029 | |
| | | ERK4 | | | | | 0.092 | |
| | | ERK5 | | | | | 0.037 | |
| | | ERK6 | | | | | 0.018 | |
| | | ERK6 | | | | | 0.017 | |
| | | ERK7 | | | | | 0.038 | |
| *Ferguson WPA* | | | | | | | | |
| | | FERG3 | | | | | 0.024 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | | | | |
| | | RR1 | 48.7885 | -104.1170 | | Wetla nd | | USFWS | 5/17/2004 | 25.42 | 8.7 |
| *Westgard WPA* | | | | | | | | | | | |
| | | WG1 | 48.9542 | -104.1106 | | Wetland | | USFWS | 5/16/2004 | 18.27 | 8.61 |
| | | WG1 | 48.9542 | -104.1106 | | Wetland | | USFWS | 7/23/2004 | 21.56 | 10.03 |
| | | WG2 | 48.9584 | -104.1096 | | Wetland | | USFWS | 5/16/2004 | 23.4 | 8.42 |
| | 214793 | WG3 | 48.9618 | -104.1100 | 37N58E15 | Wetland | | USFWS | 5/16/2004 | 13.23 | 7.96 |
| | 214793 | WG3 | 48.9618 | -104.1100 | 37N58E16 | Wetland | | USFWS | 9/9/2004 | 21.95 | 9.77 |
| | 214793 | WG3 | 48.9618 | -104.1100 | 37N58E17 | Wetland | | USFWS | 9/9/2004 | 21 | |
| *Dog Leg WPA* | | | | | | | | | | | |
| | 214746 | DL1 | 48.9414 | -104.1028 | 37N58E20 | Wetland | | USFWS | 7/23/2004 | 20 | |
| | 214746 | DL1 | 48.9414 | -104.1028 | 37N58E20 | Wetland | | USFWS | 7/23/2004 | 20.07 | 8.37 |
| | 214746 | DL1 | 48.9414 | -104.1028 | 37N58E20 | Wetland | | USFWS | 5/16/2004 | 17.79 | 8.36 |
| | | DL2 | 48.9466 | -104.0940 | | Wetland | | USFWS | 4/29/2004 | 14.02 | 8.89 |
| *Goose Lake WPA* | | | | | | | | | | | |
| | | GL1 | 48.8021 | -104.0769 | | Wetland | | USFWS | 5/13/2004 | 14 | 8.52 |
| | | GL1 | 48.8021 | -104.0769 | | Wetland | | USFWS | 7/8/2005 | 30.37 | 10.08 |
| | | GL1 | 48.8021 | -104.0769 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL1 | 48.8021 | -104.0769 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL2 | 48.7859 | -104.0756 | | Wetland | | USFWS | 5/14/2004 | 8.22 | 8.52 |
| | | GL3 | 48.7818 | -104.0721 | | Wetland | | USFWS | 5/14/2004 | 10.46 | 8.76 |
| | | GL3 | 48.7818 | -104.0721 | | Wetland | | USFWS | 7/9/2004 | 28.95 | 8.53 |
| | | GL3 | 48.7818 | -104.0721 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL3 | 48.7818 | -104.0721 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL6 | 48.8036 | -104.0642 | | Wetland | | USFWS | 5/13/2004 | 19.84 | 8.22 |
| | | GL7 | 48.7934 | -104.0573 | | Wetland | | USFWS | 5/13/2004 | 14.13 | 8.72 |
| | | GL7 | 48.7934 | -104.0573 | | Wetland | | USFWS | 7/8/2005 | 30.79 | 9.35 |
| | | GL7 | 48.7934 | -104.0573 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL7 | 48.7934 | -104.0573 | | Wetland | | USFWS | 7/11/2005 | | |
| | | GL8 | 48.7905 | -104.0492 | | Wetland | | USFWS | 5/13/2004 | 12.82 | 8.22 |
| | | GL8 | 48.7905 | -104.0492 | | Wetland | | USFWS | 7/8/2005 | 29.94 | 8.03 |
| | | GL9 | 48.7945 | -104.0494 | | Wetland | | USFWS | 5/13/2004 | 0.77 | 3.53 |
| | | GL11 | 48.8047 | -104.0568 | | Wetland | | USFWS | 5/13/2004 | 10.24 | 8.66 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | | | | | |
| | | RR1 | 16,309 | 12.98 | 10.44 | 560.5 | | | | | | |
| *Westgard WPA* | | | | | | | | | | | | |
| | | WG1 | 25,955 | 8.67 | 16.61 | 433 | | | | | | |
| | | WG1 | 31,520 | 16.13 | 20.14 | 444 | | | | | | |
| | | WG2 | 15,530 | 11.58 | 9.94 | 405 | | | | | | |
| | 214793 | WG3 | 11,863 | 8.94 | 7.62 | 377 | | | | | | |
| | 214793 | WG3 | 19,041 | 8.15 | 12.19 | 1,423 | | | | | | |
| | 214793 | WG3 | | | | | MBMG | 9.65 | 15,190 | 56.1 | 1,445 | 3,771 |
| *Dog Leg WPA* | | | | | | | | | | | | |
| | 214746 | DL1 | | | | | MBMG | 8.96 | 3,860 | 183 | 205 | 499 |
| | 214746 | DL1 | 3,850 | 15.28 | 2.45 | 56 | | | | | | |
| | 214746 | DL1 | 3,067 | 12.89 | 1.96 | 49.5 | | | | | | |
| | | DL2 | 38,152 | 9.31 | 24.42 | 1,547 | | | | | | |
| *Goose Lake WPA* | | | | | | | | | | | | |
| | | GL1 | 3,859 | 8.72 | 2.47 | 53 | | | | | | |
| | | GL1 | 3,702 | 10.8 | 2.37 | 39 | | | | | | |
| | | GL1 | | | | | TERL | | | 6.21 | 202 | 29,300 |
| | | GL1 | | | | | UWRBEBL | 9.52 | 60,500 | 0.1802 | 197.8295 | 29,078 |
| | | GL2 | 9,655 | 9.08 | 6.18 | 222 | | | | | | |
| | | GL3 | 5,209 | 8.14 | 3.33 | 46 | | | | | | |
| | | GL3 | 4,198 | 3.96 | 2.69 | 52 | | | | | | |
| | | GL3 | | | | | TERL | | | 17.8 | 37.4 | 1,050 |
| | | GL3 | | | | | UWRBEBL | 8.78 | 4,400 | 17.4586 | 37.5841 | 1,099 |
| | | GL6 | 277.5 | 8.03 | 0.18 | 5.3 | | | | | | |
| | | GL7 | 6,610 | 9.38 | 4.22 | 120 | | | | | | |
| | | GL7 | 8,370 | 8.76 | 5.36 | 137 | | | | | | |
| | | GL7 | | | | | TERL | | | 7.03 | 152 | 1,800 |
| | | GL7 | | | | | UWRBEBL | 9.35 | 7,850 | 6.3969 | 148.6409 | 2,050 |
| | | GL8 | 2,145 | 14.24 | 1.37 | 39 | | | | | | |
| | | GL8 | 2,532 | 3.58 | 1.62 | 52 | | | | | | |
| | | GL9 | 1,887 | 9.13 | 1.21 | 23 | | | | | | |
| | | GL11 | 1,829 | 10.58 | 1.17 | 61 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | | | | | |
| | | RR1 | | | | | | | | | | |
| *Westgard WPA* | | | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG2 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | 282 | 1 | <0.02 | <2.0 | 124.4 | 207.6 | 11,570 | 1,311 | <5 | <5 |
| *Dog Leg WPA* | | | | | | | | | | | | |
| | 214746 | DL1 | 71.1 | | | | 672.2 | 68.4 | 1,711 | 47.7 | | |
| | 214746 | DL1 | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | | DL2 | | | | | | | | | | |
| *Goose Lake WPA* | | | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | 818 | <0.01 | 0.02 | 4.4 | | | | | | |
| | | GL1 | 855.9 | | | | | | 44,285 | 4,631 | ND | |
| | | GL2 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | 96.8 | 0.1 | 0.82 | 20.9 | | | | | | |
| | | GL3 | 100.98 | | | | | | 850.93 | 41.04 | ND | |
| | | GL6 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | 106 | <0.01 | 0.39 | 1.5 | | | | | | |
| | | GL7 | 116.45 | | | | | | 4,920.74 | 132.72 | 113 | |
| | | GL8 | | | | | | | | | | |
| | | GL8 | | | | | | | | | | |
| | | GL9 | | | | | | | | | | |
| | | GL11 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | | | | | |
| | | RR1 | | | | | | | | | | |
| *Westgard WPA* | | | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG2 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | <5 | <20 | <200 | 26.4 | 3,472 | <49 | <40 | 5,860 | <20 | <40 |
| *Dog Leg WPA* | | | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | | DL2 | | | | | | | | | | |
| *Goose Lake WPA* | | | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | | | <50 | 143 | 23,100 | 14 | <0.5 | | 1.35 | <5 |
| | | GL1 | | | | | | | | | | |
| | | GL2 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | | | <50 | 92.9 | 2,540 | 109 | <0.5 | | 0.22 | <5 |
| | | GL3 | | | | | | | | | | |
| | | GL6 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | | | <50 | 19.3 | 1,490 | 7 | <0.5 | | 0.05 | <5 |
| | | GL7 | | | | | | | | | | |
| | | GL8 | | | | | | | | | | |
| | | GL8 | | | | | | | | | | |
| | | GL9 | | | | | | | | | | |
| | | GL11 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | | | | | |
| | | RR1 | | | | | | | | | | |
| *Westgard WPA* | | | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG1 | | | | | | | | | | |
| | | WG2 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | | | | | | | | | | |
| | 214793 | WG3 | <40 | <40 | | 1,438 | <200 | <40 | <40 | 81 | 461 | <20 |
| *Dog Leg WPA* | | | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | 214746 | DL1 | | | | | | | | | | |
| | | DL2 | | | | | | | | | | |
| *Goose Lake WPA* | | | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | | | | | | | | | | |
| | | GL1 | <5 | <5 | <0.1 | | <10 | 16 | <0.51 | 0.31 | 40 | <5 |
| | | GL1 | | | | | | | | | | |
| | | GL2 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | | | | | | | | | | |
| | | GL3 | <5 | <5 | <0.1 | | <10 | 11 | 0.58 | 0.43 | 410 | <5 |
| | | GL3 | | | | | | | | | | |
| | | GL6 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | | | | | | | | | | |
| | | GL7 | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | <0.1 | <25 | <5 |
| | | GL7 | | | | | | | | | | |
| | | GL8 | | | | | | | | | | |
| | | GL8 | | | | | | | | | | |
| | | GL9 | | | | | | | | | | |
| | | GL11 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| *Redhead Retreat WPA* | | | | | | | | |
| | | RR1 | | | | | 0.034 | |
| *Westgard WPA* | | | | | | | | |
| | | WG1 | | | | | 0.017 | |
| | | WG1 | | | | | 0.014 | |
| | | WG2 | | | | | 0.026 | |
| | 214793 | WG3 | | | | | 0.032 | |
| | 214793 | WG3 | | | | | 0.075 | |
| | 214793 | WG3 | <10 | <100 | <40 | <40 | 0.086 | |
| *Dog Leg WPA* | | | | | | | | |
| | 214746 | DL1 | | | | | 0.012 | |
| | 214746 | DL1 | | | | | 0.015 | |
| | 214746 | DL1 | | | | | 0.016 | |
