2016 Project Abstract
For the Period Ending June 30, 2020

PROJECT TITLE: Protection of State's Confined Drinking Water Aquifers – Phase II
PROJECT MANAGER: Jared Trost
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 04h as extended by M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 19

APPROPRIATION AMOUNT: $433,000
AMOUNT SPENT: $433,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

Groundwater flowing downward through till confining units (leakage) replenishes water pumped from confined aquifers, a water source for thousands of Minnesota residents. Till hydraulic properties are variable over short distances and profoundly affect leakage rates, demonstrating the importance of site-specific till data for understanding sustainability of groundwater withdrawals from confined aquifers.

Overall Project Outcome and Results

Confined (or buried) aquifers of glacial origin overlain by till confining units provide drinking water to hundreds of thousands of Minnesota residents. The sustainability of these groundwater resources is not well understood because hydraulic properties of till that control vertical groundwater fluxes (leakage) to underlying aquifers are largely unknown. The U.S. Geological Survey, Iowa State University, Minnesota Geological Survey and Minnesota Department of Health investigated hydraulic properties and groundwater flow through till confining units using field studies and heuristic MODFLOW simulations. Till confining units in each of four major geologic deposits were characterized (location in parentheses): the Des Moines lobe (Litchfield), Superior lobe (Cromwell), Wadena lobe (Hydrogeology field camp [HFC] near Akeley), and Pre-Illinoian deposits (Olivia). Hydraulic and geochemical field data were collected from sediment cores and a series of five piezometer nests. Each nest consisted of five to eight piezometers screened at short vertical intervals in hydrostratigraphic units including (if present) surficial aquifers, till confining units, confined/buried aquifers, and underlying bedrock.

Till thicknesses varied from 60 to 166 feet, and till textures ranged from a sandy loam (HFC site) to a silt loam/clay loam (Olivia site). The Cromwell, HFC, and Litchfield 1 sites were examples of "leaky" tills with high vertical hydraulic conductivity (Kv, 0.001 to 1.1 feet per day [ft/d]) and extensive vertical hydraulic connectivity between the confined aquifer and the overlying till. Estimated groundwater travel times through till at these sites ranged from 1 to 81 years, and two of these sites had tritium throughout their till profiles. The tills at the other two sites, Olivia and Litchfield 2, were effective confining units that had low Kv (0.001 to 0.0005 ft/d). Estimated groundwater travel times through the tills at these sites ranged from 165 to nearly 1,800 years, and tritium was only detected in the upper one-third of these till profiles. A conceptual understanding that emerges from the vertical till profiles is that they are not homogeneous hydrostratigraphic units with uniform properties; rather, each vertical sequence is a heterogeneous mixture of glacial sediment with differing abilities to transmit water.

The heuristic MODFLOW modeling demonstrated that, for understanding sustainability of groundwater pumping from confined aquifers, knowledge of till hydraulic properties is just as important as knowledge of

aquifer hydraulic properties. Over long periods of time (hundreds of years), pumping-induced hydraulic gradients are established in confined aquifer systems and, even in low hydraulic conductivity tills, these pumping-induced hydraulic gradients increase leakage into and through till compared to ambient conditions.

Project Results Use and Dissemination

Project results have been and will be disseminated through public presentations and publication of online reports. Results were broadly distributed to hydrology and geology professionals through 13 presentations at state, regional, and national meetings and 2 master's thesis defense presentations. Some of these events retain online versions of abstracts and presentations, which are listed below. The full list of presentations about this project is included in the project workplan. Two master's theses are also available online. A series of products from the Minnesota Geological Survey, Minnesota Department of Health, and the USGS provide geologic descriptions, aquifer test analysis results, geochemical data, and model documentation to support the interpretations written in the final, comprehensive USGS Scientific Investigations Report (SIR).

Published reports:

Final comprehensive report:

Trost, J.J., Maher, A., Simpkins, W.W., Witt, A.N., Stark, J.R., Blum, J., and Berg, A.M., 2020, Hydrogeology and groundwater geochemistry of till confining units and confined aquifers in glacial deposits near Litchfield, Cromwell, Akeley, and Olivia, Minnesota, 2014–18: U.S. Geological Survey Scientific Investigations Report 2020–5127, 80 p.,https://doi.org/10.3133/sir20205127.

Data and other supporting information:

Blum, J.L., and Woodside, J., 2017, Analysis of the Litchfield, Minnesota Well 2 (607420) aquifer test conducted on June 29, 2017, confined quaternary glacial-fluvial sand aquifer: Minnesota Department of Health, aquifer test 2617, 81 p. [Available at: https://www.health.state.mn.us/communities/environment/water/docs/swp/testlitchfield.pdf]

Lund, T., and Blum, J.L., 2017, Analysis of the Cromwell, Minnesota Well 4 (593593) aquifer test conducted on May 24, 2017, confined quaternary glacial-fluvial sand aquifer, Minnesota Department of Health, Aquifer Test 2612, 75 p. [Available at: https://www.health.state.mn.us/communities/environment/water/docs/swp/testcromwell.pdf]

Maher, A.-T., Trost, J.J., Witt, A.N., Berg, A.M., Simpkins, W.W., and Stark, J.R., 2020, Geochemical data, water-level data, and slug test analysis results from till confining units and confined aquifers in glacial deposits near Akeley, Cromwell, Litchfield, and Olivia, Minnesota, 2015–2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9IXC7D3.

Staley, A.E., Wagner, K., Nguyen, M., and Tipping, R., 2018, Core descriptions, borehole geophysics, and unit interpretations in support of Phase I and II USGS Hydrologic Properties of till Investigation, Minnesota Geological Survey, 29 p. [Available at: https://conservancy.umn.edu/handle/11299/204896]

Trost, J.J., Feinstein, D.T., and Jones, P.M., 2020, Heuristic MODFLOW models used to evaluate the effects of pumping groundwater from confined aquifers overlain by till confining units: U.S. Geological Survey data release, https://doi.org/10.5066/P9KOI6T3.

U.S. Geological Survey, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessible at https://doi.org/10.5066/F7P55KJN.

Graduate theses:

Maher, Anna-Turi, 2020, Hydrogeology and groundwater geochemistry of two glacigenic aquitard/aquifer systems in north-central and south-central Minnesota, Graduate Theses and Dissertations, 18006. [Available at: https://lib.dr.iastate.edu/etd/18006/]

Witt, Alyssa, 2017, Hydrogeological and geochemical investigation of recharge (leakage) through till aquitards to buried-valley aquifers in central and northeastern Minnesota, Graduate Theses and Dissertations, 15462. [Available at: https://lib.dr.iastate.edu/etd/15462/]

Full presentations available online:

Blum, J. Leakage is for 'Lumpers' – Lessons Learned from Aquifer Tests in Layered Till presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019. [Abstract; presentation pdf; recorded audio of presentation]

Trost, J. and Simpkins, W.W. Groundwater Flow Through Till: tortoise, hare, or not in the race? Presented at the Minnesota Groundwater Association in St Paul, Minnesota, April 25, 2019. [Abstract; presentation pdf; recorded audio of presentation]

Presentation abstracts available online:

Maher, A., Simpkins, W., Trost, J., Witt, A., Berg, A., and Stark, J. 2018. Groundwater Flow and Geochemistry of Till Confining Units Overlying Buried Glacial Aquifers: Examples from the Des Moines and Wadena Lobes in Minnesota. GSA Annual Meeting in Indianapolis, Indiana, USA [Available at: https://gsa.confex.com/gsa/2018AM/webprogram/Paper324789.html]

Maher, A., Simpkins, W.W., Witt, A., Trost, J.J., Berg, A.M., and Stark, J.R. Hydrogeologic investigation of groundwater flow in till confining beds overlying glacigenic aquifers in south-central and north-central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/313001]

Maher A., Simpkins, W.W, Trost, J., Witt, A., Berg, A., and Stark, J.R. Evidence of anthropogenic contamination in till aquitards at the hydrogeology field camp and Olivia sites in Minnesota poster presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019. [Available at: https://www.mgwa.org/wp-content/uploads/2019/spring/mgwa-spring-2019-poster-abstracts.pdf]

Simpkins, W.W., Witt, A., Blum, J., Trost, J.J., Berg, A.M., and Stark, J.R. Spatial Variability in the Vertical Connectivity of Till Confining Units: Implications for Glacial Aquifers in Minnesota presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018. [Available at: https://www.wrc.umn.edu/sites/wrc.umn.edu/files/2018_final_program_and_abstracts.pdf]

Trost, J.J., Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the source of water to wells completed in confined glacial aquifers presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018. [Available at: https://www.wrc.umn.edu/sites/wrc.umn.edu/files/2018_final_program_and_abstracts.pdf]

Trost, J.J. Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the sustainability of groundwater withdrawals from confined glacial aquifers presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/313038]

Witt, A., Simpkins, W.W., Blum, J., Trost, J.J., Berg, A.M., Stark, J.R. Spatial variability in the vertical connectivity of till confining beds: examples from the New Ulm formation in central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/312862]

Environment and Natural Resources Trust Fund (ENRTF)

M.L. 2016 Final Report

Date of Report: August 13, 2020

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2020

PROJECT TITLE: Protection of State's Confined Drinking Water Aquifers – Phase II

Project Manager: Jared Trost, Hydrologist

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Location: statewide

Total ENRTF Project Budget:	ENRTF Appropriation:	$433,000
	Amount Spent:	$433,000
	Balance:	$0

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04h as extended by M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 19

Appropriation Language:

$433,000 the second year is from the trust fund to the commissioner of natural resources for an agreement with the United States Geological Survey to continue to test methods of defining properties of confined drinking water aquifers, in order to improve water management. This appropriation is not subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

Carryforward; Extension (a) The availability of the appropriations for the following projects is extended to June 30, 2020: (7) Laws 2016, chapter 186, section 2, subdivision 4, paragraph (h), Protection of State's Confined Drinking Water Aquifers - Phase II;

I. PROJECT TITLE: Protecting the State's Confined Drinking-Water Aquifers

II. PROJECT STATEMENT:

This project completes an on-going LCCMR project to assess the quality and long-term availability of water from confined glacial drinking-water aquifers. This second phase will add two additional study sites that are needed to complete our understanding of the variability in the hydraulic properties of confining units and confined glacial aquifers throughout the state.

This project would focus on important questions about confining units and confined aquifers:

- What is the source of water replenishing confined aquifers?
- How long does it take water to move along the flow pathways?
- How much water moves along the flow pathways?
- What are the pathways for water and contaminant movement through confining units?
- What are best estimates of long-term sustainable pumping from confined drinking-water aquifers?
- How extensive and variable are confining units across the state?

Many glacial aquifers in Minnesota, used as sources of drinking water, are overlain by clayey glacial deposits (confining units, see visual elements). These confined aquifers are critical state resources because they provide the only sources of clean, reliable drinking water to tens of thousands of urban and outstate residents of Minnesota. The confining units overlaying confined aquifers are a vitally important part of aquifer systems because they form protective barriers for the confined aquifers from land-surface contamination. The confining units also, however, limit water flow (infiltration) to confined aquifers, so replenishing water in confined aquifers is a slow and limited process. We need to better understand the hydraulic properties of confining units to ensure sustainable use of water from these important drinking-water aquifers. This project will continue the assessment of the hydraulic properties of the state's important glacial confining units, such as the Des Moines and Superior lobe till confining units (see visual elements). Detailed, site-specific information about protective confining units will be measured at two additional study sites that represent the state's important confining units. The overall project is a collaborative effort among the U. S. Geological Survey (USGS), the Minnesota Geological Survey (MGS), and the Minnesota Department of Natural Resources, and the Minnesota Department of Health (MDH). It augments work completed by the County Geologic Atlas Program.

The project is a major step forward in protecting confined glacial aquifers by measuring the hydrogeological properties of these important aquifers. The work will result in a wide assessment of information about the aquifers. The project is needed to protect the quality of water in these units and to define the amount of water that can be pumped from confined aquifers (MDNR appropriation permit process) on a long-term and sustainable basis.

Problem: Confined glacial aquifers provide water to many residents in Minnesota. An important factor affecting the long-term sustainable availability of water from these aquifers is infiltration through overlying glacial till confining units. Few data exist, however, on the vertical hydraulic properties and infiltration rates through till. The lack of detailed infiltration and hydraulic data hinders the state's efforts to define the sustainability of confined aquifers. There is also a need to understand the regional variability of the properties of these confining units across the state.

It is important to protect confined drinking-water aquifers from non-sustainable over-pumping. To accomplish the goal of long-term sustainability, the sources, rates and quality of water infiltrating into confined aquifers must be understood. An important factor defining sustainable water use from confined aquifers is the rate of water movement (infiltration) through overlying confining units that replenish confined drinking-water aquifers. We currently lack information about infiltration to confined aquifers because infiltration depends upon the hydraulic properties of the overlying confining units. Infiltration-rate information is needed to manage confined aquifers so that they are protected for the future. Although the MGS and MDNR have an active County Geologic Atlas Program, which maps the extent and thickness of protective confining layers, the program needs supplementary information about hydraulic properties and infiltration to confining units. Filling this gap in understanding is also required for the MDNR water appropriation-permit process to ensure long-term sustainability of water supply from confined aquifers. This project contributes toward filling that gap in information by providing detailed site-specific data about the confining units at two study sites that represent the state's most important confining units-- the Des Moines, Superior, and Wadena lobe till deposits. Direct field measurements will provide information needed to estimate the water-bearing and water-transmitting characteristics of these aquifers.

It also is important to protect confined drinking-water aquifers from contamination. The quality of water in confined aquifers is presumed to be protected by overlying confining beds. Confining units, composed of till, are assumed to provide protection to confined groundwater supplies because infiltration water passes more slowly through these confining units than through surficial sand-and-gravel aquifers. Because of the increased transport time and reduced infiltration through till, however, water that was contaminated, say 20 years ago, may not have yet reached underlying confined drift aquifers. Thus, there may be a delayed adverse response from human activities on groundwater quality Scattered and isolated information suggests that groundwater and contaminants can flow from land surface through confining units to confined aquifers at varying rates. Thus, there is a critical need to understand how confining units protect the water quality of confined aquifers. These concerns identify our need to better understand the state's two important confining units.

Benefits: Information on the spatial variability of hydraulic properties and groundwater infiltration rates through till is necessary to plan for long-term water sustainability. In addition, this hydraulic information is essential for the MDH's wellhead protection program and will improve our ability to accurately evaluate contributing areas and develop appropriate protection plans for wells completed in confined-drift aquifers, which are more complex than unconfined aquifers. Accurate simulation of infiltration through glacial till also is a critical component for calibrating groundwater flow models. Because accurate estimates of infiltration rates are lacking, model analyses must largely rely on inferred data or results of laboratory tests.

The proposed study will increase the MDNR's understanding of the role of till confining units in water supply and the hydrologic cycle, resulting in more appropriate management decisions in glacial drift areas. Results from the specific data-collection sites will be regionalized such that results will be beneficial in other areas of this state where data are lacking. The Minnesota Pollution Control Agency (MPCA) will benefit from the study by gaining a better understanding of the vulnerability and susceptibility of confined drift aquifers to contamination. By obtaining a better understanding of infiltration through glacial till, the Twin Cities Metropolitan Council, MPCA, and environmental consultant firms will be able to more accurately simulate groundwater movement in confined aquifers. Study results will provide the MGS, colleges, and universities with basic knowledge important to educating the public on basic science. Local water utilities, where the individual hydraulic tests will be conducted, will benefit directly from results of this study. By comparing various methods of estimating groundwater leakage, study results will be beneficial to future USGS studies of recharge and infiltration through confining units in other areas of the state and the country.

Scope and Objectives: This project will estimate the hydraulic properties of two of the state's important glacial confining units, such as the Des Moines, Superior, or Wadena lobe till confining units. The approach involves conducting two additional detailed field studies in areas representing different confining unit types. Study sites will be selected in areas with existing high-capacity pumping wells (likely municipal-supply wells) to understand how pumping stress affects water movement. Scientific bore holes will be completed in the confining units and into the underlying confined aquifers. Field analyses will include hydraulic, geophysical and chemical tests. These tests may include multi-well aquifer tests, single-well pump tests, geophysical logging (e.g. gamma, temperature, fluid resistivity measurements) and measures of water chemistry.

The location of the two sites has yet to be determined. Site selection and access permission is a significant part of this study and will take place when the study begins. Study-site selection will be a collaborative effort with the MDNR, MGS, and the MDH. Study sites are will be located near appropriate municipal production wells in areas with approved wellhead protection plans, or other sites that have pumping systems installed in confined aquifers where the hydrogeology is well-characterized.

The specific objectives of the study are as follows:

- Explore available information to select appropriate study sites representing the primary glacial confining units in the state.
- Quantify the variability of hydrologic properties and infiltration through glacial confining units at two representative sites.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of December 30, 2016:

Several administrative tasks were completed to get the project moving. A detailed project work plan and budget were prepared and approved by the LCCMR. A USGS technical project proposal was prepared, reviewed and approved. A purchase agreement for geologic analysis from the Minnesota Geological Survey was prepared. A purchase agreement for drilling services from a private drilling contractor including rotary sonic core collection, monitoring well installation, and well and borehole sealing was prepared. A Joint Funding Agreement was prepared, reviewed, and signed by USGS Headquarters and by the Minnesota Department of Natural Resources.

Several meetings between the USGS, and staff from Minnesota Departments of Health and Natural Resources, and the Minnesota Geological Survey were held to discuss potential study sites. Available hydrologic and hydrogeologic data sets were acquired and organized and compiled to identify potential study sites. The project team selected one study site on Wadena Lobe deposits in Hubbard County, near Akeley, Minnesota at the University of Minnesota's Hydrocamp facility. This site was chosen because it represents a major surficial geologic deposit in the State, the site has abundant data that will support the objectives of this project, and there is little to no pumping interference from high capacity wells in proximity to the site. The second site has not been selected yet, but several candidate sites have been identified in the following counties containing Des Moines Lobe till deposits: Yellow Medicine, Redwood, Renville, Nicollet, McLeod, and Carver County.

Project Status as of June 30, 2017:

Several meetings and site visits occurred in order to select the second site for phase II. The project team selected a study site on Des Moines lobe deposits in central Renville County in the City of Olivia. A presentation was given to the Olivia City Council detailing the project. The Olivia City Council passed a motion to work with the USGS and allow USGS access to city property for the installation of a well nest.

A contract was awarded to the Minnesota Geological Survey (MGS) for technical assistance and for geological interpretation. Another contract was awarded to Traut Wells, Inc. for test drilling and well installation. A variance request for small diameter wells at the Hydrocamp site was submitted to the Minnesota Department of Health in April, and was subsequently approved. Drilling began mid-May at the University of Minnesota's Hydrocamp facility and was completed by the end of May. Four wells were installed and have been fully developed. A variance request for small diameter wells to be installed at the second site in Olivia was submitted to the Minnesota Department of Health and we are currently awaiting approval.

Project Status as of December 29, 2017:

Eight new observation wells (6 in till, 1 in a surficial aquifer and 1 in a buried aquifer) were installed near a municipal water supply in Olivia, Minnesota. A continuous core sample from land surface to 230 feet below land surface was collected prior to well installation to guide well screen placements. Six wells at the Hydrocamp site and eight wells at the Olivia site have been instrumented with pressure transducers that continuously record water levels. Water level data are available through the USGS National Water Information System (NWIS) at https://maps.waterdata.usgs.gov/mapper/index.html. Slug tests for determining hydraulic conductivity of geologic materials have been completed on all of the newly installed wells at both sites. Pore-water samples and groundwater samples from both sites have been analyzed for oxygen and deuterium isotope ratios. Groundwater samples have been collected from all wells at the two sites and lab analytical results are being provided to the project team as sample analyses are completed. Samples are being analyzed for major ions, nutrients, tritium, and oxygen and deuterium isotopes.

Amendment Request (12/29/2017):

- We request an amendment to reduce the total number of wells and well nests. Associated with this request is a reduction in the budget for Activity 1 Professional/Technical/Service Contracts for drilling from $140,000 to $127,563. Drilling expenses per foot were higher than anticipated. Originally, we proposed 2 well nests per site, for a total of 16 – 24 wells. Thus far, we have installed 1 well nest per site, totaling 13 wells. The most expensive part of drilling is collecting continuous cores, which are necessary prior to well nest installation to ensure appropriate screen placement. As we learned in phase 1 of the project, the geological materials vary greatly over short distances, so a continuous core is necessary for each well nest installation. With the funds available for the project, it is only affordable to do 1 continuous core per site and cost prohibitive to do 2 continuous cores per site, so thus far, we have installed 1 well nest per site. The original proposal included two well nests per site, one near and one far from a high capacity pumping well. At the Olivia site, a "near" and "far" response to pumping during an aquifer test is still possible with one nest because there are two high capacity wells in the buried aquifer we are observing. One well is approximately 150 feet from the well next, the other well is over 800 feet from the well nest. At the hydrocamp site, there are two high capacity wells near our well nest, one shallow and one deep. We are using the single well nest to observe pumping responses from the two different high capacity wells. Only 5 new wells were necessary at the hydrocamp site because we are using existing monitoring well infrastructure to supplement our newly installed wells. In summary, the change in design will not adversely affect our ability to complete the project objective of understanding leakage through glacial tills. Proposed revisions have been made throughout the document reflecting this amendment.
- We request an amendment to reduce the budget for equipment and supplies for Activity 1 from $11,100 to $4,377. Some field supplies that we originally planned on purchasing were provided by the drilling contractor (for example, concrete, well screens, concrete). We didn't have to purchase as much equipment for activity 1 as originally budgeted because we used equipment we had on hand.
- We request an amendment to reduce the budget for travel expenses in Minnesota for Activity 1 from $15,000 to $10,479. Substantial cost savings in travel were realized because the USGS provided free lodging at a field station near the hydrocamp site.
- We request an amendment to reduce the budget for Other Expenses (primarily shipping) for Activity 1 from $1,000 to $547. Shipping costs were lower than anticipated.

If the above amendments are granted, we request an amendment to increase budgets for salary and benefits for activity 1 and activity 2.

- First, we request an amendment to add $4,500 to the salary budget in Activity 1 to cover the time it took to for technical staff to complete the driller contracting and well permitting processes and for surveying the wells. The time required for these tasks was more than originally planned.
- Second, we request an amendment to add the remaining $19,634 in Activity 1 cost savings to the budget for salary and benefits for Activity 2. In October of 2016 (after the initial workplan budget was approved), a new USGS policy (USGS Technical Memorandum 2016.02) was enacted. This policy requires

that all USGS models be fully documented and publicly available as standalone data release products. The intent is that anyone can download the model and run it. Because this project has a modeling component, the production of this data release product will require more personnel time than what was originally budgeted. This additional product will be beneficial to Minnesota because technical staff from any agency or firm can take our published, documented models and run them to test their own hypotheses whereas a static report is a one-time document that is not interactive.

Some additional clarifications in language for Activities 1 and 2 have been proposed in the workplan document.

Amendment approved by LCCMR 1/4/18

Project Status as of June 29, 2018:

All pore and groundwater geochemical analyses for major ions, nutrients, tritium, and oxygen and deuterium isotopes of samples collected thus far are complete, and the results have been provided to the project team. Geochemical data from a variety of labs is being organized for a data release and analysis. At both Olivia and Hydrocamp sites, average linear velocity was calculated using the hydraulic gradient (calculated from the USGS National Water Information System averaged hydraulic head data from the piezometers), the hydraulic conductivities from the slug tests, and from an estimated porosity, to have an estimation of travel time through the till units. The Minnesota Geological Survey completed core descriptions and geologic unit analyses of the continuous core at both study sites. The hydraulic data collected is being compared with the geochemical data collected, to see if consistent estimations of travel time can be assessed using both the geochemical and hydraulic data. An experimental pumping test was completed at Olivia in May 2018. In July, 2018, another pumping test will be completed at Olivia. MDH has completed an initial analysis of the aquifer pumping test completed at the hydrocamp site in July 2017.

Amendment Request (11/6/2018):

- We request an amendment to reduce the budget for the technical services provided by the Minnesota Geological Survey from $20,000 to $12,374. The services were completed satisfactorily for less than the originally budgeted amount. MGS was present for field drilling activities and they have delivered a final report to us.
- We request an amendment to increase the budget for "Professional/Technical/ Service Contracts: USGS contract fee for water-level data collection, data processing and data-base maintenance and data quality control" from $16,800 to $22,400. Collection of continuous water level data was done in 13, rather than 12, wells and for a longer timeframe than originally anticipated to ensure a complete annual record for each well.
- We request an amendment to increase the budget for "Professional/Technical/ Service Contracts: contract fee for chemical analyses of water samples at USGS laboratories" from $6,500 to $10,140. The expense of squeezing pore water from core samples was higher than originally anticipated. We squeezed pore water from core samples to see if there was a difference in water quality between free-flowing groundwater and water trapped in pores of till. Differences in water quality between groundwater and pore water can provide information about preferential flow paths or about drilling fluid contamination of groundwater samples.
- We request an amendment to reduce the budget for travel expenses in Minnesota for Activity 2 from $7,100 to $3,217. The aquifer tests that we completed during the summer of 2018 required much less travel time than originally anticipated. The University of Minnesota was able to do most of the data collection for an aquifer test at the hydrocamp site.
- We request an amendment to reduce the budget for Other Expenses (primarily shipping) for Activity 2 from $500 to $20. Shipping costs were lower than anticipated.
- We request an amendment to increase the salary for Activity 2 from $153,234 to $155,982.82 to cover additional time for report writing and analysis. The aquifer test at Olivia revealed unique water level

behavior in the subsurface. Analysis of these data will take more time than originally budgeted. The other three sites (2 from the phase 1 study and 1 from phase 2) all had similar responses to pumping, but Olivia had a unique water level signal that requires special attention.

Amendment Approved by LCCMR 11/21/2018

Project Status as of December 31, 2018:

Three USGS-led publications are in preparation: (1) a Sciencebase data release of geochemical data; (2) a report summarizing the slug test data and analysis for piezometers from phase 1 and phase 2; (3) a scientific investigations report summarizing all activities and data analysis for phase 1 and phase 2.

Anna Maher, a graduate student at Iowa State University was awarded a summer National Association of Geoscience Teachers (NAGT) internship with the USGS in Minnesota to work on the project. She is presently earning her masters degree at Iowa State University with data collected as part of this project.

Major data collection efforts during the reporting period included continuous groundwater levels and aquifer tests at the hydrocamp and Olivia field sites. Data collection is now complete; data analysis and reporting is underway.

Amendment Request 1/31/2019

We request an amendment for a 6-month extension to the project. During the past month, three events beyond our control occurred that significantly affect our ability to complete all project expenditures by the June 30, 2019 deadline. First, the government shutdown halted all progress on project tasks for 5 weeks. In addition, there will be ongoing effects throughout the USGS as the agency recovers from the shutdown. Second, the staff person assigned to complete the model archive left the USGS for another job in late December. Because all of our USGS project timelines are affected by the shutdown, we don't have a fast staffing solution to backfill this position. This in turn, delays report production because publication of the final report depends on the model archive. Third, I have been trying to hire a technician for 4 months to assist with report writing. The staff position is still vacant, and delayed further because of the shutdown. The 6-month extension is requested to give time to address the immediate staffing shortages, complete data analysis and writing, and to accommodate the likely delays in USGS review and report publication processes resulting from the extended shutdown.

A revised timeline is below. The majority of project tasks will be completed by the current June 30, 2019 deadline. The primary reason for the extension is to cover time spent revising reports as part of the review process. I estimate that 20 percent or less of remaining project funds will be spent after the June 30 deadline.

2019

Task	Q1	Q2	Q3	Q4
prepare supporting publications for review: model archive, slug test report, geochemical data release, aquifer test report	x	x		
review and revise supporting publications		x	X	
Bureau approval of supporting publications			X	
publish supporting publications				x
prepare scientific investigations report (SIR) for review	x	x	X	
review and revise SIR			X	x

Task	Q1	Q2	Q3	Q4
Bureau approval of SIR				x
Publish SIR				x

Amendment Request signed into law 5/31/19

Project Status as of June 30, 2019:

The legislature approved an extension request for the project during this reporting period. All of the work during the reporting period was done for Activity two. Final reports are being prepared. A first draft of the data release pertaining to the geochemical results analyzed by non-USGS laboratories, has been completed. A model archive data release has been started. Figures, tables, and text for a final comprehensive report that summarizes phase I and II results is being prepared. The focus of writing so far has been on groundwater and pore-water ages, evidence for anthropogenic contamination of groundwater and pore water, and general characterization of groundwater geochemistry at all phase I and II sites. Several members of the project team were invited to present at the spring 2019 Minnesota Groundwater Association meeting titled "It's time to talk about till". The meeting was held at St. Paul campus of the University of Minnesota. Bill Simpkins, Jared Trost, and Justin Blum gave oral presentations to the 300+ people in attendance and Anna Maher presented a poster.

Amendment Request December 18, 2019:

We request an amendment to change the project completion date listed on the workplan and budget form from December 31, 2019 to June 30, 2020. The amended project completion date matches the project completion date in the appropriation language and the joint funding agreement between the USGS and the MN DNR.

A revised timeline is below.

2020

Task	Q1	Q2	Q3	Q4
prepare supporting publications for review: model archive, slug test report, geochemical data release, aquifer test report	Done			
review and revise supporting publications	x			
Bureau approval of supporting publications		x		
publish supporting publications		x		
prepare scientific investigations report (SIR) for review	x			
review and revise SIR	x	x		
Bureau approval of SIR		x		
SIR publicly available			x	

Amendment approved by LCCMR 2/7/2020.

Project Status as of December 18, 2019:

All of the reports being produced by the USGS from this project are in draft form. Most of the work since the last workplan update has been focused on writing text and creating figures to incorporate this project's results into a draft Scientific Investigations Report titled "Characterization of the sustainability and susceptibility of water supplies in confined glacial aquifers of Minnesota", which summarizes the phase 1 and phase 2 projects. Some time was also spent preparing a model archive titled “Interpretive MODFLOW models used to assess the sustainability and susceptibility of confined glacial aquifer water supplies in Minnesota”. This model archive is a publicly-available version of the groundwater models used for this project that everyone can access online and use to explore additional hypotheses. Finally, revisions were made to the data release titled “Water and sediment core chemistry and slug test data in support of sustainability and susceptibility of groundwater in confined aquifers in Minnesota, USA” to incorporate slug test results so they will be published and publicly available along with geochemical data sets according to current USGS policies.

Additionally, the data collected as part of this project are the topic of a master’s student’s thesis. The student expects to defend her thesis in January 2020. Justin Blum, a project partner from the Minnesota Department of Health, has been exploring methods of analysis for aquifer test data from the Olivia, Minnesota site where we observed some unexpected reverse water level fluctuations during an aquifer test.

Amendment Request May 15, 2020:

We request the following changes to the project budget. For Activity 1, we request that the equipment budget be reduced by $234.83 from $4,377 to $4,142.17; that the contract drilling services budget be increase by $0.01, from $127,563.00 to $127,563.01 to compensate for $0.01 mismatch between billing and budget in this category. For Activity 2, we request that the Minnesota Geological Survey contract budget be decreased by $47.05, from $2,497.59 to $2,450.54 to reflect the actual contract expenses; that the USGS publication expense be reduced by $2,000 from $6,000 to $4,000; that the equipment budget be reduced from $3,100 to $0.00 because we were able to use equipment we had on hand; and that the other expenses budget be increased by $0.31, from $20.00 to $20.31 to cover the difference between billing and budget in this category.

After all of these changes, we would like to move $5,815.10 into salary for writing and revising the three publications that are currently in production. The increased salary will support the project chief and a student technician for report production. We also request an amendment to the detailed allocation of salaries provided in the budget summary below. In short, the changes in allocation are the result of two things: (1) we were able to utilize more student technicians on this project than originally budgeted and (2) the USGS match increased and covered more of the USGS administrative and technical specialist staff time than was originally budgeted. The increased USGS match amount is documented in the other funds section below.

We also request an amendment to the wording for outcome 5 for activity two. As currently worded, it sounds like all wells from this project will be sealed. However, these wells were a significant investment and so wells will be sealed only where required by the land owner. No budget changes are necessary for this wording clarification. The revised wording is “seal and abandon test wells, if required by landowner, according to state well code.”

Amendment approved by LCCMR 6/3/2020

Overall Project Outcomes and Results:

Confined (or buried) aquifers of glacial origin overlain by till confining units provide drinking water to hundreds of thousands of Minnesota residents. The sustainability of these groundwater resources is not well understood because hydraulic properties of till that control vertical groundwater fluxes (leakage) to underlying aquifers are largely unknown. The U.S. Geological Survey, Iowa State University, Minnesota Geological Survey and Minnesota Department of Health investigated hydraulic properties and groundwater flow through till confining units using field studies and heuristic MODFLOW simulations. Till confining units in each of four major geologic deposits were characterized (location in parentheses): the Des Moines lobe (Litchfield), Superior lobe (Cromwell), Wadena lobe (Hydrogeology field camp [HFC] near Akeley), and Pre-Illinoian deposits (Olivia). Hydraulic and geochemical field data were collected from sediment cores and a series of five piezometer nests. Each nest consisted of five to eight piezometers screened at short vertical intervals in hydrostratigraphic units including (if present) surficial aquifers, till confining units, confined/buried aquifers, and underlying bedrock.

Till thicknesses varied from 60 to 166 feet, and till textures ranged from a sandy loam (HFC site) to a silt loam/clay loam (Olivia site). The Cromwell, HFC, and Litchfield 1 sites were examples of “leaky” tills with high vertical hydraulic conductivity (Kv, 0.001 to 1.1 feet per day [ft/d]) and extensive vertical hydraulic connectivity between the confined aquifer and the overlying till. Estimated groundwater travel times through till at these sites ranged from 1 to 81 years, and two of these sites had tritium throughout their till profiles. The tills at the other two sites, Olivia and Litchfield 2, were effective confining units that had low Kv (0.001 to 0.0005 ft/d). Estimated groundwater travel times through the tills at these sites ranged from 165 to nearly 1,800 years, and tritium was only detected in the upper one-third of these till profiles. A conceptual understanding that emerges from the vertical till profiles is that they are not homogeneous hydrostratigraphic units with uniform properties; rather, each vertical sequence is a heterogeneous mixture of glacial sediment with differing abilities to transmit water.

The heuristic MODFLOW modeling demonstrated that, for understanding sustainability of groundwater pumping from confined aquifers, knowledge of till hydraulic properties is just as important as knowledge of aquifer hydraulic properties. Over long periods of time (hundreds of years), pumping-induced hydraulic gradients are established in confined aquifer systems and, even in low hydraulic conductivity tills, these pumping-induced hydraulic gradients increase leakage into and through till compared to ambient conditions.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1:

Select sites for detailed study which represent the primary glacial confining units in the state. Construct scientific boreholes and hydraulic testing.

Description: Two additional field study sites will be selected for detailed hydrologic investigation. The sites will be located in two of three possible principal glacial confining units: the Des Moines lobe glacial till, the Superior lobe glacial till, or the Wadena lobe glacial till. Study sites will be identified and selected in consultation with staff from the MDH, MDNR, and the MGS. Study sites will be located near municipal water-supply wells that pump from confined glacial-drift aquifers where well-head protection plans have been approved by the MDH, or other sites that have pumping systems installed in confined aquifers where the hydrogeology is well-characterized. At both study sites small-diameter observation well clusters, or piezometers, will be installed in the confined-drift aquifer, the confining unit overlying the confined aquifer, and in the surficial unconfined-drift aquifer. Two well- nest installations will be located at each of the two study sites. One well cluster at each study site will be located in proximity to the pumping wells. The second well-cluster at each study site will be located at some distance from the pumping wells. The exact locations of the well nests will be determined after the study sites are selected. Well nest placement will be based on local site and access conditions and on results of preliminary groundwater modeling simulation of local groundwater pumping and hydrologic settings. Observation wells (completed in aquifers) and piezometers (completed in confining units) will be planned and sited during the first six months of the study. Wells and piezometers will be installed in the summer of 2017. Observation wells and piezometers will be installed in scientific boreholes after geophysical testing of the boreholes is completed. Pressure transducers will be installed in observation wells and piezometers to continuously measure water levels and hydraulic head over the duration of the study. Water levels and hydraulic heads will be measured in wells and in piezometers for the duration of the study. In a subset of the wells, water levels and hydraulic heads will be continuously monitored and archived in the USGS data base. Identification of well sites and piezometer-nest locations will involve a considerable amount of time and effort to ensure that the sites represent conditions typical for the primary confining units of the state. Much of the cost for this activity is for contact drilling. The MGS contract, for both activities, will be completed for $20,000. This includes assistance for site selection, field logging, core descriptions, borehole geophysics, textural and stratigraphic analysis, archiving of drilling cores, and preparation of a summary report.

Summary Budget Information for Activity 1:	ENRTF Budget:	$241,808
	Amount Spent:	$241,808
	Balance:	$ 0

Activity Completion Date: September 2017

Outcome	Completion Date
1. Identify 2 study sites in different principal glacial confining units. At each study site, locate positions for 2 well nests near existing pumping wells. Sites will be selected based on input from the MGS, MDNR and MDH. Selection will be from municipal wells with well-head protection plans in place, or other sites that have pumping systems installed in confined aquifers where the hydrogeology is well-characterized. and based on evaluation of local geological conditions.	October 2016
2. Obtain site access and site-use permission. Obtain drilling permits and well variances if needed. Meet with city officials. Travel and reconnaissance of potential sites.	December 2016
3. Install boreholes and instrument sites for hydraulic, geophysical and chemical tests to define hydraulic properties of confining units. Install 4 to 6 observation wells or piezometers per nest (totaling 16 – 24 wells) using a contract driller. Conduct geophysical surveys of boreholes. Install pressure transducers and water level recording equipment at least 12 wells. Measure, record and archive water levels in USGS databases. Much of the cost for this activity is contract drilling. Field logging, core descriptions, borehole geophysics, textural and stratigraphic analysis, core archiving, and geologic report preparation will be completed by MGS.	June 2019

Activity Status as of December 30, 2016:

Several administrative tasks were completed to get the project moving. A detailed project work plan and budget were prepared and approved by the LCCMR. A USGS technical project proposal was prepared, reviewed and approved. A purchase agreement for geologic analysis from the Minnesota Geological Survey was prepared. A purchase agreement for drilling services from a private drilling contractor including rotary sonic core collection, monitoring well installation, and well and borehole sealing was prepared. A Joint Funding Agreement was prepared, reviewed, and signed by USGS Headquarters and by the Minnesota Department of Natural Resources.

Several meetings between the USGS, and staff from Minnesota Departments of Health and Natural Resources, and the Minnesota Geological Survey were held to discuss potential study sites. Available hydrologic and hydrogeologic data sets were acquired and organized and compiled to identify potential study sites. The project team selected one study site on Wadena Lobe deposits in Hubbard County, near Akeley, Minnesota at the University of Minnesota's Hydrocamp facility. This site was chosen because it represents a major surficial geologic deposit in the State, the site has abundant data that will support the objectives of this project, and there is little to no pumping interference from high capacity wells in proximity to the site. The second site has not been selected yet, but several candidate sites have been identified in the following counties containing Des Moines Lobe till deposits: Yellow Medicine, Redwood, Renville, Nicollet, McLeod, and Carver County. The candidate sites had wells that met the following minimum criteria:

- the well is a municipal/public supply well,
- the well is located in a county that has a completed County Atlas with a sand distribution model from the Minnesota Geological Survey
- the well is owned by a city with a wellhead protection plan,
- the well depth is less than 300 feet and in a quaternary buried artesian aquifer (QBAA), and
- the stratigraphy log lists a clay layer.

Further site specific criteria, such as potential interferences from other high-capacity wells in the same aquifer, connections to surficial aquifers, willingness of the well owner to partner in the project, and accessibility for drilling are being evaluated for each candidate site now. Where possible, detailed data from the Minnesota Department of Natural Resources hydrogeologic atlas part B program are being evaluated.

Activity Status as of June 30, 2017:

A contract for technical assistance from the Minnesota Geological Survey was awarded. The decision to contract out the drilling to a local drilling company experienced in glacial drift material was decided upon because of the complicated geology, and a contract for test drilling and well installation was awarded to Trout Wells, Inc.

Meetings with city officials in Olivia, Renville, and Sacred Heart in Renville County occurred to determine which would be the best candidate for the second site location. Due to the geologic conditions, potential well nest location, and the ability to work with the city it was decided that the City of Olivia was the best candidate. Team members attended a city council meeting and obtained permission to install a nest of monitoring wells on city property.

A well variance was submitted and approved by the Minnesota Department of Health in April to allow for the use of 1.25-inch diameter wells at the University of Minnesota's Hydrocamp site. Smaller diameter wells are necessary to obtain hydraulic data in a timely and efficient manner from the monitoring wells installed in the glacial confining unit. A second variance was submitted to the MDH in min-June for the Olivia wells and we are awaiting approval.

