N.L. 2016 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Understanding Bedrock Fracture Flow to Improve Groundwater Quality
PROJECT MANAGER: Anthony C. Runkel
AFFILIATION: Minnesota Geological Survey (University of Minnesota)
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g
APPROPRIATION AMOUNT: $183,000
AMOUNT SPENT: $183,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
The principle outcome is improved understanding of how groundwater flows in fractured rock, which will lead to more effective remediation of contamination, improved strategies to protect unimpacted groundwater and address water quantity issues. These outcomes are relevant to much of southeastern and northeastern Minnesota where aquifers are dominated by fractured bedrock.

Overall Project Outcome and Results

The goal of this project was to gain an improved understanding of groundwater flow through fractured limestone bedrock by using recently developed techniques. We focused on the Platteville Formation in the Twin Cities Metropolitan area, where the formation is one of the most heavily contaminated bedrock layers in the state. There were two primary activities. One was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; on the campus of the University of Minnesota, and near Minnehaha Falls. We used recently developed techniques that included borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of fractures at an exposure of the Platteville Formation at the UMN campus site. Determining how water travels through the Platteville is achieved by combining the results of these two activities.

The project results greatly improved our understanding of how groundwater moves through the Platteville Formation. A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes would not be as effective as presumed. The results of our project can also be used in groundwater models to improve their accuracy to guide water management engineering. The relevance of our results to how groundwater contamination is characterized and remediated, and to water quantity issues, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. The rigorous techniques such as the inexpensive and efficient methods used in this project can therefore be used to improve water quality across much of Minnesota. A summary report provides greater detail on all the results of this project and their relevance.

Project Results Use and Dissemination
We have presented our results as the project progressed to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges training students who will ultimately become the next generation

of groundwater managers in Minnesota. Our results will continue to be disseminated in this fashion, and in published reports. A summary report with greater detail on all our results is already available.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2016 Work Plan Final Report

Date of Report: October 14, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Understanding Bedrock Fracture Flow to Improve Groundwater Quality

Project Manager: Anthony C. Runkel

Organization: Minnesota Geological Survey (University of Minnesota)

Mailing Address: 2609 Territorial Road

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Location: Work will take place in Hennepin County. Counties most directly impacted will be Hennepin, Ramsey, Dakota, Washington, and Anoka. Indirect impact to all of southeastern Minnesota.

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$183,000**
	Amount Spent:	**$183,000**
	Balance:	**$0**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g

Appropriation Language:
$183,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for the Minnesota Geological Survey to use new techniques of borehole testing and rock fracture mapping in the Twin Cities metropolitan area to achieve a better understanding of groundwater flow through fractured bedrock, in order to improve groundwater management. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Understanding bedrock fracture flow to improve groundwater quality

II. PROJECT STATEMENT:
Using new borehole testing and rock fracture mapping techniques we will gain a better understanding of groundwater flow through fractured bedrock in the Twin Cities that will support better management of water quality and quantity. Groundwater flow in bedrock occurs mostly through fractures (cracks in the rock) in a manner that remains difficult to predict, hampering efforts to protect and remediate groundwater. This problem is particularly acute across southeastern Minnesota, including the Twin Cities, where fractured limestone bedrock is a source of baseflow to streams, and also a source of drinking water. Contaminated water from point (e.g. petroleum products and solvents) and non-point (e.g. nitrate) sources in these limestones is well-known. Point-source contamination plumes are a particular problem in the Twin Cities, with a large number of actively monitored and remediated sites, including Superfund sites in Minneapolis, St. Louis Park, Oakdale, and Edina.

The project will focus on the Platteville Formation in the Twin Cities, a fractured limestone, which is one of the most heavily contaminated bedrock layers in the state. It is also hosts a large number of springs, such as Camp Coldwater spring, that discharge to the Mississippi River, and is the bedrock foundation for infrastructure in the urban core. At a site along the Mississippi River in Minneapolis, we will use recently developed techniques of borehole testing and installation of pressure and temperature sensors in five monitor wells, and detailed mapping of fractures at nearby rock exposures. Pressure and temperature measurements collected from the wells will provide us with information on water flow through fractures, and when evaluated in the context of nearby fracture mapping at the rock exposures, will allow us to link hydraulic (water) properties to rock (fracture) properties to provide a greater understanding of fracture flow.

Application of our results will improve the efficiency and effectiveness of remediation and monitoring at a large number of contamination sites across the Twin Cities. The results will also be applicable to water management at construction (tunneling, building foundation, roadwork) sites, and to modeling groundwater-surface water interaction in areas such as the Minnehaha Creek Watershed. The results will provide a better understanding of fracture controlled flow through limestones regionally across southeastern Minnesota, and therefore link to the mapping of these limestones as part of ongoing County Geologic Atlas mapping progam, such as the in-progress Hennepin County Atlas.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 15, 2017: The project is proceeding on schedule and very close to anticipated budget. Working in collaboration with University of Guelph hydrologists we collected information from two monitor wells on the University of Minnesota, Twin Cities campus and successfully instrumented the two holes with temperature and pressure sensors inside of flexible borehole liners, according to our original plan. The only problem encountered was tears in one of the two borehole liners, which were repaired, but possibly may occur again. An unanticipated positive addition to the project was collection of information from similar fractured rock monitor wells elsewhere in Minneapolis, as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec.