| | | DL2 | | | | | 0.041 | |
| *Goose Lake WPA* | | | | | | | | |
| | | GL1 | | | | | 0.014 | |
| | | GL1 | | | | | 0.011 | |
| | | GL1 | | <10 | <5 | | | |
| | | GL1 | | | | | 0.077 | |
| | | GL2 | | | | | 0.023 | |
| | | GL3 | | | | | 0.009 | |
| | | GL3 | | | | | 0.012 | |
| | | GL3 | | <10 | <5 | | | |
| | | GL3 | | | | | | |
| | | GL6 | | | | | 0.019 | |
| | | GL7 | | | | | 0.018 | |
| | | GL7 | | | | | 0.016 | |
| | | GL7 | | <10 | <5 | | | |
| | | GL7 | | | | | 0.017 | |
| | | GL8 | | | | | 0.018 | |
| | | GL8 | | | | | 0.021 | |
| | | GL9 | | | | | 0.012 | |
| | | GL11 | | | | | 0.033 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GL12 | 48.8094 | -104.0543 | | Wetland | | USFWS | 5/13/2004 | 5.34 | 7.52 |
| *Gjesdal East WPA* | | | | | | | | | | | |
| | | GE1 | 48.9318 | -104.0732 | | Wetland | | USFWS | 5/17/2004 | 22.03 | 9.44 |
| | | GE2 | 48.9258 | -104.0709 | | Wetland | | USFWS | 5/17/2004 | 23.51 | 9.04 |
| *Gjesdal West WPA* | | | | | | | | | | | |
| | | GW1 | 48.8870 | -104.1721 | | Wetland | | USFWS | 5/17/2004 | 22.92 | 7.54 |
| | | GW1 | 48.8870 | -104.1721 | | Wetland | | USFWS | 6/13/2005 | | |
| | | GW1 | 48.8870 | -104.1721 | | Wetland | | USFWS | 6/13/2005 | | |
| | | GW2 | 48.8844 | -104.1833 | | Wetland | | USFWS | 5/17/2004 | 16.22 | 6.68 |
| | | GW3 | 48.8861 | -104.1807 | | Wetland | | USFWS | 5/17/2004 | 18.86 | 6.45 |
| | | GW4 | 48.8871 | -104.1741 | | Wetland | | USFWS | 5/17/2004 | 20.02 | 6.85 |
| | | GW5 | 48.8879 | -104.1721 | | Wetland | | USFWS | 5/17/2004 | 23.63 | 7.34 |
| | | GW5 | 48.8879 | -104.1721 | | Wetland | | USFWS | 6/13/2005 | | |
| | | GW5 | 48.8879 | -104.1721 | | Wetland | | USFWS | 6/13/2005 | | |
| *Olson WPA* | | | | | | | | | | | |
| | | OLS | 48.5818 | -104.1221 | | Wetland | | USFWS | 7/21/2004 | 26.43 | 8.91 |
| | | OLS | 48.5818 | -104.1221 | | Wetland | | USFWS | 9/12/2004 | 16 | 9.09 |
| | | OLS | 48.5818 | -104.1221 | | Wetland | | USFWS | 7/9/2005 | 26.98 | 8.98 |
| | | OLS | 48.5818 | -104.1221 | | Wetland | | USFWS | 7/11/2005 | | |
| | | OLS | 48.5818 | -104.1221 | | Wetland | | USFWS | 7/11/2005 | | |
| *Parry WPA* | | | | | | | | | | | |
| | | PAR1 | 48.5914 | -104.1049 | | Wetland | | USFWS | 5/14/2004 | 14.81 | 8.43 |
| | | PAR1 | 48.5914 | -104.1049 | | Wetland | | USFWS | 5/14/2004 | 14.18 | 8.62 |
| | | PAR2 | 48.5901 | -104.1020 | | Wetland | | USFWS | 5/14/2004 | 14.92 | 9.45 |
| | | PAR3 | 48.5906 | -104.0904 | | Wetland | | USFWS | 5/14/2004 | 10.62 | 8.15 |
| | | PAR3 | 48.5906 | -104.0904 | | Wetland | | USFWS | 9/2/2004 | 28.15 | 8.35 |
| | | PAR4 | 48.5879 | -104.1061 | | Wetland | | USFWS | 5/14/2004 | 11.3 | 8.45 |
| | | PAR4 | 48.5879 | -104.1061 | | Wetland | | USFWS | 9/2/2004 | 25.48 | 8.54 |
| *Rich Johnson WPA* | | | | | | | | | | | |
| | | RJ1 | 48.9547 | -104.7134 | | Wetland | | USFWS | 6/15/2005 | 28.71 | 7.52 |
| | | RJ2 | 48.9547 | -104.7179 | | Wetland | | USFWS | 6/15/2005 | 22.53 | 7.1 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GL12 | 3,024 | 8.23 | 1.93 | 78 | | | | | | |
| *Gjesdal East WPA* | | | | | | | | | | | | |
| | | GE1 | 8,150 | 12 | 5.22 | 405.5 | | | | | | |
| | | GE2 | 2,740 | 9.02 | 1.75 | 49.5 | | | | | | |
| *Gjesdal West WPA* | | | | | | | | | | | | |
| | | GW1 | 754 | 7.13 | 0.48 | 123 | | | | | | |
| | | GW1 | | | | | TERL | | | 19.9 | 9.77 | <100 |
| | | GW1 | | | | | UWRBEBL | 7.53 | 521 | 20.9319 | 10.5145 | 49.83 |
| | | GW2 | 179.3 | 1.75 | 0.11 | no data | | | | | | |
| | | GW3 | 120.9 | 3.19 | 0.08 | 4.4 | | | | | | |
| | | GW4 | 166 | 3.25 | 0.11 | 0 | | | | | | |
| | | GW5 | 94.4 | 10.87 | 0.06 | 4.4 | | | | | | |
| | | GW5 | | | | | TERL | | | 14.1 | 5 | <100 |
| | | GW5 | | | | | UWRBEBL | 7.09 | 156 | 13.19 | 4.82 | 1.07 |
| *Olson WPA* | | | | | | | | | | | | |
| | | OLS | 4,314 | 7.06 | 2.75 | 30 | | | | | | |
| | | OLS | 4,772 | 7.1 | 3.05 | 33 | | | | | | |
| | | OLS | 4,602 | 9.12 | 2.95 | 33 | | | | | | |
| | | OLS | | | | | TERL | | | 4.69 | 211 | 864 |
| | | OLS | | | | | UWRBEBL | 9.26 | 4310 | 4.14 | 198.25 | 937 |
| *Parry WPA* | | | | | | | | | | | | |
| | | PAR1 | 4,902 | 6.22 | 3.13 | 53 | | | | | | |
| | | PAR1 | 4,680 | 10.09 | 3.00 | 53 | | | | | | |
| | | PAR2 | 55,185 | 7.11 | 35.32 | 1547 | | | | | | |
| | | PAR3 | 4,351 | 8.59 | 2.79 | 61 | | | | | | |
| | | PAR3 | 5,928 | 5.41 | 3.80 | 84 | | | | | | |
| | | PAR4 | 2,669 | 10.25 | 1.71 | 27 | | | | | | |
| | | PAR4 | 3,396 | 6.84 | 2.17 | 30.5 | | | | | | |
| *Rich Johnson WPA* | | | | | | | | | | | | |
| | | RJ1 | 3,593 | 3.66 | 2.30 | 45 | | | | | | |
| | | RJ2 | 3,298 | 4.25 | 2.11 | 39 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GL12 | | | | | | | | | | |
| *Gjesdal East WPA* | | | | | | | | | | | | |
| | | GE1 | | | | | | | | | | |
| | | GE2 | | | | | | | | | | |
| *Gjesdal West WPA* | | | | | | | | | | | | |
| | | GW1 | | | | | | | | | | |
| | | GW1 | 42.9 | 0.241 | 0.1 | 16.7 | | | | | | |
| | | GW1 | 43.23 | | | | | | 16.59 | 78.11 | 1.13 | |
| | | GW2 | | | | | | | | | | |
| | | GW3 | | | | | | | | | | |
| | | GW4 | | | | | | | | | | |
| | | GW5 | | | | | | | | | | |
| | | GW5 | 35.8 | 0.07 | 0.8 | 9.2 | | | | | | |
| | | GW5 | 35.3 | | | | | | 4.71 | 3.85 | 3.64 | |
| *Olson WPA* | | | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | 77.2 | <0.01 | 0.01 | 3.2 | | | | | | |
| | | OLS | 78.8 | | | | | | 1,162.62 | 22.56 | ND | |
| *Parry WPA* | | | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR2 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| *Rich Johnson WPA* | | | | | | | | | | | | |
| | | RJ1 | | | | | | | | | | |
| | | RJ2 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GL12 | | | | | | | | | | |
| *Gjesdal East WPA* | | | | | | | | | | | | |
| | | GE1 | | | | | | | | | | |
| | | GE2 | | | | | | | | | | |
| *Gjesdal West WPA* | | | | | | | | | | | | |
| | | GW1 | | | | | | | | | | |
| | | GW1 | | | <50 | 2.53 | 403 | 65 | <0.5 | | 0.51 | <5 |
| | | GW1 | | | | | | | | | | |
| | | GW2 | | | | | | | | | | |
| | | GW3 | | | | | | | | | | |
| | | GW4 | | | | | | | | | | |
| | | GW5 | | | | | | | | | | |
| | | GW5 | | | 60 | 1.29 | 90 | 54 | <0.5 | | 0.15 | <5 |
| | | GW5 | | | | | | | | | | |
| *Olson WPA* | | | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | <50 | 18.7 | 2,250 | 4 | <0.5 | | 0.06 | <5 |
| | | OLS | | | | | | | | | | |
| *Parry WPA* | | | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR2 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| *Rich Johnson WPA* | | | | | | | | | | | | |
| | | RJ1 | | | | | | | | | | |
| | | RJ2 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GL12 | | | | | | | | | | |
| *Gjesdal East WPA* | | | | | | | | | | | | |
| | | GE1 | | | | | | | | | | |
| | | GE2 | | | | | | | | | | |
| *Gjesdal West WPA* | | | | | | | | | | | | |
| | | GW1 | | | | | | | | | | |
| | | GW1 | <5 | <5 | <0.1 | | <10 | <5 | 0.21 | 0.28 | 190 | <5 |
| | | GW1 | | | | | | | | | | |
| | | GW2 | | | | | | | | | | |
| | | GW3 | | | | | | | | | | |
| | | GW4 | | | | | | | | | | |
| | | GW5 | | | | | | | | | | |
| | | GW5 | <5 | <5 | <0.1 | | <10 | <5 | 0.31 | 0.83 | 30 | <5 |
| | | GW5 | | | | | | | | | | |
| *Olson WPA* | | | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | | | | | | | | | | |
| | | OLS | <5 | <5 | <0.1 | | <10 | <5 | <0.02 | <0.1 | <25 | <5 |
| | | OLS | | | | | | | | | | |
| *Parry WPA* | | | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR1 | | | | | | | | | | |
| | | PAR2 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR3 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| | | PAR4 | | | | | | | | | | |
| *Rich Johnson WPA* | | | | | | | | | | | | |
| | | RJ1 | | | | | | | | | | |
| | | RJ2 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | | GL12 | | | | | 0.026 | |
| *Gjesdal East WPA* | | | | | | | | |
| | | GE1 | | | | | 0.050 | |
| | | GE2 | | | | | 0.018 | |
| *Gjesdal West WPA* | | | | | | | | |
| | | GW1 | | | | | 0.163 | |
| | | GW1 | | <10 | 12 | | | |
| | | GW1 | | | | | 0.150 | |
| | | GW2 | | | | | | |
| | | GW3 | | | | | 0.036 | |
| | | GW4 | | | | | 0.000 | |
| | | GW5 | | | | | 0.047 | |
| | | GW5 | | <10 | 26 | | | |
| | | GW5 | | | | | 0.025 | |
| *Olson WPA* | | | | | | | | |
| | | OLS | | | | | 0.007 | |
| | | OLS | | | | | 0.007 | |
| | | OLS | | | | | 0.007 | |
| | | OLS | | <10 | <5 | | | |
| | | OLS | | | | | 0.005 | |
| *Parry WPA* | | | | | | | | |
| | | PAR1 | | | | | 0.011 | |
| | | PAR1 | | | | | 0.011 | |
