

**Water Resources Center
Annual Technical Report
FY 2016**

Introduction

The Minnesota WRI program is administered by the University of Minnesota Water Resources Center (WRC), which is jointly supported by two colleges: the College of Food, Agricultural, and Natural Resource Sciences (CFANS) and University of Minnesota Extension. The leadership of the center includes a Director, Jeff Peterson, who was hired in 2015, and an Associate Director, Faye Sleeper, who reports to the Director. Peterson reports to the Dean of CFANS and the Dean of Extension. In addition to the leadership team, the WRC has 10 other staff members: an education coordinator, a research fellow, an associate administrator, a communications associate, an accountant, and five staff members work to coordinate and deliver the center's outreach programs. The interdisciplinary Water Resource Sciences graduate program, with a graduate faculty of over 100 members spanning 23 departments on the Twin Cities and Duluth campuses, is also administratively housed in the WRC and is managed by two co-Directors of Graduate Studies and a Graduate Program Coordinator.

Research Program Introduction

In early October 2015, the WRC released a Request for Proposals for its fiscal 2016 grant competition supported by WRRRI 104b funds. The WRC received eight proposals by the November 19 deadline. We then requested 6 external reviews for each proposal, seeking reviewers who were experts on the proposed topics from both within and outside Minnesota. As in past years, an Advisory Committee was convened to advise the WRC on funding decisions. Each committee member was provided copies of the proposal and external reviews. The committee met in December 2015 and selected three proposals to be recommended for funding. Each project was featured in our quarterly newsletter, the Minnegram.

Making Farm-Scale Decisions to Improve Watershed-Scale Environmental Quality: Policy Comparisons Based on Farm-Level Abatement Costs

Basic Information

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| Title: | Making Farm-Scale Decisions to Improve Watershed-Scale Environmental Quality: Policy Comparisons Based on Farm-Level Abatement Costs |
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| Principal Investigators: | Jay Coggins, Brent James Dalzell |

Publications

1. Wang, Zhiyu, "Economics of Water Pollution: Permit Trading, Reliability of Pollution Control, and Asymmetric Information," PhD dissertation, University of Minnesota, May 2017.
2. Wang, Zhiyu and Jay S. Coggins, "Reliable Reduction in Agricultural Runoff under Environmental Uncertainty," working paper, University of Minnesota, May 2017.
3. Wang, Zhiyu, "Reliability of Pollution Control, Implementation, and Asymmetric Information," working paper, University of Minnesota, May 2017.
4. Zhiyu Wang, "Water Quality Trading with Flow Pollution and Stock Pollution," poster presentation, Minnesota Water Resources Conference, Saint Paul, Minnesota, 2016 .
5. Zhiyu Wang, "Water Quality Trading with Flow Pollution and Stock Pollution," paper presentation, Environmental and Resources Economics Seminar, UMN, 2016
6. Zhiyu Wang, "Reliable Reduction in Agricultural Runoff under Environmental Uncertainty," paper presentation, Midwest Economics Association Annual Meeting, Cincinnati, Ohio, 2017.
7. Zhiyu Wang, "Reliable Reduction in Agricultural Runoff under Environmental Uncertainty," paper presentation, Society for Benefit-Cost Analysis Annual Conference, Washington D.C., 2017.

Annual Program Report

Project 2016MN365B: “Making Farm-Scale Decisions to Improve Watershed-Scale Environmental Quality: Policy Comparisons Based on Farm-Level Abatement Costs”

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1) Research

Work under this funding project has led to two inter-related research papers, which are described here in sequence. Both rely upon an analysis of the policy and economics related to controlling nonpoint agricultural runoff into the nation’s streams and rivers and downstream water bodies.

Paper 1: “Reliable Reduction in Agricultural Runoff under Environmental Uncertainty”

In the 2012 National Water Quality Inventory conducted by the Environmental Protection Agency (EPA), agricultural activity was identified as the top source of impairments in rivers and streams in the U.S., and the third source of impairments in lakes, reservoirs, and ponds. Excessive nutrients in agriculture runoff are linked to eutrophication, as well as other problems that negatively affect aquatic biomes and degrade ecosystem services. Between 2000 and 2015, about 0.8 million metric tons of nitrogen (nitrate and nitrite) entered the Gulf of Mexico every year, which created a “Dead Zone” covering an area about the size of Connecticut and Rhode Island combined (6,474 square miles).

When the environment is uncertain, the effects of abatement efforts are likewise uncertain. The current, common practice for studying nonpoint pollution policy is to set a deterministic target for the average reduction in pollution over time. In a landmark paper, Segerson (1988, p. 91) supports this practice by suggesting that “if the benefits of abatement are not known, the social planner could simply choose the level of abatement that would on average meet an exogenous target level of ambient pollution.” Much of the ensuing literature follows this suggestion, ignoring uncertainty in the analysis of environmental policies. This literature includes work on voluntary programs (e.g., Segerson and Wu, 2006), command and control (e.g., Rabotyagov et al., 2014), taxes (e.g., Suter et al., 2009), water quality trading (e.g., Collentine and Johnsson, 2012) and payments for ecosystem services (e.g., Carpentier et al., 1998; Khanna et al., 2003).

Although advances in biophysical and hydrological modeling can generate reasonable estimates of the effect of farm management practices on agricultural runoff, the resulting improvement in water quality cannot be known with certainty beforehand. The irreducible uncertainty is the heart of the study described here. An average target cannot account fully for the stochastic nature of pollution control. This means, first, that the probability of failure to meet a given target level of emissions reduction is not directly regulated. Even if the policy achieves a given target on average, it might still be the case that runoff exceeds the target significantly in some years. It also means, second, that an average target does not describe the entire picture of water-quality improvement, which can come from an average reduction in pollution over time or from a reduction in the frequency of extreme runoff events.

A common management practice is to use a margin of safety with a reduction target to address these issues. For example, the margin of safety is introduced as a component of Total Maximum Daily Load (TMDL) to account for “uncertainty in predicting how well pollutant reductions will result in meeting water quality standards” (United States Environmental Protection Agency, ndb). The margin of safety is developed for the sake of reliability, limiting the frequency of extreme runoff events.

In this paper we use a reliability target in controlling pollution from agricultural runoff, where reliability means achieving a given target with a specified probability over time. The main contribution of the paper is to introduce and analyze a reliability constraint in a water pollution control model. The corresponding water quality improvement is thereby achieved with a specified level of confidence. Rabotyagov et al. (2014) argue that this type of reliable reduction target in pollutants can be used to improve the resiliency of ecosystem services such as improved water quality. Using a reliability target, the pollution control problem of agricultural runoff becomes an optimization problem with chance constraints.

Solving a chance-constrained pollution-control problem requires knowledge of the probability distribution of pollution. Unfortunately, this information is typically not available. The typical practice in the literature is to assume a specific probability distribution for runoff. The chance constraint is then transformed into a deterministic constraint using a specified form for the distribution. However, validation then depends on how well the distributional assumption approximates the actual distribution. Roy (1952), on the other hand, developed a safety-first criterion in portfolio management without a distributional assumption. This criterion is based on Chebyshev’s inequality, and can also be used in pollution control to derive a robust solution that protects against the worst case of all possible probability distributions. Roy’s method creates a feasible set that meets the chance constraints for all possible probability distributions and is free from misidentification of the actual probability distribution.

In the theoretical model, we consider a group of risk-neutral farmers who wish to maximize their profits while also controlling agricultural runoff. Let R be the aggregate runoff from those farmers, and let R' be a specified reduction target, which is set by an environmental authority. The aggregate runoff R depends on both the farm management decisions X and exogenous uncertainty ϵ in the environment, reflecting unpredictable weather and streamflow conditions. The total profit of those farmers also depends on X and ϵ , where the crop prices and the costs of different farm management options are assumed constant over time.

An environmental regulator following Segerson's (1988) recommendation would approach the problem of water-quality policy by maximizing farmers' profits subject to a constraint on the expected amount of pollution. The regulator in this framework simply sets a target level of reduction that would be attained on average over time. This approach ignores the reliability of the policy, with possibly extreme exceedances occurring in some years.

An alternative approach, chance-constrained programming, is employed here, which aims to limit the probability of exceeding a given target level of runoff. We set an upper bound α on the probability that a reduction target is not attained in a period. In other words, a reduction target should be achieved with an assurance level no less than $1 - \alpha$. A reduction target R' and a reliability target α together comprise a reliability target.

