DESIGN OF AIRBORNE ELECTROMAGNETIC SURVEYS FOR ECOSYSTEM ASSESSMENT IN THE WILLISTON BASIN BASED ON GEOLOGICAL, GEOCHEMICAL, HYDROLOGIC, AND GEOGRAPHIC INFORMATION SYSTEM DATA

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INTRODUCTION AND PREVIOUS RESEARCH

Abstract

Subsurface mapping of electrical conductivity by airborne electromagnetic (AEM) surveys aids in understanding hydrogeology frameworks and in mapping both naturally occurring saline waters and those co-produced from energy development (brine). The Williston Basin in the Northern Great Plains has been a leading source of domestic oil for over 50 years, with rapid new development occurring in the Bakken and Three Forks Formations. The Williston Basin is overlain by the Prairie Pothole Region (PPR), an area of abundant wetlands that provide critical habitat for waterfowl and other wildlife. Energy development can result in the release of saline and toxic brine. In the PPR, the migration of brine may pose a serious risk to wildlife, agricultural lands, and groundwater resources.

An AEM survey of the East Poplar oil field in the western Williston Basin is a good example of an application to map hydrogeologic features to depths of 40 – 50 m. Interpretation of subsurface features greatly added groundwater models and identification of: 1) glacial features such as shallow lake sediments, buried glacial valleys, and shallow gravel units, 2) subsurface brine plumes, and 3) shallow point sources of brine associated with oil production, brine disposal, and infrastructure failures.

The U.S. Geological Survey is studying potential environmental effects using a risk assessment of energy development to aquatic resources. The extent of contamination in the Williston Basin is unknown, requiring spatial data on energy infrastructure and aquatic resources. In addition, water chemistry analyses and geophysical surveys quantified the extent of contamination and rate of brine movement in the most common geologic deposits in the PPR (till, outwash, and lacustrine). We characterized and mapped contaminated groundwater at least 0.8 km and up to 1.6 km from the likely sources. The spatial analysis identified 292,745 wetlands and 7,147 km of streams within 1.6 km of petroleum related wells. We also held a decision analysis workshop for numerous stakeholders to establish a framework to evaluate potential effects of energy development on environmental resources. This approach can prioritize AEM survey areas to examine possible risks to ecosystems and groundwater resources. Results from an integrated study that includes AEM would be critical in assisting Federal and State resource managers make science-based decisions to allocate limited resources to areas of greatest need.

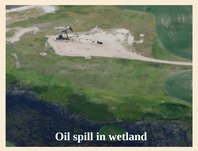
Study Area

The Prairie Pothole Region (PPR) covers 770,000 km² in the northern Great Plains and Canada and contains thousands of wetlands that are critically important to waterfowl

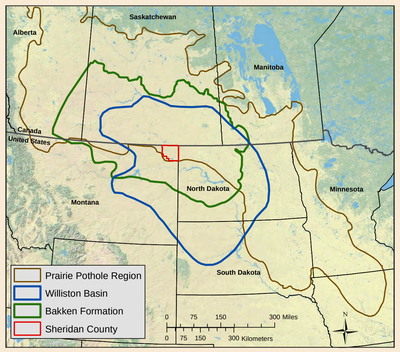
The Williston Basin has been a leading domestic source of oil and gas for decades

The Bakken Formation is experiencing rapid oil development due to advances in hydraulic fracturing and lateral drilling

Contamination from co-produced water has been documented in aquatic resources throughout the PPR and Williston Basin


Oil spill in wetland


Reserve pit for co-produced water



Water Quality

Naturally High TDS Water

- Enriched in Na, Mg, SO_4, and HCO_3
- TDS of surface and shallow groundwaters vary by landscape position but are usually <100,000 mg/L
- Chloride ranges from < 10 to 350 mg/L

Co-Produced Water

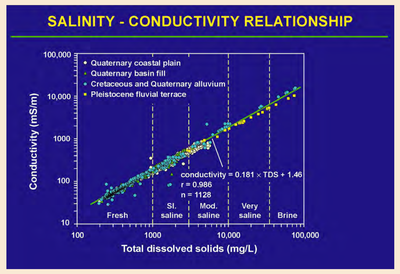
- Enriched in Na and Cl
- Co-produced waters in the Williston Basin have TDS ranging from 100,000 to 525,000 mg/L
- Chloride ranges from 30,000 to 350,000 mg/L[1]

Airborne Geophysical Surveys

Airborne electromagnetic (AEM) surveys map electrical conductivity (the reciprocal of resistivity) of the earth's sub-surface to depths ranging from 30 to 300 hundred meters[2]. The specific depths mapped depend on the electrical conductivity (EC) and the AEM method used. AEM surveys have been used to map high EC associated with co-produced waters since 1987[3]. Maps of EC also can be base lines for monitoring changes in subsurface EC as demonstrated by a repeated survey over a Mississippi oil field. The top right figure shows a frequency domain system used in many AEM studies.

