

AUG 11 2004

2001 Project Abstract

For the Period Ending June 30, 2004

TITLE: Implementing Denitrification Strategies for Minnesota's Contaminated Aquifers

PROJECT MANAGER: Paige J. Novak, Ph.D., P.E.

ORGANIZATION: University of Minnesota, Department of Civil Engineering

ADDRESS: 122 Civil Engineering, 500 Pillsbury Dr. SE, Minneapolis, MN 55455

WEB SITE ADDRESS: none

FUND: Minnesota Environment and Natural Resources Trust Fund

LEGAL CITATION: ML 2001, 1st Special Session, Ch. 2, Sec. 14, Subd. 06(c)

APPROPRIATION AMOUNT: \$230,000

Overall Project Outcome and Results

Nitrate (NO_3^-) is a common groundwater pollutant that has been linked to cancer and methemoglobinemia. We have developed a technology to stimulate biological NO_3^- reduction (denitrification) by supplying hydrogen (H_2) to groundwater via gas-permeable membranes. Autotrophic bacteria consume the dissolved H_2 , converting NO_3^- to NO_2^- and then to N_2 . The purpose of this project was to investigate this technology at a field scale, determining whether it could be successfully scaled-up and if so, developing protocols for its use. The site that was used (in Becker, MN) was non-ideal, as it contained extremely high NO_3^- (22.8 ± 1.98 mg- NO_3^- -N/L) and dissolved oxygen (DO) concentrations (7 ± 1 mg-DO/L), and was very deep (48.2 ± 0.5 ft to groundwater). Membranes installed in groundwater wells at the site were successful in delivering H_2 to the groundwater over the two-year operating period. The added H_2 stimulated DO and NO_3^- reduction, degrading up to 7 mg/L DO and converting up to 10.0 mg/L NO_3^- -N to NO_2^- -N when operated passively. Complementary laboratory and modeling studies showed that complete DO reduction and denitrification to N_2 was possible with the aquifer material and groundwater from the site, but required phosphate addition (9.62 ± 1.25 mg-P/L as a nutrient) and better contact between the membranes and the passing groundwater. Because of this, water was recirculated in the field from downgradient to upgradient membrane-containing wells to increase the number of times a parcel of water was exposed to H_2 . The depth to groundwater caused some difficulty with water recirculation, resulting in water reoxygenation. It was determined that this technology can be used at a field-scale to denitrify water that contains extremely high quantities of NO_3^- and DO, but it should only be used at shallow sites to avoid reoxygenation during water recirculation and to facilitate closer placement of membrane-containing wells.

Project Results Use and Dissemination

Results have been disseminated at several Minnesota Water conferences. In addition, two manuscripts are being written and will be submitted for publication this fall (2004), likely to the journal *Water Research*.

I. PROJECT TITLE: Implementing Denitrification Strategies for Minnesota's Contaminated 3Aquifers

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Total Biennial Project Budget:

\$ LCMR Appropriation	- \$ Amount Spent	= \$ Balance
\$230,000	\$230,000	\$0

Legal Citation: ML 2001, 1st Special Session, Ch. 2, Sec. 14, Subd. 06(c).

Appropriation Language:

6 (c) Denitrification Strategies for Minnesota's Contaminated Aquifers
\$115,000 the first year and \$115,000 the second year are from the trust fund to the University of Minnesota to assess denitrification technology to remediate nitrate-contaminated groundwater. This appropriation is available until June 30, 2004, at which time the project must be completed and final products delivered, unless an earlier date is specified in the work program.

II. and III. FINAL PROJECT SUMMARY:

Nitrate (NO_3^-) is a common groundwater pollutant that has been linked to cancer and methemoglobinemia. We have developed a technology to stimulate biological NO_3^- reduction (denitrification) by supplying hydrogen (H_2) to groundwater via gas-permeable membranes. Autotrophic bacteria consume the dissolved H_2 , converting NO_3^- to NO_2^- and then to N_2 . The purpose of this project was to investigate this technology at a field scale, determining whether it could be successfully scaled-up and if so, developing protocols for its use. The site that was used (in Becker, MN) was non-ideal, as it contained extremely high NO_3^- (22.8 ± 1.98 mg- NO_3^- -N/L) and dissolved oxygen (DO) concentrations (7 ± 1 mg-DO/L), and was very deep (48.2 ± 0.5 ft to groundwater). Membranes installed in groundwater wells at the site were successful in delivering H_2 to the groundwater over the two-year operating period. The added H_2 stimulated DO and NO_3^- reduction, degrading up to 7 mg/L DO and converting up to 10.0 mg/L NO_3^- -N to NO_2^- -N when operated passively. Complementary laboratory and modeling studies showed that complete DO reduction and denitrification to N_2 was possible with the aquifer material and groundwater from the site, but required phosphate addition (9.62 ± 1.25 mg-P/L as a nutrient) and better contact between the membranes and the passing groundwater. Because of this, water was recirculated in the field from downgradient to upgradient membrane-containing wells to increase the number of times a parcel of water was exposed to H_2 . The depth to groundwater caused