Project Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Project Status as of January 15, 2018: The project is proceeding on schedule and very close to anticipated budget. Temperature and pressure data have been successfully downloaded from the two instrumented wells. The data from one well is yielding excellent information that is providing insight into groundwater flow. Data from the second well may be compromised by a nearby steam tunnel shaft on the University of Minnesota campus, and we have therefore made arrangements to deploy the instruments in a monitor well at a nearby contamination site managed by the Minnesota Pollution Control Agency. Imaging of fractured bedrock using drone-based photography was successful, and ground-truthing of these images is progressing as planned.

Amendment Request (01/15/2018): A number of minor (~$6000 total) changes have been made to the budget as a result of costs incurred being different from original estimates, and because we are now planning a new task of instrumenting a third monitor well. Costs for two budget items (Professional/Technical Service Contracts and Equipment/Tools/Supplies) for Activity 1 totaled $1326 more than estimated. Capital expenditure for Activity 1 was $5660 less than estimated. Therefore $1326 was moved from capital expenditure to Professional/Technical Service Contracts and Equipment/Tools/Supplies to zero out those balances for Activity 1. The remaining $4334 originally budgeted for capital expenditure, along with $1000 budgeted for equipment shipping for Activity 2, has been combined into an Activity 2 budget item that includes costs for general equipment, shipping of equipment, supplies for sensors and related devises for existing and new well. Finally, $538 in unused funds for travel expenses for Activity 1 were moved to travel expenses for Activity 2. These changes to the equipment and travel budget will allow us the flexibility to cover variable costs incurred in the continued monitoring of one well on the University of Minnesota campus, and to instrument and collect data from the new well at a contamination site in Minneapolis. Amendment Approved by LCCMR 1/17/2018.

Project Status as of July 1, 2018: The project is proceeding on schedule and according to anticipated budget. Temperature and pressure data continue to be successfully downloaded from an instrumented well, yielding excellent information that is providing insight into groundwater flow. We still have plans to deploy similar instruments in a monitor well at a nearby contamination site managed by the Minnesota Pollution Control Agency. Imaging of fractured bedrock using drone-based photography was successful, and ground-truthing of these images is nearly complete. We have presented our data collected thus far, and preliminary results, to groundwater scientists and managers at local (Minnesota) and regional (North Central section of the Geological Society of America) meetings.

Project Status as of January 15, 2019: The project is proceeding on schedule. We now have over two years of data from one instrumented well. Since the last report we have successfully instrumented a second well, and collected several months of data. The field work for fracture characterization is complete, and the data are being processed and interpreted. The data have not been fully processed and interpreted, but appear to show characteristics of groundwater conditions that match up in a predictable fashion to what we have learned about fractures in the outcrop. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of groundwater flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation, monitoring strategies, and modeling. We have presented our results to water resources groups at the Minnesota Department of Health, the regional branch of the American Institute for Professional Geologists, and to local colleges. As for budget, we have spent more in salaries than predicted, but will continue to fully accomplish all of our tasks and goals, using Minnesota Geological Survey general funds.

Project Status as of June 17, 2019: We have now collected information from five wells, three on the University of Minnesota campus and two near Minnehaha Falls. This greatly exceeds the number of wells and geographic scope of the originally proposed work. The data have not been fully processed and interpreted, but appear to show characteristics of groundwater conditions that match up in a predictable fashion to what we have learned about fractures in the outcrop. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of groundwater flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation, monitoring strategies, and modeling. We have presented our results to water resources groups at the Minnesota Department of Health, the regional branch of the American Institute for Professional Geologists, and to local colleges. As for budget, we have spent more in salaries than predicted, but will continue to fully accomplish all of our tasks and goals, using Minnesota Geological Survey general funds.

AMENDMENT REQUEST June 17, 2019

We are requesting funds be shifted from the Supplies (Equipment/Tools/Supplies) and Travel budget lines to personnel.

- the supplies budget for Activity 2 would be reduced by $603 to a revised budget of $4731
- The travel budget for Activity 2 would be reduced by $377 to a revised budget of $968
- The personnel budget for Activity 2 would increase by $980 to a revised budget of $17,745

These changes are being requested because we spent slightly less money than predicted for supplies and travel. Meanwhile, we have exceeded our predicted personnel costs for Activity 2. Personnel costs exceeded our predication because we have been fortunate enough to locate and acquire permission to instrument and collect data from three additional monitor wells, with data collection continuing. This will greatly enhance our overall project results beyond our expectations. But it also required personnel effort beyond our predictions. The Minnesota Geological Survey general budget will be covering all excess salary incurred beyond the $980 made available through this amendment request.