| | | PAR2 | | | | | 0.028 | |
| | | PAR3 | | | | | 0.014 | |
| | | PAR3 | | | | | 0.014 | |
| | | PAR4 | | | | | 0.010 | |
| | | PAR4 | | | | | 0.009 | |
| *Rich Johnson WPA* | | | | | | | | |
| | | RJ1 | | | | | 0.013 | |
| | | RJ2 | | | | | 0.012 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RJ4 | 48.9567 | -104.7235 | | Wetland | | USFWS | 6/15/2005 | 20.46 | 7.48 |
| *Rivers WPA* | | | | | | | | | | | |
| | | RIV1 | 48.8005 | -104.1672 | | Wetland | | USFWS | 4/27/2004 | 8.88 | 7.35 |
| | | RIV1 | 48.8005 | -104.1672 | | Wetland | | USFWS | 6/13/2005 | | |
| | | RIV1 | 48.8005 | -104.1672 | | Wetland | | USFWS | 6/13/2005 | | |
| *Shoveler Puddle WPA* | | | | | | | | | | | |
| | | SP1 | 48.9838 | -104.3108 | | Wetland | | USFWS | 6/14/2005 | | |
| *State Line WPA* | | | | | | | | | | | |
| | | SL1 | 48.9094 | -104.0671 | | Wetland | | USFWS | 5/13/2004 | 10.62 | 8.12 |
| | | SL1 | 48.9094 | -104.0671 | | Wetland | | USFWS | 7/8/2005 | 35.01 | 8.99 |
| | | SL2 | 48.9090 | -104.0600 | | Wetland | | USFWS | 7/11/2005 | | |
| | | SL2 | 48.9090 | -104.0600 | | Wetland | | USFWS | 7/11/2005 | | |
| | | SL3 | 48.9061 | -104.0607 | | Wetland | | USFWS | 5/13/2004 | 13.2 | 8.27 |
| | | SL3 | 48.9061 | -104.0607 | | Wetland | | USFWS | 7/8/2005 | 32.59 | 7.64 |
| | | SL3 | 48.9061 | -104.0607 | | Wetland | | USFWS | 7/11/2005 | | |
| | | SL3 | 48.9061 | -104.0607 | | Wetland | | USFWS | 7/11/2005 | | |
| | | SL3A | 48.9057 | -104.0635 | | Wetland | | USFWS | 9/10/2004 | 18.58 | 8.03 |
| | | SL4 | 48.9050 | -104.0755 | | Wetland | | USFWS | 9/10/2004 | 19.73 | 8.61 |
| | | SL5 | 48.9039 | -104.0777 | | Wetland | | USFWS | 9/10/2004 | 23.27 | 8.73 |
| | | SL6 | 48.9000 | -104.0511 | | Wetland | | USFWS | 7/25/2004 | 24.44 | 8.84 |
| | | SL6 | 48.9000 | -104.0511 | | Wetland | | USFWS | 9/11/2004 | 13.56 | 9.11 |
| | | SL6 | 48.9000 | -104.0511 | | Wetland | | USFWS | 7/8/2005 | 27.23 | 8.98 |
| | | SL6 | 48.9000 | -104.0511 | | Wetland | | USFWS | 7/11/2005 | | |
| | | SL6 | 48.9000 | -104.0511 | | Wetland | | USFWS | 7/11/2005 | | |
| *Wigeon Slough WPA* | | | | | | | | | | | |
| | | WS1 | 48.9748 | -104.2362 | | Wetland | | USFWS | 4/28/2004 | 5.33 | 8.51 |
| | | WS1 | 48.9748 | -104.2362 | | Wetland | | USFWS | 6/13/2005 | | |
| | | WS2 | 48.9779 | -104.2375 | | Wetland | | USFWS | 9/14/2004 | 18.32 | 9.98 |
| | | WS3 | | | | Wetland | | USFWS | | | |
| | | WS4 | 48.9772 | -104.2533 | | Wetland | | USFWS | 4/28/2004 | 7.69 | 8.52 |
| | | WS5A | 48.9690 | -104.2546 | | Wetland | | USFWS | 4/28/2004 | 8.83 | 8.8 |
| | | WS6 | 48.9689 | -104.2505 | | Wetland | | USFWS | 4/28/2004 | 6.23 | 7.84 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RJ4 | 3,244 | 5.32 | 2.08 | 68 | | | | | | |
| *Rivers WPA* | | | | | | | | | | | | |
| | | RIV1 | 326 | 5.47 | 0.21 | 15 | | | | | | |
| | | RIV1 | | | | | TERL | | | 71.8 | 36.6 | <100 |
| | | RIV1 | | | | | UWRBEBL | 7.88 | 1,090 | 77.05 | 39.75 | 28.07 |
| *Shoveler Puddle WPA* | | | | | | | | | | | | |
| | | SP1 | | | | | | | | | | |
| *State Line WPA* | | | | | | | | | | | | |
| | | SL1 | 9,228 | 8.19 | 5.91 | 222 | | | | | | |
| | | SL1 | 21,460 | 14.55 | 13.74 | 1,335.5 | | | | | | |
| | | SL2 | | | | | TERL | | | 64 | 71.1 | 1,650 |
| | | SL2 | | | | | | 7.98 | 7,040 | 68.5 | 71.69 | 1,796 |
| | | SL3 | 2,988 | 11.11 | 1.91 | 39 | | | | | | |
| | | SL3 | 5,846 | 7.96 | 3.74 | 77 | | | | | | |
| | | SL3 | | | | | TERL | | | 134 | 110 | 1,160 |
| | | SL3 | | | | | UWRBEBL | 6.46 | 5,710 | 140.81 | 106.77 | 1,197 |
| | | SL3A | 6,260 | 6.05 | 4.01 | 68 | | | | | | |
| | | SL4 | 22,648 | 3.45 | 14.49 | 1,678 | | | | | | |
| | | SL5 | 23,569 | 10.79 | 15.09 | 1,547 | | | | | | |
| | | SL6 | 7,155 | 10.05 | 4.58 | 77 | | | | | | |
| | | SL6 | 8,713 | 8.97 | 5.58 | 86 | | | | | | |
| | | SL6 | 7,371 | 8.7 | 4.72 | 72.5 | | | | | | |
| | | SL6 | | | | | TERL | | | 16.8 | 133 | 1,600 |
| | | SL6 | | | | | UWRBEBL | 9.02 | 6,890 | 16.87 | 131.53 | 1,755 |
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS1 | 6,145 | 12 | 3.93 | 205 | | | | | | |
| | | WS1 | | | | | UWRBEBL | 8.88 | 14,160 | 441.88 | 1,502.35 | 2,384.47 |
| | | WS2 | 2,191 | 16.43 | 1.40 | 106 | | | | | | |
| | | WS3 | | | | | | | | | | |
| | | WS4 | 4,251 | 8.12 | 2.72 | 109 | | | | | | |
| | | WS5A | 2607 | 6.11 | 1.67 | 39 | | | | | | |
| | | WS6 | 2972 | 10.59 | 1.90 | 30 | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RJ4 | | | | | | | | | | |
| *Rivers WPA* | | | | | | | | | | | | |
| | | RIV1 | | | | | | | | | | |
| | | RIV1 | 135 | 0.18 | 6.53 | 7.9 | | | | | | |
| | | RIV1 | 137.32 | | | | | | 185 | 24.39 | 17.02 | |
| *Shoveler Puddle WPA* | | | | | | | | | | | | |
| | | SP1 | | | | | | | | | | |
| *State Line WPA* | | | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL2 | 33.6 | 0.08 | <0.002 | 19 | | | | | | |
| | | SL2 | 36.2 | | | | | | 3,232.03 | 101.54 | 85.19 | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | 30 | 0.28 | 0.006 | 10 | | | | | | |
| | | SL3 | 31.79 | | | | | | 2,861.61 | 68.16 | 285 | |
| | | SL3A | | | | | | | | | | |
| | | SL4 | | | | | | | | | | |
| | | SL5 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | 34.4 | <0.01 | 1.17 | 6.5 | | | | | | |
| | | SL6 | 37.85 | | | | | | 3,316.85 | 56.64 | 22.34 | |
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS1 | | | | | | | | | | |
| | | WS1 | 237.35 | | | | | | 10,579 | 537 | ND | |
| | | WS2 | | | | | | | | | | |
| | | WS3 | | | | | | | | | | |
| | | WS4 | | | | | | | | | | |
| | | WS5A | | | | | | | | | | |
| | | WS6 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RJ4 | | | | | | | | | | |
| *Rivers WPA* | | | | | | | | | | | | |
| | | RIV1 | | | | | | | | | | |
| | | RIV1 | | | <50 | 8.06 | 101 | 168 | <0.5 | | 0.21 | <5 |
| | | RIV1 | | | | | | | | | | |
| *Shoveler Puddle WPA* | | | | | | | | | | | | |
| | | SP1 | | | | | | | | | | |
| *State Line WPA* | | | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL2 | | | <50 | 15.5 | 1,760 | 105 | <0.5 | | 0.09 | <5 |
| | | SL2 | | | | | | | | | | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | | | <50 | 4.12 | 670 | 72 | <0.5 | | <0.05 | <5 |
| | | SL3 | | | | | | | | | | |
| | | SL3A | | | | | | | | | | |
| | | SL4 | | | | | | | | | | |
| | | SL5 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | <50 | 12.5 | 1,770 | 8 | <0.5 | | 0.06 | <5 |
| | | SL6 | | | | | | | | | | |
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS1 | | | | | | | | | | |
| | | WS1 | | | | | | | | | | |
| | | WS2 | | | | | | | | | | |
| | | WS3 | | | | | | | | | | |
| | | WS4 | | | | | | | | | | |
| | | WS5A | | | | | | | | | | |
| | | WS6 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RJ4 | | | | | | | | | | |
| *Rivers WPA* | | | | | | | | | | | | |
| | | RIV1 | | | | | | | | | | |
| | | RIV1 | <5 | <5 | <0.1 | | <10 | <5 | 0.13 | 0.23 | 165 | <5 |
| | | RIV1 | | | | | | | | | | |
| *Shoveler Puddle WPA* | | | | | | | | | | | | |
| | | SP1 | | | | | | | | | | |
| *State Line WPA* | | | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL1 | | | | | | | | | | |
| | | SL2 | <5 | <5 | <0.1 | | <10 | <5 | 0.52 | 1.16 | 1,000 | <5 |
| | | SL2 | | | | | | | | | | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | | | | | | | | | | |
| | | SL3 | <5 | <5 | <0.1 | | <10 | <5 | 0.13 | 0.47 | 1,300 | <5 |
| | | SL3 | | | | | | | | | | |
| | | SL3A | | | | | | | | | | |
| | | SL4 | | | | | | | | | | |
| | | SL5 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | | | | | | | | | | |
| | | SL6 | <5 | <5 | <0.1 | | <10 | <5 | <0.05 | 0.13 | 245 | <5 |
| | | SL6 | | | | | | | | | | |
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS1 | | | | | | | | | | |
| | | WS1 | | | | | | | | | | |
| | | WS2 | | | | | | | | | | |
| | | WS3 | | | | | | | | | | |
| | | WS4 | | | | | | | | | | |
| | | WS5A | | | | | | | | | | |
| | | WS6 | | | | | | | | | | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| | | RJ4 | | | | | 0.021 | |
| *Rivers WPA* | | | | | | | | |
| | | RIV1 | | | | | 0.046 | |
| | | RIV1 | | <10 | <5 | | | |
| | | RIV1 | | | | | 0.022 | |
| *Shoveler Puddle WPA* | | | | | | | | |
| | | SP1 | | | | | | dry |
| *State Line WPA* | | | | | | | | |
| | | SL1 | | | | | 0.024 | |
| | | SL1 | | | | | 0.062 | |
| | | SL2 | | <10 | 5 | | | |
| | | SL2 | | | | | | |
| | | SL3 | | | | | 0.013 | |
| | | SL3 | | | | | 0.013 | |
| | | SL3 | | <10 | 12 | | | |
| | | SL3 | | | | | | |
| | | SL3A | | | | | 0.011 | |
| | | SL4 | | | | | 0.074 | |
| | | SL5 | | | | | 0.066 | |