Figure 1 shows the difference between average targets and reliability targets. Typically, a reduction in pollution is accompanied by a reduction in the variance of pollution, while the size of the variance reduction depends on different abatement practices and their spatial allocation. Figure 1(a) shows an average target that only limits the average pollutant runoff to R' , regardless of the probability in the right tail. However, a reliability target in Figure 1(b) concerns the right tail of the runoff distribution. It restricts the probability of exceeding a reduction target R' to a reliability requirement α which is represented by the red area. Figure 1(c) shows the scenario that requires the same reliability level but more reduction. The probability distribution of pollution moves further to the left, while keeping the same probability of the right tail, i.e., the red area in the figure. Figure 1(d) displays the scenario that requires a higher reliability but the same reduction. Previously, the reliability requirement is α_1 , which is the sum of the pink area and the red area. The new reliability requirement α_2 is more stringent, and the new runoff distribution moves further to the left. The pink area is not included in the new distribution at reliability level α_2 .

The empirical application of this policy framework is based upon data from the Wolf Creek Watershed in Iowa, which is located in one of the priority watersheds identified by the Iowa Nutrient Reduction Strategy. The results show that a reliability target results in larger losses of agricultural profits than a deterministic average target. For example, to yield a 41% reliable reduction (70% reliability) in total nitrogen, a 75% loss in agricultural profit (\$59.8 million) must be undertaken. Despite the loss in profits, the target is missed in only one out of ten years, and the gap is much smaller under this reliability target (70% reliability). A deterministic average target, by contrast, misses its target five out of ten years. Therefore, the reliability target can be a valuable tool when consistently meeting the target is important. The reliability target is also used to show how current management practices can be modified. One important finding is that a constant margin of safety implies different levels of reliability when the level of target Total Maximum Daily Loads (TMDL) varies. If a given level of reliability is desirable, the margin of safety should increase with the level of TMDL.

In summary, a reliability target is costly to achieve, since it requires more abatement effort to prevent the worst runoff events from occurring. The analysis does not take into account the benefits of reduced agricultural runoff, but this is not meant to suggest that they are negligible (compared with abatement costs). Policymakers should consider incorporating a reasonable reliability target in water policy.

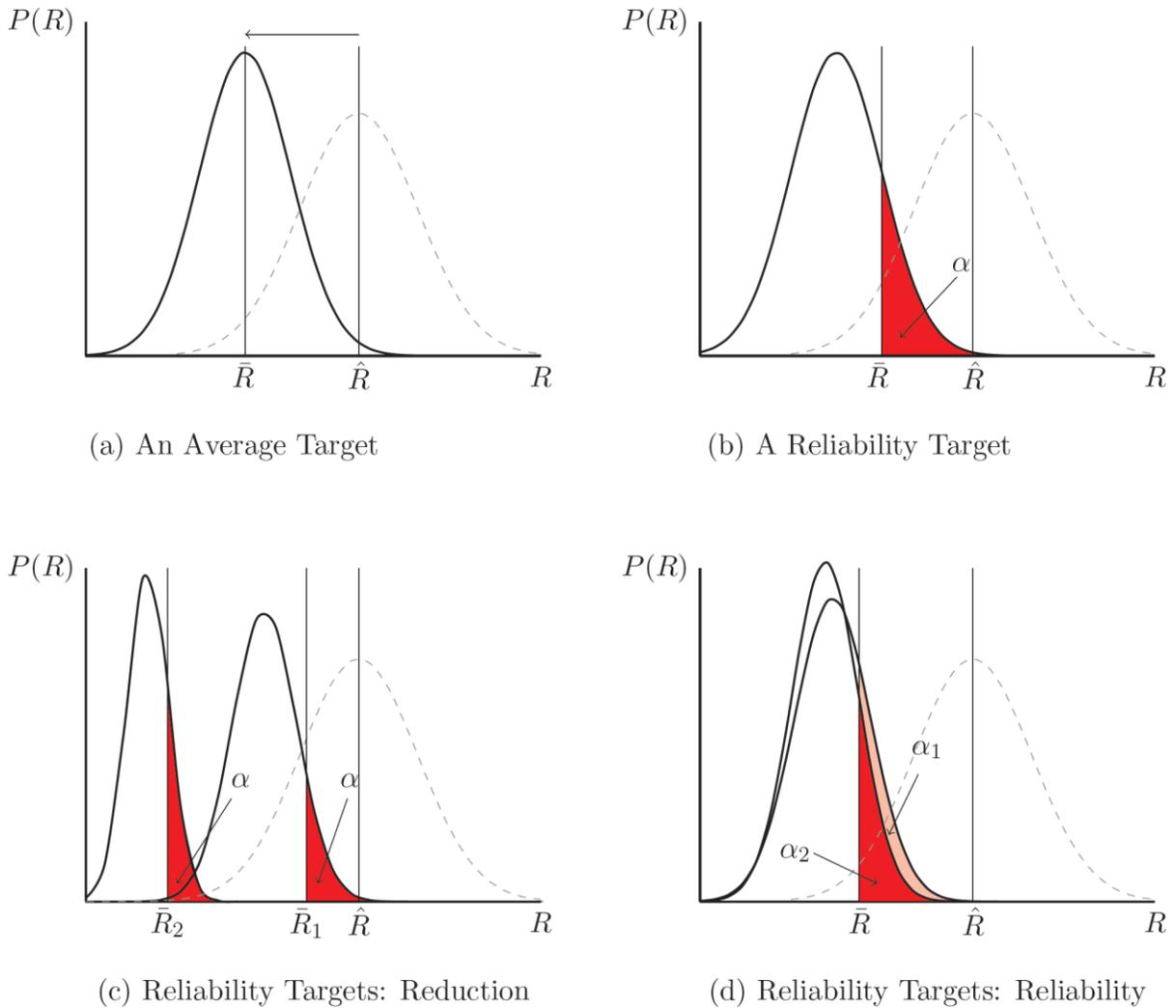


Figure 1. Reliability targets for agricultural runoff policy.

Paper 2: “Reliability of Pollution Control, Implementation, and Asymmetric Information”

Here again we focus on the stochastic nature of agricultural runoff and water-quality regulations. A large literature on water-pollution control either neglects environmental uncertainty in the analysis or takes an average target on the pollution over time, which avoids considering the fluctuation in different periods. Segerson (1988) suggests using an average target in pollution control, especially when the benefits of pollution abatement are unknown. However, considering the stochastic nature of the pollution, an average target fails to consider the fat tail problem of the pollution probability distribution, where the most serious environmental damage occurs during extreme pollution events. This type of target embeds two disadvantages in pollution control: first, it cannot directly regulate the probability of failure to achieve a given pollution reduction; second, it cannot directly count a decline in the occurrence of heavy pollution events as an

environmental improvement. Thus, it cannot properly describe the objective of pollution control under environmental uncertainty, that is, to improve the probability distribution of the pollution.

The first-best policy to achieve a reliability target on the total pollution in an area should consider each polluter's abatement effort and also how these abatement efforts collectively impact the probability distribution of the total pollution. To figure out this result, the regulator needs intensive information on polluters' abatement practices and costs. However, asymmetric information commonly exists in pollution control in practice. We may be unable to observe polluters' behaviors or to obtain the accurate information on their abatement costs. The unobservability of polluters' behaviors generates a moral hazard problem. Taking agricultural runoff problem as an example, farmers may apply more fertilizer than what they report to the regulator. The lack of polluters' information on abatement costs prevents us from deriving the first-best outcome of a reliability target in pollution control. We need to address these problems caused by asymmetric information, so as to realize the first-best outcome of a reliability target.

The usual approach to the problem, however, requires complete information on polluters' abatement costs is indispensable to determine the appropriate tax/subsidy rate so as to attain the first-best outcome of nonpoint pollution control. In this study we address the private-information problem through mechanism design. The work of Vickrey (1961), Clarke (1971), and Groves (1973) together creates the Vickery-Clarke-Groves (VCG) auction mechanism, where every participant has an incentive to reveal their private information truthfully. Duggan and Roberts (2002) design a truth-telling mechanism to achieve the first-best result of pollution control, where polluters choose the amount of permits to purchase at a price independent of their actions but they need to report their neighbor's emission level. If individual emission or individual use of a common property resource is detectable, Montero (2008) improves the work of Duggan and Roberts by incorporating the VCG-payoff structure in a permit market, where each participant only claims his own demand schedule. Polasky et al. (2014) extend the application of the VCG mechanisms into the optimal provision of ecosystem services, where the benefits are spatially dependent. These mechanisms all motivate truthful revelation, and attain the optimal outcome in environmental conservation. However, all these mechanisms assume that everyone's behavior, emission or use of a resource is observable.

This paper contributes to the literature by developing an auction mechanism to achieve the first-best result of pollution control, where polluters have both private information and unobservable actions. Inspired by the literature on truth-telling mechanisms, we develop an auction where every polluter submits his subsidy bids on how much he needs to implement each conservation practice respectively and every polluter will receive a subsidy independent of his bids. A dominant strategy in this auction for polluters is to bid their actual abatement costs. Considering the moral hazard problem, polluters may deviate from the conservation practice which he is subsidized to do, whenever the practice is unobservable. In order to solve this problem, take fertilizer application as an example, we first limit the degree of unobservability by subsidizing only the minimum fertilizer rate that farmers may consider in an area, and then incorporate a fine/reward based on the total pollution into the auction. This fine/reward will be imposed on the farmers who are subsidized to minimize their fertilizer application, and ensures that it is optimal for these farmers not to deviate. This subsidy auction can obtain the actual information on

polluters' abatement costs, so that the regulator is able to derive and to motivate polluters to achieve the first-best outcome of a reliability target in pollution control.

