2019 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Setting realistic nitrate BMP goals in southeast Minnesota
PROJECT MANAGER: John L. Nieber
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 04m**]**

APPROPRIATION AMOUNT: $350,000
AMOUNT SPENT: $350,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

The long travel time of nitrate in groundwater negatively impacts our ability to assess the effectiveness of best management practices to reduce the nitrate contamination of groundwater resources. This project developed field monitoring and modeling tools to quantity nitrate travel time and enhance the ability to assess BMP effectiveness.

Overall Project Outcome and Results

Nitrate contamination of groundwater resources results from land management practices that ineffectively control the balance of nitrogen in the soil. This inadequate control leads to excessive leaching of nitrate from the soil, eventually loading the groundwater aquifers underlying the managed area. Best Management Practices (BMPs) have been developed to reduce the leaching of nitrate from the soil profile, and this should then have a positive impact on the quality of water in the groundwater aquifers located in the area of BMP presence. The response of the nitrate concentration at a given location in an aquifer, say for instance at a private or municipal well, will be affected by the history of landuse activity in the landscape upgradient (upstream) of the location of concern. The history is important because of the lag time, that is, the travel time (on the order of years to centuries) required for contaminated water to flow in the groundwater from the point of contamination to the well. This lagging of the response of the nitrate concentration at the well confounds the interpretation of the causes for the nitrate found in the well, thereby making it difficult to determine whether BMPs implemented in upgradient fields are actually working effectively. This project involved the development of methodologies to quantify the lag time for groundwater to flow from a landscape point to a well. The methods developed involved using chemical tracers to quantify the age of groundwater collected at wells, and development of models that can be utilized to calculate lag times. With this information, and a history of landuse practices on the landscape, it is then possible to evaluate the effectiveness of BMPs in the landscape. It is also possible to identify, with some degree of certainty, the source of nitrate that is contaminating a given well.

Project Results Use and Dissemination

The project involved an ongoing collaboration with Mr. Kevin Kuehner, director of the Field-to-Streams Partnership in Preston. A complex groundwater model we developed for Trout Brook is being shared with the Dakota County SWCD to assist with the assessment of BMPs for reducing nitrate concentrations in Trout Brook. A simplified model of groundwater flow and chemical transport was developed to facilitate relatively easy assessment of the effect of landuse practices, and will be available to consultants, agency personnel, and academic institutions. The project has resulted in the submission of follow-up research proposals to one federal agency and one non-profit institution.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2019 ENRTF Work Plan, Final Report

Today's Date: August 15, 2022

Final Report

Date of Work Plan Approval: June 5, 2019

Project Completion Date: June 30, 2022

PROJECT TITLE: Setting realistic nitrate BMP goals in southeast Minnesota

Project Manager: John L. Nieber

Organization: University of Minnesota

College/Department/Division: College of Food, Agriculture and Natural Resources

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Location: Southeast Minnesota

Total Project Budget: $350,000

Amount Spent: $350,000

Balance: $0

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 04m

Appropriation Language: $350,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to develop advanced water-flow and age-dating tools to improve the ability of state agencies to assess how well nitrate reduction best management practices are working in southeastern Minnesota.

I. PROJECT STATEMENT:

This project will provide tools for improving the ability of state agencies to assess how well nitrate reduction BMPs are working in southeastern Minnesota. Nitrate contamination of groundwater is a serious concern because of the direct impact on drinking water safety and resulting nitrate concentrations in the streams into which groundwater discharges. The karst region of southeastern Minnesota, and the sandplain region of central Minnesota are both areas where the impact is most severe due to the close connection between surface conditions and aquifers in those regions. Reducing nitrate contamination of groundwater aquifers has becoming a priority in the state because of the need to protect drinking water quality (MDA Draft Groundwater Protections Rule), and also to meet the nutrient reduction goals set by the MPCA for 2025 (25% nitrate reduction) and 2050 (45% nitrate reduction).

Various degrees of nitrate contamination are present in the four major aquifers in southeastern Minnesota (Galena, Prairie du Chien, Jordan, and Ironton-Galesville aquifers), with the shallowest, the Galena and Prairie du Chien having the highest contamination. With time nitrate is moving into the deeper aquifers (Jordan, and Ironton-Galesville aquifers). The deeper aquifers are important sources of drinking water in the region, while all four aquifers discharge to surface streams at various locations within the region.

Efforts are underway in the region to reduce nitrate leaching to groundwater through the use of improved nitrogen best management practices, but assessments as to whether those practices are being effective within the region is not clear because of the difficulty to interpret collected monitoring data. Some data shows increasing trends for nitrate concentrations, while other data shows decreasing trends. A main part of the problem with water-quality interpretation has to do with the time required for water containing nitrate to travel through the groundwater system before discharging to streams. More detailed information about the age of water in these aquifers and the time of travel of water within the aquifers is needed to be able to provide improved assessments of trends in nitrate concentrations throughout the region.

II. OVERALL PROJECT STATUS UPDATES:

First Update March 1, 2020

Four major activities have occurred during the first nine months of the project.

1. The region of study is rather large and it was reasoned that to get the most out of the funds available for the project that we would choose specified study locations within the project area rather than trying to cover the entire project area. Overall, the sites that were selected do span the entire project area from the north to the south of the area. During discussions with all project team members it was decided to look at up to four site locations. Criteria for site selection included: a). sites should have ongoing nitrogen BMPs being implemented for at least a few years; b). sites should have sufficient locations where observation wells and springs would be available for sampling; c). it would be advantageous if the sites already have some ongoing hydrologic and water quality monitoring activities. After consultation with DNR, MPCA and MDA personnel, and internal discussions, three sites were selected. These sites are the Crystal Creek (Fillmore County) and Bridge Creek (Houston County) watersheds located in the South Branch of the Root River watershed, and Trout Brook, a tributary to the Cannon River in Dakota County. Crystal Creek and Bridge Creek are currently being monitored by the MDA within the scope of the Root River Field to Streams Partnership Project, and hydrologic and water quality monitoring data are available since 2010. The Trout Brook watershed is being monitored more or less sporatically in activities organized by the MPCA, the DNR and Dakota County SWCD, and data area available since 1985. All of these sites have Geological Atlas data available for the project.
2. Developing a precise sampling plan for groundwater age-dating component of the project is very critical because of the high sensitivity of the age-dating technique to errors in sampling. Errors include inadequate care in taking samples, and choice of less than optimal locations/timing for sampling. We

trust the sample analytics that will be conducted on collected samples, but the quality and value of the results rests entirely on the sampling procedures, location of sampling and timing of sampling. With these concerns in mind Jared Trost worked with the USGS Reston office to develop a sampling plan, and the draft plan is given in Appendix A.2. The draft plan was developed during the 2019 Fall period. The draft plan will probably be amended and improved once the actual sampling is initiated. The initiation of the sampling had to wait until sites were selected and could not occur until at least spring at the earliest. It is expected that the sampling will begin in June 2020.

3. Groundwater quality data for nitrate concentrations at sampled wells were acquired from the MDA. These data are from the volunteer groundwater monitoring program and cover the period 2010 - present (2019). We have been using these data with landuse maps for the areas of focus to identify the sources of nitrogen that are leading to the concentrations of nitrate in the wells. We expect that this analysis will help us to identify trends of nitrate contamination and relate those trends to established BMP practices. The analysis follows the concept outlined in the papers by Ransom et al. (2018) and Almarasi et al. (2020).
4. Geological data for each of the study locations are available through the MGS County Atlas data. Digital shape files for the aquifer data are being provided by the MGS via Anthony Runkel. To date we had begun to work with a vertical cross-section for the Bridge Creek site. For that cross-section we have developed an initial setup for a groundwater model and have conducted some computer simulations of the groundwater flow within the cross-section. Groundwater travel times will be derived for each of the aquifers present in the cross-section, and these travel times will be used along with landuse information to determine the transport of nitrate through the aquifers under the current recharge conditions. These travel times will eventually be compared to groundwater ages derived from the age-dating work that is being planned.

Second Update September 1, 2020

Two major activities have occurred during the past six months.

1. Development of groundwater models.
    a. Groundwater model based on COMSOL multiphysics. The model results reported in the March 1, 2020 update is continuing to be applied. However, the effort now is to develop full three-dimensional geologic structures for the modeling. The effort on this should be completed by the March 1, 2021 update.
    b. We purchased a license to the Groundwater Modeling System (GMS) software for use in the project. Specifically we are using the MODFLOW and MODPATH features in GMS for creating the groundwater flow models. As mentioned in the March 1 report, three small watershed areas are the focus of the present study. These include Trout Brook (Dakota County), Bridge Creek (Houston County), and Crystal Creek (Fillmore County). We selected the MODFLOW model because it is the model that is commonly used in Minnesota by state agencies and consultants (e.g., the Metro Model is based on MODFLOW). The GMS software makes the development of groundwater models easier to accomplish because it readily allows one to import digital geologic information such as the information available from the Minnesota Geologic Atlas (MGS).
    c. There is a need to have simpler flow models that might be useful in stakeholder meetings and in uncertainty analysis. To fit this need we have opted to apply a simpler groundwater flow model, OnekaPy (Barnes and Soule, 2020), which is based on the Analytic Element Method.

   d. We have developed a map of groundwater flow patterns based on piezometric water level data for the entire southeast region. The results will be used to quantify travel time distributions as an alternative to the models described above. The advantage of these maps is that it is easy for a stakeholder to see the results as they compare to the field observations.
2. Sampling of water sources and sample chemical analysis.
   a. Water samples have been collected from wells and springs for all of the study watersheds. Analysis of stable isotopes has been completed on some of the samples as those samples are being tested at a laboratory in the Department of Earth Sciences at the University of Minnesota. Testing of samples for SF6, CFCs, 3H and 3He, the elements that will be used for decadal age-dating is delayed because the USGS lab in Maryland where the testing is to be was closed until recently due to COVID-19. We hope to have results back from the testing lab in late fall.
   b. Results of nitrate tests on water samples collected by various government agencies have been acquired from the agency sources. The total number of data values acquired to date is over 136,000. The sampling dates range back to the 1970's.

Third Update March 1, 2021

1. Water sample analysis. Water samples were collected at the three study watershed locations from springs and wells to quantify age of groundwater. Chemical analyses include stable isotopes (work by Joe Magner, UofM) and rare components (SF6, CFCs, 3H and 3He) (work by Jared Trost, USGS). More sampling is planned but we have some preliminary groundwater age data.
2. Model analysis and results. A groundwater model has been completed for one of the study areas and development and testing for the other two areas is ongoing. These models are based on MODFLOW. We have a preliminary lumped parameter model developed and are working to revise and test the model and make it available for resource managers in agencies and consultants.
3. Presentations, outreach;
   a. Two presentations on the project were given at the Minnesota Water Resource conference in October, 2020.
   b. A manuscript has been completed on the use of machine learning in modeling streamflow on one of the study watersheds.
   c. Continuing to work closely with Kevin Kuehner at MDA in terms of data collection, analysis, and planning for outreach activities. Kevin organized a meeting between the LCCMR project group and MDA lag-time group.
4. Submitted a proposal to the University of Minnesota Water Resources Centers competitive WINS grant program. The objective of the research was to use machine learning methods to conduct causal analysis based on the ongoing work in the LCCMR project.

Fourth Update September 1, 2021

1. All water samples for the decadal age dating have been collected by the USGS and the laboratory analysis of these are nearly complete for all of the samples. Some of the constituent analyses are still incomplete at the laboratory but it is expected that all laboratory analysis will be complete by December 2021. Analysis of the laboratory results is ongoing. Preliminary estimates of groundwater age have been developed, but more complete analysis with a USGS travel time model is being undertaken now.

2. Sample of waters for stable isotopes continues. These data are helpful in estimating the source of waters samples in wells, springs, and streamflow. This sampling and analysis will continue right up to the end of the project duration.
3. Groundwater flow models have been developed for the three main study areas, Trout Brook, Crystal Creek, and Bridge Creek. These models are currently being calibrated. The models are being used to quantify groundwater age and groundwater travel time and calculated values will be compared to the groundwater age derived from the chemical sampling. The age-dating derived from the chemical sampling will be used to further refine the calibration of the groundwater models.
4. Further progress on the development of the convolution travel time model. The model is being developed to provide users with a readily available tool to assess effectiveness of BMPs and to assess the lag time between BMP implementation and expectations for receiving benefits. The model currently operates well but will need to be tested against a standard model like MODFLOW. Also, features such as user-friendly interface and graphical displays still need to be developed.
5. Some statistical analysis has been completed on assessing the reliability of available well data and assessments of trends in nitrate concentrations related to corresponding landuse conditions. Work on this will continue for the duration of the project.
6. Analysis of well data to assess the sources of nitrate (e.g., septic systems, manure, fertilized fields, etc.) found at wells has been started and will continue on for the duration of the project.
7. The research team continues to collaborate with Kevin Kuehner at MDA.
8. The WINS proposal mentioned in the March 2021 report was not selected for funding. Another proposal nearly identical to the WINS proposal was submitted to the USGS-NIWR program in June, 2021.
9. A presentation is planned for November (18^{th}) at the Minnesota Groundwater Association Fall Meeting. The presentation will be a one-hour long event in which a series of brief talks covering the outcomes of the various activities in this project. Individual presentations will be made by different members of the project team.

Amendment request 10/25/21

Due to an increase in supply expenses, we request to move the following amounts to balance the budget:

- Personnel totals will increase to a total of $248,874 to cover the cost of salary expenses for laboratory chemical analysis conducted at the UofM Department of Earth Sciences
- Professional/Technical/Service contracts totals will stay the same to a total of $93,800
- Equipment/Tools/Supplies will increase to a total of $3,726
- Travel in Minnesota will decrease to a total of $1,600. Most of travel on the project is now complete. A small amount is left in the budget for any additional travel.
- Other/chemical analysis will be reduced from $14,188 to $2,000. We determined samples could be more efficiently processed paying for staff time in a laboratory in the University of Minnesota Department of Earth Sciences.

Amendment approved by LCCMR 11/8/21

Fifth Update March 1, 2022

1. A presentation was given on November 18^{th} at the Minnesota Groundwater Association 2021 Fall Meeting. The presentation was one-hour long event in which a series of brief talks covering the outcomes of the various activities in this project. The presentation had the following parts: John Nieber - project overview; Tony Runkel - illustration of the geology of the region and issues with nitrate

pollution; Kerry Holmberg – statistical analysis of well and spring nitrate data; Jared Trost – results of the age dating of groundwater in the region; Philip Margarit – modeling of groundwater flow and transport in three watersheds in the region; and Andy Holmberg – simplified model of groundwater transport in the region.

2. The modeling of groundwater in the three small areas (Trout Brook, Bridge Creek, Crystal Creek) of the southeast has been improved. Models are set up for all three areas, and calibrations for Trout Brook and Bridge Creek are nearly complete. Calibration still needs to be completed for Crystal Creek.
3. The age-dating analysis conducted by Jared Trost with the USGS is now complete. The final results are not reported yet because the USGS procedure is to have the results approved by the USGS before release. Near final results were presented at the 2021 Fall MGWA meeting.
4. Work has continued on the development of a simple groundwater transport model. The model is based on a convolution integral approach. The model uses an established groundwater flow field based on field measurements to simulate the transport of a chemical in the groundwater. The user of the model will be able to track the pathway of a contaminant from point of origin and determine the effect of landuse changes in a region on water quality at select wells or springs.
5. The causal analysis (Bayesian inference) study reported in the September 2021 report is still in progress and there is nothing to report at this time. That work will be completed in late spring.

Amendment request 03/01/22

Shortly after the approval of the amendment in October, 2021, there were two items that exceeded the budgeted amounts. We request to move the following amounts to balance the budget:

- The Personnel category will decrease by $1,000.
- Equipment/Tools/Supplies will increase by $250 to a total of $3,976. The $250 should be moved from the Personnel category.
- Other/chemical analysis be increased by $750 to $2,750. The $750 should be moved from the Personnel category

Amendment approved by LCCMR 3/28/22

Sixth Update. Final report, September 15, 2022

Amendment request 1/5/23

As of the last amendment, 3/1/22, there are some slight changes in the amounts needed for the personnel costs, the equipment/tools/supplies, and the Other/chemical analysis categories. The amounts to move around in the budget to account for these slight differences are outlined below.

- Personnel totals were slightly less than budgeted at the last amendment, and should decrease by $61 to $248,813.
- Equipment/Tools/Supplies total was $107 over the last amended amount with the total becoming $3,833.
- Travel in Minnesota was less than the amount from the last amendment ($1,600), and ended up being $1,299. This last figure should be the total travel cost and the budget should be amended to that amount. As of the 3/1/22 report most of travel on the project was complete, but at that time we wanted the $1,600 in the budget for any travel between 3/1/22 and the end of the project.
- The other/chemical analysis had been reduced from $14,188 to $2,000 in the last amendment. We determined samples could be more efficiently processed paying for staff time in a laboratory in the

University of Minnesota Department of Earth Sciences. However, we ended up underestimating this amount slightly, and required $2,255 to complete the work. So this budget amount should be amended to $2,255.

Amendment approved by LCCMR 2/3/23

Overall Project Outcomes and Results

Nitrate contamination of groundwater resources results from land management practices ineffectively control the balance of nitrogen in the soil. This inadequate control leads to excessive leaching of nitrate from the soil, eventually loading the groundwater aquifers underlying the managed area. Improved land management practices, called Best Management Practices (BMPs) have been developed to reduce the leaching of nitrate from the soil profile, and this would then have a positive impact of the quality of water in the groundwater aquifers located in the area of BMP presence. The response of the nitrate concentration quality at a given location in an aquifer, say for instance at a private or municipal well, will be affected by the history of landuse activity in the landscape upgradient (upstream) of the location of concern. The history is important because of the lag time, that is, the travel time (on the order of years to centuries) requires for contaminated water to flow in the groundwater from the point of contamination to the well. This lagging of the response of the nitrate concentration at the well confounds the interpretation of the causes for nitrate concentration found for the well, thereby making it difficult to determine whether BMPs implemented in upgradient fields are actually working effectively. This project involved the development of methodologies to quantify the lag time for groundwater to flow from a landscape point to a well. The methods developed involved using chemical tracers to quantify the age of groundwater collected at wells, and development of models that can be utilized to calculate lag times. With this information, and a history of landuse practices on the landscape it is then possible to evaluate the effectiveness of BMPs in the landscape. It is also possible to identify the source of nitrate that is contaminating the well water.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1

Title: Develop decadal resolution age-dating of water in the four major aquifers in southeast Minnesota

Description: Water samples will be collected mostly from wells and a few selected springs within the area represented by the inset map on the illustration. Water samples will be analyzed for determining sulfur-hexafluoride, chlorofluorocarbons, tritium and helium-3 concentrations. The sampling and analyses need to be done with extreme expert care due to the low concentrations of these elements and the need to avoid sample contamination. These data will be used to quantify the age of the aquifer water with an accuracy of $\pm$ 10 years, a much higher resolution than currently available. Additional sampling of streamflows, aquifers and springs will be conducted to measure chloride, nitrate, and the stable isotopes of oxygen and hydrogen. These data will be used to quantify the source of water (which aquifer the flows originate from) in the streamflows, and to help quantify travel time of water in the aquifers.

ACTIVITY 1

ENRTF BUDGET: $124,870
Amount spent: $124,870
Balance: $0

Outcome	Completion Date
1. Quantified age of groundwater in the major aquifers in southeastern Minnesota. The time resolution will be $\pm$ 10 years.	10/31/2020

2. Estimates of the travel time distributions of water in the major aquifers based on the chemical analyses.	03/31/2021

First Update March 1, 2020

1. Three sites were selected for detailed study. The three sites are the Crystal Creek watershed, the Bridge Creek watershed, and the Trout Brook watershed. A map showing the locations of the first two of these study areas is illustrated in Figure 1.1. Maps illustrating more details of the three study areas are presented in Figure 1.2 (a-c). The Crystal Creek and Bridge Creek watershed are currently locations where the MDA is monitoring hydrology and water quality through the Root River Field to Stream Partnership Project. Within that project fertilizer and crop management BMPs have been implemented since 2010, and monitoring is being conducted to evaluate the benefits of those BMPs on groundwater quality as well as quality of spring water and stream water. The Trout Brook watershed is a location where monitoring of hydrology and water quality has been ongoing since about 1985. Monitoring activities have been conducted by the MPCA, DNR, and Dakota County SWCD, the University of Minnestoa, and the Minnesota Geological Survey. At these sites we will be collecting water samples for age-dating of groundwater.
2. Plans for the sampling of groundwater and springs at the three study sites have been drawn up and a draft plan is complete (see Appendix A.2 for details). It is critically important that sampling be done correctly because the chemical signatures being used for the age-dating are very sensitive to any errors in sampling. Errors include possible contamination of samples, and inappropriate location and/or timing of sampling. Implementation of the sampling plan required a delay until site selection was made, and also until the weather would allow. Delays in sampling due to the Corona virus presence in the Minnesota are possible. However, we are hopeful that sampling will be able to start around June 1.