We are also proposing a change to XI. REPORTING REQUIREMENTS, asking for a no-cost extension to the August 15, 2019 deadline for when we submit our final report and associated products. We propose to extend this date two months, to October 15, 2019. This change is being requested because we have exceeded the number of wells we originally proposed to instrument, and also exceeded the duration of the instrumentation and data collection. Instead of monitoring two wells for two years, we have now monitored five wells, and continue to collect data from some of them. This significantly improves our overall project results, and broadens the geographic scope of our investigation to include the Minnehaha Falls area. Although the salary overruns incurred are being covered by the MGS general budget, this additional data does require additional time for synthesis and writing a report of our results with associated products.

Amendment Approved by LCCMR 6/26/2019.

Overall Project Outcomes and Results: The goal in this project was to gain an improved understanding of groundwater flow through fractured limestone bedrock by using recently developed techniques. We focused on the Platteville Formation in the Twin Cities Metropolitan area, where the formation is one of the most heavily contaminated bedrock layers in the state. There were two primary activities. One was collection of a variety of geologic and hydrologic information from monitor wells. This was accomplished at two sites near the Mississippi River in Minneapolis; on the campus of the University of Minnesota, and near Minnehaha Falls. We used recently developed techniques that included borehole geophysical testing and instrumentation with multiple pressure and temperature sensors. Two monitor wells at each site were instrumented with sensors. A second activity was detailed mapping of fractures at an exposure of the Platteville Formation at the UMN campus site. Determining how water travels through the Platteville is achieved by combining the results of these two activities.

The project results greatly improved our understanding of how groundwater moves through the Platteville Formation. A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes would not be as effective as presumed. The results of our project can also be used in groundwater models to improve their accuracy to guide water management engineering. The relevance of our results to how groundwater contamination is characterized and remediated, and to water quantity issues, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. The rigorous techniques such as the inexpensive and efficient methods used in this project can therefore be used to improve water quality across much of Minnesota. A summary report provides greater detail on all the results of this project and their relevance.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Monitor well testing and installation of pressure and temperature sensors.

Description: We will use borehole geophysical and video tools to identify and measure fractures, and measure water flow, in two monitor wells on University of Minnesota campus. That information will be used to design and install flexible borehole liners (1 each well) and sensors (15 each well) that will measure pressure and

temperature every five seconds. This work will be conducted by Minnesota Geological Survey scientists, working with the Centre for Applied Groundwater Research, University of Guelph, Ontario, the latter under a Professional/Technical Service contract.

Summary Budget Information for Activity 1:

ENRTF Budget: $110,800
Amount Spent: $ 110,800
Balance: $ 0

Outcome	Completion Date
1. Depiction of fracture patterns in the two monitor wells, that can be compared with fracture patterns that we characterize from outcrops (Activity 3)	February 15, 2017
2. Measurements of groundwater flow through fractures in the two monitor wells	February 15, 2017
3. Borehole liners and sensors installed in the two wells will provide temperature and pressure data for a period of two years (Activity 2)	February 15, 2017

Activity Status as of January 15, 2017: Working in collaboration with hydrologists from the University of Guelph, Minnesota Geological Survey staff measured fractures, water flow and other properties in the two monitor wells on the University of Minnesota Twin Cities campus in August, 2016. We purchased two flexible borehole liners, and a total of 27 sensors and successfully installed them in the wells in late August and early September. The cost of the liners was $661.66 more than budgeted due to the inclusion of venting tubes that were deemed necessary to facilitate liner insertion. This negative balance will be addressed in a future amendment request.

An unanticipated issue was that the flexible liner in one monitor well developed two small leaks (tears in the liner), which were repaired, and the liner successfully reinstalled. As we continue our project, extracting and reinstalling the liners, it is possible that other leaks will develop, which may require purchase of new liners. If this is necessary we will request an amendment to our budget and cover the cost from other categories. The status overall is very close to what we anticipated.

The holes are now successfully instrumented with sensors that are continuously collecting temperature and pressure data, and we will be downloading those data in February or March, as part of Activity 2, when outside temperatures are warmer.

An unanticipated positive addition to the project was collection of information from similar fractured rock monitor wells elsewhere in Minneapolis, as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Most of Activity 1 was completed at the time of the previous status report, as described above. Remaining activities included interpretation of data acquired from the two monitor wells and adjustments made to the sensor installations.

Activity Status as of July 1, 2018: Completed

Activity Status as of January 15, 2019: Completed

Activity Status as of June 17, 2019: Completed

Final Report Summary: We instrumented five monitor wells with sensors that continuously collected temperature and pressure data. Four of the five monitor wells yielded extremely useful information. This doubles the number of wells (two) we intended to collect information from. The additional monitor wells were added as a result of our collaboration with unpaid project partner Kelton Barr of Braun Intertec. This greatly enhanced the value of our project because the additional information led to improved predictability of

groundwater flow through the Platteville Formation across a larger area of the Twin Cities Metro, as described for Activity 4.

ACTIVITY 2: Collect groundwater pressure and temperature data from monitor wells for 3 years
Description: Scientists from the Minnesota Geological Survey will extract sensors from wells at approximately 6 month intervals to download temperature and pressure data, followed by re-insertion of sensors for additional data collection. As of December 28, 2017 we now have plans to instrument a third well, at a Minneapolis contamination site.

