Risk of Contamination of Aquatic Resources from Energy Development in the Williston Basin Based on a Spatial, Chemical, and Geophysical Assessment

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Introduction

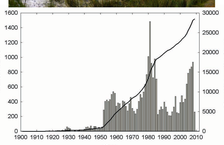
Abstract

The Williston Basin of Montana, North Dakota, and South Dakota has been a leading domestic oil producing region for over half a century, with extensive new development associated with the Bakken Formation. Overlapping the Williston Basin is the Prairie Pothole Region (PPR), an area of abundant wetlands that provide critical habitats for breeding and migrating waterfowl and other wildlife. Energy exploration, development, and production can result in the release of saline and toxic co-produced waters (brine). Hydraulic fracturing methods have resulted in rapid development of the extensive energy resources in the Bakken Formation and potential contamination impacts from this practice are a concern to land managers. The migration of flow-back and co-produced waters may pose a serious risk to prairie wetland and stream-dependent wildlife, agricultural lands, and groundwater resources.

An interdisciplinary team of U.S. Geological Survey researchers is developing risk assessment tools for land managers by studying the potential environmental impacts of brine contamination to wetland, stream, and groundwater resources. The extent of contamination in the Williston Basin is unknown; therefore, we gathered spatial data on energy production infrastructure and aquatic resources and conducted a risk assessment based on proximity. In addition, water chemistry analyses and geophysical surveys were conducted at three Waterfowl Production Areas to quantify the extent of contamination and the rate of brine plume movement in the most common geologic settings within the PPR (till, outwash, and lacustrine deposits). We characterized and mapped subsurface brine plume migration over 1.6 km from the likely sources. The spatial assessment identified 292,745 wetlands and 7,147 km of stream reach within 1.6 km of petroleum-related wells. The science team organized a decision analysis workshop attended by numerous stakeholders to establish a broad framework for evaluating the potential effects of energy development on environmental resources. The test topic was a risk assessment for the location of well pads relative to wetland proximity. Our study will assist federal and state land and resource managers to make science-based decisions for allocating limited monitoring and mitigation resources to areas of highest priority.

Overview/Study Area

- The Williston Basin has been a top domestic oil producing region since the 1960s.
- There is a heightened public awareness of environmental risks associated with extensive new development of energy resources in the Bakken Formation. Public concerns include:
  - Climate fluctuations (ex. recent flooding events)
  - Water resource demands (3 million gallons of water to hydrofrac a typical Bakken well)
- Superimposed over the Williston Basin is the PPR which includes critical wetland breeding and nesting habitats of importance to a large proportion of North America's waterfowl.



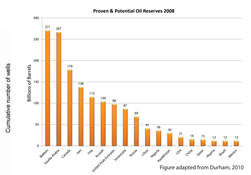


Figure adapted from Durham, 2010

- The table below shows number and area of wetlands and the length of stream reach within 0.4 km, 0.8 km and 1.6 km of petroleum related wells calculated in a GIS.

Wetlands within the buffer regions from wells

	0.4-km buffer		0.8-km buffer		1.6-km buffer	
Wetland Classification	Area, km²	Number	Area, km²	Number	Area, km²	Number
Temporary	39	27,499	83	64,911	163	125,641
Seasonal	135	31,128	289	73,120	577	148,743
Semipermanent	115	3,618	218	8,006	416	16,589
Riverine	25	95	40	142	49	235
Lake	187	378	346	799	577	1,537
Total:	501	62,718	975	146,978	1,780	292,745

Stream reach (km) within buffer region from wells

0.4-km buffer	0.8-km buffer	1.6-km buffer
1,380	3,291	7,147

- Regulations were enacted during the late 1970s to outlaw the usage of unlined, earthen reserve pits for co-produced fluids or brines. Therefore, wells drilled prior to 1980 are more likely to have unlined reserve pits and a higher likelihood of contaminating wetlands, streams, and groundwater.
- The table below shows number and area of wetlands and the length of stream reach within 0.4 km, 0.8 km and 1.6 km of petroleum related wells drilled prior to 1980 calculated in a GIS.