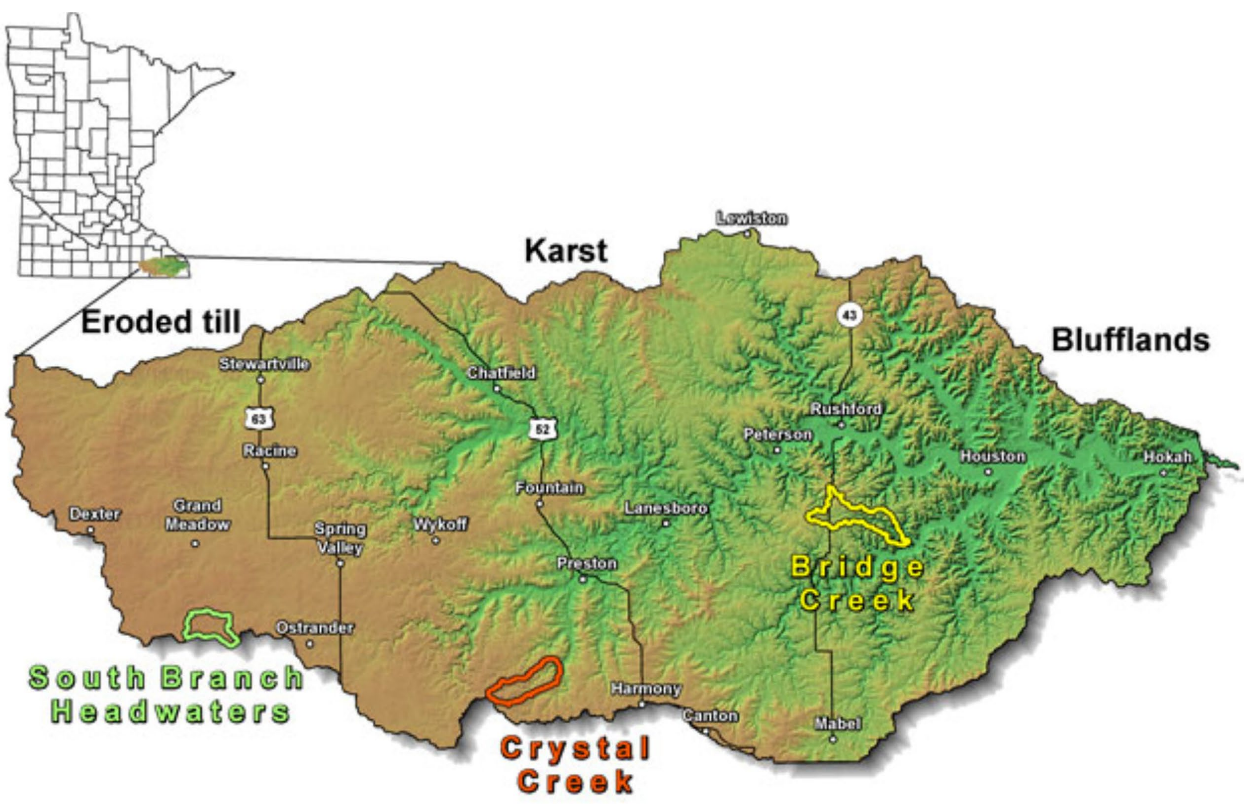
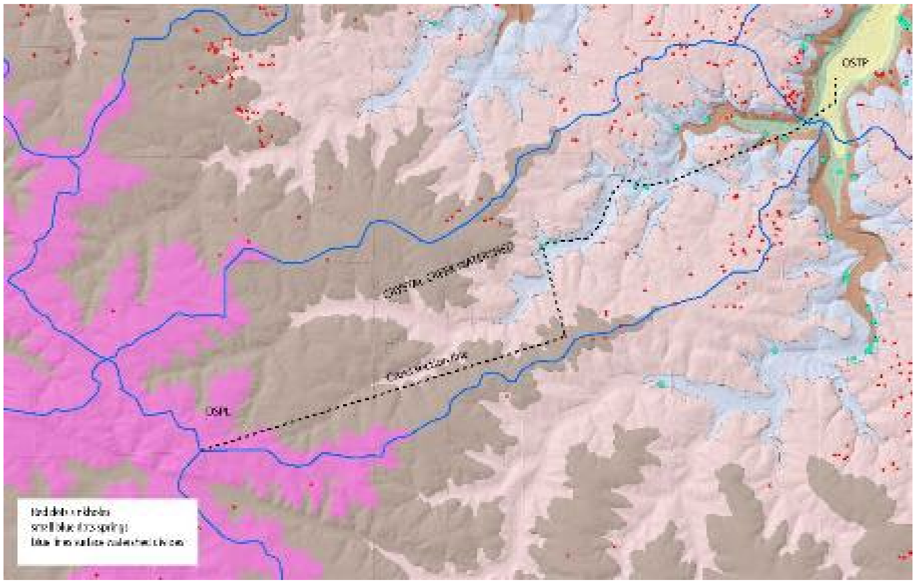
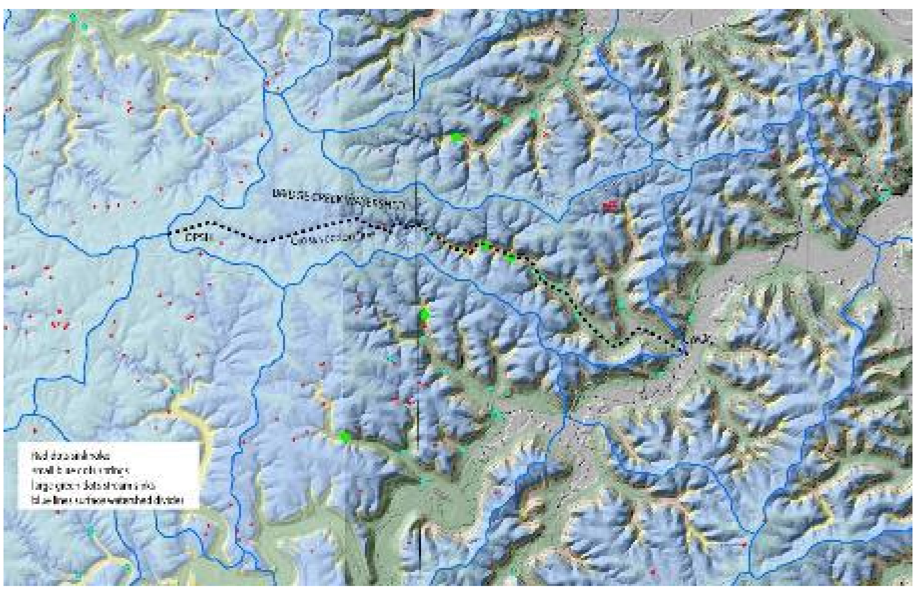


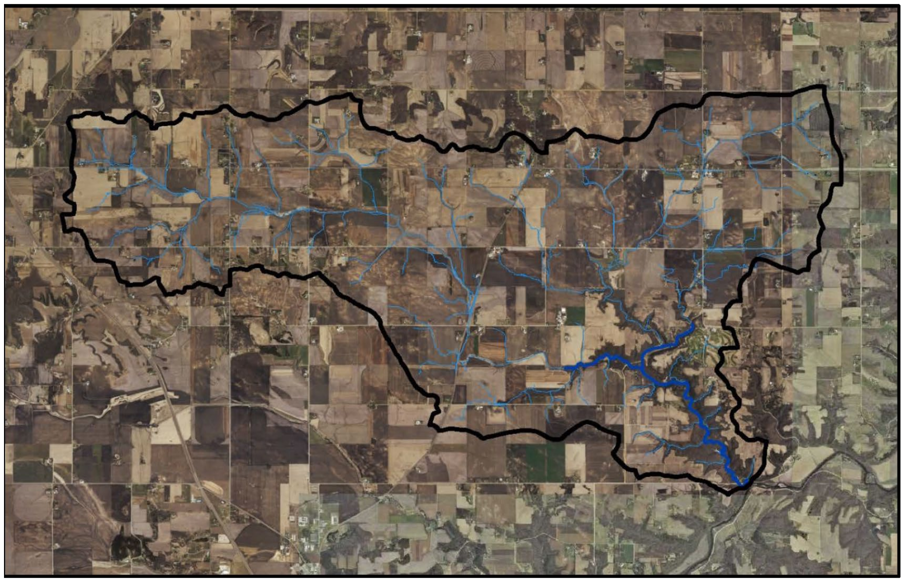
Figure 1.1. Map of the Root River watershed with subwatersheds associated with the Root River Field to Stream Partnership program. The two subwatersheds, Crystal Creek (Fillmore County) and Bridge Creek (Houston County) are selected study sites for the current project.



a.



b.



c.

Figure 1.2. Maps showing the three areas that are the focus of the study within the southeast region. a. Crystal Creek watershed (provided by Julia Steenberg, Minnesota Geological Survey); b. Bridge Creek watershed (provided by Julia Steenberg, Minnesota Geological Survey); and c. Trout Brook watershed (from Trout Brook Subwatershed Analysis, Dakota County Soil and Water Conservation District, March 2016).

Second Update September 1, 2020

1. Water samples have been collected from wells and springs for all of the study watersheds. Analysis of stable isotopes has been completed on some of the samples as those samples are being tested at a laboratory in the Department of Earth Sciences at the University of Minnesota. Testing of samples for SF6, CFCs, 3H and 3He, the elements that will be used for decadal age-dating is delayed because the USGS lab in Maryland where the testing is to be was closed until recently due to COVID-19. We hope to have results back from the testing lab in late fall.
2. Results of nitrate tests on water samples collected by various government agencies have been acquired from the agency sources. The total number of data values acquired to date is over 136,000. The sampling dates range back to the 1970’s. A summary of the content and source of the data is given in Table 1.1.

Table 1.1 Summary of water sample analysis for samples collected since 1970 in the southeaster region of Minnesota. Source of the samples is given along with the constituents measured in the chemical analysis.

Project Area	Data Source	Well Count	Data Points	Year Range	Constituents
Data Points	MDH Wells	1302	12200	1992-2019	Only nitrate, Other constituent data available
	MPCA Wells	~500	12750	1990s (2005) - current	94 parameters including P, K, Mg, Alk, Cl, Ca, Br, Na, SO4 and meds
	Dakota County Wells	~6000	21377	1970s - current	18 contituents including H-He, pesticides, sulfate, chloride, and manganese.
	MDA Wells	~700	5807	2007-2019	Nitrate, Nitrite, Fl, Cl, SO4
	MDNR Groundwater Databa	1150	21503	1992- current	54 constituents including cations and anions, tritium, and a number of trace elements
	Olmsted County Wells	6680	60680	1970s - current	10 constituents including nitrate,chloride, sulfate, atrazine
	DNR Springs	3300	1137	1978-current	7 chemical parameters including nitrate, pH, DO
	UMN current project		1100	2020	
	Total for Wells/springs	**19300**	**136554**	**1970's to current**	
	Feedlots MPCA	9579	116192	1985-current	Animal units per year and feedlot descriptors
	Crop Data Layer - MDA			2006-2019	Crops per 30m parcel
	BWSR BMPs		1896	2002-2019	mapped features of best management practices (BMPS) from the Board of Water and
	BWSR RIM		642	1986-2018	BWSR Rim conservation easements
	MAWQCP BMPs		501	2015-2019	Minnesota Agricultural Water Quality Certification Program
	Precipitation Grid		4332	2000-2018	Average precipitation per basin per year

Third Update March 1, 2021

1. Water samples collected in the fall and sent to the USGS lab in Maryland have been returned with completed analyses for SF6, CFCs, 3H and 3He. Preliminary age-dating results are now available for two of the field sites, Trout Brook and Bridge Creek. The preliminary ages of the groundwater range between 20 years and 30 years. Additional analysis of the sample analysis is required and is based on a lumped parameter model developed by the USGS. Jared Trost is currently conducted this analysis.
2. Plans are being made to collect additional water samples. Due to the high cost of sample analysis we budgeted for a total of 10-12 samples, and we have now fulfilled about 8 of those samples. We expect to take the remaining samples during this spring period.
3. Analysis of samples for stable isotopes have been completed by the laboratory at the University of Minnesota and Joe Magner is currently evaluating the sample results to draw preliminary conclusions. A more complete idea of the age dating using the stable isotopes will come after analysis of samples that have been collected late winter and early spring this year.

Fourth Update September 1, 2021

1. The USGS has completed field sampling for this project. During the last reporting period, four additional water samples were collected in May, 2021 for a total of 12 age-dating samples. The following is a summary of the samples collected. Six samples (three springs, two wells, and one piezometer in a stream bed) were collected within the Trout Brook watershed in southern Dakota County. Two samples (one piezometer in a stream bed and one spring) were collected from the Bridge Creek watershed in Houston County and two samples (one spring and one domestic well) were collected in the Crystal Creek watershed in Fillmore County . Both of these watersheds are part of the Root River Field to Stream Partnership (https://rootriverfieldtostream.org/). The final two samples were collected from the "highway 76 spring" area in Houston County (one spring sample and one well sample). This spring is part of the Minnesota Department of Agriculture's long-term pesticide monitoring program. Two of the samples from springs at Trout Brook were field replicates collected to evaluate the repeatability of the sampling and analytical procedures. All the samples were sent to USGS laboratories for analysis of chlorofluorocarbons, sulfahexafluoride, tritium, dissolved noble gases (helium-3, helium-4, neon-20, neon-22, argon-40, argon-36, krypton-86, krypton-84, xenon-130, xenon-132) , and dissolved gases (carbon dioxide, oxygen, nitrogen, methane, and argon). All lab analytical data have been received for the first eight samples. Only noble gas data have been received for the four new samples collected in May 2021. Age tracer data (chlorofluorocarbons, sulfahexafluoride) and dissolved gas data (carbon dioxide, oxygen, nitrogen, and argon) are expected in September 2021. Tritium data are expected by December 2021. Lab reports indicate that the first eight samples were of high quality and datable. The noble gas data from the 4 samples from May 2021 also indicate high quality, datable samples. All of the lab data received so far have been reviewed and uploaded into the USGS National Water Information System database. Preliminary mean sample age dates for the first eight samples were provided from the labs and indicate mean sample ages between about 10 and 30 years. Groundwater age distribution modeling is underway with TracerLPM (Jurgens and others, 2012) and DGMETA (Jurgens and others, 2020).
2. Analysis of stable isotopes in water samples taken at the field sites has been completed although we still do continue to take samples during particularly interesting weather events that will provide distinctive flow travel time information. Evaluation of the stable isotope data is continuing and will be completed by the March 1, 2022 report. However, it is expected that sampling will continue until the end of the project in June.

Fifth Update March 1, 2022

1. The age-dating analysis using TracerLPM and DGMETA has been completed by the USGS and is in internal review within the USGS for final approval of the results.
2. The stable isotope work for quantifying groundwater age is continuing. Water samples will continue to be collected until the end of the project. A report on results to date would have been possible except that we are still waiting for analysis of samples that were sent to the laboratory at the University of Waterloo in Quebec quite some time ago. We hope that the results will be sent to us within the next two months.

Final Report Summary

1. The USGS completed field sampling for this project in the fall of 2021. The following is a summary of the samples collected. Six samples (three springs, two wells, and one piezometer in a stream bed) were collected within the Trout Brook watershed in southern Dakota County. Two samples (one piezometer in a stream bed and one spring) were collected from the Bridge Creek watershed in Houston County and two samples (one spring and one domestic well) were collected in the Crystal Creek watershed in Fillmore County. Both of these last two watersheds are part of the Root River Field-to-Stream Watershed Partnership (https://rootriverfieldtostream.org/). Also, two samples were collected from the "highway 76 spring" area in Houston County (one spring sample and one well sample). This spring is part of the Minnesota Department of Agriculture's long-term pesticide monitoring program. Two of the samples from springs at Trout Brook were field replicates collected to evaluate the repeatability of the sampling and analytical procedures. All the samples were sent to USGS laboratories for analysis of chlorofluorocarbons, sulfahexafluoride, tritium, dissolved noble gases (helium-3, helium-4, neon-20, neon-22, argon-40, argon-36, krypton-86, krypton-84, xenon-130, xenon-132) , and dissolved gases (carbon dioxide, oxygen, nitrogen, methane, and argon). All lab analytical results were completed by late fall of 2021. Laboratory reports indicated that the samples were of high quality and datable. All of the lab data were reviewed and uploaded into the USGS National Water Information System database. The laboratory data were used in a groundwater age distribution modeling activity with the TracerLPM (Jurgens and others, 2012) and DGMETA (Jurgens and others, 2020) models. The USGS approved report on the groundwater ages is published and available online at Faulkner, K.E., and Trost, J.J., 2022, Groundwater data and age information from samples collected in Minnesota: U.S. Geological Survey data release, https://doi.org/10.5066/P9XVBIWP.

2. The analysis of water samples collected for age-dating using stable isotopes has been completed. The samples were analyzed at a laboratory at the University of Waterloo in Quebec. The delay in getting those results was due to COVID-related laboratory restrictions. Results were received mid-spring in 2022.

   All three of the study areas (Trout Brook, Crystal Creek and Bridge Creek) are different but have somewhat similar valley types and riparian water exchange. The primary driving factor during the study was the seasonal precipitation input. In a normal to wetter year the isotopic data show larger amplitude shifts between seasons with trendlines that adjust depending on the temperature of the new water additions. Data collected in late 2020 into 2021 showed the smallest amplitudes suggesting that core aquifer water was the primary source water with mean core aquifer transit time greater than 10 years to over 20 years. These data results are generally consistent with the USGS age dating results.

3. The USGS provide cost match on this project. That cost match was expended by the USGS in the salary of Jared Trost, the collaborator from the USGS. The amount of match was $37,043.

4. Maps of the distribution of landuse within the southeast region are required for a regional analysis of nitrate contamination of groundwater. Landuse data dating back to the mid-1990's was acquired and maps illustrating the landuse distribution were produced. An example of one of the regional maps is given in Figure F.1. A sample map of landuses at a refined scale is presented in Figure F.2. This landuse information is intended to be used with the Bayesian inference analysis and the convolution integral model presented in Activity 3.

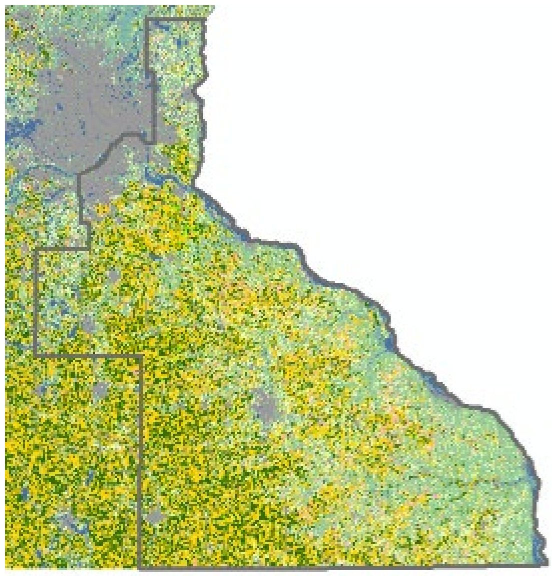


Figure F.1. Distribution of lanuse in the southeast region of Minnesota.

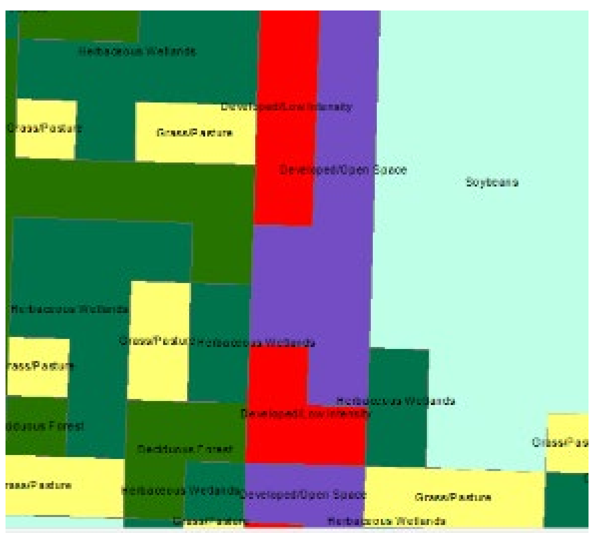


Figure F.2. Landuse distribution shown at a small section selected from Figure F.1.

ACTIVITY 2

Title: Determine travel times for flows within the major aquifers to streams based on hydraulic analyses.

Description: Springshed boundaries of the four major aquifers will be delineated using geological information derived from the County Geologic Atlases available for the region. A groundwater flow model will be constructed using the detailed geological information and applied to calculation of travel time within the individual aquifers. The model will be formulated to be able to include the complex fracture flow and dissolution-channel flow characteristic of groundwater flow in the karst region of the southeast. The model will be calibrated to match recorded flows and nitrate concentrations emerging from sampled springs. The calibrated model will then be able to be used with monitoring data to assess the impact of existing BMPs on water quality.