Well installations and coring at the Hydrocamp site were completed by Traut Wells, Inc. Four small diameter wells were installed in a glacial drift confining unit that overlies a confined aquifer. A well was not installed in the sand and gravel aquifer at this site because there is already one installed in the area as part of the University of Minnesota's Hydrocamp. Data from Hydrocamp wells will be used to supplement the USGS data at this site. The four wells installed were fully developed in early June.

Activity Status as of December 29, 2017:

Activity one is nearly complete. A total of 13 new wells in 2 well nests have been installed. Remaining tasks to be completed include ongoing measurements of water levels in wells and completion of the geologic report by the Minnesota Geological Survey. The data required for the geologic report have been collected, but the report is still being written. Eight new observation wells (6 in till, 1 in a surficial aquifer and 1 in a buried aquifer) were installed near a municipal water supply in Olivia, Minnesota. A continuous core sample from land surface to 230 feet below land surface was collected prior to well installation to guide well screen placements. This core was logged and archived by the Minnesota Geological Survey. Six wells at the Hydrocamp site and eight wells at the Olivia site have been instrumented with pressure transducers that continuously record water levels. Water level data are available through the USGS National Water Information System (NWIS) at https://maps.waterdata.usgs.gov/mapper/index.html. Pore-water samples and groundwater samples from both sites have been analyzed for oxygen and deuterium isotope ratios. Pore-water samples from squeezed core samples have a low chance of being affected by drilling fluids, whereas groundwater collected from wells installed in till could have been affected by the drilling process. For the isotope data generated so far, the pore-water samples agree well with groundwater samples. This indicates that the groundwater samples from wells are indicative of environmental conditions and rather than interference from drilling fluids. Additional comparisons will be made as more chemistry data sets become available. Groundwater samples have been collected from all wells at the two sites and lab analytical results are being provided to the project team as sample analyses are completed.

Activity Status as of June 29, 2018:

Activity one is complete, with the exception that continuous water level data is still being collected by the transducers installed in the piezometers. This data is available through the USGS National Water Information

System (NWIS) at https://maps.waterdata.usgs.gov/mapper/index.html. The continuous core at both study sites has been analyzed by the Minnesota Geological Survey, and a draft of the core description report has been written. A final report is in revision. All geochemical data including stable isotopes of oxygen and hydrogen, tritium, major ions, and nutrients, have been analyzed by the laboratories involved, and the data has been released to project partners. Though the oxygen and deuterium stable isotope data from the pore water and groundwater samples are similar and agree well, chloride and nitrate concentrations are higher in pore water compared to groundwater at both sites. A tritium peak is present at Hydrocamp close to the top of the till unit, but not present at Olivia. Summaries of the geochemical data have been prepared by Anna Maher, an Iowa State graduate student, in consultation with Dr. Bill Simpkins and presented at several professional meetings. These data will be the subject of her master's thesis. A data release is being prepared.

Activity Status as of December 31, 2018:

Data collection is complete and all transducers have been removed from wells. All water-level data are available through the USGS National Water Information System (NWIS) at https://maps.waterdata.usgs.gov/mapper/index.html. Geochemical data sets have been compiled into a common format in preparation for a data release.

Activity Status as of June 30, 2019:

No activity during this reporting period.

Activity Status as of December 31, 2019:

No activity during this reporting period.

Final Report Summary:

NOTE: this final summary includes results from phase 1 and phase 2 of the study. The field activities and data collection at the Olivia and Hydrogeology Field Camp (HFC) sites were funded with this project. The field activities and data collection at the Litchfield and Cromwell sites were funded with phase 1 (Protection of State's Confined Drinking Water Aquifers M.L. 2014, Chp. 226, Sec. 2, Subd. 03h).

NOTE: the following text is from a draft of a USGS Scientific Investigations Report (SIR) that is now published. The information in the USGS SIR supersedes the information in this report.

USGS Scientific Investigations Report:

Trost, J.J., Maher, A., Simpkins, W.W., Witt, A.N., Stark, J.R., Blum, J., and Berg, A.M., 2020, Hydrogeology and groundwater geochemistry of till confining units and confined aquifers in glacial deposits near Litchfield, Cromwell, Akeley, and Olivia, Minnesota, 2014–18: U.S. Geological Survey Scientific Investigations Report 2020–5127, 80 p.,https://doi.org/10.3133/sir20205127.

The information within this report has been finalized but remains subject to revision. It is being provided to meet the need for timely best science. The information is provided on the condition that neither the U.S. Geological Survey nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of this information. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Abbreviations used in this report

Abbreviation	Description
Br	Bromide
CO_3	Carbonate
Cl	Chloride

Abbreviation	Description
DO	Dissolved oxygen
F	Fluoride
Fe	Iron
ft	feet
ft/d	Feet per day
gpm	Gallons per minute
^3H	Tritium
HCO_3	Bicarbonate
K	Hydraulic conductivity or potassium
Kh	Horizontal hydraulic conductivity
Kv	Vertical hydraulic conductivity
m	meter
Mg	Magnesium
MGY	Million gallons per year
MGS	Minnesota Geological Survey
mg/L	Milligrams per liter
mi	Mile
Mn	Manganese
Na	Sodium
NH_3	Ammonia
NO_2	Nitrite
NO_3	Nitrate
N_2	Nitrogen gas
P	Phosphorus
PO_4	Phosphate
SO_4	Sulfate
TU	Tritium units
$\delta^{18}O$	Delta O-18, a measure of the ratio of stable isotopes oxygen-18 and oxygen-16
$\delta^{2}H$	Delta H-2, a measure of the ratio of stable isotopes hydrogen-2 and hydrogen-1

Introduction

Confined aquifers of glacial origin overlain by till confining units provide drinking water to thousands of Minnesota residents. These till confining units are typically conceptualized as having very low potential for transmitting water, thus the confined aquifers below may be prone to unsustainable groundwater withdrawals. Quantification of the recharge (leakage) rate through till is essential to understanding the long-term sustainability of groundwater pumping from confined aquifers. Although the well yields of these confined aquifers are sufficient for some Minnesota communities, long-term sustainability issues can arise because of the small size of the aquifer or low groundwater recharge rates. Strain on the water supply can be the result of the water demand exceeding the recharge rate to the aquifer, or from reduction of the recharge rate to the aquifer due to climate (Delin, 1986; Lindgren, 1996; Lindgren, 2002).

Buried aquifers can be confined or unconfined and the field components of this study focused solely on confined aquifers. Groundwater in confined aquifers is isolated from the atmosphere at the point of discharge by poorly conductive geologic formations (for example, overlying till confining units) and the confined aquifer is subject to pressures higher than atmospheric pressure. This means that when a well is drilled through an overlying confining unit into a confined aquifer, water rises in the well to some level above the top of the aquifer. The water level in the well represents the confining pressure at the top of the aquifer (Driscoll, 1986). On the other hand, buried, unconfined aquifers do not have a confining pressure. When a well is installed in a buried unconfined aquifer, the water level in the well will be below the top of the aquifer.

Confined aquifers may be protected from anthropogenic contamination by a confining unit overlying them, but properties such as the hydraulic conductivity (K) and the thickness of the confining unit, the presence or absence of fracture flow, and the confining unit geochemical environment may either impede the flow of contaminants or allow the flow of contaminants through a confining unit to an underlying aquifer (Bradbury and others, 2006). Investigations concerning confining unit properties are less abundant compared to investigations on aquifer properties (Cherry and others, 2004). Field studies of hydrogeology and/or geochemistry of till confining units have been completed in Alberta, Saskatchewan, Manitoba, Wisconsin, Iowa, and Minnesota (Grisak and Cherry, 1975; Fortin and others, 1991; Simpkins and Bradbury, 1992; Simpkins and Parkin, 1993; Witt, 2017). These studies have found a wide range of hydraulic properties and geochemical environments in confining units. For instance, K in studied till confining units has been estimated to be as low as 6×10^{-6} feet per day (ft/d) (Simpkins and Parkin, 1993) and as high as 2×10^{-1} ft/d (Witt, 2017). Properties may also vary spatially throughout a till confining unit as well, with the presence of features such as sand lenses, erosional surfaces, joints, and fractures being locally significant to the flux of groundwater in the till (Gerber and Howard, 2000).

Purpose and Scope

The primary objective of this report is to present the results of field studies and modeling approaches designed to quantify the variability of hydrologic properties and fluxes through till confining units to confined aquifers at four representative sites in Minnesota. The results of this study give insight to the and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota.

Description of study sites

Four field sites were selected for inclusion in this study. Field sites were representative of deposits from major glacial lobe extents in Minnesota. Sites were in three late Wisconsin deposits: the Des Moines Lobe, the Superior Lobe, and the Wadena Lobe, as well as one pre-Illinoian deposit underlying the Des Moines Lobe (fig. 1; Hobbs and Goebel, 1982). Candidate field sites were required to have: (1) a small number (less than 5) of high-capacity pumping wells withdrawing water from a Quaternary buried artesian (confined) aquifer, as classified by the Minnesota Geological Survey; (2) a confined aquifer within 300 feet of land surface; (3) a completed wellhead protection plan (or comparable form of local site hydrogeological characterization); (4) a completed county geologic atlas (or comparable detailed geological data compilation); and (5) information on the integrity of the high-capacity well construction. Sites meeting these minimum criteria were identified and then municipalities or land-owners were contacted to gage their willingness in partnering with the USGS in the study.

The Litchfield and Olivia study sites are located within the footprint of the Des Moines Lobe in central Minnesota. The city of Litchfield, where the Litchfield site is located, has a population of 6,726 and is located in central Minnesota (Meeker County) (U.S. Census Bureau, 2010). The population of Litchfield relies on four municipal wells that pump approximately 340 million gallons per year (MGY) (Haglund and Robertson, 2000). The Litchfield site, has two piezometer nests installed for this study, referred to as the Litchfield 1 (LFO1) site and the Litchfield 2 (LFO2) site.

The town of Olivia, where the Olivia site is located, has a population of 2,484 and is located thirty-five miles southwest of Litchfield (Renville County) (U.S. Census Bureau, 2010). The population of Olivia draws their water supply from two confined aquifers. The water use in the town of Olivia, from the confined aquifer in this study, is around 64 MGY (Robertson, 2011). The Olivia site has one piezometer nest installed for this study. Both the Litchfield and Olivia towns draw municipal water from glacigenic confined aquifers of limited areal extent. The physical setting at both sites consists of low-relief ground moraine typical of the Des Moines lobe. Row crop agriculture is the dominant land use in the region. The land area surrounding both sites usually receives about 27-29 inches of precipitation annually (Minnesota Department of Natural Resources, 2020).

The town of Cromwell has a population of 231 and is in the footprint of the Superior Lobe in Carlton County, Minnesota (fig. 1) (U.S. Census Bureau, 2010). The population of Cromwell relies on two municipal wells pumping approximately 6 MGY from a glacigenic confined aquifer (Walsh, 2012). The Cromwell field site has two piezometer nests installed for this study, referred to as the Cromwell 1 (CWO1) site and the Cromwell 2 (CWO2) site. However, in this study the two nests, which are about 160 feet apart, are discussed as one nest referred to as the CWO1/O2 site. The CWO1/O2 site is situated on a topographic high of hummocky topography consisting primarily of sand and gravel. Land cover consists of moderately forested woodlands and some agriculture. The annual precipitation around the town of Cromwell is about 29-31 inches (Minnesota Department of Natural Resources, 2020).

The Hydrogeology Field Camp (HFC) site is located within the footprint of the Wadena lobe on the far eastern edge of Hubbard County, and is not located in a town (fig. 1). The town of Akeley, Minnesota is located to the northwest of the field site. There are over 60 observation wells at this location that are operated as part of the University of Minnesota's Hydrogeology Field Camp. The HFC site has one piezometer nest installed for this study. The area is highly wooded, and numerous lakes are present near the site. The annual precipitation in the area surrounding the HFC site is about 26 to 28 inches (Minnesota Department of Natural Resources, 2020).

Geologic setting

The following is a summary of detailed geologic reports produced during this study (Wagner and Tipping, 2016; Staley and Nguyen, 2018; Staley and others, 2018) and the glacial history of the sites. Generalized lithologies are presented in the completion diagram figures ((2, 3, 4, 5, 6, and 7). The depths and thicknesses shown in the generalized lithologies in these figures are simplified compared to the very detailed stratigraphy presented in the geologic reports (Wagner and Tipping, 2016; Staley and Nguyen, 2018; Staley and others, 2018).

Litchfield

At the Litchfield site, till of the Villard Member of the New Ulm Formation overlies the confined aquifer (Wagner and Tipping, 2016). The glaciofluvial deposit that comprises the confined aquifer is most likely outwash of the Hewitt Formation (Wagner and Tipping, 2016). The Villard Member till was deposited by glacial ice (and its meltwater) that moved into Minnesota from the Winnipeg provenance to the north, eventually depositing the Pine City moraine (Johnson and others, 2016). The till age is not exactly known, but is estimated as about 12,300 carbon-14 years before present (14C yr BP) (about 14,450 calendar years before present (cal yr BP)) (Clayton and Moran, 1982; Johnson and others, 2016). More recent publications suggest that the formation of the Pine City moraine is older, about 13,000 14C yr BP (about 16,000 cal yr BP) (Jennings and others, 2013; Johnson and others, 2016). The lobe eventually advanced as far south as Des Moines, Iowa by 14,000 (14 kA) 14C yr BP.

The mean particle-size distribution of the till for the Litchfield site, determined by the Minnesota Geological Survey (MGS) from two continuous till cores from both the LFO1 and LFO2 sites, sampled at approximately four-foot intervals, is 49 percent sand, 33 percent silt and 18 percent clay (Wagner and Tipping, 2016). This distribution is very similar to the equivalent Alden Member till of the Dows Formation near Ames, Iowa (Helmke and others, 2005b). Particle-size distribution of the LFO1 and LFO2 till cores, from the MGS report by Staley and others (2018), was used to calculate separate mean particles-size distributions for the LFO1 and LFO2 sites. At LFO1, the mean particle-size is 47 percent sand, 34 percent silt, and 19 percent clay; and at the LFO2 site the mean particle-size is 52 percent sand, 31 percent silt, and 17 percent clay (Figure 8).

Sediment of the New Ulm Formation is yellow-brown and oxidized in the upper 15 ft, and grey brown and unoxidized below this depth. Carbonate clasts and a calcareous matrix are present throughout, except in the top 3 ft of the LFO1 core. Fractures were described in the LFO1 and LFO2 cores to depths of approximately 60 and 90 ft, respectively. Most fractures lacked iron staining common to fracture surfaces in the equivalent till in Iowa (Helmke and others, 2005b). Some fractures may be artifacts of the coring process and subsequent unloading; However, McKay and Federicia (1995) found that till fractures can occur below depths where oxidation staining occurs.

Sediment sequences differ between the LFO1 (figure 2) and LFO2 (figure 3) sites. At the LFO1 site, fine-grained, sandy and silty deltaic and glaciolacustrine sediment with some gravel occurs above the till. Wagner and Tipping

(2016) interpreted this as a deltaic deposit resulting from a series of meltwater plumes into Glacial Lake Litchfield (Meyer, 2015). The sand and gravel unit is not found at the LFO2 site, which lies at approximately 25 ft higher in elevation than the LFO1 site (Wagner and Tipping, 2016). The confined sand and gravel aquifer unit begins at approximately 98 and 117 ft below land surface at the LFO1 site and the LFO2 site, respectively. Till thickness varies between the two piezometer nests. At the LFO1 site the till is approximately 60 ft thick, and at the LFO2 site, the till is approximately 115 ft thick. The aquifer is approximately 44 ft thick at the LFO2 site, based on borehole geophysical logs and the generalized borehole lithostratigraphy (Wagner and Tipping, 2016). Cores at the two sites that were collected for MGS analysis did not include the confined aquifer sediments and did not analyze the thickness of the confined aquifer (Wagner and Tipping, 2016; Staley and others, 2018). The confined aquifer at the Litchfield sites may be underlain by pre-Wisconsin till of the Sauk Centre Member of the Lake Henry Formation (Meyer, 2015).

Cromwell

The stratigraphic sequence at the Cromwell site (figs. 4 and 5) is more complicated than that at the Litchfield site. The Superior lobe advanced and retreated from the Lake Superior basin multiple times during the late Wisconsin glacial episode. As the climate warmed, the extent of those advances into Minnesota became successively smaller. The Cromwell Formation, which consists of till, glaciofluvial, and glaciolacustrine sediment of Superior provenance, is the primary glacial lithostratigraphic unit present at the Cromwell site and in northeastern Minnesota. The exact age of the unit at Cromwell is not well constrained (Johnson and others, 2016). The St. Croix phase of the Superior Lobe advanced ice over the Cromwell site in west-central and south-central Minnesota between 15 and 20 kA 14C yr BP. The Superior lobe advanced over the Cromwell site later during the Automba phase between 13.5 and 14 kA 14C yr BP (Jennings and Johnson, 2011). It was during ice retreat at the end of the Automba phase that the Cromwell Formation till was likely deposited on top of Cromwell Formation sand and gravel the confined aquifer at the site. After the retreat of the Superior lobe, the St. Louis sublobe advanced over the Cromwell site from the northwest at approximately 12.5 kA 14C yr BP (about 15,000 cal yr BP) (Jennings and others, 2013) and deposited the Aitkin Member of the Cromwell Formation.

Core was not retrieved from the CWO1 site (figure 4), and the MGS reconstructed the geology through analysis of downhole gamma ray logs. Core samples were collected at the CWO2 site (figure 5); however, the high frequency of clasts greater than 2 inches in diameter interfered with the coring process and resulted in the collection of fewer core samples than expected. Two glacigenic units were identified at the Cromwell site. Starting at land surface, 4 ft of silt loam till of the Alborn Member of the Aitkin Formation overlies 40 ft of sand and gravel outwash of the Cromwell Formation deposited during the Automba Phase of the Superior Lobe. The Alborn Member is likely responsible for the hummocky topography at the site. Below the sand and gravel deposits lies about 126 ft of sandy loam to loam till with cross-stratified, fine to very coarse sand and gravel layers, also likely deposited during the Automba Phase. The confined aquifer below these deposits are a sand and gravel unit within the Cromwell Formation, underlain by Paleoproterozoic slate of the Thomson Formation (Boerboom, 2009).

Sediment of both the Cromwell Formation and the Aitkin Formation were typically reddish-brown, and a calcareous matrix was present in the core below 43.5 ft. The Cromwell Formation till had a mean particle-size distribution of 57 percent sand, 31 percent silt, and 13 percent clay (fig. 8), which is about 8 percent more sand than the New Ulm till. The Aitkin Formation till was not analyzed for particle-size distribution.

Hydrogeology Field Camp

The HFC site (figure 7) has glacial sediment deposits of the Wadena Lobe. Glacial ice brought northeast sourced sediments from the Rainy provenance, and deposited the Hewitt Formation till, outwash, and lake sediments (Johnson and others, 2016). Two depositional events known as the Alexandria and Itasca phases have been identified. The Alexandria phase represents the first ice advance and the Itasca phase is associated with a later, second ice advance (Knaeble and Hougardy, 2018). Deposits of both phases are assigned to the Hewitt Formation, which has an estimated age of about 30,000 14C yr BP. This age suggests that the Wadena lobe was actively depositing sediments in the early part of late Wisconsin time (Johnson and others, 2016).

The till at the HFC site underlies a 105-foot-thick coarse-grained sand and gravel outwash deposit of the Hewitt Formation. The Hewitt Formation till is a sandy loam, with a mean particle size of about 67 percent sand, 22 percent silt, and 11 percent clay (fig. 8; Staley and Nguyen, 2018). The till is brown in color, lacks shale clasts, but has moderate carbonate clasts of around 10-25 percent (Staley and Nguyen, 2018). The thickness of the till unit is about 102 feet. The entirety of the Hewitt Formation till is considered one unit (Staley and Nguyen, 2018).

Below the Hewitt Formation till to a depth of 250 feet is Pre-Wisconsin Browerville Formation lake sediments, outwash, and glacial till (Staley and Nguyen, 2018). The confined aquifer below the Hewitt Formation is composed of Browerville Formation fine-grained sand and gravel glaciolacustrine (glacial lake) sediments and outwash sediments and is about 23 feet in thickness (Staley and Nguyen, 2018). Immediately below the confined aquifer is till of the Browerville Formation, which starts at a depth of 230 feet below land surface and has a thickness of about 20 feet (Staley and Nguyen, 2018).

Olivia

At the Olivia site (figure 6), late Wisconsin New Ulm Formation till of the Des Moines Lobe was expected to be present because thick sequences of New Ulm Formation till have been mapped around the Olivia area (Staley and Nguyen, 2018; Knaeble, 2013; Bradt, 2017). During the Pleistocene, several glacial advances and retreats occurred in the study site area, with the most recent till deposition being the New Ulm Formation from the Des Moines Lobe (Knaeble, 2013). The age range for Des Moines lobe glaciation in Minnesota is 16 kA to 12 kA calendar years ago (Knaeble, 2006). However, the entire till sequence at Olivia is interpreted to be of the Good Thunder Formation, an informally named pre-Wisconsin till (Staley and Nguyen, 2018). Radiocarbon-dated wood deposits from the Good Thunder Formation estimate its age as greater than 48,500 14C yr BP (Knaeble, 2013).

The Good Thunder Formation till present at Olivia is typically grey in color, with a loam to silty- and clayey- loam texture and a mean particle size of around 37 percent for sand, 40 percent for silt, and 23 percent for clay (fig. 8). The till is high in carbonates (usually greater than 50 percent), low in gray shale percentage (between 0-10 percent), and Cretaceous grains are present (between 1-10 percent) (Staley and Nguyen, 2018). Four possible members of the Good Thunder Formation are present at Olivia, based on Cretaceous percentage and density changes through the till formation (Staley and Nguyen, 2018). The overall thickness of the Good Thunder Formation till at Olivia is about 166 feet. Sand bodies are also often present in the formation, stratigraphically dividing the different members (Staley and Nguyen, 2018).

Above the Good Thunder Formation is a thin layer of Holocene sediment that is about 10 feet in thickness, which is topped by about 4 feet of fill (Staley and Nguyen, 2018). Below the Good Thunder Formation is a silt and fine- to coarse-grained sand aquifer, likely a glaciofluvial outwash deposit of uncertain origin (Staley and Nguyen, 2018). The confined aquifer is about 48 feet thick. Underneath the aquifer at a depth of 229.5 feet below land surface lies Cretaceous shale bedrock (Staley and Nguyen, 2018).

Methods of study

Field study design and piezometer installation

Piezometer “nests” were installed at each site to assess the vertical flux of water and transport of chemicals from land surface to the underlying confined aquifer system. A piezometer nest is a series of piezometers installed adjacent to one another and screened at separate short intervals below land surface. The nest design enables vertically discrete observations throughout the geologic profile from near land surface through the till into the confined aquifer. The nest design has been commonly used to investigate hydrologic properties of tills (for example, Shaw and Hendry, 1998; Simpkins and Parkin, 1993). Small diameter (approximately 1.25 inch) piezometers were installed in the confining units in order to reduce the volume of water required for observable water level fluctuations in geologic materials with low hydraulic conductivity. Piezometers (or wells) with a 2-inch diameter were installed in the confined aquifers.

At the Litchfield and Cromwell sites, two nests were installed at each site, one of which was near a municipal pumping center and one which was farther from a municipal pumping center. After the initial installation, the two Cromwell nests (the CWO1 and CWO2 sites) were considered together as a single nest (CWO1/O2) and are mostly presented as such throughout this report. The near and far nest design was intended to facilitate aquifer test analyses. At the Olivia and HFC sites, only one piezometer nest was installed near a pumping center.

A total of 19 piezometers were installed in 2015 at the Litchfield and Cromwell sites for this study (table 1). The LFO1 site consisted of five piezometers and was located approximately 1,500 feet from the nearest municipal pumping well (figs. 1 and 2). The LFO2 site consisted of six piezometers and was located within the city municipal well field and was approximately 500 feet from the nearest municipal well (figs. 1 and 3). Five pumping wells are nearby the LFO1 and LFO2 sites (fig. 1). The CWO1 site consisted of three piezometers and was located approximately 150 feet from the nearest municipal pumping well (figs. 1 and 4). The CWO2 site consisted of five piezometers and was located approximately 160 feet from CWO1 and 50 feet from the nearest municipal pumping well (figs. 1 and 5). Two pumping wells are nearby the CWO1 and CWO2 sites. The CWO1 and CWO2 sites contain piezometers that are sequential in depth and are within 160 feet (ft) of each other.

A total of 12 piezometers were installed in 2017 at the Olivia and HFC sites for this study (table 1). At the Olivia site, eight piezometers were installed approximately 60 feet from the nearest municipal pumping well (figs. 1 and 6; table 1). Two other municipal pumping wells are located near the site, one about 1,000 feet from the piezometer nest and the other about 4,000 feet from the piezometer nest. At the HFC site, four piezometers were installed approximately 50 feet from the nearest pumping well (figs. 1 and 7). The HFC site also includes several wells previously installed by the University of Minnesota, including two in the surficial aquifer and five in the confined aquifer (table 1).

Drilling operations for sediment core collection and piezometer installation varied across the four sites. The following is a general description and detailed drilling and piezometer construction information is provided in Appendix table 1.1. A hollow-stem auger rig was used for sediment core collection and installation at the LFO1, LFO2, and CWO2 sites. Hollow stem methods are commonly used for till investigations because sediment core samples can be collected during drilling, and drilling fluids, which could contaminant the till formation, are not required (Shaw and Hendry, 1998; Simpkins and Bradbury, 1992). Sediment core samples were collected into acetate liners with a cutter head and split core barrel assembly. Rocks in the till impeded the installation of piezometers at the CWO1 site, so a direct mud rotary rig was used to install the three piezometers (CWO1-A, CWO1-B, and CWO1-C). Sample cuttings were taken from the drilling mud at the CWO1 site (Witt, 2017).

Rotary-sonic drilling methods were used for core collection and piezometer installations at the Olivia and HFC sites. Rotary-sonic drilling methods enabled continuous core collection and eliminated problems caused by cobbles and boulders in the till, but did require water and drilling fluids. At the Olivia site, untreated water from the municipal supply system was used during drilling operations and at the HFC site, water from the surficial aquifer was used during drilling operations. At each of the Olivia and HFC sites, one continuous sediment core profile extending from land surface to the confined aquifer was collected. Core samples were extruded from the core barrel directly into plastic sleeves (Staley and others, 2018). All installed piezometers were developed with an inertial pump to establish a good connection between the well screen and the surrounding geologic material.

At all sites, the piezometer screened intervals were determined with consideration of the site geology, the vertical distribution of sample points, and the driller's confidence in successful piezometer completion. Lithologic changes and oxidation state were documented from the sediment core samples that were collected during drilling operations. Where lithologic boundaries were encountered, piezometer screens were generally placed directly above the boundary, as recommended by Hart and others (2008). Lithological changes selected for piezometer screen placement were spaced somewhat uniformly within the till units. In some cases, the screened interval was determined by where the drillers were confident that a piezometer completion would be successful.

ACTIVITY 2:

Conduct hydraulic, physical, geophysical and chemical testing of aquifers and confining beds. Analyze data from tests at each of two sites to determine hydraulic and hydrogeological properties of confining beds and aquifers at each of two study locations using computer simulations.

Description: Activity 2 will be conducted during the second and third years of the study. This activity is focused on defining hydraulic and hydrogeological properties of two of the state's most important confining units. The approach is to conduct two detailed field tests-- one in each of two areas that represent a principal confining unit in the state. The field study sites will be located adjacent to existing high-capacity pumping wells to observe how pumping stress affects water movement based on properties of the confining beds. Scientific bore holes are being completed in and through the confining units and aquifers to collect the required data. Field analyses will include hydraulic, geophysical and chemical tests and conceptual groundwater modeling. These tests will include aquifer tests, geophysical logging (e.g. gamma, temperature, and fluid resistivity) and measures of water chemistry.

This activity is focused on testing and analyses of local hydraulic and hydrogeological properties to determine infiltration rates and physical properties of confining units and aquifers. Geophysical, geotechnical, isotopic, chemical and hydraulic testing at each site will be conducted. These properties of the confining beds will include infiltration and leakage rates, grain-size and soil texture, vertical and horizontal hydraulic conductivity, and hydrologic storage. Geologic, geophysical and water chemistry samples are being collected from boreholes and observation wells installed for the study. Hydraulic-head data from piezometers and observation wells completed in aquifers and confining beds will be analyzed based on the hydraulic responses to pumping. Water levels will be measured continuously in some observation wells using pressure transducers and data loggers. Vertical hydraulic conductivity and infiltration rates will be estimated for the confining units based on analytical techniques and on results from hydrologic models at each of the sites, under pumping conditions measured in underlying and overlying aquifers. The rates of infiltration to confined aquifers also will be determined using environmental tracers such as chlorofluorocarbons, sulfur hexafluoride, or tritium by measuring vertical profiles of these environmental tracer concentrations through the confining units. The average rates of infiltration also will be computed based on the vertical gradient of water movement through the confining unit. Test and observations should prove useful in evaluating the effects of till weathering and fracturing. Site-scale groundwater flow models will be used to simulate individual hydraulic tests and to test hypotheses regarding recharge through till. A USGS Scientific Investigations Report. The report will summarize the project, the data collected during the project and the results of the analyses of data collected from the project.

Summary Budget Information for Activity 2:	ENRTF Budget:	$191,192
	Amount Spent:	$191,192
	Balance:	$ 0

Activity Completion Date: September 2019

Outcome	Completion Date
1. Conduct hydraulic, geotechnical, geophysical and isotopic tests at the 2 study sites to determine hydraulic properties of aquifers and confining units. Includes aquifer tests on at least 16 of the monitoring wells and piezometers, groundwater sampling and chemical analyses.	October 2017
2. Analyze and interpret hydraulic test and geochemistry data to define hydraulic properties and infiltration rates at each study site	December 2017

Outcome	Completion Date
3. Conduct conceptual groundwater modeling of pumping responses to further quantify aquifer and confining bed properties.	August 2019
4. Prepare report manuscript and obtain USGS publication approval.	August, 2020
5. seal and abandon test wells, if required by landowner, according to state well code	June, 2020

Activity Status as of December 30, 2016:

No activities to report.

Activity Status as of June 30, 2017:

No activities to report.

Activity Status as of December 29, 2017:

Slug tests (5 or 6 per well) have been completed in all of the newly installed wells at both sites. All of the tests were analyzed using Aqtesolve software to determine the hydraulic conductivity of the geologic materials surrounding the well screens. Tritium samples were collected from each well and we are awaiting lab results from these samples. These data will provide information about when the groundwater was last in contact with the atmosphere. A draft report for phase 1 is prepared and information from phase 2 is being incorporated into the report as new data become available. Task 2 in activity 2 is not yet completed because we are still waiting for geochemical data from labs, this task will be completed by August, 2018.

Activity Status as of June 29, 2018:

A pumping test for Olivia is scheduled for early July, 2018; it will be a cooperative effort between the City of Olivia, USGS, and the MDH. Continuous water level data are being collected by transducers, and estimates of hydraulic conductivity, hydraulic gradient, and travel time through the till units, have been completed. A downward hydraulic gradient was found at both Olivia and the Hydrocamp (HFC) site. A geometric mean hydraulic conductivity, through the till at HFC, is around 5x10^-2 ft/d. At Olivia, the geometric mean hydraulic conductivity through the till unit is around 8x10^-3 ft/d. The estimated vertical travel time from the top of the till to the bottom of the till unit at HFC, is around 30 years, while Olivia is around 125 years. These estimates will be re-evaluated when more vertical hydraulic conductivity data become available from pumping tests and continuous water-level data. The geochemical data is presently being organized and prepared for a data release and more detailed analysis. An interesting observation is that a tritium peak was found at the hydrocamp site near the top of the till unit, which gives an indication of the travel time through the system. A tritium peak was not observed in the piezometers at Olivia.

Activity Status as of December 31, 2018:

Field data collection has been completed for this task. Two aquifer tests were completed during the last reporting period. In July, the piezometers installed as part of this project at the hydrocamp site were again used for an aquifer test. The aquifer test data collection process and data analysis were used to train students who attended the summer hydrogeology field camp. Also in July, an aquifer test was completed at the Olivia field site with cooperation from the city of Olivia and the MN Department of Health. Analysis of this aquifer test is ongoing. There is a strong poroelastic response of the till confining unit to pumping at this site which did not occur at the other three sites. This observation highlights the diversity of till properties in Minnesota. The poroelastic response of the till wells manifests itself as water level increases in the till piezometers during pumping. When the pump turns on at the other three sites (Litchfield, Cromwell, Hydrocamp), water levels decline in the buried aquifer and decline to a lesser degree in the overlying till units. However, when the pump turns on at the Olivia site, water levels decline in the confined aquifer and *increase* in the piezometers completed in the overlying till. Water levels in till increased throughout the entire duration of the aquifer test. This response is documented in the literature, but requires a very different approach to data analysis than the other three sites. As part of this aquifer test, a graduate student and the project manager designed a routine for extracting pumping and water level data from municipal SCADA systems. The engineering firm that installed the SCADA system required at least $11,000 to access digital minute-resolution data. By combining a go-pro camera, tripod, SCADA gui, and R scripts, we were able to extract minute by minute pumping and water level data for the aquifer test at a fraction of the $11,000.

All of the geochemical data have been compiled and organized for phases 1 and 2 in preparation for publication of a ScienceBase data release. Graduate student Anna Maher and project partner Bill Simpkins have analyzed most of the geochemical data. Of particular interest is understanding what the geochemical data indicate about anthropogenic influences at depth in till. Tills are typically perceived as barriers that stop land-surface contaminants from reaching confined aquifers. One indicator of anthropogenic contamination is a chloride to bromide mass ratio (Cl/Br) greater than 250 [*Katz, B.G., S.M. Eberts, and L.J. Kaufman, 2011. Using Cl/Br ratios and other indicators to assess potential impacts on groundwater quality from septic systems: A review and examples from principal aquifers in the United States. J. Hydrol. 397:151-166.]* The Cl/Br mass ratios at Olivia are higher than 250 in three piezometers, OT-20, OT-145, and OT-175. The OT-175 piezometer is completed in till immediately above the confined aquifer. This observation at Olivia could mean that land surface contaminants penetrate much deeper into a tight till than previously thought, or it might mean that the approximate indicators in Katz et al. (2011) are not necessarily applicable to tills. Either way, this observation is changing our understanding of till properties.

Drilling and installing piezometers in till for short-term projects is challenging because water moves slowly and influences from drilling procedures can linger longer than the project period. The geochemical data at one till piezometer at the hydrocamp (HFC) site (HT-140) indicates possible bentonite (drilling fluid) contamination because of the high sodium concentration compared to the other wells at the HFC site. The lessons such as this learned during this project will be useful for future endeavors.

Activity Status as of June 30, 2019:

Final reports are being prepared. A first draft of the data release pertaining to the geochemical results analyzed by non-USGS laboratories, has been completed. A model archive data release has been started. Figures, tables, and text for a final comprehensive report that summarizes phase I and II results is being prepared. The focus of writing so far has been on groundwater and pore water ages, evidence for anthropogenic contamination of groundwater and pore water, and general characterization of groundwater geochemistry at all phase I and II sites. The following three paragraphs summarize the geochemical results of phase II sites.

During this project we collected several data sets that can provide insights about the time it takes groundwater to travel through till to underlying confined aquifers. Hydraulic data (slug tests, aquifer tests, and water levels) indicate it takes about 30 years for water to travel vertically through the sandy till to the confined aquifer at the UMN hydrocamp field site (HFC) and about 125 years for water to travel vertically through the clayey till to the confined aquifer at the Olivia site.

Stable isotope results generally agree with the hydraulic data at both sites. For example, tritium (^3H) is commonly used by MDH to indicate whether water in a confined aquifer is “recent”. If water samples have tritium, that means the water is of “recent age”; it was in the atmosphere after the 1950s (when atomic bombs were tested). If water samples lack tritium, the water is “old” and was last in the atmosphere before the 1950s. Tritium distributions through the tills and confined aquifers generally agree with the travel times estimated with the hydraulic data. At HFC, ^3H is present throughout the till unit while at Olivia, ^3H is absent below 20 feet below land surface.

Two indicators of anthropogenic influence on groundwater are chloride (Cl) concentrations and chloride to bromide (Cl/Br) mass ratios. High Cl (>30 mg/L) and high Cl/Br (>250) indicate probable anthropogenic contamination of groundwater from things like road salt application and water softening. Cl/Br mass ratios are elevated in several of the groundwater samples from deep piezometers at Olivia where ^3H is not present. At first glance, this appears to be a contradiction between the stable isotope data and chloride data. However, groundwater from the till at Olivia has extremely low bromide concentrations and so the high Cl/Br ratio may be a reflection of low bromide rather than elevated chlorides. The chloride and bromide data at each of the sites continues to be evaluated.

Nitrate (NO_3) reduction is happening in the till confining units at both HFC and Olivia, and most groundwater samples have no detectable NO_3. Phosphorus (P) samples at both sites also do not show elevated concentrations.

Analysis of groundwater type is useful for characterizing overall hydrogeochemistry of the sites, as well as hydrochemical facies through the till units. At both sites, bicarbonate dominates the groundwater geochemistry. The two shallowest piezometers at Olivia are calcium bicarbonate type water, and the deeper piezometers are a mix of calcium bicarbonate to sodium bicarbonate type water. This may be evidence of cation exchange through the till unit at Olivia. For HFC, all groundwater samples are calcium bicarbonate type water, except for the piezometer HT-140. HT-140 is either a natural outlier in sodium content or shows signs of sodium-bentonite contamination. There is the possibility that some of the piezometers at the Olivia site that are in the sodium bicarbonate range are also affected by sodium-bentonite contamination.

Activity Status as of December 31, 2019:

In the previous reporting period, we provided an overall written summary of major conclusions from this project. In this status update, we present modifications to those conclusions (where necessary), a few more high-level conclusions, and a discussion about interpreting chloride bromide ratios as evidence for anthropogenic influence on groundwater quality. Many more figures and table will be provided in the final report.

Revisions to previous conclusions:

First, some of our hydraulic property analyses were redone. We made some incorrect assumptions for analyzing the slug test data during the previous reporting period. Therefore, slug test data have been re-analyzed, resulting in estimates of till hydraulic conductivity (K) that are lower than the previous estimates for the HFC and Olivia sites. The new analyses found geometric mean K values of around $4x10^{-3}$ ft/d in the till at Olivia and $2.8x10^{-2}$ ft/d in the till at HFC. The revised till K values suggest longer travel times of groundwater through the till compared to the previous values. “Travel time” means the time it takes a parcel of water to move vertically from the top of the till profile to the bottom of the till and enter the underlying aquifer. With the revised K values, we estimate a travel time at Olivia being around 210 years and for HFC 60 years. A second aquifer test was completed at the HFC site in July 2019. The bulk HFC till K value ($3.1x10^{-3}$ ft/d) derived from this aquifer test indicates a travel time through the till of about 50 years, which agrees well with the revised slug test results (travel time of 60 years).

Additional major conclusions:

This project showed through multiple lines of evidence that groundwater does flow through till to underlying aquifers. Till is not an impermeable boundary that protects confined aquifers indefinitely. First, hydraulic head relationships demonstrated primarily downward flow with some faster than anticipated rates. Second, post-glacial groundwater (water less than 10,000 years old) was found throughout till profiles at all sites. Third, there were clear instances of anthropogenic tracers (chloride) at depth at an urban site (Litchfield). Fourth, interpretive groundwater modeling showed that pumping can increase leakage rates of groundwater through till. Lastly, we observed wide-ranging leakage rates of groundwater through till, even at a single site.

Discussion about interpreting chloride bromide ratios

Two indicators of anthropogenic influence on groundwater are chloride (Cl) concentrations and chloride to bromide (Cl/Br) mass ratios. High Cl (>30 mg/L) and high Cl/Br (>250) indicate probable anthropogenic influence of groundwater quality from things like road salt application and water softening. At the HFC site, there is no evidence of anthropogenic chloride in groundwater (see figure below), but data from the Olivia site is less clear.

Chloride and Cl/Br ratios are clearly elevated at Olivia in the OT-20 piezometer, indicating likely anthropogenic influence in groundwater at 20 feet below land surface. This sample point is still far above the confined aquifer, which is located about 200 feet below land surface. Cl/Br mass ratios are also elevated above a general contamination indicator threshold of 250 in samples from deep piezometers at Olivia screened at 105, 145, and 175 ft below land surface. Does this high Cl/Br ratio indicate anthropogenic influence throughout a 175-ft dense till profile? If so, it challenges our fundamental understanding of groundwater flow through tills and suggests that confined aquifers underlying tills are much more susceptible to chemicals from the surface than previously thought.

How useful is the 250 Cl/Br ratio for identifying the potential for contamination in till groundwater? Chloride use for road de-icing has increased substantially since 1940 in Minnesota. The hydraulic conductivity and tritium data both suggest it would take much longer than 77 years (1940 - 2017) for chloride applied at land surface to reach a depth of 175 ft below land surface. The tritium data show that water that was in the atmosphere in the 1940s is not detectable lower than 60 ft below land surface. If the chloride isn't from anthropogenic sources, is there another possible source? Naturally high chloride can come from geologic sources such as shale, which is present in the Olivia till (usually around 1-10 % in the till).