Summary Budget Information for Activity 2:

ENRTF Budget: $23,444
Amount Spent: $ 23,444
Balance: $ 0

Outcome	Completion Date
1. Acquisition of two years of continuous (five second intervals) data showing temperature and pressure variability that provide an understanding of groundwater flow conditions	November 1, 2018

Activity Status as of January 15, 2017: Sensors are successfully installed (Activity 1), and we anticipate our first download of data to occur in February or March depending on weather conditions.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: We have now downloaded data from the two monitor wells multiple times. The installations are successfully providing temperature and pressure data as planned. Data have been processed, calibrated, and disseminated to collaborators. The data from one of the two monitor wells reveal very useful insights into groundwater flow conditions. The data from the second of two monitor wells appear to be far less useful, because of the unanticipated presence of a leaky underground shaft close to the well. We have therefore made plans to install and collect data from a third monitor well, at a contamination site in Minneapolis, working in collaboration with the Minnesota Pollution Control Agency and Braun Intertec. The minor changes to our budget as part of our Amendment request are intended to give us more flexibility to install and collect data from this third monitor well.

Activity Status as of July 1, 2018: We have now downloaded data from the two monitor wells multiple times. The installations are successfully providing temperature and pressure data as planned. Data have been processed, calibrated, and disseminated to collaborators. The data from one of the two monitor wells continues to provide us with very useful insights into groundwater flow conditions. The data from the second of two monitor wells appear to be far less useful, because of the unanticipated presence of a leaky underground shaft close to the well. We have therefore discontinued collection of data from that well, and made plans to install and collect data from a third monitor well, at a contamination site in Minneapolis, working in collaboration with the Minnesota Pollution Control Agency and Braun Intertec.

Activity Status as of January 15, 2019: We have now downloaded data from three monitor wells multiple times. Data have been processed, calibrated, and disseminated to collaborators. The most recently instrumented of these wells is for the first time providing us with information on groundwater conditions in a more highly fractured setting, giving us a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems. Our results have been promising enough, especially with the recently instrumented well, that we continue to

monitor and collect data, which may continue beyond the formal duration of this project, using alternate sources of funding.

Activity Status as of June 17, 2019: We have now downloaded data from five monitor wells multiple times. Data from three of the wells have been processed, calibrated, and disseminated to collaborators. More recently we were able to take advantage of two wells drilled by Metropolitan Council near Minnehaha Falls, which gives us a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems, and will also have relevance to ongoing concerns about Camp Coldwater Spring near Minnehaha Falls. Our results have been promising enough, especially with these recently instrumented wells, that we continue to monitor and collect data, which will continue beyond the formal duration of this project, using alternate sources (MGS general budget) of funding.

Final Report Summary: We acquired useful data from four monitor wells multiple times over a period of nearly three years. By adding a second study site with two wells, beyond the scope of the original project, we were able to gain a broader perspective on how flow conditions change from place to place, when the geologic setting changes. The gives our results broader application to groundwater contamination problems, and will also have relevance to ongoing concerns about Camp Coldwater Spring near Minnehaha Falls and to water level issues within the Minnehaha Creek Watershed. Our results were promising enough, especially with these added monitor wells, that we continued to monitor and collect data beyond the formal duration of this project, using alternate sources (MGS general budget) of funding.

ACTIVITY 3: Map fractures in bedrock along Mississippi River near the tested monitor wells
Description: Fractures (cracks) in the limestone of the Platteville Formation will be mapped by photo-based trace mapping of exposures along east bank of Mississippi River, about 500 yards from monitor wells tested as part of Activity 1. This process includes high-resolution, seamless photograph collected by a camera mounted on a drone, near Washington Avenue bridge. Fractures shown on the photograph will be traced on the photograph electronically in the office, and then adjusted and measured in the field, on the outcropping. The final product with be a depiction of the natural fractures system in the Platteville Formation.

Summary Budget Information for Activity 3:

ENRTF Budget: $ 18,450
Amount Spent: $ 18,450
Balance: $ 0

Outcome	Completion Date
1. Documentation of the fracture patterns that control groundwater flow	November 1, 2018

Activity Status as of January 15, 2017: No activity. Planned to begin in March or April, 2017

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring roughly half complete. Progress is as planned.

Activity Status as of July 1, 2018: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring is nearly complete, with field work to be entirely finished this fall (2018). Progress is as planned.

Activity Status as of January 15, 2019: Completed

Activity Status as of June 17, 2019: Completed

Final Report Summary: Outcrop photographed and videoed using drone. Photos and videos processed and compiled into 3 dimensional images. Computer and field-based fracture tracing and measuring was completed. Results demonstrated that the Platteville Formation contains seven layers where fractures are not continuous. This is important because those layers can hinder vertical transport of contamination to deeper levels in the groundwater system. The position of those layers is compared to the information we collected from monitor wells, to determine how groundwater flows in the Platteville Formation, as part of Activity 4.