ACTIVITY 2

ENRTF BUDGET: $83,725
Amount spent: $83,725
Balance: $0

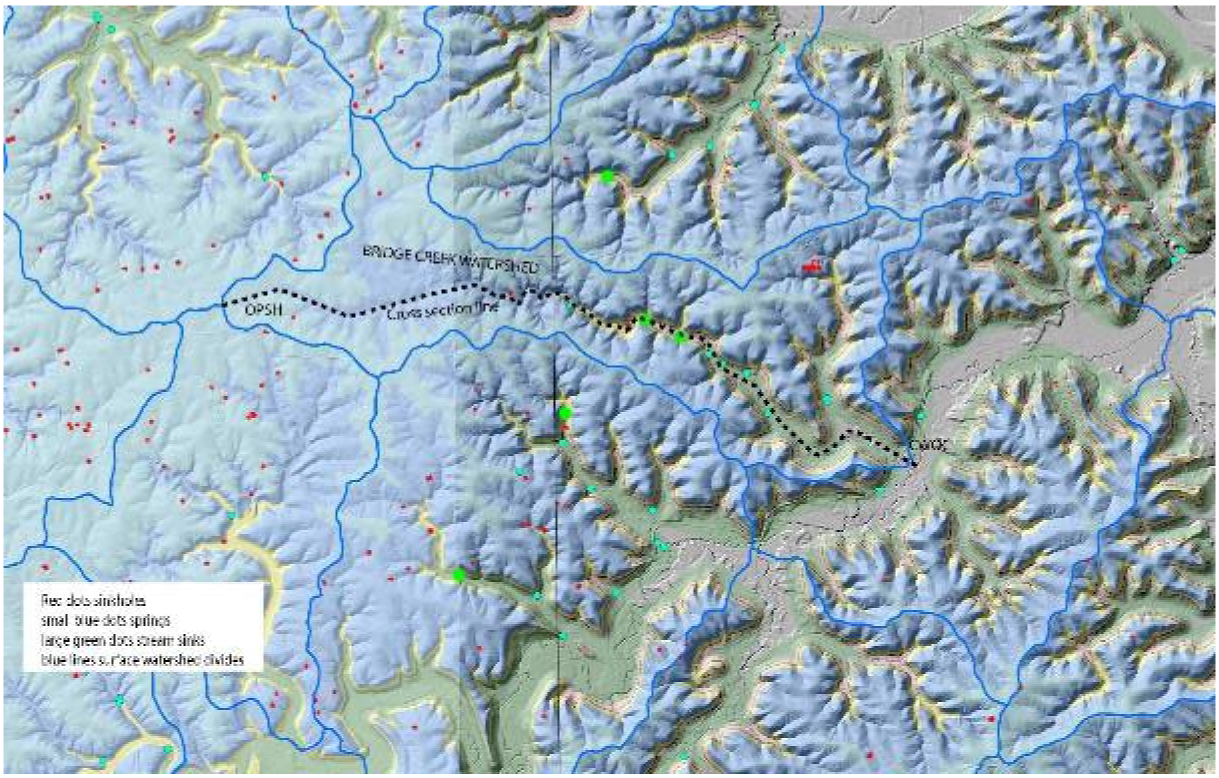
Outcome	Completion Date
1. Maps illustrating calculated travel time distributions of water within the four studied aquifers.	06/30/2021
2. Interpretation of the aquifer sources of water in streamflows and an assessment of the current trends in nitrate concentrations from each source.	10/31/2021
3. Calibrated groundwater flow model. The calibrated model will be documented and made ready for use by state agencies and consultants.	03/31/2022

First Update March 1, 2020

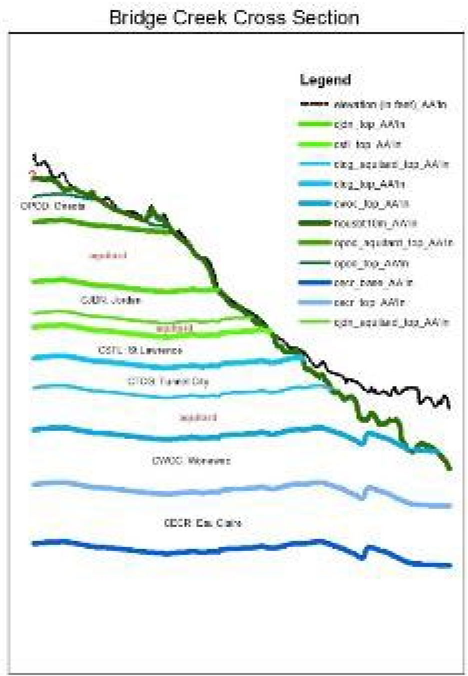
1. Digital files of aquifer information for the aquifers located in the three study areas are available from the MGS. An image of an example file is shown in Figure 2.1. This image is a cross-section for the Bridge Creek watershed. A plan view of the watershed showing the location of the cross-section is shown in Figure 2.1.a, while the cross-section is given in Figure 2.1.b. The scale of the cross-section is highly exaggerated in the vertical so that the details of the layers of aquifers and aquitards can be visualized. In future work we will be acquiring digital files for full three-dimensional geological domains for each of the three watersheds.
2. The analysis of flow fields in the aquifer systems at the study sites will be conducted using the COMSOL-MP (COMSOL, 2019) commercial software. The software is based on the finite element numerical method. As a preliminary trial for analysis of the hydraulic flow field for the vertical cross-section shown in Figure 2.1.b, an illustration of a finite element grid is shown in Figure 2.2.a. Hydraulic properties (from Anthony Runkel; see references Runkel et al., 2003, 2006, 2018) of the different geological layers are summarized Table 2.1, and a trial run with the finite element model was conducted using a specified hydraulic head on the left side of the cross-section. The land surface was treatment with a seepage face boundary condition; no rainfall flux was applied on the land surface. The result of the trial run (for steady-state flow conditions) is illustrated in Figure 2.2.b. The result is shown in terms of the flow field, where the arrows show the flow direction, and the size of the arrows indicate the flow magnitude. More work is needed to improve the boundary conditions used, for instance, to include a net recharge along the land surface boundary. In addition, next steps will be to develop similar models for Crystal Creek and for Trout Brook, but also to develop full three-dimensional models based on digital geological data acquired from the MGS for all three study areas. The calculated flow fields will be utilized in deriving the travel time distributions for the aquifers layers.
3. Nitrate concentration data available from multiple sources have been acquired. These include data for water samples collected from wells and springs. Data exist for meaurements as far back as 1976. The data sources include MDA, MDH, DNR, MGS, Dakota County SWCD, and Olmsted County. These data provide the opportunity to relate nitrate concentrations in groundwater to the landuses within the area

and we are currently conducting analysis of those data to identify and quantify trends in nitrate concentrations at wells and in spring discharges.

4. It is of interest to be able to detect differences in nitrate concentrations in samples collected at wells and at springs. The question is how many samples are required to be able to state with confidence that differences in measured concentration are actually significant. We conducted an analysis to quantify the number of samples required to detect significant differences in concentration, and the summary results of the analysis are presented in Appendix A.3.



a.

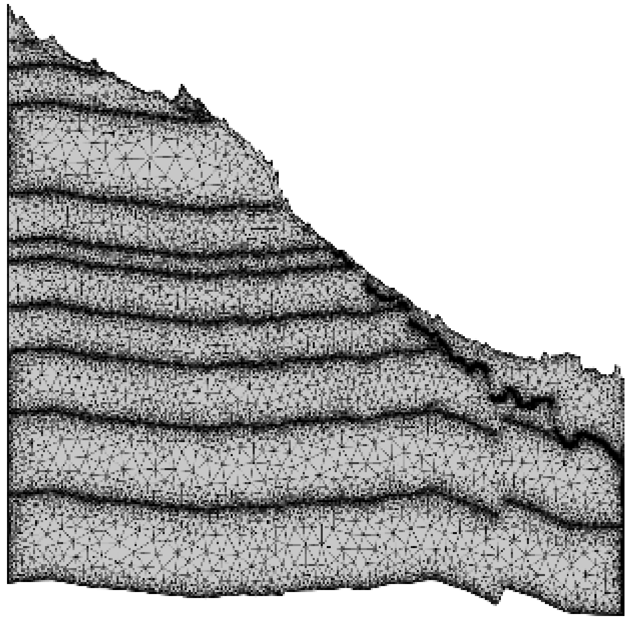


b.

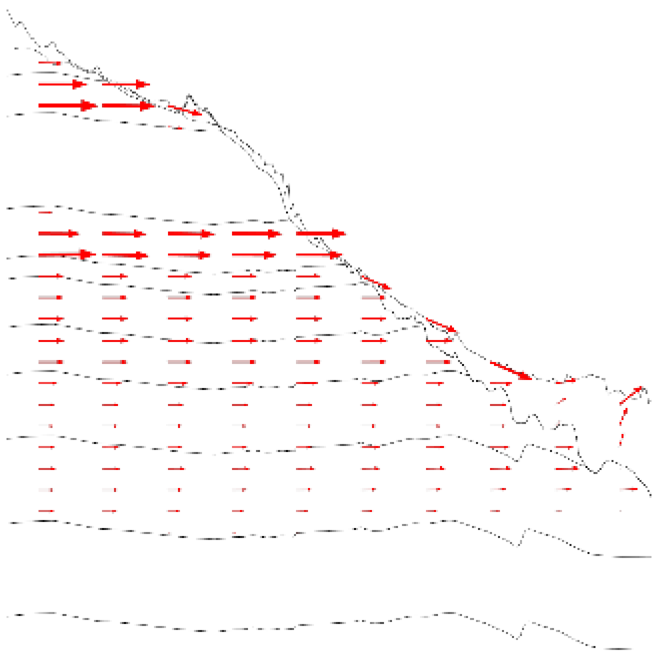
Figure 2.1. a. Plan view of the Bridge Creek watershed showing the location of the vertical cross-section that is illustrated in b.

Table 2.1. Hydraulic properties of the geological layers at the Bridge Creek cross-section

Layer name	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)	Effective porosity
Surface	9.02	3.04	0.25
Oneota	18.3	0.183	0.10
Upper aquitard	0.0304	0.0000304	0.08
Jordan	9.0	0.09	0.25
Middle aquitard	4.6	0.0000304	0.15
St. Lawrence	4.6	0.0000304	0.15
Tunnel city	4.6	0.046	0.20
Lower aquitard	3.04	0.0000304	0.15
Wonewoc	4.6	0.046	0.25
Eau Claire	0.00304	0.00000304	0.15



a.



b.

Figure 2.2. a. Finite element discretization of the Bridge Creek vertical cross-section given in Figure 2.1.b. b. An example of flow pattern in the layered aquifer system for the Bridge Creek vertical cross-section. The flow velocities are indicated by the arrows and the arrow size is proportional to velocity magnitude.

Second Update September 1, 2020

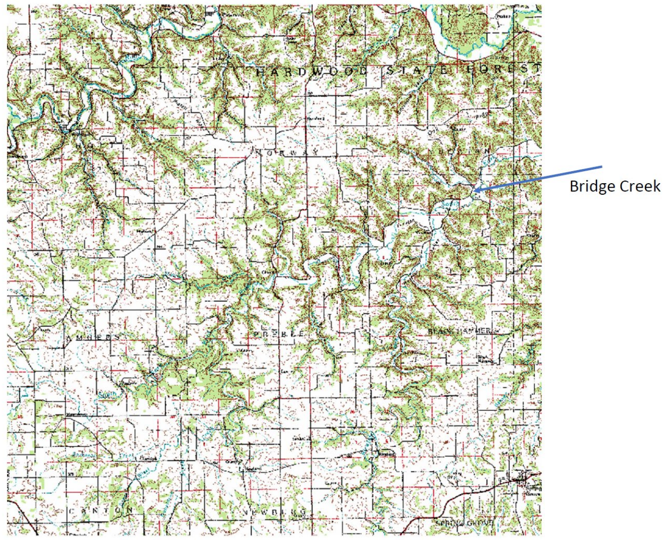
Development of groundwater models.

a. We continue to work with the COMSOL model described in the March 1, 2020 update. In that update we showed results for flows in a vertical cross-section. Currently we are working on building the three-dimensional models of the geology. We expect to have COMSOL models of the three-dimensional groundwater flow systems for each of the study areas completed by the March 1, 2021 update.

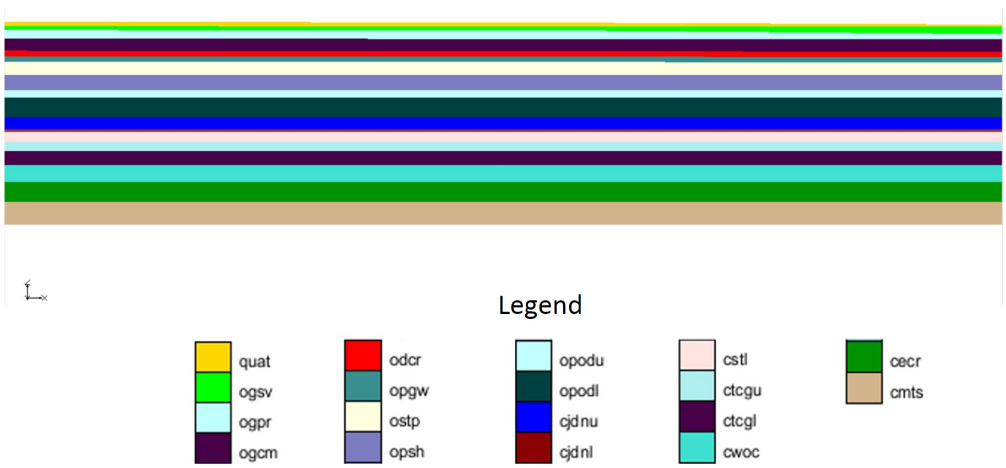
b. We purchased a license to the Groundwater Modeling System (GMS) software for use in the project. Specifically we are using the MODFLOW and MODPATH features in GMS for creating the groundwater flow models. As mentioned in the March 1 report, three small watershed areas are the focus of the present study. These include Trout Brook (Dakota County), Bridge Creek (Houston County), and Crystal Creek (Fillmore County). The geologic stratigraphy of the region where these watersheds are located is very complex with multiple layers (up to 11) of aquifers and aquitards. Some information about the vertical section of Bridge Creek was presented in the previous report. We have acquired the geological strata for the areas surrounding each of the study watersheds from the Minnesota Geological Survey. The data is in the form of shape files that can be imported into GMS for producing a layered aquifer domain for modeling. The work on producing those groundwater models from the geologic data has been completed and we now have functioning groundwater flow models for each of these three areas. The task with these models is to simulate realistic groundwater flow fields for each of the study areas, and then to develop maps of travel time distributions within the watersheds. The MODFLOW model is used to generate the flow field, and MODPATH will be used to develop the travel time distribution maps. The generated travel time distributions will be compared to the age-dating data, and will used in developing simplied models of nitrate transport from the land surface to wells and springs/streams. A few select images from the groundwater flow models are given in Figure 2.3.

c. MODFLOW is a complex groundwater model. We are also interested in applying simpler models since they may be very useful to stakeholder in the future. For this we have opted to apply a simpler groundwater flow model, OnekaPy, which is based on the Analytic Element Method. The model utilized well piezometric levels and aquifer hydraulic properties to determine the probable areas (capture zones) of the land surface that will contribute contaminants to a given well or spring. The entire region is being mapped with these capture zones and this will assist with linking the well nitrate data with land uses.

d. Rasters of piezometric water level data for the entire region were acquired from the Minnesota Department of Natural Resources. These data were used to produce maps of groundwater flow patterns and flow velocity for the entire region. These are then being used along with the maps of land use to determine the potential for transport of nitrate from the land surface to well locations and to spring discharge points. This approach is simpler than the OnekaPy approach described above, but was being implemented prior to the implementation of the OnekaPy model and so it will be completed and reported in the project final report. It is considered valuable from the standpoint of explaining the groundwater flow process in the area without resorting to the complexities associated with models like MODFLOW or OnekaPy.


Bridge Creek

a.


Legend
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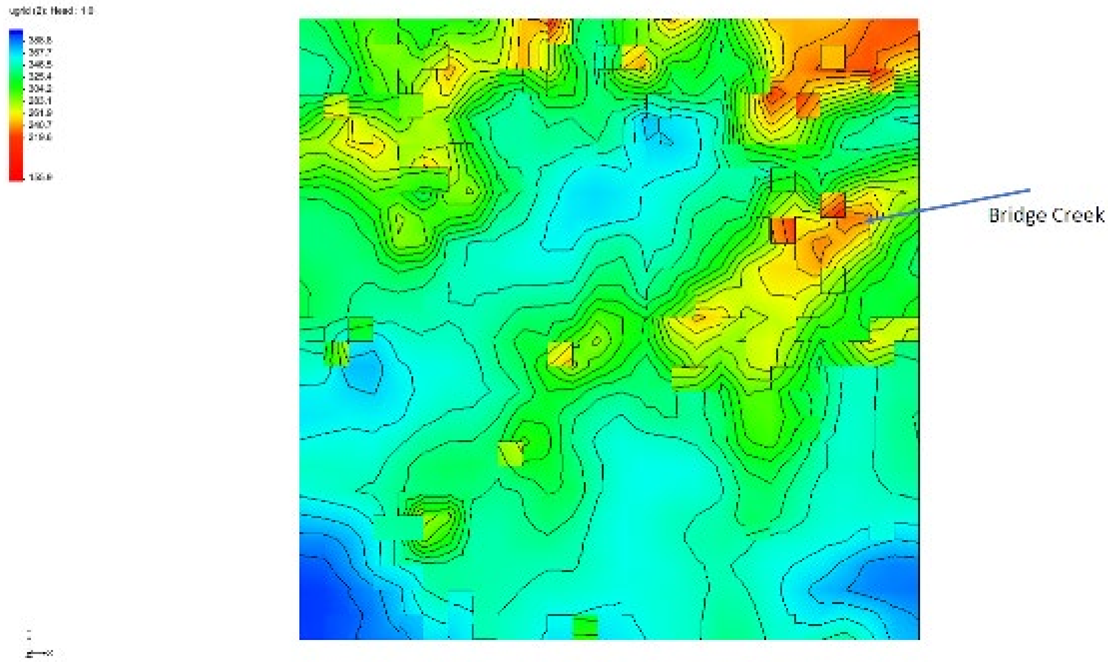


c.

Figure 2.3. Images of the MODFLOW model for Bridge Creek watershed. A. Topographic map of the area showing Bridge Creek location. B. Stratigraphic layers for the geology in the Bridge Creek area as represented in the MODFLOW model. See Table 2.1 for some details on the stratigraphic layers. C. Piezometric contours derived from the MODFLOW model; numbers in the legend are piezometric level in meters.

Third Update March 1, 2021

1. A MODFLOW/MODPATH model for the Trout Brooks site has been developed and the model is working properly. We have preliminary calibration completed and will continue to improve the model. An image of the model output showing the flow pathlines (developed using particle tracking) is shown in Figure 2.4. This model seems to be properly simulating the streamflow from Trout Brook corresponding to an average annual recharge rate of about 15 cm (estimated by the USGS with the USGS water balance model). In the figure one can see the streams for Pine Creek, Trout Brook, the Cannon River, and Lake Byllesby.

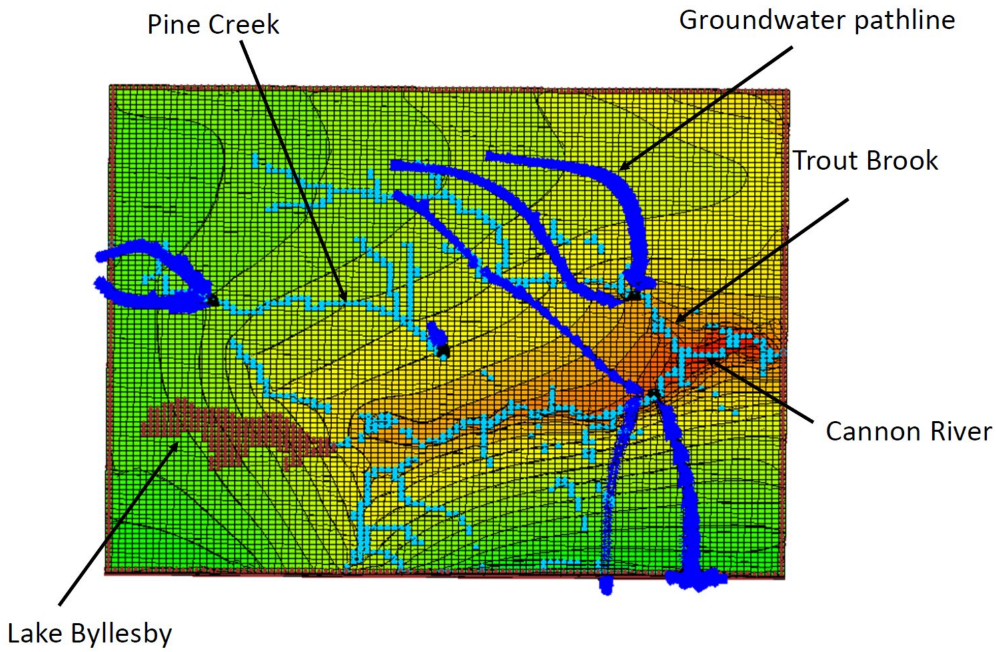


Figure 2.4. Images of the MODFLOW model for the Trout Brook area. The horizontal dimension of the regions shown is about 22 km (13.8 mi). The solid contour lines are the lines of equipotential for the groundwater flow system. The heavy blue traces on the map are the pathlines for flow in the groundwater system. These pathlines provide information about the possible travel time of groundwater that ends up discharging at the streams or springs.