some difficulty with water recirculation, resulting in water reoxygenation. It was determined that this technology can be used at a field-scale to denitrify water that contains extremely high quantities of NO_3^- and DO, but it should only be used at shallow sites to avoid reoxygenation during water recirculation and to facilitate closer placement of membrane-containing wells.

IV. OUTLINE OF PROJECT RESULTS:

Result 1:

One site will be chosen with the assistance of the Minnesota Department of Agriculture and the Minnesota Pollution Control Agency for the field demonstration. If funds are sufficient, a second site, using a less intensive sampling regime, may be studied as well. Laboratory work in support of the field demonstration will be performed at the University of Minnesota (sample analysis, etc.). Hollow fiber membrane units will be installed in the contaminated aquifer and the area will be monitored for nitrate, H_2 , denitrification intermediates, and bacteria. The appropriate permits and variances will be obtained with the assistance of the project partners prior to the field trial. H_2 will be measured at the sites with the assistance of the Minnesota Pollution Control Agency.

LCMR Budget: \$216,278

Balance: \$0

Personnel: \$136,635 for supervision and project coordination (Novak and Semmens), graduate research assistants for technical assistance in the laboratory and the field (2 for 24 months), and for administrative assistance that is essentially needed and directly related to the project

Equipment: \$73,103 for field study supplies (e.g. well drilling, geoprobes, membrane modules, well casing, H_2), laboratory supplies, equipment maintenance

Other: \$6,540 for travel to the site, office supplies

Completion Date:

It is our intent to complete Result 1 by June 30, 2004.

Result Status:

Field Site Selection

We had considerable difficulty obtaining access to a field site within an hour of the University of Minnesota. The project partners, the Minnesota Department of Agriculture and the Minnesota Pollution Control Agency, were unable to assist in this effort as a result of budget cuts. A site was finally selected in Becker, Minnesota on property owned by Xcel Energy, southeast of the Sherco power plant and near the Mississippi River. The surficial aquifer was sand and gravel with good permeability and fairly uniform flow through the site. The distance to groundwater was very deep, 48.2 ± 0.5 ft. This resulted in a number of problems, (1) increased well installation costs which caused fewer wells to be installed, and (2) mandated use of more expensive positive displacement pumps for water sampling and later water recirculation experiments. In addition, there was no electricity at the site, requiring us to pay for the installation of an electrical box. Background NO_3^- and DO levels were extremely high; this was good in that it presented a worst-case-scenario in which to

challenge our technology. We had not expected such difficulty in finding a site where we were allowed access, and in hindsight, the selection of the site had important ramifications, particularly with respect to costs and our ability to test multiple operational scenarios.

Modeling Results

A model was used to predict treatment efficiency in the field and evaluate alternative operational strategies. Laboratory experiments were conducted to determine the kinetics of denitrification in the aquifer material obtained from the field site for input into the model. These studies showed that NO_3^- degradation was zero-order (approximately 0.01 mg NO_3^- -N/g wet sediment/day) at concentrations over 5 mg/L NO_3^- -N.

The mathematical model used in this study was an extension of an existing two-dimensional model that incorporated advective-dispersive transport and biodegradation of one electron donor (formate) and two electron acceptors (nitrate and nitrite) coupled with the growth and decay of a single microbial population (Killingstad *et al.* 2002). The model was modified to account for the transfer of H_2 through hollow-fiber membranes, according to the gas transfer correlation developed by Fang *et al.* (2002). The model was also extended to include three electron acceptors (DO , NO_3^- , NO_2^-). The microbial population was modeled as a single facultative population attached to sediment particles. The microbes occupy no space within the model and do not affect the physical transport of solutes. The model was validated with previously published data from our laboratory (Haugen *et al.*, 2002). Field site model simulations included a site-wide model showing the entire field site study area and model runs focused on one apparent flow path through two wells. Once the model was shown to predict concentration profiles at the field site, hypothetical model simulations were performed to predict optimum well placement and membrane module design. Model fits were evaluated by determining a normalized residual mean square function.