The empirical application in the paper is again based upon data from the Wolf Creek Watershed in Iowa. We analyze the reliability of pollution control under asymmetric information. The Wolf Creek Watershed has a serious nitrogen runoff problem. It is located in the Middle Cedar Watershed, one of nine priority 8-digit Hydrological Unit Code watersheds of pollution control identified in the Iowa Nutrient Reduction Strategy. The Wolf Creek Watershed is 846 km² (327 square miles). About 83% of the area is cropland, and annual crop profit was \$79.6 million from 2004 to 2013. The entire watershed is in No. 104 Major Land resource Area, according to its soil pattern, climate, water resources and land use. During the period from 2004 to 2013, an average of 2.3 million kilograms total nitrogen (TN) ran off this watershed annually, fluctuating from 0.6 million to 4.6 million kilograms.

This study uses the Soil and Water Assessment Tool (SWAT) to simulate the effect of different farming practices on crop production and nitrogen runoff. There are 11 farm-management alternatives to abate the pollution in the analysis, including such practices as reduced tillage, grass buffer strips, land retirement, and reduced fertilizer application. We assume that reduced fertilizer use is the minimum fertilizer rate that farmers will consider in the area. The implementation costs of different farm-management practices are obtained from studies on conservation practices in Iowa (Kling et al., 2007). The input costs and crop prices are inflation-adjusted averages during 2011-2015. We assume no market uncertainty in the analysis.

Our results, based upon a subsidy auction that induces farmers to report their true cost of runoff reduction, are able to induce farm-management practices to achieve different reliability targets. In the efficient solution, land retirement from row-crop production and cover crop/reduced fertilizer are widely used. Land retirement is effective and indispensable in achieving a reliable reduction in the pollution. More area is converted to prairie with a more stringent target. The total subsidy paid to farmers is higher than their total cost of reducing runoff. The information rent, i.e. the difference between total subsidy and the total cost, exists to motivate every subbasin to disclose its actual cost. The information rent seems to increase slightly with a more stringent reliability target. The size of information rent is significant, and almost half of the total subsidy is paid for this information rent. However, there is no way to avoid it, without harming the cost-effectiveness of meeting a reliability target.

The main result of the paper is to show that by properly setting the values of the penalty and the reward, farmers will opt in and use the proper amount of fertilizer to attain the reliability target of pollution control in a cost-effective way. This auction is shown to minimize total abatement cost of meeting a reliability target under asymmetric information.

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2) Publications

- Wang, Zhiyu, "Economics of Water Pollution: Permit Trading, Reliability of Pollution Control, and Asymmetric Information," PhD dissertation, University of Minnesota, May 2017.
- Wang, Zhiyu and Jay S. Coggins, "Reliable Reduction in Agricultural Runoff under Environmental Uncertainty," working paper, University of Minnesota, May 2017.

Wang, Zhiyu, “Reliability of Pollution Control, Implementation, and Asymmetric Information,” working paper, University of Minnesota, May 2017.

3) Student support

Zhiyu Wang was supported as a PhD Research Assistant on the project for most of two years. She will defend her dissertation in June 2017.

4) Presentations

Zhiyu Wang, “Water Quality Trading with Flow Pollution and Stock Pollution,” poster presentation, Minnesota Water Resources Conference, Saint Paul, Minnesota, 2016 .

Zhiyu Wang, “Water Quality Trading with Flow Pollution and Stock Pollution,” paper presentation, Environmental and Resources Economics Seminar, UMN, 2016

Zhiyu Wang, “Reliable Reduction in Agricultural Runoff under Environmental Uncertainty,” paper presentation, Midwest Economics Association Annual Meeting, Cincinnati, Ohio, 2017.

Zhiyu Wang, “Reliable Reduction in Agricultural Runoff under Environmental Uncertainty,” paper presentation, Society for Benefit-Cost Analysis Annual Conference, Washington D.C., 2017.

5) Awards

N/A

6) Related funding

N/A

Development of a reactive-transport model for arsenic mobility in glacial aquifers using arsenic and iron X-ray absorption spectroscopy data

Basic Information

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| Descriptors: | None |
| Principal Investigators: | Brandy Marie Toner, GeneHua Crystal Ng |

Publications

1. Nicholas, S. L., Erickson, M. L., Woodruff, L. G., Knaeble, A. R., Marcus, M. A., Lynch, J. K., and Toner, B. M., accepted. Solid-phase arsenic speciation in aquifer sediments: a micro-X-ray absorption spectroscopy approach for quantifying trace-level speciation. *Geochim Cosmochim Acta*. DOI:10.1016/j.gca.2017.05.018
2. Ng, G.-H.C., A. Dunshee, D.A. Repert, R.L. Smith, D. L. Stoliker, J.K. Bohlke, T.D. McCobb, D.R. LeBlanc, D.B. Kent (2016), "Modeling the effect of temperature variability on groundwater arsenic plumes downgradient of eutrophic lakes." GSA Annual Meeting 2016, Denver, CO. (Invited Presentation).
3. Dunshee, A., G.-H.C. Ng, B. Toner, and M. Erickson (2017), "Reactive Transport Modeling of Arsenic Mobilization Processes in Glacial Aquifers in Western Minnesota." Shared Water, Shared Responsibility: Engaging Minnesota's Communities, Students, & Policy-Makers, Water Resources Center, University of Minnesota, March 23, 2017, Minneapolis, MN. (poster)
4. Dunshee, A., G.-H.C. Ng, and B. Toner (2017), "Reactive Transport Modeling of Arsenic Mobilization Processes in Glacial Aquifers in Western Minnesota." MnDRIVE Mini-Symposium with Barr Engineering, April 25th, 2017, Minneapolis, MN. (poster)

Development of a reactive-transport model for arsenic mobility in glacial aquifers using arsenic and iron X-ray absorption spectroscopy data

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Report: May 24, 2017

1) RESEARCH

1.1 Introduction

West-central Minnesota is a geographic nexus of drinking-water wells with arsenic (As) concentrations above the EPA maximum contaminant level (MCL) of $10 \mu\text{g As L}^{-1}$ (Welch 2000). Distribution of As-affected wells is heterogeneous with respect to location and well depth (Erickson and Barnes 2005a). The scale of the problem facing Minnesota is illustrated by the results of the Minnesota Arsenic Study (MARS): 50% of the 869 domestic wells tested in west-central Minnesota had elevated As concentrations (greater than $10 \mu\text{g As L}^{-1}$) (Minnesota Department of Health 2001). It is clear that the frequency of As contamination in domestic wells in Minnesota poses a serious and widespread public health concern. While As-removal systems can be purchased by individuals, they are expensive, require maintenance, and do not provide alarms for high As concentrations or system failure (Erickson and Barnes 2004). In response to these challenges, the Minnesota well code now requires that each new well – estimated at 8,000-12,000 wells annually – be tested for As. These data provide families and businesses with information about drinking water quality. However, the information comes only after the well has been drilled. The best practice would be to place domestic wells where the probability of clean water is highest.

Previous work comparing well construction with well-water As concentrations found that wells with short screens set close to an aquitard were more likely to have elevated As concentrations than wells in which the screen was longer and farther from the aquitard (Erickson and Barnes 2005b). This suggested that the original solid-phase source of the As was in the till, and that geochemical processes at the aquitard-aquifer interface could be liberating As to groundwater. These findings led us to hypothesize that if a geochemical process at the aquifer-aquitard

interface were releasing As from the aquitard (composed of glacial till sediments), then As speciation in the bulk aquitard would be different from the aquifer-aquitard interface. Evidence to support this hypothesis would include chemically reduced As (and Fe) in sulfide minerals in bulk aquitard sediments and chemically oxidized oxidized As (and Fe) in altered till near aquifer sediments.

For Minnesota glacial aquifers, we have been working to understand the geologic sources and chemical forms of As present (Nicholas et al. accepted). We see these as critical first steps toward understanding the (bio)geochemical processes releasing As to groundwater. The overarching strategy we employed was to: (1) measure the chemical forms of As in glacial deposits (*speciation*); (2) identify mechanism leading to As release from geologic strata to groundwater (*biogeochemical processes*); and (3) develop a reactive-transport model to understand the occurrence of As-bearing deposits at risk of releasing As to groundwater (*distribution*).

1.2 New Research Effort

Our goal was to understand how mechanisms of As release to groundwater, knowledge gained from specific rotosonic cores, translates to As in groundwater on a larger geographic scales in Minnesota. The research is important because the products and outcomes will allow us to assist in recommending strategies for placement of drinking water wells that produce higher quality water.