2. Preliminary MODFLOW models have been completed for Bridge Creek and for Crystal Creek, and with what we have learned from the modeling of Trout Brook we expect to have working models for those two areas before the fourth update.
3. Work is continuing with the COMSOL model mentioned in some of the earlier updates. The biggest task has been getting the stratigraphic data into a format suitable for use in the COMSOL model. This task was much more easily done in the GMS interface used for the MODFLOW model. We intend to have a working COMSOL model completed by the fourth update.
4. For all of these models the plan is to use the working models to map out the groundwater ages as modelled by the models, and then compare those to the groundwater ages developed based on the groundwater sampling.

Fourth Update September 1, 2021

1. Through this study, three working MODFLOW groundwater flow models were developed for the test watersheds of Bridge Creek, Crystal Creek, and Trout Brook. These models were developed using stratigraphic raster data provided to us by the Minnesota Geological Survey (MGS) to construct the geology of each model area. Each model consists of a 100 by 100 cell structured grid. Hydrologic properties for each stratigraphic unit were additionally supplied by the MGS to guide our model creation. Each model was created with the stream package (STR) for our rivers and streams, a recharge package (RCH), and a general head boundary (GHB) package to allow groundwater flow in and out of the model domain as well as to represent the lakes within the model areas. General head boundaries were

developed for each layer and head values were derived from contours provided by MGS. In areas where head contours for the upper layers did not cover the entire boundary of the model, a water table elevation raster from USGS and elevation values for stream surfaces were used to derive water table head values. The values for the RCH package were derived from the Minnesota statewide soil-water-balance model developed by the USGS for the time period of 2002 through 2015 to obtain an accurate mean relative distribution of recharge throughout the model areas. The models are currently in the calibration process and will be calibrated using the integrated PEST calibration scheme within our modeling software. The time-period the models will be calibrated to is 2010-2019. The hydraulic conductivities of the aquifer layers, the streams' conductance, the multiplier for the recharge grid, and the general head boundaries' conductance will be parameterized for calibration. The calibration targets consist of the stream flow data provided along with hydraulic head data from wells. Well data was provided to us by the Minnesota Pollution Control Agency (MPCA), Minnesota Department of Natural Resources (MNDNR), and the Minnesota Department of Health (MDH). Stream flow data was provided by the MNDNR's cooperative stream gauging network. Confidence intervals were calculated for the streamflow data and the well data that had multiple measurements over time. Well data that consisted of a single measurement were given an interval of 2 meters of variance to account for head changes over time. Stream flow data was adjusted to the calibration period based on annual precipitation data. Adjustments were made based on the average percent increase from normal precipitation for the period of record for stream flow and the percent increase from normal precipitation for the calibration period in each catchment. The calibration scheme we will apply to our models will adjust the parameters individually to achieve computed heads and flows in our models within the calibration targets for our observations to validate the models to our real-world systems. Following calibration, we will be utilizing the particle tracking model MODPATH to obtain travel time distributions and mean travel times for discharge locations within each model area. This will allow us to see not only mean travel time, but also provide us the ability to investigate individual flowlines at our discharge locations. Through our particle tracking work, we can also observe the sources and contributing areas to each location to provide greater insight into where the groundwater is coming from along with the when. Our travel time modeling will be compared to values obtained from age tracer sampling in the field. These models will be further calibrated manually to match our field derived values more closely. This will then allow us to observe both local and regional trends on groundwater age and groundwater age distribution.

2. Analysis of nitrate trends in well and spring samples. A very large dataset has provided us with the opportunity to examine questions about the variability of groundwater nitrate concentrations, to estimate how many samples are required at a given location to detect a trend, and to relate any identified trends to land use conditions. This analysis has been conducted for the entire southeast region where we have accumulated landuse information and nitrate concentration data. One limitation we face is that readily available landuse information exists only back to the late 1990's. Available nitrate concentration data go back even to the mid-1950's, but acquiring landuse data at corresponding times would require manpower far beyond the scope of this project because the data are not archived in an easily accessible format.
3. Analysis of the nitrate data and landuse data is being conducted to assess the source of nitrate found at given sampling locations. The analysis is based on the methodology descried by Ransom et al. (2016). Data for the analysis includes well locations, nitrate concentrations, concentrations of other chemical tracers, and groundwater flow field characteristics. The analysis is based on a Bayesian statistics analysis

of the data. This analysis began in summer 2021 and will continue through March 2022. A more detailed description of the methodology is given in Appendix A.4.

Fifth Update March 1, 2022

1. The modeling efforts in Southeastern Minnesota as a part of this project have been able to create 3 working groundwater flow models developed for the test watersheds of Trout Brook, Bridge Creek, and Crystal Creek. These models were created using stratigraphic data from the Minnesota Geological Survey (MGS), County Well Index data from the Minnesota Department of Health (MDH) and MGS, streamflow data from the Cooperative Stream Gaging Network developed by the Minnesota Department of Natural Resources (MNDNR), observation well data provided by the Cooperative Groundwater Monitoring Network developed by the MNDNR and monitoring well data provided by the Minnesota Pollution Control Agency (MPCA), high capacity pumping well data was provided by the MPARS dataset developed by the MNDNR, and the recharge data was provided by the Soil Water Balance (SWB) model provided by the United States Geological Survey (USGS). The models were created using the stream package (STR), the recharge package (RCH), the general head package for lakes and outer boundaries (GHB), and the multi-node well package (MNW2). These packages were chosen to allow for the advanced well package to better simulate the effects of pumping wells, the more advanced stream package to simulate streamflow routing in the model, and the general head boundary package to simulate simplified lakes and an open system on the model boundaries to allow for groundwater movement into and out of the model area.

   Two models have been calibrated thus far, Trout Brook and Bridge Creek. Both models were calibrated to streamflow data and groundwater level data using the non-linear parameter estimation software PEST. Calibration targets for streamflow were based on confidence intervals for the range of values of baseflow in the streams. The baseflow was calculated using timeseries flow data and running a baseflow separation digital filter over the continuous data. Groundwater level calibration targets were given a confidence interval of 2 meters for wells with single measurements, and confidence intervals were calculated individually for wells with timeseries data. The calibration group weights for the stream flow targets and the well head targets were set to be an equal weight to each other during the calibration process to allow for equal consideration of stream flows and groundwater levels. Hydraulic conductivities, streambed conductance, boundary conductance, and recharge were the parameters that were allowed to be adjusted during the calibration process. The models were calibrated to the period of 2010-2019. Crystal Creek, the third model area, is currently in the process of being calibrated.

   So far, Trout Brook has been utilized for travel time analysis with MODPATH, simulating results that are in line with what was found from the age tracer field sampling in the watershed. The models are additionally being used outside of the scope of the project to run transient simulations to investigate baseflow recession characteristics in the watershed as a part of additional graduate research. These models and their results so far have been presented at the Fall 2021 Minnesota Groundwater Association Meeting and the Fall 2021 American Geophysical Union Meeting, with an additional presentation of our models planned with Dakota County and other government partners.

   Some images from the modeling are shown in Appendix A.6.
2. Work on the causal analysis (see report from September 1, 2021, Appendix 4 for background) that uses Bayesian inference to identify the sources of nitrogen that lead to the contamination measured at private wells and monitoring wells is ongoing. We were hoping to complete this by this report, however

the completion has been delayed and it is expected the results will be complete by early summer in time for the final report.

Final Report Summary

1. Groundwater flow models developed for the three study areas in the southeast have been completed, and the calibration has been attempted on all of the models. The models are based on the MODFLOW software, the same groundwater flow model that is the basis for the METRO model. Three areas of the southeast were focused in the model, Trout Brook in Dakota County, Crystal Creek in Filmore County, and Bridge Creek in Houston County. Calibration of the models was completely successful for the Trout Brook model, however not so for the Crystal Creek and the Bridge Creek models. While we have working models for both of these areas, the models lack complete calibration. The reason for the lack of success at getting complete calibration is reasoned to be due to the high degree of karst that occurs in these two areas. The version of MODFLOW used for the project does not account for conduit flow (a feature of karst aquifers) and we have only recently acquired a model add-on to make it possible to account for karst in the model. We will continue to work on these two models beyond the end of the LCCMR support as the graduate student, Philip Margarit, working on the project has selected these two watersheds as part of his Ph.D. dissertation work. In doing this Philip has established a collaboration with a new faculty person at Carlton University who is an expert in karst aquifer systems.

   Some images of modeling results for the Trout Brook area are presented in the following figures. These results are for the calibrated model. Figure F.3 shows the piezometric surface map for the area, which includes Trout Brook, Pine Creek, and Lake Byllesby.

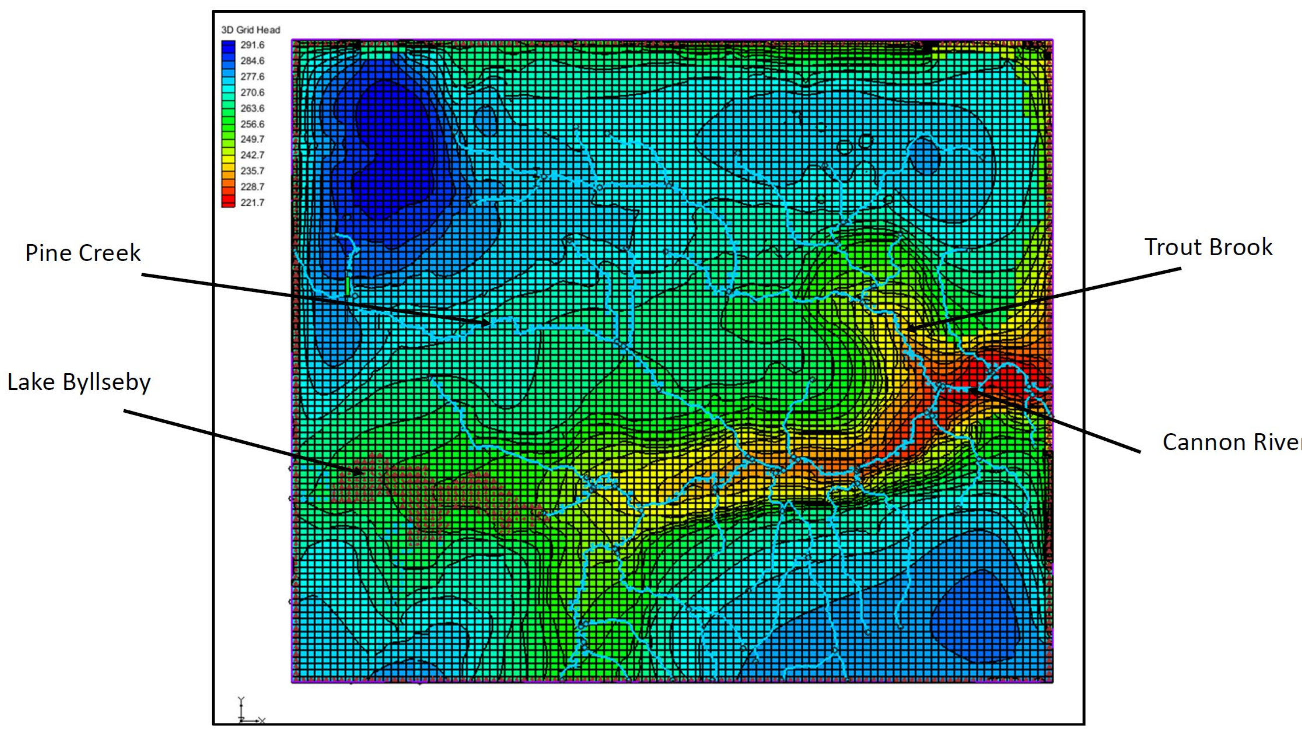


Figure F.3. Image from the MODFLOW model showing the stream channels and Cannon River channel, Lake Byllesby, and piezometric contour lines for the calibrated MODFLOW model.

The groundwater flow pathway corresponding to the piezometric flow field shown in Figure F.3 is illustrated in Figure F.4. The flow paths were derived using the particle trackjng feature in MODFLOW.

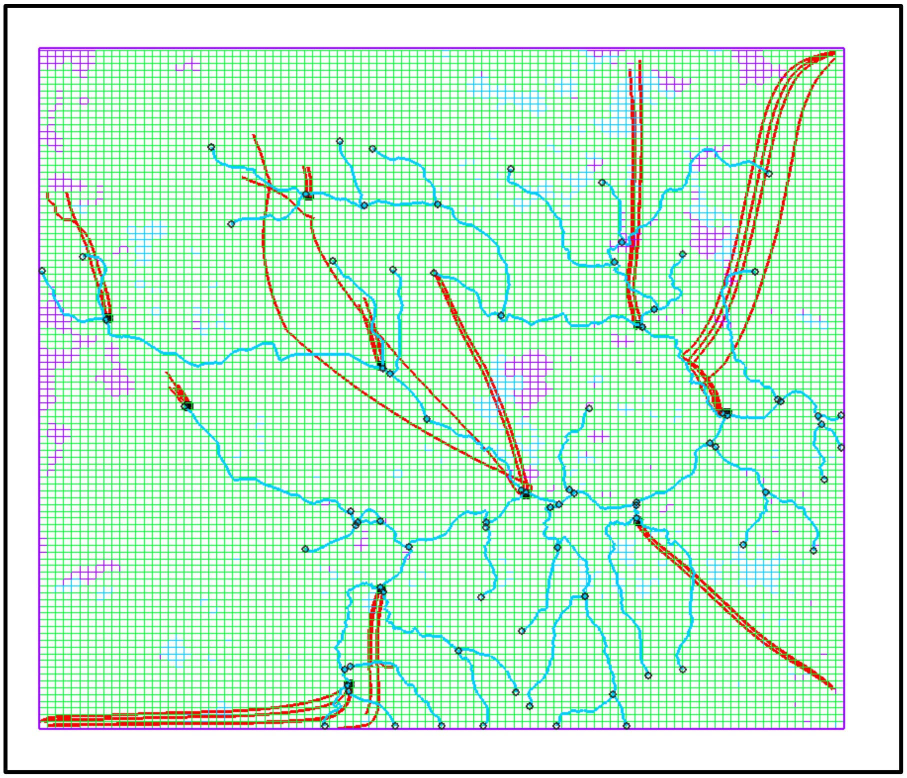


Figure F.4. Image from the MODFLOW model showing a sampling of pathlines taken by groundwater flowing through the area. The pathlines were derived using the particle tracking feature in MODFLOW.

The groundwater ages derived by MODFLOW are in agreement with the values derived by the USGS analysis (shown in red font).

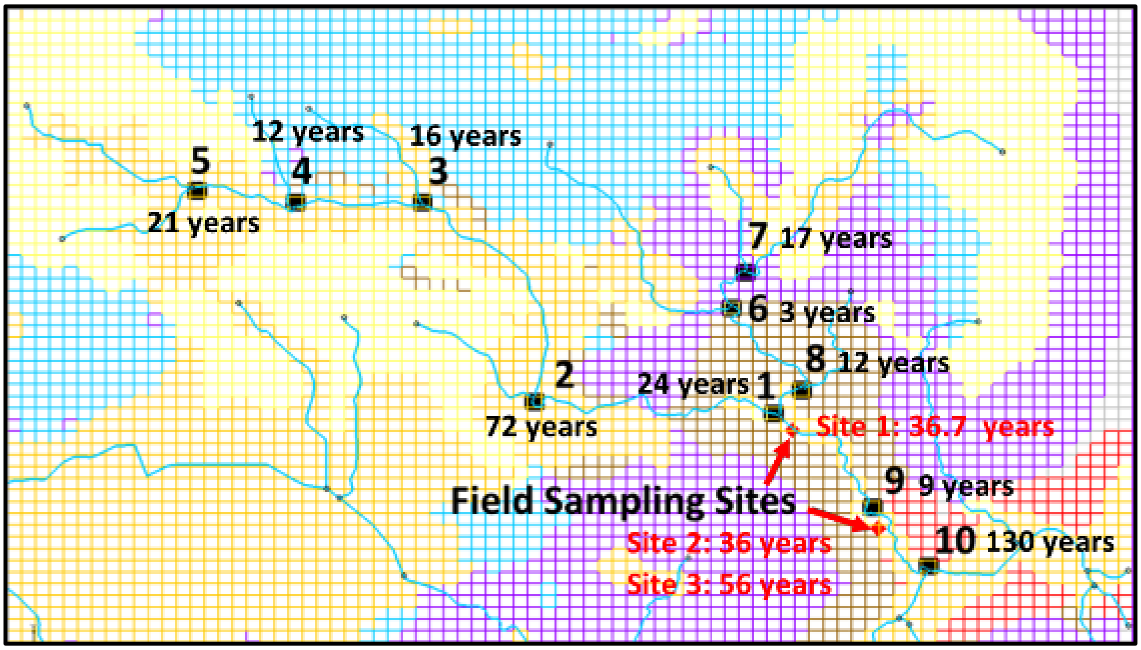


Figure F.5. Results of the modeling of groundwater age using the MODFLOW model with the particle tracking feature, compared to the groundwater age derived from the chemistry by the USGS study. These results are for Trout Brook.

ACTIVITY 3

Title: Develop tools for estimating lag-time for nitrate transport through major aquifers, and for interpreting monitoring data for evaluation of BMP effectiveness.

Description: A mathematical modeling tool will be developed for use in applying travel time distributions for groundwater for the determination of the lag-time required for nitrate to travel from the land surface to the aquifer discharge point. This model will be supplemented by '**smart machine/learning machine**' technologies to improve the ability to quickly, efficiently and accurately interpret flow and chemical monitoring data.

ACTIVITY 3

ENRTF BUDGET: $66,000
Amount spent: $66,000
Balance: $0

Outcome	Completion Date
1. Report outlining the features of the modeling tools and results of testing the tools for the major aquifers in southeastern Minnesota. The modeling tools will be provided to state agencies and available on-line for use by consultants and educators.	03/31/2022

First Update March 1, 2020

Nothing to report.

Second Update September 1, 2020

Conceptual development of the travel time modeling tool has received some attention, but it is still too early to provide any formal formulation of the model. We expect to report something more substantial for the March 1, 2021 update.

Third Update March 1, 2021

1. A preliminary travel time contaminant transport model has been developed. This model is characterized as being a lumped parameter computational model. This model utilizes mapped out flow pathways in a groundwater system to calculate the time of arrival of a contaminant at a well or spring. The flow pathways can be derived from water level data acquired from monitoring wells, and the history of landuse along the flow pathway is mapped out but in time and space. This model will be useful in determining whether BMPs put into the landscape will reduce contaminant concentrations at wells. The software has to this point been developed in MATLAB, and since using this programming package for the model would require a site license, we are transferring the model software to a free software platform, "R". As a final product for this project it will be possible to provide this model on the "Cloud" so that one can utilize it without having to work with the software itself. Currently we have a very rough draft description of the model. A detailed description of the model will be provided in the March 2022 report.
2. A next step in using this lumped parameter model will be to test it against more complete models like MODFLOW to assure that the lumped parameter model yields realistic predictions.

Fourth Update September 1, 2021

1. The travel time contaminant transport model has been developed further. The model is based on a convolution scheme accounting for spatial and temporal variability of nitrogen loading rate in the landscape. The model calculates the transport of a solute (in this case it is nitrate) from a source to a location of interest (e.g., a monitoring well, a drinking water supply well, a spring). Loading rates can vary spatially across the landscape and with time. The model utilizes an analytical solution for the transient movement and dispersion of an instantaneous areal source. Convolution (integration) of the inputs from a distribution of areal sources, over space and over time yields the temporal distribution of solute concentration at the point of interest. The model utilizes the groundwater velocity field provided by the OnekaPy model (Barnes and Soule, 2020) using observation well data. Tests with the model so far show that it can be used to evaluate the effective of different spatially-distributed best management practices on the reduction of contaminants (nitrate) at points of interest (e.g., wells). As mentioned in the March 1, 2021 report, this model is intended for use by anyone interested in evaluating nitrate contamination of groundwater and is being developed in a format to make it possible to run the model on the Cloud. A preliminary report on the model is presented in Appendix A.5.
2. The travel time contaminant transport model still needs to be tested against the more complete groundwater transport model, MODFLOW/MODPATH. A test of the model against MODFLOW/MODPATH is expected to be completed by the March 1, 2022 reporting date.

Fifth Update March 1, 2022

1. Work has continued on the development of the flow and transport model. The model is based on a convolution integral approach to solving the transport equation. The model is being developed in Python programming language. A draft description of the model was reported in Appendix 5 in September 2021 report, and work on a final report model description is underway. That report will provide details of the

model as well as a user-manual for the model. Illustration of some graphical output from the model are presented in Appendix A.5.1.

2. A comparison of the model to a complete transport model like MODFLOW or COMSOL-MP has not yet been completed, but the comparison will be completed within the next reporting period.