The model predicted that denitrification would occur in narrow bands (referred to as "pinstriping") beginning at the membrane module-containing wells and extending downgradient in 0.15 m-wide swaths. The model also correctly predicted the downgradient monitoring wells in which NO_2^- would be detected and the observed steady state concentrations of NO_3^- , NO_2^- , and DO in the field during two of the field experiments. Model results for one of the membrane module-containing wells were within 11%, 10%, and 4% of measured concentrations for NO_3^- , NO_2^- , and DO , respectively.

Because the model was able to simulate laboratory data (Haugen *et al.*, 2002) and the majority of the field data, it was used to determine how membrane surface area would affect denitrification in the field and how many membrane wells would ideally be required to reduce both NO_3^- and NO_2^- below regulated values. Using experimental results for membrane spacing (Fang *et al.*, 2002), the membrane fiber can be coiled at a frequency of approximately 600 coils/m. This would produce a total membrane surface area of 0.77 m^2 per well. An operating H_2 pressure of 20 psi within the modules was assumed. Model results from this simulation showed that DO was reduced to approximately 1 mg/L within 6 days and NO_3^- levels were reduced from approximately 25.0 mg-N/L to less than 5.0 mg-N/L within 35 days. At this time NO_2^- degradation began and concentrations were reduced to approximately 10 mg-N/L by Day 60. Although significant, this would not be adequate to

reach the required maximum contaminant levels for NO_2^- ; therefore, closer well spacing for the membrane-containing wells would also be required. Additional simulations were therefore used to determine the well spacing requirements to achieve degradation of both NO_3^- and NO_2^- below the regulated values of 10.0 mg/L as N and 1.0 mg/L as N, respectively. Simulations suggested that if the current module design was used, membrane-containing wells would need to be placed at intervals of three times the well diameter normal to flow and two modules deep in the direction of flow. Simulations were also performed using a commercial software package, GMS-MODFLOW, to determine if low rates of water recirculation through the site could increase the zone of influence without the added expense of more membrane module-containing wells. These simulations showed that when water was pumped out of a single downgradient well at a rate of 4 L/min and recirculated to four upgradient membrane-containing wells (1 L/min flow to each well), a uniform distribution of H_2 could be generated around these five wells, removing the “pinstriping” pattern.

Laboratory Column Experiment Results

Laboratory column experiments were also performed to gain a better understanding of the impact of trace nutrients and membrane-groundwater contact on denitrification, and also to better understand the filtration of organic material, generated during biological growth, by the aquifer material. The columns were 4 inches in diameter and extended approximately 2 yards beyond the location of the membrane (where H_2 addition occurred). The columns were packed with aquifer material from the Becker field site, fed with water created to simulate the groundwater at the site (same mineral composition and DO and NO_3^- concentration), and operated at 10°C (the approximate groundwater temperature at the Becker site). Two columns were plumbed in series, with the first column receiving H_2 via a membrane. The third column served as a no- H_2 control and was identical to the first column except that no H_2 was delivered to the water as it passed through the column. Two operating parameters were varied in the column experiments: (1) feed water phosphate concentration (a nutrient for biological growth) and (2) H_2 pressure in the membrane lumen.

No DO or NO_3^- reduction was observed in the control column throughout the experiment. The initial H_2 pressure inside the membranes was 3.5 psi; this stimulated the reduction of some DO and NO_3^- , resulting in 2.2 mg DO/L and 1.9 mg NO_2^- -N/L downgradient of the membrane module within 27 days. Between Days 32 and 37, the H_2 pressure inside the membranes was increased to 10 psi (as at the field site). As a result, the DO decreased to 1.2 mg/L and the NO_2^- increased to 7.9 mg NO_2^- -N/L. On Day 37, the H_2 pressure was increased to 15 psi. A steady conversion of NO_3^- to NO_2^- occurred after Day 38, and eventually all of the NO_3^- (~24 mg-N/L) was converted to NO_2^- . At a lumen H_2 pressure of 15 psi the H_2 was not completely utilized. An excess of dissolved H_2 between 27-35 μM was detected throughout the column downgradient of the membrane. This indicated that the microorganisms present were limited by something else, perhaps phosphorous. Others (Kruithof *et al.*, 1988; Chang *et al.*, 1999) have shown similar NO_2^- accumulation in phosphorous-limited environments; for this reason, both the control and experimental columns were augmented with 0.6 mg-P/L on Day 139; the phosphorous concentration was increased to 4.0 mg-P/L on Day 150. Between Days 150 and 168, the phosphorous concentration downgradient of the membrane module was zero. Changes in NO_2^- accumulation were not observed during this time period, and the influent phosphorous