The chloride and bromide data from the Olivia site continue to be evaluated to try and resolve these questions. Additional sampling and analysis is needed to more completely resolve this issue. Analysis of archived core material would provide information about whether or not the geologic material is the source of chloride. A second round of groundwater sampling at the Olivia site would help us evaluate if the source of chloride may have resulted from drilling operations. However, these activities are beyond the scope of the current project and will not be evaluated unless additional funding is secured.

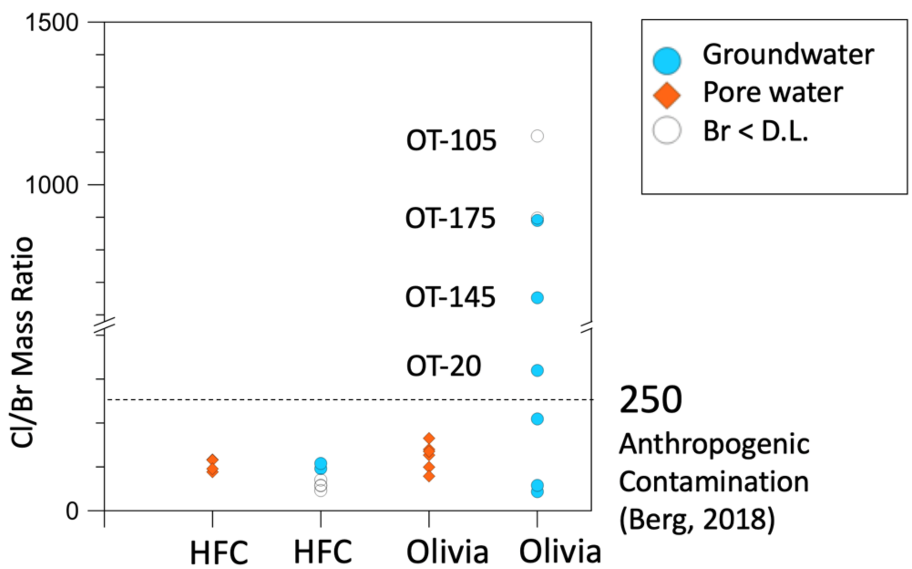

Figure showing chloride to bromide mass ratios (Cl/Br) at the Hydrogeology Field Camp (HFC) site and the Olivia site.

Final Report Summary:

NOTE: this final summary includes results from phase 1 and phase 2 of the study. The field activities and data collection at the Olivia and Hydrogeology Field Camp (HFC) sites were funded with this project. The field activities and data collection at the Litchfield and Cromwell sites were funded with phase 1 (Protection of State's Confined Drinking Water Aquifers M.L. 2014, Chp. 226, Sec. 2, Subd. 03h).

NOTE: the following text is from a draft of a USGS Scientific Investigations Report (SIR) that is now published. The information in the USGS SIR supersedes the information in this report.

USGS Scientific Investigations Report:
Trost, J.J., Maher, A., Simpkins, W.W., Witt, A.N., Stark, J.R., Blum, J., and Berg, A.M., 2020, Hydrogeology and groundwater geochemistry of till confining units and confined aquifers in glacial deposits near Litchfield, Cromwell, Akeley, and Olivia, Minnesota, 2014–18: U.S. Geological Survey Scientific Investigations Report 2020–5127, 80 p.,https://doi.org/10.3133/sir20205127.

Methods of study (continued)

Hydrology

Several techniques were used to assess the hydrologic properties and leakage through till confining units at the four study sites: continuous and discrete water-level monitoring, slug tests, aquifer tests, and calculations according to Darcy's Law to estimate recharge rates and travel times. Different techniques were used to evaluate the scale-dependency of hydrologic measurements. Previous studies have demonstrated that hydraulic conductivity values increase with measurement scale. For example, laboratory measurements of hydraulic conductivity in till are significantly lower than field measurements of the same materials (Bradbury and Muldoon, 1990; Grisak and Cherry, 1975; Grisak and others, 1976).

Continuous and discrete monitoring of water-level responses to pumping and precipitation events can be used to qualitatively assess hydraulic connectivity between aquifers and till confining units (as was done for this study), but they can also be used to quantitatively estimate the vertical hydraulic conductivity (K_v) of till confining units (Cherry and others, 2004). Previous studies have used head variations in confined aquifers and confining units induced by pumping over long-term time periods (years to decades) as evidence for extremely low confining unit K_v values (for example, Husain and others, 1998). Other studies have monitored hydraulic head in surficial aquifers and confining unit material to determine confining unit K_v values (for example, Keller and others, 1989).

Lab tests and slug tests are commonly used to assess the hydraulic properties of till confining units, although these represent relatively small volumes of till. Vertical fractures or stratigraphic windows (higher K openings through low-K material) can be important transport features through till, but the results of laboratory measurements on core samples rarely reflect these features (Cherry and others, 2004). Slug tests, in combination with sediment core samples, can indicate the presence and nature of important transport features, such as fractures or high-permeability zones, in till confining units if the slug tests happen to intersect those features (Cherry and others, 2004). Beyond potential identification of important transport features, slug tests have limited usefulness for determining the vertical K_v of the till matrix because, in vertical holes, the slug response primarily depends on the horizontal component of the hydraulic conductivity (K_h). However, slug tests can indicate the presence of permeable zones, providing valuable insight concerning the internal nature of the confining unit (Cherry and others, 2004).

Aquifer tests designed with the specific purpose of determining till confining unit properties are another, larger-scale approach to estimating the K_v of tills. Aquifer tests measure a much larger volume of till than slug tests and are more likely to capture the effects of features most important for transport through till (Cherry and others, 2004). The piezometers installed as part of this study were used during an aquifer test at each site to measure hydraulic head responses within the till confining unit and the pumped aquifer (Cherry and others, 2004). Several analytical methods, such as Neuman and Witherspoon (1972), exist to determine confining unit properties from properly executed aquifer tests.

Water-level and precipitation monitoring

Water levels in the piezometers and municipal water supply wells were measured at discrete intervals by hand and logged every 15 minutes with pressure transducers in a subset of piezometers. These data were collected to determine how water levels and hydraulic gradients vary through time in surficial aquifers, till confining units, and confined aquifers. Manual water-level measurements were done in piezometers and wells using a Solinst or Keck electric tape or a Lufkin steel tape between July 2015 and April 2017 for the Litchfield and Cromwell sites and intermittently for the Olivia and HFC sites between October 2017 to October 2018. Submersible pressure transducers (OTT Orpheus Mini) recorded water-level and temperature data in 12 piezometers at the Litchfield and Cromwell sites between December 2015 and April 2017 (appendix table 1.1). OTT Orpheus Mini submersible pressure transducers also recorded water-level and temperature data in 14 piezometers and wells at the Olivia and HFC sites between October 2017 to October 2018 (appendix table 1.1).

Precipitation was also monitored continuously (every 15 minutes) with HOBO RG3 tipping bucket rain gages at the LFO2 site and the Cromwell site between December 2015 and April 2017, at the Olivia site between August 2017 to October 2018, and at the HFC site from June 2017 to October 2018.

All discrete and continuous water-level and precipitation data collected throughout this study were reviewed and approved according to various USGS technical policies, which are available at https://water.usgs.gov/admin/memo/GW. These data are available at https://waterdata.usgs.gov/nwis by searching for the USGS site identification numbers listed in table 1. An R script for downloading these data is provided in the data release accompanying this report (Maher and others, 2020).

Slug tests

Rising-head and falling-head slug tests were conducted in each piezometer to estimate hydraulic conductivity (K). Generally, three rising-head and three falling-head were completed for each piezometer, though some piezometers had fewer tests completed because of field conditions or slow recoveries. For each rising or falling head slug test, a solid PVC slug was rapidly added (falling-head test) or removed (rising-head test) from the piezometer and water level measurements were recorded either manually or with a submersible pressure transducer. A Druck PDCR 1800 transducer and Campbell Scientific CR10X datalogger were used to record water levels at most piezometers, except a few piezometers at the Litchfield and Cromwell sites had only manual water-level measurements made with an electric tape. The manual measurements provided sufficient data quality in these piezometers since these piezometers are screened in units with hydraulic conductivities below 32 feet per day (Butler and others, 1996).

Slug tests results were analyzed with the AQTESOLV program (version 4.5; Duffield, 2007) using the most appropriate methods which included: KGS method for unconfined or confined settings (Hyder and others, 1994), Butler method (Butler, 1998), and the Springer-Gelhar method (Springer and Gelhar, 1991). Analytical methods for each slug test were selected on the basis of the hydrostratigraphic placement of the piezometers (unconfined versus confined), piezometer construction (all piezometers are partially penetrating), as well as the water level response to the slug (non-oscillatory versus oscillatory). A discussion of method selection for slug test analyses is provided in Appendix 2, and an example of an Aqtesolv analysis done for OT-20 at the Olivia site is shown in Figure 9. The Maher and others (2020) data release contains all AQTESOLV analyses done for this study.

Aquifer tests

The vertical arrangement of well screens near high-capacity pumping wells provided an opportunity to evaluate the vertical hydraulic conductivity of tills from aquifer test data. Constant rate pumping tests were conducted at all sites to estimate the hydrologic properties of the aquifers and overlying till confining units at the Litchfield, Cromwell, Olivia, and HFC sites (table 2). An aquifer test was completed at the Cromwell site on May 24, 2017 and at the Litchfield site on June 29, 2017. An aquifer test was completed at the Olivia site from July 10, 2018 to July 13, 2018. Two aquifer tests were completed at the HFC site, but only the second test was valid. This test was completed between July 18 and July 22, 2018. Water levels during the aquifer tests were measured with pressure transducers (OTT Orpheus Mini or Solinst) recording data at one-minute intervals. Staff from the Minnesota Department of Health led the aquifer test planning and data analysis. Detailed methods and documentation are available in reports from the Minnesota Department of Health (Blum and Woodside, 2017; Lund and Blum, 2017; Blum, 2019a; Blum, 2019b).

Calculations of groundwater flow through till according to Darcy's Law

Calculations based on Darcy's Law were used to estimate travel times and leakage through till confining units into the confined aquifer (Simpkins and Bradbury, 1992; Hendry and Wassenaar, 1999; Witt, 2017; Maher, 2020). The following equations were used for computations of discharge and travel time through till confining units. According to Darcy's Law, discharge, Q, is calculated as:

$$Q = -KIA \qquad (1)$$

and dividing the discharge by the cross-sectional area, the specific discharge (q) is calculated:

$$q = -KI \qquad (2)$$

and dividing the specific discharge by the effective porosity of the till, an average linear velocity is calculated (V_z):

$$V_z = \frac{q}{n_e} \qquad (3)$$

and finally, dividing the till thickness by the average linear velocity, a travel time through till (T) is calculated:

$$T = \frac{L}{V_z} \qquad (4)$$

where:

Q = discharge (synonyms in this report include leakage through till and recharge to confined aquifer), in length^3 per unit time;

K = hydraulic conductivity, in length per unit time;
I = hydraulic gradient (length/length);
A = cross-section area of flow (length * length);
q = specific discharge (length per unit time);
V_z= average linear velocity (length per unit time);
n_e = effective porosity (unitless);
T = travel time (time); and
L = thickness of the till confining unit (length)

For all sites, an effective porosity of 0.25 was used for travel time calculations, which is within the range of values used in calculations for fluxes of groundwater or solutes through till (McKay and others 1993). Because of large uncertainties in the sizes of the confined aquifers at each site, the calculations were done using a cross-sectional area (A) of 1 square mile. The hydraulic gradient used in the calculation was the mean hydraulic gradient at each piezometer nest, determined by taking the mean of the hydraulic gradients between all till piezometers at a given site. The till thickness (L) was determined from cores at each well nest. Two calculations of travel time, specific discharge, and discharge were done for each piezometer nest: the first calculation was done using the geometric mean of all K values from slug tests and the second calculation was done using the representative Kv value determined from each site's aquifer test. Isotropy between Kh and Kv is assumed for all calculations using the geometric mean K from slug tests.

Groundwater geochemistry

Groundwater samples and pore-water samples were collected to evaluate the vertical distribution of anthropogenic chemicals, groundwater ages, and oxidation-reduction (redox) conditions from land surface through till confining units to the underlying confined aquifer. All groundwater sampling procedures and methods were completed according to the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated).

Groundwater samples for lab analyses were collected after three well volumes were purged and field parameters (dissolved oxygen, pH, specific conductance, and temperature) were stable. Field parameters were measured during the purging process with a YSI 6820 multi-parameter sonde. Samples for stable isotopes of oxygen and hydrogen ($\delta^{18}O$ and $\delta^{2}H$) and tritium (^{3}H) analyses were collected raw, without filtration. Samples collected for cation analysis were filtered through a 0.45-micron filter into a polyethylene bottle, acidified to pH less than 2 with nitric acid, and chilled on ice until analysis. Samples for anion analysis and alkalinity were filtered through a 0.45-micron filter into a polyethylene bottle and chilled on ice until analysis. Samples for nutrients (NH_3, NO_2, NO_3, and P) were filtered through a 0.45-micron filter into a brown polyethylene bottle and chilled on ice until analysis. Alkalinity (mg/L as CaCO3) was determined on filtered samples within 24 hours of sample collection using a Hach Digital Titrator and the inflection point method. Table 3 lists the analyses completed on groundwater samples.

Pore-water samples were extracted from till core samples to evaluate differences in water chemistry between hydraulically conductive flowpaths (groundwater) and water bound within the till matrix (pore-water). Six-inch long subsamples of core samples extracted from boreholes during drilling operations were used for pore-water extraction. These subsamples were collected at or near the screened interval of a piezometer and prepared for storage and analysis in a similar manner to Gerber and Howard (1996). Core subsamples were scraped clean on the outside to remove potential contamination from drilling equipment or fluid. The subsamples were then wrapped in at least two layers of plastic wrap, taped, wrapped in at least two layers of aluminum foil, taped again, labeled, and then bagged. The core subsamples were then sent to the San Diego Geochemistry Lab at the USGS California Water Science Center where a hydraulic press was used to extract pore fluid. Pressures between 8,000 and 9,500 pounds per square inch (psi) were used to extract the pore fluid. Table 3 lists the analyses completed on pore-water (interstitial water, WI) samples.

The following are brief descriptions of analytical methods used to determine concentrations of analytes in groundwater and pore-water samples. Ammonia concentrations measured in samples at the USGS NWQL were determined with a salicylate-hypochlorite colorimetry method (Fishman, 1993). Dissolved phosphorus concentrations measured in samples at the USGS NWQL were determined by colorimetry according to EPA method 365.1 (Odell, 1993). Anion concentrations measured in samples at either the University of Minnesota Geochemistry lab or Ion Chrom lab were determined by anion chromatography using a Dionex ICS 5000 with an AS19 4 micron (2x250 mm) column (Maher and others, 2020). At the USGS NWQL, anion concentrations were determined by ion chromatography and cation concentrations were determined by inductively coupled plasma atomic emission spectroscopy (Fishman and Friedman, 1989; Fishman, 1993; American Public Health Association and others, 1998). Nitrate+nitrite concentrations measured in samples at the USGS NWQL were determined with an enzyme reduction-diazotization colorimetry method (Patton and Kryskalla, 2011) and nitrite concentrations were determined by colorimetry (Fishman, 1993). Stable isotope analyses were done at the Iowa State Stable Isotope Lab on a Picarro L2130-i Isotopic Liquid Water Analyzer, with autosampler and ChemCorrect software. Reference standards for isotopic corrections varied between runs and are identified in the accompanying data release (Maher and others, 2020). Tritium concentrations in samples at the University of Waterloo Environmental Isotopes lab were determined by electrolytic enrichment and an LKB Wallace 1220 Quantulus counter (Maher and others, 2020).

All geochemical data from non-USGS labs is provided in a data release accompanying this report, along with an R-script to retrieve geochemistry data from USGS National Water Information System, NWIS (Maher and others, 2020). Alternatively, USGS NWIS water-quality data are available at https://waterdata.usgs.gov/nwis and can be retrieved using the USGS site identification numbers listed in table 1.

Quality assurance samples were collected during the field study, including field replicates, field blanks, and split samples sent to separate laboratories. A summary of quality assurance at USGS labs and comparisons between USGS and non-USGS labs is found in Appendix 3. A summary of the quality assurance information from non-USGS labs is included in the metadata of the data release accompanying this report (Maher and others, 2020).

Groundwater modeling

Assessing the sustainability of groundwater withdrawals from confined aquifers is challenging because their hydrogeologic settings at locally relevant scales are highly uncertain. The field investigations at the Litchfield site, in particular, established that the hydrologic properties of till overlying confined aquifers can be highly variable over short distances. Furthermore, the extent of confined aquifers and their connections to other buried and possibly confined aquifer systems are not well understood because of the complex glacial geologic history of Minnesota. The MGS has mapped buried aquifers (sand bodies that may or may not be confined) using the best available data (well logs from well installations) through the County Geologic Atlas Program. However, there are still large uncertainties about the connectivity and extent of buried aquifer systems. The field studies presented in this report could not address questions about water movement with and without pumping because the sites were near municipal supply wells that consistently pumped groundwater. To better understand how till properties, aquifer properties, and pumping affects fluxes of water through till, a series of heuristic steady state groundwater-flow models was developed (table 4). The software package, Groundwater Vistas (Environmental Simulations Incorporated), was used to develop MODFLOW-2005 (Harbaugh, 2005) models for this analysis. The specific goal of the modeling exercise was to evaluate the variability in water fluxes into and through till to confined aquifers that are being pumped across the range of hydrogeologic settings observed at the field sites.

The basic structure of the heuristic model domain was approximately 20 miles by 20 miles with a cell size of 500 ft by 500 ft (shown in fig. 10). The model contained seven layers: a surficial unit which contained several rivers and lakes, three layers of “upper” till which represented the confining unit, two layers that contained the buried sand aquifer and a “middle” unit, and a layer of “lower” till. Under non-pumping conditions, the potentiometric level in the buried sand aquifer indicated a confined aquifer. However, the persistence of confined conditions throughout all model runs was not tracked and so the sand unit is referred to as a “buried sand unit” or “buried aquifer” to encompass the possibility of confined or unconfined conditions for all model runs. For most models runs, the surficial unit (layer 1) was 40 ft thick, the till unit was 80 ft thick (layers 2-4), the buried sand unit and surrounding middle unit (layers 5-6) were 80 ft thick, and the lower till unit was 200 ft thick (fig. 10). Differences in layer thicknesses for specific model runs are listed in table 4. The buried aquifer was in the middle of the model domain to minimize the potential for boundary conditions to directly influence water fluxes in the aquifer. Three pumping wells were screened in the buried sand aquifer. The northern and southern model boundaries were specified head boundaries and the east and west model boundaries were no-flow boundaries. A regional north-to-south horizontal hydraulic gradient of 0.001 was specified. A vertical downward gradient of 0.15 was assigned to model boundary cells. A constant recharge rate of 4 inches/year was applied at the surface of the model for all but two model runs, which is the statewide average from Smith and Westenbroek (2015). Lakes and streams were generally modelled as groundwater discharge features with head-dependent flux boundaries using the MODFLOW RIV and DRN packages, respectively (Harbaugh and others, 2000). Lakes and streams were assigned bed conductances of 1 ft/d and 5 ft/d, respectively. All model input files, output files, and executables are available through a model archive (Trost and others, 2020).

Several model parameters, including vertical and horizontal hydraulic conductivities of till and aquifer material, till thickness, buried aquifer size, pumping rate, and penetration of pumping wells were varied in the model scenarios (table 4). The range of model parameter values chosen for evaluation were informed by the observations made at the Litchfield and Cromwell sites and other applicable studies and data sets. Table 4 also lists the naming convention for the model runs, which corresponds to figures and tables of model output later in the report.

Steady state model runs beginning with Ls, Ms, or Hs comprise a set of "permutation runs" in which ranges of parameters for specific portions of the model system were evaluated (table 4). The names of the permutation model runs are six-letter codes representing the relative values (H = high, M = middle, and L = low) of the three hydraulic properties varied among simulations. The high (H) and low (L) model parameter values are inclusive of Litchfield and Cromwell, typically extending slightly above and below observations at these sites. The three hydraulic properties varied were: the maximum lateral dimensions of the buried sand unit in model layers 5 and 6 (naming convention = "s"); the upper till vertical hydraulic conductivity in model layers 2-4 (naming convention = "v"); and the horizontal hydraulic conductivity in middle unit in model layers 5 and 6 surrounding buried sand unit (naming convention = "c"). In all permutation runs, the horizontal hydraulic conductivity of the upper till (layers 2-4) was fixed at 0.05 ft/day. The vertical hydraulic conductivity of the middle unit (layers 5-6) was assigned the same value as the vertical hydraulic conductivity of the till in layers 2-4. For example, from table 4, a model run titled LsMcHv means the buried sand unit was assigned the low size of 1.0 mi by 0.5 mi, the middle unit (layers 5 and 6) was assigned the "middle" horizontal hydraulic conductivity of 5.0 ft/day, and the till units (layers 2-4) were assigned the "high" vertical hydraulic conductivity of 2.0 ft/day. The "base model" is labeled MsMvMc, and contained model parameter values that represented an approximate midpoint among observations from the field study sites.

A set of "variation" steady-state model runs was also completed (table 4). In this set of model runs, six additional properties were evaluated through comparison to the base model, MsMvMc. Model run names ending in "_H" indicate the "high" parameter value and names ending in "_L" indicate the low parameter value. These high and low values were also informed by field data collected as part of this project. The model runs titled CRtrlk and LFtrlk stand for "Cromwell transmissivity-like" and "Litchfield transmissivity-like". In these model runs, the transmissivity of the buried aquifer and the leakance of the upper till unit were assigned values determined from the Cromwell and Litchfield aquifer test results (Blum and Woodside, 2017; Lund and Blum, 2017).

Several response variables were extracted from model output and compared among the model runs. To check for boundary effects on water fluxes, the change in flux from constant head cells on the north and south model boundaries was compared between ambient (pumping turned off) and stressed (pumping turned on) periods. The following response variables were compared: (1) the source of water to buried aquifer, (2) pumping-induced leakage of water from the surficial unit in layer one to the till in layer two under and (3) the maximum drawdown in the surficial unit (layer one) and the till unit (layer three). The programs for extracting model output are provided in the model archive (Trost and others, 2020).

For the source of water to the buried aquifer, the relative contributions of water entering the buried aquifer from above, from the sides, and from below were compared among model runs. The leakage of water from the surficial unit in layer one to the till in layer two was quantified within a five mi by five mi "local area" (red outline in fig. 10) centered on the pumping wells and buried aquifer. The following equation was used to compute leakage as a percent of total inputs into layer one within the 5 mi by 5 mi local area:

$$L_{D,PCT} = \frac{V_D}{(V_R+V_L+V_I)} \times 100$$

where,

$L_{D,PCT}$ = percent downward leakage from layer one to layer two;

V_D = volume of water flowing downward from layer one to layer two;

V_R = volume of groundwater recharge within the local area (water reaching the water table from precipitation and percolating through soil);

V_L = the volume of groundwater inputs entering the local area from the sides and below; and

V_I = the volume of induced flow from local streams into layer one within the local area (typically zero or very small).

The pumping-induced increase in leakage was then calculated as the difference between the percent downward leakage during ambient and stressed (pumped) periods. The recharge rate was four inches per year for all but two model runs (SURF_L, SURF_H, table 4) so increases in the percent of downward leakage from ambient to stressed conditions indicated a pumping-induced reduction in lateral groundwater flow out of the local area and/or a reduction in the contribution of groundwater discharge to lakes and streams within the local area (fig. 10).

Characterization of glacial till and aquifer systems

The following section presents the hydrogeologic, geochemical, and modeling findings of this study.

Hydrogeology

Several physical and hydrogeological properties of the till and confined aquifer units at each site are summarized in table 4. Figure 11 provides a visualization of the hydraulic properties measured in vertical profiles at each site. In the following sections, a qualitative evaluation of the vertical profiles of hydraulic head responses to pumping and weather, a discussion of hydraulic conductivity distributions in till and calculations of leakage (recharge) through till confining units are presented.

Hydraulic head responses to pumping and weather

The piezometer nests at the Litchfield, Cromwell, and Olivia sites were installed near high-capacity municipal pumping wells, and aquifer tests were conducted at all the study sites providing an opportunity to observe hydraulic head fluctuations in vertical till profiles. Piezometer screens that are not hydraulically connected to the aquifer being pumped were not expected to show a hydraulic head change due to pumping stress over the short-term pumping cycles that occurred during this study (Cherry and others, 2004). If till piezometers show a drawdown response to short-term pumping, it demonstrates a likely hydraulic connection between the confined aquifer and the till piezometer. In this study, a wide range of tills were examined and hydraulic connections are possible because of a conductive matrix with high percentages of sand (for example, tills at the HFC and Cromwell sites) or from fractures in more clayey till (Cherry and others, 2004). If, for example, a piezometer intersected or is very near to a fracture that is hydraulically connected to the aquifer being pumped, then it is likely that a drawdown response would be observed in that piezometer (Cherry and others, 2004). Similarly, hydraulic connectivity from the surface downward can be examined by till piezometer responses to snowmelt or other significant infiltration events (Cherry and others, 2004).

The LFO1 and LFO2 sites showed decreasing hydraulic head values with depth, providing evidence for a downward gradient (fig. 11). At both sites, the downward gradients increased with depth through the till, with the largest hydraulic head losses occurring near the base of the till. A larger downward gradient was present at the LFO2 site compared to the LFO1 site. The continuous water levels data at the LFO1 and LFO2 sites show varying responses to the municipal supply well pumping (data available on https://waterdata.usgs.gov/nwis) In the two aquifer piezometers, LFO1-F and LFO2-F, a clear daily to sub-daily oscillation in hydraulic head from the high-capacity wells is evident. The LFO2 site is nearer to the pumping well, and as expected, LFO2-F shows a much larger oscillation in hydraulic head, up to four feet, from pumping than LFO1-F, which shows only about one-foot variations in hydraulic head. Both buried aquifer piezometers show three larger decreases in water level in June, July, and August of 2016 (data not shown). These large drops occurred during dry periods, and ended at or just before precipitation events, suggesting that these water-level fluctuations are caused by a high-capacity irrigation system that withdrew water from the same confined aquifer system as the municipal wells. According to the DNR (2020), three agricultural irrigation wells that use groundwater resources are within about a mile from the Litchfield site, with the closest irrigation well about a half mile away.

Hydraulic-head data from the LFO2 site demonstrate the presence of a till confining unit (data available on https://waterdata.usgs.gov/nwis). Water-level fluctuations from pumping stress are not apparent at LFO2-D, 30 ft above the till/aquifer boundary. There is not a large sand lens that could dampen the head fluctuation response between the till/aquifer boundary and LFO2-D (fig. 3). This piezometer also did not show a drawdown response during the aquifer test after 24 hours of pumping at 787 gpm (Blum and Woodside, 2017). This indicates there is a confining unit within 30 feet of the till/aquifer boundary that limits the hydraulic connectivity between the aquifer and the till.

Water levels in LFO2-A (screened 17 to 20 ft below land surface and LFO2-C (screened 57 – 60 ft below land surface) responded very similarly to surficial inputs, suggesting hydraulic connections through the till from 20 to 60 ft below land surface. Patterns in water levels at LFO2-D did not resemble those of LFO2-A, suggesting that LFO2-D is also reasonably hydraulically isolated from surficial processes. Taken together, this suggests that the most effective confining unit at LFO2 exists above and below LFO2-D and that at least the upper 60 feet of till at the LFO2 site are hydraulically connected.

A very different "leaky" response was observed at the far nest, the LFO1 site. LFO1-D is screened in till approximately 25 feet above the top of the confined aquifer/till boundary, and water level patterns in this piezometer closely resemble those observed in the confined aquifer. Even the daily oscillations from the cycling on and off of the Litchfield municipal wells are evident at LFO1-D, indicating a reasonable hydraulic connection from the aquifer through the bottom 25 feet of till. During the aquifer test at the Litchfield site, drawdown was observed in all of the till piezometers (LFO1-C,LFO1-D, and LFO1-F) indicating a hydraulic connection through the majority of the till layer. Water level patterns at LFO1-D bear a stronger resemblance to the confined aquifer than to the surficial aquifer, which is monitored by LFO1-B. Sharp water-level rises in LFO1-B are linked to rainfall events. Further time-series analysis is needed to determine if the routine pumping signal is apparent in the LFO1-B well. The till at the LFO1 site is only approximately 58 feet thick, and nearly half of this sequence is hydraulically well connected between the top of the confined aquifer and LFO1-D.

The hydraulic head data from the Cromwell site (CWO1/O2) demonstrate a very "leaky" till unit. At this site, a very slight upward gradient (fig. 11) was observed. All the piezometers with continuous water-level data showed similar seasonal patterns in water levels (data available on https://waterdata.usgs.gov/nwis) Throughout the entire profile, from the surficial aquifer (CWO2-A) down to the bedrock (CWO1-C), an increase in water levels was seen between April and May, which likely coincided with spring snowmelt and a large precipitation event on April 24th, 2016 of 1.65 inches. Sub-daily oscillations in hydraulic head caused by pumping from Cromwell municipal wells are evident in the bedrock (CWO1-C), the confined aquifer (CWO1-B), and two till piezometers (CWO1-A and CWO1-D), but not in the surficial aquifer (CWO2-A). Drawdowns were observed in all till piezometers installed at this site (CWO2-B through CWO1-A) during the aquifer test (Lund and Blum, 2017). The till at the CWO1/O2 site is about 130 ft thick, and CWO2-B is screened approximately 14 feet below the top of the till. This means that hydraulic connectivity was observed through 90 percent of the till thickness at the Cromwell site.

The hydraulic head data from the Olivia site demonstrate that portions of the till are an effective confining unit, limiting hydraulic connectivity between the confined aquifer and overlying till. The Olivia site has an overall downward hydraulic gradient (fig. 11). The vertical gradient between OT-13 in the surficial aquifer and OT-20 near the top of the till unit is very small (0.03) and depending on the time of year can have a slightly upward gradient. Mainly, the lack of a vertical gradient between OT-13 and OT-20 suggests horizontal flow may dominate in the top of the till and surficial aquifer in the area where the piezometer nest is installed. The gradient between OT-20 and OT-60 is also small (0.02) but is downward through the till throughout the year. Larger downward vertical gradients exist from OT-60 through OT-175. An extremely large gradient (2.25) exists between the piezometer screened in the bottom of the till, OT-175, and the piezometer screened in the confined aquifer, OB-7. Very large vertical hydraulic gradients such as this have been observed in confining units before, and at the Olivia site it may be due to the presence of thin layers of glaciolacustrine sediments near the bottom of the till unit (Hart and others, 2008). During a 10-hour aquifer test the confined aquifer was pumped at 232 gpm and no drawdown response was observed in any till piezometers, including OT-175 which is only 12 ft above the till/aquifer boundary (Blum, 2019b). However, the lack of a hydraulic response was confounded because of reverse water level fluctuations (RWF).

The upper portion of the tills at the Olivia site, to a depth of at least 60 feet, are hydraulically connected. Groundwater recharge events, especially in spring/summer, cause hydraulic-head increases (of up to about 3-5 ft) in piezometers OT-13, OT-20, and OT-60 (data available at https://waterdata.usgs.gov/nwis). Geologic descriptions and textural analyses of the till from about 30 to 60 feet are not appreciably different from 60 to 150 feet, suggesting that fractures may explain the hydraulic connections in the upper portion of the till. No visible fractures were reported in the geologic description of the cores (Staley and Nguyen, 2018), but fractures without visible staining are present in tills (Cherry and others, 2004; Helmke and others, 2005a; Helmke and others, 2005b).

Hydraulic head observations at the Olivia site were unique in that several till piezometers exhibited reverse water level fluctuations (RWF) in response to pumping. Routine pumping by the City of Olivia from the confined aquifer typically caused hydraulic head changes of approximately 10 feet at well OB-7, which is screened in the confined aquifer. At first glance, OT-175 and OT-145 appear to be responding hydraulically to the pumping, however, the fluctuations at these piezometers are RWFs, meaning water levels increased in response to pumping. Figure 12 shows hydraulic heads during the aquifer test completed in July, 2018. Well OB-7 shows a typical drawdown response when the pump turns on, however, the piezometers OT-175, OT-145, OT-105, and OT-60 all show varying degrees of RWF in that water levels in these wells increase as the hydraulic head in the aquifer decreases. Analysis of the RWF from the aquifer test data reveal no hydraulic response of any of these piezometers to the pumping, rather the hydraulic head changes are attributed to a poroelastic response of the system to pumping (Blum, 2019b).

The hydraulic head data from the HFC site demonstrate a somewhat “leaky” till unit. The overall vertical gradient at the HFC site is also downward, but with very small gradients (fig. 11). The confined aquifer at the HFC site is not continuously pumped and so the hydraulic heads measured at this site generally represent a static condition. The hydraulic head difference between HT-115, which is screened about 10 ft below the start of the till confining unit, and HT-140 in the till unit is very low. The average gradient between these two piezometers is very near zero. There is a narrow band of higher sand content between these piezometers (Staley and Nguyen, 2018), which could be a zone of increased horizontal groundwater flow and might explain why there is such a small gradient between these piezometers. The vertical hydraulic gradient between MW-01 in the surficial aquifer and HT-115 is also very low, at about 0.005.

Hydraulic connections were observed throughout the till profile at the HFC site, although these were difficult to observe until the system is pumped. The surficial aquifer is relatively thick and immediate responses to rainfall events were not very noticeable; there is little to no variability in hydraulic head from April to June, 2018. The only time water was pumped at this site was during aquifer tests. When the surficial aquifer was pumped for an aquifer test in 2017, a drawdown response was observed down to HT-175, which is 71 feet below the top of the till unit. During the 2018 aquifer test, when the confined aquifer below the till was pumped, a drawdown response was observed up through the till at piezometers HT-200, HT-175, and HT-140 (fig. 12). This suggests that there are hydraulic connections throughout the till profile, and if this confined aquifer were pumped regularly such that a stronger downward gradient were established, there could be relatively fast downward flow through the sandy till.

Reverse water level fluctuations (RWF)

RWF responses were observed in till piezometers during aquifer tests at three of the four sites study sites. At the Cromwell and HFC sites, brief RWF responses were observed when pumps turned on or off and at the Olivia site. A prolonged RWF response that lasted the entire duration of the aquifer test was observed in several till piezometers (Lund and Blum, 2017; Blum, 2019a; Blum, 2019b). These RWF observations are usually attributed to a poroelastic response, or a “deformation-induced effect” (Hsieh, 1996), where pumping in the aquifer causes a reduction in pressure, which then leads to the expansion of water and a compression of the aquifer skeleton (Berg and others, 2011; Kim and Parizek, 2005). Deformation of the aquifer skeleton can then lead to strains that can cause confining units to have RWF responses. Often, these are either a brief response at the beginning of the pumping, where there is a temporary increase in the water level in the confining unit, called the Noordbergum effect, or a quick, temporary drop in water level at the end of pumping called the Rhade effect (Berg and others, 2011; Kim and Parizek, 2005). Both Noordbergum and Rhade effects are clearly visible in HT-115 during the aquifer test at the HFC site (fig. 12). At the Cromwell site, piezometers CWO2-B and CWO2-C demonstrated the Noordbergum and Rhade effects as the pump cycled on and off during the aquifer test period (Lund and Blum, 2017, Justin Blum, personal communication, December 9, 2019).

The prolonged RWF response in the till at the Olivia site is unusual because it lasted for the entire aquifer test (fig. 12). Evaluation of the Cromwell RWF data showed hysteretic RWF responses to pumping and recovery when steady-state gradient conditions in till were not achieved, but identical RWF responses when steady-state conditions were achieved. The hysteresis of responses depends on the ambient hydraulic gradient but can be overcome by achieving steady-state conditions during an aquifer test. Non-hysteretic RWF responses are necessary for accurate observation of hydraulic responses to pumping (Justin Blum, personal communication, December 9, 2019). The pumping time (10 hours) for the Olivia site aquifer test was not enough to achieve a steady-state gradient within the till confining unit. It is estimated that a minimum pumping period of 20-30 days would be required for a detectable hydraulic response for the deep till piezometers at the Olivia site (Blum, 2019b).

Hydraulic Conductivity (K)

A total of 141 slug tests were completed on the piezometers for this study. The calculated hydraulic conductivities are summarized in table 5. Additional input data, Aqtesolve model parameters, and model residual summaries are provided in Appendix 2 (tables 2.1, 2.2, and 2.3. All of the water-level data, Aqtesolve files, and graphical outputs are available at the data release accompanying this report (Maher and others, 2020). Additionally, vertical hydraulic conductivities were determined from the aquifer tests completed at each study site (table 6, fig. 11). These data are the basis for the following discussion.

Slug tests in vertical wells primarily measure the horizontal hydraulic conductivity (Kh), but still provide insight into the ability of till to transmit water (Cherry and others, 2004). In this study, site-wide geometric mean K values from slug tests did not correlate well with average textural compositions of the till units (percent sand, silt, and clay). The Cromwell and HFC sites had very high sand content tills, 57 percent and 67 percent, respectively, whereas the till at the LFO1 site had 47 percent sand, the till at the LFO2 site had 52 percent sand, and the till at the Olivia site had 37 percent sand. The vertical hydraulic gradients were much smaller in the sandy till units at the Cromwell and HFC sites compared to the Olivia and Litchfield sites, which suggests a greater resistance to vertical groundwater flow as the percent sand decreases (table 6; fig. 11).

At the Litchfield site, the values of K from slug tests range from 306 ft/d for sand and gravel aquifer to 1×10^{-5} ft/d for till (figure 11 and table 5). The geometric mean K values of till at the LFO1 and LFO2 sites are 7×10^{-2} and 2×10^{-4} ft/d, respectively (table 6). These values for K are within previously observed values for Des Moines lobe till, although the K values at the LFO1 site were slightly higher than expected (Simpkins and Parkin, 1993; Helmke and others, 2005a; Helmke and others, 2005b). Only two piezometers were used to estimate the geometric mean K value of till at the LFO1 site. LFO1-E, which was intended to be screened solely in till, appears to be connected to the aquifer and so was excluded from the geometric mean calculations. The large difference in mean K values between the two study sites in Litchfield was unexpected. The average sand content in the till at the LFO1 site (47 percent) was lower than the average sand content of the till at the LFO2 site and yet the K was two orders of magnitude higher at LFO1 compared to LFO2. The large difference between these sites could be due to differences in till deposition or a greater influence of till fractures on the hydraulic observations at the LFO1 site compared to the LFO2 site. The LFO2 site K values may be more indicative of the properties of the till matrix.

At the Olivia site, the K values ranged from about 3 ft/day for sand and gravel to a low of 2×10^{-4} ft/d for till (table 5, fig. 11). The geometric mean K of all of the slug tests in the till confining unit is 4×10^{-3} ft/d, which is higher than at the LFO2 site, despite the Olivia site's lower sand and higher clay content compared to the LFO2 site. As previously discussed, the upper portion of the Olivia till (to a depth of 60 ft) is hydraulically connected, with some data suggesting the presence of fractures. The till deposit at the Olivia site is older than the deposit at the Litchfield site and could therefore be more weathered, and may explain, in part the higher hydraulic conductivities observed at the Olivia site. One extremely low K outlier, 6×10^{-6} ft/d, observed at piezometer OT-35, was not considered for the calculation of the geometric mean K or plotted on figure 11. This piezometer had only one "slug" test completed that lasted for 14 months. The well was purged after installation in August 2017 and the water levels had not fully recovered before the project's data collection ended. It is hypothesized that the screen of this piezometer was affected by bentonite during the installation process. However, water samples were not collected to evaluate this hypothesis. An alternative hypothesis is that this till piezometer does not intersect any fractures and is a demonstration of a clayey till matrix response.

At the Cromwell site, K values ranged from about 23 ft/d for sand and gravel to 9×10^{-3} ft/d for till (table 5, fig. 11). The geometric mean K value for all slug tests in the till confining unit is 0.06 ft/d. The till K values at this site were remarkably similar to the till K values at the LFO1 site, despite a 10 percent difference in sand content and 6 percent difference in clay content (table 6).

At the HFC site, K values ranged from 73 ft/d in sand and gravel and 4 x 10^{-4} ft/d in till for the slug test results (table 5, fig. 11). The geometric mean K value in the till confining unit is 3 x 10^{-2} ft/d, which again is similar to the LFO1 site despite a 20 percent higher sand content at the HFC site compared to the LFO1 site (table 6).