Final Report Summary

1. A simplified model for predicting the effect of landuse on down-gradient water quality has been completed. The model is based on a convolution integral approach. The conducts a numerical integration of the following integral equation (convolution integral),

$$\mathbf{C}(t) = \frac{1}{d}\int_0^d \left[\int_0^t \frac{M(x,k)}{2\sqrt{\pi D(x)k}} exp(\frac{-(x-v(x)k)}{4D(x)k})dk \right] dx$$

where C(t) is the concentration at the well at time t (mg/l), d is the distance from the well to the groundwater divide (m), M(x,k) is the nitrate loading rate (kg/ m^2), D(x) is the hydrodynamic dispersion (m^2/yr), x is the distance from the well (m), and v(x) is the groundwater flow velocity (m/yr). The model is very similar to the model published by Jurgens et al. (2016).

The modeling software is based on Python programming language and is completely interactive with informative visuals. An example of one visual is the aerial view of the area of interest, given in Figure F.6.

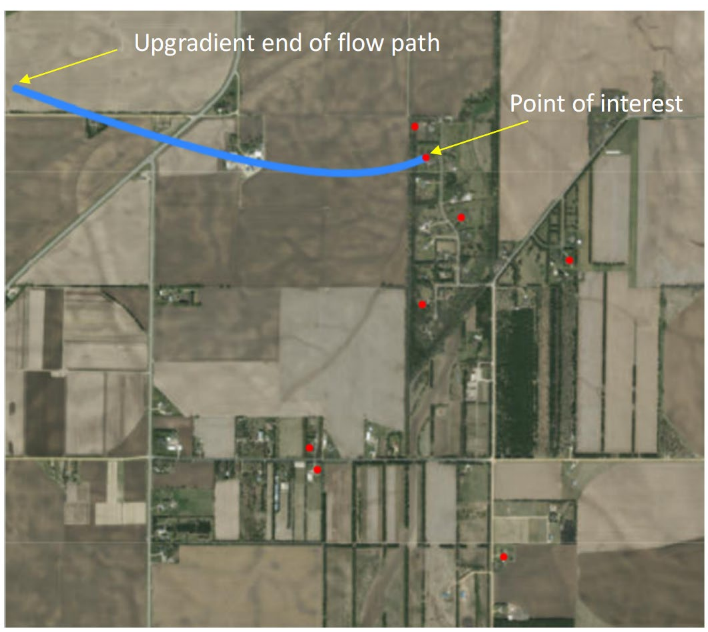


Figure F.6. Illustration of the graphics presented by the convolution model to focus on the area of interest and to assess the landuse information. The blue line shows the pathway taken by groundwater, and this is derived based on the piezometric field given by wells (shown by red dots).

The model is intended to be useful to assess the impact of landuse changes along a groundwater flow pathway in the landscape on the quality of water at a down-gradient well or spring. The model allows one to select a well or other point of interest in the landscape, determine the local groundwater flow in the area based on information from local wells and information about the aquifer properties (hydraulic conductivity, saturated thickness), and input scenarios of chemical loading rates (determined based on landuse types) along the groundwater flow pathway. The output from the model is the graphical display of nitrate concentrations with time over a selected period, generally on the order of several decades. This model can then be used to see what time lag one would expect before changes in concentration at the well/spring will be expected.

The model has been tested by comparing it to a full three-dimensional groundwater flow model and the comparisons show that the convolution model matches the results acceptably. Some differences exist because of the one-dimensional character of the flow field used in the convolution model. Application of the model is shown below in Figure F.7, which is for the case where the loading rate along the groundwater flow path is uniform both in time and space. The lag time from the most distant point is about 40 years. For the case of a spatially non-uniform loading rate the result is shown in Figure F.8. For this case the loading rate was reduced along a portion of the landscape, and one can see that the maximum concentration achieved is a bit less than that shown in Figure F.7. For the case where the loading rate is non-uniform both in space and time, the result is shown in Figure F.9.

This model is currently not available online because it still requires the development of a user-manual, which is currently underway.

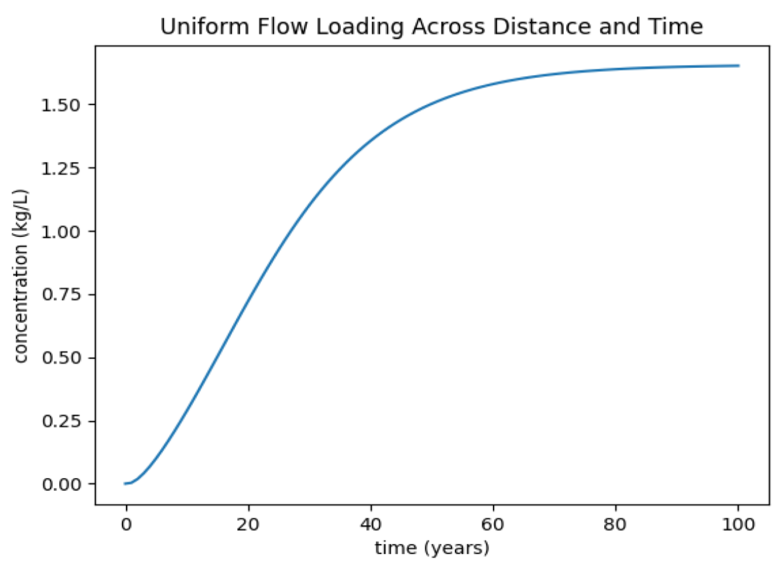


Figure F.7. The temporal distribution of solute concentration at the well as a result of a uniform loading of the landscape along the groundwater flow path.

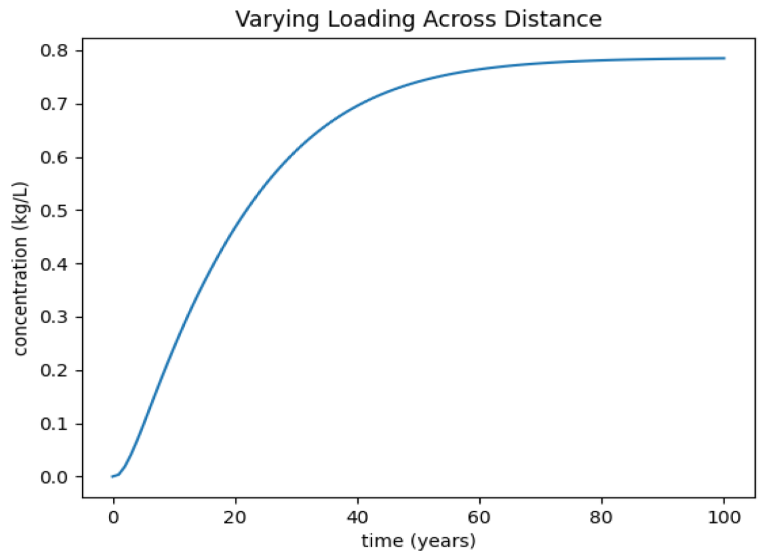


Figure F.8. The temporal distribution of solute concentration at the well as a result of a spatially non-uniform loading of the landscape along the groundwater flow path.

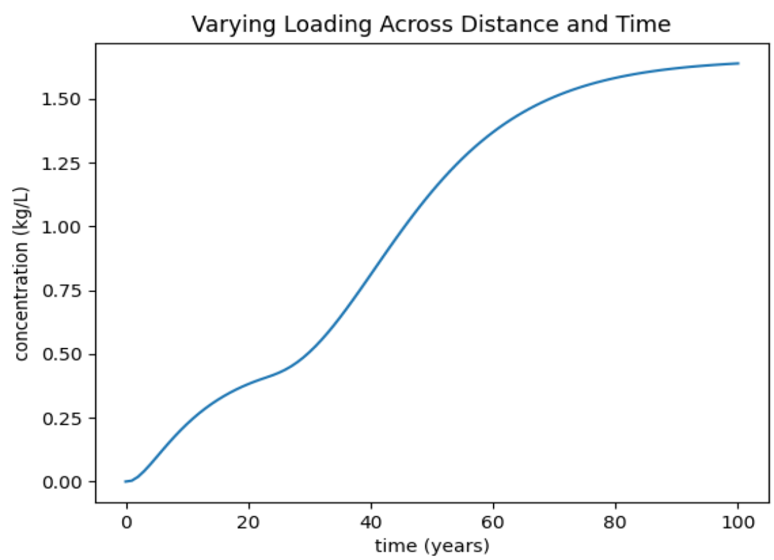


Figure F.9. The temporal distribution of solute concentration at the well as a result of a spatially and temporally non-uniform loading of the landscape along the groundwater flow path. In this case the land surface loading rate was decreased for a period time and then increased back up again.

2. The other modeling effort intended for the project was to use some aspects of machine learning in quantifying the cause for nitrate contamination at a well or spring. The methodology, described in minor details in Appendix A.4, is based on Bayesian analysis as outlined by Ransom et al. (2016) where they analyzed nitrate contaminated wells in California. For this effort the landuse information for the region was set up along with specific wells and the water quality data (nitrate, chloride, and other cations/anions) to determine the probable source of nitrate contaminating a well. We compiled over

139,000 samples of nitrate collected by various agencies and after cleaning up the data found that 57,883 of the samples were good for analysis. These samples are from 23,823 wells. Among the wells that have nitrate and enough cations/anion analysis we found about 100 wells. Along with the groundwater flow field (can be derived from the convolution model described above) we will be able to complete the Bayesian analysis. The issue however is that the student who was doing the analysis (Mr. Xiang Li) left the university temporarily for a full-time position in Duluth and had to drop this work for the time being. Once the student is fully established in his new position he will again work on these data and complete the work. A report for those results will be submitted to the LCCMR for inclusion with the rest of the report.

IV. DISSEMINATION:

Description: The results of the proposed research will be reported in the peer-reviewed literature, and will be presented at scientific meetings such as the annual Minnesota Water Conference, forum(s) at the Minnesota Department of Agriculture, and to national/international audiences at meetings such as those hosted by the American Geophysical Union. The proposed project has Mr. Kevin Kuehner as a collaborator from the Minnesota Department of Agriculture and he is currently managing a project on nitrate reduction BMPs in the South Branch of the Root River. With Kevin as a collaborator it will be possible for the practical applications of the results of the proposed project to be presented to farmer/producers he is working with within the region. In addition, the project team, through Dr. Joe Magner is making connections with crop consultants who have an interest in the successful outcome of the proposed project. Interactions with a group of crop consultants with regard to fertilizer management will help to increase the impact of the proposed project results.

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENRTF Acknowledgement Guidelines.

First Update March 1, 2020

Nothing to report.

Second Update September 1, 2020

Nothing to report. However, we will be reporting in the March 1, 2020 that we intend to give a poster presentation on the project at the Minnesota Water Resources Conference in October.

Third Update March 1, 2021

1. Completed the following presentations
   a. Holmberg, K. et al., Analysis of Groundwater Nitrates in Southeastern Minnesota, Minnesota Water Resources Conference in October, 2020.
   b. Li, Xiang et al., Physics Guided Deep Learning Models for Hydrology, 2020 Fall meeting of the American Geophysical Union, December 2020.
   c. Li, Xiang et al., KGML Implementation for Predicting Watershed Discharge: Case Study for the South Branch of the Root River Watershed, 2020 Annual Meeting of the Soil Science Society of America, November 2020.

2. Submitted one manuscript on the topic of modeling streamflow using machine learning methods.

   Xu, S., X. Li, A. Khandelwal, X. Jia, M, Stienbach, C. Duffy, J. Nieber and V. Kumar, 2020. Physics guided machine learning methods for hydrology, Association for the Advancement of Artificial Intelligence (www.aaai.org); also presented at the November, 2020 AAAI conference.

3. We have made contact with the MDA lag-time group. That group is quantifying the lag-time between chemical application at the land surface and when the chemical reaches the underlying water table. The group is doing this for all vulnerable areas in Minnesota, mostly focuses on the central sand plains and the southeastern region. We intend to continue to have frequent conversations with the MDA lag-time group to share ideas and results. Kevin Kuehner was instrumental in making the connection to the MDA lag-time group.

Fourth Update September 1, 2021

1. We continue to work with Kevin Kuehner at MDA.
2. We will make a one-hour presentation on all project activities at the Fall meeting of the Minnesota Groundwater Association, November 18, 2021.

Fifth Update March 1, 2022

1. Staff from the department of environment at Dakota County have contact us to get some help with modeling the flow and transport of nitrate in the Trout Brook watershed. A meeting has been arranged for March, 2022 to have a meeting between members of the research team and members from Dakota County to share with them the modeling we have done with MODFLOW.
2. Our research team has met with the MDA Lag-Time committee. Members of that committee are interested in the time it requires for water to pass through the unsaturated zone overlying aquifers. We are interested in that as well, but also about the lag time within aquifers. We will continue to communicate with the MDA Lag-Time committee.
3. Interest in sharing information has been expressed with a LCCMR research team led by Dr. Peter Kang to model nitrate fate and transport in karst areas of southeast Minnesota. We will be meeting with Dr. Kang's group sometime in April.
4. Philip Margarit, one of the graduate students on the project presented his work on modeling flow and groundwater age modeling at the 2021 Fall Meeting of the American Geophysical Union in New Orleans, December.

Final Report Summary

1. Our project team worked met with a group from the Dakota County Soil and Water Conservation District to discuss sharing of modeling work we have completed for Trout Brook. The Dakota County SWCD is interested in the work because of concerns over high nitrate concentrations observed in Trout Brook and want to determine what BMPs can be used to realistically reduce those concentrations. The calibrated MODFLOW model has been offered to the County for their use.
2. We currently have an informal collaboration with Dr. Peter Kang at the University of Minnesota. Dr. Kang is investigating the nitrate issuing from Bear Spring located in the southeast region.

3. The use of the MODFLOW model on the project has brought about an effort to include more watershed modeling and groundwater flow modeling activities in undergraduate and graduate courses. We have been applying MODFLOW through the Groundwater Modeling System (GMS) managed by Aquaveo Inc. The Watershed Modeling System (WMS) is the 'sister' software to GMS and is now used in courses in Bioproducts and Biosystems Engineering at the University of Minnesota.

V. ADDITIONAL BUDGET INFORMATION:

A. Personnel and Capital Expenditures

No ENRTF funding required:

Dr. John L. Nieber, Professor, Dept. of Bioproducts and Biosystems Engineering. Serve as project principal investigator.

Dr. David Mulla, Professor, Dept. of Soil, Water and Climate. Assist with assessments of chemical leaching to groundwater within the region of study.

Dr. Bruce Wilson, Professor, Dept. of Bioproducts and Biosystems Engineering. Assist with the probabilistic, statistical and time series analyses of flow and chemical data.

ENRTF funding required:

Dr. Robert Tipping, Minn. Geol. Survey. Lead effort on water chemical sampling, and historical chemical data compilation and analysis.

Dr. Anthony Runkel, , Minn. Geol. Survey. Lead the effort on aquifer identification, characterization, and hydrogeological assessments.

Dr. Joseph Magner, Professor, Dept. of Bioproducts and Biosystems Engineering. Assist with interpretation of chemical tracer data.

Assistant Research Scientist, Professor, Dept. of Bioproducts and Biosystems Engineering. Manage field sampling and chemical analysis of samples.

Graduate Research Assistant, Univ. of Minn. Assist with all aspects of the project including field sampling, data analysis, and modeling.

Undergraduate Research Assistants, Univ. of Minn. Assist with all aspects of the project including field sampling and modeling.

Explanation of Capital Expenditures Greater Than $5,000:

Explanation of Use of Classified Staff:

N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours for entire duration of project: 6,840	Divide total personnel hours by 2,080 hours in 1 yr = TOTAL FTE: 3.3

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

Enter Total Estimated Contract Personnel Hours for entire duration of project: 1,726	Divide total contract hours by 2,080 hours in 1 yr = TOTAL FTE: 0.83

VI. PROJECT PARTNERS:

A. Partners outside of project manager's organization receiving ENRTF funding

Mr. Jared Trost, USGS. Develop the aquifer water age dating (decadal scale) using various chemical tracers.

B. Partners outside of project manager's organization NOT receiving ENRTF funding

Mr. Kevin Keuhner, Minnesota Dept. of Agriculture. Assist with data acquisition from field sites, and work with landowners associated with BMPs.

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

Setting realistic planning horizons for the time required to meet water-quality standards in aquifers and streams should account for the lag time that occurs between landuse improvement and water-quality response. This project will provide a framework for interpreting water-quality monitoring data (well data and stream data) to assess the effectiveness of established BMPs. The framework will be applicable to other contaminants such as pesticides. The results of the project will provide detailed groundwater flow information also useful to other environmental management activities such as well-head protection mapping. This project should be viewed as being a piece of a larger effort that should be initiated to map the lag-time for aquifers around the entire state of Minnesota. The project will also provide support for the training of one Ph.D. graduate student and several undergraduate students.

The topic of the project is one of national and international interest, with a broad variety of scientists having interest. It is expected that the project manager will continue to work with computer scientists and other hydrologists in developing the tools proposed to be developed within this project. Over the past three years the project manager has collaborated with Dr. Vipin Kumar in the Department of Computer Sciences at the University of Minnesota on the application of smart machine/machine learning techniques applied to hydrologic modeling. The collaboration was funded by a small seed grant from the University of Minnesota Digital Technology Center and then by a 2-year grant from the National Science Foundation that involved five other universities. Future research into this topic is of interest to us, and it is hoped that the progress made so far will result in additional funds from federal agency sources. The ENTF funding was critical to the further development of this collaboration.

1. As a result of the work completed on this project we prepared a proposal to the National Institute for Water Research (USGS) to conduct additional sampling and modeling work for the southeast region. The proposal was not selected for funding this time around, but we will make another attempt in the Spring of 2023.
2. Also, as a result of the work completed on this project, we were able to acquire some funding from the Anishinaabe Agricultural Institute to conduct similar research in the Pineland Sands region of Minnesota. This work is ongoing, and currently there is a 2023 LCCMR project proposal to significantly expand the study.
3. Philip Margarit, a Ph.D. student supported by the funding from this project is now a candidate for the Ph.D. degree and intends to do work on the modeling of the karst flow phenomena observed in Crystal Creek and Bridge Creek. He is currently supported by funding from the Anishinaabe Agricultural Institute and will do work on the Pineland Sand region as well.

VIII. REPORTING REQUIREMENTS:

- Project status update reports will be submitted March 1 and September 1 each year of the project
- A final report and associated products will be submitted between June 30 and August 15, 2022

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

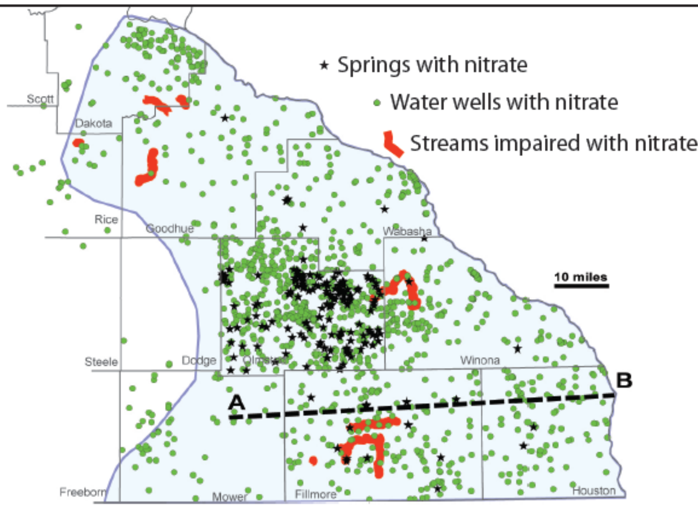
A. Budget Spreadsheet. Accompanying the workplan.

B. Visual Component or Map.

Environment and Natural Resources Trust Fund (ENRTF)
2019 Main Proposal
Project: Setting realistic nitrate BMP goals in southeast Minnesota

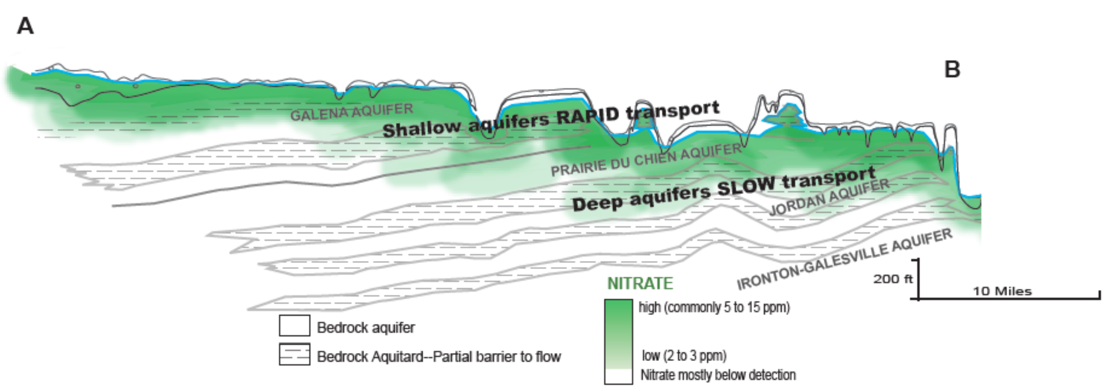
SETTING REALISTIC NITRATE BMP GOALS IN SOUTHEAST MINNESOTA

NITRATE AND OTHER CONTAMINANTS ARE COMMMON IN GROUNDWATER OF SOUTHEASTERN MINNESOTA



KNOWING THE RATE OF NITRATE MOVEMENT IS CRUCIAL FOR MEASURING THE EFFECTIVENESS OF BEST MANAGEMENT PRACTICES

NITRATE TRAVELS AT VERY DIFFERENT RATES THROUGH THE VARIOUS AQUIFERS



OUR PROJECT WILL CALCULATE THE TRAVEL TIMES FOR NITRATE THROUGH SE MINNESOTA AQUIFERS

PROJECT RESULTS WILL PROVIDE A TOOL FOR WATER MANAGERS TO SET REALISTIC BEST MANAGEMENT PRACTICE GOALS

C. Parcel List Spreadsheet, N/A
D. Acquisition, Easements, and Restoration Requirements, N/A
E. Research Addendum. To be submitted, 9/14/18

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Appendix A.2. Summary of age-dating sampling approach for LCCMR workplan update. By Jared Trost 12/30/19

The goal of the age-dating analysis is to provide information about the travel time and age distribution of water in the groundwater system. The age-dating data will help constrain groundwater models used to evaluate realistic nitrate reduction goals for southeastern Minnesota. The tracers to be used for determining groundwater age work for the time period 1940's – present. They are listed in Table A.2.1. A total of 10 samples will be analyzed for tracers: 9 field samples + 1 replicate sample, though the replicate may not be necessary and could be replaced by another field sample, but this needs to be discussed yet. Wells that show pre-1940s water from prior tritium analyses (i.e. tritium was not detected) will not be considered for age-dating sampling.