Our research approach was to develop a reactive-transport model to test hypotheses about As release mechanisms and extrapolate speciation data on As to Minnesota aquifers. The research has lead to new advances in model parameterization through the use of As speciation data. The research was a new collaboration between PI Toner and Co-PI Ng. We used this research to generate seed data for an externally funded proposal involving geochemical observations, in laboratory and field settings, and reactive- transport modeling for Minnesota glacial aquifers.

Our long-term research goal is to locate and preserve safe drinking water for communities in Minnesota. Our strategy is to identify the distribution of As-bearing glacial deposits at risk of releasing As to groundwater. We have developed new analytical methods to measure the processes releasing As to groundwater (Toner et al. 2011; Nicholas et al. *accepted*). Those field and laboratory methods have enabled the development of new modeling tools that can be implemented to evaluate the risk of arsenic mobilization in Minnesota groundwater.

To our knowledge, our project is the first implementation of reactive-transport modeling of As in Minnesota. Elsewhere in the world, models have provided valuable insights into As release to water (e.g. Charlet et al. 2007; Jung et al. 2009; Nath et al. 2008; Postma et al. 2007; Wallis et al. 2011; Colombani et al. 2015). However, their ability to reliably represent field conditions depends on careful calibration to adequate setting-specific data. Although certain geochemical relationships apply (nearly) universally (e.g. carbonate chemistry speciation), As release depends on many unique features, such as the density of sorption sites, the accessibility of Fe oxyhydroxides to microbes, and the available reservoir of arsenic-bearing sulfide minerals.

A major challenge in model calibration is whether available data are sufficient for constraining these unique parameters. Because the distinct As release pathways depend on Fe mineral structure and produce characteristic As forms, quantification and characterization of As and Fe speciation provide highly valuable constraints on model parameterization. Synchrotron X-ray absorption spectroscopy (XAS) techniques probe speciation details and are recognized for their utility in developing sorption models (Goldberg et al. 2007). However, most previous As modeling attempts have instead relied on simpler lab extraction techniques (see above references and review in Sracek et al. 2004), which are far easier to implement but generate only operationally defined results that introduce significant uncertainty to the model calibration.

1.3 Approach and Objectives

Our focus was on three intensively studied sites where As speciation in the solid phase was previously measured (Nicholas et al. accepted). We developed model products applicable to glaciated regions of Minnesota.

Objectives: (1) Compile and synthesize physical and geochemical data on As-release processes at example study sites; (2) develop and calibrate a reactive-transport model of As dynamics using the compiled data, including XAS speciation data; and (3) with the calibrated reactive-transport model, assess controls on As release at the example study sites and evaluate the potential for regional trends.

1.4 Methods and Procedures

In consultation with Minnesota Geological Survey scientists, we identified and sub-sampled archived rotosonic cores hailing from Traverse, Grant, Stevens, Douglas, Pope, Big Stone, and Swift counties of west-central MN (10 cores, 253 samples). The archived cores were curated by the Minnesota Department of Natural Resources, Division of Lands and Minerals.

Ottertail County core OTT-3, Traverse-Grant County core TG-3, and Upper Minnesota River Basin core UMRB-2, shown in **Figure 1**, served as the three intensive study sites for the proposed work. The well water chemistry within 10 km radii from these core locations (grey circles) is reported in **Table 1**.

We implemented a reactive multicomponent transport model PHT3D (Prommer et al. 2003), which coupled groundwater flow from MODFLOW2005 (Harbaugh 2005), the transport component of the model MT3DMS (Zheng and Wang 1999), and the geochemical capabilities of PHREEQC-2 (Parkhurst and Appelo 1999). Some previous As modeling work has focused on geochemical processes using models such as PHREEQC (e.g., Charlet et al. 2007; Nath et al. 2008; Postma et al. 2007). Our choice of PHT3D allows the flexibility to consider more complicated transport processes that are likely involved at the aquifer-aquitard interface. PHT3D has been employed previously to evaluate As processes (Jung et al. 2009; Wallis et al. 2011; Colombani et al. 2015).

Multicomponent geochemical models represent coupled reactions among various aqueous, mineral, gas, and sorbed species. This makes it possible to evaluate the diverse geochemical influences on As release to groundwater, including redox reactions, pH sensitivities, mineral precipitation and dissolution, and arsenic sorption to sediments. Standard aqueous reactions such as carbonate speciation and oxidation relationships

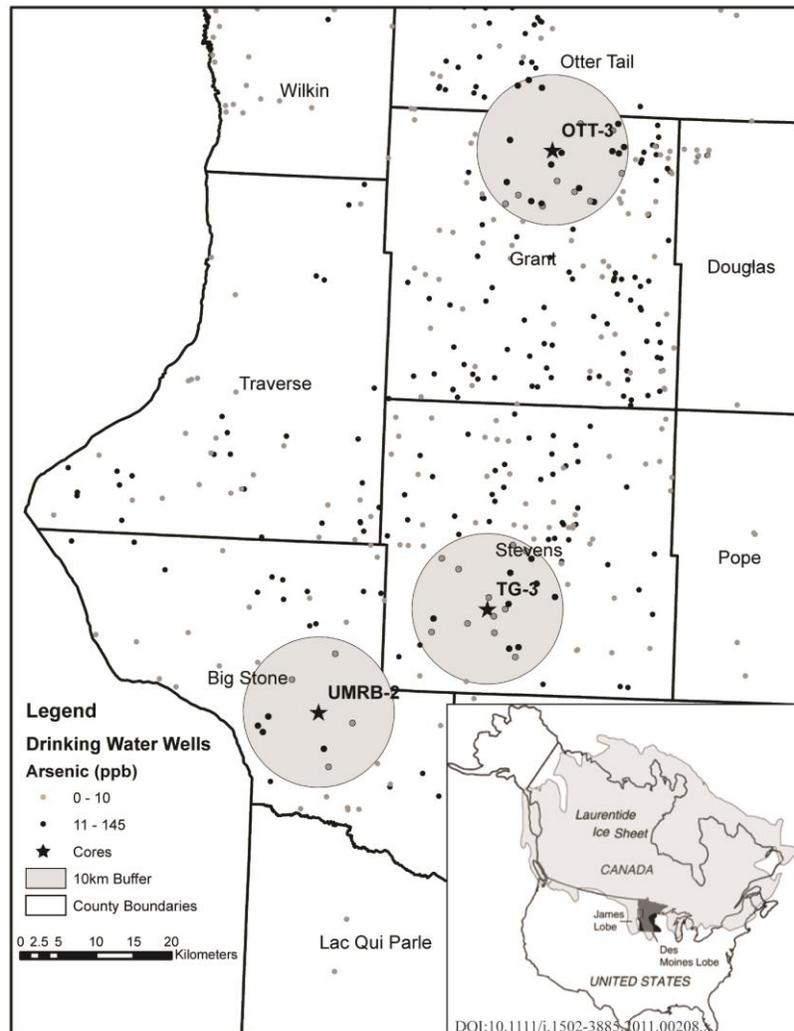


Figure 1. Map of Des Moines lobe glacial advance, west-central Minnesota, USA, showing As-affected wells, and 10km buffer around cores. Nicholas et al. accepted.

apply through the model's geochemical database of thermodynamic equilibrium constants. The arsenic model required other specific sediment-related components, such as Fe oxyhydroxide minerals, sulfide minerals, and surface complexation processes for sorption.

Table 1. Summary of groundwater properties in 10 km radii of rotosonic cores for which As speciation was measured (Nicholas et al. accepted).

| | OTT-3 | | TG-3 | | UMRB-2 | |
|---------------------------|----------------|--------------|----------------|--------------|----------------|--------------|
| | As exceeds MCL | As below MCL | As exceeds MCL | As below MCL | As exceeds MCL | As below MCL |
| | n = 8 | n = 6 | n = 5 | n = 5 | n = 4 | n = 3 |
| As μgL^{-1} | 25.3 | 3.6 | 34.0 | 3.1 | 45.3 | 0.5 |
| Eh mV | 141 | 114 | 134 | 175 | 224 | 133.9 |
| pH | 7.2 | 7.7 | 7.2 | 7.3 | 7.3 | 7.5 |
| Fe μgL^{-1} | 1792 | 1950 | 3867 | 1416 | 3845 | 1351 |
| Sulfate mgL^{-1} | 312 | 289 | 1062 | 1153 | 801 | 480 |

1.5 Results and Discussion

In the first stage of the model development and implementation, we relied on a different glacial aquifer site on Cape Cod, MA. This site has a more straight-forward As release mechanism and more extensive water chemistry data than our three Minnesota sites. Arsenic release at the Cape Cod site occurs exclusively through the reductive dissolution of Fe oxyhydroxide minerals - which releases sorbed As - as high concentrations of organic carbon lake water flows into underlying aquifer sediments. This well-constrained understanding at this site enabled us to implement a parameterization framework in PHT3D for As sorption on Fe oxyhydroxides based on the models by Dzombak and Morel (1990) and Appelo et al. (2002). With the model, we showed that seasonal temperature variability causes non-linear As release dynamics that cannot be predicted by average conditions (Figure 2).