Slug tests measure the horizontal hydrologic properties of a small (compared to aquifer tests) volume of till surrounding the sand pack, on the order of cubic meters (Bradbury and Muldoon, 1990). Studies have suggested that a standard slug test has a sample volume of about 24 cubic meters for depths of 1-3.7 meters (Seo, 1996; Beckie and Harvey, 2002; Young and others, 2020). Confining units can have higher anisotropy compared to aquifers, with horizontal K possibly being higher because of stratification, or vertical K possibly being higher because of fractures (Cherry and others, 2004). Also, the material nearby the piezometer/well screen is the main material controlling the Kh value during a slug test (Cherry and others, 2004). Thus, slug tests can be affected by drilling/installation , as discussed in the sources of uncertainty section. It is therefore not surprising that site-averaged textural compositions and geometric mean K values were not well correlated. For example, the correlation coefficient of the geometric mean K and site-average percent sand (n = 5 sites) is 0.27. If the K value of each individual piezometer is paired with the nearest textural composition data from cores (Wagner and Tipping, 2016; Staley and Nguyen, 2018), the correlation coefficient between K and percent sand does not substantially improve; the correlation coefficient is 0.29 with 20 till piezometers. Across these diverse types of till, there is much more than textural composition driving the hydraulic properties of till at the localized scale measured with slug tests.

In contrast, during aquifer tests, hydraulic responses in a much larger volume of till, on the order of hundreds of cubic meters, are measured. The bulk Kv values determined from aquifer tests for each site correlate much more strongly with the site-averaged percent sand in the till. Across the five sites, the correlation coefficient between percent sand and the log of the bulk Kv is 0.61. The bulk Kv values from aquifer tests are even more strongly correlated with the percent clay at each site with a correlation coefficient of -0.73. Taken together, these two correlations indicate that bulk till textural composition is an important factor controlling leakage through till to underlying aquifers at the scale measured with aquifer tests.

While hydraulic conductivities provide information about a formation's ability to transmit water, evidence of hydraulic connections during periods of stress provide information about actual flowpaths that may behave very differently than those predicted from measured K values. Figure 13 demonstrates, qualitatively, the importance of till textural composition to hydraulic connections between till and underlying aquifers; connections that only become apparent when a significant pumping stress is present in the system. The aquifer tests conducted for this study were a much more prolonged, continuous pumping stress compared to the routine pumping by municipalities. The triangle symbols in this plot represent piezometers that did not exhibit a drawdown response during the aquifer test whereas square symbols represent piezometers that did exhibit a drawdown response. Almost every piezometer screened in till with at least 55 percent sand and less than 15 percent clay experienced a drawdown response. Conversely, almost every piezometer with less than 55 percent sand and more than 15 percent clay did not show a drawdown response. There are a couple of outliers to this general classification, but overall there is a consistent separation among these tills as to which materials exhibit hydraulic connectivity during pumping stress.

Leakage (recharge) through tills

Calculations of travel time through the till, specific discharge, and leakage from till according to Darcy methods vary by three to four orders of magnitude across the sites (table 7). At three of four sites, a downward gradient through the till was observed, and so the calculations represent the downward flux of water through till into the confined aquifer. At the Cromwell site, there was an upward gradient and so the calculations represent the upward flux of water from the confined aquifer through the till to the surficial aquifer.

Specific discharge is given in inches and represents leakage from till as volume divided by a cross-sectional area (equation 2). In most cases, the calculated specific discharge is constrained by the properties of the till (table 7). In other words, specific discharge from the till is less than or equal to precipitation-driven annual groundwater recharge to the water table aquifer, as estimated by Smith and Westenbroek (2015). Two specific discharge rates, 177 inches per year at LFO1 and 84 inches per year at the Cromwell site, are substantially greater than the precipitation-driven groundwater recharge to the to the water table aquifer (table 7). In these cases, the specific discharge across the till/confined aquifer boundary cannot be realized in a simple one-dimensional flow system where the only input to groundwater is diffuse recharge from precipitation directly above the vertical profile of interest. Lateral groundwater flow could supply additional water such that these fluxes could be realized. In fact, this is likely occurring at the Cromwell site. At the Cromwell site, the hydraulic gradient is slightly upward, and one hypothesis is that the groundwater is flowing laterally from a distant recharge location to the confined aquifer at the Cromwell site (Witt, 2017).

At all sites except for the HFC site, average linear velocities and travel times vary widely between calculations using the geometric mean K from slug tests and the Kv from aquifer tests. Both calculations (K and Kv) are valid, but represent very different volumes of till and water. Calculations of travel time that use the bulk Kv assume that the hydraulic gradient and till thicknesses determined at each piezometer nest are representative of a large till volume. When the geometric mean K from slug tests is used to calculate travels times through till, the resulting travel times vary from 1 year to over 900 years (table 7). Interestingly, these extremes were observed at LFO1 and LFO2, respectively, which are a half mile apart. The geometric mean K calculations represent very localized flow conditions and the Litchfield site demonstrates two very different flowpaths through which water travels to the confined aquifer. When the Kv from aquifer tests is used to calculate travel times through till at all sites, travel times vary over a similar range, from 4 to 730 years, but the minimum occurs at the Cromwell site and the maximum occurs at the Olivia site. At the Litchfield site, calculations with the bulk Kv produce estimated travel times of 74 years at LFO1 and 165 years at LFO2; this is the average travel time of a much larger volume of water compared to the volume represented by the geometric mean K. The Olivia and Cromwell sites also have a large difference in travel time estimates from the bulk Kv and the geometric mean K. Taken together, this suggests that measurements made at the Oliva, Litchfield, and Cromwell piezometer nests represent a subset of the “population” of flowpaths through till that was not aligned with the “average” condition. At the HFC site, the K and Kv methods both produce similar travel time estimates, suggesting that the piezometer nest is representative of an “average” flowpath to the confined aquifer.

A comparison between the areal extent of till/aquifer surface required to meet the pumping rates of the high capacity wells (table 7) and the mapping of confined aquifers reveals uncertainty about aquifer geometry and/or the source of water to wells. The areal estimates assume (1) the only source of water to the confined aquifer is leakage from till and (2) the bulk Kv from aquifer tests is a representative hydraulic conductivity for the leakage that occurs in response to pumping for water supply.

According to the Darcy calculations, Litchfield's groundwater pumping requires between 8 and 9 square miles of till to meet the pumping demands and Olivia's pumping requires 7 square miles (table 7). These areal extents are larger than the areal extents of the aquifers as mapped in geologic maps based on well and borehole logs. The Renville County Geologic atlas shows that the areal extent of the confined aquifer at Oliva is only 0.08 square miles (Bradt, 2017) and the Meeker County Geologic Atlas shows an approximate areal extent of the aquifer at Litchfield of 3 square miles (Meyer, 2015). The Olivia aquifer test indicated an aquifer boundary within 350 feet of the pumping well and well records indicate that the aquifer is most likely a buried alluvial channel with a complex shape (Blum, 2019b). The glacial deposits at Litchfield are a complex mixture of till layers and sand bodies, with many possible lateral connections between buried sand bodies (Meyer, 2015).

The source of water to the confined aquifers is much more complex than the simple conceptual system discussed here of one-dimensional flow from land surface through till to a confined aquifer. Uncertainty of the distribution of till hydraulic properties, the extent of confined aquifers, and the connections between aquifers make evaluations of the sustainability of groundwater pumping from confined aquifers challenging. In a later section of this report, heuristic MODFLOW models are used to evaluate the flux of water into and through till in a variety of hydrogeologic settings and pumping rates representative of the field sites.

Groundwater geochemistry and water quality

Several laboratories provided analytical services for this study. The data from each lab was acceptable for the purposes of our study, unless otherwise noted in the text of this report. A summary of the quality assurance evaluation for these labs is found in Appendix 3 and in the metadata of the data release accompanying this report (Maher and others, 2020).

Background information

Background information and context for interpreting the geochemical constituents evaluated in this study are presented in this section. Information is included for stable isotopes of water (^{18}O and ^{2}H), enriched tritium (^{3}H), chloride (Cl), chloride to bromide ratios, nitrate (NO_3), phosphorus (P), oxidation-reduction (redox) conditions, and major ions.

During the Wisconsin glaciation, glacial ice locked up a large portion of the ^{16}O and H from precipitation in the northern hemisphere, thus leaving most of the ^{18}O and ^{2}H in the oceans, where it became enriched in those isotopes. Till deposited by that ice under a very cold climate may retain some of that isotopic signature, manifested by $\delta^{18}O$ values approaching -30 ‰ and $\delta^{2}H$ values approaching -200 ‰ (Remenda and others, 1994). Unfractured, thick, and unweathered confining units in North America have been found to hold glacial-age groundwater if the residence time of the groundwater is long enough (Remenda and others, 1994).

Enriched ^3H was released into the atmosphere during the hydrogen bomb testing in the 1950s and 1960s. Today it is used as an indicator of relative groundwater "age". Groundwater age is an indication of when water in the groundwater system was last exposed to the atmosphere. If there are detectable levels of ^3H (greater than 0.8 tritium units (TU)), then at least some of the water in the sample is considered to have been in the atmosphere "post-bomb" and likely reached the groundwater system sometime after the 1950's. Samples with detectable concentrations could be a mixture of old, pre-bomb water and post-bomb water, but at least some post-bomb water is present. If there is no detectable ^3H, then the sample water is considered to be "pre-bomb" and the water likely reached the groundwater system prior to the 1950's. For this report, samples with detectable ^3H are considered to have "modern", post-1950s water and samples without detectable ^3H are considered to be "old", pre-1950's water. The special case of high ^3H concentrations (greater than 15 TU) is also considered as groundwater ^3H peaks related to the bomb peak that occurred in the mid-1960s have a ^3H concentration of 15 TU or greater (Berg, 2019).

Chloride (Cl) concentrations can be naturally occurring in groundwater or influenced by anthropogenic activities. Salt (NaCl) can occur naturally in groundwater from the presence of halite deposits, weathering of bedrock, briny water, seawater, surficial materials, soils, and volcanic activity (Mullaney and others, 2009). In the United States salt use has been increasing, mainly because of deicing activities, since the 1950s (Mullaney and others, 2009). Minnesota is known to have an influx of Cl from road salt contamination or wastewater correlated with urban land use (Kroening and Ferrey, 2013). Anthropogenic salt contamination in groundwater can come from sources other than deicing, including landfills that have food waste and products containing salt, water softeners, septic systems, household use, and from agricultural use (Mullaney and others, 2009). Agricultural salt groundwater contamination can come from animal feed, fertilizers, and pesticides. Some fertilizers have potassium chloride (KCl), which raises Cl levels but not Na levels in water resources (Mullaney and others, 2009).

Background groundwater concentrations of Cl are generally in the range of 5 mg/L in till of the Des Moines lobe in Iowa, while anthropogenically affected concentrations range from 20 to more than 100 mg/L (Simpkins, 2010). Background Cl levels in Quaternary sediments in Canada and Illinois are generally between 15-20 mg/L (Howard and Beck, 1993) and 1 to 15 mg/L (Kelly and others, 2012), respectively. There are some Cretaceous aquifers in southwestern and south-central Minnesota that are known to have naturally high concentrations of Cl, up to 1,500 mg/L, (Kroening and Ferrey, 2013). Upward flux of groundwater from older aquifers, such as the Ordovician aged Red River-Winnipeg aquifer in northwestern Minnesota, has been known to increase salinity in groundwater in the overlying sediments (Ruhl and Adolphson, 1986).

Chloride and bromide (Br) concentrations and ratios have been used to investigate groundwater pollution, such as septic tank and road salt contamination (Katz and others, 2011). The anions Cl and Br are ideal conservative tracers in water, because neither anion has significant ion exchange reactions at low temperatures, both are very soluble, both are not likely to be adsorbed to mineral surfaces, and because they only form minerals during extreme evaporation (Alcalá and Custadio, 2008). A variety of reports in Minnesota have shown different thresholds for classifying the Cl concentration and Cl to Br ratio as evidence of anthropogenically-sourced Cl. In Renville County (the County containing the Olivia site), a Cl concentration above 5 mg/L combined with a Cl/Br mass ratio above around 200 possibly indicates anthropogenic contamination (Bradt, 2017). Other studies in Minnesota have used a Cl/Br mass ratio of 250 or above as evidence of possible anthropogenic contamination (Berg, 2018), or a minimum mass ratio of 300 (Kroening and Ferrey, 2013).

Nitrogen fertilizers are the primary cause of increasing NO_3 concentrations in groundwater throughout the U.S. (Spalding and Exner, 1993; Sebilo and others, 2013). Other anthropogenic sources of increased NO_3 include waste from animals and contaminated rainfall because of the combustion of fossil fuels (Kroening and Ferrey, 2013). Normally groundwater in Minnesota that is not influenced by NO_3 from anthropogenic activities has concentrations of NO_3 of 1.1 mg/L or less (Kroening and Ferrey, 2013). In Minnesota, the aquifers most affected by NO_3 contamination are shallow sand and gravel aquifers underlying agricultural areas (Kroening and Ferrey, 2013).

Phosphorus (P) concentrations in Minnesota groundwater have been found to be more strongly related to geology, rather than land use (Kroening and Ferrey, 2013). Rocks and sediments that contain phosphorus bearing minerals can weather and contribute P to groundwater (Kroening and Ferrey, 2013). Shale is one such rock, and sand and gravel aquifers in Minnesota deposited by glacial lobes sourced from the west/northwest tend to have higher P concentrations because of the presence of carbonates and shale, compared to aquifer material deposited by northeast glacial lobes (Kroening and Ferrey, 2013). Anthropogenically sourced P in groundwater is usually from fertilizer use or waste (Minnesota Pollution Control Agency, 1999). Concentrations of P can also increase with increasing residence time, which may be associated with elevated iron and manganese (Minnesota Pollution Control Agency, 1999). Groundwater with low redox potentials can result in the dissociation of iron (Fe)-P minerals, releasing adsorbed P (Burkart and others, 2004). The median P concentration for buried Quaternary aquifers in Minnesota is 0.124 mg/L (Minnesota Pollution Control Agency, 1999).

The oxidation-reduction (redox) state of groundwater is an important factor in determining the presence of harmful constituents in groundwater (McMahon and others, 2011). The byproducts of reducing environments tend to be Mn^{2+}, ferrous iron (Fe^{2+}), hydrogen sulfide (H_2S), and methane (CH_4) (National Water-Quality Assessment Program, 2009). Zones can form in the subsurface where one electron-accepting process can dominate. Zones commonly form in subsurface recharge areas of aquifers. Near the point of recharge at the beginning of the groundwater flowpath, dissolved oxygen (DO) reduction is the dominant process, followed by a zone of NO_3 reduction below, followed by a zone of ferric iron reduction, and then the deepest zone is usually one of sulfate reduction (McMahon and others, 2011). These zones follow flow paths, and often increasing age in groundwater systems can have a relationship with increased reducing conditions (McMahon and others, 2011). Under reducing conditions, nitrate is typically not of concern because it is readily reduced, but other constituents become problematic for human health. The most common contaminants are geogenic, that is, they are “naturally” occurring in the system and are not introduced from anthropogenic activities. For example, under reducing conditions, phosphorus concentration can increase because of dissociation of Fe-P minerals (Burkhart and others, 2004), arsenic can be released, and certain metals can become soluble (McMahon and others, 2011).

Characterizing the major ion geochemistry of groundwater provides information about how groundwater geochemical composition evolves with residence time, through contact with different geologic units, and influences from anthropogenic activities. Major ion chemistry is useful for defining hydrochemical facies (Blanchette and others, 2010). Previous research has found cation exchange of Na on sediments with Ca and Mg along the direction of groundwater flow, leading to more Ca and Mg dominated groundwater in water near the beginning of a flow path and more Na-dominated groundwater associated with older water that is further along a flow path (Hendry and Schwartz 1990). Major cations (calcium (Ca), magnesium (Mg), and Na plus K) and major anions (carbonate (CO_3) plus bicarbonate (HCO_3), SO_4, and Cl, fluoride (F), nitrite (NO_2) plus nitrate(NO_3)) were examined via Piper plot (Piper, 1944), in order to characterize the groundwater types at each site. The ions presented in Piper plots account for most of the electrical balance in the groundwater (Ging and others, 1996).

Groundwater age and evidence for infiltration of anthropogenic chemicals

Stable isotopes of oxygen and deuterium showed no evidence of glacial-age groundwater greater than 11,000 years old in the till confining units at any site. This aligns with the range of travel times predicted from the Darcy calculations, which ranged from 1 to 900 years across the sites. Values of $\delta^{18}O$ ranged from -7.4 ‰ to -12.0 ‰ and values of $\delta^{2}H$ ranged from -84.1 ‰ to -55.7 ‰ (fig. 14), both of which are well outside of the range of glacial-aged water. All but one sample fell along the global meteoric water line (fig. 14). The two northern sites, HFC and Cromwell, generally had lower $\delta^{18}O$ and $\delta^{2}H$ values than the two southern sites, Olivia and Litchfield. This trend is expected because fractionation increases with distance from the Gulf of Mexico, causing $\delta^{18}O$ and $\delta^{2}H$ values to decrease with increasing latitude. The only sample that plots distant from the global meteoric water line (Craig, 1961) is from a surficial aquifer well, MW-01, at the HFC site. This sample is most likely showing an evaporative signal, indicating that surface water from nearby lakes is recharging the surficial aquifer (Palmer and others, 2007). Stable isotope values from pore water are very consistent with the groundwater samples from piezometers (fig. 14). These data suggest that the groundwater values mostly reflect what is in the till, and not an artifact left from the drilling process.

Enriched ^{3}H shows differences in travel times through till among the sites which generally agree with travel time estimates from Darcy's Law. Tritium data suggests faster fluxes of groundwater through till at the HFC site and LFO1 site compared to Olivia and LFO2 (fig. 15). Tritium was detected above 1 TU in all till piezometers at HFC and LFO1, indicating the presence of modern water throughout the till profile. Both sites have a ^{3}H peak within the till confining units. The ^{3}H peak is near the bottom of the till at the LFO1 site, whereas at the HFC site, the ^{3}H peak is near the top of the till unit. The peak value at the LFO1 site was 16.1 TU and the peak at the HFC site is 21.1 TU, both of which fall in the range of a mid-1960s bomb peak ^{3}H value.

The travel time from the water table to the deepest till piezometer (LFO1-E) was 50 years (1966 – 2016), under the assumption that the ^{3}H peak at LFO1-E represented water that reached the surficial aquifer in 1966.). This lies within the range of travel times (1 to 74 years) estimated according to Darcy's Law (table 7). Travel time estimates at LFO1 from ^{3}H are expected to be on the high side of the Darcy calculations because vertical travel through the surficial aquifer is not considered in the Darcy calculations in table 7 but is included in the ^{3}H estimate.

For HT-115, using the assumption that the ^{3}H peak represents water that reached the surficial aquifer in 1967, the travel time through the 59-ft thickness of saturated material, including 48 feet of surficial aquifer and 11 feet of till, was 50 years (1967 – 2017). The Darcy's Law calculation indicates a slightly faster travel time through till: 50-56 years to travel a vertical distance of 100 ft (table 7).

At the Olivia and LFO2 sites, ^{3}H concentrations of about 5-6 TU are only seen in shallower areas of the till unit (fig. 15). At LFO2, ^{3}H was only detected in the two uppermost till piezometers, to about 35 feet into the till and at Olivia, ^{3}H was only detected in the uppermost till piezometer, at a depth of about 8 feet into the till. Therefore, most of the till thickness these sites contained non-modern water (older than 1953). The Darcy's Law calculations of travel time through till at these sites are in the hundreds of years, so in a very general sense, the ^{3}H data corroborate the Darcy's Law travel time calculations.

At the Cromwell site, ^3H concentrations of around 5 TU are present in the surficial unit as well as the confined aquifer, but not the till in between. The hydraulic gradient data and the ^3H data suggest that recharge to the confined aquifer enters the system somewhere up-gradient in the same buried aquifer system or perhaps through a window through the overlying till confining unit where the hydraulic gradient in the till is downward. This suggests that the till sequence observed near the water supply well may have little direct influence on the quality and quantity of water at Cromwell. Rather, the anthropogenic activities and geologic materials at a distal recharge area (yet to be defined) may affect the water observed in the confined aquifer at the Cromwell site.

Anthropogenically-sourced Cl inputs are variable among the four study sites. Three of the sites, Litchfield, Cromwell, and Olivia, in municipalities with higher road densities and likely higher road salt applications compared to the HFC site, which is in the middle of a large forested area with few roads. Furthermore, the land surrounding the towns of Litchfield and Olivia is predominantly row-crop agriculture, with additional fertilizer inputs containing chloride might regularly be applied.

Chloride concentrations, as well as Cl/Br mass ratios in the groundwater at the Litchfield, Cromwell, and Olivia sites, suggest anthropogenically-sourced Cl is present in the till profile, though the depth of penetration varies by site. A Cl/Br ratio above 250 is considered to be a possible indicator of anthropogenically-sourced Cl for this discussion (Berg, 2018). Except for the LFO1 nest, all observed Cl/Br mass ratios from pore water suggest no anthropogenic contamination. At the LFO1 site, groundwater and pore-water Cl/Br ratios are above or near 250 (fig. 15).

Chloride concentration profiles at the LFO1 and LFO2 sites were very different (fig. 15). At LFO1, pore-water and groundwater Cl concentrations in the till unit stayed around 20-40 mg/L, except for one pore-water outlier that was near 300 mg/l. Most pore water concentrations are higher than the groundwater concentrations. The confined aquifer had higher groundwater and pore water Cl concentrations than the till unit (except for the outlier). The Cl/Br mass ratios are near 250 in the till unit, with exception of the pore water sample outlier, while in the confined aquifer there are Cl/Br mass ratios above 250 (a possible minimum for Cl contamination from Berg, 2018). At LFO2, the highest concentration of Cl in groundwater, about 40 mg/L, was in the shallowest piezometer, and then Cl decreases in groundwater through the till unit. Pore water has concentrations that range between 20 to slightly above 40 mg/L in the till unit. Most Cl/Br mass ratios are very near to 250 for many of the groundwater samples, but are below 250 for pore water samples.

At the CWO1/O2 site, which has an overall upward hydraulic gradient through the vertical transect, groundwater Cl concentrations decreased with depth to near background values in the till and ranged from 1 to 45 mg/L (fig. 15). These values indicated evidence of anthropogenic input near the surface in the shallow aquifer there, but not significantly in the underlying confining unit and confined aquifer. Cl/Br mass ratios are near 250 in the till, but the surficial unit shows a Cl/Br mass ratio nearing 2,000, which is a strong indication of anthropogenically-sourced Cl. With the presumed water source containing little Cl coming upwards from below, the fact that concentrations are not large in the till confining unit section above it is consistent with ^3H and hydraulic gradient data. The high Cl/Br mass ratio and Cl concentration in the surficial unit may indicate anthropogenic contamination.

At the HFC site, the pore water samples have higher Cl concentrations when compared to the groundwater. The Cl range at the site goes from 0.46 to 50 mg/L (fig. 15). All groundwater samples are below 5 mg/L, and all pore water samples are above 20 mg/L. The elevated Cl present in the pore water is consistent with ^3H data, which shows a ^3H peak 115 feet below land surface, and ^3H present throughout the till confining unit. However, the groundwater concentrations are not consistent with the pore water concentrations. The groundwater concentrations suggest that there has not been Cl contamination at the HFC site, while the pore water suggests there may have been anthropogenic loading of Cl. However, neither groundwater nor porewater Cl/Br mass ratios suggest anthropogenic contamination, being well below 250.

The Olivia site Cl concentrations in groundwater and pore water are consistent throughout the till formation. The range of Cl at the site goes from 7 to 86 mg/L, with both the pore water and groundwater showing the highest concentration at 20 feet below land surface (fig. 15). As was seen at both the HFC and LFO1 sites, all pore water samples have higher Cl concentrations concentration compared to the groundwater samples at similar depth intervals. Observing the groundwater results alone demonstrated that all except the sample at 20 feet are between 5- 20 mg/L. The pore water results were different, with concentrations above 20 mg/L for all samples. The Olivia site groundwater had the highest Cl/Br mass ratios in deeper piezometers in the confining unit. The highest mass ratio where the Br was detectable is in OT-175 (around 175 feet below land surface) at a mass ratio of 890. However, all Cl/Br mass ratios from pore water are below 250. For the Olivia groundwater samples, most of the Cl concentrations were similar within the till unit, and the Br concentrations vary more, with some below the detection limit.

Bromide can sorb to clays in certain circumstances. At some pH levels, Br adsorption can occur onto clay minerals such as kaolinite and montmorillonite as well as iron and aluminum oxides (Goldberg and Kabengi, 2010). The pH mineral adsorption of Br can occur up to a pH of 8, however there is minimal adsorption above a pH of 7 (Goldberg and Kabengi, 2010). Almost all field measurements of groundwater pH for the four sites had a pH above 7, and the two piezometers that had groundwater pH slightly lower than 7 were shallow (around 20 feet or less below land surface) and possibly influenced by a more recent influx of precipitation. This suggested that if there was Br adsorption, there was minimal adsorption. Nevertheless, Br concentrations of pore water and groundwater were compared with clay content of co-located samples from detailed geologic analyses (Staley and others, 2019). No strong correlations between Br and clay content were evident.

Some differences in Cl concentrations between groundwater and pore water were observed at the sites where both types of water were sampled. The differences in Cl concentrations between pore water and groundwater may be due to several processes. One possibility is that the sampled water came from two different sampling scales. The cores collected and squeezed for pore water are 6-in long and 4-inches in diameter and contain a water volume of about 0.31 L (0.08 gallons) including a porosity of 25%, whereas the samples for groundwater represent a 5 ft screen and a borehole annulus diameter of 6.75 inches, which contains about 8.8 L (2.3 gallons) of water. Thus, the concentration found in the pore water could be diluted up to 28.4 times along the piezometer screen, assuming the Cl concentration in the groundwater is not the same along the entire screened interval. Another explanation was that evaporation could have increased the concentration of Cl in the pore water. However, $\delta^{18}O$ and $\delta^{2}H$ values did not show an evaporation influence in the pore water from the till core samples. Possibly, drilling/installation processes introduced more dilute groundwater to the formation and lowered groundwater Cl concentration in the till.

Groundwater nutrients and oxidation/reduction (redox) conditions

The only locations where NO_3-N concentrations were greater than one mg/L were the uppermost piezometers at Olivia, Litchfield and Cromwell (fig. 16). Deeper wells and piezometers all had extremely low or undetectable concentrations. This finding was important considering the broader landscape at two of the sites, Litchfield and Olivia, was dominated by row crop agriculture. Much higher groundwater NO3 concentrations in confined aquifers have been found in Iowa, usually 10 mg/L NO_3-N or greater (Rodvang and Simpkins, 2001; Eidem and others, 1999). The HFC site had no detectable NO_3-N (less than 0.01 mg/L) present in any groundwater samples (fig. 16).

Pore-water NO_3-N concentrations tended to be higher than the corresponding groundwater samples (fig. 16). The high pore-water NO_3-N values are likely from inadequate sample handing procedures and likely are not an accurate representation of in situ pore-water NO_3-N. This difference is likely due to the processing of the core samples. Groundwater samples were held to strict holding times and were chilled until lab analyses were completed. The cores were stored for months prior to being squeezed. After the pore-water was extracted from the core, the pore-water was not chilled continuously before being analyzed for NO_3. Given that there were reducing conditions in the sediments and that cores were not processed in an anoxic environment, it is possible that ammonia was present in the pore-water and was oxidized to nitrate during the sample handling.

Based on studies elsewhere in the Des Moines lobe (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995), as well as this study's data, the likelihood of anthropogenically-sourced Cl in till where NO_3 is absent provides evidence of NO_3 removal by denitrification in the till. Denitrification eventually converts NO_3 to N_2 gas. Simpkins and Parkin (1993) demonstrated the presence of the intermediate denitrification product, N_2O, as evidence of denitrification driven by organic carbon in till and loess in till of the Des Moines lobe. Groundwater with the highest concentration of NO_3-N at the Litchfield and Cromwell sites also had the highest nitrite (NO_2) concentration, which could indicate active denitrification and conversion of NO_3 to NO_2 as another intermediate step. At the Olivia site, the highest groundwater sample NO_2 concentration was also where the NO_3 concentration was highest (OT-13), and from the pore water samples, NO_2 was below detection limit.

Based on the vertical distribution of P at the all the sites and the groundwater flow systems and ages, there is little evidence of vertical penetration of P from the surface into the subsurface (fig. 16). The lack of evidence for vertical penetration may suggest that much of the P may be geologic in origin. The concentration of P in groundwater at the LFO1 site was less than 0.020 mg/L through the entire vertical profile. The concentration in extracted pore water decreased with depth and ranged from less than 0.020 to 0.070 mg/L. Phosphorus concentration increased with depth in groundwater at the LFO2 site, and ranged from less than 0.003 to 0.147 mg/L, with the highest concentration occurring midway through the till. The concentration of P in extracted pore water from the LFO2 site was below 0.020 mg/L for each sample and did not show the high concentration shown in the groundwater. The concentration of P in groundwater at the CWO1/O2 site increased with depth to the base of the till unit, and then decreased in the aquifer. The concentration ranged from 0.007 mg/L in the surficial sand and gravel to 0.123 mg/L at the base of the till. In short, the evidence for P moving vertically in groundwater at these sites was lacking.

At the HFC site, the P groundwater concentrations range from 0.005 mg/L to 0.082 mg/L. The lowest concentration was found in the surficial aquifer, and the highest concentration was found in the confined aquifer. The HFC site pore water samples were all below the detection limit, except for HT-175, which had a total P concentration of 0.082 mg/L. Groundwater samples at the Olivia site range from 0.021 to 0.102 mg/L for P concentration, with the highest concentration from a municipal well in the confined aquifer. The shallowest piezometer in the surficial aquifer has a concentration of 0.072 mg/L for P. The highest concentration of P in the confining unit was 0.076 mg/L, and the lowest in the confining unit was 0.021 mg/L. For pore water samples at the Olivia site, all samples were below the detection limit.

The redox conditions of the till confining units at all sites suggest reducing conditions are prevalent in the till. Some till unit groundwater samples suggest more strongly reducing conditions in some of the till units compared to others. For example, the Olivia site has a large increase in dissolved Fe and a decrease in SO_4 from the top to the bottom of the till unit, suggesting possible reduction of SO_4, while at the LFO2 site SO_4 is seen throughout the till unit. Anomalies in dissolved oxygen (DO) concentrations in groundwater where there is no NO_3 present in the groundwater occurred at more than one site. The LFO1, LFO2, and Olivia sites all had the presence of DO at depths where NO_3 was not found.

Dissolved oxygen in the groundwater samples did not always decrease with depth at the sites. For the CWO1/O2 site, there was a quick decline in DO with depth, as the groundwater concentration decreased from 0.5 mg/L to 0.2 mg/L in the first 80 feet of the formation (fig. 17). Furthermore, the DO concentration stayed low (0.2 mg/L) for the rest of the remained of the core and into the confined aquifer. A DO concentration as high as 0.2 mg/L may indicate no oxygen present, since the uncertainty for DO readings is ±0.2 mg/L (Lewis, 2006). Manganese concentrations at the CWO1/O2 site had a range of 70 to 749 ug/L, with the highest concentration in the shallowest piezometer. The iron concentrations were from 13.7 to 1,240 ug/L, with the highest groundwater concentration found in piezometer CWO1-B, around 225 feet BLS. For SO_4, the CWO1/O2 site groundwater samples usually had a higher concentration of SO_4 present in the first 130 feet ranging from 0.30 to 77 mg/L, and then the piezometers below that did show lower concentrations ranging from 0.60 to 3 mg/L. Iron and Mn would tend to covary, both increases and decreases, through the till unit. Nitrate was absent in the till unit (fig. 17).

At the Litchfield site, both the LFO1 and LFO2 nests had higher DO concentrations in the till compared to the confined aquifer or the surficial aquifer (fig. 17). These till DO concentrations were higher than expected with the presence of dissolved Fe and Mn, and the lack of NO_3-N indicated reducing conditions (figs. 16 and 17). The LFO1 site only had anion information pertaining to redox conditions, but the LFO2 site had both anion and cation data. Manganese at the LFO2 site ranged from 92 to 515 ug/L, and Fe ranged from 7.4 to 2150 ug/L. Manganese increased with depth to the highest concentration around 60 feet BLS, and then decreased in concentration with increasing depth. Iron concentrations in the groundwater at the LFO2 site had a peak concentration of 2060 ug/L around 80 feet BLS, but the highest concentration was in the confined aquifer. Sulfate at the LFO2 site ranged from 48 to 202 mg/L, with the highest concentration in groundwater closer to the surface at around 34 feet BLS. At the LFO1 site, SO_4 ranged from 58 to 113 mg/L, with the highest concentration around 50 feet BLS.

At the Cromwell site, the till and confined aquifer were generally reducing environments (fig. 17). Dissolved oxygen was very low and dissolved Fe and Mn were present throughout the profile. NO3-N was present in the surficial aquifer, but then not detected below that point (fig. 16).

At the Olivia site, there was evidence for the presence of reducing environments throughout the till confining unit, though there was an anomalously high DO value at piezometer OT-60 (fig. 17). Groundwater concentrations of NO_3 at the Olivia site were below detection limit in the till confining unit below the shallowest piezometer (fig. 16). The Olivia site DO concentrations had a range from 0.2 to 6 mg/L, with the DO increasing with depth to 6 mg/L at OT-60 (around 60 ft. BLS), and then decreasing to 0.2 mg/L by piezometer OT-145 (around 143 ft. BLS) (fig. 17). The range for Mn at the site was 49 to 3300 ug/L. Manganese at the Olivia site peaks in concentration around 20 ft. BLS (OT-20), then decreased in the groundwater from piezometers in the till confining unit before increasing slightly in the confined aquifer. The Fe concentrations had a range from 0.06 to a little over 1.8 mg/L. Iron concentration in the groundwater sample from OT-60 does drop significantly, perhaps in connection to the unusually high concentration of DO. After this initial drop, there was a steady increase in Fe concentration throughout the till, and then a decrease in concentration in the confined aquifer. Sulfate concentrations at the Olivia site were between 1.7 to 42 mg/L, with the highest concentration found in samples from OT-20. Sulfate concentrations decrease after 20 ft. BLS, increase again in OT-145, and then decrease in concentrations in the confined aquifer. Other than the DO concentration for OT-60, the lack of NO_3 and the presence of dissolved Fe and Mn did indicate a primarily reducing environment throughout the till at the Olivia site (figs. 16 and 17). There may be an Fe-reducing zone in the bottom half of the till confining unit, where there was a steady rise in Fe concentration.

The HFC site till confining unit demonstrated definitive signs of a reducing environment, as there was a lack of DO and NO_3, and there was an increase in diss. Fe concentrations with depth and a decrease in SO_4 with depth after a peak concentration (figs. 16 and 17). The HFC site DO concentrations did not vary much through the till confining unit, only ranging from 0.2 to 0.3 mg/L (fig. 17). Manganese groundwater concentrations had a range from 0.1 to 0.89 mg/L at the HFC site, with an increase in concentration from HT-115 (approximately 114 ft. BLS) to HT-175 (approximately 174 ft. BLS), before the concentration declined in the till right above the confined aquifer and into the aquifer. Iron concentrations had a range from 0.022 to 0.49 mg/L, with the peak concentration found in the groundwater sample from HT-115. Iron concentrations then remained steady in the till and declined in the confining unit. The HFC site SO_4 concentrations had a range from 7 to 40 mg/L, with a steady increase in SO_4 until a peak concentration at HT-140 (approximately 140 ft. BLS), which was followed by a steady decline in SO_4 in the till below and into the confined aquifer.

The anomalously high DO concentrations at the Litchfield and Olivia sites may be explained by several possibilities. Dissolved oxygen was measured in the field by pumping groundwater directly from the piezometers and through a YSI multi-parameter water quality monitor. There was the possibility that air bubbles trapped in the tubing or aeration of the groundwater from pumping may have affected the results with the anomalous DO concentrations (Lewis, 2006). Another possibility was that piezometer installation could have resulted in oxygenation in some of the piezometers, which can than affect redox analytes (Cherry and others, 2004). This may explain why the increase in DO at Olivia affected the Fe concentration. The other possibility was that the anomalous DO groundwater samples were natural, although that would be unusual for groundwater in confining units at the depths where samples were taken. Perhaps secondary porosity features, such as fractures, could explain the DO concentrations, if the DO concentrations were representative of the groundwater at the piezometer screened interval depths. However, for the LFO2 and Olivia sites, ^3H concentrations did not suggest the presence of younger, more oxygenated groundwater that might have reached the depths in the till that the increased DO concentrations are present.

Groundwater type

A Piper plot (Piper, 1944) was used to characterize the groundwater type and evolution at each site (figure 18). Some evidence for groundwater geochemistry evolution through the till unit flow paths (shallowest to deepest) was found at two of the sites. The Olivia site showed possible differences between shallower, younger groundwater, and deeper, older groundwater along the vertical transect. The two shallowest piezometers at the Olivia site have more Ca- HCO_3 and Mg-HCO_3 dominant water, while below 60 feet in depth the piezometer groundwater samples were Na-HCO_3, or approaching Na-HCO_3, type water. At the LFO2 site, the two most shallow piezometers had higher Ca and Mg, and less Na when compared to the groundwater from piezometers deeper in the till. However, at the LFO2 site all groundwater samples were still in the Ca-HCO_3 and Mg-HCO_3 (or between Ca and Mg) type water range except for groundwater from LFO2-E, the deepest till piezometer, which approaches the Na-HCO_3 type water range. Most of the sites stayed within the Ca or Mg cation (or between) dominant water-type and the HCO_3 anion dominant water-type, with some groundwater samples approaching the Na end member for cations or the sulfate end member for anions. The HFC site does have one groundwater outlier from piezometer HT-140, that is Na-HCO_3 dominant. This could suggest Na-bentonite contamination from the piezometer installation process occurred at HT-140, or that there is some geologic influence on the groundwater that intercepts the HT-140 screened interval.

Geochemistry summary

In conclusion, the geochemical data show that the Olivia and LFO2 sites most likely had longer travel times through vertical till profiles, based on the lack of ^3H found at depth in the till units and the presence of possible groundwater type evolution with depth. The HFC and LFO1 sites' geochemical data showed evidence for a faster groundwater flux through the vertical till profiles because of ^3H presence throughout both till units, and the lack of groundwater type evolution with depth. The Cromwell site geochemical data showed that while modern groundwater was reaching the confined aquifer below the till unit at the site, the vertical transect through the till observed was not likely how the water was reaching the confined aquifer (based mainly on the ^3H data). Possible anthropogenically-sourced Cl did not always agree with the groundwater ^3H data, as seen at the Olivia and LFO2 sites, where Cl/Br concentrations in the till unit were close to or above 250 when no ^3H was present. This was possibly due to a geologic source of Cl along the flow paths, a Cl influence during the drilling process, or perhaps the till systems were experiencing anthropogenic Cl loading and the movement of Cl in the till groundwater systems was different than the movement of ^3H (an example being possible differences in diffusion versus advection within till for Cl anions compared to ^3H).

Field component sources of uncertainty

Sources of uncertainty for the hydraulic properties in this study often stem from the lack of data that comes from observing point information in a complicated 3-dimensional groundwater system. At each site, one or two continuous cores from boreholes were analyzed by the MGS and were used for understanding the stratigraphy and hydrostratigraphy for the entire vertical transects. Heterogeneity in the geology of the systems, such as sand or clay lenses, may have been missed because of the inability to analyze all cores from piezometer installation. The geometric mean K_h values for the till units are based on slug test results from the piezometer screened intervals, however values of K_h between the screened intervals are unknown. Possibly, an important geologic layer with a distinct K_h value that affects the vertical flux of groundwater could have been overlooked. There is also the possibility that drilling, and installation of the piezometers and wells had an effect on the hydraulic conductivities estimated from slug and pumping tests. For instance, drilling, especially auger drilling, can produce a smear zone along a borehole that creates a zone of lower K along the wall of the borehole, when the actual formation has a higher K (Cherry and others, 2004).

For the geochemical properties observed during this study, there is also the possibility that drilling and installation of piezometers effected the samples. Sodium-bentonite contamination of groundwater and intrusion into screened intervals may have occurred during the piezometer installation process for some piezometers. Analytes that are associated with bentonite contamination include Cl, Br, Na, and SO_4, which can increase initially after installation and then decrease through time (Remenda and Van der Kamp 1997). Though, confined aquifer groundwater samples have a similar amount of Na to till piezometer groundwater samples for the Olivia, HFC, and Cromwell 1/2 sites (data available on https://waterdata.usgs.gov/nwis/). At the LFO2 site, there is less Na is the confined aquifer compared to till piezometers. At the HFC site, HT-140 groundwater may have Na-bentonite contamination since the groundwater from this sample has very high Na concentration, compared to all other piezometer and well groundwater samples. These sources of uncertainty in whether or not the till groundwater was affected by piezometer drilling and installation partially stem from only having one round of USGS (major cations, anions, and nutrients) sampling completed.

Heuristic groundwater modeling

A series of model scenarios demonstrated that pumping groundwater from buried aquifers affected water levels and fluxes through the till. The pumping magnitude effects varied substantially across the range of hydrogeologic properties observed at the field sites in this study. Response variables extracted from steady-state model outputs are given in table 8.