ACTIVITY 4: Synthesize information, disseminate results to groundwater managers.
Description: Compile and interpret pressure and temperature data collected from the five monitor wells, to understand how water flows through fractures. Compare and evaluate these results to fracture patterns mapped at nearby rock exposure to link together fracture patterns with water flow. Produce reports and presentations summarizing the results, which will be disseminated to organizations that have a role in managing groundwater quality and quantity, such as MPCA, DNR, County environmental managers, and environmental consulting industry.

Summary Budget Information for Activity 4:

ENRTF Budget: $ 30,306
Amount Spent: $ 30,306
Balance: $ 0

Outcome	Completion Date
1. Peer reviewed report(s) and public presentations of results that explain how fractures control groundwater flow, which will lead to more effective remediation of contamination sites, and improve management strategies to better protect fractured rock aquifers from further degradation	July 1, 2019

Activity Status as of January 15, 2017: No activity.

Activity Status as of July 1, 2017: No status report submitted per LCCMR instructions.

Activity Status as of January 15, 2018: Data downloaded from two monitor wells has been synthesized and interpreted. Results thus far from fracture tracing have been interpreted and compared to pressure and temperature data from monitor wells.

Activity Status as of July 1, 2018: Downloaded data continues to be synthesized and interpreted. Results thus far from fracture tracing have been interpreted and compared to this pressure and temperature data.

Activity Status as of January 15, 2019: We have begun to process data from the monitor wells and fractured outcrop into formats where they can be more readily compared to one another, fully interpreted, and disseminated to groups with interest in groundwater contamination. Preliminary interpretation appears to show great promise in linking fracture patterns to the groundwater data we have collected from monitor wells. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation and monitoring strategies. We have presented our results to water resources

groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Activity Status as of June 17, 2019: We continue to process data from the monitor wells and fractured outcrop into formats where they can be more readily compared to one another, fully interpreted, and disseminated to groups with interest in groundwater contamination. Preliminary interpretation appears to show great promise in linking fracture patterns to the groundwater data we have collected from monitor wells. Together, these results are providing the first detailed insight into how fracture patterns dictate variable degrees of flow connectivity in the Platteville Formation. These results will also apply to many other hydrogeologic units in Minnesota. This has important implications for predicting contaminant transport and devising groundwater remediation and monitoring strategies. We have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Final Report Summary: A key outcome was identification of predictable low permeability layers within the Platteville Formation that can hinder vertical transport of contaminants. The presence of these layers means that conventional techniques for monitoring and remediating contamination plumes are not as effective as presumed. Other results of our project such as the three dimensional depiction of fractures, and the relative differences in vertical connectivity across the Platteville Formation can be used in groundwater models to improve their accuracy. These models provide guidance for water management engineering inherent to many of the construction projects in central TCMA, and for groundwater-surface water modelling, such as within the Minnehaha Creek Watershed. The relevance of our results to how groundwater contamination is characterized and remediated, and for improving groundwater models, applies not only to the Platteville Formation, but to all fractured rock aquifers and aquitards in Minnesota. We therefore encourage greater application of more rigorous techniques such as the inexpensive and efficient methods used in this project. We have presented our results as the project progressed to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

V. DISSEMINATION:

Description: We will disseminate results to organizations that have a role in managing groundwater quality and quantity, such as MPCA, MNDNR, County environmental managers, and environmental consulting industry. Dissemination will include presentations at meetings such as the Minnesota Ground Water Association, and begin before the project ends, as we progressively acquire data. At the conclusion of the project, the results will appear in published, peer-reviewed report(s), that are routinely disseminated widely by the Minnesota Geological Survey (MGS), including through our website at http://www.mngs.umn.edu/. MGS reports also include links to all raw data that support the conclusions of the report. Results are also likely to be of sufficient interest and applicability to be published in one or more national or international journals.

Status as of January 15, 2017: No activity

Status as of July 1, 2017: No activity

Status as of January 15, 2018: No activity

Status as of July 1, 2018: We have started to compile data into illustrations for our anticipated report(s). Meanwhile, we have presented our data collected thus far, and preliminary results, to groundwater scientists and managers at local (Minnesota) and regional (North Central section of the Geological Society of America) meetings.

Status as of January 15, 2019: Since the previous report, we have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Status as of June 17, 2019: Since the previous report, we have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, and to local colleges.

Final Report Summary:
We have presented our results to water resources groups at the Minnesota Department of Health, Minnesota Pollution Control Agency, the regional division of the American Institute for Professional Geologists, the regional (North Central section of the Geological Society of America) meetings, and to local colleges. Our technical report (submitted as an accompanying document) will be published by the Minnesota Geological Survey and disseminated through our website at http://www.mngs.umn.edu/. We will also continue to present the results to consultants and government agencies involved with groundwater quality and quantity issues.