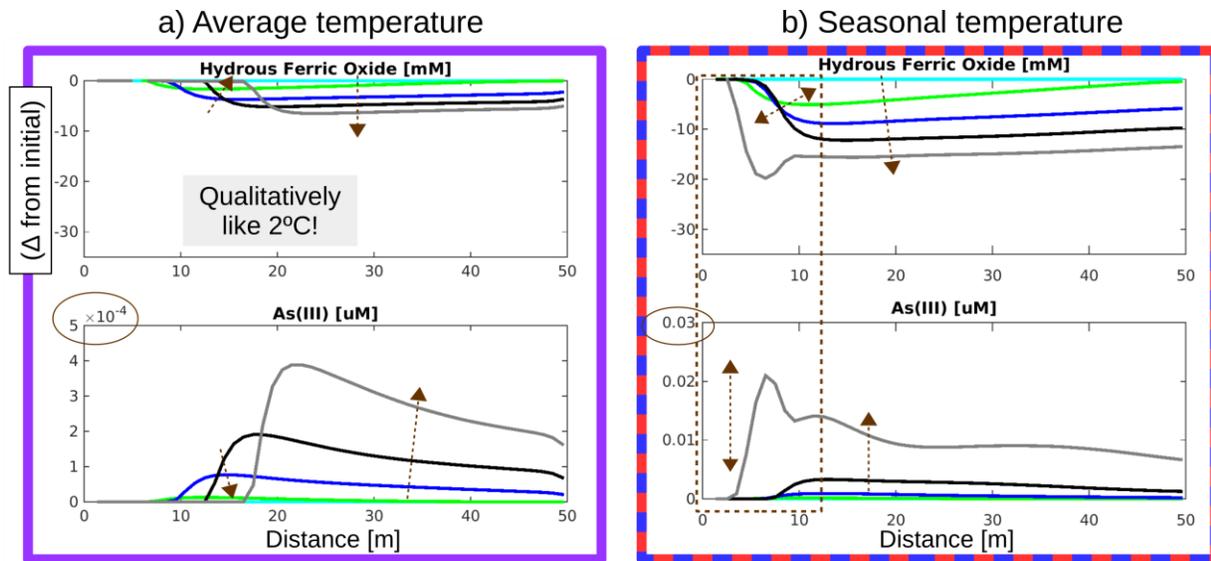


Figure 2. Simulated release of dissolved As due to reductive dissolution of Fe oxyhydroxides (“Hydrus Ferric Oxide”), based on measurements from a glacial aquifer on Cape Cod. Distance is from the lake water-aquifer interface, where elevated organic content levels enter sediments and trigger Fe(III) reduction. a) Simulations using average annual temperatures show relatively little reduction dissolution of Fe oxyhydroxides and correspondingly low dissolved As concentrations compared to b) simulations using seasonal varying temperatures.

The parameterization of As sorption on Fe oxyhydroxides was then incorporated into our three models for the Minnesota sites. However, XAS speciation data from the sediments indicate that only one of the sites (“TG-3”) is likely to have As mobilization due primarily to reductive dissolution of Fe oxyhydroxides. Weathered sediments at the “OTT-3” site likely contain low concentrations of organic carbon content needed reducing Fe oxyhydroxides, and instead, As is hypothesized to desorb at the aquifer-aquitard interface. XAS analyses of the samples from the third site “UMRB-2” show the aquitard to still contain As-bearing Fe sulfide minerals from the original glacial till material, which may be dissolving as the source of As in groundwater.

For each site, we have implemented the PHT3D model to represent a vertical column consisting of an aquitard unit adjacent to an aquifer unit. In the model domain, we specify different mineral phases in each depending on the unit and the particular site, based on the XAS speciation data. We then simulate the water chemistry changes that occur as different chemical species diffuse across the aquifer-aquitard interface and trigger geochemical reactions that can release As from where they are sorbed onto Fe oxyhydroxide sediments or integrated into sulfide mineral phases.

Figure 3 shows the vertical column model domain, where the mid-point is the interface between the aquitard (upper half) and aquifer (lower half). In simulations of OTT-3, it can be seen that As is first mostly sorbed at the interface, and over time, As desorbs from the interface

and gradually migrates downward into the lower aquifer portion of the domain. Dissolved As(5+) (arsenate) appears correspondingly in the groundwater as expected for this site, but concentrations do appear to stay elevated, because As re-sorbs in the lower aquifer. Difficulty in simulating sustained, desorbed As may result due to incorrectly specified water chemistry, or because more site-specific sorption parameter calibration is needed. Simulations of TG-3 in Figure 3 shows the reductive dissolution of Fe oxyhydroxide minerals ($\text{Fe}(\text{OH})_3(\text{s})$), which triggers dissolved As(5+) to appear along the interface. UMRB-2 simulations include the mineral orpiment (As_2S_3) in the upper aquitard portion of the model domain. It can be seen that orpiment quickly dissolves, thus releasing elevated concentrations of dissolved As(+3) (arsenite). However, these As concentrations are unnaturally high, indicating that a slower kinetic dissolution of orpiment may be needed in the model.

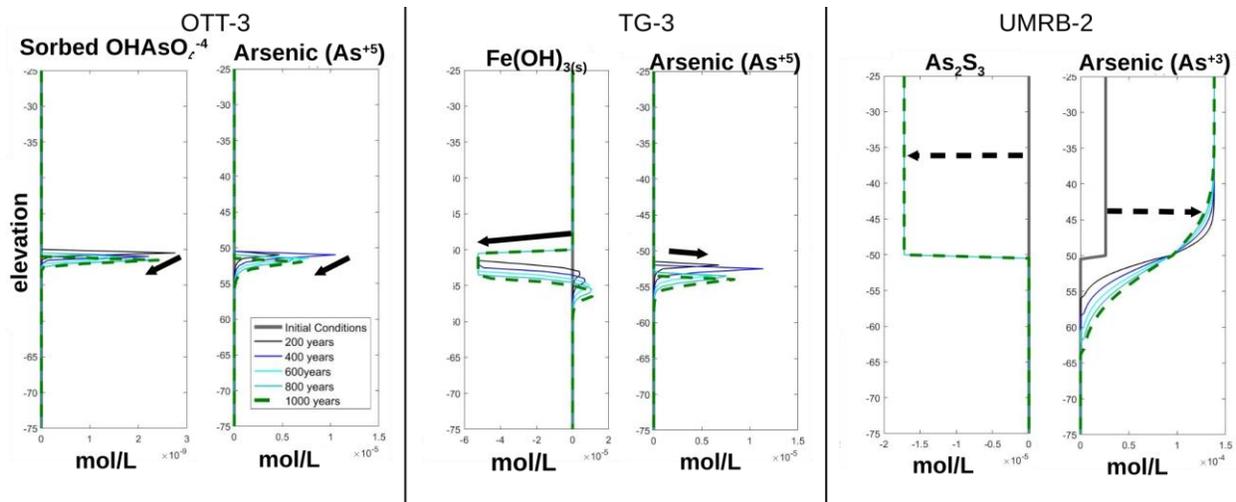


Figure 3. Simulated single vertical columns for three sites in Minnesota corresponding to rotosonic sites where XAS analyses were carried out. The upper column represents aquitard geochemical conditions, the lower column represents aquifer geochemical conditions, and the mid-point is the interface. For “OTT-3” simulations, As (“ As^{5+} ”) desorbs over time at the interface, although it mostly then quickly resorbs (“sorbed OHAsO_4^{4-} ”) as it migrates lower into the aquifer. For “TG-3” simulations, dissolved As (As^{3+}) is mobilized along the interface due to reductive dissolution of Fe oxyhydroxide minerals ($\text{Fe}(\text{OH})_3(\text{s})$). For “UMRB-2” simulations, dissolved As (As^{3+}) is released due to dissolution of arsenic-bearing Fe sulfide minerals such as orpiment (As_2S_3). Although overall trends are constrained by XAS analyses, simulation details require further model calibration and adjustment.

1.6 Conclusions and Future Work

This new collaborative work between PIs Toner and Ng has led to the development of a preliminary As modeling framework for glacial aquifers that is constrained by XAS speciation analyses. While extensive water chemistry and a simpler dynamical system in a glacial aquifer in Cape Cod provided the launching point for the sorption parameterization, the detailed XAS data was needed to guide the modeling of more complex As mobilization mechanisms in

Minnesota aquifers. More work is needed, however, to more carefully calibrate the sorption model to our measurements, and for parameterizing arsenic-bearing Fe sulfide minerals. Furthermore, difficulties in matching observed trends at the three Minnesota sites has been connected to the lateral groundwater flow in the aquifer domain, which likely advects away solutes diffusing from the aquitard and introduces sources of dissolved oxygen. We are in the process of extending the model to 2D cross-sectional transects as well as re-calibrating geochemical parameters. We are seeking further funding from LCCMR (see section 6 below) to collect measurements beyond the three rotosonic cores to help better constrain the model.