The USGS will use TracerLPM (Jurgens et al., 2012) to interpret groundwater age distributions from environmental tracer data. TracerLPM an interactive Excel® (2007 or later) workbook program that uses environmental tracer data along with lumped parameter models (LPMs) to evaluate the age distribution of samples. Lumped parameter models are mathematical models of transport based on simplified aquifer geometry and flow configurations that account for effects of hydrodynamic dispersion or mixing within the aquifer, well bore, or discharge area. Because the age distributions are determined through a lumped parameter modeling approach, it is advantageous to collect samples from sites where a reasonable conceptual understanding of the flow system is available.

Springs are likely not good sites to collect samples for age dating for two reasons. First, during our field trip, John Barry mentioned that water sampled from wells upgradient of springs often has low DO, but water sampled at springs often has high DO. This suggests that groundwater is exposed to modern air just upgradient of the spring. This mixing with modern air will skew groundwater age dates young that don't reflect the entire groundwater flowpath. Second, the TracerLPM method uses a lumped parameter modeling approach and therefore it is advantageous to collect samples from sites where a reasonable conceptual understanding of the flow system is available. This is not the case at springs, where water from multiple aquifers and flowpaths may be mixing.

The schematic illustrated in Figure A.2.1 is of an idealized environmental tracer sampling scheme for a watershed or springshed:

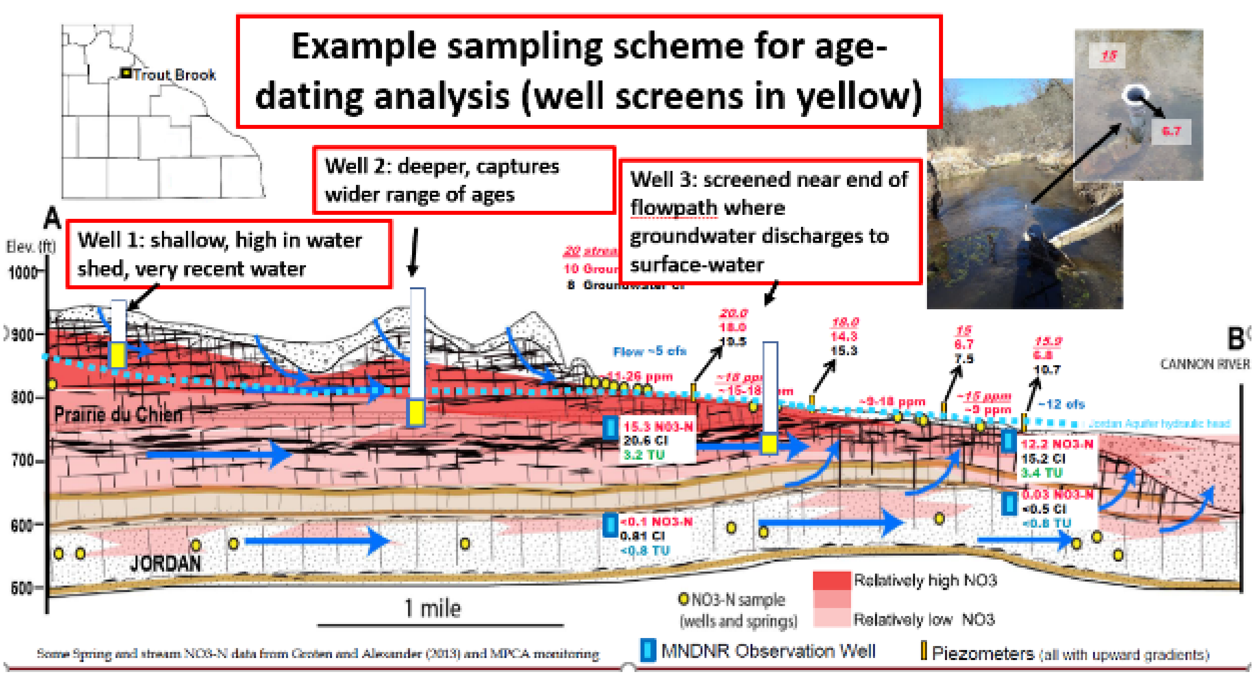


Figure A.2.1. Schematic of an idealized sampling scheme for a watershed or springshed.

The following is a start of a list of ideal characteristics for selecting sites for age-dating evaluation:

1. High probability of post-1940's recharge. Wells that are tritium positive should be considered. Wells that are tritium dead, or likely tritium dead (e.g. in the deepest aquifer), should be excluded from consideration.
2. Sites should be wells or piezometers. Sites should not be springs because of the possibility of modern-air contamination and the modeling approach required to estimate groundwater ages.
3. Well sites need to have known construction (screen length, location, drilling log available, etc.) and of good integrity.
4. Field personnel need to be able to collect samples from wells before the pressure tank (if domestic wells).
5. Sites should follow along a groundwater flow path. This will facilitate cross-sectional modeling by John Nieber's group.
6. Well or piezometer sites should be screened in a single aquifer

Additional characteristics that would be beneficial:

1. Well or piezometer sites should have as short of a screen as possible
2. Sites with historical nitrate, major ion, or other water quality data.

Table A.2.1. Analytes to be used for determining the age of groundwater samples.

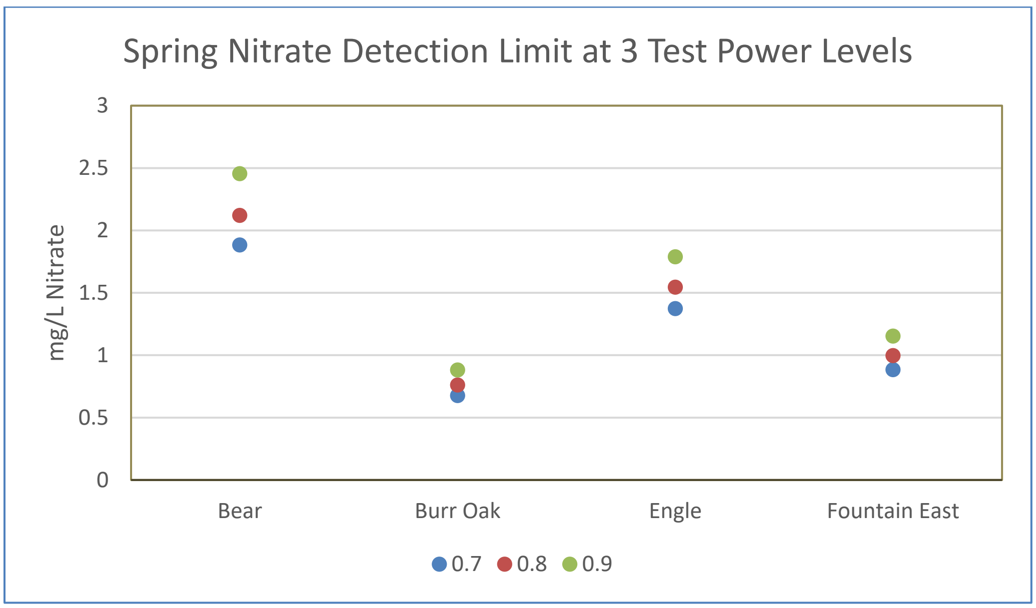
Analytes	Cost per sample	Age-date range
trichlorofluoromethane ($CFCl_3$ or CFC–11), dichlorodifluoromethane (CF_2Cl_2 or CFC–12), and trichlorotrifluoroethane ($C_2F_3Cl_3$ or CFC–113)	$220	~1940's to present
Helium, Neon, 3He/4He with tritium by 3He ingrowth	$1350	~1940's to present
SF_6	Free for a couple of samples to test if they would be valid tracers, but collect all samples. If no contamination in 2 of them, then could get all of them analyzed.	1990 to present
Dissolved gases: nitrogen [N2], argon [Ar], carbon dioxide, methane, and oxygen	$200	used to estimate recharge temperatures and excess air concentrations in the samples. Recharge temperatures will be used to establish CFCs and SF_6 concentrations and $^3H/^3He$ ratios at the time of recharge, which are needed to determine an age date for the water.

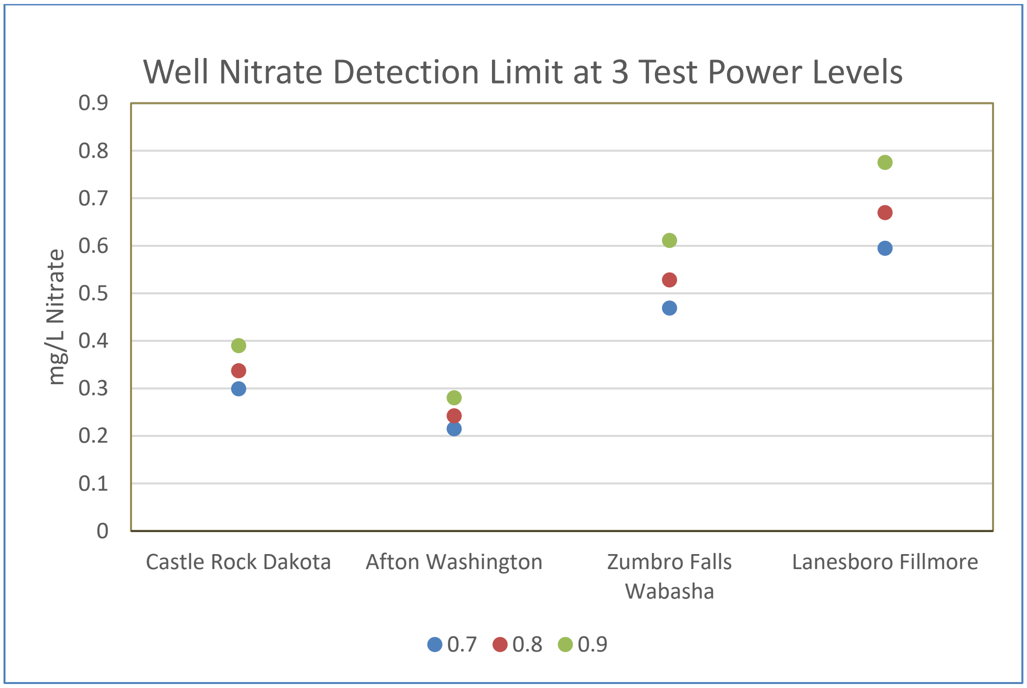
Appendix A.3. Analysis of sample number required for trend detection. Kerry Holmberg, December 30, 2019.

Four springs and four wells from our project area were selected to examine nitrate concentrations and variance of the data. Sites were selected based on number of samples and absence of trend over time. Minimum detection levels and the number of samples needed to detect differences in concentration levels were calculated. In general, spring nitrate levels (9.13-19.75) and variance (1.76-2.72) were significantly higher than well nitrate concentration (0.93-6.72) and variance (0.32-0.98). Minimum detection levels and number of samples needed to detect differences were also higher in springs compared to wells.

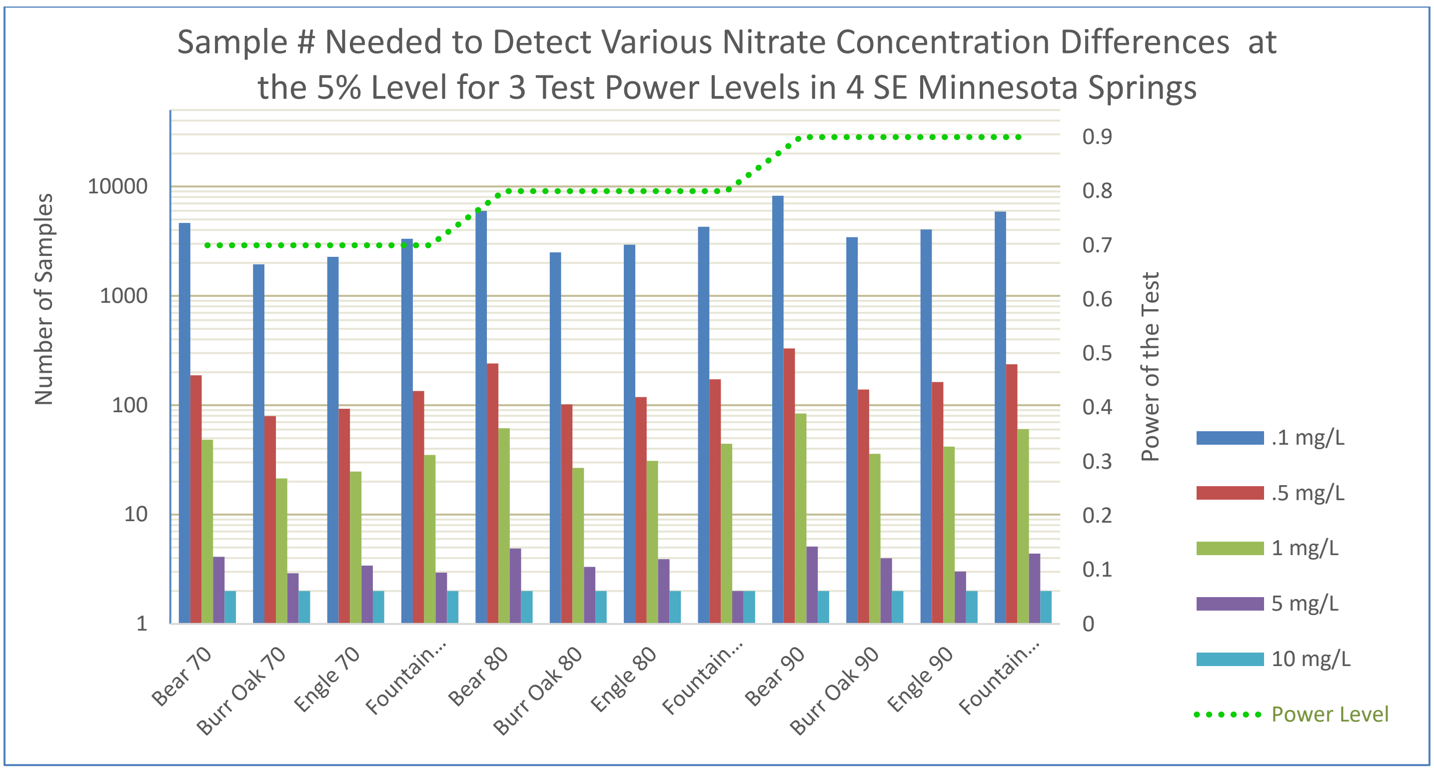
Spring	Mean (mg/L)	Stdev	n
Bear Olmsted	19.75	2.72	14
Burr Oak Filmore	12.54	1.76	43
Engle Filmore	9.13	1.91	13
Fountain East Filmore	11.26	2.30	43

Well	Mean (mg/L)	Stdev	n
Castle Rock Dakota	6.72	0.61	27
Afton Washington	0.93	0.32	15
Zumbro Falls Wabasha	3.01	0.78	18
Lanesboro Fillmore	2.67	0.98	18

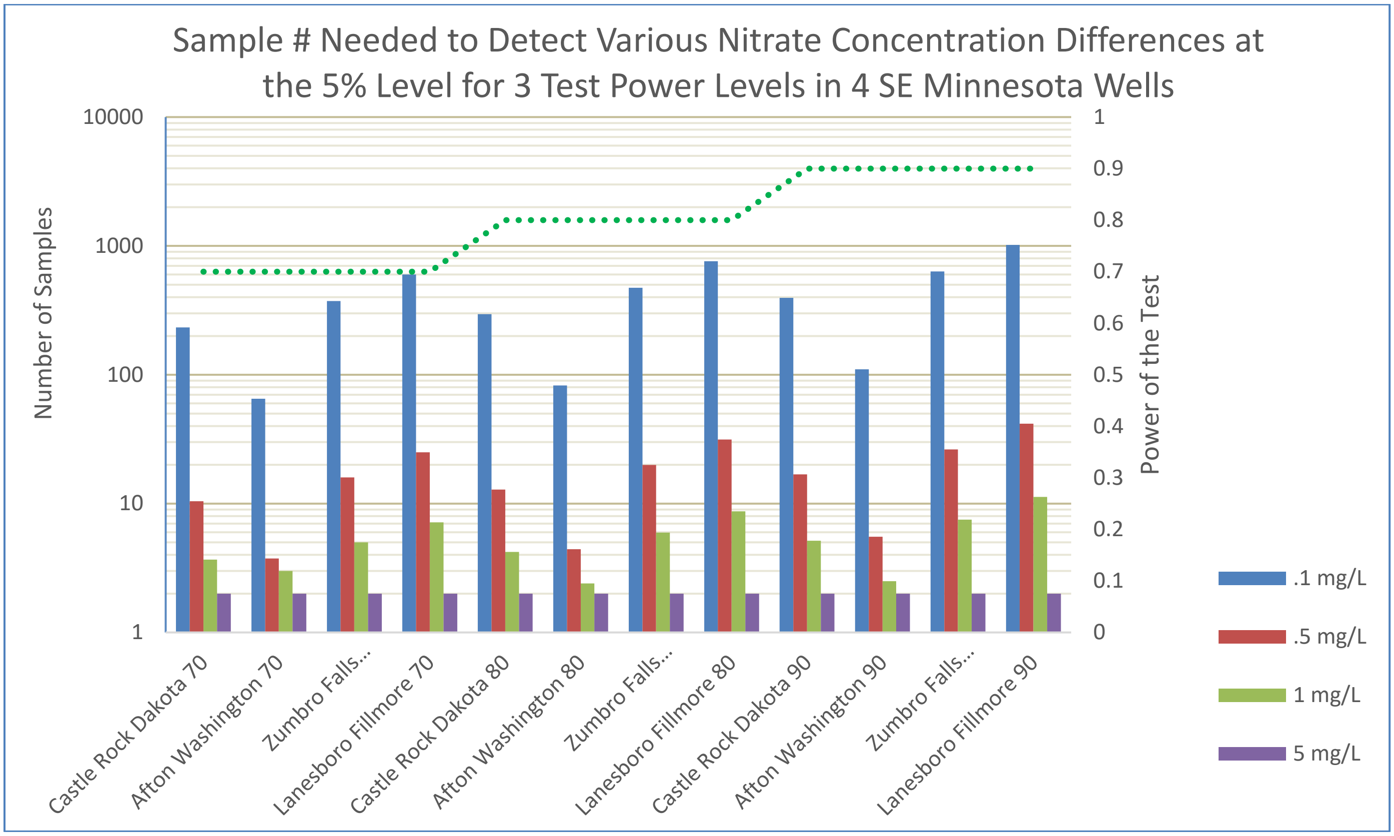




Well Nitrate Detection Limit at 3 Test Power Levels
mg/L Nitrate
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Castle Rock Dakota
Afton Washington
Zumbro Falls Wabasha
Lanesboro Fillmore
0.7
0.8
0.9



Sample # Needed to Detect Various Nitrate Concentration Differences at the 5% Level for 3 Test Power Levels in 4 SE Minnesota Springs
Number of Samples
10000
1000
100
10
1
Power of the Test
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Bear 70
Burr Oak 70
Engle 70
Fountain...
Bear 80
Burr Oak 80
Engle 80
Fountain...
Bear 90
Burr Oak 90
Engle 90
Fountain...
.1 mg/L
.5 mg/L
1 mg/L
5 mg/L
10 mg/L
Power Level


Sample # Needed to Detect Various Nitrate Concentration Differences at the 5% Level for 3 Test Power Levels in 4 SE Minnesota Wells
Number of Samples
Power of the Test
10000
1000
100
10
1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Castle Rock Dakota 70
Afton Washington 70
Zumbro Falls...
Lanesboro Fillmore 70
Castle Rock Dakota 80
Afton Washington 80
Zumbro Falls...
Lanesboro Fillmore 80
Castle Rock Dakota 90
Afton Washington 90
Zumbro Falls...
Lanesboro Fillmore 90
.1 mg/L
.5 mg/L
1 mg/L
5 mg/L

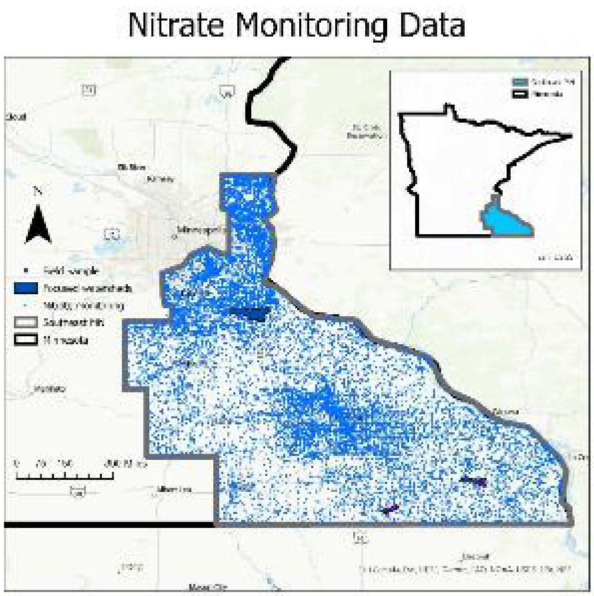
Appendix A.4. Analysis to estimate source apportionment for nitrate in wells.