| | | SL6 | | | | | 0.011 | |
| | | SL6 | | | | | 0.010 | |
| | | SL6 | | | | | 0.010 | |
| | | SL6 | | <10 | <5 | | | |
| | | SL6 | | | | | 0.008 | |
| *Wigeon Slough WPA* | | | | | | | | |
| | | WS1 | | | | | 0.033 | |
| | | WS1 | | | | | | |
| | | WS2 | | | | | 0.048 | |
| | | WS3 | | | | | | |
| | | WS4 | | | | | 0.026 | |
| | | WS5A | | | | | 0.015 | |
| | | WS6 | | | | | 0.010 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | | | | |
| | | WS7 | 48.9739 | -104.2469 | | Wetland | | USFWS | 4/28/2004 | 7.15 | 8.29 |
| | | WS8 | 48.9751 | -104.2497 | | Wetland | | USFWS | 5/16/2004 | 22.41 | 9.32 |
| *Non-WPA Sites* | | | | | | | | | | | |
| | 3774 | 1986Q0957 | 48.5341 | -104.1722 | 32N58E10CCCC | Well | 210 | MBMG | 6/10/1986 | 0 | |
| | 4148 | 1985Q0832 | 48.8727 | -104.0486 | 36N58E13DADD | Well | 69 | MBMG | 7/23/1985 | 8.9 | |
| | 4149 | 1973Q0402 | 48.8277 | -104.1330 | 36N58E33CCB | Well | 0 | MBMG | 7/1/1973 | 0 | |
| | 206548 | 2003-09 | 48.5593 | -104.1396 | 32N59E2ABCC | Well | 180 | MBMG | 12/12/2003 | 7.81 | |
| | 206548 | 2003-09 | 48.5593 | -104.1396 | 32N59E2ABCC | Well | 180 | MBMG | 9/11/2005 | 9.3 | |
| | 890422 | 1989Q0485 | 48.7961 | -104.1436 | 35N58E8DDDA | Well | 42 | MBMG | 4/19/1989 | 5.5 | |
| | 890423 | 1989Q0486 | 48.7900 | -104.1452 | 35N58E17ADAC | Well | 23 | MBMG | 4/19/1989 | 4.5 | |
| | 890424 | 1989Q0487 | 48.7913 | -104.1450 | 35N58E17AADC | Well | 36 | MBMG | 4/19/1989 | 1 | |
| | 890425 | 1989Q0488 | 48.7908 | -104.1452 | 35N58E17ADAB | Well | 28 | MBMG | 4/19/1989 | 6 | |
| | 890426 | 1989Q0489 | 48.8565 | -104.1145 | 36N58E22CBDA | Well | 38 | MBMG | 4/21/1989 | 9 | |
| | 890427 | 1989Q0490 | 48.8558 | -104.1158 | 36N58E22CDBB | Well | 43 | MBMG | 4/21/1989 | 8.7 | |
| | 890428 | 1989Q0491 | 48.8516 | -104.1086 | 36N58E27ABBD | Well | 22 | MBMG | 4/20/1989 | 9 | |
| | 890429 | 1989Q0492 | 48.8511 | -104.1044 | 36N58E27AABC | Well | 8 | MBMG | 4/21/1989 | 6.9 | |
| | 890430 | 1989Q0493 | 48.8502 | -104.1183 | 36N58E27BBCA | Well | 27 | MBMG | 4/1/1989 | 8.2 | |
| | 890431 | 1989Q0494 | 48.8502 | -104.1177 | 36N58E27BBDC | Well | 33 | MBMG | 4/20/1989 | 8.9 | |
| | 890432 | 1989Q0495 | 48.8525 | -104.1116 | 36N58E27BAAB | Well | 17 | MBMG | 4/20/1989 | 8.2 | |
| | 890433 | 1989Q0496 | 48.8522 | -104.1105 | 36N58E27BAAA | Well | 23 | MBMG | 4/20/1989 | 8.5 | |
| | 890434 | 1989Q0497 | 48.8361 | -104.1386 | 36N58E33BBDA | Well | 27 | MBMG | 4/20/1989 | 7 | |
| | 890435 | 1989Q0498 | 48.9841 | -104.2288 | 37N57E5DCDA | Well | 18 | MBMG | 4/22/1989 | 7.7 | |
| | 890437 | 1989Q0500 | 48.9886 | -104.1250 | 37N58E6CAAC | Well | 43 | MBMG | 4/21/1989 | 9.8 | |
| | 890438 | 1989Q0501 | 48.7027 | -104.0905 | 34N58E14BDAC | Well | 32 | MBMG | 4/18/1989 | 8.2 | |
| | 890439 | 1989Q0502 | 48.7033 | -104.0913 | 34N58E14BDBD | Well | 32 | MBMG | 4/18/1989 | 7.9 | |
| | 890440 | 1989Q0503 | 48.6994 | -104.0863 | 34N58E14DBBD | Well | 31 | MBMG | 4/18/1989 | 7.8 | |
| | 890441 | 1989Q0504 | 48.6988 | -104.0866 | 34N58E14DBBD | Well | 30 | MBMG | 4/18/1989 | 7.8 | |
| | 890442 | 1989Q0505 | 48.7955 | -104.1358 | 35N58E9CDCD | Well | 32 | MBMG | 4/19/1989 | 5 | |
| | 890443 | 1989Q0506 | 48.7963 | -104.1361 | 35N58E9CDCA | Well | 28 | MBMG | 4/19/1989 | 5 | |
| | 890444 | 1989Q0507 | 48.8272 | -104.1452 | 36N58E32DDAB | Well | 33 | MBMG | 4/20/1989 | 9 | |
| | 890927 | 1989Q1376 | 48.8558 | -104.1158 | 36N58E22CDBB | Well | 43 | MBMG | 10/11/1989 | 11.4 | |
| | 890928 | 1989Q1377 | 48.8511 | -104.1063 | 36N58E27ABAC | Well | 18 | MBMG | 10/12/1989 | 14.2 | |
| | 890929 | 1989Q1378 | 48.8513 | -104.1077 | 36N58E27ABBD | Well | 20.5 | MBMG | 10/17/1989 | 15.9 | |
| | 890930 | 1989Q1379 | 48.8505 | -104.1063 | 36N58E27ABDB | Well | 17 | MBMG | 10/12/1989 | 15.9 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS7 | 5,895 | 7.17 | 3.77 | 189 | | | | | | |
| | | WS8 | 25,072 | 11.16 | 16.05 | 349 | | | | | | |
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 3774 | 1986Q0957 | | | | | MBMG | 7.59 | 1,522 | 171 | 73.2 | 60.5 |
| | 4148 | 1985Q0832 | | | | | MBMG | 7.52 | 1,375 | 115 | 47.8 | 139 |
| | 4149 | 1973Q0402 | | | | | MBMG | 7.44 | 331 | 1,663 | 857 | 5,000 |
| | 206548 | 2003-09 | | | | | MBMG | 7.81 | 2,160 | 84.2 | 48.9 | 369 |
| | 206548 | 2003-09 | | | | | MBMG | 7.58 | 2,150 | 79.4 | 45.9 | 404 |
| | 890422 | 1989Q0485 | | | | | MBMG | 6.88 | 61,872.9 | 4,120 | 6,120 | 3,920 |
| | 890423 | 1989Q0486 | | | | | MBMG | 6.76 | 10,879 | 7,270 | 6,250 | 23,000 |
| | 890424 | 1989Q0487 | | | | | MBMG | 7.67 | 4,598.9 | 514 | 276 | 496 |
| | 890425 | 1989Q0488 | | | | | MBMG | 7 | 71,781.6 | 3,230 | 4,370 | 20,200 |
| | 890426 | 1989Q0489 | | | | | MBMG | 7.31 | 3,249.9 | 405 | 122 | 157 |
| | 890427 | 1989Q0490 | | | | | MBMG | 7.55 | 1,829.7 | 226 | 76.5 | 119 |
| | 890428 | 1989Q0491 | | | | | MBMG | 7.36 | 18,850.3 | 988 | 412 | 2,640 |
| | 890429 | 1989Q0492 | | | | | MBMG | 7.3 | 29,096.4 | 501 | 193 | 6,180 |
| | 890430 | 1989Q0493 | | | | | MBMG | 7.65 | 1,202.6 | 142 | 66.5 | 27.6 |
| | 890431 | 1989Q0494 | | | | | MBMG | 7.34 | 1,111.6 | 128 | 46.4 | 57 |
| | 890432 | 1989Q0495 | | | | | MBMG | 7.45 | 6,232.7 | 66.9 | 31.7 | 719 |
| | 890433 | 1989Q0496 | | | | | MBMG | 7.08 | 59,537.8 | 2,120 | 1,120 | 11,100 |
| | 890434 | 1989Q0497 | | | | | MBMG | 7.14 | 71,208 | 3,330 | 4,290 | 10,600 |
| | 890435 | 1989Q0498 | | | | | MBMG | 7.4 | 88,377 | 8,940 | 3,080 | 12,800 |
| | 890437 | 1989Q0500 | | | | | MBMG | 7.52 | 6,280.2 | 452 | 287 | 879 |
| | 890438 | 1989Q0501 | | | | | MBMG | 7.87 | 3,540.6 | 311 | 150 | 161 |
| | 890439 | 1989Q0502 | | | | | MBMG | 7.93 | 1,581.4 | 140 | 88.1 | 29.3 |
| | 890440 | 1989Q0503 | | | | | MBMG | 7.9 | 412 | 52.7 | 14.5 | 5.6 |
| | 890441 | 1989Q0504 | | | | | MBMG | 6.97 | 8,425.3 | 488 | 84.8 | 1060 |
| | 890442 | 1989Q0505 | | | | | MBMG | 6.93 | 70,990.4 | 5,380 | 2,910 | 32,500 |
| | 890443 | 1989Q0506 | | | | | MBMG | 6.92 | 6,923 | 3,720 | 4,080 | 39,500 |
| | 890444 | 1989Q0507 | | | | | MBMG | 7.1 | 95,261 | 3,630 | 1,090 | 21,600 |
| | 890927 | 1989Q1376 | | | | | MBMG | 7.73 | 2,213.3 | 200 | 83.6 | 132 |
| | 890928 | 1989Q1377 | | | | | MBMG | 7.44 | 4,448 | 1,190 | 410 | 9,420 |
| | 890929 | 1989Q1378 | | | | | MBMG | 7.49 | 2,255.7 | 790 | 240 | 6,500 |
| | 890930 | 1989Q1379 | | | | | MBMG | 7.67 | 8,817.1 | 180 | 62.54 | 1,590 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS7 | | | | | | | | | | |
| | | WS8 | | | | | | | | | | |
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 3774 | 1986Q0957 | 5.1 | 2.84 | 0.41 | 30.6 | 422 | 0 | 497 | 7.1 | 0.09 | 0.3 |
| | 4148 | 1985Q0832 | 6.1 | 1.63 | 0.41 | 26.1 | 418 | 0 | 356 | 39.6 | 5.87 | 0.3 |
| | 4149 | 1973Q0402 | 32 | 0.09 | 1.42 | 9.2 | 272 | 0 | 413 | 12,770 | <.023 | <.1 |
| | 206548 | 2003-09 | 7.26 | 4.99 | 0.15 | 24.5 | 1209 | 0 | 291 | 51.8 | <0.5 | <0.5 |
| | 206548 | 2003-09 | 7.24 | | | | 1,138.3 | 0 | 262 | 47.4 | | |
| | 890422 | 1989Q0485 | 66.6 | <.002 | 4.89 | 13.5 | 397 | 0 | 2030 | 30,200 | 1.7 | 2 |
| | 890423 | 1989Q0486 | 219 | <.002 | 0.06 | 14.2 | 256.7 | 0 | 540 | 65,800 | 14 | 2 |
| | 890424 | 1989Q0487 | 18.2 | <.002 | 1.17 | 15.2 | 697 | 0 | 2700 | 81 | 0.35 | 0.1 |
| | 890425 | 1989Q0488 | 216 | <.002 | 3 | 13.6 | 325 | 0 | 2840 | 46,400 | 6.51 | 1 |
| | 890426 | 1989Q0489 | 11.4 | 7.87 | 0.97 | 24.3 | 626 | 0 | 1330 | 10.2 | 0.04 | 0.3 |
| | 890427 | 1989Q0490 | 9.5 | 0.77 | 0.86 | 22.5 | 591.5 | 0 | 633 | 17.1 | 0.05 | 0.4 |
| | 890428 | 1989Q0491 | 45.1 | 0.02 | 3.8 | 16.4 | 252.3 | 0 | 144 | 6,680 | 2.22 | <1 |
| | 890429 | 1989Q0492 | 110 | 0.02 | 0.01 | 15.4 | 304 | 0 | 234 | 10,600 | 12 | <1 |
| | 890430 | 1989Q0493 | 6 | 0.93 | 0.57 | 23.2 | 344 | 0 | 370 | 26 | 0.05 | 0.3 |
| | 890431 | 1989Q0494 | 7.7 | 0.26 | 1.44 | 22.7 | 381 | 0 | 258 | 56.5 | 0.03 | 0.3 |
| | 890432 | 1989Q0495 | 12 | 0.002 | 0.17 | 19.4 | 325 | 0 | 111 | 1,060 | 3.12 | 0.3 |
| | 890433 | 1989Q0496 | 162 | 0.01 | 3.95 | 16.3 | 258.7 | 0 | 116 | 23,600 | 32 | <2 |
| | 890434 | 1989Q0497 | 74.9 | <.002 | 3.96 | 15.3 | 204.5 | 0 | 2840 | 33,200 | 1.6 | 1 |
| | 890435 | 1989Q0498 | 275 | <.002 | 0.05 | 12.2 | 259.6 | 0 | 121 | 44,300 | 9.7 | 0.2 |
| | 890437 | 1989Q0500 | 18.5 | 0.43 | 1.59 | 22.7 | 893 | 0 | 3140 | 177 | 0.03 | 0.1 |
| | 890438 | 1989Q0501 | 7.2 | 1.26 | 0.11 | 28.9 | 335 | 0 | 291 | 773 | 26.9 | 0.3 |
| | 890439 | 1989Q0502 | 3.3 | 0.06 | 0.01 | 26.6 | 355 | 0 | 343 | 18.6 | 29.2 | 0.2 |