VI. PROJECT BUDGET SUMMARY:
A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$82,703	1 MGS senior scientist for project management, borehole equipment installation, fracture characterization, and synthesis of results; 16.6% time per year for 3 years, 74% salary, 26% benefits ($45,438); 3 MGS staff for assistance with borehole equipment installation, fracture characterization, and synthesis of results, as follows: 1 MGS senior scientist 8.3% time per year for 3 years, 74% salary, 26% benefits ($21,403); 1 scientist MGS 4.2% time per year for 3 years, 74% salary, 26% benefits ($8,202); 1 assistant scientist MGS 4.2% time per year for 3 years, 74% salary, 26% benefits ($6,680)
Professional/Technical/Service Contracts:	$41464	1 contract with Centre for Applied Groundwater Research (CAGR) , University of Guelph, Ontario: Acquisition of borehole data from two monitor wells that will provide recognition of rock fractures in the wells, and where and in what direction natural groundwater flow occurs. Includes directional temperature logs (CAGR is sole source provider), acoustic and optical televiewer logs, and full waveform sonic logs. Design and installation of a borehole liner and 15 sensors (a technique developed and deployed only by CAGR) in each of two monitor wells (total 2 borehole liners and 30 sensor arrays designed and installed) ($40,000); 1 contract for drone-based photography to image fractured rock along Mississippi River at University of Minnesota, provider TBD ($800)
Equipment/Tools/Supplies:	$8475	Borehole liners to be installed in two monitor wells. FLUTe brand flexible liners, Total of 2

		liners @ $1541 ea ($3082). Shipping of equipment ("Green Machine") necessary to extract and reinsert borehole liner ($1000)
Capital Expenditures over $5,000:	$49,390	Data logger sensors that measure pressure and temperature (to be installed in two boreholes): Total 30 sensors @ $1827.50 ea , plus shipping @ $225 ($55,050)
Fee Title Acquisition:	$	
Easement Acquisition:	$	
Professional Services for Acquisition:	$	
Printing:	$	
Travel Expenses in MN:	$968	Truck rental for monitor well liner installation, retrieval, re-installation (to retrieve data 4 times during course of project) (rental, 5 weeks @ $269/week) ($1345)
Other:	$	
TOTAL ENRTF BUDGET:	**$183,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: Thirty data logger sensors that measure pressure and temperature to be installed in two boreholes will be purchased and will be continue to be used by the Minnesota Geological Survey for the life of these sensors for similar projects and purposes. If the instrument is sold prior to its useful life, proceeds from the sale will be paid back to the Environment and Natural Resources Trust Fund.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 1.0 FTE

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0.2 FTE

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
	$	$	
State			
University of Minnesota	$95,486	$95,486	In-kind Services To Be Applied To Project During Project Period: The University of Minnesota's Facilities and Administrative rate is 52% of modified total direct costs (total direct less graduate student fringe, capital equipment, subawards over $25,000 and on-site facilities rental). The amount, if F&A expenses would have been allowed on this project, would be $95,486
TOTAL OTHER FUNDS:	**$95486**	**$95,486**	

VII. PROJECT STRATEGY:

A. Project Partners:

Project Partners Receiving Funds:

- **Centre for Applied Groundwater Research** , University of Guelph, Ontario, led by Dr. Beth Parker. $40,000 for geophysical testing and installation of pressure and temperature sensors as a contracted collaboration. This Centre is uniquely capable of acquiring temperature profiles that measure flow direction through fractures in monitor wells, and in installation of the nested pressure and temperature sensors, a procedure developed by their group. The information acquired from these procedures is key to understanding flow through fractures in the two monitor wells we are testing on the University of Minnesota campus. Contribution to interpretation of final results and publication during final year of project will be an unpaid contribution.

Project Partners Not Receiving Funds:

- **Braun Intertec,** Bloomington, Minnesota. Kelton Barr, Principal Hydrogeologist, providing unpaid consultation at all stages of the investigation. Mr. Barr has over 40 years of experience remediating fractured limestone contamination sites in the Twin Cities.

B. Project Impact and Long-term Strategy:

Application of our results will improve the efficiency and effectiveness of remediation and monitoring at a large number of contamination sites across the Twin Cities. The results will also be applicable to water management at construction (tunneling, building foundation, roadwork) sites, and to modeling groundwater-surface water interaction in areas such as the Minnehaha Creek Watershed. The results will provide a better understanding of fracture controlled flow through limestones regionally across southeastern Minnesota, and therefore link to the mapping of these limestones as part of ongoing County Geologic Atlas mapping progam, such as the in-progress Hennepin County Atlas. The borehole equipment purchased for this project, and the investigative methods, can be subsequently deployed in both wells and springs at other sites in southeastern Minnesota.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Proposed project builds on over 5 years of research by MGS staff on fractured rock groundwater flow in the Platteville Formation, funded through Minnesota Geological Survey base funding, and a 2010 Metropolitan Council grant.	~July 1, 2010-July 1, 2015	$60,000
ENTRF funded a 2010 project "Investigation of the hydrologic properties of the St. Lawrence Formation" (M.L. 2010, Chp. 362, Sec. 2, Subd. 3a). The results of that investigation have led to the development of techniques and concepts that we will apply to this proposed project.	July 1, 2010-June 30, 2013	$307,000