The up-to-date progress for the project is a complete collection of the data from multiple sources and a plan to execute in the next step. The complete preparation of the dataset lay a firm foundation for next step's analysis on nitrate source apportionment, the method of which stems from Baysien analysis family (Ransom, Katherine M., Grote, 2016).

Data preparation

Nitrate data

We've compiled a complete set of nitrate data for wells covering the southeast Minnesota. In total, it covers 57883 unique wells from multiple government agencies and private owners, including county level database (Dakota county, Olmstead), DNR (Minnesota Department of natural resources), MPCA (Minnesota Pollution Control Agency), MDH (Minnesota Department of Health), MDA (Minnesota Department of Agriculture). Although those data were originally formatted differently, we've cleaned and organized the data consistently into our database.



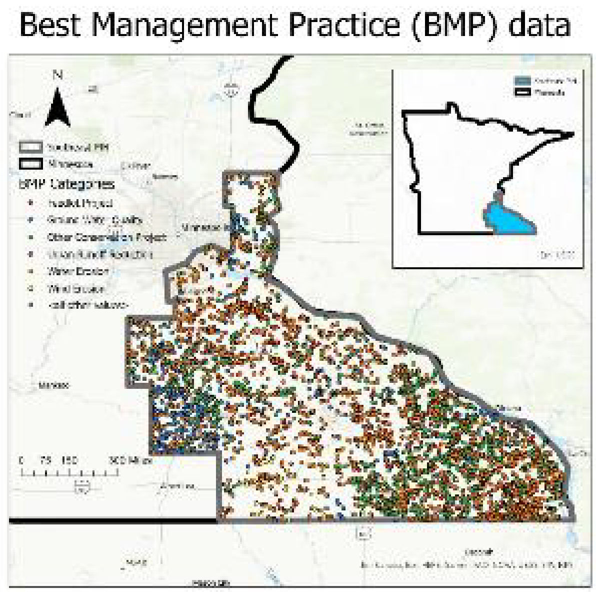


Fig A.4.1. Nitrate data

Fig A.4.2. BMP data.

The earliest nitrate measurement was in 1970s, a majority of nitrate records are between 2008 and 2020.

BMP data

In addition to the nitrate data, we've also prepared spatial BMP (best management practices) data, land use data and chemical tracer data. BMP data preserves spatial-temporal information about implemented best management practices. It not only records the location of BMP but also its initiation and ending date. The expected nitrate reduction goal is also marked in the BMP data, which offers another opportunity to evaluate the effectiveness of certain practices. BMP data are compiled from 2 sources, MPCA and BWSR (Minnesota Board of Water and Soil Resources). As shown in Figure, all BMP practices are categorized into 7 general groups: feedlot project, ground water quality, urban runoff reduction, water erosion and wind erosion. There're 4718 BMP practice sites spanning the study area, which were created between 2013 and 2019.

Others

Land use data are compiled from NLCD (National land cover) database on an annual basis from 2013 to 2018. Besides, chemical tracer data have also been prepared from the WQP (Water Quality Portal) published from National Water Quality Monitoring Council. WQP compiled environmental and water quality data on a national wide from all agencies and platforms with publicly available water quality data. These agencies include EPA (Environmental Protection Agency), USGS (United States Geological Survey) and state-level agencies. We've prepared the chloride data, boron data covering the south east MN. These 2 tracers are selected because their records are complete and dense in contrast to other tracer data and can still preserve the nitrate signature functionality from multiple sources. We'll keep enriching the chemical tracer data when more data becomes available.

Method

We'll perform Bayesian analysis to stochastically estimate nitrate apportionment. This method has been applied to the San Joaquin Valley of California (Ransom, Katherine M., Grote, 2016) and it was found that domestic wells were dominated by the manure sources. The Bayesian approach took advantage of understanding groundwater contamination system from a probabilistic view, which accounts for uncertainties from many sources in complicated groundwater system. This implementation is expected to give an insight towards understanding what sources of regional nitrate input contribute to the nitrate contamination. For a given monitoring well, we'll estimate the nitrate contribution from multiple surrounding relevant sources, such as, manure, fertilizer, septic waste, and natural sources of nitrate.

The Bayesian analysis require a prior knowledge of nitrate apportionment, it will use the observed nitrate concentration data to update this prior nitrate apportionment to yield a posterior probabilistic estimate. With the abundant nitrate data and increasingly enriched chemical tracer data, we expect that our next step analysis will yield a nitrate apportionment estimate for most of wells in our study area where both tracer and nitrate data are available. With this understanding, we can further leverage the land use information to inform a more effective land use management to achieve nitrate reduction goals. We'll analyze the land use information from wells to understand the land use contribution to certain nitrate apportionment. This land use information is based on regional hydrological capture zone, which was defined empirically as a circle from (Ransom, Katherine M., Grote, 2016). Hydrologic capture zone is a well source area bounded by groundwater flow direction and other hydrologic information, such as conductivity, recharge rate. It will define a region where the hydrologic dynamics impact nitrate contamination and transport significantly. To hold a hydrological consistent understanding, we'll refine the analysis from (Ransom, Katherine M., Grote, 2016) by calculating the groundwater contributing area based on the Monte Carlo simulation. The groundwater capture zone will be a probabilistic field instead of a fixed circle. We calculated the groundwater contributing area using pythonic package (OneKaPy; Barnes and Soule, 2020).

Considering the expensive computation task (Monte Carlo simulation for each well in our study area), we used the computation power of MSI (Minnesota Supercomputer Institute), where the PI holds an active account. On a single laptop, the Monte Carlo simulation to estimate the groundwater capture zone will take about half an hour. Its computation scale on 57883 wells will be extremely time consuming. Therefore, we decide to deploy MSI for computation efficiency and we've already established its computation framework on MSI. The computation is configured on a multi-core and large memory system approximating supercomputer scale such that further parameter tuning and execution will not be time consuming. At present, the Monte Carlo simulation to estimate groundwater capture zone for all wells within the study area will be completed within one day.

Appendix A.5. Rough draft description of the travel time model

Dispersion Convolution Model

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June 2021

1 Introduction

This model uses dispersion and time and space dependent loading rates to predict the concentration of nitrate at the observation well at a given time. In order to do this, we assume advective - dispersive flow and derive velocity from the piezometric head using Darcy's Law.

2 The Model

The model has the following assumptions:

- Advective - dispersive flow
- Darcy's Law

2.1 Variables/Parameters

The model has the following variables:

- t: time water has traveled
- x: the distance from observation well.

The model has the following parameters:

- M loading rate
- v the average velocity
- λ dispersion constant. $\lambda = c * L$ where $c \in \mathbb{R}_{>0}$ is a constant to fit dispersion to model.
- D dispersion coefficient $= \lambda * v$

2.2 Theory

We use the following advective - dispersion equation to predict the concentration c loaded x meters away from the well at time t:

$$c(x,t) = \frac{M}{2\sqrt{\pi Dt}} exp(\frac{-(x-vt)^2}{4Dt})$$

.

To account for varying parameters across distance and time, we increase the dimension of our parameters. We get the following:

- $M(x,t)$ the loading rate of distance x at time t.
- v(x) is the average velocity from location x.
- D(x) is the dispersion coefficient of path starting at location i such that $D(i) = c \cdot x \cdot v(x)$

With this new dimension, we get the following:

$$c(x,t) = \frac{M(x,t)}{2\sqrt{\pi D(x)t}} exp(\frac{-(x-v(x)t}{4D(x)t}).$$

To obtain the concentration of distance x at time t, we must consider every load at distance i before time t. We denote this total concentration as C(x,t). We get the following:

$$C(x,t) = \int_0^t \frac{M(x,k)}{2\sqrt{\pi D(x)k}} exp(\frac{-(x-v(x)k)}{4D(x)k})dk.$$

Finally, to calculate the concentration at the well for time t, we calculate the average concentration across the distances.We denote this as **C** We get the following:

$$\mathbf{C}(t) = \int_0^d x \cdot \left[\int_0^t \frac{M(x,k)}{2\sqrt{\pi D(x)k}} exp(\frac{-(x-v(x)k)}{4D(x)k})dk \right] dx.$$

where d is the largest distance considered.

2.3 Deriving Average Velocity

There are two methods of deriving average velocity.

2.3.1 Method 1: User provided velocity function

The first option is the user can provide a velocity function for the model to use to calculate average velocity. This can take the form of a constant or a function of distance.

2.3.2 Method 2: Darcy's Law

The second option is he user can provide data on the static water level for the model to apply Darcy's Law to calculate the velocity.

2.3.3 Average Velocity

Using Runge-Kutta-4 numerical method, we calculate the expected time it will take for a particle to travel to the well. We calculate the average velocity by dividing distance traveled by time:

$$velocity = \frac{distance\ traveled}{time}$$

2.4 Inputs

The model takes the following inputs:

- Loading rates in the form of a matrix indexed by distance and time.
- Velocity function – either coordinates with static water level or user defined function (mentioned in section 2.4)
- Porosity of soil
- Hydraulic conductivity
- dmax – maximum distance model uses to calculate concentration at well.
- dd – distance step – distance between points on the flow path.
- dt – time step
- dtau – time step of integral approximation (see below).
- λ – dispersion constant

2.5 Computational Implementation

Python implementation takes the solution to the advective-dispersive flow problem and iterates it along all distances of the flow path. The average velocity for each point along the flow path is calculated using the Runge-Kutta-4 numerical method. Each average velocity is stored into an array which is ordered by distance from observation well. We denote this array as $\boldsymbol{v}$. The matrix of loading rates, $\boldsymbol{M}$, is provided by the user and indexed by distance and time. The concentration C is a matrix indexed by distance and time. We calculate values of C by taking a left Riemann sum with width of dtau. We get the following:

$$C(x,t) = dtau \cdot \sum_{k=0}^{\lfloor t/dtau \rfloor} \frac{M(x,w)}{2\sqrt{\pi D(x)w}} exp(\frac{-(x-v(x)w)}{4D(x)w})$$

where $w = k \cdot dtau$

The average concentration at time t is calculated by taking the mean of concentrations from all points of the flow path. We get

$$\mathbf{C}(t) = \frac{1}{N}\sum_{k=0}^{N-1} C(r,t)$$

where $r = k \cdot dd$, and $N = \frac{dmax}{dd}$ (number of points along flow path).

3 features

3.1 1 & 2 dimensional flow

Model allows for 1-dimensional and two-dimensional flow. Using Runge Kutta 4, average velocity is calculated by documenting distance traveled and time at which said distance is achieved.

3.2 3-dimensional flow?

coming soon... Model will eventually account for well screen.

A.5.1. Illustrative modeling results

The convolution model described above has been programmed using Python software. It allows the user to input the geographical location of water levels (from wells) and the water levels as a way to map out the distribution of groundwater velocity in an area. From this velocity distribution the model then determines the groundwater flow pathway along which groundwater will flow to reach the location of the well point of interest. Such a flow path is shown in Figure A.5.1.1. This pathway is 3,000 m long, and groundwater flow moves along the pathway from the left toward the right.

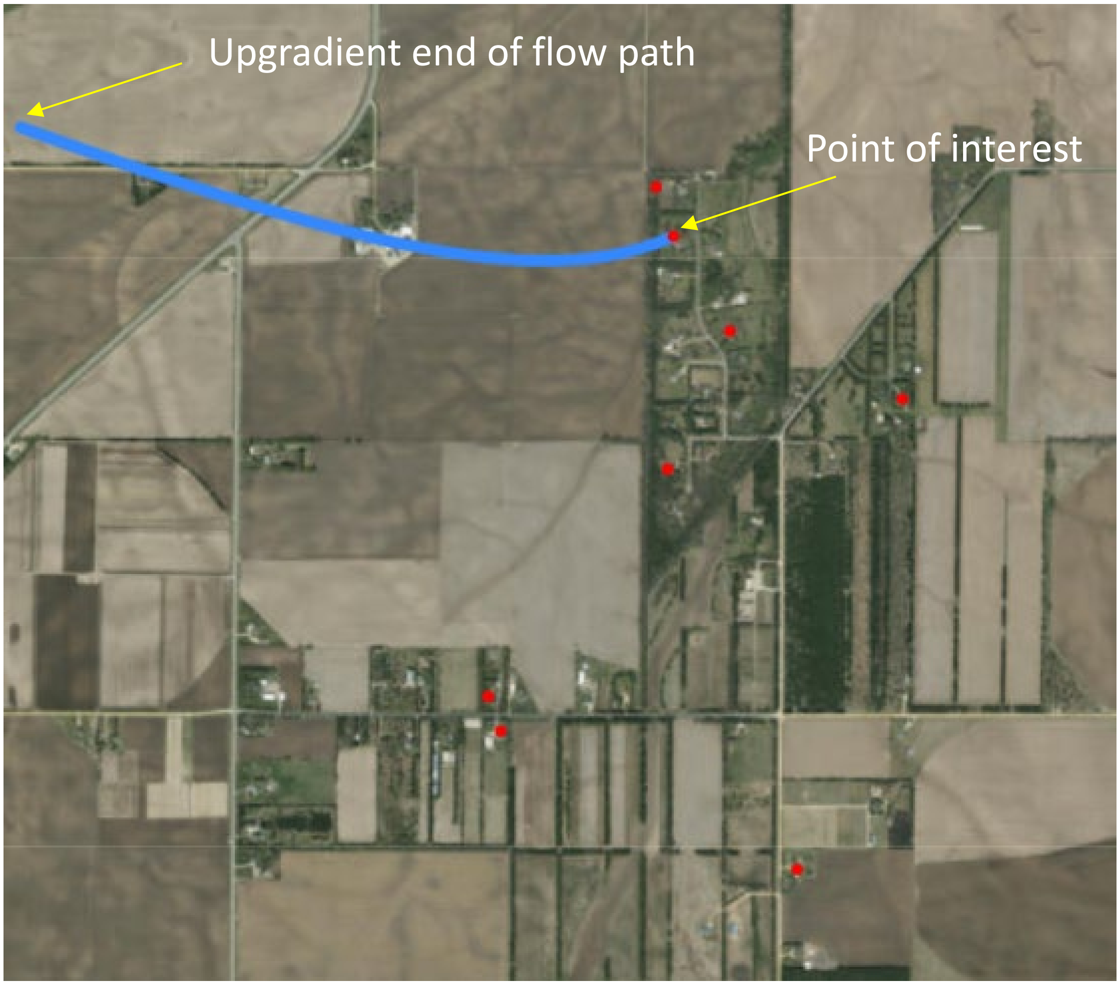

Figure A.5.1.1. Path along which groundwater flows going from the left end of the blue line toward the right end of the blue line. The location of the end of the line on the right is the location where there might be a drinking water well, or a monitoring well. The red dots indication locations of wells used in observing the water level in the groundwater aquifer.

The model takes input about the leaching rate of a chemical at the land surface overlying the groundwater pathway, and converts that chemical concentration at the receiving well location. An example output is shown in Figure A.5.1.2 where the chemical loading on the land surface along the flow pathway is uniform along the path. The loading begins at year zero and continue on in time. We see that the concentration at the point of interest reaches a constant value, which occurs when the chemical loading from the farthest point on the pathway reaches the well point. The units on the concentration in the graph are not important here, only the form of the distribution of the concentration with time. We see that there is quite a delay, on the order of decades, before all of the field to be contributing contaminant to the well point.

A second example of output from the model is presented in Figure A.5.1.3. For this case the loading rate in the mid-section of pathway is 1/10 that of the rest of the line. The effect of this reduced loading rate on the temporal distribution of concentration at the well point is noticeable, both by the reduced final value, but also by the reduction in the rate of rise of the concentration at the well point at about the 8th year. The ability to adjust the loading rate along the flow pathway will make it so that the user will be able to quantify the effect of changes in landuse practices, and so so fairly easily.

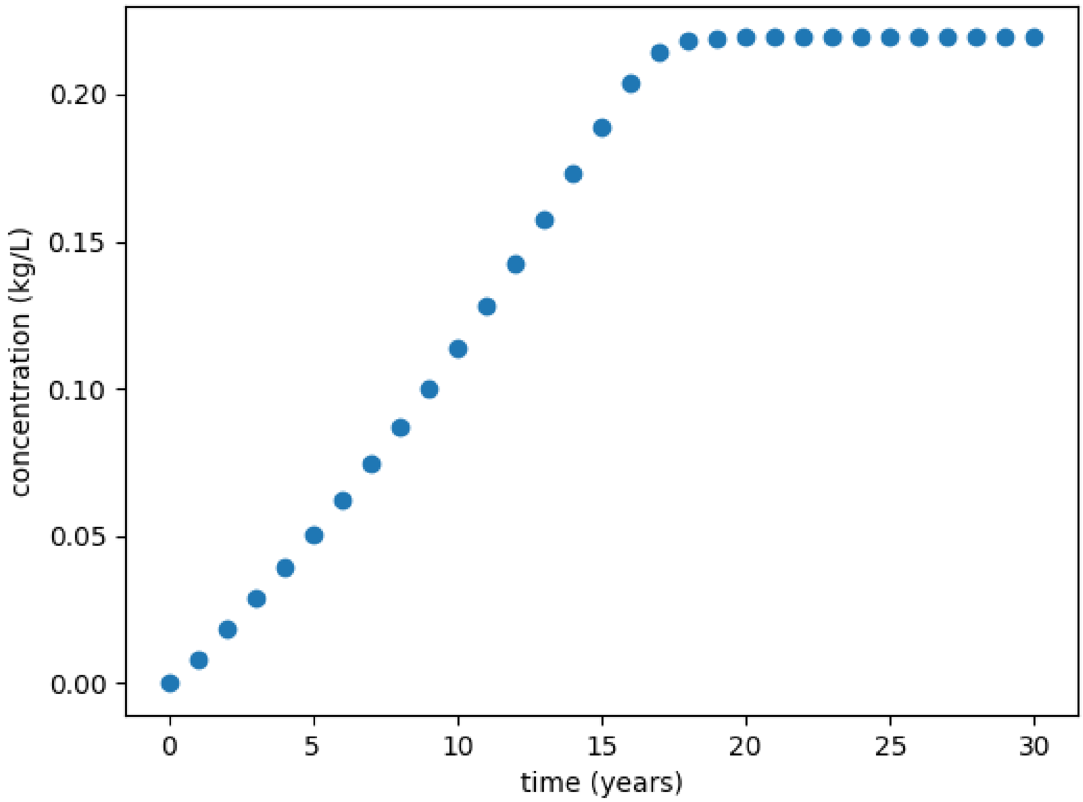

Figure A.5.1.2. The temporal variation of concentration at the well point for the case where the land surface loading of chemical along the pathway (blue line in Figure A.5.1.1) is uniform along the line and constant with time.