A compilation of the observed relationship between salinity and electrically logged EC is shown in the bottom right figure. High EC can also be caused by natural high salinity groundwater and by high ion exchange clays that have a high EC. Noise can be created in AEM surveys by power lines, pipelines, and other metallic features associated with hydro-carbon production. None-the-less, AEM applications have largely been successful in mapping high salinity contaminant plumes to depths of 40 meters in high EC terrains.

A major consideration in use of AEM methods is their expense, with the typical project costing at least $100,000. Cost for recent surveys (2010) for hydrologic framework studies have been on the order of $9 an acre. Consequently, the approach used in the STEPPE project to identify high vulnerability areas is ideal to select high priority areas for more detailed studies, including AEM surveys.



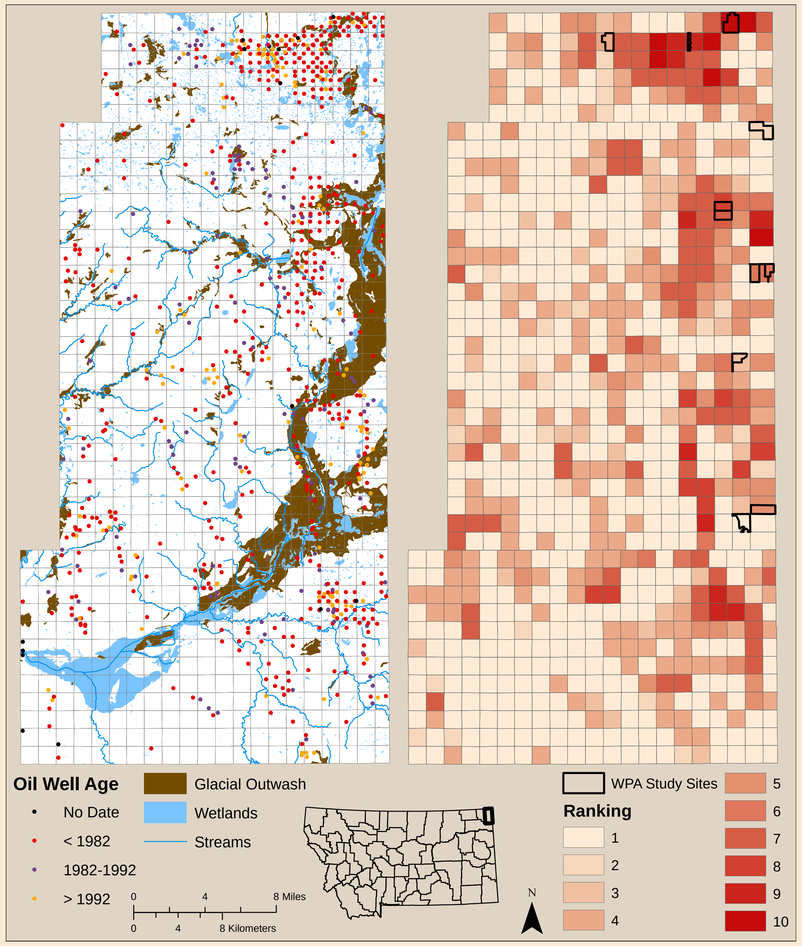
For more information on the STEPPE project go to:

http://steppe.cr.usgs.gov

VULNERABILITY ASSESSMENTS

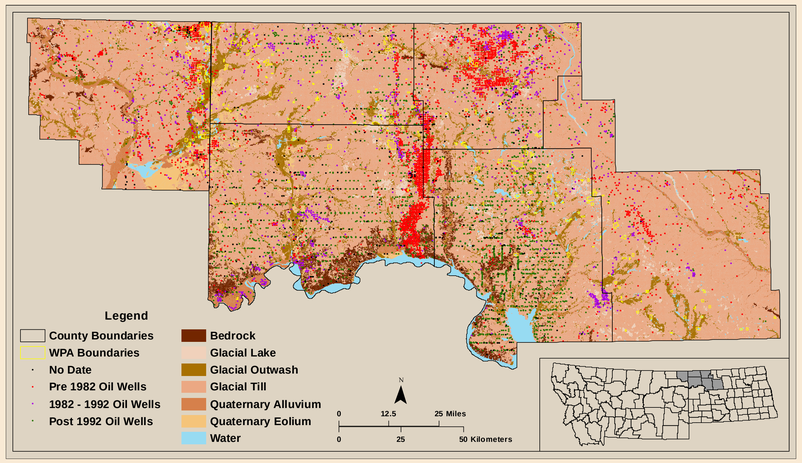
Regional-scale mapping of groundwater vulnerability commonly uses the index method[4], where important indices are identified and quantitatively combined with different numerical scores and weights to model the relative importance of the physical attributes in influencing vulnerability, the natural variability, and the availability and spatial resolution of data.

Eastern Sheridan County, Montana



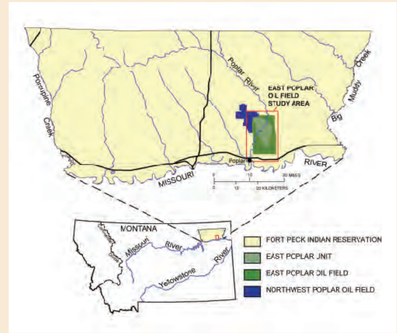
780 sections were modeled based on age and density of oil wells, percent of wetland area, percent of outwash area, and total stream length per section. Scores were binned into 10 equal interval ranks with 2 surface water and 2 groundwater samples collected from the section with the greatest acreage of Waterfowl Production Area land in each bin. Co-produced water contamination generally increased with greater vulnerability assessment scores with a better correlation for groundwater samples than surface water samples. Full results will be published by Preston et al. in Science of the Total Environment in late 2013[5].

Lostwood National Wildlife Refuge Complex



A similar vulnerability assessment is being conducted to examine potential co-produced water contamination on 199 parcels managed by the Fish and Wildlife Service in the Lostwood National Wildlife Refuge Complex using the variables described in the Sheridan County assessment and will also include breeding bird pair data. All data shown in map are from public sources.

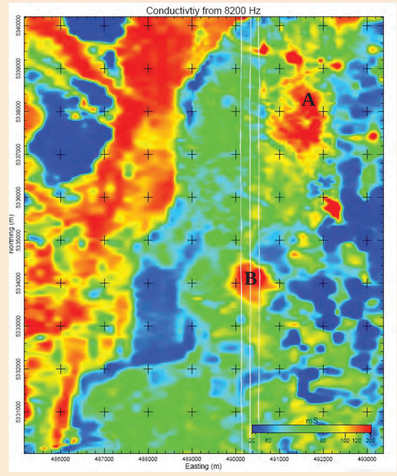
EAST POPLAR OIL FIELD SURVEYS



Areas of high conductivity in shallow aquifers in the East Poplar oil field (EPOF) area have been identified in collaborative studies by the USGS, the Fort Peck Assiniboine and Sioux Tribes, Pioneer Natural Resources (PNR), and other energy companies to delineate areas of co-produced water contamination. The EPOF area is located on the Fort Peck Indian Reservation and along the western edge of the Williston basin and demonstrates methods that can be used by the STEPPE project throughout the basin. Ground electromagnetic methods were first used during the early 1990s to delineate more than 12 square miles of brine contamination in a portion of the EPOF area[6]. An AEM survey was conducted in August 2004 and covered 1,094 linear miles in a 106 square-mile area that includes the EPOF. North – south flight lines were spaced at 100 m and 200 m. More than 40 boreholes have been logged using induction EC and gamma techniques by the USGS and by PNR[7]. Water from hundreds of wells has been sampled by multiple entities.

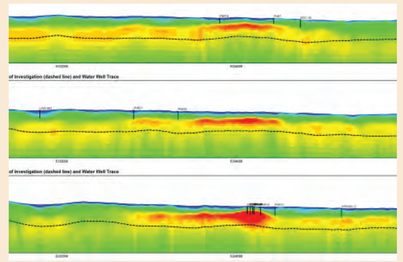
http://mt.water.usgs.gov/projects/east_poplar/index.html