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

IX. VISUAL COMPONENT or MAP(S): See attached visual component

X. RESEARCH ADDENDUM: N/A

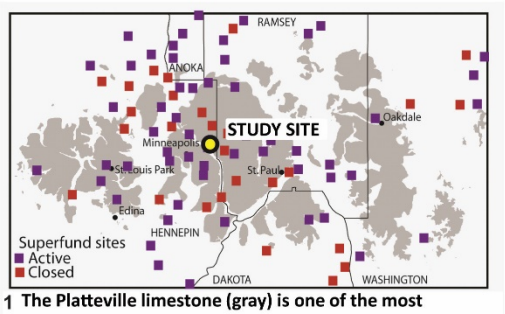
XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 15, 2017, July 1, 2017, January 15, 2018, July 1, 2018, January 15, 2019. A final report and associated products will be submitted between June 30 and October 15, 2019.

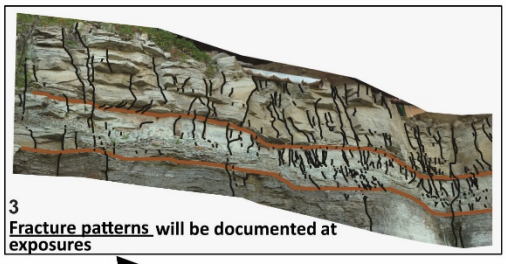
Understanding Bedrock Fracture Flow to Improve Groundwater Quality

Environment and Natural Resources Trust Fund (ENTRF) (Proposal ID:049-B)

Anthony Runkel, Minnesota Geological Survey



1 The Platteville limestone (gray) is one of the most heavily polluted formations in the state

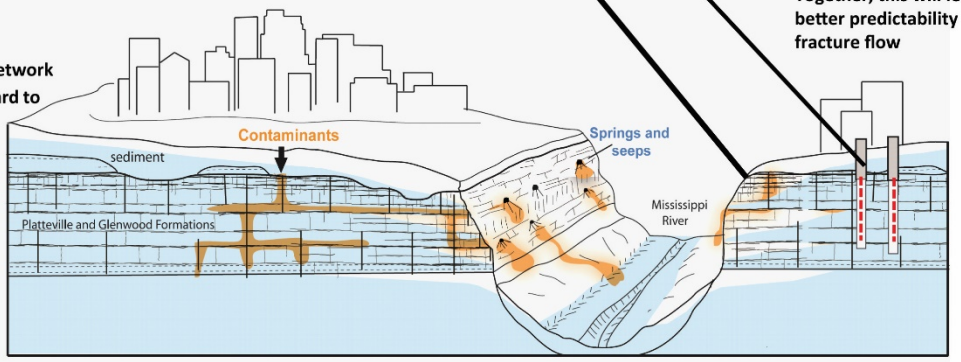


3 Fracture patterns will be documented at exposures

4 Pressure and temperature in wells will record water flow through fractures

5 Together, this will lead to better predictability of fracture flow

2 Contaminants move through a complex network of fractures, downward to deeper aquifers and laterally to rivers in a manner difficult to predict



UNIVERSITY OF MINNESOTA

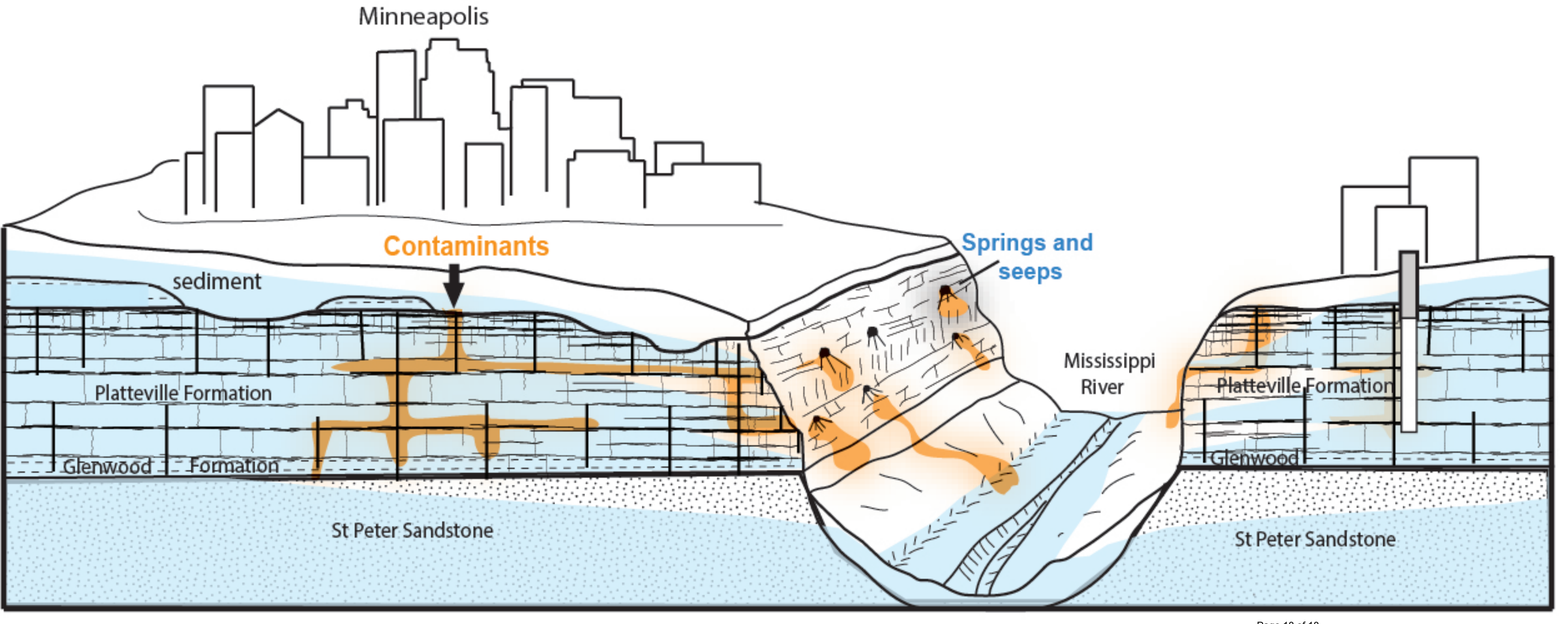
Depiction of the fractured limestone and contamination plumes beneath the Twin Cities