1.7 References

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Nicholas, S. L., Erickson, M. L., Woodruff, L. G., Knaeble, A. R., Marcus, M. A., Lynch, J. K., and Toner, B. M., accepted. Solid-phase arsenic speciation in aquifer sediments: a micro-X-ray absorption spectroscopy approach for quantifying trace-level speciation. *Geochim Cosmochim Acta*. DOI:10.1016/j.gca.2017.05.018

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systems: Documentation and user's guide, Contract Rep. SERDP-99-1, U.S. Army Eng. Res. and Dev. Cent., Vicksburg, Miss.

2) PUBLICATIONS

Nicholas, S. L., Erickson, M. L., Woodruff, L. G., Knaeble, A. R., Marcus, M. A., Lynch, J. K., and Toner, B. M., accepted. Solid-phase arsenic speciation in aquifer sediments: a micro-X-ray absorption spectroscopy approach for quantifying trace-level speciation. *Geochim Cosmochim Acta*. DOI:10.1016/j.gca.2017.05.018

3) STUDENT SUPPORT

Aubrey Dunshee, Earth Sciences Department Undergraduate Researcher

4) PRESENTATIONS

Ng, G.-H.C., A. Dunshee, D.A. Repert, R.L. Smith, D. L. Stoliker, J.K. Bohlke, T.D. McCobb, D.R. LeBlanc, D.B. Kent (2016), "Modeling the effect of temperature variability on groundwater arsenic plumes downgradient of eutrophic lakes." GSA Annual Meeting 2016, Denver, CO. (Invited Presentation).

Dunshee, A., G.-H.C. Ng, B. Toner, and M. Erickson (2017), "Reactive Transport Modeling of Arsenic Mobilization Processes in Glacial Aquifers in Western Minnesota." Shared Water, Shared Responsibility: Engaging Minnesota's Communities, Students, & Policy-Makers, Water Resources Center, University of Minnesota, March 23, 2017, Minneapolis, MN. (poster)

Dunshee, A., G.-H.C. Ng, and B. Toner (2017), "Reactive Transport Modeling of Arsenic Mobilization Processes in Glacial Aquifers in Western Minnesota." MnDRIVE Mini-Symposium with Barr Engineering, April 25th, 2017, Minneapolis, MN. (poster)

5) AWARDS

Aubrey Dunshee
Competitive Internship
National Association of Geoscience Teachers
United States Geological Survey (USGS) Cooperative Field Training Program
USGS Eastern Geographic Science Center
12201 Sunrise Valley Drive, Reston, VA, 20192
Dates: May 15, 2017 to August 18, 2017

6) RELATED FUNDING

The WRC/USGS/NIWR funding led to the development of a new proposal:

Developing a Map of Arsenic Risk in Groundwater

PI: Crystal Ng (University of Minnesota, UMN)

Co-PIs: Brandy Toner (UMN), Melinda Erickson (U.S. Geological Survey)

Source: LCCMR (Legislative Citizen Commission on Minnesota Resources)

Amount: \$549,880

Duration: 36 months

Enhanced Microbial Sulfate Removal and Recovery through a Novel Electrode-Integrated Bioreactor

Basic Information

| | |
|---------------------------------|-------------------------------------------------------------------------------------------------|
| Title: | Enhanced Microbial Sulfate Removal and Recovery through a Novel Electrode-Integrated Bioreactor |
| Project Number: | 2016MN372B |
| Start Date: | 3/1/2016 |
| End Date: | 2/28/2018 |
| Funding Source: | 104B |
| Congressional District: | Minnesota |
| Research Category: | Water Quality |
| Focus Category: | Treatment, Water Quality, Geochemical Processes |
| Descriptors: | None |
| Principal Investigators: | ChanLan Chun, Daniel Seth Jones |

Publications

1. Chan Lan Chun, An integrated microbial process for sulfate remediation. Frontier in Mine Water Technology, September 26, 2016 Minneapolis MN (Oral)
2. Dan C. Takaki, Tobin Deen, Daniel S. Jones, and Chan Lan Chun, Enhanced microbial sulfate removal through a novel electrode-integrated bioreactor, St. Louis River Summit March 14-15, 2017 (Poster)
3. Tyler Untiedt and Chan Lan Chun, Discovering novel microbes involved in sulfur cycling in bioelectrochemical systems. 23rd year UMD Undergraduate Research and Activities Showcase, April 18, 2017 (Poster)

Progress Report

Enhanced Microbial Sulfate Removal and Recovery through a Novel Electrode-Integrated Bioreactor

Principal Investigators: Chan Lan Chun and Daniel S. Jones
Contributing Staff: Daniel Takaki and Tobin Deen
Organization: University of Minnesota, Duluth and Twin Cities

OBJECTIVES OF THIS STUDY

The main goal of this research is to develop an alternative treatment approach in which low electrical potential is used to sustain biological sulfate reduction by continuously supplying electron donor substrates. The use of electric potential can create desired electron flows that indirectly and directly stimulate microbial sulfur transformations. The specific objectives of this study are to:

1. Determine the efficacy of electrolysis of water/iron to enhance microbial sulfate reduction and sulfur recovery from high sulfate waste streams.
2. Develop electrode-integrated fixed-bed bioreactor by combining naturally-occurring microorganisms and supplying electrolytic hydrogen and oxygen.
3. Determine how the microbial community responsible for the biological transformations (sulfate reduction, elemental sulfur production) responds to electrochemically-stimulated production of reductants and oxidants.

The results from a number of tasks that have been completed in the process of accomplishing these objectives will be discussed in detail in the following technical summary.

Enhanced sulfate reduction by electrolytic hydrogen supply

A sediment bioelectrochemical bioreactor (SBR) has been developed to test if electrolysis of water/iron can be used to finely control the supply of hydrogen and oxygen for microbial sulfate reduction. Electrolysis was achieved in sediment with stainless electrodes that are separated by several cm. A schematic diagram of the SBR with the associated reactions is shown in Figure 1. The reactor is an open mesocosm system maintained at room temperature in order to closely mimic conditions to be found *in situ*. Low electrical potentials were applied to stimulate and sustain the process by continually supplying electron donor

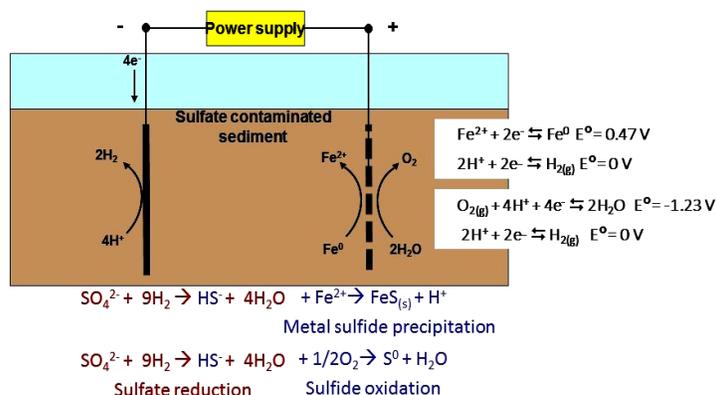


Figure 1. Schematic diagram of the SBRs and the associated reactions occurred in the SBRs

substrates to the sulfate reducing bacteria. Simultaneously, anodic iron dissolution from a stainless-steel electrode occurred and reacted with sulfide produced from biological sulfate reduction, to form iron sulfide. Reactors contained creek sediment impacted with high strength sulfate (Second Creek, MN). Synthetic mine water with a sulfate concentration of 1000 ppm was treated within reactors operated at different applied voltages (1.2, 1.6, and 2.0V) with control reactors (open circuit). Pore water was periodically collected at set distances from the electrode using a Rhizon soil water sampler (Soilwater Corp.) to monitor sulfur chemistry (sulfate and sulfide) and physiochemical changes in the sediment. Physiochemical properties measured in the SBR include sulfate redox potential, pH, and dissolved oxygen (DO). Sediment samples were also taken at each sampling point for the analyses of functional genes associated sulfate biotransformation and microbial communities in the SBRs.