| | 890440 | 1989Q0503 | 2.1 | <.002 | 0.002 | 19.9 | 195.7 | 0 | 10 | 14 | 2.81 | 0.05 |
| | 890441 | 1989Q0504 | 39.3 | 0.032 | 0.59 | 20.9 | 209.8 | 0 | 24 | 2,570 | 16.1 | 0.1 |
| | 890442 | 1989Q0505 | 395 | <.002 | 1.62 | 11 | 290 | 0 | 1890 | 68,000 | 1 | 1 |
| | 890443 | 1989Q0506 | 301 | <.002 | 1.84 | 11.1 | 240.1 | 0 | 1630 | 78,600 | 0.4 | 1 |
| | 890444 | 1989Q0507 | 60.8 | 0.37 | 1.96 | 14.4 | 276.2 | 0 | 197 | 42,300 | 17 | <5 |
| | 890927 | 1989Q1376 | 11 | <.004 | 0.03 | 25.1 | 605 | 0 | 612 | 13.9 | 0.12 | 0.1 |
| | 890928 | 1989Q1377 | 202 | 1.28 | 5.71 | 20 | 325 | 0 | 268 | 18,000 | 27.43 | 0.06 |
| | 890929 | 1989Q1378 | 154 | <.004 | 0.75 | 22.8 | 270 | 0 | 177 | 12,000 | 0.07 | 0.9 |
| | 890930 | 1989Q1379 | 54.57 | <.004 | 0.42 | 23.8 | 353 | 0 | 183 | 2,650 | 9.7 | 0.9 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS7 | | | | | | | | | | |
| | | WS8 | | | | | | | | | | |
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 3774 | 1986Q0957 | <.1 | <2. | <30 | 0 | 190 | | 0 | 100 | <2 | 0 |
| | 4148 | 1985Q0832 | <.1 | | | 7.5 | | | 0 | 200 | | 0 |
| | 4149 | 1973Q0402 | | | | 0 | | | 0 | | | 0 |
| | 206548 | 2003-09 | <0.5 | <5 | <30 | 13.3 | 255 | 27.3 | <2 | 942 | <1 | <2 |
| | 206548 | 2003-09 | | | | | | | | | | |
| | 890422 | 1989Q0485 | 0.4 | <2 | <30 | 0 | 330 | | 0 | <100 | 66 | 0 |
| | 890423 | 1989Q0486 | <1 | 6 | <30 | 0 | 290 | | 0 | <100 | 96 | 0 |
| | 890424 | 1989Q0487 | <.1 | <2 | <30 | 0 | 410 | | 0 | 700 | <2 | 0 |
| | 890425 | 1989Q0488 | <1 | <2 | <30 | 0 | 9,760 | | 0 | <100 | 63 | 0 |
| | 890426 | 1989Q0489 | <.1 | <2 | 110 | 0 | 570 | | 0 | <100 | <2 | 0 |
| | 890427 | 1989Q0490 | <.1 | <2 | <30 | 0 | 530 | | 0 | 200 | <2 | 0 |
| | 890428 | 1989Q0491 | <.1 | <2 | 100 | 0 | 5,750 | | 0 | <100 | 13 | 0 |
| | 890429 | 1989Q0492 | <.1 | <2 | <30 | 0 | 17,500 | | 0 | <100 | <2 | 0 |
| | 890430 | 1989Q0493 | <.1 | <2 | <30 | 0 | 80 | | 0 | 100 | <2 | 0 |
| | 890431 | 1989Q0494 | <.1 | <2 | <30 | 0 | 200 | | 0 | <100 | <2 | 0 |
| | 890432 | 1989Q0495 | <.1 | <2 | <30 | 0 | 1,590 | | 0 | <100 | <2 | 0 |
| | 890433 | 1989Q0496 | <1 | <2 | <30 | 0 | 15,700 | | 0 | <100 | 23 | 0 |
| | 890434 | 1989Q0497 | <1 | 17 | <30 | 0 | 930 | | 0 | <100 | 46 | 0 |
| | 890435 | 1989Q0498 | <1 | 26 | <30 | 0 | 4,220 | | 0 | <100 | 67 | 0 |
| | 890437 | 1989Q0500 | <.1 | <2 | <30 | 0 | 560 | | 0 | 1400 | <2 | 0 |
| | 890438 | 1989Q0501 | 0.1 | <2 | 380 | 0 | <20. | | 0 | <100 | <2 | 0 |
| | 890439 | 1989Q0502 | <.1 | <2 | <30 | 0 | 110 | | 0 | <100 | <2 | 0 |
| | 890440 | 1989Q0503 | <.1 | <2 | <30 | 0 | 80 | | 0 | <100 | <2 | 0 |
| | 890441 | 1989Q0504 | <.1 | <2 | <30 | 0 | 290 | | 0 | <100 | <2 | 0 |
| | 890442 | 1989Q0505 | <1 | 47 | <30 | 0 | 24,700 | | 0 | <100 | 120 | 0 |
| | 890443 | 1989Q0506 | <1 | 34 | <30 | 0 | 11,900 | | 0 | <100 | 73 | 0 |
| | 890444 | 1989Q0507 | <1 | 19 | 100 | 0 | 14,800 | | 0 | <100 | 39 | 0 |
| | 890927 | 1989Q1376 | | <4 | <40 | 0 | 491 | | 0 | 300 | <5 | 0 |
| | 890928 | 1989Q1377 | | | 168 | 0 | 28,500 | 355 | 0 | 65,400 | 8 | 0 |
| | 890929 | 1989Q1378 | | 7 | 100 | 0 | 17,800 | | 0 | <100 | <5 | 0 |
| | 890930 | 1989Q1379 | | <4 | 120 | 0 | 5,470 | | 0 | 4,400 | <5 | 0 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | | | | | |
| | | WS7 | | | | | | | | | | |
| | | WS8 | | | | | | | | | | |
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 3774 | 1986Q0957 | <2 | <2 | 0 | 100 | <20 | <10 | | | 790 | 3 |
| | 4148 | 1985Q0832 | | | 0 | 0 | | | | | 0 | |
| | 4149 | 1973Q0402 | | | 0 | 0 | | | | | 0 | |
| | 206548 | 2003-09 | <10 | <5 | | 57.8 | <10 | <2 | <10 | 7.45 | 836 | <1 |
| | 206548 | 2003-09 | | | | | | | | | | |
| | 890422 | 1989Q0485 | <2 | 92 | 0 | 1,800 | 30 | 250 | | | 13,600 | <1 |
| | 890423 | 1989Q0486 | <2 | 110 | 0 | 7,780 | <20 | 180 | | | 73,600 | <1 |
| | 890424 | 1989Q0487 | <2 | <2 | 0 | 510 | <20 | 10 | | | 2,730 | 4 |
| | 890425 | 1989Q0488 | <2 | 66 | 0 | 8,080 | <20 | 170 | | | 68,900 | <1 |
| | 890426 | 1989Q0489 | <2 | <2 | 0 | 190 | <20 | <10 | | | 1,940 | 4 |
| | 890427 | 1989Q0490 | <2 | <2 | 0 | 120 | <20 | <10 | | | 990 | 2 |
| | 890428 | 1989Q0491 | 22 | 34 | 0 | 1,070 | <20 | 50 | | | 7,120 | 12 |
| | 890429 | 1989Q0492 | <2 | 12 | 0 | 2,080 | <20 | <10 | | | 9,810 | 14 |
| | 890430 | 1989Q0493 | <2 | 3 | 0 | 110 | <20 | <10 | | | 600 | 3 |
| | 890431 | 1989Q0494 | <2 | <2 | 0 | 120 | <20 | <10 | | | 580 | 1 |
| | 890432 | 1989Q0495 | <2 | <2 | 0 | 280 | <20 | <10 | | | 700 | <1 |
| | 890433 | 1989Q0496 | 23 | 66 | 0 | 3,950 | 60 | 70 | | | 25,700 | <1 |
| | 890434 | 1989Q0497 | <2 | 66 | 0 | 3,410 | <20 | 110 | | | 26,700 | <1 |
| | 890435 | 1989Q0498 | <2 | 110 | 0 | 4,200 | 40 | 130 | | | 32,100 | <1 |
| | 890437 | 1989Q0500 | <2 | <2 | 0 | 480 | <20 | <10 | | | 2,820 | 8 |
| | 890438 | 1989Q0501 | <2 | 5 | 0 | 44 | <20 | <10 | | | 650 | 38 |
| | 890439 | 1989Q0502 | <2 | <2 | 0 | 18 | <20 | <10 | | | 250 | 6 |
| | 890440 | 1989Q0503 | <2 | <2 | 0 | 19 | <20 | <10 | | | 89 | 1 |
| | 890441 | 1989Q0504 | 2 | 14 | 0 | 540 | <20 | <10 | | | 9,680 | 19 |
| | 890442 | 1989Q0505 | <2 | 96 | 0 | 13,100 | <20 | 140 | | | 95,100 | 140 |
| | 890443 | 1989Q0506 | <2 | 78 | 0 | 12,400 | <20 | 150 | | | 78,900 | 110 |
| | 890444 | 1989Q0507 | 30 | 78 | 0 | 5,840 | <20 | 70 | | | 22,400 | <1 |
| | 890927 | 1989Q1376 | <5 | <4 | 0 | 143 | <40 | <20 | | | 1,050 | <4 |
| | 890928 | 1989Q1377 | 7 | 23 | 0 | 4,440 | <40 | 42 | 220 | | 18,700 | <4 |
| | 890929 | 1989Q1378 | <5 | 16 | 0 | 2,840 | <40 | 20 | 140 | | 13,800 | <4 |
| | 890930 | 1989Q1379 | <5 | 4 | 0 | 730 | <40 | <20 | <50 | | 3,580 | <4 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| *Wigeon Slough WPA* | | | | | | | | |
| | | WS7 | | | | | 0.032 | |
| | | WS8 | | | | | 0.014 | |
| *Non-WPA Sites* | | | | | | | | |
| | 3774 | 1986Q0957 | 0 | <1 | 17 | <4 | 0.005 | |
| | 4148 | 1985Q0832 | 0 | | | | 0.029 | |
| | 4149 | 1973Q0402 | 0 | | | | 38.580 | |
| | 206548 | 2003-09 | <3 | <10 | <2 | <2 | 0.024 | |
| | 206548 | 2003-09 | | | | | 0.022 | |
| | 890422 | 1989Q0485 | 0 | 5 | 17 | <10 | 0.488 | |
| | 890423 | 1989Q0486 | 0 | <1 | 13 | <4 | 6.048 | |
| | 890424 | 1989Q0487 | 0 | <1 | 9 | <4 | 0.018 | |
| | 890425 | 1989Q0488 | 0 | 9 | 13 | <4 | 0.646 | |
| | 890426 | 1989Q0489 | 0 | <1 | <3 | 29 | 0.003 | |
| | 890427 | 1989Q0490 | 0 | <1 | <3 | <4 | 0.009 | |
| | 890428 | 1989Q0491 | 0 | 36 | 9 | 33 | 0.354 | |
| | 890429 | 1989Q0492 | 0 | 6 | 4 | <4 | 0.364 | |
| | 890430 | 1989Q0493 | 0 | <1 | <3 | <4 | 0.022 | |
| | 890431 | 1989Q0494 | 0 | <1 | <3 | <4 | 0.051 | |
| | 890432 | 1989Q0495 | 0 | <1 | <3 | <4 | 0.170 | |
| | 890433 | 1989Q0496 | 0 | 57 | 15 | 14 | 0.396 | |
| | 890434 | 1989Q0497 | 0 | 10 | 6 | <4 | 0.466 | |
| | 890435 | 1989Q0498 | 0 | 34 | 14 | <4 | 0.501 | |
| | 890437 | 1989Q0500 | 0 | <1 | 7 | <4 | 0.028 | |
| | 890438 | 1989Q0501 | 0 | 12 | 9 | <4 | 0.218 | |
| | 890439 | 1989Q0502 | 0 | <1 | <3 | <4 | 0.012 | |
| | 890440 | 1989Q0503 | 0 | <1 | <3 | <4 | 0.034 | |
| | 890441 | 1989Q0504 | 0 | 11 | 5 | <4 | 0.305 | |
| | 890442 | 1989Q0505 | 0 | 34 | 12 | <4 | 0.958 | |
| | 890443 | 1989Q0506 | 0 | 14 | 50 | <4 | 11.353 | |
| | 890444 | 1989Q0507 | 0 | 61 | 36 | 50 | 0.444 | |
| | 890927 | 1989Q1376 | 0 | <4 | <7 | <6 | 0.006 | |
| | 890928 | 1989Q1377 | 0 | 20 | 13 | 11 | 4.047 | |
| | 890929 | 1989Q1378 | 0 | 13 | 7 | 7 | 5.320 | |
| | 890930 | 1989Q1379 | 0 | 7 | 7 | <6 | 0.301 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Latitude | Longitude | TRS | Site Type | Depth | Agency | Sample Date | Water Temp. (°C) | Field pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | | | | |
| | 890931 | 1989Q1380 | 48.8500 | -104.1066 | 36N58E27ABDC | Well | 13 | MBMG | 10/12/1989 | 16.3 | |
| | 890932 | 1989Q1381 | 48.8461 | -104.0994 | 36N58E27ADDD | Well | 23 | MBMG | 10/12/1989 | 14 | |
| | 890933 | 1989Q1382 | 48.8486 | -104.0994 | 36N58E22ADAA | Well | 17 | MBMG | 10/12/1989 | 14.3 | |
| | 890934 | 1989Q1383 | 48.8527 | -104.0994 | 36N58E27AAAA | Well | 27 | MBMG | 10/12/1989 | 13.7 | |
| | 890935 | 1989Q1384 | 48.8508 | -104.0994 | 36N58E27AADA | Well | 17 | MBMG | 10/12/1989 | 12.9 | |
| | 890941 | 1989Q1390 | 48.8527 | -104.1061 | 36N58E27ABAB | Well | 15 | MBMG | 10/13/1989 | 10.3 | |
| | 890942 | 1989Q1391 | 48.8513 | -104.1125 | 36N58E27BAAC | Well | 18.9 | MBMG | 10/12/1989 | 13.9 | |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Field SC (µS/cm) | Field DO (mg/L) | Field TDS (g/L) | Field Chloride Conc. (mg/L) | Lab | Lab pH | Lab SC (µS/cm) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 890931 | 1989Q1380 | | | | | MBMG | 7.79 | 2,968 | 92.92 | 40.66 | 447 |