Wetlands within the buffer regions from wells drilled prior to 1980

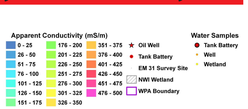
	0.4-km buffer		0.8-km buffer		1.6-km buffer	
Wetland Classification	Area, km²	Number	Area, km²	Number	Area, km²	Number
Temporary	25	16,506	56	41,880	123	91,884
Seasonal	81	18,551	180	45,313	403	102,015
Semipermanent	73	2,201	146	5,097	297	11,548
Riverine	22	79	36	110	51	181
Lake	83	246	187	510	413	1,177
Total:	285	37,583	605	92,910	1,288	206,805

Stream reach (km) within buffer region from wells drilled prior to 1980

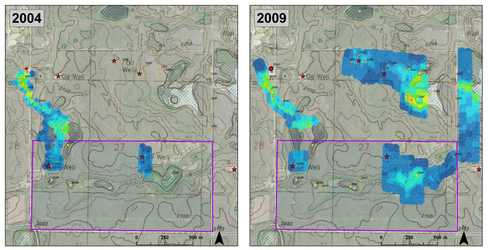
0.4-km buffer	0.8-km buffer	1.6-km buffer
736	2,091	5,002

EM-31 Geophysical Surveys

Used Geonics EM-31, EM-34, and Geophex GEM2 systems to record apparent electrical conductivity (EC) which reflects the subsurface electrical properties of soils and pore fluids (only EM-31 data shown). High EC can be caused by saline pore fluid or conductive silts. Geochemical data for this area suggests high EC correlates with saline contamination. The EM-31 has an exploration depth of approximately 6m.

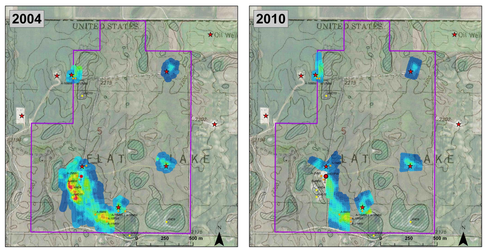


Rabenberg WPA: Glacial Outwash



Apparent conductivity measurements in 2004 and 2009 ranged from <10 mS/m to ~450 mS/m, with the greatest values in the slough below the tank battery in both years. Elevated EC associated with the tank battery plume was measured as far as surveyed in 2004, near groundwater well RAB 2, and over a mile from the tank battery in 2009 with the EM-34 (data not shown). In 2009, elevated EC was measured north of the Rabenberg WPA boundary, delineating contaminated saline groundwater plumes emanating from the oil wells. Surface-water and groundwater samples in 2004 and 2009 confirmed the presence of saline contamination in areas of elevated EC.

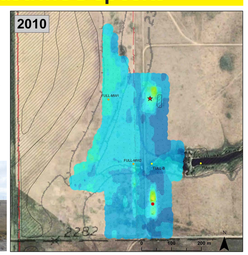
Anderson WPA: Glacial Till



Apparent conductivity measurements ranged from <10 mS/m to 485 mS/m in 2004 and <10 mS/m to 310 mS/m in 2010. The greatest EC values were measured near wetlands AND 4 and AND 11 in 2004 and near groundwater wells A-MW 10 and A-MW 14 in 2010. The area of greatest EC surveyed in 2004 was surveyed with the GEM2 in 2010 (data not shown). Conductivity measurements near the majority of oil wells were lower in 2010 than 2004; however, all surveyed sites still exhibited elevated conductivities in 2010. Surface-water and groundwater samples in 2004 and 2010 confirmed the presence of saline contamination in areas of elevated EC.

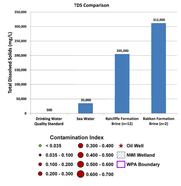
Fuller WPA: Lacustrine Deposits

Apparent conductivity measurements ranged from 25 mS/m to 310 mS/m in 2010. No previous geophysical surveys had been conducted at the Fuller WPA site. Areas of elevated EC were measured near the oil well pad and the tank battery. The increase in EC near FUL-MW1 is likely due to silt content in the soil as the water sample from this well was uncontaminated. All other water samples showed minor levels of contamination.



Water Chemistry

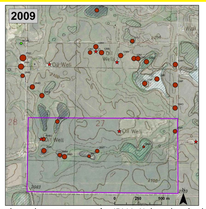
- Produced brine water from formations within the Williston Basin are extremely saline, averaging 300,000 mg/L TDS.[3]
- Produced brine is NaCl dominated. Water in wetlands and shallow aquifers of the PPR is NaSO[4] dominated. Brine from oil development is expected to have a negative effect on wetland communities that support waterfowl.
- Water samples were analyzed for major ions, trace elements, halides, and Sr isotopes.
- Contamination index (CI) was developed to rapidly field assess brine contamination to naturally saline waters.[5]
- Strontium (Sr) concentration of produced brine is several orders of magnitude larger than naturally saline groundwater and wetlands.
- Minute concentrations of brine contamination can be detected in shallow ground and surface water using binary mixing trends of major ions and Sr isotopes.
- The largest $^{87}Sr/^{86}Sr$ value represents the least contaminated end member.[4]