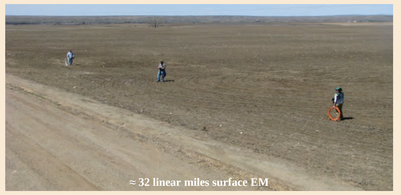
Geophysical Surveys

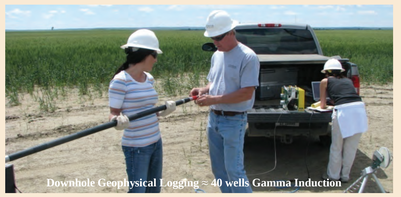


The map on the left shows the distribution of apparent EC at 8200 Hz from the AEM survey. Red areas are high EC. High EC in the northwest part of the survey is due mostly to the shallow and conductive Bearpaw shale. The shale is deeper on the east side of the survey area where glacial deposits extend to depths of 30 meters. High EC in areas A and B delineate groundwater that has become contaminated by high salinity co-produced water during energy production. Contamination in area A is due largely to shallow sources and the contamination in area B is due to saline water migrating up an abandoned well.

Conductivity depth sections (bottom left) are oriented south to north along the white flight lines on the EC map. Black dashed lines in each section represent the maximum depth of resolution. Dark red areas indicate saline ground-water in area B. Lighter yellow areas generally indicate the top of the Bearpaw shale. Though the contamination has been defined by ground geophysics and boreholes, the AEM survey shows a detailed extent, laterally and vertically.




≈ 32 linear miles surface EM


Downhole Geophysical Logging ≈ 40 wells Gamma Induction

FUTURE WORK

- White paper for application of airborne electromagnetic (AEM) surveys to specific areas within the region of the STEPPE study
- Conduct ground and where possible borehole geophysical surveys in high priority areas from vulnerability studies and for Federal Lands.

ACKNOWLEDGEMENTS AND REFERENCES

Funding for the Sheridan County vulnerability assessment was provided by the USGS State Partnership Program and completed with collaboration from Jon Reiten of the Montana Bureau of Mines and Geology, Jerry Rodriguez of Medicine Lake National Wildlife Refuge (MLNWR), and Mickey McCall of the Sheridan County Conservation District. Funding for the Lostwood Refuge vulnerability assessment was provided by the U.S. Fish and Wildlife Service Region 6 Inventory and Monitoring Program and is beeing completed with collboration from Mike Borgreen of MLNWR. East Poplar oil field geophysical surveys were supported by the Fort Peck Tribes' Office of Environmental Protection with strong collaboration between the USGS, Fort Peck Tribes, and local oil and gas companies.

[1] Iampen, H.T., and Rostron, B.J., 2000, Hydrogeochemistry of pre-Mississippian brines, Williston Basin, Canada–USA: Journal of Geochemical Exploration, v. 69–70, p. 29–35.

[2] Smith, B.D., Thamke, J.N., Cain, M.J., Tyrrell, C., and Hill, P.L., 2006a, Helicopter electromagnetic and magnetic survey maps and data, East Poplar Oil Field Area, Fort Peck Indian Reservation, Northeastern Montana, August 2004: U.S. Geological Survey Open-File Report, 2006-1216, 18 p.

[3] Smith, B.D., Grauch, V.J.S., McCafferty, A.E., Smith, D.V., Rodriguez, B.R., Pool, D.R., Deszcz-Pan, M., and Labson, V.F., 2007, Airborne Electromagnetic and Magnetic Surveys for Ground-Water Resources, in, B. Milkereit, editor, Exploration in the New Millennium,Proceedings of the Fifth Decennial International Conference on Mineral Exploration, 4p

[4] Focazio, M.J., Reilly, T.E., Rupert, M.G., and Helsel, D.R., 2002, Assessing ground-water vulnerability to contamination: Providing scientifically defensible information for decision makers: U.S. Geological Survey Circular 1224, 33 p.

[5] Preston, T.M., Chesley-Preston, T.L., and Thamke, J.N., A GIS based vulnerability assessment of contamination to aquatic resources from oil and gas development in eastern Sheridan County, MT: Science of the Total Environment (in press)

[6] Thamke, J.N., and Craigg, S.D., 1997, Saline-water contamination in Quaternary deposits and the Poplar River, East Poplar oil field, northeastern Montana: U.S. Geological Survey Water-Resources Investigations Report 97-4000, 37 p.

[7] Smith, B.D., Thamke, J.N, Tyrrell, C., 2006b, Geophysical and Hydrologic Studies of Shallow Aquifer Contamination, East Poplar Oil Field Area, and Northeastern Montana: Proceedings Symposium on Engineering and Environmental Geophysics Seattle WA, 16p.