The north and south constant head boundary conditions minimally contributed to the water pumped from the buried sand unit for all but three model scenarios (table 8). In these three scenarios, approximately 10 percent of the pumped water originated from the boundary cells. Calculations of water emanating from boundary cells were implemented as a quality assurance measure, but still yielded useful information about the water source to the wells. These three scenarios all had a low Kv till overlying the buried sand unit and a high Kh of the middle unit (LvHc). Eighty to 90 percent of the water entered the buried sand unit through its sides. The implication is that in this hydrogeologic setting, the contributing area for pumping is laterally extensive, extending farther than 10 mi from the pumping center.

The small buried sand unit size of 1.0 mi by 0.5 mi (Ls) generally could not sustain pumping at 900 gpm, unless the buried sand unit was surrounded by conductive till (Hc). The most comparable field site to this situation is the Olivia site where two municipal wells were completed in a buried sand and gravel aquifer that is mapped to be 0.08 mi^2 (Bradt, 2017), though the aquifer could be larger because its extent has been estimated with very limited data. These wells pump at an approximate rate of 123 gpm and the geometric mean of the hydraulic conductivity of the till confining unit was 0.004 ft/day. The pumping rate has been maintained for many years in this small confined aquifer, but substantially increasing the pumping may not be feasible under the assumption that the aquifer truly is small.

Across all of the model scenarios, very little water entered the buried sand unit from the till below as water was being pumped from the buried sand unit. The maximum contribution from below among all of the scenarios was 9.7 percent, which occurred in an extreme case with a small, isolated buried sand unit (0.5 mi^2, Ls), under low-conductivity till (0.001 ft/day, Lv), and surrounded on all sides by low-conductivity material (0.05 ft/day, Lc). When the aquifer size was increased and surrounded by low conductivity till, the percent contribution from below decreased to about 4 to 5 percent. When the K_v of the overlying till and K_h of the middle unit was increased, the percent contribution from below generally decreased to below 1 percent of the total water entering the buried sand unit.

Leakage from the surficial unit into the till within the local area under ambient (no pumping) conditions varied in response to several hydrogeologic factors and indicated that till properties as well as the fluxes of water through material underlying the till were important. Not surprisingly, as till Kv became smaller, the amount of leakage also decreased and lateral flow through the surficial unit increased. However, the size of this response was affected by the Kh of the material underlying the till. For example, in the LsHvLc (small sand unit, high till Kv, low middle unit Kh) the ambient leakage into the till was small, only about six percent of inputs into the surficial unit, but when the Kh of the middle unit was increased (Hc, 30 ft/day), the leakage into the top of the till increased to 37 percent (table 4). The ambient leakage into the upper till also increased as the size of the buried sand unit increased.

Evaluation of variations in till vertical hydraulic conductivity, aquifer size, and middle unit horizontal hydraulic conductivity on drawdown, leakage into till, and source of water to wells

Three response variables across the full range of permutation parameter values are presented in figure 19: (1) maximum drawdown in the till (plots A - C, (2) pumping-induced increase in leakage to till from surficial unit (plots D – F), and (3) the amount of water entering the buried sand unit across the top face of the unit (plots G – I). For the following discussion, the term “sensitivity” will be used to describe, in relative terms, how much a given response variable changed across the range of model parameter values used in the series of permutation model runs. Comparing the same-colored lines across rows of graphs in figure 19 provided a visual for the sensitivity of response variables to aquifer size. The slope of the same-colored lines in each graph provided a visual for the sensitivity of each response variable to the Kv of the till unit. The vertical separation between points for a given Kv value provided a visual for the sensitivity of each response variable to the Kh of the middle unit surrounding the buried sand unit.

A couple of general trends in response variable sensitivity to parameter changes are apparent across most of the plots in figure 19. Comparing the solid red and blue lines demonstrated that the response variables were much more sensitive to changes in the middle unit Kh with low overlying till Kv, as demonstrated from the vertical separation of points when till Kv = 0.001 ft/day. Secondly, the response variables tended to be more sensitive to changes in till Kv between 0.001 and 0.05 ft/day than between 0.05 to 2.0 ft/day.

The maximum drawdown in the till in model layer 3 was highly variable across the permutation runs (Fig. 19, A-C). In plot A, the dotted lines indicated that the specified pumping rate of 900 gpm was not sustained and therefore cannot be compared directly to the other model runs. In the remaining model runs, the maximum drawdown decreased as the Kv of the till increased. This seemed counter-intuitive, especially in light of field results from this project where short-term drawdowns were not apparent in low K tills. However, keep in mind the results discussed here were from steady-state models and show conditions after 1,000 years of pumping. The maximum drawdown in the till generally decreased as the buried sand body size increased and the maximum drawdown was especially sensitive to aquifer size below 4.5 mi^2 (compare green lines in fig A and B). At low till Kv, there is a consistent inverse relation between the middle unit Kh and drawdown in the till.

In all cases, the introduction of pumping stress to the model system increased the amount of water leaking from the surficial unit into the top of the till unit (fig. 19 D – F). These pumping-induced increases in leakage represented a reduction in groundwater discharge out of the local area and groundwater discharge to local streams and lakes that is not met by increased fluxes from outside the local area (fig 10, model layout). In some model scenarios, over 20 percent of the inputs within the

5 mi local were lost from the surficial unit due to pumping. Generally, the magnitude of the increase in leakage increased as the ambient leakage (no pumping) decreased (table 4). In other words, the largest pumping-induced increases in leakage occurred in low Kv tills. As with the drawdown results, this seemed counter-intuitive based on our field study, but this modeling represented long-term conditions.

There is a strong interaction between the middle unit Kh and the overlying till Kv on pumping-induced leakage. It was highly sensitive to the middle unit Kh at low till Kv (0.001 ft/day), and insensitive to middle unit Kh at high till Kv. Pumping-induced leakage was insensitive to changes in aquifer size. The practical implication of this result is that in order to accurately model these fluxes, which are important for managing water resources near the surface, reliable information on either the till Kv or the connectivity among buried aquifers is needed.

The relative amounts of water reaching a confined aquifer from above (and by implication, from the sides) changed drastically with the range of hydrogeologic characteristics observed in this study (fig. 19 G – I). As previously discussed, water entering the buried sand unit from below was almost always less than one percent of the total. Not surprisingly, the percent of water entering the aquifer from above increased as the lateral extent of the aquifer increased. At one extreme, 98 percent of the water entered the aquifer directly from the till above. This model run had a conductive till overlying a large sand body surrounded by poorly conductive materials (HsHvLc). In the other extreme case, only about 10 percent of the water entered the aquifer directly from the till above. This model run had poorly conductive till overlying a small sand body that was adjacent to conductive till (LsLvHc). This model run had an extensive contributing area, as indicated by the increased water supplied by the model boundary 10 miles away from the pumping center.

Evaluation of variations in pumping and aquifer transmissivity on drawdown, leakage into till, and source of water to wells

For the next set of model runs, a set of sensitivity runs were completed in which one model parameter or set of parameters was varied and the remainder of the model parameters are from the base model (MsMvMc) (fig. 19; table 8).

Increases in pumping from 300 gpm to 2,250 gpm caused higher drawdowns in the till, substantially increased the percentage of water leaking into the till from the surficial unit, and only moderately decreased the percentage of water entering the aquifer directly from the overlying till (fig. 20). At the 300 gpm pumping rate, pumping only increased the leakage by about 4 percent, but at the 2,250 gpm pumping rate, the leakage increased to over 40 percent of water inputs to the surficial unit within the local area. These pumping-induced increases in leakage represented a reduction in groundwater discharge out of the local area and groundwater discharge to local streams and lakes that was not met by increased fluxes from outside the local area (fig 10, model layout). These results indicated that the effect of pumping on surface-water resources depended on the pumping rate. The 900 gpm rate was representative of the pumping rate from the confined aquifer at Litchfield. The city of Litchfield pumps at an average rate of 630 gpm, or 340 million gallons per year, and there are other high capacity permits within the same buried aquifer, as was evident from the large summer drawdowns in the buried aquifer hydrographs and from the aquifer test data (Blum and Woodside, 2017). At the 900 gpm pumping rate, pumping increased leakage into the upper till by about 14 percent, as compared to ambient conditions.

Two model runs, CRtrlk and LFtrlk, were intended to be “Cromwell transmissivity-like” and “Litchfield transmissivity-like”. These models were not intended to replicate actual observed responses at these sites, rather these model runs were used to compare and contrast responses to pumping. In these two scenarios, the till Kv and aquifer transmissivity were set to approximate results from aquifer tests completed at each site. The steady-state models show, over long periods of time, a greater drawdown in a Litchfield-like setting compared to a Cromwell-like setting. This was consistent with the model results presented earlier, where less conductive tills exhibited higher drawdowns in steady-state conditions. The pumping-induced increase in leakage to till was about the same between the two model runs. About 80 percent of the water in the Cromwell-like scenario entered the buried aquifer directly from the overlying till compared, to only about 30 percent in the Litchfield-like scenario. This meant that there was a more laterally extensive contributing area for a Litchfield-like setting than compared to a Cromwell-like setting, which has implications for managing drinking water quality. Because till Kv and buried aquifer Kh were varied simultaneously in these model runs, it was difficult to tell which parameter was exerting a greater effect on the response variables. In a separate set of variation runs (BSkh), the response variables were sensitive to changes in the buried sand Kh from 30 to 100 ft/day, and the response variables were sensitive to changes in till Kv between 0.0001 and 0.05, suggesting that both attributes played a role in the different responses of the Cromwell-like and Litchfield-like setting.

Summary

Confined aquifers overlain by till confining units provide drinking water to thousands of Minnesota residents. Vertical leakage through overlying till confining units is largely unknown, causing uncertainty in predicting aquifer sustainability. As part of a study of confined aquifer sustainability, the U.S. Geological Survey, Iowa State University, Minnesota Geological Survey and Minnesota Department of Health investigated vertical groundwater flow through till confining units at four representative sites in Minnesota. Glacial deposits of the Des Moines Lobe (New Ulm Formation till) were characterized in Litchfield, Minnesota, glacial deposits of the Superior Lobe (Cromwell and Aitkin Formation tills) were characterized in Cromwell, Minnesota, glacial deposits of pre-Wisconsin age (Good Thunder Formation till) were characterized at Olivia, Minnesota, and glacial deposits of the Wadena Lobe (Hewitt Formation till) were characterized at the Hydrogeology Field Camp (HFC) site near Akeley, Minnesota.

Field data were primarily collected from a series of five piezometer nests, two at the Litchfield site and one at every other study site. A total of 31 piezometers were installed. Each nest comprised between five and eight piezometers screened at discrete vertical intervals through hydrostratigraphic units present at the sites including (if present) surficial aquifers, till confining units, confined aquifers, and underlying bedrock.

A combination of hydrologic and geologic data, geochemical analyses, and modeling techniques were used to quantify the variability of hydraulic properties and flux of water through till confining units to confined aquifers. Pressure transducers were emplaced measure hydraulic head fluctuations. Groundwater samples from the piezometers and pore water samples from till cores were analyzed for major ions, nutrients, enriched tritium, and stable isotopes (oxygen, δ18O and deuterium, δ2H) of water. Slug tests were performed to estimate the horizontal hydraulic conductivity (Kh) at each piezometer screen and aquifer tests were performed to estimate the bulk vertical hydraulic conductivity (Kv) of the till confining units. A series of heuristic steady state MODFLOW models were used to evaluate groundwater fluxes in till confining across the range of till hydraulic characteristics observed at the field sites.

The first Litchfield piezometer nest (LFO1) was in a leaky 60-ft thick till profile with an average of 47 percent sand, 34 percent silt, and 19 percent clay. The site had an average downward hydraulic gradient of 0.56 in the till, and the largest gradient was near the base of the till. Drawdown responses were observed in all till piezometers during the aquifer test at the site. The geometric mean Kh of two till piezometers was 0.07 feet per day (ft/day), whereas the bulk Kv determined from an aquifer test at Litchfield was 0.001 ft/day. These two K values along with other site information to were used calculate specific discharge and travel time through till according to Darcy's Law. Specific discharge ranges from 2.4 inches per year (in/yr, Kv) to 177 in/yr (Kh) and travel times vary from 1 year (yr, Kh) to 74 yr (Kv). Tritium was detected in all till piezometers, indicating the presence of modern water throughout the till profile. "Modern" indicates groundwater that was last exposed to the atmosphere sometime after 1953. Chloride to bromide ratios are near 250 throughout the till, indicating a possible presence of anthropogenic-sourced chloride throughout the till.

The second Litchfield piezometer nest (LFO2) was only a half mile away from LFO1 and in the same New Ulm Formation, but contained an effective confining unit in the lower portion of the till. It was a 115-ft thick till profile with an average of 52 percent sand, 31 percent silt, and 17 percent clay. The site had an average downward hydraulic gradient of 0.48 in the till, and the largest gradient was near the base of the till. Drawdown responses were not observed in any till piezometers during the aquifer test at the site. The geometric mean Kh of five till piezometers was 0.0002 feet per day (ft/day), whereas the bulk Kv determined from an aquifer test at Litchfield was 0.001 ft/day. These two K values along with other site information to were used calculate specific discharge and travel time through till according to Darcy's Law. Specific discharge ranges from 0.4 in/yr (Kh) to 2.1 in/yr (Kv) and travel times vary from 165 yr (Kv) to 912 yr (Kh). Tritium was only detected in the two uppermost till piezometers, to about 35 feet into the till, indicating non-modern water (older than 1953) was present through most of the till profile. Chloride to bromide ratios are near 250 to about 60 ft into the till, indicating a possible presence of anthropogenic-sourced chloride to this depth.

The Cromwell nest was in a leaky 120-ft thick till profile with an average of 57 percent sand, 31 percent silt, and 13 percent clay. The site had an average upward hydraulic gradient of 0.02 in the till, but gradient directions were variable throughout the till. Drawdown responses were observed in all till piezometers during the aquifer test at the site. The geometric mean Kh of five till piezometers was 0.06 feet per day (ft/day), whereas the bulk Kv determined from an aquifer test was 1.1 ft/day. These two K values along with other site information to were used calculate specific discharge and travel time through till according to Darcy's Law. Because of the upward gradient at this site, fluxes are from the base of the till to the overlying surficial aquifer. Specific discharge ranges from 4.4 in/yr (Kh) to 84 in/yr (Kv) and travel times vary from 4 yr (Kv) to 81 yr (Kh). However, these calculations ignore the broader flow environment at this site. Tritium was not detected in till, but was detected in the surficial aquifer and the confined aquifer. The hydraulic gradient data and the ^3H data suggest that recharge to the confined aquifer enters the system somewhere up-gradient in the same buried aquifer system or perhaps through a window through the overlying till confining unit where the hydraulic gradient in the till is downward. This suggests that the till sequence observed near the water supply well may have little direct influence on the quality and quantity of water at Cromwell. Rather, the anthropogenic activities and geologic materials at a distal recharge area (yet to be defined) may affect the water observed in the confined aquifer at the Cromwell site. Chloride to bromide ratios were variable in the till and were above 250 at a couple locations.

The HFC nest was in a leaky 100-ft thick till profile with an average of 67 percent sand, 22 percent silt, and 11 percent clay. The site had an average downward hydraulic gradient of 0.04 in the till. Drawdown responses were observed in all but the uppermost till piezometer during the aquifer test at the site. The geometric mean Kh of two till piezometers was 0.03 feet per day (ft/day), and the bulk Kv determined from an aquifer test was 0.031 ft/day. These two K values along with other site information to were used calculate specific discharge and travel time through till according to Darcy's Law. Specific discharge ranges from 5.4 in/yr (Kh) to 6.0 in/yr (Kv) and travel times vary from 50 yr (Kv) to 56 yr (Kh). Tritium was detected in all till piezometers, indicating the presence of modern water throughout the till profile. Chloride to bromide ratios were well below 250 throughout the till, indicating that anthropogenic-sourced chloride is not a major factor at this site, likely because this site is in a remote forested region.

The Olivia nest contained an effective confining unit in the lower portion of the till above the confined aquifer. It was a 166-ft thick till profile with an average of 37 percent sand, 40 percent silt, and 23 percent clay. The site had an average downward hydraulic gradient of 0.13 in the till, with the largest gradients at the base of the till and an extremely large gradient of 2.25 across the till/confined aquifer boundary. Drawdown responses during an aquifer test were not observed in any till piezometers because of a prolonged reverse water-level fluctuation response in most till piezometers. The geometric mean Kh of five till piezometers was 0.004 feet per day (ft/day), and the bulk Kv determined from an aquifer test was 0.0012 ft/day. These two K values along with other site information to were used calculate specific discharge and travel time through till according to Darcy's Law. Specific discharge ranges from 0.7 in/yr (Kv) to 2.3 in/yr (Kh) and travel times vary from 214 yr (Kh) to 730 yr (Kv). Tritium was only detected in the uppermost till piezometer, at a depth of about 8 feet into the till, indicating non-modern water (older than 1953) was present through most of the till profile. In this same piezometer, chloride to bromide ratios were above 250, indicating the likely presence of anthropogenic-sourced chloride. Chloride to bromide ratios were far above 250 in the lower half of the till, but primarily because of extremely low bromide concentrations and not from elevated chloride concentrations compared to the uppermost till piezometer.

Stable isotopes of oxygen and deuterium showed no evidence of glacial-age groundwater greater than 11,000 years old in the till confining units at any site. This is corroborated by calculations of travel time according to Darcy's law and ^3H concentrations

Diverse tills were evaluated at the four study sites and comparisons across sites yield some useful insights for generalizing these results.

Till hydraulic properties are highly variable in vertical profile. Vertical hydraulic gradients were smaller at sandy sites compared to clayey sites. Vertical sequences of till deposits show evidence of extensive vertical hydraulic connectivity. The five sequences of till varied in thickness from 60 to 166 feet and relatively narrow sections of the lower portion of till were effective confining units, at two sites, Olivia and LFO2. Sites with sandy till at Cromwell and HFC, were "leaky" confining units, showing drawdown responses throughout their profiles during aquifer tests. The upper portions of till were hydraulically connected at three sites as evidenced by similarities in hydraulic head fluctuations between the surficial aquifer and till piezometers.

Till hydraulic properties are also highly spatially variable. Two piezometer nests in the same New Ulm Formation at the Litchfield site and separated by only a half mile, had the highest and lowest geometric mean hydraulic conductivity (K) of all piezometer nests. One site, LFO2, had till with an effective confining unit that limited vertical flow to the underlying aquifer whereas the other site, LFO1, had a very leaky till profile.

A drawdown response to pumping from the confined aquifer was typically observed in till piezometers screened in sediments with at least 55 percent sand and less than 15 percent clay. The average percent sand and clay for a given till profile was correlated with log of the bulk vertical hydraulic conductivity (Kv) determined from aquifer tests. However, the percent sand or clay from core sections at the same depth as piezometer screens were not correlated with the Kh determined from slug tests. This indicates that factors in addition to textural composition are affecting the hydraulic properties of till (or measurement thereof) at the localized scale of slug tests, but at the larger aquifer-test scale, textural composition is indicative of bulk till hydraulic characteristics.

The heuristic modeling demonstrates the importance of having accurate information about the hydrogeologic setting (particularly about the vertical hydraulic conductivity of overlying till, the areal extent of the buried aquifer, and the lateral connectivity of the buried aquifer to other aquifers) when evaluating the sustainability of pumping water from confined aquifer systems. Three response variables were examined in detail from the steady state models: maximum drawdown in till, pumping-induced leakage from the surficial unit into the till confining unit, and the source of water to the buried sand unit (expressed as the percent of water entering the aquifer directly from the overlying till). Over long periods of time (hundreds of years), pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients increased leakage into and through till. The percentage of water entering a buried aquifer directly from the overlying till ranged from 10 to 98 percent among the model scenarios; when only 10 percent of the water entered the aquifer from above, water fluxes increased at the model boundary, 10 miles away from the pumping center. The percentage of water entering the aquifer from above was demonstrated to be sensitive to buried aquifer size, Kv of till, and Kh of material adjacent to the buried aquifer. In almost all cases, less than one percent of the water entered the buried sand from the underlying till.

In conclusion, groundwater flowing vertically downward through till confining units (leakage) replenishes water pumped from confined aquifers. Till hydraulic properties, such as presented in this report, are required to quantify leakage rates through till. Till hydraulic properties are variable over short distances and profoundly affect leakage rates, demonstrating the importance of site-specific till hydraulic data for evaluating the sustainability of groundwater withdrawals from confined aquifers.

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Staley, A.E., Wagner, K., Nguyen, M., and Tipping, R., 2018, Core descriptions, borehole geophysics, and unit interpretations in support of Phase I and II USGS Hydrologic Properties of till Investigation, Minnesota Geological Survey, 29 p.

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Appendix 1-Well and piezometer construction details

This appendix contains tables with detailed well and piezometer construction information.

Appendix 2-Slug test information

All water-level data used for slug test analyses, Aqtesolve files, and plots are available at the data release for this report (Maher and others, 2020).

The program AQTESOLVE has curve matching solutions for slug tests done in confined and unconfined aquifers. During the slug test analyses, the KGS model (Hyder and others, 1994) was used to analyze the water level response to slug tests. The KGS model has a solution for confined and confined aquifers. This method applies a curved solution to declining or rising water-level data collected during a single-well, slug test in an unconfined or a confined aquifer with a completely or partially penetrating well. The KGS method assumes the following:

- The unconfined or confined aquifer is infinite in extent, homogeneous, and of uniform thickness;
- the potentiometric surface of the aquifer is initially horizontal;
- the slug is introduced or removed instantaneously to/from the well;
- head losses during the test are negligible;
- the water-level response from the slug test is classified as unsteady or overdamped (non-oscillating); and
- water is released instantaneously from storage with decline of hydraulic head; and
- The KGS model provides corrections for low permeability materials around the well screen, such as mud residue from well installation, and can consider hydraulic conductivity anisotropy (Arnold, 2015).

A confined KGS model without wellbore skin is identical to the Dougherty-Babu (1984) solution (Duffield, 2007). This equation takes into account the following physical parameters of where the piezometer is emplaced: confined aquifer thickness/saturated thickness, the distance from the water table to the top of the screen, the distance from the water table to the bottom of the piezometer screen, the screen thickness, the elevation of the piezometer from the base of the aquifer, and the elevation of the top of the piezometer screen from the base of the aquifer (Duffield, 2007). For the unconfined KGS model without a wellbore skin, the following physical parameters of where the piezometer is emplaced are considered: the depth to the top of the well screen, the depth below top of aquifer, the screen length, and the saturated thickness of the unconfined aquifer (Duffield, 2007).

Since the piezometers in the till are not below the confining unit (they are in the confining unit) they are not confined, and do not have a potentiometric surface as a piezometer screened in a confined aquifer does. Therefore, since the till piezometers are physically not confined, the unconfined solution was used to estimate hydraulic conductivity.

Different solutions were used for the piezometers screened in the confined aquifers and the unconfined aquifers at the sites. The KGS model for confined aquifers without a wellbore skin was used for analyzing the results from slug tests from piezometers in the confined aquifers, that did not have an oscillatory response. The KGS model for confined aquifers has the same assumptions as for unconfined, except that the aquifer is confined instead of unconfined (Duffield 2007). The Butler (1998) inertial solution was used for results in confined aquifers that showed inertial effects because of an oscillatory water-level response. The Butler (1998) inertial solution accounts for oscillatory responses in confined aquifers due to a high K (Duffield 2007). Assumptions of the Butler (1998) solution were the same as the KGS solution, except that the flow is in a quasi-steady state and the wells must be partially penetrating (Duffield 2007).

For unconfined aquifer results that showed inertial affects present during the slug tests, the Springer-Gelhar (1991) inertial solution was used to account for the oscillatory affects. The assumptions of the Springer-Gelhar (1991) inertial solution are the same as the Butler (1998) solution except that the aquifer is unconfined, and the wells can be either fully or partially penetrating.

Appendix 3-Quality assurance for water quality samples

Replicates of groundwater samples for three piezometers, HT-200 from the HFC site, OT-145 from the Olivia site, and LFO2-F from the Litchfield site, were analyzed (Table 3.1). Equipment blanks were done for three piezometers, CWO2-C from the Cromwell site, HT-175 from the HFC site, and OT-60 from the Olivia site (Table 3.1). Most groundwater replicate samples range between 0 to 5 percent difference between the replicates and the non-replicates sample analyte concentrations. A few range from five to ten percent difference in analyte concentration. The piezometer replicate samples that have greater than a ten percent difference from the non-replicates for HT-200 included the sample for filtered, inflection-point titration carbonate concentration with a percent difference of 80%, filtered iron concentration with a percent difference of 11.1%, filtered phosphorus concentration with a percent difference of 11.1%, and filtered nitrate with a percent difference of 10.5%. The replicate for the groundwater sample for OT-145 had no percent differences between the replicate and non-replicate analyte concentrations that were above ten percent. For LFO2-F, the only piezometer replicate sample that was above a ten percent difference was the sample analyzed for filtered, inflection-point titration carbonate with a percent difference of 18.2%. Almost all equipment blanks analyzed were below detection limits for the analytes sampled. The only exception was the filtered, inflection-point titration alkalinity for all three piezometers, ranging between 1 to 3 mg/L as $CaCO_3$, filtered, inflection-point titration bicarbonate where the piezometers ranged from 1.6 to 5.2 mg/L, and manganese where two of the piezometers (CWO2-C and OT-60) have detectable manganese ranging from 0.22 to 0.24 ug/L. These concentrations are still very low, especially when compared to the concentrations observed in the samples.

Laboratory comparisons were done for groundwater samples from the OT-13, OT-20, and OT-35 piezometers, which were collected at the same time for both the USGS National Water Quality Laboratory (USGSNWQL) and for Rick Knurr (who worked at the University of Minnesota Laboratory during the Litchfield and Cromwell site analyses and then worked at the Ion Chrom Analytical Laboratory during the Olivia and HFC site analyses) (Table 3.2). Only major anions were collected for both laboratories, and only the Olivia site piezometers were taken at the same time, during October, 2017, for the three piezometers listed above. Percent differences may be large, especially with lower concentrations of analytes.

The NO_3 and NO_2 samples most likely had the holding time exceeded between when the whole samples were first delivered to the USGSNWQL laboratory and the split samples were sent to the Ion Chrom Analytical laboratory. Because of the sensitivity on nutrient anions, this may have led to the presence of NO_3 or NO_2 occurring in the sample analyzed by the Ion Chrom Analytical laboratory, when originally the sample had no occurrence of the analytes, as seen in the USGSNWQL analysis.

Chloride and Br concentrations between the two labs show that Cl concentration percent differences were low (less than 2 percent) and bromide percent differences tended to be slightly higher (9 to 20 percent), perhaps because of the lower concentrations of Br compared to Cl. Fluoride concentrations tended to be slightly higher for the USGS NWQL lab compared to Ion Chrom Analytical. Sulfate concentrations were very similar between both labs and were all below five percent difference. Only one piezometer groundwater sample can be compared for NO_3-N (OT-13), as the rest of the samples had one or both NO_3-N below the detection limit. The resulting comparison of NO_3-N had a relatively low percent difference, at 3.5 percent. The percent differences may represent variation between the laboratory analyses and uncertainty with laboratory procedures.

V. DISSEMINATION:

Description: Project milestone results will be communicated to LCCMR staff and to project partners with semi-annual written results. Final results from the project will be presented at a scientific conference and through the publication of a USGS Scientific Investigations Report. The final report will be delivered by June 30, 2020.

Status as of December 30, 2016:

The project workplan was approved by LCCMR. Details about project plans and planning data have been shared and discussed with staff from MNDNR, MDH and the MGS. Two quarterly progress reports have been prepared for USGS management. The detailed project proposal was reviewed and approved by technical specialists from the USGS. One site near Akeley, Minnesota has been selected and permission has been granted to work at that location. In support of the second site, project details were communicated to MDH staff, who were successful in acquiring wellhead protection plans from cities identified as potential study sites.

Status as of June 30, 2017:

Status as of December 29, 2017:

Details about project plans and planning data have been shared and discussed with staff from MNDNR, MDH and the MGS. Quarterly progress reports have been prepared for USGS management.

Status as of June 29, 2018:

The following presentations were given since the last reporting period:

Trost, J.J. Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the sustainability of groundwater withdrawals from confined glacial aquifers presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018 [Link]

Maher, A., Simpkins, W.W., Witt, A., Trost, J.J., Berg, A.M., and Stark, J.R. Hydrogeologic investigation of groundwater flow in till confining beds overlying glacigenic aquifers in south-central and north-central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018 [Link].

Maher, A., Simpkins, W,W., Witt, A., Trost, J., Berg, A., and Stark, J.R. Assessing the Sustainability of Glacigenic Aquifers Underlying Till Aquitards in Minnesota poster presented at the Iowa State Environmental Science Symposium in Ames, Iowa, April 4, 2018.

Maher, A., Simpkins, W,W., Witt, A., Trost, J., Berg, A., and Stark, J.R. Investigation of Groundwater Flow in Till Aquitards Overlying Glacigenic Aquifers at two Sites in Minnesota presented at the Iowa State Geology Seminar in Ames, Iowa, March 2-3, 2018.

Witt, A., Simpkins, W.W., Blum, J., Trost, J.J., Berg, A.M., Stark, J.R. Spatial variability in the vertical connectivity of till confining beds: examples from the New Ulm formation in central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018 [Link].

2 additional abstracts were accepted to the fall 2018 Minnesota Water Resources Conference to be held in St. Paul, Minnesota

Status as of December 31, 2018:

The following presentations were given since the last reporting period:

Maher, A., Simpkins, W., Trost, J., Witt, A., Berg, A., and Stark, J. 2018. Groundwater Flow and Geochemistry of Till Confining Units Overlying Buried Glacial Aquifers: Examples from the Des Moines and Wadena Lobes in Minnesota. GSA Annual Meeting in Indianapolis, Indiana, USA

Trost, J.J., Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the sustainability of groundwater withdrawals from confined glacial aquifers presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018.

Simpkins, W.W., Witt, A., Blum, J., Trost, J.J., Berg, A.M., and Stark, J.R. Spatial Variability in the Vertical Connectivity of Till Confining Units: Implications for Glacial Aquifers in Minnesota presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018.

Status as of June 30, 2019:

The following presentations were given since the last reporting period:

Blum, J. Leakage is for 'Lumpers' – Lessons Learned from Aquifer Tests in Layered Till presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019.

Maher A., Simpkins, W.W, Trost, J., Witt, A., Berg, A., and Stark, J.R. Evidence of anthropogenic contamination in till aquitards at the hydrogeology field camp and Olivia sites in Minnesota poster presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019.

Maher, A., Simpkins, W.W., Witt, A., Trost, J., Berg, A., and Stark, J.R. Groundwater and pore water geochemistry in two till aquitards in Minnesota poster presented at the Iowa State Environmental Science Symposium in Ames, Iowa, April 3, 2019.

Maher, A., Simpkins, W.W., Witt, A., Trost, J., Berg, A., and Stark, J.R. Groundwater geochemistry in Two Till Aquitards in Minnesota: Evidence of Anthropogenic Contamination? Presented at the Iowa State Geology Seminar in Ames, Iowa, March 2, 2019.

Trost, J. and Simpkins, W.W. Groundwater Flow Through Till: tortoise, hare, or not in the race? Presented at the Minnesota Groundwater Association in St Paul, Minnesota, April 25, 2019.

Status as of December 31, 2019:

The following presentation is now available online: Trost, J. and Simpkins, W.W. Groundwater Flow Through Till: tortoise, hare, or not in the race? Presented at the Minnesota Groundwater Association in St Paul, Minnesota, April 25, 2019.

Final Report Summary:

Project results have been and will be disseminated through public presentations and publication of online reports. Results were broadly distributed to hydrology and geology professionals through 13 presentations at state, regional, and national meetings and 2 master's thesis defense presentations. Some of these events retain online versions of abstracts and presentations, which are listed below. The full list of presentations about this project is included in the project workplan. Two master's theses are also available online. A series of products from the Minnesota Geological Survey, Minnesota Department of Health, and the USGS provide geologic descriptions, aquifer test analysis results, geochemical data, and model documentation to support the interpretations written in the final, comprehensive USGS Scientific Investigations Report (SIR).

Published reports:

Final comprehensive report:

Trost, J.J., Maher, A., Simpkins, W.W., Witt, A.N., Stark, J.R., Blum, J., and Berg, A.M., 2020, Hydrogeology and groundwater geochemistry of till confining units and confined aquifers in glacial deposits near Litchfield, Cromwell, Akeley, and Olivia, Minnesota, 2014–18: U.S. Geological Survey Scientific Investigations Report 2020–5127, 80 p.,https://doi.org/10.3133/sir20205127.

Data and other supporting information:

Blum, J.L., and Woodside, J., 2017, Analysis of the Litchfield, Minnesota Well 2 (607420) aquifer test conducted on June 29, 2017, confined quaternary glacial-fluvial sand aquifer: Minnesota Department of Health, aquifer test 2617, 81 p. [Available at: https://www.health.state.mn.us/communities/environment/water/docs/swp/testlitchfield.pdf]

Lund, T., and Blum, J.L., 2017, Analysis of the Cromwell, Minnesota Well 4 (593593) aquifer test conducted on May 24, 2017, confined quaternary glacial-fluvial sand aquifer, Minnesota Department of Health, Aquifer Test 2612, 75 p. [Available at: https://www.health.state.mn.us/communities/environment/water/docs/swp/testcromwell.pdf]

Maher, A.-T., Trost, J.J., Witt, A.N., Berg, A.M., Simpkins, W.W., and Stark, J.R., 2020, Geochemical data, water-level data, and slug test analysis results from till confining units and confined aquifers in glacial deposits near Akeley, Cromwell, Litchfield, and Olivia, Minnesota, 2015–2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9IXC7D3.

Staley, A.E., Wagner, K., Nguyen, M., and Tipping, R., 2018, Core descriptions, borehole geophysics, and unit interpretations in support of Phase I and II USGS Hydrologic Properties of till Investigation, Minnesota Geological Survey, 29 p. [Available at: https://conservancy.umn.edu/handle/11299/204896]

Trost, J.J., Feinstein, D.T., and Jones, P.M., 2020, Heuristic MODFLOW models used to evaluate the effects of pumping groundwater from confined aquifers overlain by till confining units: U.S. Geological Survey data release, https://doi.org/10.5066/P9KOI6T3.

U.S. Geological Survey, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessible at https://doi.org/10.5066/F7P55KJN.

Graduate theses:

Maher, Anna-Turi, 2020, Hydrogeology and groundwater geochemistry of two glacigenic aquitard/aquifer systems in north-central and south-central Minnesota, Graduate Theses and Dissertations, 18006. [Available at: https://lib.dr.iastate.edu/etd/18006/]

Witt, Alyssa, 2017, Hydrogeological and geochemical investigation of recharge (leakage) through till aquitards to buried-valley aquifers in central and northeastern Minnesota, Graduate Theses and Dissertations, 15462. [Available at: https://lib.dr.iastate.edu/etd/15462/]

Full presentations available online:

Blum, J. Leakage is for 'Lumpers' – Lessons Learned from Aquifer Tests in Layered Till presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019. [Abstract; presentation pdf; recorded audio of presentation]

Trost, J. and Simpkins, W.W. Groundwater Flow Through Till: tortoise, hare, or not in the race? Presented at the Minnesota Groundwater Association in St Paul, Minnesota, April 25, 2019. [Abstract; presentation pdf; recorded audio of presentation]

Presentation abstracts available online:

Maher, A., Simpkins, W., Trost, J., Witt, A., Berg, A., and Stark, J. 2018. Groundwater Flow and Geochemistry of Till Confining Units Overlying Buried Glacial Aquifers: Examples from the Des Moines and Wadena Lobes in Minnesota. GSA Annual Meeting in Indianapolis, Indiana, USA [Available at: https://gsa.confex.com/gsa/2018AM/webprogram/Paper324789.html]

Maher, A., Simpkins, W.W., Witt, A., Trost, J.J., Berg, A.M., and Stark, J.R. Hydrogeologic investigation of groundwater flow in till confining beds overlying glacigenic aquifers in south-central and north-central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/313001]

Maher A., Simpkins, W.W, Trost, J., Witt, A., Berg, A., and Stark, J.R. Evidence of anthropogenic contamination in till aquitards at the hydrogeology field camp and Olivia sites in Minnesota poster presented at the Minnesota Ground Water Association in St Paul, Minnesota, April 25, 2019. [Available at: https://www.mgwa.org/wp-content/uploads/2019/spring/mgwa-spring-2019-poster-abstracts.pdf]

Simpkins, W.W., Witt, A., Blum, J., Trost, J.J., Berg, A.M., and Stark, J.R. Spatial Variability in the Vertical Connectivity of Till Confining Units: Implications for Glacial Aquifers in Minnesota presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018. [Available at: https://www.wrc.umn.edu/sites/wrc.umn.edu/files/2018_final_program_and_abstracts.pdf]

Trost, J.J., Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the source of water to wells completed in confined glacial aquifers presented at the Minnesota Water Resources Conference in St. Paul, Minnesota, October 16-17, 2018. [Available at: https://www.wrc.umn.edu/sites/wrc.umn.edu/files/2018_final_program_and_abstracts.pdf]

Trost, J.J. Feinstein, D.T., Simpkins, W.W., Witt, A., and Stark, J.R. Evaluating the sustainability of groundwater withdrawals from confined glacial aquifers presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/313038]

Witt, A., Simpkins, W.W., Blum, J., Trost, J.J., Berg, A.M., Stark, J.R. Spatial variability in the vertical connectivity of till confining beds: examples from the New Ulm formation in central Minnesota presented at the North Central Geologic Society of America conference in Ames, Iowa, April 16-17, 2018. [Available at: https://gsa.confex.com/gsa/2018NC/meetingapp.cgi/Paper/312862]

VI. Project Budget SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$228,598	project chief at an average of 14 % FTE each year for 4 years ($84,016); support hydrologists/groundwater specialist at 2 % FTE for 4 years ($37,067); hydrologic technicians at 8 % FTE for 4 years ($34,186); student technicians at 31 % FTE for 4 years ($58,210); water quality technical specialist at 0.4 % FTE for 4 years ($3,462); IT technician at 2 % FTE for 4 years ($5,660); contract administrator at 1 % FTE for 4 years ($5,997)
Professional/Technical/Service Contracts:	$186,431	Minnesota Geological Survey (MGS) support of glacial geologic interpretation and well siting. The MGS contract, includes assistance for site selection, field logging, core descriptions, borehole geophysics, textural and stratigraphic analysis, archiving of drilling cores, and preparation of a summary report. ($12,327) Drilling contracts: drilling, well installation, well sealing, and abandonment TBD through competitive bid ($137,563) Groundwater data collection and data processing and archival in USGS database--internal USGS subcontract ($22,400) Contract for chemical analyses of water samples at USGS laboratories.($10,140) Reports: USGS contract fee for USGS report preparation, editing and production (Science Publishing network- This includes electronic publishing and distribution of report products ($4,000)
Equipment/Tools/Supplies:	$4,142	Field supplies and data collection: pumps, pressure transducers, electronic recording devices, well packers, well casing, and shelters.
Travel Expenses in MN:	$13,262	Mileage ($3,225), lodging ($5,278), meals ($4,759)
Other: See detailed budget	$567	Postage and shipping
TOTAL ENRTF BUDGET:	$ 433,000	

Explanation of Use of Classified Staff: NA

Explanation of Capital Expenditures Greater Than $5,000: NA

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.3

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 2.2 (estimated)

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state: (USGS matching funds)	157,430	$223,042	34% of direct and indirect costs minus exempted contract costs. Covers indirect project costs.
TOTAL OTHER FUNDS:	$157,430	$223,042	

VII. PROJECT STRATEGY:

A. Project Partners: U. S. Geological Survey, Minnesota Geological Survey, Minnesota Department of Natural Resources, Minnestoa Department of Health

Project Team/Partners

B.