concentration was increased again to approximately 8.7 mg-P/L on Day 169. This concentration of phosphorous was fed for 22 days, resulting in approximately 39% complete denitrification (to N_2) within 200 cm of the membrane. Again, the phosphorous was entirely consumed downgradient of the membrane, suggesting that it remained the limiting nutrient in the system. Therefore, the phosphorous concentration in the feed water was again increased, to 13.6 mg-P/L, on Day 193. This concentration of phosphorous was maintained for the duration of the experiment. With this increased phosphorous concentration in the feed, complete denitrification increased to 64% on Day 204, and then stabilized at approximately 90% conversion of NO_3^- to N_2 between Days 210 and 232. Residual phosphorous was observed in the column, but it appeared that approximately 9.6 mg-P/L was assimilated by the bacteria in the column. On Day 226, detectable H_2 was no longer present downgradient of the membrane. With the phosphorous demand met, it appeared that H_2 was once again the limiting nutrient. Therefore, the membrane gas pressure was increased to 17 psi on Day 227. At this point, 100% denitrification from NO_3^- to N_2 was observed within 160 cm of the membrane and excess H_2 was again detected downgradient.

Increased total organic carbon (TOC) concentrations were not observed in the effluent of the H_2 -fed column, although biomass growth was encouraged by H_2 . Furthermore, no significant change in TOC was observed after the addition of phosphorous. This suggests that the aquifer material can filter and retain the biomass and TOC generated by H_2 -stimulated denitrification.

Field Study Results

The main purpose of this research was to test our membrane-based H_2 -addition technology at a field-scale. An array of twenty wells was installed at the field site in Becker, MN, seven of which contained membrane modules that were used for H_2 addition. The other wells served as monitoring wells. Several membrane module designs were tested at the site. The design that was able to operate effectively over a long period of time was a closed-end spiral-wound module designed with a wetted end to allow for condensate removal.

The membrane modules were operated in a passive mode for several months during which gas was fed to the modules at a lumen pressure of 10 psi and natural groundwater flow was relied upon to disperse the H_2 and carry it downgradient. Two experiments were conducted while operating in this manner. The average DO, NO_3^- , and TOC concentrations in the field before H_2 addition were 7 ± 2 mg/L (95% confidence interval), 21.2 ± 8.1 mg/L ($n=97$), and 0.5 mg-C/L ± 0.4 mg-C/L. NO_2^- was never detected in any samples collected in the field before H_2 addition. In the first experiment, the DO concentration in one of the monitoring wells began to decrease and reached a pseudo-steady state concentration of approximately 2 mg/L 13 days after the H_2 addition began. After the H_2 was turned on, the NO_3^- concentrations decreased steadily until Day 19, when they leveled off at approximately 15 mg-N/L. NO_2^- was observed in 4 monitoring wells downgradient of the H_2 -addition wells; no NO_2^- was detected in wells upgradient of the H_2 -addition wells. The NO_2^- concentrations approximately mirrored those of NO_3^- , indicating that NO_3^- was converted to NO_2^- . Based on nitrogen mass balances at the site, no significant NO_2^- reduction to N_2 occurred. DO and NO_3^- concentrations increased and NO_2^- concentrations decreased after a period of time. This was thought to be a result of slight shifts in groundwater flow direction, moving the

swath or “pinstripe” of impacted water slightly off-center of the monitoring wells. After H₂ was turned off, the DO, NO₃⁻, and NO₂⁻ returned to background levels. These observations indicate that although electron donor was added to the site, the system remained electron donor-limited.

Samples were typically not taken from wells containing membrane modules because of concern about disturbing the biofilm on the membrane. Nevertheless, on Day 60 one of the membrane modules was removed and two water samples were collected. Analysis showed average NO₃⁻, NO₂⁻, and DO concentrations of 21.4 mg-N/L, 1.9 mg-N/L, and 1 mg/L, respectively. Because the concentration of NO₂⁻ was lower than that observed in downgradient monitoring wells, it was thought that H₂ flowed downgradient and degradation did not occur solely within the membrane module well volume. The same trend was observed in the column experiments. This membrane-containing well also showed substantially elevated TOC levels. The TOC was effectively filtered by the aquifer material and elevated TOC levels were not detected in downgradient monitoring wells.