Overall, the application of electrical potential to mining-impacted sediment stimulated indigenous microbial metabolisms responsible for sulfate reduction in sediment. Among the voltage we tested, the enhancement of sulfate reduction increases with the applied voltage since high current generate the greater supply of electrolytic hydrogen to microbial communities including sulfate reduction. In the SBRs operated at 2 V, biological sulfate reduction occurred over a 14-day span. Initial sulfate concentration was ~12 mM in circumneutral pH and was reduced to as low as 0.34 mM in the pore water within the reactors with 2.0 V. Control reactors that operated as open circuit reactors showed no reduction during the 14-day period. Enhanced sulfate reduction to sulfide (HS^-) initially occurred in the proximity of cathode where electrolytic hydrogen was produced and the area where sulfate reduction occur were expanded with time. Simultaneously, reactive iron species were electrically released from stainless electrode (anode) in the SBR (Figure 2A). The reaction iron species from the anode were bound with sulfide generated from biological sulfate reduction, which results in the formation of iron sulfide precipitates. Figure 2B shows an increase of precipitated sulfide concentration in the sediment near the cathode in the SBRs with 2.0V (in duplicate; Reactor 3 and 4). Porewater sulfide measurements were taken throughout the experiment as well, but no significant concentrations were reported.

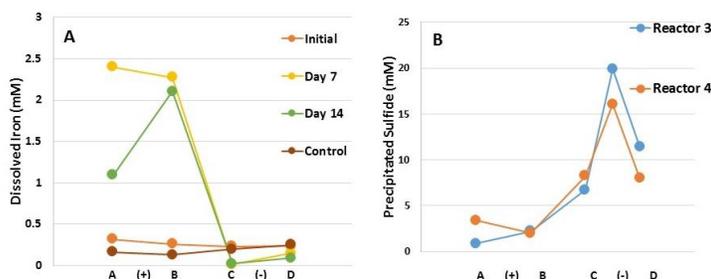


Figure 2. Dissolved iron concentration in porewater in the SBRs (A) and precipitated sulfide concentration in the sediment (B) across the reactors.

Iron sulfide formation were confirmed by digital photographs and scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM-EDX). Figure 3A and 3B visually confirmed the formation of iron sulfide precipitation as vertical black band near cathode in the SBR with 2.0V while there was no visual changes in control reactors. Figure 3C and 3D show SEM micrographs of sediments near the cathode collected from the control and SBR (largely black band). EDX elemental mapping characterization indicates greater abundance of the iron sulfide precipitates in the sediment of the SBRs that that of control reactors (Figure 3E & 3F). The size of iron sulfide precipitate ranges from less than 1 μm to 20 μm . X-ray diffraction analysis of the iron precipitates are currently in progress to examine their crystallinity.

In addition to sulfur chemistry and physiochemical analyses, we have collected sediment samples and extracted microbial DNA to examine the microbial community responsible for the biological transformations (sulfate reduction, elemental sulfur production) responds to electrochemically-stimulated production of reductants and oxidants. Currently, quantitative polymerase chain reaction (qPCR) has been used to quantify the population density of all bacteria (16S rRNA gene) and sulfate reducing bacteria (*dsrA* and *dsrB* genes; dissimilatory sulfate reductase subunit). Characterization of total microbial community dynamics in the experiments using 16S rRNA amplicon sequencing is in progress to investigate changes in the abundance of clades associated with sulfate reduction, sulfide oxidation, methanogenesis, and fermentation.

Develop electrode-integrated fixed-bed bioreactor for sulfate treatment

Based on the results of SBRs, a flow-through fixed-bed bioelectrochemical reactor was developed to examine the effect of water electrolysis on microbial sulfur transformation. A

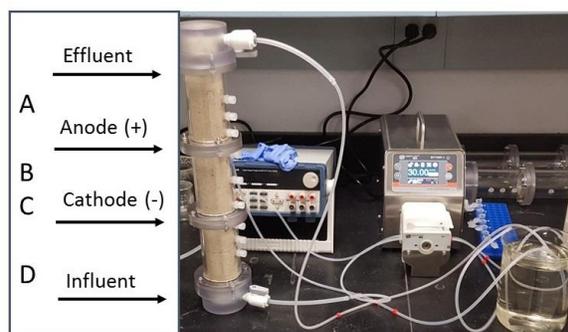


Figure 4. Flow-through fixed-bed bioelectrochemical reactors with reference points.

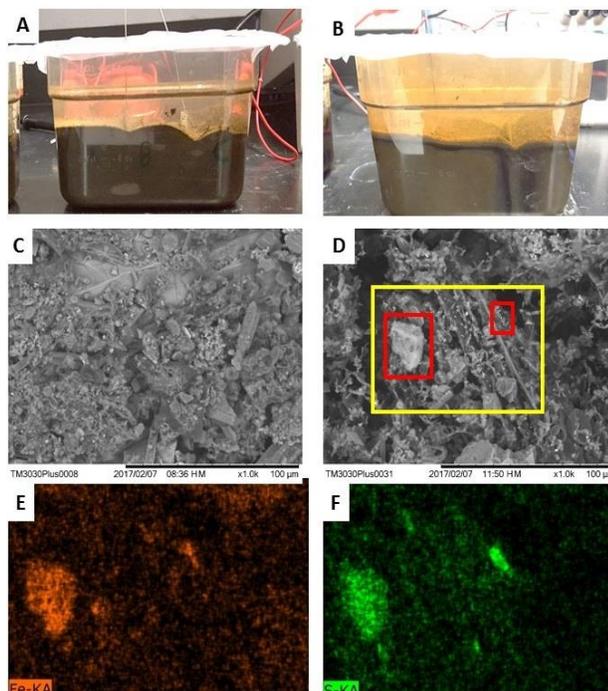


Figure 3. The photographs of the control (A) and the SBR (B) operated under 2V for 4 weeks and SEM micrographs of sediment near the cathode in the control (C) and the SBR (D). EDX elemental mapping of iron (E) and sulfur (F) in yellow box area of SEM micrograph D. The red boxes in the image D show iron sulfide precipitates.

general configuration of the bioelectrochemical cell is shown in Figure 4. The bioelectrochemical reactors with stainless steel electrodes were inoculated with pure bacterial strain isolated or naturally-occurring bacterial consortium from creek sediment impacted by mining activities

(Second Creek, MN). and were fed with a synthetic mine water medium with a sulfate concentration of 1000 ppm. The configuration has been evaluated and determined by measuring the gradient of pH, redox potential, concentration of dissolved oxygen and iron along the flow path at set distance from the electrode. During operation, pore water was periodically collected along the flow path at set distances from the electrode using Rhizon samplers (Soilwater Corp.), along with influent and effluent samples to monitor physiochemical changes in the reactors.

Sulfate reducing bacteria were isolated from mining-impacted sediment for bioelectrochemical cell experiments. Bacteria were enriched using a liquid medium (DSMZ Medium 194) in anoxic serum bottles at 15 °C. A bacterium was isolated using sequential 2 % inoculations. The sulfate reduction in the culture was confirmed by monitoring sulfate concentration (Figure 5). The bacterial isolates was identified as a strain of *Desulfovibrio*, a sulfate reducing bacteria through 16S rRNA identification (full length). The strain has since been cultured using an artificial mine water medium for the bioelectrochemical reactors.

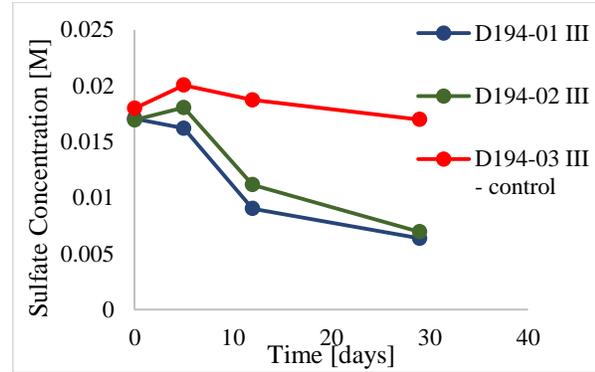


Figure 5. Sulfate reduction by bacterial isolates from mining-impacted sediment.

We also have developed a mathematical model to describe biological sulfate reduction and iron sulfide formation in fixed-bed bioelectrochemical reactors. A section of this project is focused on modeling the bioelectrochemical reactors. An initial model was created for a flow-through anoxic sediment column with integrated electrodes. The model used an advection-dispersion-reaction equation for both dissolved hydrogen and sulfate. For the reaction rate, we used a hydrogenotrophic reaction model experimentally determined from anaerobic sewage reactors.

$$\frac{dH_2}{dt} = D_H \frac{d^2H_2}{dx^2} - u \frac{dH_2}{dx} - k(SO_4, H_2) + \dot{m}_H$$

$$\frac{dSO_4}{dt} = D_S \frac{d^2SO_4}{dx^2} - u \frac{dSO_4}{dx} - k(SO_4, H_2)$$

$$k(SO_4, H_2) = \frac{u_{max}[H_2]}{K_H + [H_2]} \left[1 - \frac{[H_2S]}{K_I} \right] \left[\frac{[SO_4^{2-}]}{K_S + [SO_4^{2-}]} \right]$$

A finite difference method was used to discretize the coupled hydrogen and sulfate equations in MATLAB using kinetic values from Poinapen and Ekama and estimated experimental values. The biochemical kinetic value will be modified based on our isolate, *Desulfovibrio* sp. As a representative result, the simulation showed that the system was hydrogen limited and reached a rapid equilibrium in hydrogen concentration (Figure 6). Various conditions including sulfide inhibition, iron electrolysis, different physiochemical conditions (e.g. sulfate, conductivity,

electrode distance) have been simulated. The experimental results were used to validate a mathematical model of the system, which will then be used for process optimization.