Name	Affiliation	Role
James Walsh *	Minnesota Department of Health	Site selection—Site selection support
Steve Robertson *	Minnesota Department of Health	Site selection support
Jared Trost	United States Geological Survey	Project Chief
Andrew Berg	United States Geological Survey	Drilling support and data collection
Studies Section Chief	United States Geological Survey	Project Management
Angela Hughes	United States Geological Survey	Administrative Support
Jim Berg*	Minnesota Department of Natural Resources	Site selection support
Tony Runkel*	Minnesota Geological Survey	Glacial Stratigraphy-Hydraulic testing, Reporting
Bob Tipping	Minnesota Geological Survey	Glacial stratigraphy- Hydraulic testing, Reporting

* Participation as collaborator and advisor not receiving ENRTF funding

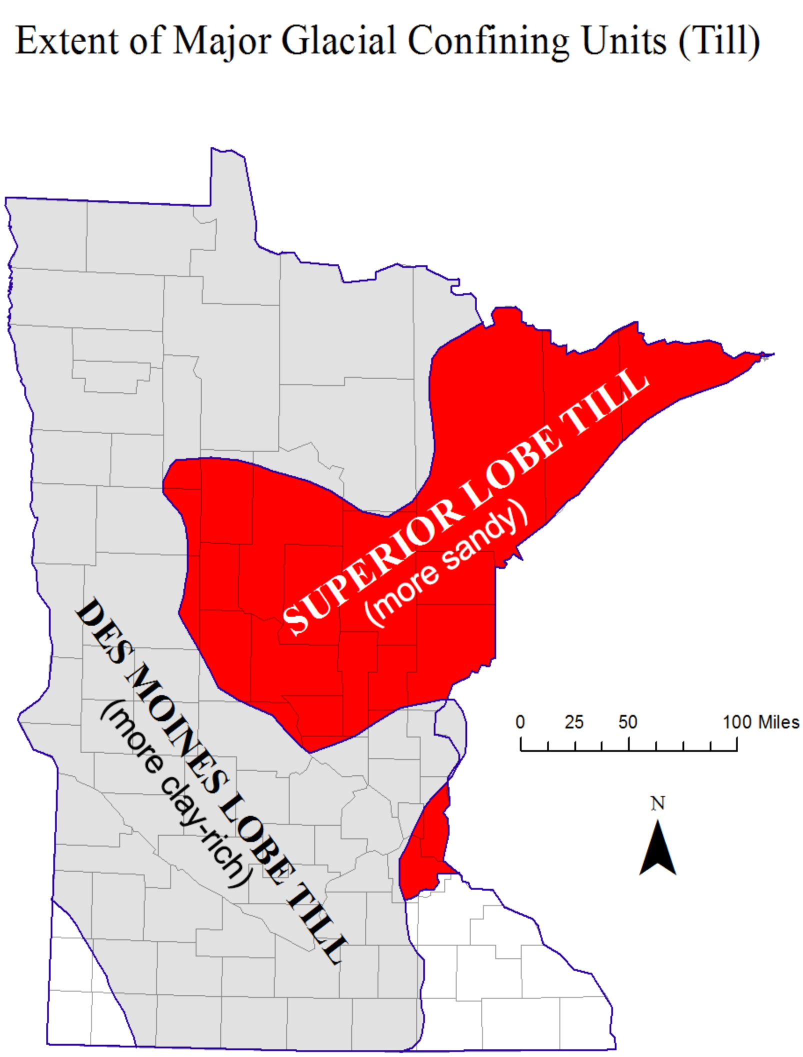
Project Impact and Long-term Strategy: This project provides critical information for sustainable management of Minnesota's groundwater resources. The project complements and augments work being done by the County Geologic Atlas Program (MGS and MDNR) and fits with MDNR's planned changes to MDNR water appropriation-permit program. The project fulfills strategic directions for understanding water budgets described in the University of Minnesota's Water Sustainability Framework. The project represents a major step toward defining the hydrogeological properties of the important protective Des Moines, Superior, and Wadena lobe confining till units throughout the state. The project is similar to an ongoing LCCMR project focused on confining properties of the St. Lawrence bedrock confining unit.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
ENRTF funding—phase 1, M.L. 2014, Chp. 226, Sec. 2, Subd. 03h	2014-2017	$ 394,000
USGS matching funds	2014-2017	$ 96,000

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

IX. VISUAL COMPONENT or MAP(S):



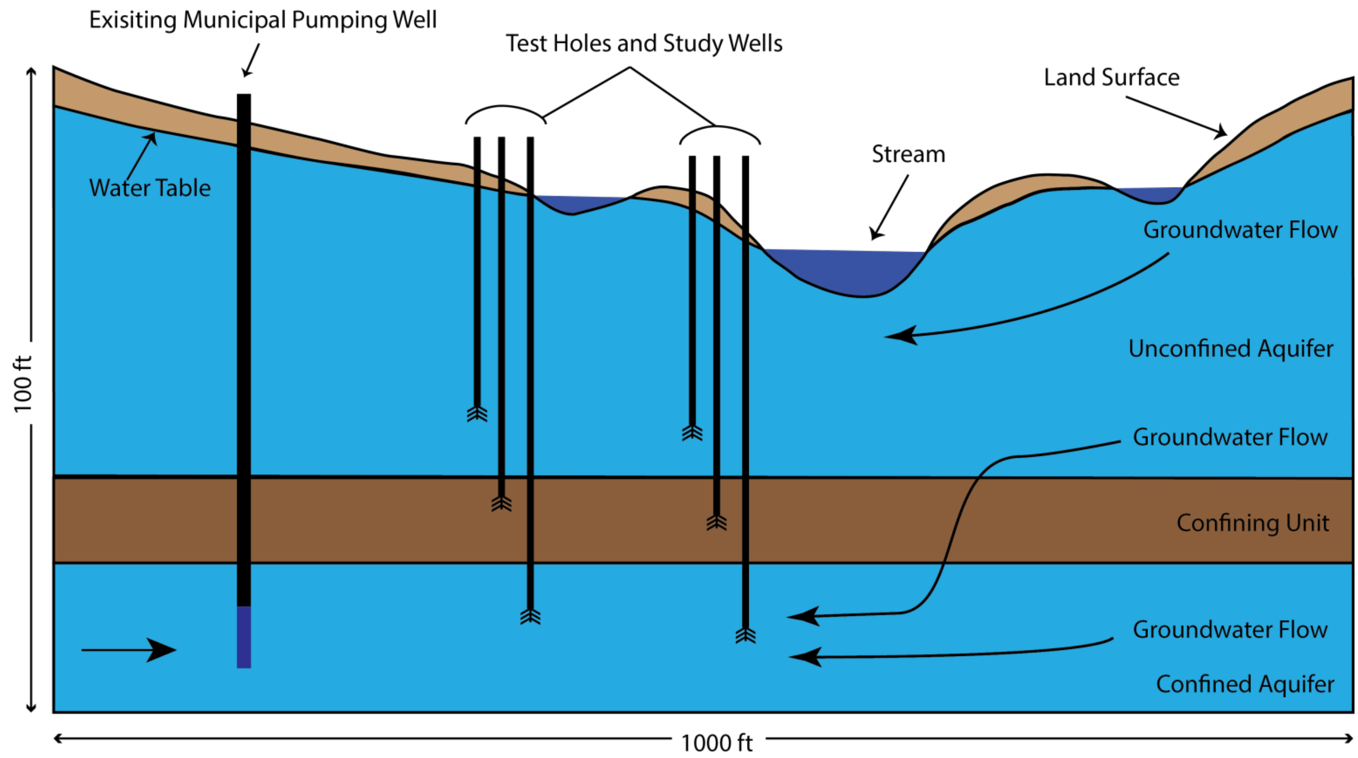


Figure 2. Expected well and piezometer installation site plan

X. RESEARCH ADDENDUM:

A detailed proposal is being prepared and will be reviewed and revised according to USGS policy. The approved proposal will then be added to this document. The expected date of proposal approval is February 15, 2016.

XI. REPORTING REQUIREMENTS:

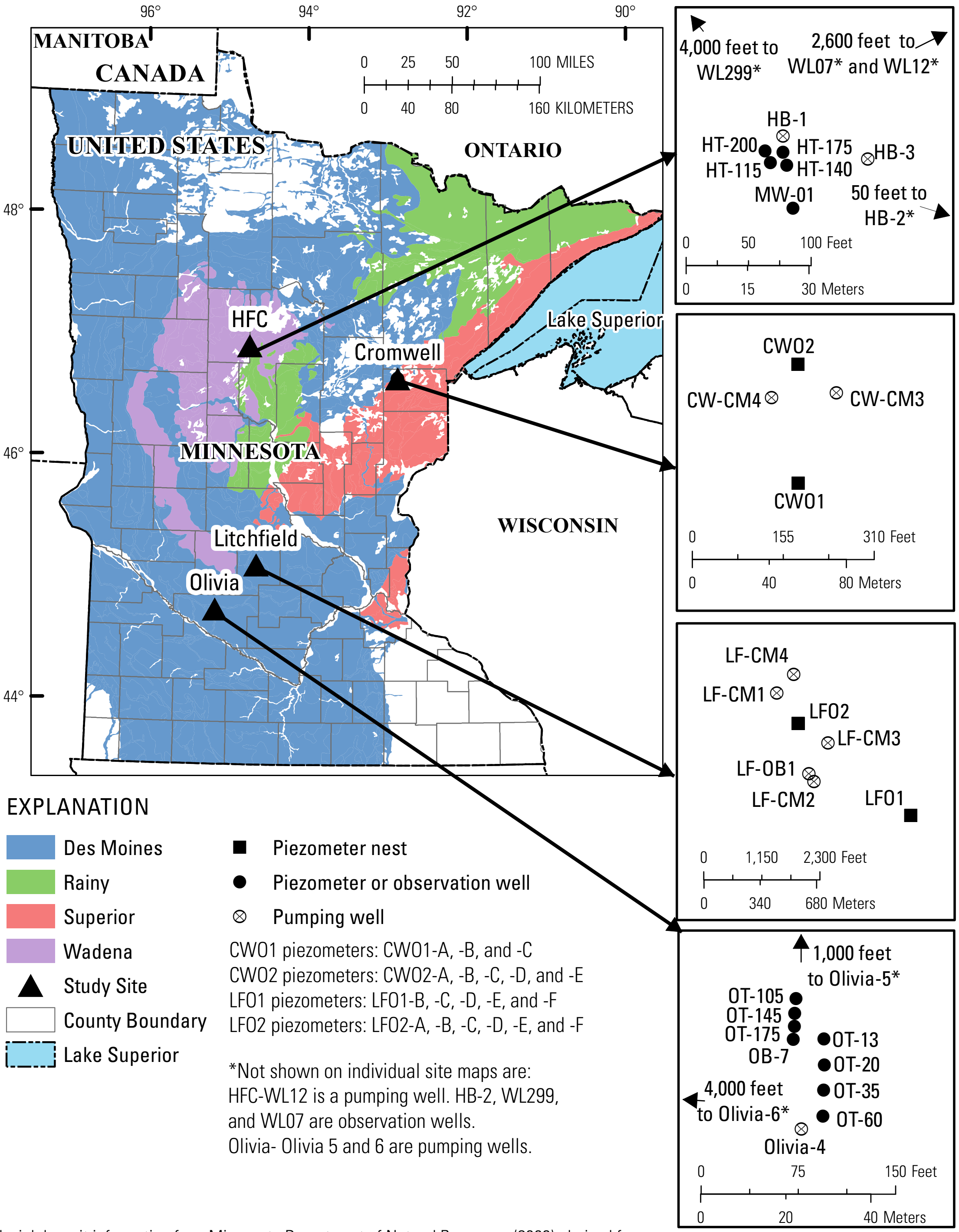
Periodic work plan status update reports will be submitted no later than: December 30, 2016, June 30, 2017, December 29, 2017, June 29, 2018, December 31, 2018, and June 30, 2019. A final report and associated products will be submitted to the USGS review process between June 30 and September 15, 2019. The expected date of published final report is expected to be December 30, 2019.

Environment and Natural Resources Trust Fund
M.L. 2016 Final Project Budget

Project Title: Protection of State’s Confined Drinking Water Aquifers – Phase II
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04h as extended by M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 19
Project Manager: Jared Trost
Organization: U. S. Geological Survey
M.L. 2016 ENRTF Appropriation: $ 433,000
Project Length and Completion Date: 4 years, June 30, 2020
Date of Report: 8/13/2020

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 6/3/2020	Amount Spent as of 6/30/2020	Activity 1 Balance	Revised Activity 2 Budget 6/3/2020	Amount Spent as of 6/30/2020	Activity 2 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM								
Personnel (Wages and Benefits)	$66,800	$66,800	$0.00	$161,798.10	$161,798.10	$0.00	$228,598.10	$0.00
Jared Trost (project chief-hydrologist): (71% salary, 29% benefits) average of 14 % FTE each year for 4 years ($84,016);								
USGS Hydrologist/groundwater specialist (Tim Cowdery, Melinda Erickson, hydrologists): (71% salary, 29% benefits): 2 % FTE for 4 years ($37,067)								
Richard Kiesling (Water Quality Technical Specialist): (78 % salary, 22% benefits): 0.4 % FTE for 4 years ($3,462);								
Andrew Berg hydrologic technicians): (73% salary, 27 % benefits): 8 % FTE for 4 years ($34,186)								
student employee (hydrologic technician): (80% salary, 20 % benefits): at 31 % FTE for 4 years ($58,210)								
IT specialist: (72% salary, 28 % benefits): at 2 % FTE for 4 years ($5,660)								
Lisa Syde-Hagen (Contract administrator) (72 % salary, 28 % benefits): 1 % FTE for 4 years ($5,997)								
Professional/Technical/Service Contracts								
Professional/Technical/Service Contracts: Contracted drilling services. Competitive bid. Cost is an estimate. Includes coring, the installation of wells and piezometers and well abandonment.	$127,563.01	$127,563.01	$0.00	$10,000.00	$10,000.00	$0.00	$137,563.01	$0.00
Professional/Technical/Service Contracts: Minnesota Geological Survey (MGS). Technical support for description and interpretations of geological materials from drill sites. Includes $2,100 in travel expenses	$9,876.41	$9,876.41	$0.00	$2,450.54	$2,450.54	$0.00	$12,326.95	$0.00
Professional/Technical/ Service Contracts: USGS contract fee for water-level data collection, data processing and data-base maintenance and data quality control.	$22,400.00	$22,400.00	$0.00			$0.00	$22,400.00	$0.00
Professional/Technical/ Service Contracts: contract fee for chemical analyses of water samples at USGS laboratories.		$0.00	$0.00	$10,140.08	$10,140.08	$0.00	$10,140.08	$0.00
Professional/Technical/ Service Contracts: USGS contract fee for USGS report preparation, editing and production (Scientific Publications Network). This includes electronic publishing and distribution of report products.		$0.00	$0.00	$4,000.00	$4,000.00	$0.00	$4,000.00	$0.00
Equipment/Tools/Supplies								

Equipment/Tools/ Supplies: Miscellaneous field equipment and supplies for data collection. Includes pumps, pressure transducers, electronic recording devices, well packers, well casing and well screens	$4,142.17	$4,142.17	$0.00	$0.00	$0.00	$0.00	$4,142.17	$0.00
Travel expenses in Minnesota								
USGS travel to field sites and to local meetings; Includes expenses for presenting at local conferences, vehicles, and lodging and meals	$10,478.67	$10,478.67	$0.00	$2,783.55	$2,783.55	$0.00	$13,262.22	$0.00
Other Expenses								
Expenses for shipping and laboratory expenses for MGS and USGS laboratories.	$547.16	$547.16	$0.00	$20.31	$20.31	$0.00	$567.47	$0.00
COLUMN TOTAL	$241,807.42	$241,807.42	$0.00	$191,192.58	$191,192.58	$0.00	$433,000.00	$0.00



Glacial deposit information from Minnesota Department of Natural Resources (2006), derived from Hobbs and Goebel (1982).
Hydrographic information from Minnesota Department of Natural Resources (2018), and county boundary information from Minnesota Department of Natural Resources (2014).
Piezometer and well information from the USGS National Water Information System (2019).

Figure 1. Site map showing the location of the Litchfield (LF01 and LF02), Cromwell (CW01 and CW02), Hydrogeology field camp (HFC), and Olivia sites in Minnesota in relation to late Wisconsin lobe deposits, and the piezometers and pumping wells at each site.

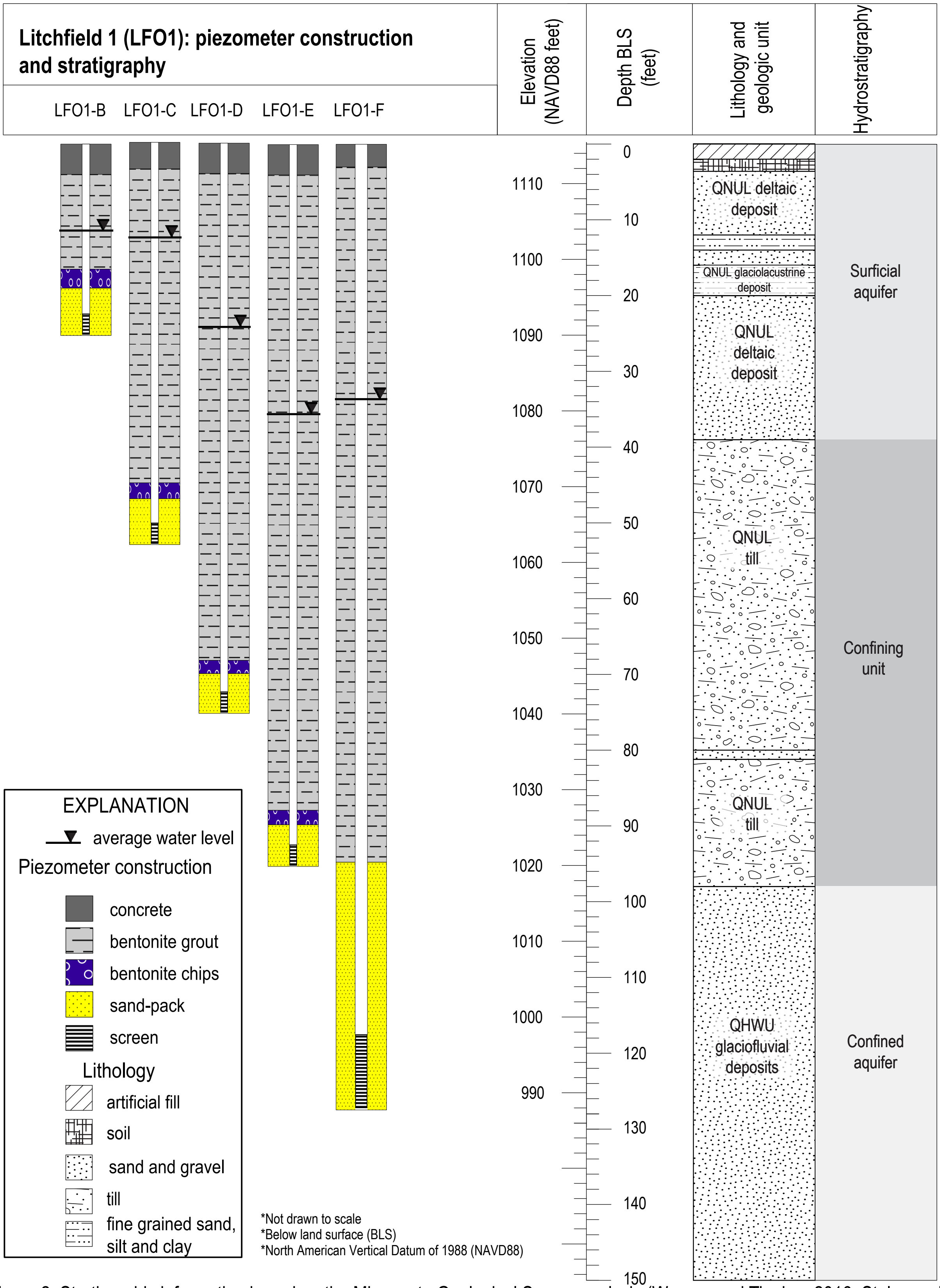


Figure 2: Stratigraphic information based on the Minnesota Geological Survey analysis (Wagner and Tipping, 2016; Staley and others, 2018). Unit abbreviations are as follows: QNUL, Villard Member of the New Ulm Formation; QHWU, Hewitt Formation.

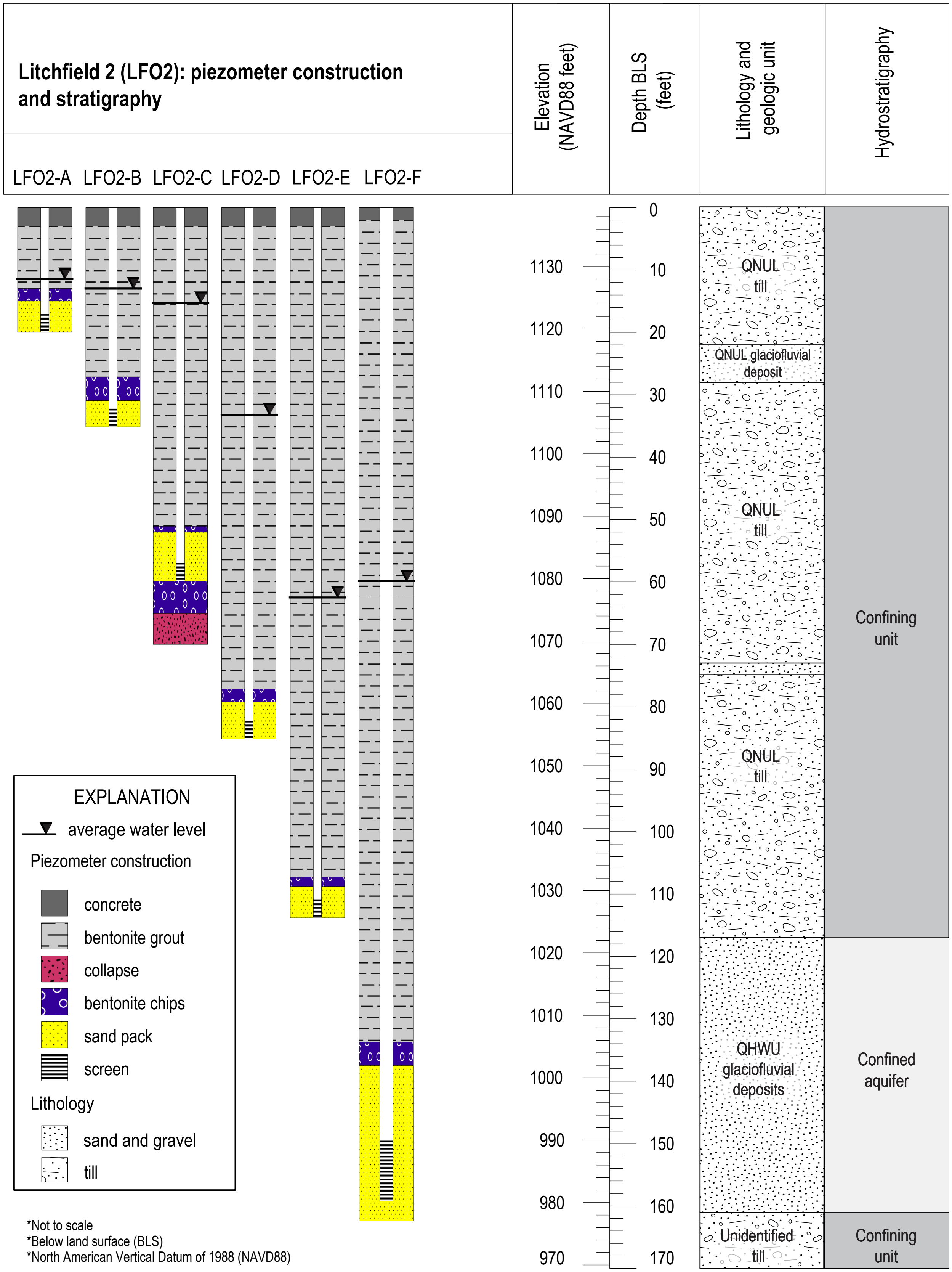


Figure 3: Stratigraphic information based on the Minnesota Geological Survey analysis (Wagner and Tipping, 2016; Staley and others, 2018). Unit abbreviations are as follows: QNUL, Villard Member of the New Ulm Formation; QHWU, Hewitt Formation.

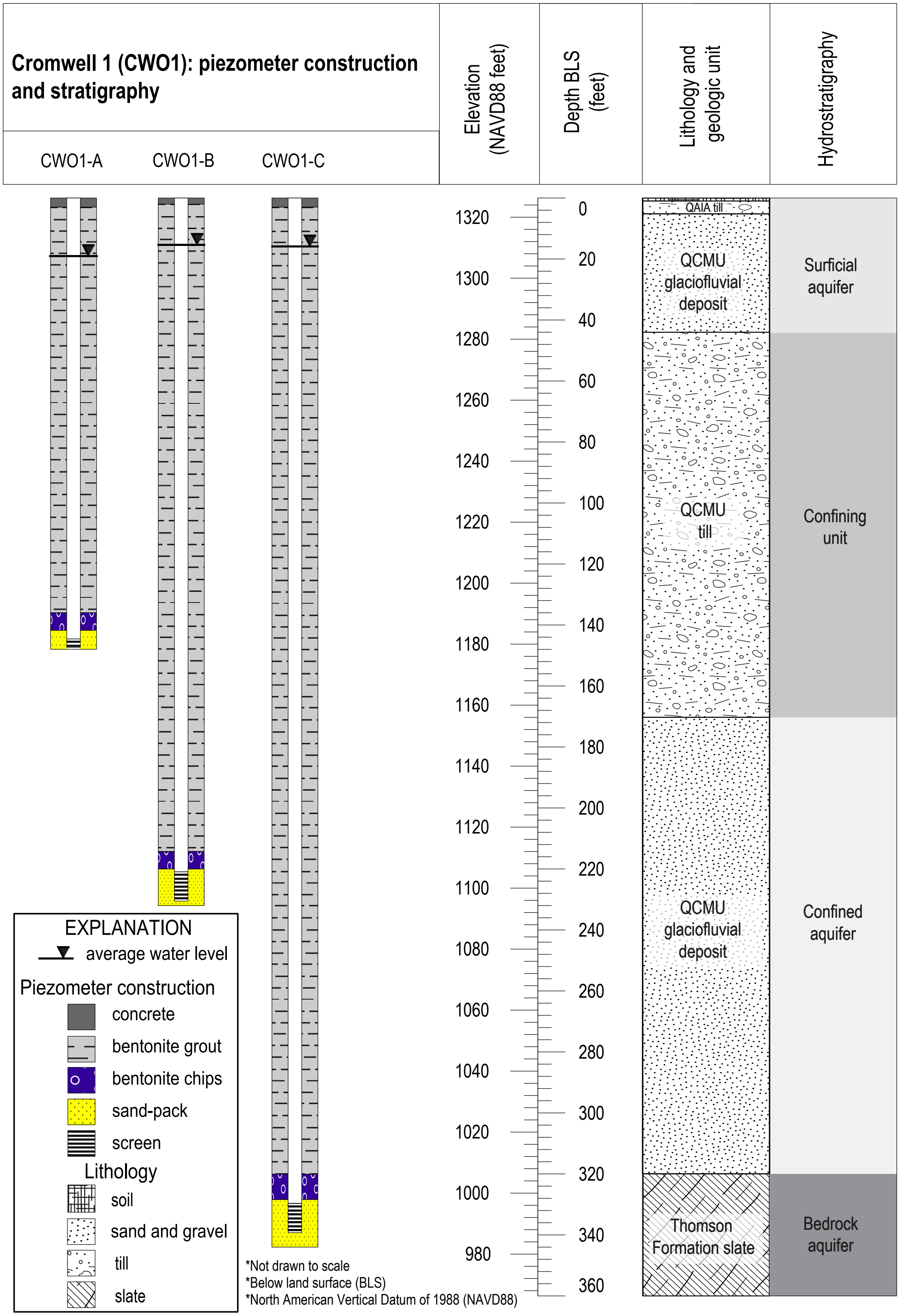


Figure 4: Stratigraphic information based on the Minnesota Geological Survey analysis (Staley and others, 2018) and Knaeble and Hobbs (2009). Unit abbreviations are as follows: QAIA, Alborn Member of the Aitkin Formation; QCMU, Cromwell Formation.

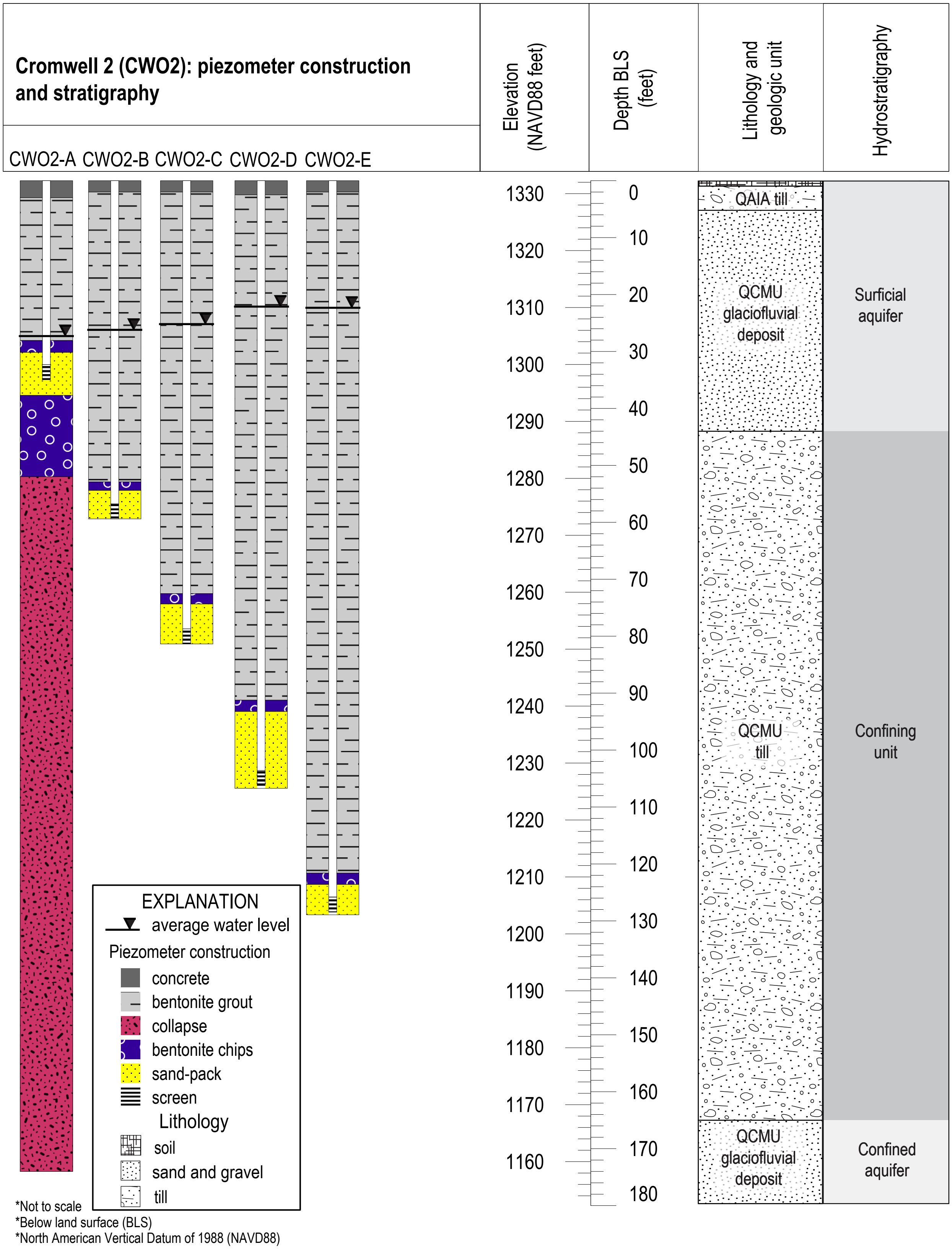


Figure 5: Stratigraphic information based on the Minnesota Geological Survey analysis (Staley and others, 2018) and Knaeble and Hobbs (2009). Unit abbreviations are as follows: QAIA, Alborn Member of the Aitkin Formation; QCMU, Cromwell Formation.

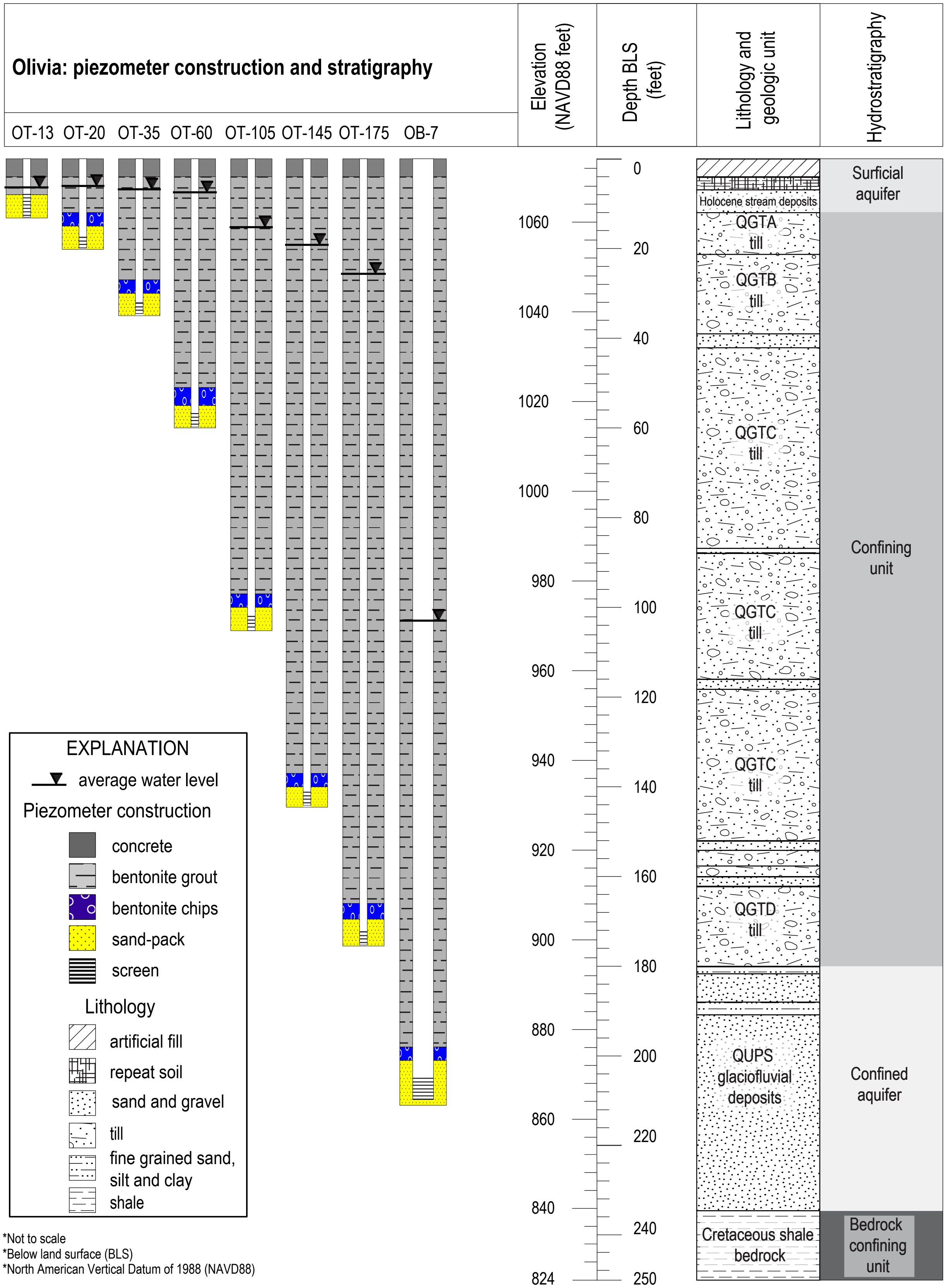


Figure 6: Stratigraphic information based on the Minnesota Geological Survey analysis (Staley and others, 2018). Unit abbreviations are as follows: QGT, Good Thunder Formation (A, Member 1; B, Member 2; C, Member 3; D, Member 4); QUPS; undefined Pleistocene sediment.

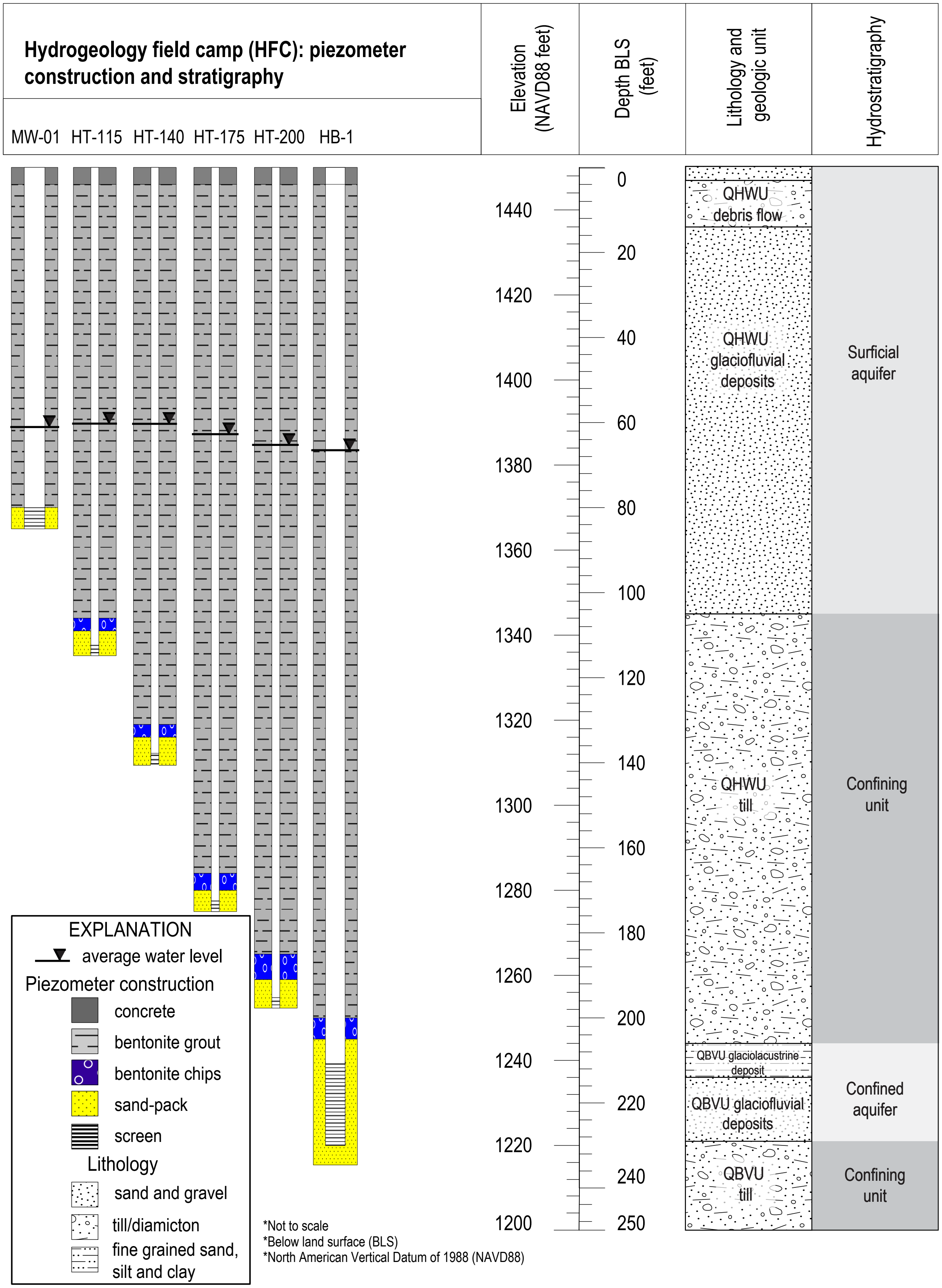
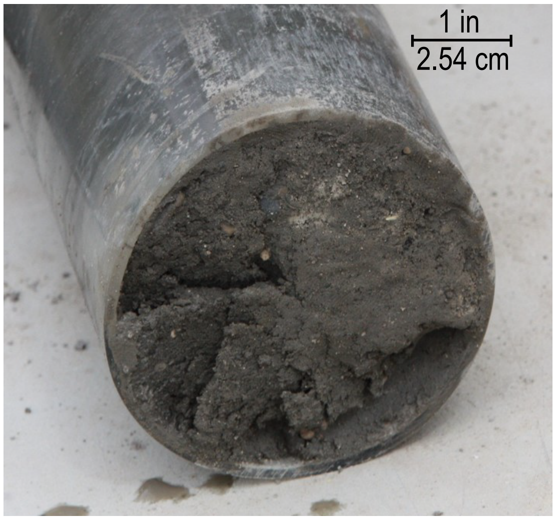
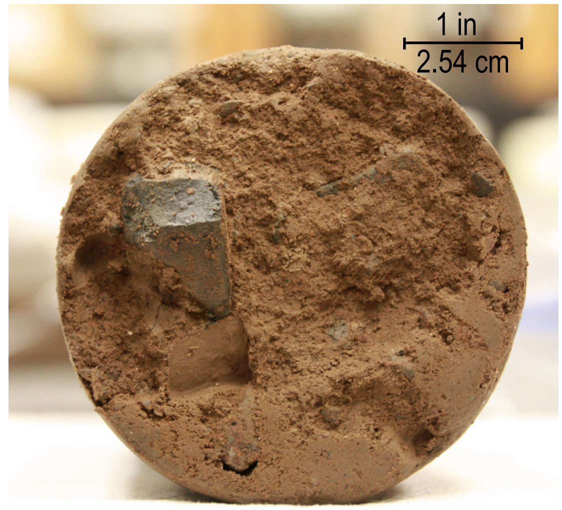


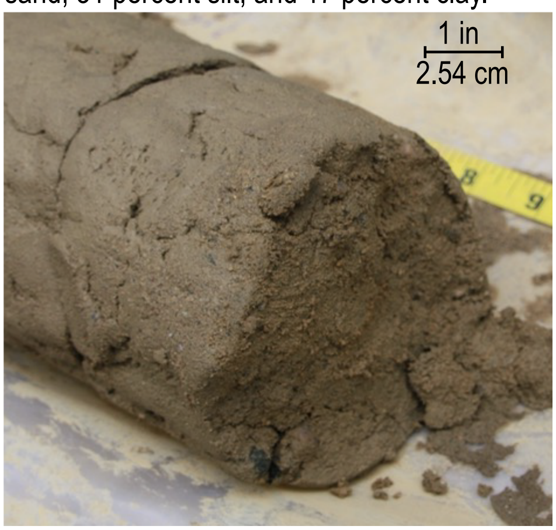
Figure 7: Stratigraphic information based on the Minnesota Geological Survey analysis (Staley and others, 2018). Unit abbreviations are as follows: QHWU, Hewitt Formation; QBVU, Browerville Formation.