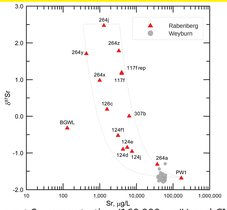


$$CI = \frac{Chloride\ Concentration\ \left(\frac{mg}{L}\right)}{Specific\ Conductance\ \left(\frac{\mu S}{cm}\right)}$$ [5]

$CI > 0.035$ *indicates brine contamination*

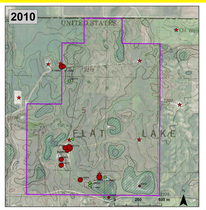
Rabenberg WPA

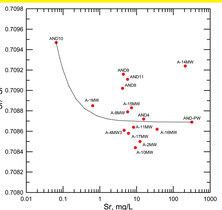




Produced-water sample (PW-1) has both the largest Sr concentration (168,000 µg/L) and CI value (0.543), the smallest ^{87}Sr value, and is in the range of values reported for produced-water samples in the Weyburn field in Saskatchewan[4]. A background wetland sample (BGWL), containing primarily snowmelt, had the smallest Sr concentration and is the only sample with a CI <0.035 (0.022). The well sample (264A) with the largest CI also plots closest to the produced-water sample, indicating that mixing with PW-1 is very likely.

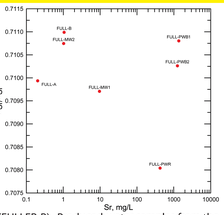
Anderson WPA





CI values ranged from 0.005 (A-1MW) to 0.651 (AND-PW). Produced-water sample (AND-PW) has the largest Sr concentration (319,000 µg/L). One wetland sample (AND10) and one well sample (A-1MW) are not contaminated by brine as indicated by the low CI and low Sr concentrations. Three well samples (A-10MW, A-11MW, and A-16MW) have low CI values that are not supported by the Sr concentrations and Sr isotope ratios. The well sample (A-14MW) with the largest CI also has the second-largest Sr concentration.

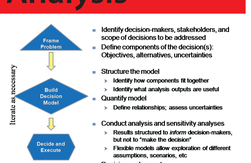
Fuller WPA



CI values ranged from 0.015 (FULL-MW1) to 0.044 (FULLER-B). Produced-water samples from the Ratcliffe (FULL-PWR) and the Bakken Formations (FULL-PWB1 and FULL-PWB2) have the largest Sr concentrations (423,000 µg/L, 1,360,000 µg/L, and 1,250,000 µg/L, respectively). One well sample (FULL-MW1) has a CI < 0.035, but has larger Sr concentration than the other water samples.

Decision Analysis*

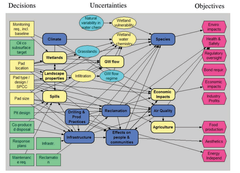
- *Decision Analysis (DA) is a formal approach for structuring, modeling, and evaluating decisions that contain a complex set of factors
- We held a four-day DA workshop to identify science and information needs relevant to decision-makers.
- We identified relevant decision-makers and the scope of their decisions. Decisions were then broken down into components: objectives, alternatives and uncertainties.
- Following the framing step, we reduced the scope of our analysis to develop a prototype decision model applicable to the U.S. Fish and Wildlife Service, one of the participants in the workshop.
- The scope of this decision problem was to develop best management practices for well or well pad development in the vicinity of publicly managed resources (i.e. wetlands). This same strategy could assess the risk of past well development.
- Our modeling exercise identified information needs to be addressed in future workshops:
  - Including perspectives from the energy industry and private land owners
  - Better defining the spatiotemporal scale of energy development
  - Considering alternative strategies: mitigation, remediation and development
  - Value of information that we might collect in future studies



Decision-makers	Decision types
Oil Industry	Lease acquisition (where to develop) Well development (where, when, and how) Operations (fracing, water disposal, etc.)
Land and mineral owners (including agricultural entities)	Whether to lease and under what conditions What activities to allow on their lands What activities to conduct/given development (e.g. cropping choices)
Regulatory agencies (varied)	Well permitting (Yes/No and specific conditions) Infrastructure permitting Hauling regulations / road safety Enforcement
Land and resource management agencies (e.g. USFWS , NPS, Private landownerships)	Recommendations/consultation on well development on or near managed resources Management of any adverse impacts from development on those resources
Local communities	Decisions about how to manage the "boom"

Five Main Objectives Identified

1. Maximize sustainability of habitats for species of interest
2. Minimize adverse impacts of well development
3. Maximize the economic benefits from well development
4. Minimize conflict between stake holders
5. Maximize accountability of industry for adverse impacts