| | 890932 | 1989Q1381 | | | | | MBMG | 7.51 | 21,375 | 1970 | 1,120 | 1,410 |
| | 890933 | 1989Q1382 | | | | | MBMG | 7.7 | 40,603 | 945 | 1,400 | 7,500 |
| | 890934 | 1989Q1383 | | | | | MBMG | 7.55 | 1,596.4 | 173 | 74.6 | 46.2 |
| | 890935 | 1989Q1384 | | | | | MBMG | 7.47 | 78,617 | 1900 | 1,340 | 18,800 |
| | 890941 | 1989Q1390 | | | | | MBMG | 7.09 | 9,211.4 | 469 | 457 | 745 |
| | 890942 | 1989Q1391 | | | | | MBMG | 7.51 | 1,203 | 116 | 57.05 | 26.9 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | K (mg/L) | Fe (mg/L) | Mn (mg/L) | $SiO_2$ (mg/L) | $HCO_3$ (mg/L) | $CO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) | $NO_3$ (mg/L) | F (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 890931 | 1989Q1380 | 19.5 | <.004 | 0.01 | 26.8 | 262 | 0 | 110 | 718 | 15.7 | 0.3 |
| | 890932 | 1989Q1381 | 44.51 | 0.51 | 2.7 | 22.5 | 314 | 0 | 1,220 | 7,840 | 1.1 | 1 |
| | 890933 | 1989Q1382 | 123 | <.004 | 0.22 | 22.2 | 299 | 0 | 1,450 | 16,300 | 2.4 | 0.2 |
| | 890934 | 1989Q1383 | 7.75 | <.004 | 0.64 | 25.7 | 395 | 0 | 430 | 40.1 | 0.08 | 0.14 |
| | 890935 | 1989Q1384 | 340 | <.004 | 0.38 | 20.8 | 425 | 0 | 268 | 36,500 | 13.6 | |
| | 890941 | 1989Q1390 | 52.65 | 9.47 | 2.38 | 31.4 | 311 | 0 | 859 | 2,560 | 0.89 | 0.2 |
| | 890942 | 1989Q1391 | 9.06 | 0.98 | 0.83 | 27.2 | 375 | 0 | 257 | 6.6 | 0.06 | 0.3 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | $OPO_4$ (mg/L) | Ag (µg/L) | Al (µg/L) | As (µg/L) | B (µg/L) | Ba (µg/L) | Be (µg/L) | Br (µg/L) | Cd (µg/L) | Co (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 890931 | 1989Q1380 | | <4 | 56 | 0 | 1,390 | | 0 | 1,700 | <5 | 0 |
| | 890932 | 1989Q1381 | | 7 | 100 | 0 | 265 | | 0 | 15,900 | 11 | 0 |
| | 890933 | 1989Q1382 | | 6 | <40 | 0 | 1,840 | | 0 | <100 | 12 | 0 |
| | 890934 | 1989Q1383 | | <4 | <40 | 0 | 83 | | 0 | <100 | <5 | 0 |
| | 890935 | 1989Q1384 | | 14 | 90 | 0 | 34,200 | 300 | 0 | 12,300 | 12 | 0 |
| | 890941 | 1989Q1390 | | <4 | <40 | 0 | 310 | | 0 | 2,100 | <5 | 0 |
| | 890942 | 1989Q1391 | | <4 | <40 | 0 | 157 | | 0 | <100 | <5 | 0 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | Cr (µg/L) | Cu (µg/L) | Hg (µg/L) | Li (µg/L) | Mo (µg/L) | Ni (µg/L) | Pb (µg/L) | Se (µg/L) | Sr (µg/L) | Ti (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | | | | | |
| | 890931 | 1989Q1380 | <5 | <4 | 0 | 196 | <40 | <20 | <50 | | 1,010 | <4 |
| | 890932 | 1989Q1381 | 6 | 26 | 0 | 447 | <40 | 60 | 310 | | 5,600 | <4 |
| | 890933 | 1989Q1382 | <5 | 20 | 0 | 2,780 | <40 | <20 | 270 | | 12,800 | 9 |
| | 890934 | 1989Q1383 | <5 | <4 | 0 | 34 | <40 | <20 | <50 | | 469 | <4 |
| | 890935 | 1989Q1384 | 7 | 31 | 0 | 9,230 | <40 | 20 | 400 | | 24,800 | <4 |
| | 890941 | 1989Q1390 | <5 | <4 | 0 | 267 | <40 | 23 | 110 | | 2,110 | <4 |
| | 890942 | 1989Q1391 | <5 | <4 | 0 | 69 | <40 | <20 | | | 477 | <4 |

Appendix B. Analytical results of inorganic analyses for surface and groundwater samples.

| Location | GWIC ID | Site Name | U (µg/L) | V (µg/L) | Zn (µg/L) | Zr (µg/L) | Chloride Index | Comments |
|---|---|---|---|---|---|---|---|---|
| *Non-WPA Sites* | | | | | | | | |
| | 890931 | 1989Q1380 | 0 | <4 | <7 | <6 | 0.242 | |
| | 890932 | 1989Q1381 | 0 | 22 | 14 | 7 | 0.367 | |
| | 890933 | 1989Q1382 | 0 | 14 | <6 | <6 | 0.401 | |
| | 890934 | 1989Q1383 | 0 | <4 | 7 | <6 | 0.025 | |
| | 890935 | 1989Q1384 | 0 | 27 | 9 | 18 | 0.464 | |
| | 890941 | 1989Q1390 | 0 | <4 | 8 | <6 | 0.278 | |
| | 890942 | 1989Q1391 | 0 | <4 | <7 | <6 | 0.005 | |

# APPENDIX C

**Analytical results of organic analyses of soil samples**

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | Latitude | Longitude | Site Type | Agency | Sample Date | Total Petroleum Hydrocarbons | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | DW | WW |
| *Anderson WPA* | | | | | | | | |
| | A-2S | 48.9876 | -104.1044 | Soil | USFWS | 9/13/2005 | 8,210.00 | 6,551.58 |
| | A-2S | 48.9876 | -104.1044 | Soil | USFWS | 9/11/2006 | | |
| | A-3S | 48.9872 | -104.1046 | Soil | USFWS | 9/13/2005 | 50.00 | 41.00 |
| | A-4S | 48.9873 | -104.1041 | Soil | USFWS | 9/13/2005 | 22,600.00 | 19,390.80 |
| | A-5S | 48.9867 | -104.1039 | Soil | USFWS | 9/13/2005 | 50.00 | 42.75 |
| | A-14S | 48.9849 | -104.0992 | Soil | USFWS | 9/14/2005 | 382.00 | 290.70 |
| | A-14S | 48.9849 | -104.0992 | Soil | USFWS | 9/11/2006 | | |
| *Jerde WPA* | | | | | | | | |
| | JP-1S | 48.9545 | -104.1874 | Soil | USFWS | 9/15/2005 | 50.00 | 42.90 |
| | JP-1S | 48.9545 | -104.1874 | Soil | USFWS | 9/11/2006 | | |
| *Melby WPA* | | | | | | | | |
| | M-3S | 48.6391 | -104.0832 | Soil | USFWS | 9/16/2005 | 89,200.00 | 64,224.00 |
| | M-3S | 48.6391 | -104.0832 | Soil | USFWS | 9/11/2006 | | |
| | M-3S | 48.6391 | -104.0832 | Soil | USFWS | 9/11/2006 | | |
| *Mallad Pond WPA* | | | | | | | | |
| | MP-1S | 48.5756 | -104.1357 | Soil | USFWS | 9/16/2005 | 524.00 | 486.80 |
| | MP-1S | 48.5756 | -104.1357 | Soil | USFWS | 9/11/2006 | | |
| *Medicine Lake NWR* | | | | | | | | |
| | RE-2S | 48.5262 | -104.2575 | Soil | USFWS | 9/17/2005 | 246.00 | 190.65 |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-decane | | n-docosane | | n-dodecane | | n-dotriacontane | | n-eicosane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 218.00 | 175.49 | 955.00 | 768.78 | 309.00 | 248.75 | 306.00 | 246.33 | 1,100.00 | 885.50 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.32 | 0.26 | 0.36 | 0.29 | 1.10 | 0.88 | <0.02 | 0.02 | 0.83 | 0.67 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.01 | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | <0.01 | 0.01 | 0.02 | 0.02 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 2,810.00 | 2,509.33 | 184.00 | 164.31 | 2,570.00 | 2,295.01 | 77.00 | 68.76 | 269.00 | 240.22 |
| | M-3S | 219.00 | 183.74 | 28.00 | 23.49 | 241.00 | 202.20 | 7.50 | 6.29 | 36.00 | 30.20 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | <0.01 | 0.01 | 0.02 | 0.02 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-heneicosane | | n-hentriacontane | | n-heptacosane | | n-heptadecane | |
|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | |
| | A-2S | | | | | | | | |
| | A-2S | 948.00 | 763.14 | 352.00 | 283.36 | 653.00 | 525.67 | 2,330.00 | 1,875.65 |
| | A-3S | | | | | | | | |
| | A-4S | | | | | | | | |
| | A-5S | | | | | | | | |
| | A-14S | | | | | | | | |
| | A-14S | 0.57 | 0.46 | 0.32 | 0.26 | 0.28 | 0.22 | 1.30 | 1.04 |
| *Jerde WPA* | | | | | | | | | |
| | JP-1S | | | | | | | | |
| | JP-1S | 0.026 | 0.02 | 0.086 | 0.07 | 0.14 | 0.12 | 0.029 | 0.02 |
| *Melby WPA* | | | | | | | | | |
| | M-3S | | | | | | | | |
| | M-3S | 214.00 | 191.10 | 99.00 | 88.41 | 221.00 | 197.35 | 2,000.00 | 1,786.00 |
| | M-3S | 29.00 | 24.33 | 9.50 | 7.97 | 23.00 | 19.30 | 251.00 | 210.59 |
| *Mallad Pond WPA* | | | | | | | | | |
| | MP-1S | | | | | | | | |
| | MP-1S | 0.02 | 0.02 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 |
| *Medicine Lake NWR* | | | | | | | | | |
| | RE-2S | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-hexacosane | | n-hexadecane | | n-nonacosane | | n-nonadecane | | n-octacosane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 695.00 | 559.48 | 1,870.00 | 1,505.35 | 438.00 | 352.59 | 1,470.00 | 1,183.35 | 561.00 | 451.61 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.21 | 0.17 | 1.30 | 1.04 | 0.24 | 0.19 | 1.00 | 0.80 | 0.14 | 0.11 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | 0.051 | 0.04 | 0.027 | 0.02 | 0.16 | 0.14 | 0.024 | 0.02 | 0.11 | 0.09 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 176.00 | 157.17 | 1,530.00 | 1,366.29 | 97.00 | 86.62 | 736.00 | 657.25 | 124.00 | 110.73 |
| | M-3S | 23.00 | 19.30 | 201.00 | 168.64 | 13.00 | 10.91 | 107.00 | 89.77 | 13.00 | 10.91 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | 0.03 | 0.02 | 0.04 | 0.04 | 0.08 | 0.07 | 0.03 | 0.03 | 0.03 | 0.03 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-octadecane | | n-pentacosane | | n-pentadecane | | n-tetracosane | | n-tetradecane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 1,340.00 | 1,078.70 | 720.00 | 579.60 | 806.00 | 648.83 | 798.00 | 642.39 | 468.00 | 376.74 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 1.00 | 0.80 | 0.25 | 0.20 | 1.30 | 1.04 | 0.25 | 0.20 | 1.30 | 1.04 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | 0.031 | 0.03 | 0.066 | 0.06 | 0.036 | 0.03 | 0.047 | 0.04 | 0.012 | 0.01 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 508.00 | 453.64 | 186.00 | 166.10 | 2,030.00 | 1,812.79 | 176.00 | 157.17 | 2,270.00 | 2,027.11 |