A) New Ulm Formation till from the Litchfield site. The mean particle size distribution of the till at the LFO1 site is 47 percent sand, 34 percent silt, and 19 percent clay; and at the LFO2 site is 52 percent sand, 31 percent silt, and 17 percent clay.



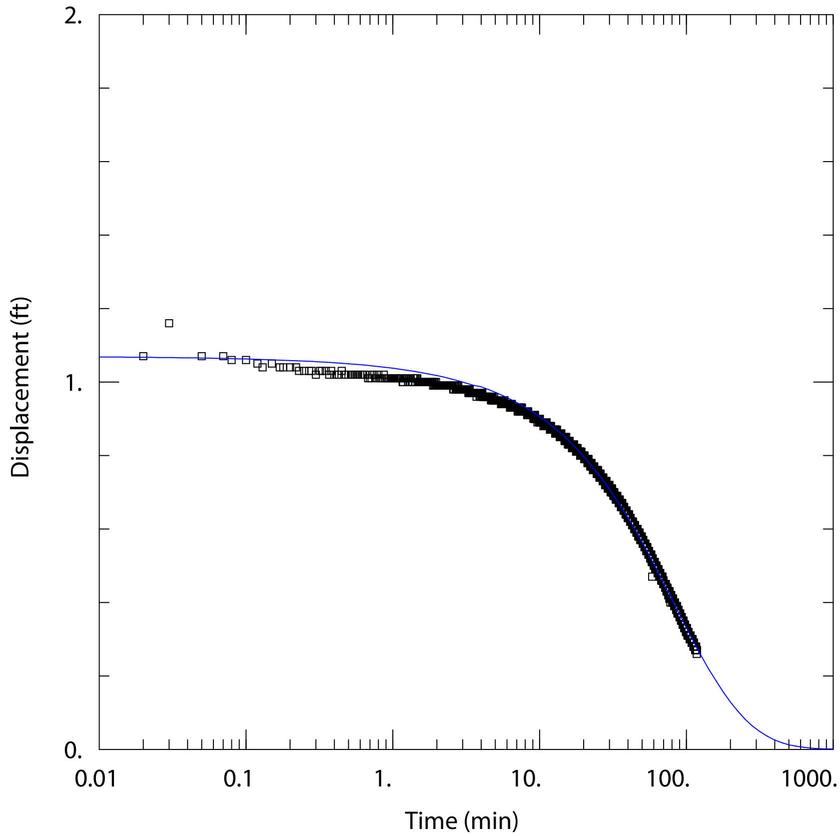
B) Cromwell Formation till from the Cromwell site. The till has a mean particle size distribution of 57 percent sand, 31 percent silt, and 13 percent clay.



C) Hewitt Formation till from the HFC site. The till has a mean particle size distribution of 67 percent sand, 22 percent silt, and 11 percent clay.

D) Good Thunder Formation till from the Olivia site. The till has a mean particle size distribution of 37 percent sand, 40 percent silt, and 23 percent clay.

Figure 8: Images of till from cores extracted from: A) the Litchfield site, Litchfield 1 (LFO1) and Litchfield 2 (LFO2), B) the Cromwell site, C) the Hydrogeology field camp site (HFC), and D) the Olivia site. Mean particle size information from Staley and Nguyen (2018) and Wagner and Tipping (2016). The Cromwell site mean particle size is based on till core from the CWO2 piezometer nest. [in, inch; cm, centimeter]



WELL TEST ANALYSIS

Data Set: C:\...\OT-20 Falling1_2019.aqt
Date: 04/09/20 Time: 00:35:58

PROJECT INFORMATION

Company: USGS
Location: Olivia
Test Well: OT-20

AQUIFER DATA

Saturated Thickness: 177. ft

WELL DATA (OT-20)

Initial Displacement: 1.07 ft
Total Well Penetration Depth: 16.42 ft
Casing Radius: 0.055 ft
Static Water Column Height: 16.26 ft
Screen Length: 5.2 ft
Well Radius: 0.2813 ft

SOLUTION

Aquifer Model: Unconfined
Solution Method: KGS Model

Kr = 0.01188 ft/day
Kz/Kr = 1.
Ss = 2.722E-5 ft^{-1}

Figure 9: Aqtesolv result from piezometer OT-20 at the Olivia site, showing time in minutes versus displacement in feet.

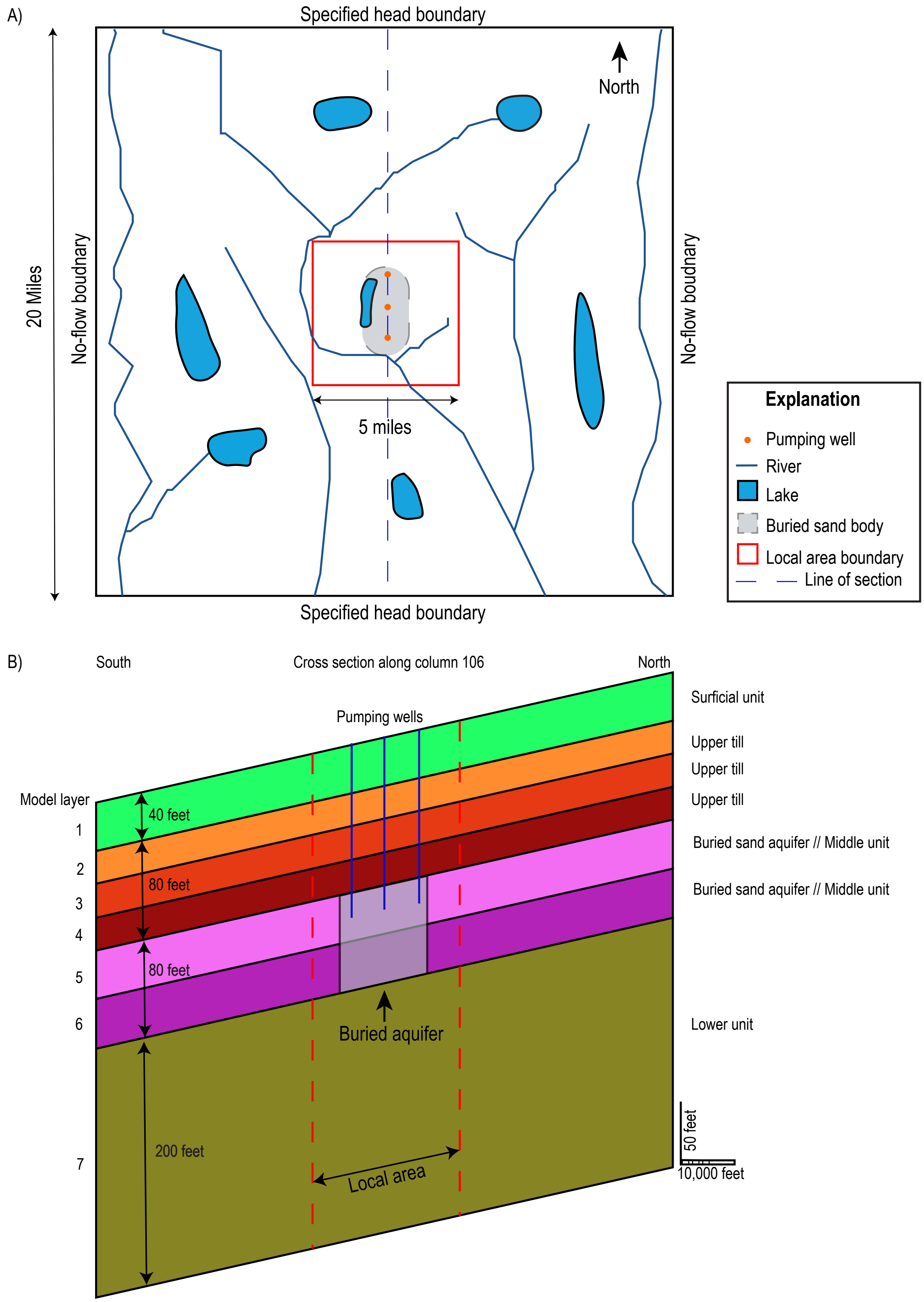


Figure 10: Interpretive model layout (A) top view and (B) cross section view.

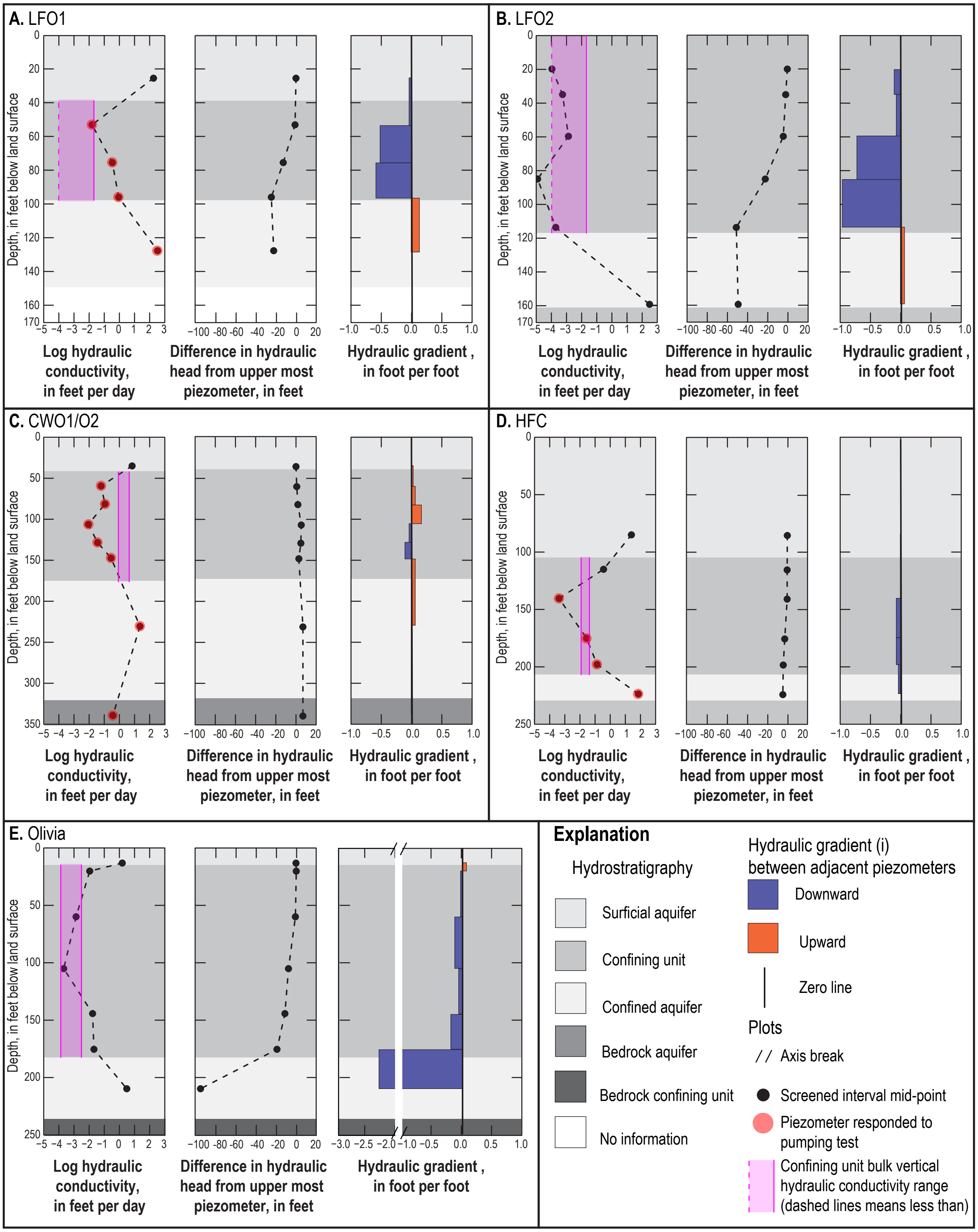
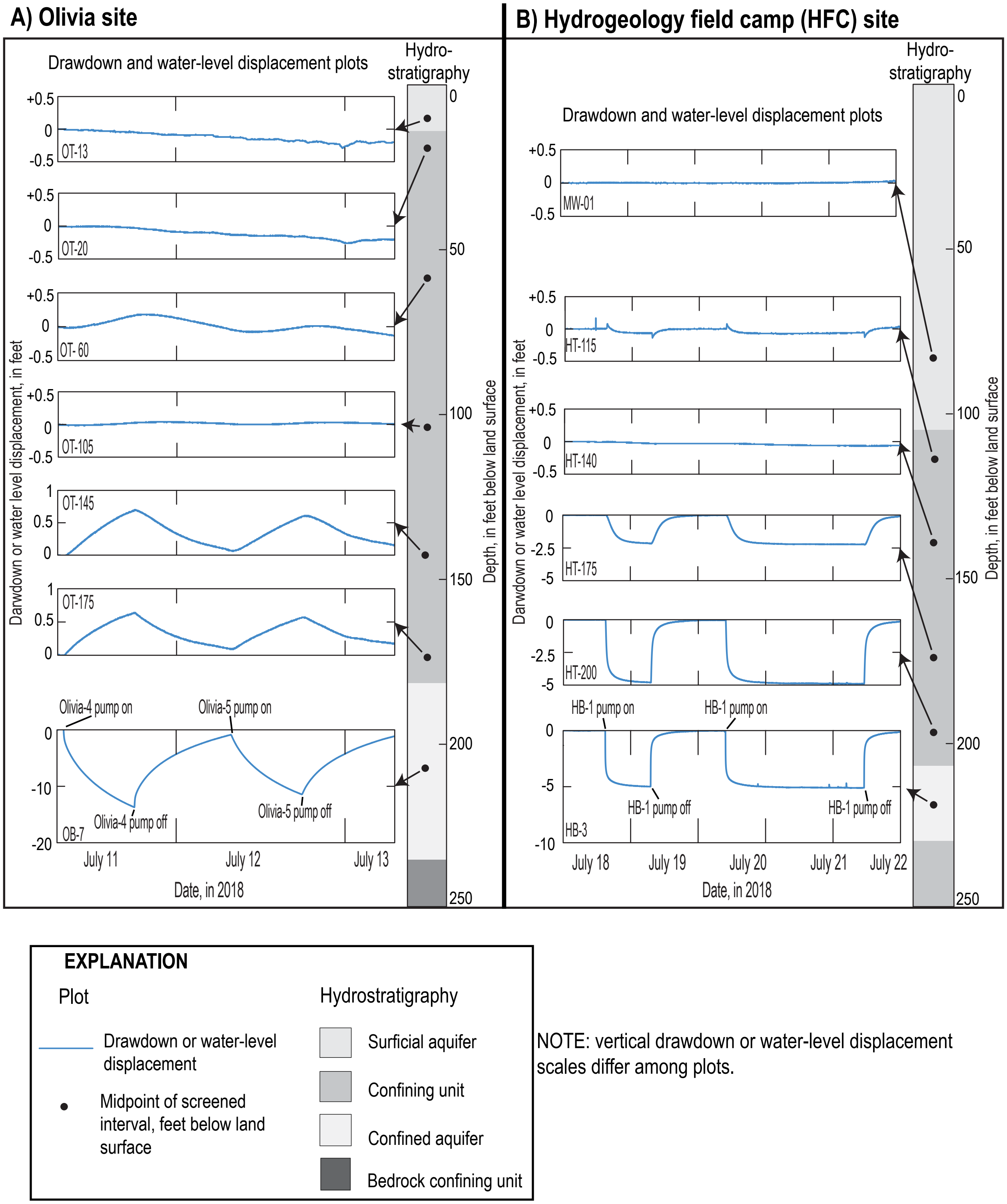
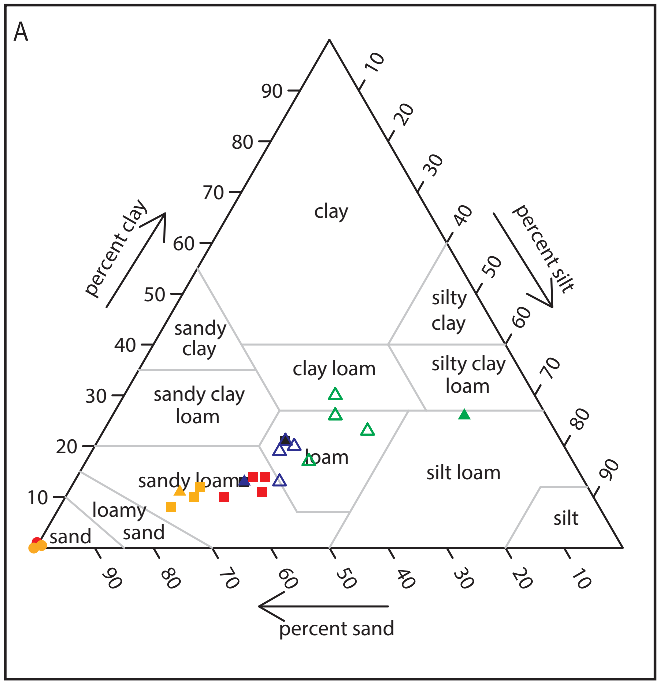


Figure 11: Hydraulic information (log hydraulic conductivity from slug test analyses, hydraulic head ft NAVD88 (feet North American Vertical Datum 1988), hydraulic gradient (i) between piezometers for A) LFO1, B) LFO2, C) Cromwell (CWO1/O2), D) Hydrogeology field camp (HFC), E) Olivia. If no upward or downward bar is present between two piezometers, the gradient was close to zero. Bulk vertical hydraulic conductivity ranges from Minnesota Department of Health pumping test analyses (Blum and Woodside, 2017; Lund and Blum, 2017; Blum, 2019a, and Blum, 2019b).



NOTE: vertical drawdown or water-level displacement scales differ among plots.

Figure 12: Drawdown and water-level displacement in piezometer nests during constant-rate aquifer tests completed at the (A) Olivia site and (B) Hydrogeology field camp (HFC) site near Akeley, Minnesota.



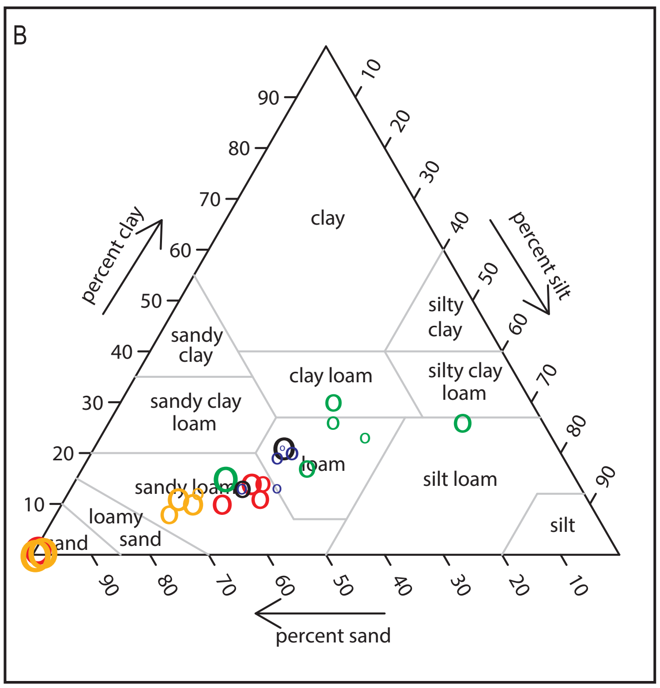
EXPLANATION

For both A and B plots:
Color of the symbol represents the site

Litchfield 1 (LFO1)
Litchfield 2 (LFO2)
Olivia
Cromwell (CWO1/O2)
Hydrogeology field camp (HFC)

For plot A:
Shape of the symbol represents the aquifer test response

● =aquifer well
■ =till piezometer with drawdown observed during a pumping test
▲ =deepest till piezometer at a site with no drawdown observed during a pumping test
△ =shallower (than the deepest till piezometer) till piezometer, with no drawdown response during a pumping test



For plot B:
Size corresponds with log hydraulic conductivity in feet per day

Log hydraulic conductivity = −4.9 (1×10^{-5} feet per day)

Log hydraulic conductivity = 1.9 (80 feet per day)

Figure 13: A) Plot showing the relation between clay, sand, and silt content, and presence or absence of an aquifer test drawdown response at the screened interval of piezometers. B) Plot showing the relation between clay, sand, and silt content and estimated slug test hydraulic conductivity values for piezometers.

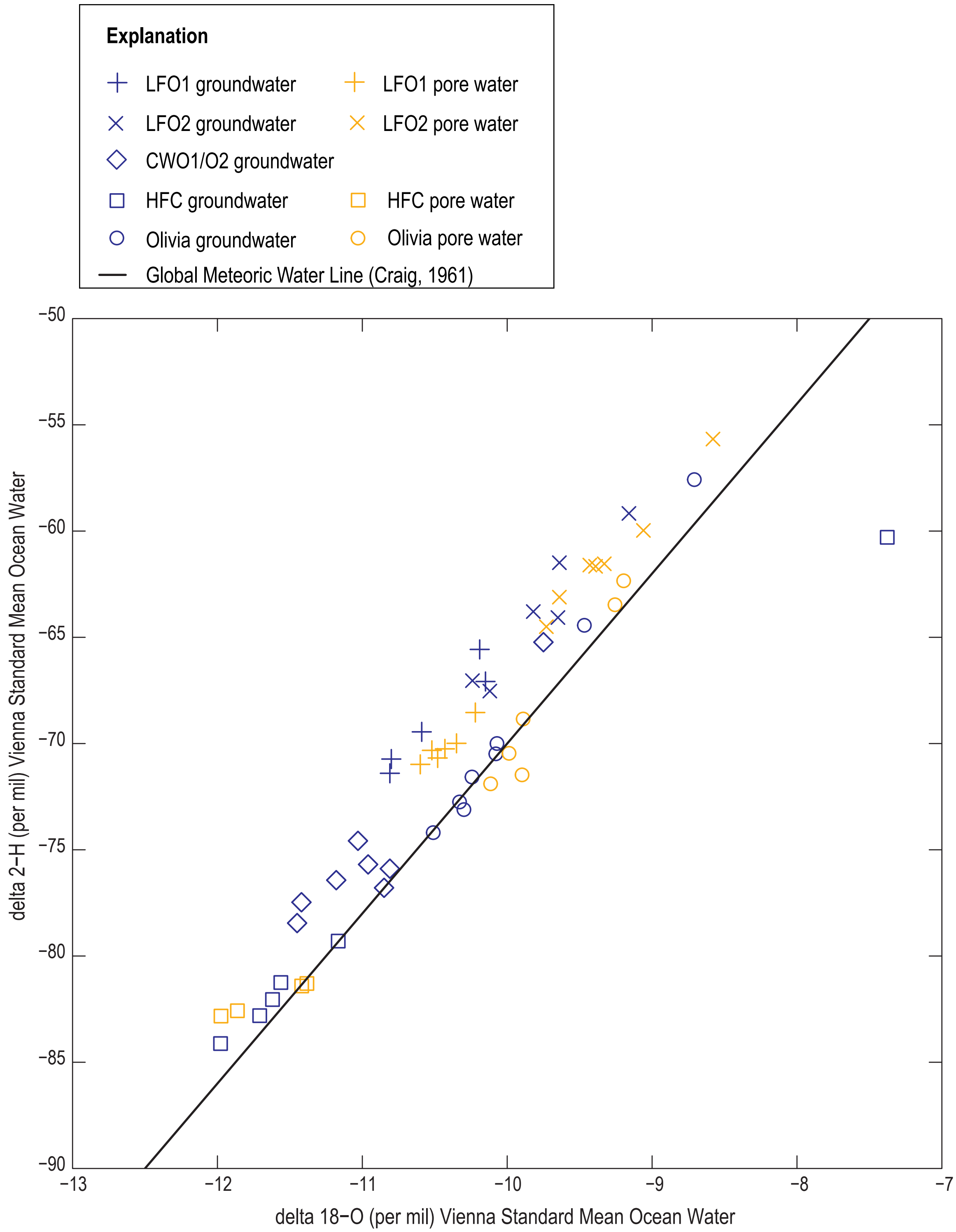


Figure 14: Results of stable isotope analysis of the Litchfield 1 (LFO1), Litchfield 2 (LFO2), Cromwell (CWO1/O2), Olivia, and Hydrogeology field camp (HFC) sites.

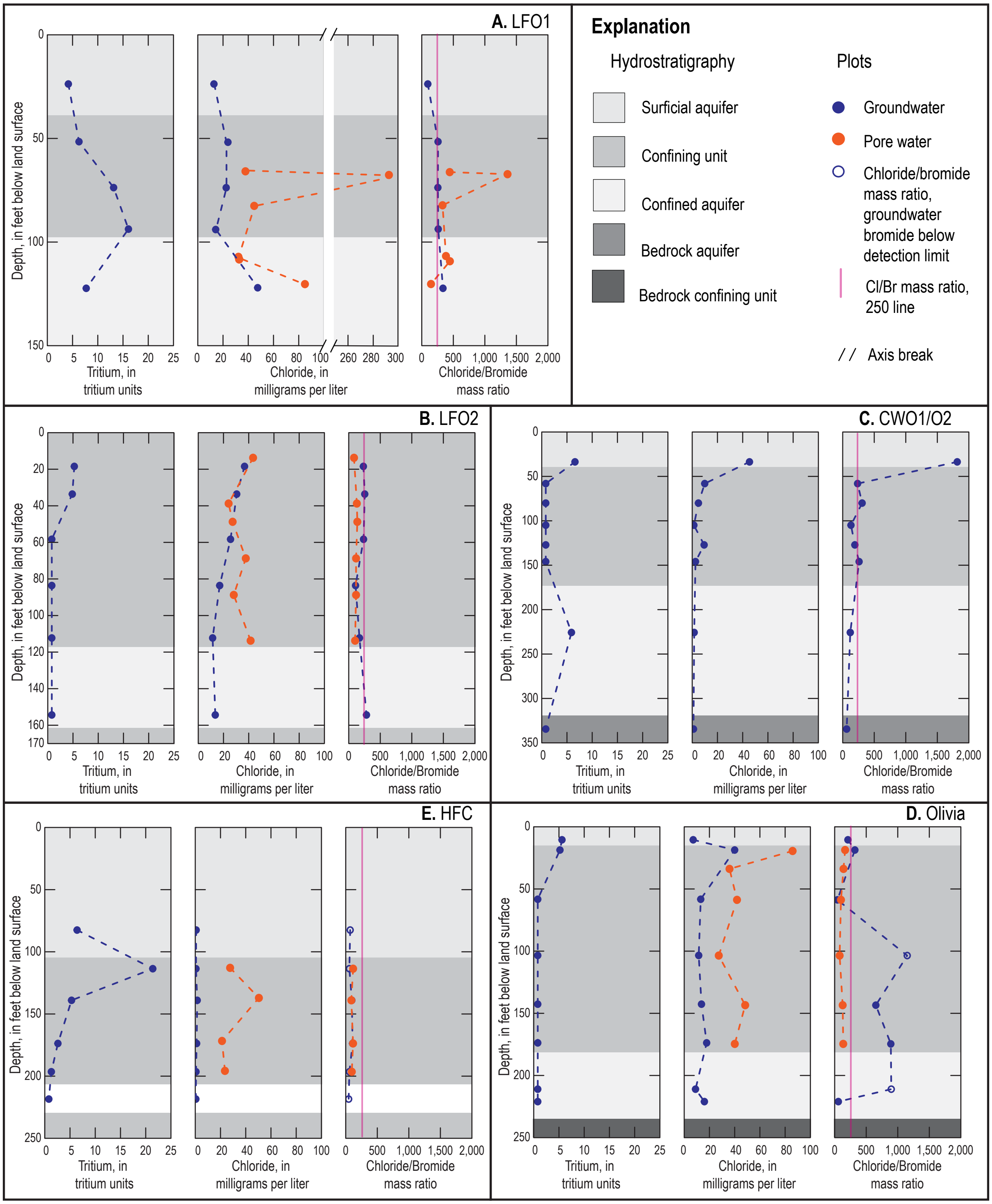


Figure 15: Possible anthropogenic analytes (tritium, chloride, and chloride/bromide mass ratio) results for the Litchfield 1 (LFO1), Litchfield 2 (LFO2), Cromwell (CWO1/O2), Hydrogeology field camp (HFC), and Olivia sites. The 250 line for the chloride/bromide mass ratio is from Berg (2018). Above 250 suggests possible chloride anthropogenic contamination, where below 250 suggests no chloride anthropogenic contamination.

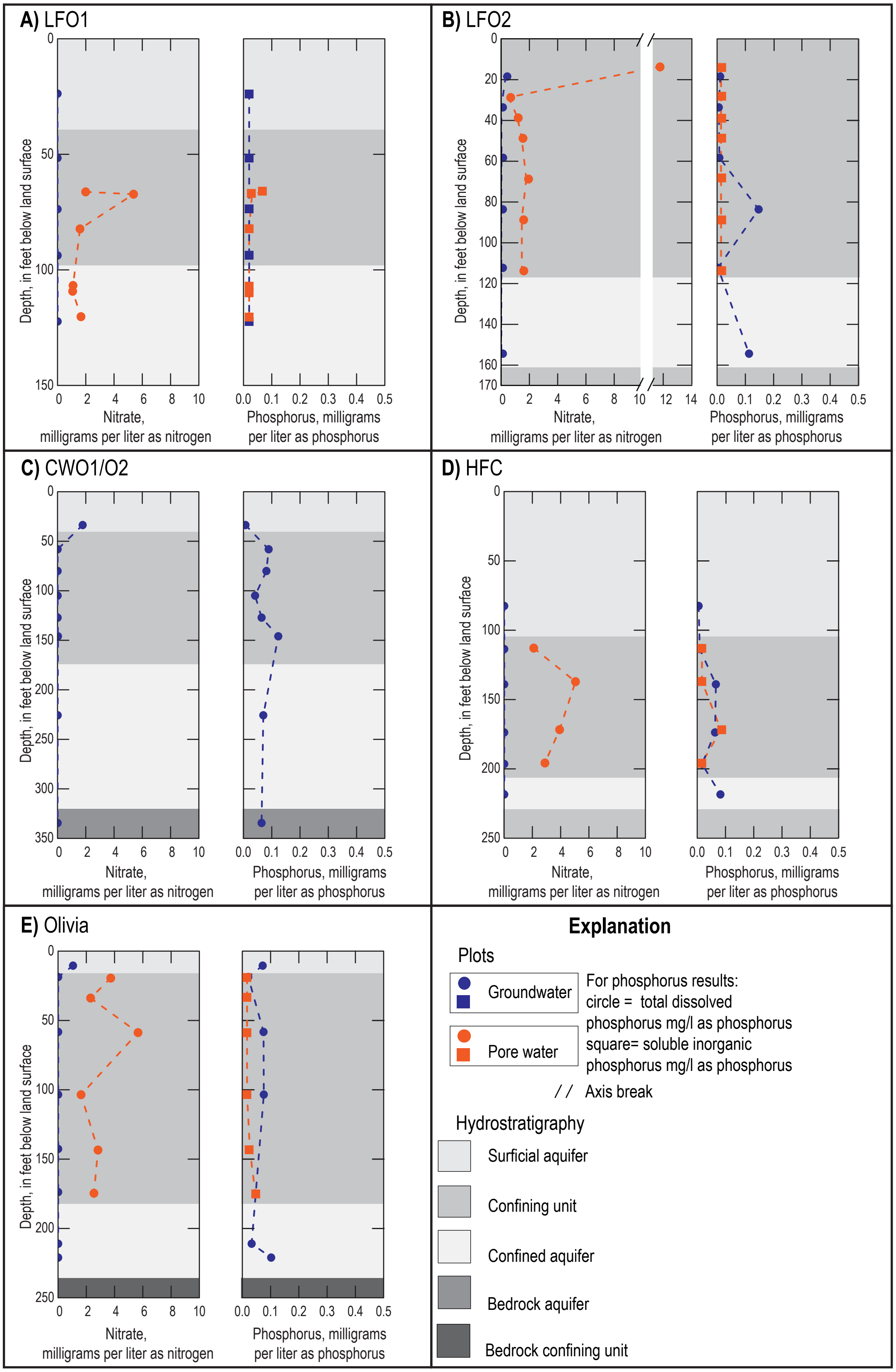


Figure 16: Nutrient (nitrate and phosphorus) results for the A) Litchfield 1 (LFO1), B) Litchfield 2 (LFO2), C) Cromwell (CWO1/O2), D) Hydrogeology field camp (HFC), E) Olivia sites. For phosphorus, the USGS National Water Quality Lab includes all phosphorus, milligrams per liter as phosphorus results, and Ion Chrom Analytical includes all phosphate, milligrams per liter as phosphorus results.

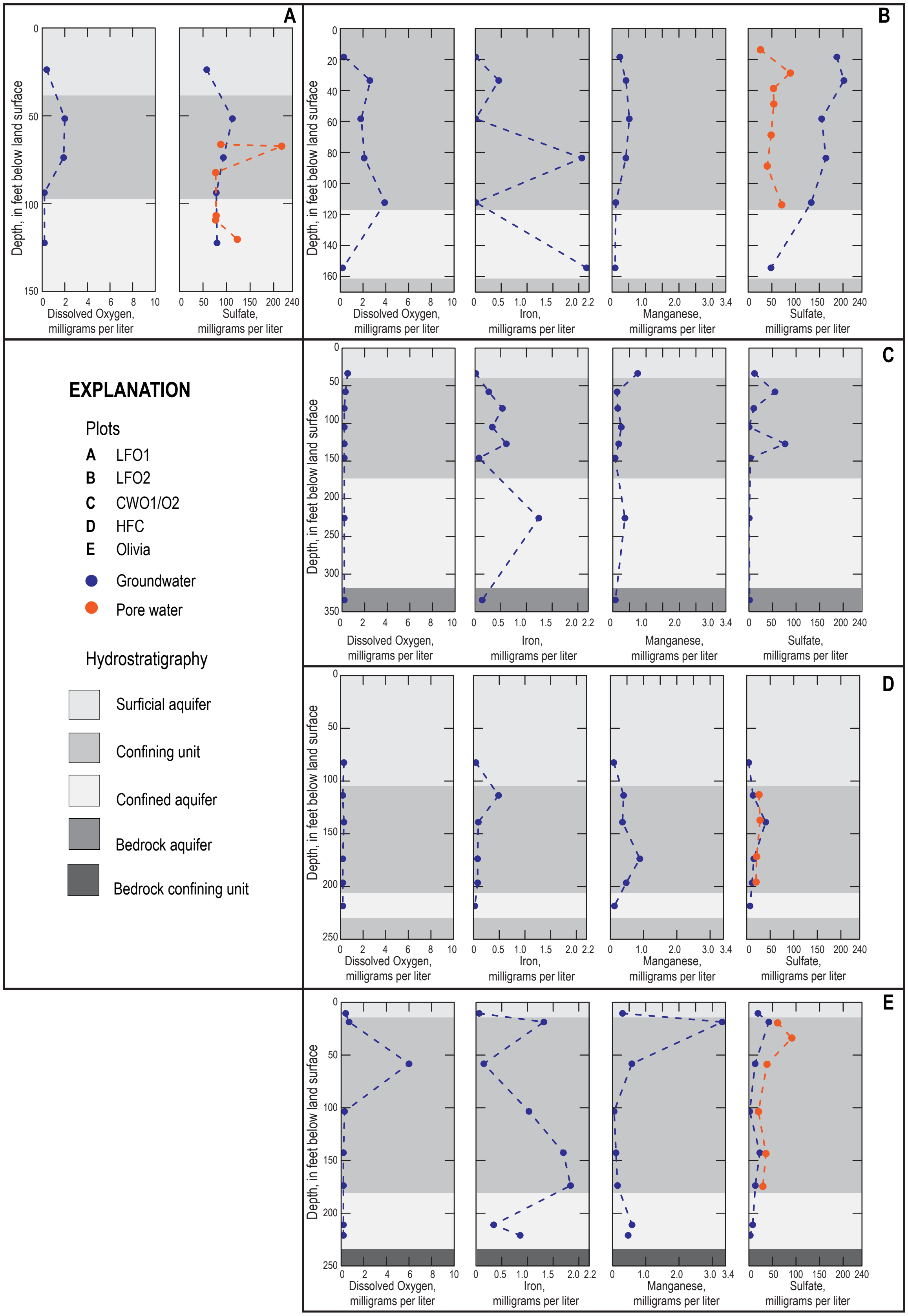


Figure 17: Redox (dissolved oxygen, iron, manganese, and sulfate) results for the Litchfield 1 (LFO1), Litchfield 2 (LFO2), Cromwell (CWO1/O2), Hydrogeology field camp (HFC), and Olivia sites.

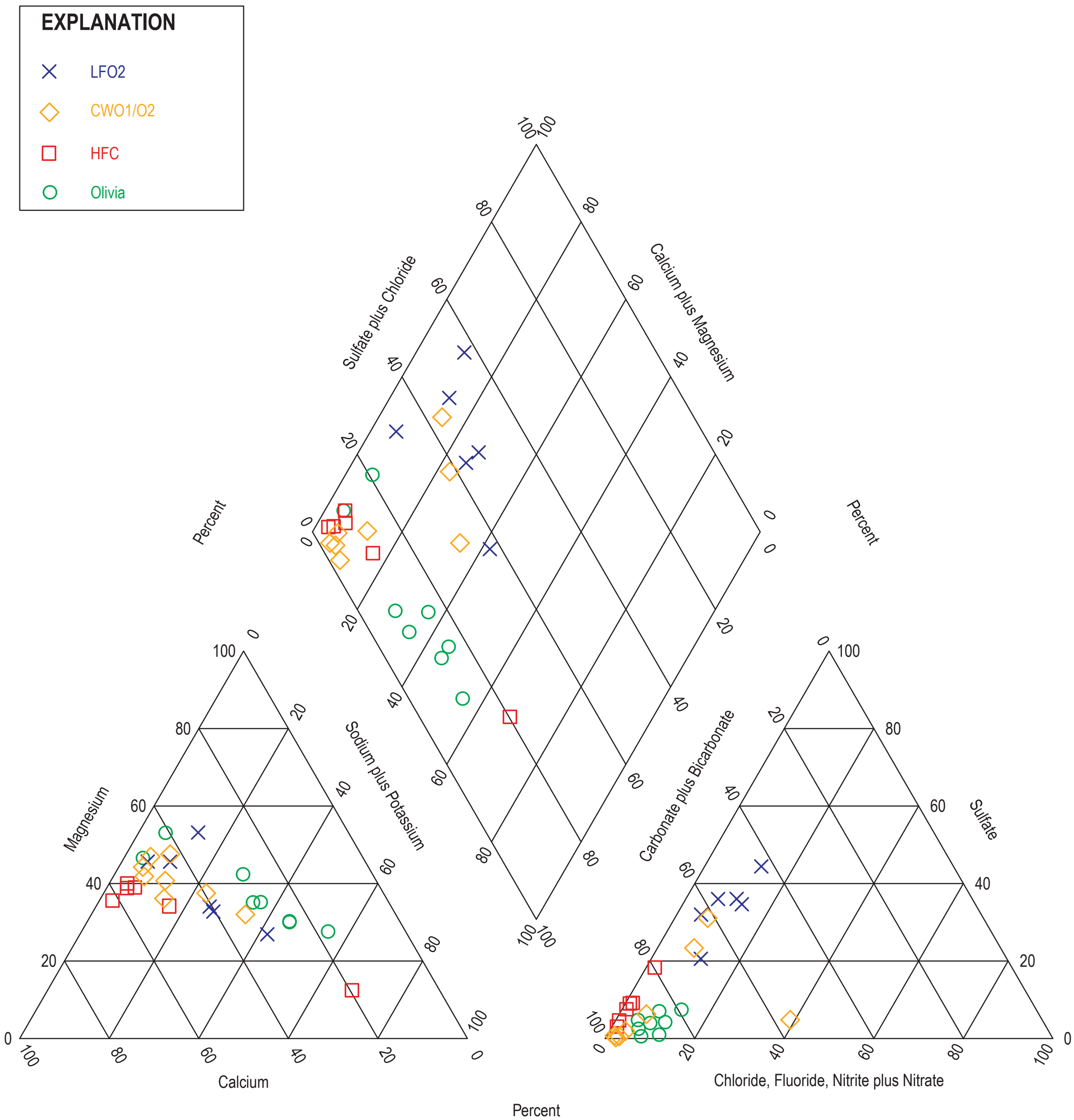


Figure 18: Piper diagram with USGS National Water Quality Laboratory cation and anion results for the Cromwell (CWO1/O2), Litchfield 2 (LFO2), Hydrogeology field camp (HFC), and Olivia sites.