In the second experiment, the largest quantity of NO₂⁻ production and DO reduction was once again observed in one monitoring well. The DO in this well remained constant at 6 mg/L until Day 10 when it was reduced to 5 mg/L; it remained approximately at this level throughout the remainder of the study. Small amounts of NO₂⁻ were observed in downgradient wells after Day 10 (0.32 to 1.69 mg-N/L). As in experiment 1, NO₃⁻ and NO₂⁻ profiles approximately mirrored one another. The somewhat “spotty” observation of denitrification in the field was likely a result of the expected “pinstriping” phenomenon. Again, evidence of denitrification was observed in the membrane-containing wells (sampled on Day 18 and Day 42). Results showed average concentrations of NO₃⁻, NO₂⁻, and DO of 19.2 ± 3.3 mg-N/L, 5.1 ± 2.6 mg-N/L, and 3 ± 1 mg/L, respectively, in these wells. The membrane-containing well in which the highest level of denitrification was observed had NO₃⁻, NO₂⁻, and DO concentrations of 14.6 mg-N/L, 9.5 mg-N/L, and 1 mg/L, respectively. This represents an increase in the denitrification occurring within the immediate vicinity of the membrane module-containing wells over time and a concomitant decrease in the zone of influence of these wells. Again, increased TOC was observed in the membrane module-containing wells. Increases in TOC levels were not observed downgradient, again showing that the aquifer filtered out biomass as the water traveled through it.

A third field experiment was performed in which a deep-well convertible jet-pump was installed to recirculate downgradient groundwater to the membrane-containing wells upgradient. It was thought that such recirculation would increase the zone of influence around each membrane module by increasing dispersion, H₂ gas transfer to the groundwater as a result of higher water velocities, and the number of times a single parcel of water was exposed to the membranes. During 91 days of pump operation, approximately 8.0 mg/L NO₃⁻-N was periodically converted to NO₂⁻-N, and DO concentrations were periodically reduced by approximately 5 mg/L. Constant reductions in NO₃⁻ and DO concentrations were not observed, however. This was attributed to the mixing of treated and untreated water at the downgradient pump location. In addition, because of the difficulties associated with operating the pump at this depth, oxygen was re-entrained in the water as it recirculated, continually increasing the H₂ demand rather than decreasing it. It was determined that

although recirculation should effectively remove the levels of DO and NO_3^- observed at the Becker site, a more effective (and expensive) pump would be required to operate at these depths, and finer membrane-well spacing might also be necessary.

The membrane module design devised for use in this research performed well. Mechanisms to remove water condensation worked well, preventing problems with membrane clogging. In addition, the membrane modules were connected in parallel; therefore, faulty membranes could easily be replaced without affecting other modules.

Conclusions and Recommendations

In general, this study was successful in that it showed that even under extreme conditions of high DO and NO_3^- (7 ± 1 mg-DO/L and 22.8 ± 2.0 mg- NO_3^- -N/L, respectively), complete denitrification to N_2 was possible if good membrane-water contact occurred, high lumen H_2 pressures were used (17 psi) and adequate trace nutrients were present (as observed in the column studies). Nevertheless, when this technology was implemented in the field using discrete membrane-containing wells to deliver H_2 to the subsurface, the zone of influence of each membrane module was small. Therefore, closer well spacing (every 1.0-1.5 ft) and water recirculation is likely to be necessary to achieve complete denitrification in the field. This would only be possible at a site where the depth to groundwater is relatively shallow, approximately <25 ft. In addition, the NO_2^- accumulation observed in the column reactor prior to phosphate addition was similar to that observed in all three field studies, indicating that the sediment at the Becker, MN field site is phosphorous limited and phosphorous addition may be necessary at some sites to achieve denitrification *in situ*.

References

- Chang, C.C., Tseng, S.K., Huang, H.K. 1999. Hydrogenotrophic denitrification with immobilized *Alcaligenes eutrophus* for drinking water treatment. *Bioresource Technology*, 69:53-58.
- Fang, Y., Hozalski, R.M., Clapp, L.W., Novak, P.J., Semmens, M.J. 2002. Passive dissolution of hydrogen gas into groundwater using hollow-fiber membranes. *Water Research*, 36:3533-3542.
- Haugen K.S., Semmens M.J., Novak P.J. 2002. A novel *in situ* technology for the treatment of nitrate contaminated groundwater. *Water Research*, 36:3497-3506.
- Killingstad, M.W., Widdowson, M.A., Smith, R.L. 2002. Modeling enhanced *in situ* denitrification in groundwater. *Journal of Environmental Engineering*, 128:491-504.
- Kruithof, J.C., Van Bennekom, C.A., Dierx, H.A.L., Hijnen, W.A.M., Van Paassen, J.A.M., Schippers, J.C. 1988. Nitrate Removal from Ground water by Sulfur/Limestone Filtration. *Water Supply*, 6:207-17.