The reactors have been operated at 0-3V producing cathodic hydrogen and anodic iron dissolution. The sulfur chemistry in the pore water of the reactors was assessed to determine the effect of low voltage on the efficacy of sulfate reduction. The characterization and quantification of microbial community responsible for the biological transformations (sulfate reduction, elemental sulfur production) are in progress.

In summary, electrolysis generated the gradient of hydrogen and reactive iron species between electrodes. As a consequence, microbial metabolisms were stimulated differently in a particular zone. The findings will result in a proof of concept application of electrical potential to stimulate and sustain biological sulfate reduction and simultaneously facilitate the subsequent removal of the reduced sulfide in a controlled manner.

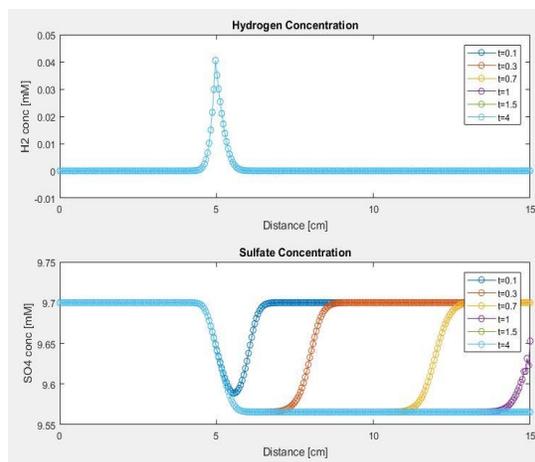


Figure 5. Mathematical simulation of H₂ and SO₄ concentrations for the sediment column under experimental conditions over 4 days in the fixed-bed bioelectrochemical reactors.

Presentations

Chan Lan Chun, An integrated microbial process for sulfate remediation. Frontier in Mine Water Technology, September 26, 2016 Minneapolis MN (Oral)

Dan C. Takaki, Tobin Deen, Daniel S. Jones, and Chan Lan Chun, Enhanced microbial sulfate removal through a novel electrode-integrated bioreactor, St. Louis River Summit March 14-15, 2017 (Poster)

Tyler Untiedt and Chan Lan Chun, Discovering novel microbes involved in sulfur cycling in bioelectrochemical systems. 23rd year UMD Undergraduate Research and Activities Showcase, April 18, 2017 (Poster)

Student Support

Two master students and one undergraduate student were partially funded from the grant to carry out the project.

Information Transfer Program Introduction

We did not fund any information transfers projects with our WRII funds.

USGS Summer Intern Program

None.

| Student Support | | | | | |
|------------------------|-------------------------------|-------------------------------|-----------------------------|----------------------------|--------------|
| Category | Section 104 Base Grant | Section 104 NCGP Award | NIWR-USGS Internship | Supplemental Awards | Total |
| Undergraduate | 2 | 0 | 0 | 0 | 2 |
| Masters | 2 | 0 | 0 | 0 | 2 |
| Ph.D. | 1 | 0 | 0 | 0 | 1 |
| Post-Doc. | 0 | 0 | 0 | 0 | 0 |
| Total | 5 | 0 | 0 | 0 | 5 |

Notable Awards and Achievements

Governor Mark Dayton appeared at the October 2016 Minnesota Water Resources Conference and delivered a State of Minnesota Proclamation, proclaiming the week of October 19-26, 2016 as Water Resources Professionals Week.

Bill Arnold (WRS faculty) was named a Distinguished McKnight University Professor for 2016. This award recognizes outstanding faculty members who recently achieved full professor status. The announcement appears on the Scholars Walk website.

Jay Austin (WRS faculty) Professor in Physics and Large Lakes Observatory, SCSE is the recipient of the 2016-17 Chancellor's Award for Distinguished Research/Creative Activity.

Anna Baker (WRS student) received a WRS Travel Grant for \$567 to present a poster entitled "Sediment as Modulator of Phosphorus Dynamics in Post-Glacial Channels" at the Geological Society of the Americas North East/North Central meeting in Pittsburgh, PA on March 19-21, 2017.

Brian Bohman (WRS student) received a WRS Travel Grant for \$500 to present a poster entitled "Evaluating Nitrogen Stress and Yield Impacts from Variable-Rate Nitrogen Applications for Potatoes" at the ACS Fall Meeting in Phoenix, AZ on November 6-10, 2016.

Ellen Cooney (WRS student) received a WRS Travel Grant for \$1,000 to present a poster entitled "Impact of Extreme Rain Events on Lake Superior's Biogeochemistry" at the AGU Chapman Conference on Extreme Climate Events in San Juan, Puerto Rico on January 22-27, 2017.

Brad Gordon (WRS student) received a WRS Travel Grant for \$420 to present a poster entitled "Comparing nitrate reductions in a reed canary grass monoculture, switchgrass monoculture, and wet prairie community in wetland mesocosms" at the Midwest Chapter Meeting of Society of Ecological Restoration in Grand Rapids, MN on March 24-26, 2017.

Karen Gran (WRS faculty) associate professor, Earth & Environmental Sciences, SCSE, is the recipient of the 2016-17 Outstanding Graduate Faculty Advisor Award.

John Gulliver (WRS faculty) received the 2016 Richard P. Braun Distinguished Service Award from the University of Minnesota's Center for Transportation Studies. This award is given annually to a transportation professional for outstanding leadership in research and innovation.

Sarah Hobbie (WRS faculty) has been named a Distinguished McKnight University Professor. The Distinguished McKnight University Professorship program recognizes outstanding faculty members who have recently achieved full professor status.

Lucinda Johnson (WRS faculty) was reappointed to the International Joint Commission's Science Advisory Board's Science and Policy Committee for a second three-year term beginning January 1, 2017.

Sophie LaFond-Hudson (WRS student) received a WRS Travel Grant for \$157 to give a presentation entitled "Iron Sulfide Precipitates on the Roots of Wild Rice" at the annual meeting of the Midwest Chapter of the Society of Environmental Toxicology and Chemistry in Minneapolis on March 20-22, 2017.

Ann Lewandowski (WRC) and Steve Kelley (Humphrey School of Public Affairs) led a review of the process used by the Minnesota Department of Health (MDH) to select chemicals to be examined as part of their

Contaminants of Emerging Concern (CEC) program. The team made recommendations for improving the transparency of the process and engagement of stakeholders. MDH submitted the report to the legislature on June 1st. It is available on the MDH CEC web site.

Kathrine McLellan (WRS student) received two fellowships, Smith Partners and Butler Jessen. The Smith Partners Sustainability Fellowship supports interdisciplinary study for Water Resources graduate students to pursue the connections between sustainable water resources management, economics, and public policy. The Fellowship affirms the University's commitment to sustainability initiatives through cultivation of interdisciplinary problem-solving, collaborative leadership, and public private partnerships. The Butler Jessen Water Resources Science Fellowship supports students admitted into graduate programs within the University of Minnesota's Water Resources Center, a leader in freshwater management that connects University of Minnesota expertise to research problems on the national level.

Jeff Peterson (WRC Director) was appointed to the Water Use Advisory Council by The Foundation for Food and Agriculture Research. Foundation for Food and Agriculture Research Advisory Council members advise foundation staff and board members regarding program development and implementation, potential partnerships, and other matters of significance to the organization's mission of supporting innovative science addressing today's food and agriculture challenges.

Deb Swackhamer (former WRC co-director) was the invited Plenary Speaker for the 10th biennial National Water Quality Monitoring Conference held in Tampa, Florida May 2-6, 2016. Her plenary was a retrospective on how water monitoring has advanced aquatic systems understanding, and national policy development. It was entitled "Assessing Our Waters: Old Ways and New."

Larissa Scott (WRS student) received a summer travel grant of \$575. Scott is attending and presenting a poster for her preliminary results from the Stewart River for the Techniques for Stream-Groundwater Investigations Workshop, in Crested Butte, CO, in August 2016.

Seth Thompson (WRS student) received a WRS Travel Grant for \$588 to present a poster entitled "Stoichiometry of Water-Extractable Organic Matter in North American Grasslands" at the annual meeting of the Association of the Sciences of Limnology and Oceanography in Hawaii on February 26-March 3, 2017.

Rachel VanAllen (WRS student) received a WRS Travel Grant for \$600 to present a poster entitled "Effects of sea level rise and coastal marsh transgression on soil organic matter in a Chesapeake Bay salt marsh" at the American Geophysical Union Fall Meeting in San Francisco, CA on December 12-16, 2016.