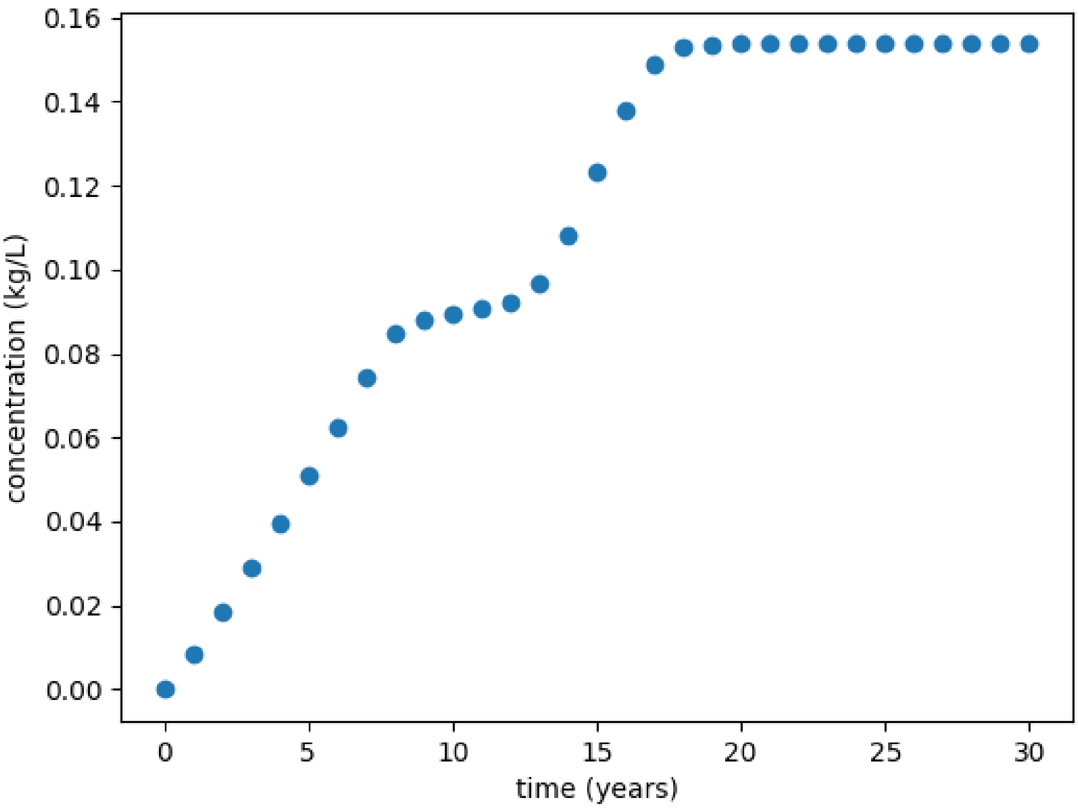

Figure A.5.1.3. The temporal variation of concentration at the well point for the case where the land surface loading of chemical along the pathway (blue line in Figure A.5.1.1) is not uniform but is constant with time. The loading rate in the middle one-third section along the blue line is 1/10 that of the other two sections.

Appendix A.6. Groundwater modeling in selected areas.

The flow field generated by the MODFLOW model for the Trout Brook location is shown in Figure A.6.1.

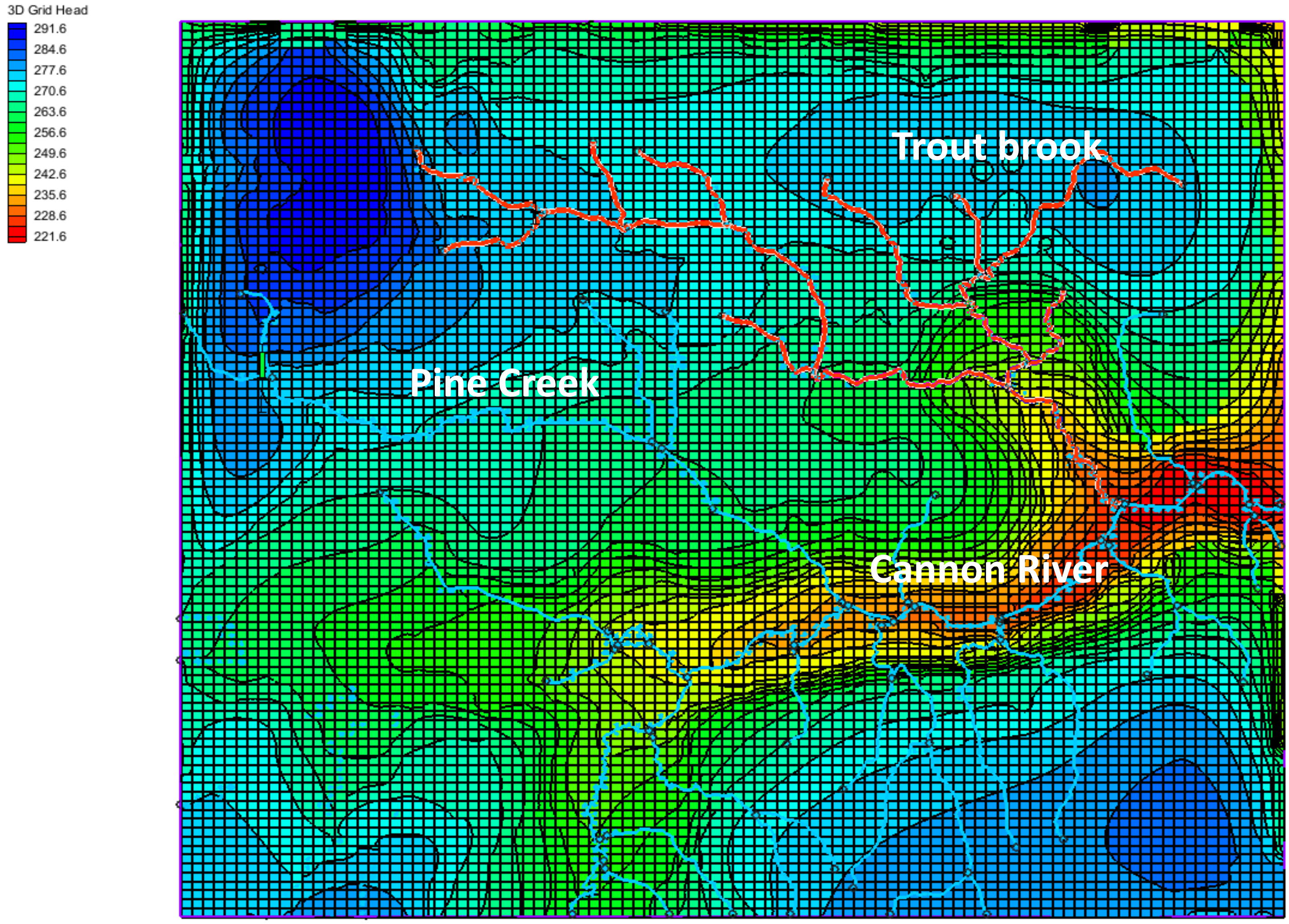

Figure A.6.1. Map showing distribution of piezometric head for the Trout Brook watershed; also shown are Pine Creek and Cannon River.

With the groundwater flow model for Trout Brook, the particle transport option in MODFLOW was used with the modelled flow field to generate a model of groundwater age. The model can calculate age by modeling the backtracking movement of a particle starting at the point of interest to the point where the water first enters into the flow domain. The younger ages are coming from the shallow aquifer, while the older water (e.g., 130 years) is coming through deeper aquifer sources.

Groundwater flow fields for both Bridge Creek and Crystal Creek are shown in Figures A.6.1.3 and A.6.1.4 respectively.

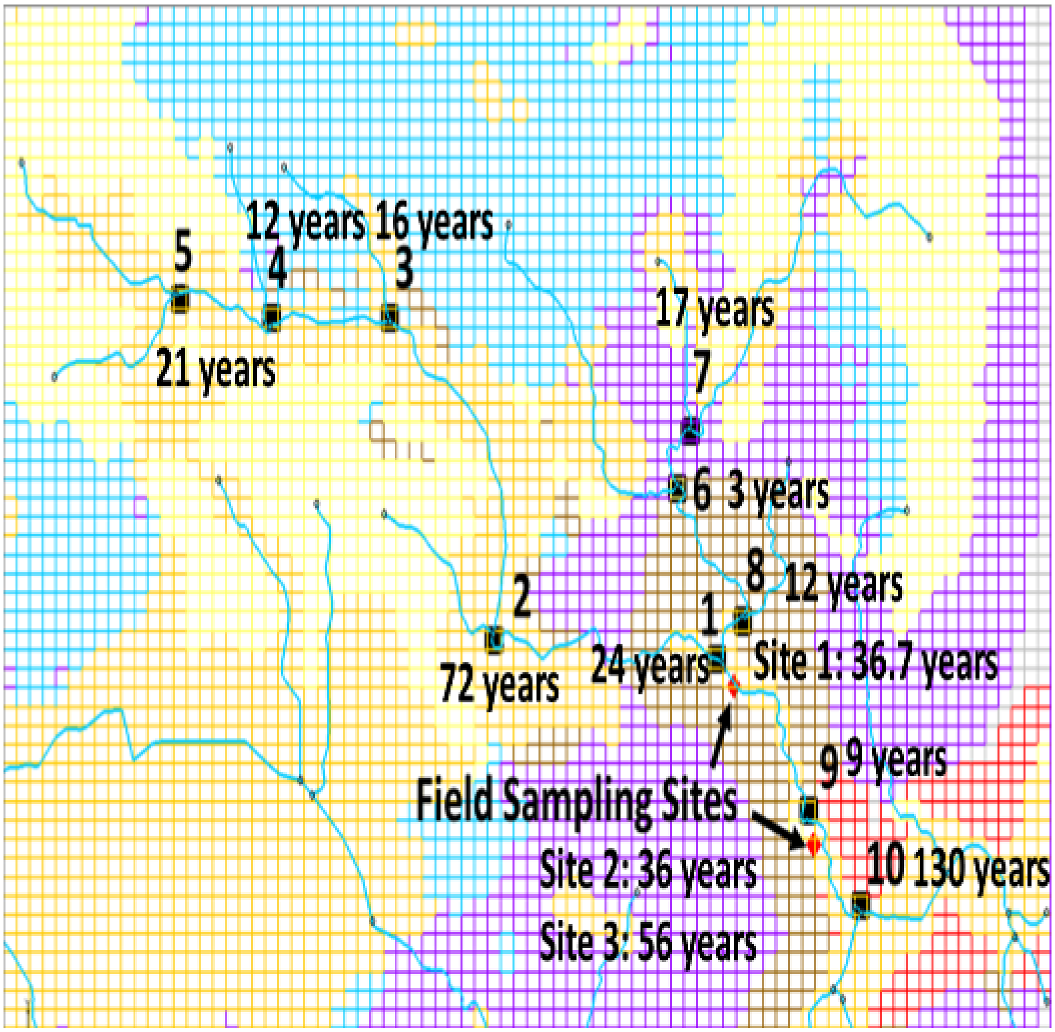

Figure A.6.2. The distribution of groundwater ages (years) for different locations within the Trout Brook watershed area. The USGS has developed groundwater ages for the same locations and there is relatively good agreement between the modeled results and the results coming out of the USGS analysis.

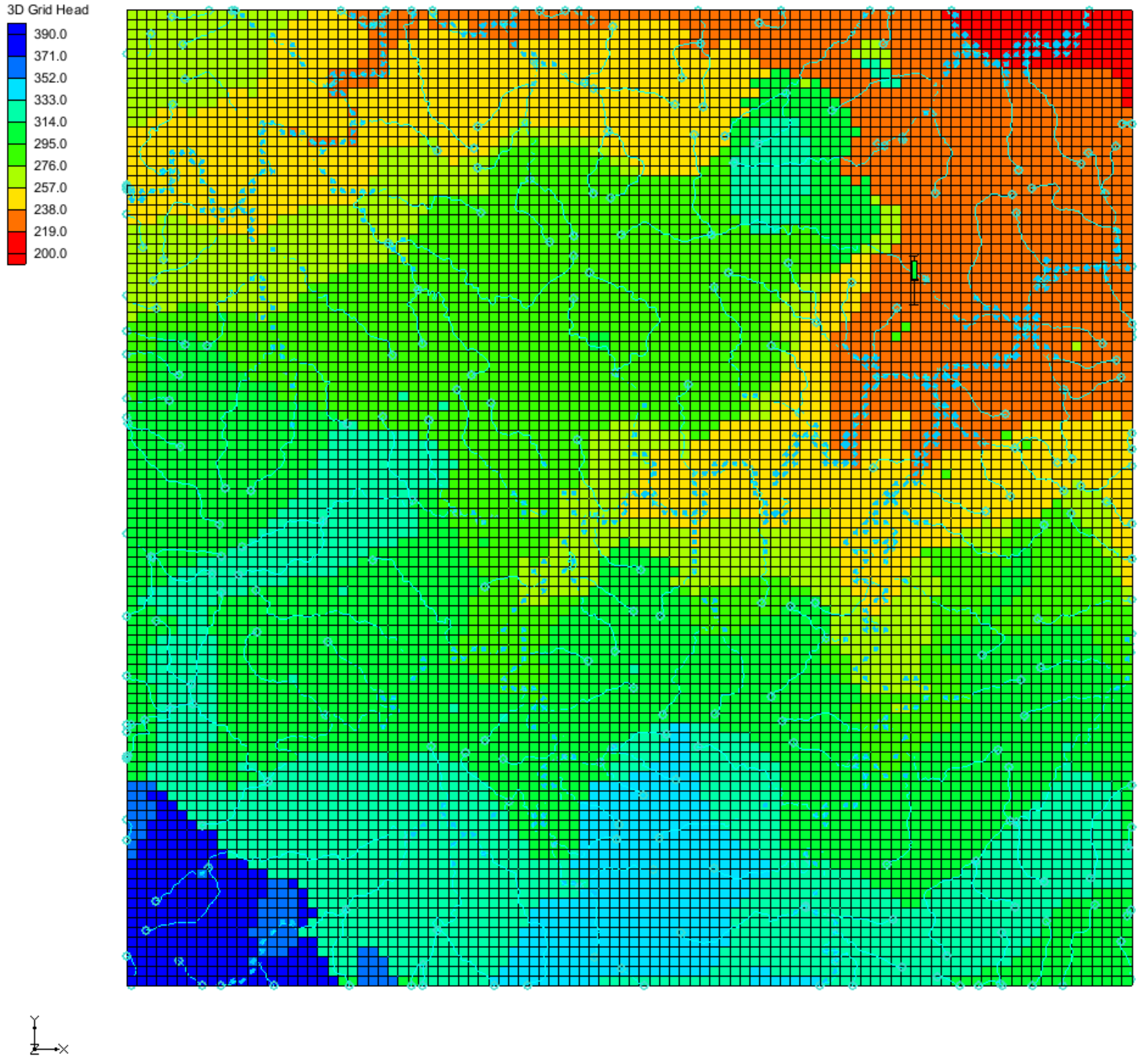

Figure A.6.3. Map showing distribution of piezometric head for the Bridge Creek watershed.

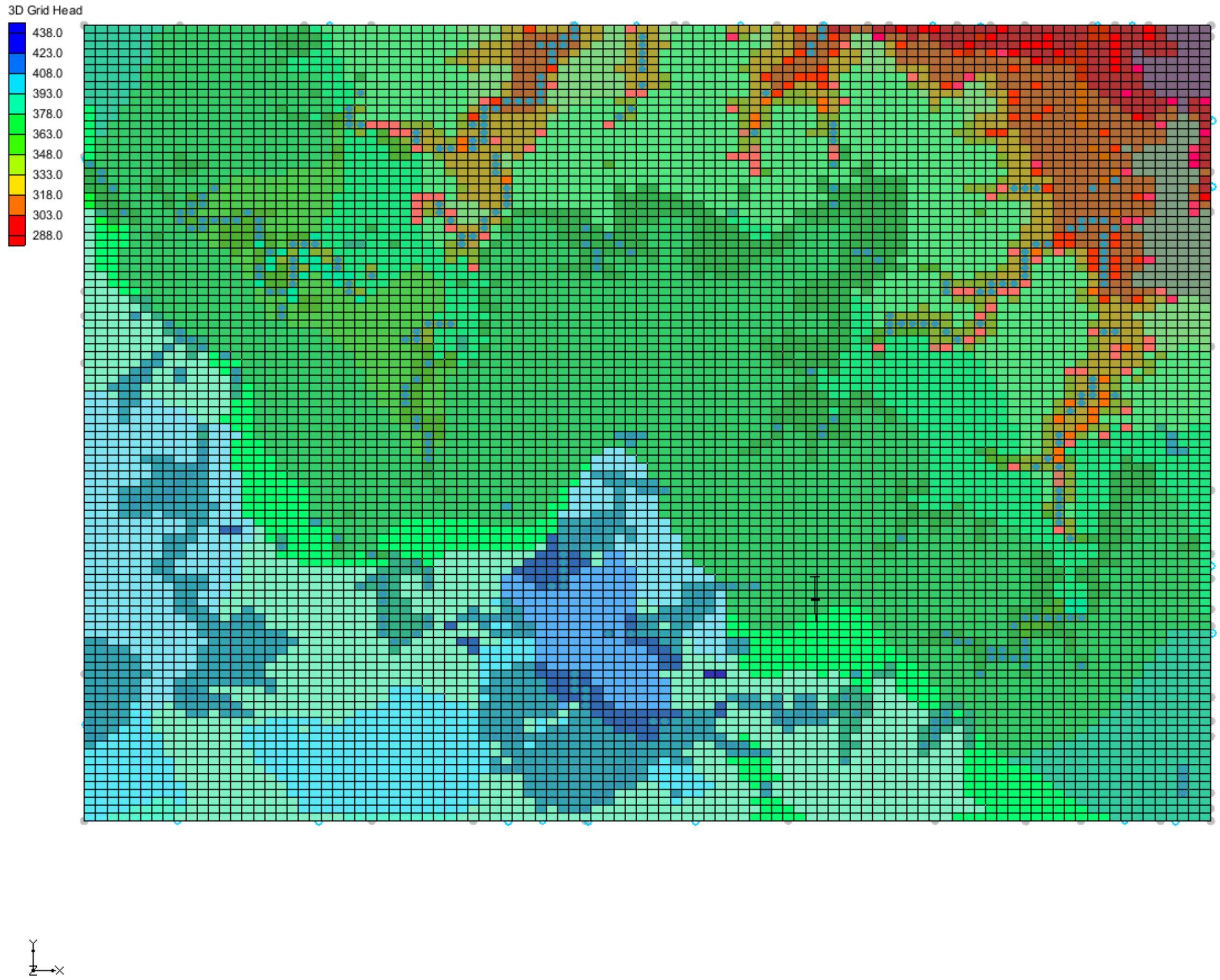

Figure A.6.4. Map showing distribution of piezometric head for the Crystal Creek watershed.

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2019 Project Budget - Final
Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 04m
Project Manager: John L. Nieber
Project Title: Setting realistic nitrate BMP goals in southeast Minnesota
Organization: University of Minnesota
Project Budget: $350,000
Project Length and Completion Date: 3 years; June 30, 2022
Today's Date: August 15, 2022

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Budget 11/3/22	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits)	$ 248,813	$ 248,813	$ -
Robert Tipping; Hydrogeologist/hydrogeochemist, Minnesota Geological Survey. Lead effort on water chemical sampling, and historical chemical data compilation and analysis. 72.6% salary, 27.4% fringe. 13% of full time, soft money, 7/1/19-6/30/22.			
Anthony Runkel; Hydrogeologist, Minnesota Geological Survey. Lead the effort on aquifer identification, characterization, and hydrogeological assessments. 72.6% salary, 27.4% fringe. 13% of full time, soft money,7/1/19-6/30/22.			
Joseph Magner; Hydrogeologist, University of Minnesota, Department of Bioproducts and Biosystems Engineering. Assist with effort on travel time estimation and evaluation of geochemical analysis results. 66.5% salary, 33.5% fringe. 8% of full time, soft money, 7/1/19-6/30/21			
Graduate Research Assistants; One Ph.D. Assist with all aspects of the project. 61% salary, 39% fringe. 50% of full time, 7/1/19-6/30/22.			
Senior Scientist, University of Minnesota, Department of Bioproducts and Biosystems Engineering. Manage field sampling activitiesdel. 72.6% salary, 27.4% fringe. 8% of full time, soft money, 7/1/19-			
Undergraduate Research Assistants; Number to be determined. Assist with all aspects of the project. 100% salary, 0% fringe. 100% of full time in summer, 25% full time in school year, 7/1/19-			
Laboratory technician, Department of Earth Sciences,			
Professional/Technical/Service Contracts	$ 93,800	$ 93,800	$ -
Age-dating of water samples. Subcontract with the USGS, Minnesota Water Science Center Office. The water samples will be tested for elements that are extremely difficult to analyze, and the sampling itself requires a very specific skill possessed by a very limited group of scientists. Water sample analysis cost, for 10 samples and 1 replicate, four chemical constituents (sulfur-hexafloride, chloroflorocarbon, tritrium and helium-3) analyzed for each sample, is $21,890 ($1,990 per sample). Cost for sample collection and analysis of sample analytical results for age-dating of water, $89,709; this includes travel costs, salary for USGS researchers, and equipments for water sampling.			
Equipment/Tools/Supplies	$ 3,833	$ 3,833	$ -
Miscellaneous lab supplies need for bottles for collecting samples, batteries on equipment, other misc supplies, repairs and calibration of equipment, etc.			
Capital Expenditures Over $5,000		$ -	
Fee Title Acquisition		$ -	
Easement Acquisition		$ -	
Professional Services for Acquisition		$ -	
Printing		$ -	
Travel expenses in Minnesota	$ 1,299	$ 1,299	$ -
Travel will be limited to visiting field sites to collect water samples and monitor streamflows, and to participate in meetings with agency staff and stakeholders to present results of the project activities.			
Other; chemical analysis	$ 2,255	$ 2,255	$ -
	$ 350,000	$ 350,000	$ -
COLUMN TOTAL			
		Spent	**Balance**

OTHER FUNDS CONTRIBUTED TO THE PROJECT	**Status (secured or pending)**		$ -	
Non-State:	pending	$ 37,043	$ 37,043	$ -
State:	secured	$ 168,153	$ 168,153	$ -
In kind:				
			Spent	**Balance**
PAST AND CURRENT ENRTF APPROPRIATIONS	**Amount legally obligated but not yet spent**			

Current appropriation:				
Past appropriations:				