Result 2:

A limited cost analysis will be performed with the assistance of several membrane companies. Implementation alternatives will be investigated on the basis of cost. Dissemination of information will be accomplished through presentations to local agencies, presentations at scientific meetings, and publication of manuscripts.

LCMR Budget: \$13,722

Balance: \$0

Personnel: \$11,958 for supervision and review (Novak and Semmens), graduate student research assistants (1 for 3 months), and for administrative assistance that is essentially needed and directly related to the project

Equipment: \$667 for presentation production charges.

Other: \$1,097 for publication charges, etc.

Completion Date:

It is our intent to complete Result 2 by June 30, 2004.

Result Status:

Results have been disseminated at several Minnesota Water conferences. In addition, two manuscripts are being written and will be submitted for publication this fall (2004), likely to the journal *Water Research*, an excellent journal with a high impact factor. These papers will be forwarded to the LCMR office once they have been accepted for publication. This project also resulted in the generation of two Master's theses (**1 included** and one to be sent to the LCMR office when it is completed, approximately September 30, 2004).

A true cost analysis could not be performed; nevertheless, a report and CD containing a spreadsheet is included that is designed to assist in the design of such a system ("**Transition Plan**"). Costing would need to be performed on a case-by-case basis given the depth to groundwater, site area, and NO_3^- and DO concentrations at a particular site.

V. TOTAL PROJECT BUDGET:

All Results: Personnel:	\$148,593
All Results: Equipment:	\$73,770
All Results: Other:	\$7,637
TOTAL BUDGET	\$230,000

See Attachment A for budget details

IV. PAST, PRESENT AND FUTURE SPENDING:

Funds have not been spent on the project described above; however, a considerable amount of money has been spent or allocated to studies that directly support the proposed project. A recent grant was received to study autotrophic denitrification with membrane-delivered H_2 at a pilot scale. The principal investigators are also performing research on membrane fouling and the gas transfer properties of the membranes under groundwater flow conditions. There is no current spending. Future spending may depend on the success of the proposed project.

A. Past Spending: none, see above.

B. Current and Future Spending: none, see above.

C. Project Partners:

Michael J. Semmens, Ph.D., P.E. is a co-manager of the project. He is also at the University of Minnesota, Department of Civil Engineering.

Project partners include Joseph Zachmann at the Minnesota Department of Agriculture **(combined in-kind contribution for various MDA staff and services: \$10,000)** and Michael Trojan and Mark Ferrey at the Minnesota Pollution Control Agency **(combined in-kind contribution for various MPCA staff and services: \$10,000)**.

D. Time: The proposed project should be completed in the allotted two-year period. Nevertheless, if needed, the allocation extends to June 30, 2004.

VII. DISSEMINATION:

The target audience for results from this research will be professionals in the area of nitrate removal from contaminated drinking water supplies. Specific targets will be environmental engineers and scientists in academia, state agencies such as the MDA and MPCA, and environmental consultants. Results will be disseminated through scholarly publications in peer-reviewed journals such as *Water Research*. Results from the research project will also be presented at regional conferences such as the *Minnesota Water* conference.

VIII. LOCATION:

The project will take place at the University of Minnesota, Twin Cities Campus (analysis, planning, etc.) and at a field site to be determined. Field studies will be conducted in a well-characterized NO₃⁻-contaminated shallow aquifer in Minnesota, ideally within an hour drive of the University of Minnesota Twin Cities Campus. If we have to select a poorly characterized site, or a site that is further away from the University of Minnesota, it may be necessary to modify the budget slightly for travel and equipment. An aquifer without nearby potable water consumers will be chosen due to the experimental nature of the study. The site will be selected in the summer/late spring of 2001 with the assistance of the MDA and MPCA.

IX. REPORTING REQUIREMENTS:

Periodic workprogram progress reports will be submitted not later than January 1, 2002, July 1, 2002, and January 1, 2003. A final workprogram report and associated products will be submitted by June 30, 2003, or by the completion date as set in the appropriation.

X. RESEARCH PROJECTS:

See Attachment B.