Conclusions

- Saline contamination has traveled down-gradient at least 1.6 km at Rabenberg and 1.2 km at Anderson since initial contamination.
- Lateral transport of saline contamination is much greater than vertical transport.
  - From the geophysical and water chemistry data it appears that horizontal transport is 500 times greater than vertical transport rates in outwash.
- 33% of the wetlands within the portion of the PPR that intersects the Williston Basin are within 1.6 km of petroleum related wells.
- Sr isotopes are useful indicators to detect small amounts of brine contamination.
- To best understand the pathways and extent of brine contamination, the integration of hydrology, geochemistry, and geophysics is important.
  - Hydrologic characteristics include transmissivity, aquifer delineation, and understanding groundwater flow paths
  - Geochemical characteristics include major-ion and trace-element concentrations and strontium-isotope ratios
  - Geophysical characteristics include ground-surface EC mapping
- Co-produced waters had CI values ranging from 0.543 in the Mississippian Ratcliffe Formation (Rabenberg) to 0.822 in the Devonian/Mississippian Bakken Formation (near Fuller). Surface and groundwater samples had CI values ranging from 0.005 to 0.485 (both at Anderson).
- All of the 26 water samples classified as contaminated at the Rabenberg site in 1989 had CI values in 2009 greater than 0.035, as did the two groundwater wells that were uncontaminated in 1989.
- One of these two wells was hydraulically up-gradient from a contaminated groundwater plume, but hydraulically down-gradient from a flow line break that occurred in 2006. Contamination in this well in 2009 shows the continued threat to aquatic resources from routine oil field operations.
- All 10 of the water samples classified as contaminated at the Anderson site in 2004/2005 had CI values in 2010 greater than 0.035. The five sites with CI values below 0.035 in 2004/2005 remained below 0.035 in 2010.
- Three of the four water samples at the Fuller site had CI values above 0.035.
- In total, 45 of the 48 surface and groundwater samples collected at the three study sites had CI values and/or Sr ratios indicating contamination from co-produced waters.
- A complete account of all conclusions from this study will be published in a USGS Professional Paper, expected 2012.

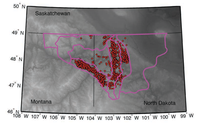
Parallel/Future Work

- **Groundwater availability in the Lower Tertiary and Upper Cretaceous aquifer system.**
  - Important source of water in energy development
  - Shallow and accessible
  - Important source of stock/domestic water
  - Williston Basin is large O/G field and largest lignite field
  - PRB has substantial coal and coal bed methane

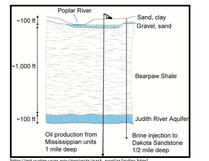
- **Development of methods for quantifying water requirements for possible future Bakken development[2]**
  - Building from existing USGS oil and gas assessment methodologies
  - Region is divided into assessment units based on geology and other factors
  - "Cells" represent the area drained by one well, and size can vary between assessment units
  - All relevant quantities are probabilistic distributions, and are combined with Monte Carlo techniques
  - Resulting water requirement quantities are intended for comparison with available water resources (see above)

	No. wells	min (Gal)	mean (Gal)	max (Gal)
2006	21	92 k	460 k	2.5 M
2007	107	17 k	620 k	3.1 M
2008	365	20 k	710 k	1.8 M
2009	483	6.0 k	920 k	3.5 M
2010	712	1.0 k	1.6 M	4.7 M
2011	114	120 k	1.7 M	3.1 M

Approximate amount of frac water per well in North Dakota

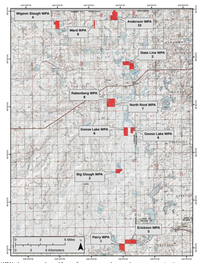


- **East Poplar oil field brine contamination in ground water resources from traditional petroleum production methods**
  - Traditional o/g development over 60 years
  - Enormous amounts of brine produced
  - Brine disposed in pits and injected into deep wells
  - Contamination has resulted in shallow sole-source aquifer and the Poplar River
  - Contamination appears to be in one of the City of Poplar's public-water supply wells, which is no longer in use.



http://mt.water.usgs.gov/projects/east_poplar/index.html

- **A GIS based vulnerability assessment of contamination to aquatic resources from oil and gas development in eastern Sheridan County, MT**
  - Ranked sections (1-100 scale) within eastern Sheridan County on their risk of contamination to aquatic resources based on
    - Age and density of oil wells
    - Proximity of oil wells to wetlands and streams
    - Type of glacial deposit
  - Selected ten sections containing Waterfowl Protection Areas (WPA) across the range of values
  - Collected two groundwater and two surface-water samples from each selected WPA



WPA's that were selected for surface-water and groundwater contamination samples. Number indicates rank (the higher the value the greater the likelihood of contamination).

- **Define priority areas for collecting baseline data and define types of baseline data needed**
  - Ground and airborne electrical geophysical methods utilized in framework studies
  - Regional water chemistry and aquifer characterization

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