| | M-3S | 57.00 | 47.82 | 24.00 | 20.14 | 244.00 | 204.72 | 21.00 | 17.62 | 252.00 | 211.43 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | 0.02 | 0.02 | 0.06 | 0.06 | 0.06 | 0.05 | 0.03 | 0.03 | 0.03 | 0.02 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-tetratriacontane | | n-triacontane | | n-tricosane | | n-tridecane | | n-tritriacontane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 85.00 | 68.43 | 467.00 | 375.94 | 798.00 | 642.39 | 367.00 | 295.44 | 180.00 | 144.90 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | <0.02 | 0.02 | 0.07 | 0.05 | 0.35 | 0.28 | 1.20 | 0.96 | 0.14 | 0.11 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | 0.015 | 0.01 | 0.015 | 0.01 | 0.042 | 0.04 | <0.01 | 0.01 | 0.038 | 0.03 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 27.00 | 24.11 | 99.00 | 88.41 | 179.00 | 159.85 | 3,290.00 | 2,937.97 | 74.00 | 66.08 |
| | M-3S | 3.90 | 3.27 | 10.00 | 8.39 | 22.00 | 18.46 | 350.00 | 293.65 | 5.00 | 4.20 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | n-undecane | | phytane | | pristane | | 1,6,7-Trimethyl-naphthalene | | 1-methylnaphthalene | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 297.00 | 239.09 | 502.00 | 404.11 | 368.00 | 296.24 | 40.80 | 32.84 | 104.00 | 83.72 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.75 | 0.60 | 0.61 | 0.49 | 0.51 | 0.41 | 0.10 | 0.08 | 0.12 | 0.10 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.01 | 0.01 | <0.01 | 0.01 | 0.044 | 0.04 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 3,480.00 | 3,107.64 | 65.00 | 58.05 | 49.00 | 43.76 | 24.00 | 21.43 | 108.00 | 96.44 |
| | M-3S | 319.00 | 267.64 | 8.10 | 6.80 | 5.80 | 4.87 | 3.70 | 3.10 | 14.50 | 12.17 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | 1-methylphenanthrene | | 2,6-dimethylnaphthalene | | 2-methylnaphthalene | | acenaphthalene | | acenaphthene | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 32.50 | 26.16 | 90.60 | 72.93 | 123.00 | 99.02 | 0.97 | 0.78 | 4.90 | 3.94 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.05 | 0.04 | 0.20 | 0.16 | 0.16 | 0.13 | <0.005 | 0.00 | 0.03 | 0.03 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 45.30 | 40.45 | 54.50 | 48.67 | 148.00 | 132.16 | 1.70 | 1.52 | 3.30 | 2.95 |
| | M-3S | 6.30 | 5.29 | 6.70 | 5.62 | 17.10 | 14.35 | 0.37 | 0.31 | <0.05 | 0.04 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | anthracene | | Benzo(a)anthracene | | benzo(a)pyrene | | benzo(b)fluoranthene | | benzo(e)pyrene | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 2.19 | 1.76 | 1.30 | 1.05 | <0.05 | 0.04 | 0.61 | 0.49 | | |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.01 | 0.01 | 0.15 | 0.12 | <0.005 | 0.00 | 0.10 | 0.08 | 0.04 | 0.03 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 1.47 | 1.31 | 0.10 | 0.09 | 5.20 | 4.64 | 1.50 | 1.34 | 6.50 | 5.80 |
| | M-3S | <0.05 | 0.04 | <0.05 | 0.04 | <0.05 | 0.04 | <0.05 | 0.04 | 1.30 | 1.09 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | benzo(g,h,i)perylene | | benzo(k)fluoranthene | | biphenyl | | C1-chrysenes | | C1-dibenzothiophenes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 2.39 | 1.92 | 1.12 | 0.90 | 16.90 | 13.60 | 4.90 | 3.94 | 61.20 | 49.27 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.21 | 0.17 | 0.06 | 0.04 | 0.04 | 0.03 | <0.005 | 0.00 | 0.06 | 0.05 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 1.20 | 1.07 | 0.88 | 0.79 | 7.00 | 6.25 | 14.60 | 13.04 | 22.10 | 19.74 |
| | M-3S | 0.42 | 0.35 | <0.05 | 0.04 | 0.77 | 0.65 | 1.10 | 0.92 | 2.90 | 2.43 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | 0.04 | 0.04 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | C1-Fluoranthenes & Pyrenes | | C1-fluorenes | | C1-naphthalenes | | C1-phenanthrenes | | C2-chrysenes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 14.70 | 11.83 | 35.10 | 28.26 | 227.00 | 182.74 | 134.00 | 107.87 | 1.87 | 1.51 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.09 | 0.07 | 0.07 | 0.05 | 0.28 | 0.22 | 0.27 | 0.22 | <0.005 | 0.00 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 11.80 | 10.54 | 12.30 | 10.98 | 256.00 | 228.61 | 168.00 | 150.02 | 5.24 | 4.68 |
| | M-3S | 2.50 | 2.10 | 2.88 | 2.42 | 31.60 | 26.51 | 24.90 | 20.89 | <0.05 | 0.04 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | C2-dibenzothiophenes | | C2-fluorenes | | C2-naphthalenes | | C2-phenanthrenes | | C3-chrysenes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | DW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | <0.05 | 0.04 | <0.05 | 0.04 | 413.00 | 332.47 | 199.00 | 160.20 | <0.05 | 0.04 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | <0.005 | 0.00 | <0.005 | 0.00 | 0.75 | 0.60 | 0.37 | 0.30 | <0.005 | 0.00 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | <0.05 | 0.04 | <0.05 | 0.04 | 286.00 | 255.40 | 154.00 | 137.52 | <0.05 | 0.04 |
| | M-3S | <0.05 | 0.04 | <0.05 | 0.04 | 38.00 | 31.88 | 24.20 | 20.30 | <0.05 | 0.04 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | C3-dibenzothiophenes | | C3-fluorenes | | C3-naphthalenes | | C3-phenanthrenes | | C4-chrysenes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | <0.05 | 0.04 | <0.05 | 0.04 | | | 71.30 | 57.40 | <0.05 | 0.04 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | <0.005 | 0.00 | <0.005 | 0.00 | 0.86 | 0.69 | 0.11 | 0.09 | <0.005 | 0.00 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | <0.05 | 0.04 | <0.05 | 0.04 | 147.00 | 131.27 | 58.10 | 51.88 | <0.05 | 0.04 |
| | M-3S | <0.05 | 0.04 | <0.05 | 0.04 | 23.30 | 19.55 | 9.40 | 7.89 | <0.05 | 0.04 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | C4-naphthalenes | | C4-phenanthrenes | | chrysene | | Dibenz(a,h)anthracene | | dibenzothiophene | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | 71.60 | 57.64 | 7.94 | 6.39 | <0.05 | 0.04 | <0.05 | 0.04 | 43.60 | 35.10 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.21 | 0.17 | 0.02 | 0.01 | <0.005 | 0.00 | 0.68 | 0.55 | 0.03 | 0.02 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 114.00 | 101.80 | 20.90 | 18.66 | 7.90 | 7.05 | 0.59 | 0.53 | 10.00 | 8.93 |
| | M-3S | 11.30 | 9.48 | 2.40 | 2.01 | 2.30 | 1.93 | <0.05 | 0.04 | 1.50 | 1.26 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | 0.03 | 0.03 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | fluoranthene | | fluorene | | indeno(1,2,3-cd)pyrene | | naphthalene | | perylene | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DW | WW | DW | WW | DW | WW | DW | WW | DW | WW |
| *Anderson WPA* | | | | | | | | | | | |
| | A-2S | | | | | | | | | | |
| | A-2S | <0.05 | 0.04 | | | 0.83 | 0.67 | 41.80 | 33.65 | 1.83 | 1.47 |
| | A-3S | | | | | | | | | | |
| | A-4S | | | | | | | | | | |
| | A-5S | | | | | | | | | | |
| | A-14S | | | | | | | | | | |
| | A-14S | 0.04 | 0.03 | 0.03 | 0.03 | 0.14 | 0.11 | 0.03 | 0.02 | 0.10 | 0.08 |
| *Jerde WPA* | | | | | | | | | | | |
| | JP-1S | | | | | | | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | 0.02 | 0.01 |
| *Melby WPA* | | | | | | | | | | | |
| | M-3S | | | | | | | | | | |
| | M-3S | 0.39 | 0.35 | 8.60 | 7.68 | 0.09 | 0.08 | 72.10 | 64.39 | 0.80 | 0.71 |
| | M-3S | <0.05 | 0.04 | 1.40 | 1.17 | 0.64 | 0.54 | 7.80 | 6.54 | 1.20 | 1.01 |
| *Mallad Pond WPA* | | | | | | | | | | | |
| | MP-1S | | | | | | | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | | | | | | | |
| | RE-2S | | | | | | | | | | |

Appendix C. Analytical results of organic analyses of soil samples (ppm).

| Location | Site Name | phenanthrene | | pyrene | |
|---|---|---|---|---|---|
| | | DW | WW | DW | WW |
| *Anderson WPA* | | | | | |
| | A-2S | | | | |
| | A-2S | 39.80 | 32.04 | 3.90 | 3.14 |
| | A-3S | | | | |
| | A-4S | | | | |
| | A-5S | | | | |
| | A-14S | | | | |
| | A-14S | 0.06 | 0.05 | 0.04 | 0.03 |
| *Jerde WPA* | | | | | |
| | JP-1S | | | | |
| | JP-1S | <0.005 | 0.00 | <0.005 | 0.00 |
| *Melby WPA* | | | | | |
| | M-3S | | | | |
| | M-3S | 56.70 | 50.63 | 5.40 | 4.82 |
| | M-3S | 8.30 | 6.96 | 0.96 | 0.81 |
| *Mallad Pond WPA* | | | | | |
| | MP-1S | | | | |
| | MP-1S | <0.005 | 0.00 | <0.005 | 0.00 |
| *Medicine Lake NWR* | | | | | |
| | RE-2S | | | | |

# APPENDIX D

**Analytical results of organic analyses of groundwater samples**

Appendix D. Analytical results of organic analyses of groundwater samples .