Final Attachment A (Budget Sheet) Budget detail for M.L. 2016 Environment and Natural Resources Trust Fund Projects

Project Title: Understanding Bedrock Fracture Flow to Improve Groundwater Quality
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04g
Project Manager: Anthony C. Runkel
Organization: Minnesota Geological Survey (University of Minnesota)
M.L. 2016 ENRTF Appropriation: $ 183,000
Project Length and Completion Date: 3 years, June 30, 2019
Date of Report: October 14, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 01/15/2018	Amount Spent	Activity 1 Balance	Revised Activity 2 Budget 06/17/2019	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	Activity 4 Budget	Amount Spent	Activity 4 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM							**Map fractures in bedrock along Mississippi River near the tested monitor wells**			**Synthesize information, disseminate results to groundwater managers.**				
Personnel (Wages and Benefits)	$17,002	$17,002	$0	$17,745	$17,745	$0	$17,650	$17,650	$0	$30,306	$30,306	$0	$82,703	$0
1 senior scientist, Project Manager, MGS: $45,438 (16.6% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 senior scientist, MGS: $21,403 (8.3% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 scientist MGS: $8202 (4.2% time per year for 3 years, 74% salary, 26% benefits)						$0								
1 assistant scientist MGS: $6680 (4.2% time per year for 3 years, 74% salary, 26% benefits)						$0								
Professional/Technical/Service Contracts						$0								
Photography of fractured bedrock along east bank of Mississippi river at U of Minnesota campus, using camera mounted on drone.						$0	$800	$800	$0				$800	$0
Centre for Applied Groundwater Research (CAGR) , University of Guelph, Ontario: Acquisition of borehole data from two monitor wells that will provide recognition of rock fractures in the wells, and where and in what direction natural groundwater flow occurs. Includes directional temperature logs (CAGR is sole source provider), acoustic and optical televiewer logs, and full waveform sonic logs. Design and installation of a borehole liner and 15 sensors (a technique developed and deployed only by CAGR) in each of two monitor wells (total 2 borehole liners and 30 sensor arrays	$40,664	$40,664	$0			$0							$40,664	$0
Equipment/Tools/Supplies						$0								
Borehole liners to be installed in two monitor wells. FLUTe brand flexible liners, Total of 2 liners @ $1541 ea	$3,744	$3,744	$0			$0							$3,744	$0
Shipping of equipment ("Green Machine") necessary to extract and reinsert borehole liner ($1000)					$0	$0							$0	$0
General equipment, shipping of equipment, supplies for sensors and related devices for existing and new well.				$4,731	$4,731	$0							$4,731	$0
Capital Expenditures Over $5,000						$0								
Data logger sensors that measure pressure and temperature (to be installed in two boreholes): Total 30 sensors @ $1827.50 ea, plus $225 shipping ($55,050)	$49,390	$49,390	$0			$0							$49,390	$0
Travel expenses in Minnesota						$0								
Equipment rental (truck) for monitor well liner installation, retrieval, re-installation (to retrieve data 4 times during course of project) (truck rental, 5 weeks @ $269/week ; total $1345)	$0	$0	$0	$968	$968	$0							$968	$0
Describe the expense—one row per type/category. Add rows as needed. Be specific.														
COLUMN TOTAL	**$110,800**	**$110,800**	**$0**	**$23,444**	**$23,444**	**$0**	**$18,450**	**$18,450**	**$0**	**$30,306**	**$30,306**	**$0**	**$183,000**	**$0**

Understanding Bedrock Fracture Flow to Improve Groundwater Quality



GROUNDWATER CONTAMINATION IN FRACTURED ROCK