| Location | Site Name | Latitude | Longitude | Site Type | Agency | Sample Date | Total Petroleum Hydrocarbons (mg/L) | n-decane (µg/L) | n-docosane (µg/L) | n-dodecane (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | | | |
| | A-2MW | 48.9876 | -104.1044 | Well | USFWS | 9/14/2005 | 300 | | | |
| | A-2MW | 48.9876 | -104.1044 | Well | USFWS | 8/31/2006 | | <0.5 | <0.5 | <0.5 |
| | A-3MW | 48.9872 | -104.1046 | Well | USFWS | 9/13/2005 | 550 | | | |
| | A-3MW | 48.9872 | -104.1046 | Well | USFWS | 8/31/2006 | | <0.5 | 5.00 | 6.00 |
| | A-4MW | 48.9873 | -104.1041 | Well | USFWS | 9/13/2005 | 810 | | | |
| | A-4MW | 48.9873 | -104.1041 | Well | USFWS | 8/31/2006 | | <0.5 | <0.5 | <0.5 |
| | A-5DMW | 48.9867 | -104.1039 | Well | USFWS | 9/13/2005 | 510 | | | |
| | A-14MW | 48.9849 | -104.0992 | Well | USFWS | 9/14/2005 | 570 | | | |
| | A-14MW | 48.9849 | -104.0992 | Well | USFWS | 8/31/2006 | | 0.80 | 0.80 | 0.70 |
| *Jerde WPA* | | | | | | | | | | |
| | JP-1MW | 48.9545 | -104.1874 | Well | USFWS | 9/14/2005 | 500 | | | |
| | JP-2MW | 48.9547 | -104.1878 | Well | USFWS | 9/14/2005 | 210 | | | |
| | JP-2MW | 48.9547 | -104.1878 | Well | USFWS | 8/31/2006 | | <0.5 | <0.5 | <0.5 |
| *Melby WPA* | | | | | | | | | | |
| | M-3MW | 48.6391 | -104.0832 | Well | USFWS | 9/16/2005 | 810 | | | |
| | M-3MW | 48.6391 | -104.0832 | Well | USFWS | 8/31/2006 | | <0.5 | 3.50 | 3.80 |
| *Mallard Pond WPA* | | | | | | | | | | |
| | MP-1MW | 48.5756 | -104.1357 | Well | USFWS | 9/16/2005 | 240 | | | |
| *Medicine Lake NWR* | | | | | | | | | | |
| | RE-2MW | 48.5262 | -104.2575 | Well | USFWS | 9/17/2005 | 290 | | | |
| | RE-2MW | 48.5262 | -104.2575 | Well | USFWS | 8/31/2006 | | <0.5 | 0.50 | <0.5 |
| | RW-1MW | 48.5254 | -104.2645 | Well | USFWS | 9/17/2005 | <100 | | | |
| *Rabenberg WPA* | | | | | | | | | | |
| | RS-1MW | 48.8504 | -104.1226 | Well | USFWS | 9/15/2005 | <100 | | | |
| | RS-2MW | 48.8499 | -104.1225 | Well | USFWS | 9/15/2005 | 460 | | | |
| | RS-3MW | 48.8484 | -104.1210 | Well | USFWS | 9/15/2005 | 410 | | | |
| | RS-4MW | 48.8477 | -104.1193 | Well | USFWS | 9/15/2005 | <100 | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | n-dotriacontane (µg/L) | n-eicosane (µg/L) | n-heneicosane (µg/L) | n-hentriacontane (µg/L) | n-heptacosane (µg/L) | n-heptadecane (µg/L) | n-hexacosane (µg/L) | n-hexadecane (µg/L) |
|---|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | | |
| | A-2MW | | | | | | | | |
| | A-2MW | <0.5 | <0.5 | <0.5 | <0.5 | 0.80 | <0.5 | 1.10 | <0.5 |
| | A-3MW | | | | | | | | |
| | A-3MW | <0.5 | <0.5 | <0.5 | <0.5 | 2.80 | <0.5 | 2.90 | <0.5 |
| | A-4MW | | | | | | | | |
| | A-4MW | 0.90 | <0.5 | <0.5 | 0.70 | 0.90 | <0.5 | <0.5 | <0.5 |
| | A-5DMW | | | | | | | | |
| | A-14MW | | | | | | | | |
| | A-14MW | <0.5 | <0.5 | <0.5 | 0.90 | 6.20 | <0.5 | 6.60 | <0.5 |
| *Jerde WPA* | | | | | | | | | |
| | JP-1MW | | | | | | | | |
| | JP-2MW | | | | | | | | |
| | JP-2MW | 0.50 | <0.5 | <0.5 | <0.5 | 1.60 | <0.5 | 1.10 | <0.5 |
| *Melby WPA* | | | | | | | | | |
| | M-3MW | | | | | | | | |
| | M-3MW | 1.60 | 4.90 | 4.00 | 2.20 | 4.00 | 25.00 | 3.00 | 19.00 |
| *Mallard Pond WPA* | | | | | | | | | |
| | MP-1MW | | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | | |
| | RE-2MW | | | | | | | | |
| | RE-2MW | <0.5 | <0.5 | <0.5 | 1.70 | 2.60 | <0.5 | 2.00 | <0.5 |
| | RW-1MW | | | | | | | | |
| *Rabenberg WPA* | | | | | | | | | |
| | RS-1MW | | | | | | | | |
| | RS-2MW | | | | | | | | |
| | RS-3MW | | | | | | | | |
| | RS-4MW | | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples

| Location | Site Name | n-nonacosane (µg/L) | n-nonadecane (µg/L) | n-octacosane (µg/L) | n-octadecane (µg/L) | n-pentacosane (µg/L) | n-pentadecane (µg/L) | n-tetracosane (µg/L) | n-tetradecane (µg/L) |
|---|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | | |
| | A-2MW | | | | | | | | |
| | A-2MW | 0.80 | <0.5 | 0.70 | <0.5 | 0.90 | <0.5 | 0.70 | <0.5 |
| | A-3MW | | | | | | | | |
| | A-3MW | 1.20 | <0.5 | 1.10 | <0.5 | 2.20 | <0.5 | 1.50 | <0.5 |
| | A-4MW | | | | | | | | |
| | A-4MW | <0.5 | <0.5 | <0.5 | <0.5 | 0.60 | <0.5 | <0.5 | <0.5 |
| | A-5DMW | | | | | | | | |
| | A-14MW | | | | | | | | |
| | A-14MW | 2.70 | <0.5 | 3.90 | <0.5 | 5.20 | <0.5 | 3.80 | 0.60 |
| *Jerde WPA* | | | | | | | | | |
| | JP-1MW | | | | | | | | |
| | JP-2MW | | | | | | | | |
| | JP-2MW | <0.5 | <0.5 | 0.90 | <0.5 | 1.10 | <0.5 | 0.50 | <0.5 |
| *Melby WPA* | | | | | | | | | |
| | M-3MW | | | | | | | | |
| | M-3MW | 2.70 | 11.00 | 2.60 | 7.70 | 3.60 | 19.00 | 3.70 | 18.00 |
| *Mallard Pond WPA* | | | | | | | | | |
| | MP-1MW | | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | | |
| | RE-2MW | | | | | | | | |
| | RE-2MW | 1.80 | 0.50 | 1.90 | <0.5 | 1.70 | <0.5 | 1.40 | <0.5 |
| | RW-1MW | | | | | | | | |
| *Rabenberg WPA* | | | | | | | | | |
| | RS-1MW | | | | | | | | |
| | RS-2MW | | | | | | | | |
| | RS-3MW | | | | | | | | |
| | RS-4MW | | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | n-tetratriacontane (µg/L) | n-triacontane (µg/L) | n-tricosane (µg/L) | n-tridecane (µg/L) | n-tritriacontane (µg/L) | n-undecane (µg/L) | phytane (µg/L) | pristane (µg/L) |
|---|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | | |
| | A-2MW | | | | | | | | |
| | A-2MW | <0.5 | <0.5 | 0.70 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| | A-3MW | | | | | | | | |
| | A-3MW | 0.70 | 0.90 | 1.10 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| | A-4MW | | | | | | | | |
| | A-4MW | <0.5 | <0.5 | 0.50 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| | A-5DMW | | | | | | | | |
| | A-14MW | | | | | | | | |
| | A-14MW | 0.50 | 1.60 | 2.30 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| *Jerde WPA* | | | | | | | | | |
| | JP-1MW | | | | | | | | |
| | JP-2MW | | | | | | | | |
| | JP-2MW | <0.5 | <0.5 | 0.70 | <0.5 | 0.50 | <0.5 | <0.5 | <0.5 |
| *Melby WPA* | | | | | | | | | |
| | M-3MW | | | | | | | | |
| | M-3MW | 0.80 | 2.20 | 3.70 | 15.00 | 0.90 | 1.40 | 1.80 | 0.90 |
| *Mallard Pond WPA* | | | | | | | | | |
| | MP-1MW | | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | | |
| | RE-2MW | | | | | | | | |
| | RE-2MW | 1.10 | 2.50 | 0.90 | <0.5 | 0.60 | <0.5 | <0.5 | <0.5 |
| | RW-1MW | | | | | | | | |
| *Rabenberg WPA* | | | | | | | | | |
| | RS-1MW | | | | | | | | |
| | RS-2MW | | | | | | | | |
| | RS-3MW | | | | | | | | |
| | RS-4MW | | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | 1-methylnaphthalene (µg/L) | 1-methylphenanthrene (µg/L) | 2,6-dimethylnaphthalene (µg/L) | 2-methylnaphthalene (µg/L) | acenaphthalene (µg/L) | acenaphthene (µg/L) | anthracene (µg/L) |
|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | |
| | A-2MW | | | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-5DMW | | | | | | | |
| | A-14MW | | | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | | | |
| | JP-1MW | | | | | | | |
| | JP-2MW | | | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | | | |
| | M-3MW | | | | | | | |
| | M-3MW | 2.60 | 0.30 | 0.70 | 0.60 | <0.3 | <0.3 | <0.3 |
| *Mallard Pond WPA* | | | | | | | | |
| | MP-1MW | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | |
| | RE-2MW | | | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | RW-1MW | | | | | | | |
| *Rabenberg WPA* | | | | | | | | |
| | RS-1MW | | | | | | | |
| | RS-2MW | | | | | | | |
| | RS-3MW | | | | | | | |
| | RS-4MW | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | Benzo(a)anthracene (µg/L) | benzo(a)pyrene (µg/L) | benzo(b)fluoranthene (µg/L) | benzo(e)pyrene (µg/L) | benzo(g,h,i)perylene (µg/L) |
|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | |
| | A-2MW | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-5DMW | | | | | |
| | A-14MW | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | |
| | JP-1MW | | | | | |
| | JP-2MW | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | |
| | M-3MW | | | | | |
| | M-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Mallard Pond WPA* | | | | | | |
| | MP-1MW | | | | | |
| *Medicine Lake NWR* | | | | | | |
| | RE-2MW | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | RW-1MW | | | | | |
| *Rabenberg WPA* | | | | | | |
| | RS-1MW | | | | | |
| | RS-2MW | | | | | |
| | RS-3MW | | | | | |
| | RS-4MW | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | biphenyl (µg/L) | C1-chrysenes (µg/L) | C1-dibenzothiophenes (µg/L) | C1-Fluoranthenes & Pyrenes (µg/L) | C1-fluorenes (µg/L) | C1-naphthalenes (µg/L) | C1-phenanthrenes (µg/L) |
|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | |
| | A-2MW | | | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-5DMW | | | | | | | |
| | A-14MW | | | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | | | |
| | JP-1MW | | | | | | | |
| | JP-2MW | | | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | | | |
| | M-3MW | | | | | | | |
| | M-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 3.20 | 2.20 |
| *Mallard Pond WPA* | | | | | | | | |
| | MP-1MW | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | |
| | RE-2MW | | | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | RW-1MW | | | | | | | |
| *Rabenberg WPA* | | | | | | | | |
| | RS-1MW | | | | | | | |
| | RS-2MW | | | | | | | |
| | RS-3MW | | | | | | | |
| | RS-4MW | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | C2-dibenzothiophenes (µg/L) | C2-fluorenes (µg/L) | C2-naphthalenes (µg/L) | C2-phenanthrenes (µg/L) | C3-chrysenes (µg/L) | C3-dibenzothiophenes (µg/L) | C3-fluorenes (µg/L) |
|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | |
| | A-2MW | | | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-5DMW | | | | | | | |
| | A-14MW | | | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | | | |
| | JP-1MW | | | | | | | |
| | JP-2MW | | | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | | | |
| | M-3MW | | | | | | | |
| | M-3MW | <0.3 | <0.3 | 3.90 | 1.70 | <0.3 | <0.3 | <0.3 |
| *Mallard Pond WPA* | | | | | | | | |
| | MP-1MW | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | |
| | RE-2MW | | | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | RW-1MW | | | | | | | |
| *Rabenberg WPA* | | | | | | | | |
| | RS-1MW | | | | | | | |
| | RS-2MW | | | | | | | |
| | RS-3MW | | | | | | | |
| | RS-4MW | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | C3-naphthalenes (µg/L) | C3-phenanthrenes (µg/L) | C4-chrysenes (µg/L) | C4-naphthalenes (µg/L) | C4-phenanthrenes (µg/L) | chrysene (µg/L) | Dibenz(a,h)anthracene (µg/L) |
|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | |
| | A-2MW | | | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-5DMW | | | | | | | |
| | A-14MW | | | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | | | |
| | JP-1MW | | | | | | | |
| | JP-2MW | | | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | | | |
| | M-3MW | | | | | | | |
| | M-3MW | 2.00 | <0.3 | <0.3 | 0.50 | <0.3 | <0.3 | 0.30 |
| *Mallard Pond WPA* | | | | | | | | |
| | MP-1MW | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | |
| | RE-2MW | | | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | RW-1MW | | | | | | | |
| *Rabenberg WPA* | | | | | | | | |
| | RS-1MW | | | | | | | |
| | RS-2MW | | | | | | | |
| | RS-3MW | | | | | | | |
| | RS-4MW | | | | | | | |

Appendix D. Analytical results of organic analyses of groundwater samples.

| Location | Site Name | dibenzothiophene (µg/L) | fluoranthene (µg/L) | fluorene (µg/L) | indeno(1,2,3-cd)pyrene (µg/L) | naphthalene (µg/L) | perylene (µg/L) | phenanthrene (µg/L) | pyrene (µg/L) |
|---|---|---|---|---|---|---|---|---|---|
| *Anderson WPA* | | | | | | | | | |
| | A-2MW | | | | | | | | |
| | A-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-3MW | | | | | | | | |
| | A-3MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| | A-4MW | | | | | | | | |
| | A-4MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 0.50 | <0.3 | <0.3 |
| | A-5DMW | | | | | | | | |
| | A-14MW | | | | | | | | |
| | A-14MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 0.30 | <0.3 | <0.3 |
| *Jerde WPA* | | | | | | | | | |
| | JP-1MW | | | | | | | | |
| | JP-2MW | | | | | | | | |
| | JP-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 0.40 | <0.3 | <0.3 |
| *Melby WPA* | | | | | | | | | |
| | M-3MW | | | | | | | | |
| | M-3MW | <0.3 | <0.3 | <0.3 | <0.3 | 0.70 | <0.3 | 0.50 | <0.3 |
| *Mallard Pond WPA* | | | | | | | | | |
| | MP-1MW | | | | | | | | |
| *Medicine Lake NWR* | | | | | | | | | |
| | RE-2MW | | | | | | | | |
| | RE-2MW | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 0.50 | <0.3 | <0.3 |
| | RW-1MW | | | | | | | | |
| *Rabenberg WPA* | | | | | | | | | |
| | RS-1MW | | | | | | | | |
| | RS-2MW | | | | | | | | |
| | RS-3MW | | | | | | | | |
| | RS-4MW | | | | | | | | |