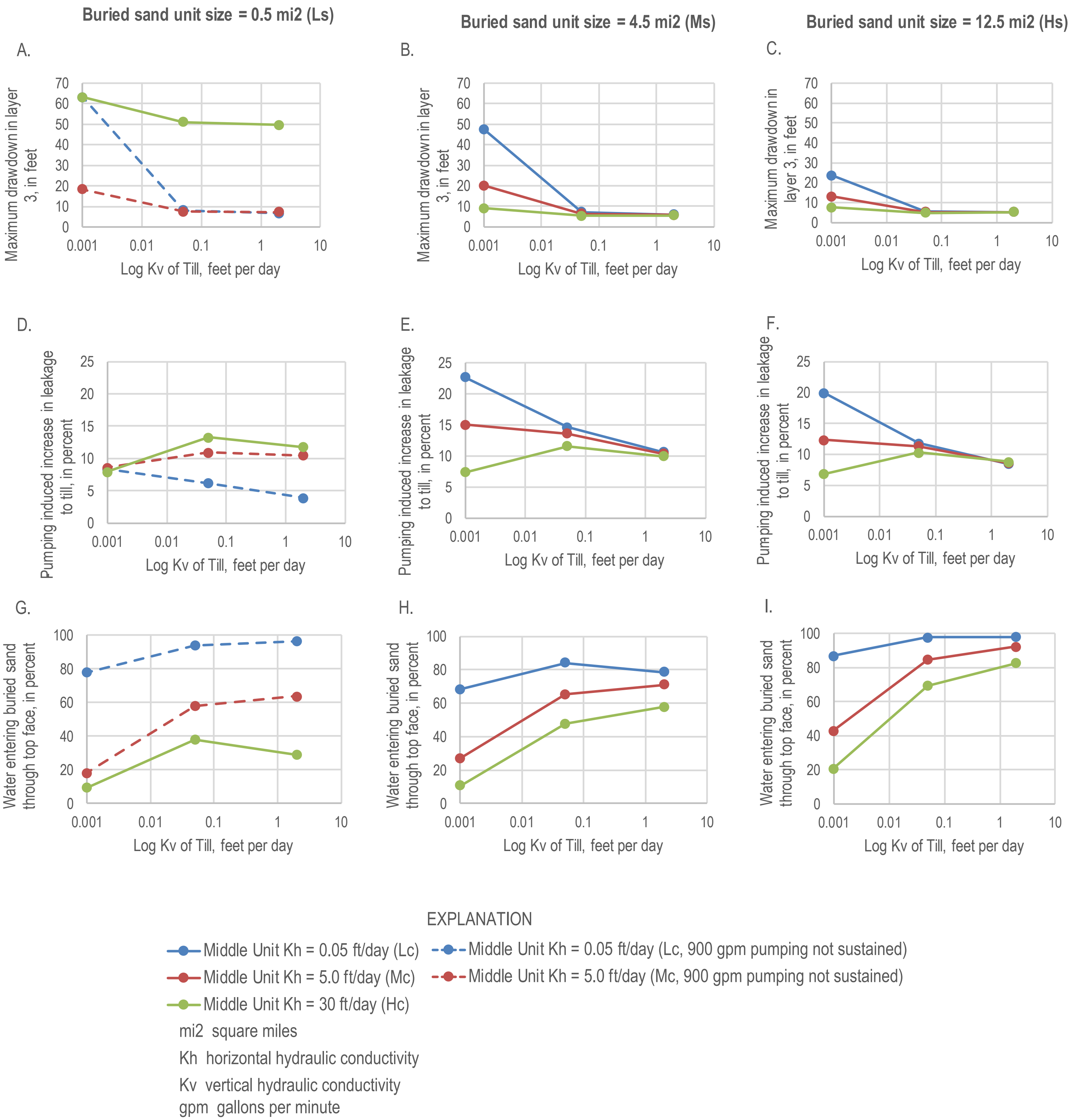


Figure 19. Plots of interpretive MODFLOW model output including changes in maximum drawdown in till (A - C), pumping-induced increase in leakage to till from surficial unit (D - F), and the amount of water entering the aquifer through its top face (G - I).

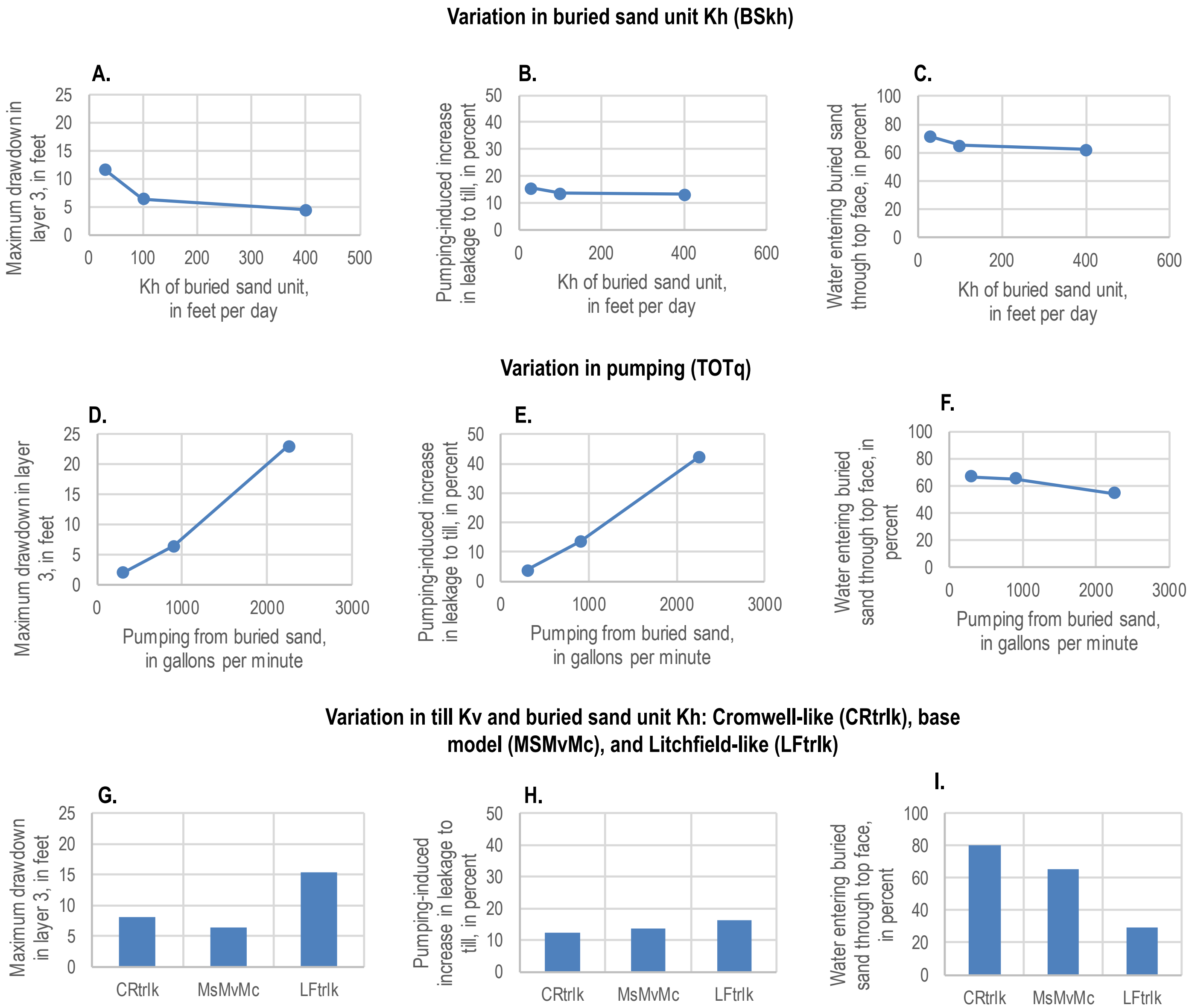
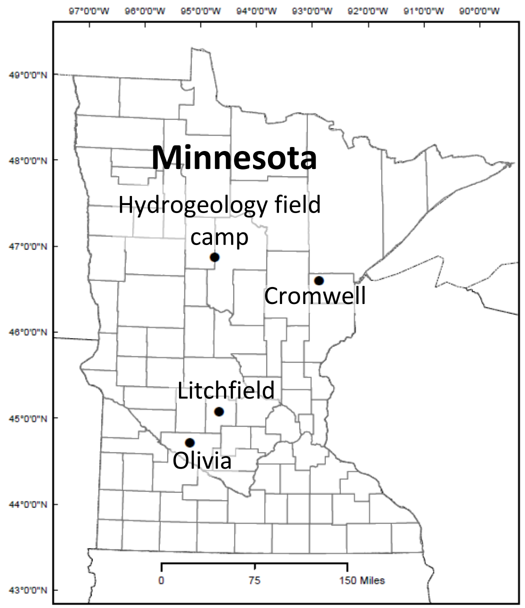


Figure 20. Plots of interpretive MODFLOW model output for variation model runs including changes in maximum drawdown in till, pumping-induced increase in leakage to till from surficial unit, and the amount of water entering the aquifer through its top face for variations in the buried sand horizontal hydraulic conductivity (Kh, A - C), variations in total pumping (D - F), and variations in till vertical hydraulic conductivity (Kv) and buried sand Kh (G - I).



Protection of State's Confined Drinking Water Aquifers

M.L. 2016, Chp. 186, Sec. 2, Subd. 04h as extended by M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 19

Methods: Field data were collected from sediment cores and a series of five well nests. Each nest comprised five to eight piezometers screened at short vertical intervals surficial aquifers, till, confined aquifers, and underlying bedrock. Travel times through the till were evaluated with Darcy's Law and stable isotope concentrations. Interpretive MODFLOW simulations used the range of till hydraulic properties observed at the field sites to evaluate water fluxes through till.

Conclusions

- Till is not impermeable; groundwater flows downward (leaks) through till at most field sites
- Groundwater travel times through till are highly variable, even at a single site
- Modeling suggests that hydraulic information about till is just as important as aquifer mapping for understanding sustainable water withdrawals from confined aquifers
- Site specific till data is necessary for understanding the sustainability of groundwater withdrawals from confined aquifers

Key

Till- unsorted glacial sediment with grain sizes ranging from clay to boulders. May not transmit water well and slow water flow down (confines the aquifer buried by the till).

Confined aquifer- sand and gravel of glacial origin, buried under till, that transmits water well and can be used for water supply.

K → K **K (hydraulic conductivity) in feet/day-** ease of which a fluid (in this case water) can move through a material. The larger the K, the easier it is for a fluid to move through the material

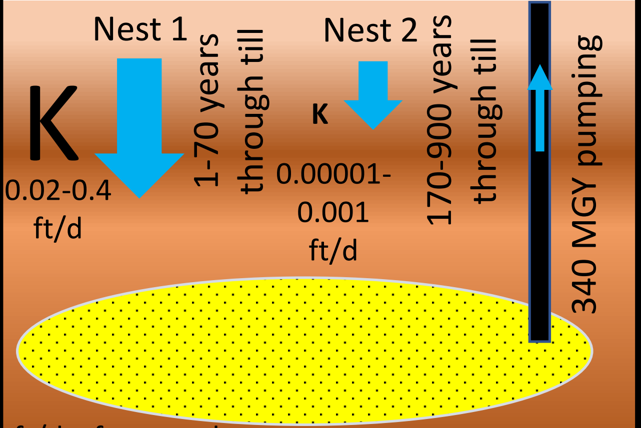
Direction of water flow through till- (downwards or upwards). Larger arrow in the till means larger flux of water.

Litchfield site

New Ulm Formation Till

- Two nests ½ mile apart
- Management implication: nest 1 is leakier than nest 2, requiring more careful attention to potential sources of contamination

4 inches

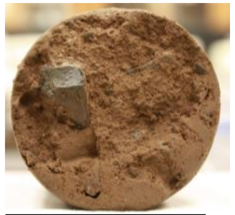


ft/d = feet per day
MGY = millions of gallons per year

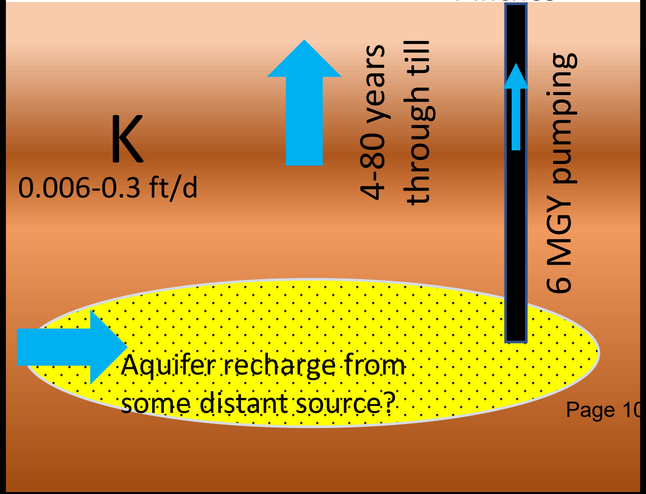
Cromwell site

Cromwell Formation Till

- Only site with an upward hydraulic gradient through till
- Management implication: aquifer recharge is likely from some distant source



4 inches

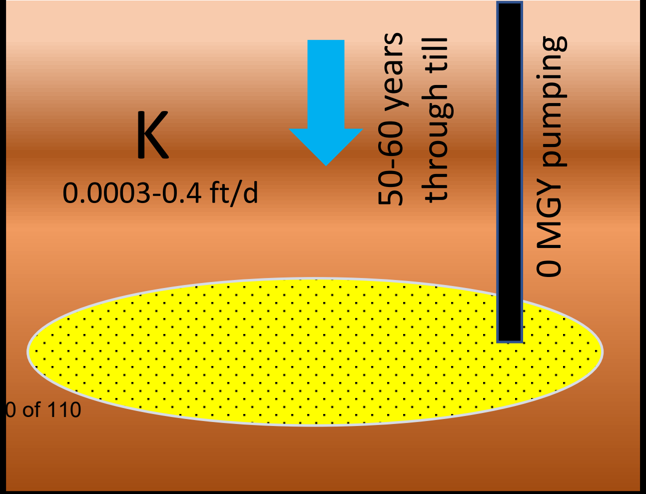


Hydrogeology field camp site

Hewitt Formation Till

- No routine pumping; hydraulic gradients and travel times represent ambient conditions

4 inches

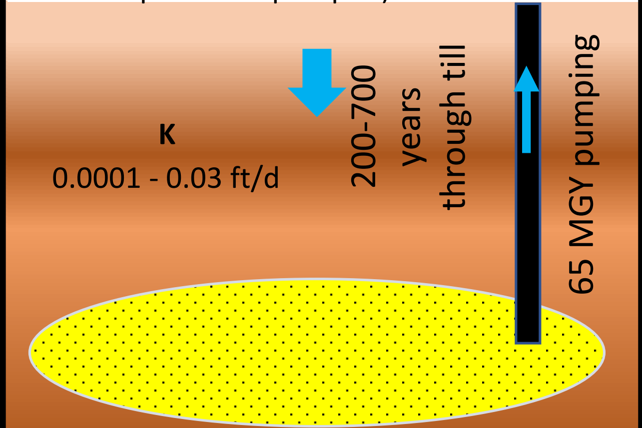


Olivia site

Good Thunder Formation Till

- Tiny confined aquifer (mapped as 0.08 mi^2), and yet pumping is maintained
- Reverse water level response during pumping (i.e. water levels increased in till wells when aquifer was pumped)

4 inches



Aquifers not drawn to scale; size varied between sites.

Table 1. Well and piezometer identification, vertical placement, and water level information.

[ft NAVD88; feet in North American Vertical Datum of 1988; in, inch; ft, feet; ft BLS, feet below land surface; ft ALS, feet above land surface; HFC, Hydrogeology Field Camp near Akeley, Minn.; USGS, U.S. Geological Survey; MN040, agency code representing the Minnesota Geological Survey in the U.S. Geological Survey's National Water Information System database; ----, not calculated

Well or piezometer short name	Field site	Agency code	USGS site ID	Minnesota unique well number	Installed during this study	Hydrostratigraphy of screened interval	Land surface elevation (ft NAVD88)	Screened interval (ft BLS)	Average hydraulic head (ft NAVD88)	Average water level (ft BLS)
LFO1-B	Litchfield	USGS	450814094315001	773062	Yes	surficial aquifer	1115.22	22.4 - 25.06	1103.94	11.28
LFO1-C	Litchfield	USGS	450814094315002	773060	Yes	till	1115.45	50.23 - 52.89	1102.99	12.46
LFO1-D	Litchfield	USGS	450814094315003	773059	Yes	till	1115.34	72.4 - 75.06	1091.30	24.04
LFO1-E	Litchfield	USGS	450814094315004	773058	Yes	till	1115.15	92.41 - 95.07	1079.50	35.65
LFO1-F	Litchfield	USGS	450814094315006	773057	Yes	confined aquifer	1115.19	117.5 - 127.12	1081.83	33.36
LFO2-A	Litchfield	USGS	450832094321201	773056	Yes	till	1139.45	17.12 - 19.78	1128.00	11.45
LFO2-B	Litchfield	USGS	450832094321202	773055	Yes	till	1139.29	32.26 - 34.92	1126.36	12.93
LFO2-C	Litchfield	USGS	450832094321203	773054	Yes	till	1139.72	56.97 - 59.63	1123.98	15.74
LFO2-D	Litchfield	USGS	450832094321204	773053	Yes	till	1139.18	82.27 - 84.93	1106.12	33.06
LFO2-E	Litchfield	USGS	450832094321205	773052	Yes	till	1139.64	110.95 - 113.61	1077.43	62.21
LFO2-F	Litchfield	USGS	450832094321206	773051	Yes	confined aquifer	1139.47	149.56 - 159.18	1079.28	60.19
LF-OB1	Litchfield	MN040	450821094320601	607417	No	confined aquifer	1123.14	122 - 127	---	---
LF-CM1	Litchfield	MN040	450837094321601	764258	No	confined aquifer	1145.14	136.5 - 161.5	---	---
LF-CM2	Litchfield	MN040	450820094320801	607420	No	confined aquifer	1123.23	107 - 132	---	---
LF-CM3	Litchfield	MN040	450828094320601	632077	No	confined aquifer	1121.20	108 - 136	---	---
LF-CM4	Litchfield	MN040	450851094321201	632078	No	confined aquifer	1142.83	123 - 147	---	---
CWO1-A	Cromwell	USGS	464110092531401	773071	Yes	till	1326.28	144.56 - 147.36	1307.49	18.79
CWO1-B	Cromwell	USGS	464110092531402	773070	Yes	confined aquifer	1326.29	220.91 - 230.53	1311.53	14.76
CWO1-C	Cromwell	USGS	464110092531403	773069	Yes	bedrock aquifer	1326.25	329.63 - 339.25	1311.51	14.74
CWO2-A	Cromwell	USGS	464112092531401	773068	Yes	surficial aquifer	1332.28	32.3 - 34.96	1304.66	27.62
CWO2-B	Cromwell	USGS	464112092531402	773067	Yes	till	1332.59	56.75 - 59.41	1305.40	27.19
CWO2-C	Cromwell	USGS	464112092531403	773066	Yes	till	1332.33	78.7 - 81.36	1306.54	25.79
CWO2-D	Cromwell	USGS	464112092531404	773065	Yes	till	1332.13	103.58 - 106.24	1309.87	22.26
CWO2-E	Cromwell	USGS	464112092531405	773064	Yes	till	1332.44	125.78 - 128.44	1309.46	22.98

Well or piezometer short name	Field site	Agency code	USGS site ID	Minnesota unique well number	Installed during this study	Hydrostratigraphy of screened interval	Land surface elevation (ft NAVD88)	Screened interval (ft BLS)	Average hydraulic head (ft NAVD88)	Average water level (ft BLS)
CW-CM3	Cromwell	MN040	464109092530701	519761	No	confined aquifer	1327	180 - 190	---	---
CW-CM4	Cromwell	MN040	464111092531401	593593	No	confined aquifer	1327.88	210 - 230	---	---
HT-115	HFC	USGS	465652094394801	773075	Yes	till	1452.00	112.35 - 114.83	1391.43	60.57
HT-140	HFC	USGS	465652094394802	773076	Yes	till	1452.39	137.77 - 140.25	1391.43	60.96
HT-175	HFC	USGS	465652094394803	773077	Yes	till	1452.04	172.47 - 174.95	1389.01	63.03
HT-200	HFC	USGS	465652094394804	773078	Yes	till	1452.04	195.22 - 197.7	1387.57	64.47
HB-1	HFC	MN040	465653094394701	809697	No	confined aquifer	1451.98	210 - 230	---	---
HB-2	HFC	MN040	465651094394001	819726	No	confined aquifer	1454.83	214 - 224	---	---
HB-3	HFC	MN040	465652094394701	825587	No	confined aquifer	1453.03	213.33 - 223.53	1387.15	65.88
MW-01	HFC	MN040	465652094394501	569489	No	surficial aquifer	1453.54	80 - 85	1391.60	61.94
WL07	HFC	MN040	465711094392601	243680	No	surficial aquifer	1502.20	126.3 - 128.3	---	---
WL12	HFC	MN040	465712094404201	243843	No	confined aquifer	1467.42	340 - 344	---	---
WL299	HFC	MN040	465725094403207	243849	No	confined aquifer	1400.46	0 - 0	---	---
OT-13	Olivia	USGS	444630095002202	773086	Yes	surficial aquifer	1070.51	7.89 - 13.03	1063.92	6.59
OT-20	Olivia	USGS	444630095002203	773085	Yes	till	1070.75	17.44 - 19.91	1064.19	6.56
OT-35	Olivia	USGS	444630095002204	773084	Yes	till	1070.60	32.08 - 34.55	1063.92	6.68[a]
OT-60	Olivia	USGS	444630095002205	773083	Yes	till	1070.67	56.74 - 59.77	1063.33	7.34
OT-105	Olivia	USGS	444630095002206	773082	Yes	till	1071.61	101.95 - 104.94	1056.47	15.14
OT-145	Olivia	USGS	444630095002207	773081	Yes	till	1071.44	141.15 - 144.13	1052.93	18.51
OT-175	Olivia	USGS	444630095002208	773080	Yes	till	1071.46	172.26 - 175.26	1045.07	26.39
OB-7	Olivia	USGS	444630095002209	773079	Yes	confined aquifer	1071.39	204.92 - 209.71	969.27	102.12
Olivia-4	Olivia	USGS	444630095002201	228797	No	confined aquifer	1071.00	204 - 228	---	---
Olivia-5	Olivia	USGS	444639095002201	228796	No	confined aquifer	1075.01	196 - 218	---	---
Olivia-6	Olivia	MN040	444637095013701	241525	No	confined aquifer	1087.00	333 - 343	---	---

[a]This water level is not an average, it is the final water level reading. The water level in this well took the entire project period to recover from being drawn down for well development and therefore the final water level best represented an approximate "static" water level.

Table 2. Summary of aquifer test information, from Blum and Woodside, 2017; Lund and Blum, 2017; Blum, 2019a, and Blum, 2019b.

[Kv, vertical hydraulic conductivity; ---, unknown; gpm, gallons per minute]

Site	Well name	Minnesota unique well number	Date/time pumping start	Date/time recovery start	Pumping duration (minutes)	Total discharge (gallons)	Rate (gpm)	Analytical method to determine representative till Kv	Aqtesolve or manual
Cromwell	CW-CM4	593593	5/24/2017 12:10	5/25/2017 12:25	1,454.90	242,350	167	Neumann-Witherspoon (1969)	Aqtesolve
Litchfield	Litchfield nest 1, composite	---	7/5/2017 19:00	7/10/2017 10:55	6,715	15,444,500	2,300	Neumann-Witherspoon (1969)	Aqtesolve
Hydrogeology Field Camp (HFC)	HB-1	809697	7/20/2018 10:44	7/22/2018 12:02	2,958.15	Not reported	75	Hantush-Jacob (1955)	Aqtesolve
Olivia	Olivia composite (Olivia-4 and Olivia-5)	228797 and 228796	7/11/2018 7:54	7/12/2018 17:46	1,210	Not reported	232-227	Moench (1985) Case 1	Aqtesolve

Table 3. Summary of water quality sampling events and analytical labs used for water sample analysis

[---, no samples collected; WG, groundwater sample, WI, interstitial (pore) water]

Lab	Analytes	Well nest: Litchfield 1 (LFO1)	Well nest: Litchfield 2 (LFO2)	Well nest: Cromwell (CWO1/O2)	Well nest: Hydrogeology field camp (HFC)	Well nest: Olivia[a]
		Sample medium and month of sampling event				
USGS field staff	alkalinity, **Field parameters:** specific conductance, dissolved oxygen, temperature, pH	WG: July 2015 WG: May 2016	WG: July 2015 WG: May 2016	WG: July 2015 WG: May 2016	WG: Sept. - October 2017	WG: Sept. - October 2017
Rick Knurr (University of Minnesota and Ion Chrom Laboratory)	**Major anions:** bromide [Br], chloride [Cl], acetate [CH3CO2], fluoride [F], sulfate [SO4], thiosulfate [S2O3]); **Nutrients:** (nitrite [NO2], nitrate [NO3], phosphate [PO4]	WI: June 2015 WG: July 2015 WG:May 2016	WI: June 2015 WG: July 2015 WG:May 2016	WG: July 2015 WI: July 2015 WG:May 2016	WI: May 2017	WI: August 2017 WG: Sept.- October 2017
USGS National Water quality laboratory	**Major anions:** (Br, Cl, F, SO4); **Major cations:** (potassium [K], calcium [Ca], magnesium [Mg], manganese [Mn], sulfur [S], iron [Fe], sodium [Na]); **Nutrients:** ammonia [NH3], total phosphorus [P], nitrite [NO2], nitrate [NO3]	---	WG: May 2016	WG: May 2016	WG: Sept. - October 2017	WG: Sept. - October 2017
Iowa State University Stable Isotope Lab	**Stable isotopes:** delta oxygen-18 ($\delta^{18}O$) and delta hydrogen-2 ($\delta^{2}H$)	WI: June 2015 WG: July 2015 WG:May 2016	WI: June 2015 WG: July 2015 WG:May 2016	WG: July 2015 WI: July 2015 WG:May 2016	WI: May 2017 WG: Sept.- October 2017	WI: August 2017 WG: Sept.- October 2017
University of Waterloo, Ontario, Canada Environmental Isotopes Lab	enriched tritium (^{3}H)	WG: May 2016	WG: May 2016	WG: May 2016	WG: Sept. - October 2017	WG: Sept. - October 2017
San Diego Geochemistry Lab (USGS California Water Science Center)	Pore-water extraction from cores, specific conductance, pH	WI: June 2015	WI: June 2015	WI: July 2015	WI: May 2017	WI: August 2017

[a]Piezometer OT-35 was never sampled at this nest.

Table 4. Model parameters that were varied in the interpretive groundwater model scenarios along with the model naming scheme.

[Kv, vertical hydraulic conductivity; Kh, horizontal hydraulic conductivity]

Model run type	Model parameter value	Units	Low parameter value	Base model parameter value	High parameter value	Source(s) that informed model property values
permutation	Vertical hydraulic conductivity (K_v) of upper till and lower unit	feet per day	0.001	0.05	2	a,b
		naming convention:	Lv	Mv	Hv	
	Lateral connectivity of buried aquifer to adjacent till and aquifers (represented as horizontal hydraulic conductivity [K_h] of middle unit)	feet per day	0.05	5	30	a,b,c
		naming convention:	Lc	Mc	Hc	
	Buried sand body (aquifer) size	mile x mile	1.0 x 0.5	3.0 x 1.5	5.0 x 2.5	c
		naming convention:	Ls	Ms	Hs	
variation	Buried sand body (aquifer) horizontal hydraulic conductivity (K_h)	feet per day	30	100	400	a, b
		naming convention:	BSkh_L	MsMvMc	BSkh_H	
	Thickness of upper till	feet	40	80	160	d, e
		naming convention:	UTtk_L	MsMvMc	UTtk_H	
	Total pumping rate	gallons per minute	300	900	2250	f
		naming convention:	TOTq_L	MsMvMc	TOTq_H	
	Screen length and penetration of pumping wells	screen length and location in aquifer	40 foot screen in lower aquifer layer	80 foot screen across both aquifer layers (full penetration)	40 foot screen in upper aquifer layer	g
		naming convention:	Ppen_L	MsMvMc	Ppen_H	
	Kh of surficial unit; Kv of surficial unit	feet per day; feet per day	5.0; 0.5	70; 7.0	400; 40	a,b,e
	recharge rate	inches per year	2	4	8	h
	thickness of surficial unit	feet	80	40	40	a,b,e
		naming convention:	SURF_L	MsMvMc	SURF_H	
	Transmissivity of buried sand body (aquifer)	$feet^2$ per day (feet per day)	4400 (Kh = 55.5)	8000 (Kh = 100)	8990 (Kh = 112.4)	a,b,e
	low and high parameter values are calculated from the leakance of upper till as observed in Litchfield and Cromwell aquifer tests (expressed as vertical hydraulic conductivity)	feet per day	0.6769	0.05	0.0016	a,b
		naming convention:	CRtrlk	MsMvMc	LFtrlk	

[a]Minnesota Department of Heath, 2017a
[b]Minnesota Department of Heath, 2017b
[c]Meyer, 2015
[d]Wagner and Tipping, 2016
[e]Witt, 2017
[f]Minnesota Department of Natural Resources, 2017
[g]Minnesota Department of Health, 2017c
[h]Smith and Westenbroek, 2015

Table 5. Summary of hydraulic conductivity (K) values from slug tests, lithology, and slug test analysis method used.

[K, hydraulic conductivity; Springer-Gelhar, Springer and Gelhar, 1991; KGS, Hyder and others, 1994; Butler, Butler, 1998]

Piezometer	Mean K	Minimum K	Maximum K	Falling head tests	Rising head tests	Lithology	Analysis method
	feet per day			count			
LFO1-B	1.78E+02	1.05E+02	2.44E+02	3	3	silty to coarse sand	Springer-Gelhar
LFO1-C	1.57E-02	1.50E-02	1.63E-02	1	1	till	KGS
LFO1-D	3.40E-01	2.53E-01	4.27E-01	1	1	till	KGS
LFO1-E	8.88E-01	5.04E-01	1.55E+00	3	3	till/sand and gravel	KGS
LFO1-F	3.34E+02	2.78E+02	3.89E+02	2	2	sand and gravel	Butler
LFO2-A	1.10E-04	2.17E-05	1.99E-04	1	1	till	KGS
LFO2-B	5.52E-04	2.09E-04	8.95E-04	1	1	till	KGS
LFO2-C	1.34E-03	1.34E-03	1.34E-03	1	1	till	KGS
LFO2-D	1.22E-05	1.22E-05	1.22E-05	1	0	till	KGS
LFO2-E	1.95E-04	1.11E-04	2.80E-04	1	1	till	KGS
LFO2-F	3.06E+02	2.28E+02	3.74E+02	3	3	sand and gravel	Butler
CWO1-A	2.84E-01	2.63E-01	3.06E-01	1	1	till	KGS
CWO1-B	2.31E+01	1.91E+01	2.81E+01	3	3	sand and gravel	Butler (1), KGS (5)
CWO1-C	3.49E-01	2.48E-01	5.62E-01	3	3	slate	KGS
CWO2-A	6.88E+00	4.71E+00	9.57E+00	3	3	sand and gravel	KGS
CWO2-B	6.21E-02	5.89E-02	6.54E-02	1	1	till	KGS
CWO2-C	1.12E-01	1.02E-01	1.23E-01	1	1	till	KGS
CWO2-D	8.97E-03	6.15E-03	1.18E-02	1	1	till	KGS
CWO2-E	3.60E-02	3.55E-02	3.65E-02	1	1	till	KGS
MW-01	2.49E+01	1.94E+01	3.15E+01	3	3	sand and gravel	Springer-Gelhar
HT-115	3.64E-01	3.37E-01	3.77E-01	3	3	till	KGS
HT-140	4.16E-04	2.61E-04	5.06E-04	3	3	till	KGS
HT-175	2.78E-02	1.51E-02	6.45E-02	3	3	till	KGS
HT-200	1.36E-01	1.24E-01	1.54E-01	3	3	till	KGS
HB-3	7.27E+01	6.50E+01	8.03E+01	3	3	sand and gravel	Butler
OT-13	1.55E+00	1.12E+00	1.97E+00	3	3	sand and gravel	KGS
OT-20	1.09E-02	6.50E-03	1.46E-02	3	3	till	KGS
OT-35	6.07E-06	6.07E-06	6.07E-06	0	1	till	KGS
OT-60	1.38E-03	6.47E-04	2.27E-03	3	2	till	KGS
OT-105	2.11E-04	1.00E-04	3.41E-04	3	3	till	KGS
OT-145	1.71E-02	6.45E-04	3.32E-02	3	3	till	KGS
OT-175	2.09E-02	1.28E-02	3.02E-02	3	3	till	KGS
OB-7	3.07E+00	1.44E+00	4.17E+00	3	3	sand and gravel	KGS

Table 6. Summary of physical and hydraulic properties of till and confined aquifers at the Litchfield, Cromwell, Olivia, and Hydrogeology Field Camp (HFC) sites.

[K, hydraulic conductivity; Kv, vertical hydraulic conductivity]

		Site				
Property	**Units**	**Litchfield 1 (LFO1)[b]**	**Litchfield 2 (LFO2)[b]**	**Cromwell (CWO1/O2)[c]**	**Hydrogeology field camp (HFC[d])**	**Olivia[e]**
Glacial Lobe	---	Des Moines	Des Moines	Superior	Wadena	Undetermined
Age[a]	---	Late Wisconsin	Late Wisconsin	Late Wisconsin	Late Wisconsin	Pre-Illinoian
		Till properties				
Geologic Formation[a]	---	New Ulm Villard Member	New Ulm Villard Member	Cromwell	Hewitt	Good Thunder
Average till grain size[a]	percent [sand:silt:clay]	47:34:19	52:31:17	57:31:13	67:22:11	37:40:23
Till texture[a]	---	loam to sandy loam		sandy loam	sandy loam to loamy sand	clay loam to loam
Average lithologic composition[a]	percent [crystalline:carbonate:shale]	56:28:16		98:3:0	97:3:0	45:53:2
till thickness (ft)	feet	60	115	120	100	166
Hydraulic gradient through till	dimensionless	0.56 downward	0.48 downward	0.02 upward	0.04 downward	0.13 downward
Slug test geometric mean K	feet per day	0.07	0.0002	0.06	0.03	0.004
Slug test K range	feet per day	0.02 - 0.4	0.00001 - 0.001	0.006 - 0.3	0.0003 - 0.4	0.0001 - 0.03
Aquifer test representative Kv	feet per day	0.001		1.1	0.031	0.0012
Aquifer test Kv range	feet per day	<0.0001 - 0.02		0.8-4.1	0.011-0.037	0.00012 - 0.003
Gradient across till/confined aquifer boundary	dimensionless	0.05	0.13	0.05	0.02	2.25
		Confined aquifer properties (determined from aquifer tests)				
Transmissivity	feet^2 per day	9,000		4,400	1,850	8,230
Thickness	feet	29		145	14	54
Kh	feet per day	310		30	132	152
Vertical anisotropy	dimensionless	1		0.5	1	1
Storativity	dimensionless	7.50E-05		2.00E-04	5.80E-05	5.40E-05
Leakage factor	feet	21,000		---	2,630	2,570
Well efficiency	percent	---		---	0.1	0.5

[a]Staley et al., 2018

[b]Aquifer test results from Blum and Woodside, 2017

[c]Aquifer test results from Lund and Blum, 2017

[d]Aquifer test results from Blum, 2019a

[e]Aquifer test results from Blum, 2019b

Table 7. Hydraulic characteristics of till, annual pumping rates, and estimates of travel time and flux through one square mile of till based on Darcy's Law for each study site.

[Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity

Site name	Mean hydraulic gradient, i (dimension-less)	Till thickness (feet)	Potential groundwater recharge (inches per year)[a]	Hydraulic conductivity source	Hydraulic conductivity (feet per day)	Mean linear velocity (feet per day)	Travel time through till (years)	Specific discharge (leakage), q (inches per year)	Recharge (leakage) from till, Q (gallons per year)	Pumping (gallons per year)	Area of till required to meet pumping demand (square miles)
Litchfield 1 (LFO1)	0.56 downward	60	4 to 8	slug test geometric mean Kh	0.07	0.4	1	177	3.1E+09	3.4E+08	
				aquifer test Kv (Blum, 2017a)	0.001	0.002	74	2.4	4.2E+07		8
Litchfield 2 (LFO2)	0.48 downward	115	4 to 8	slug test geometric mean Kh	0.0002	0.0003	912	0.4	6.6E+06	3.4E+08	
				aquifer test Kv (Blum, 2017a)	0.001	0.002	165	2.1	3.6E+07		9
Cromwell (CWO1/O2)	0.02 upward	120	4 to 8	slug test geometric mean Kh	0.06	0.004	81	4.4	7.7E+07	6.0E+06	
				aquifer test Kv (Blum, 2017b)	1.10	0.08	4	84	1.5E+09		NA
Hydrogeology field camp (HFC)	0.04 downward	100	4 to 8	slug test geometric mean Kh	0.03	0.005	56	5.4	9.3E+07	0.0E+00	
				aquifer test Kv (Blum, 2019a)	0.03	0.01	50	6.0	1.0E+08		0
Olivia	0.13 downward	166	2 to 6	slug test geometric mean Kh	0.004	0.002	214	2.3	4.0E+07	6.5E+07	
				aquifer test Kv (Blum, 2019b)	0.001	0.0006	730	0.7	1.2E+07		5

[a]Smith and Westenbroek, 2015

Table 8. Summary of results extracted from steady-state model ouput.

[gpm, gallons per minute]

Model run name	Sustained pumping	Percent of water pumped by wells from boundary conditions	Ambient-Percent of inputs to surficial unit (layer 1) that leaks into upper till (layer 2) within local area	Stressed-Percent of inputs to surficial unit (layer 1) that leaks into upper till (layer 2) within local area	Pumping-induced increase in percent of inputs leaking into upper till (layer 2)	Percent of water entering buried sand unit from below	Percent of water entering buried sand unit through the side faces	Percent of water entering buried sand unit through the top face	Drawdown in layer 1 (surficial unit)	Drawdown in layer 3 (till)
	gpm	percent							feet	
LsLvLc	291	0.4	0.5	8.8	8.3	9.7	21.9	78.0	4.4	63.1
LsLvMc	501	0.3	1.8	10.4	8.6	0.9	80.7	18.4	1.7	18.4
LsLvHc	900	10.3	3.6	11.5	7.9	0.4	90.0	9.6	1.1	10.5
LsMvLc	304	0.0	2.7	8.9	6.2	2.5	3.5	94.1	5.2	8.0
LsMvMc	577	0.0	11.9	22.8	10.9	0.4	41.6	58.0	5.0	7.4
LsMvHc	900	0.1	22.2	35.5	13.3	0.2	61.7	38.2	4.4	6.4
LsHvLc	304	0.0	6.3	10.2	3.9	0.7	2.6	96.7	6.1	6.6
LsHvMc	625	0.0	18.7	29.2	10.5	0.4	35.6	63.9	6.8	7.3
LsHvHc	900	0.0	37.1	48.8	11.8	0.2	70.8	29.0	6.2	6.7
MsLvLc	900	0.0	1.3	24.0	22.7	4.9	27.0	68.2	5.2	47.6
MsLvMc	900	0.4	2.5	17.6	15.1	0.5	72.4	27.1	2.3	20.2
MsLvHc	900	10.6	3.9	11.3	7.4	0.2	89.0	10.8	1.0	9.1
MsMvLc	900	0.0	11.2	25.8	14.6	0.7	15.2	84.1	5.2	7.2
MsMvMc	900	0.0	17.5	31.1	13.6	0.2	34.7	65.1	4.4	6.4
MsMvHc	900	0.1	24.2	35.8	11.6	0.1	52.2	47.7	3.5	5.4
MsHvLc	900	0.0	21.8	32.5	10.6	0.2	21.2	78.6	5.5	6.0
MsHvMc	900	0.0	28.3	38.7	10.4	0.1	28.9	70.9	5.4	5.9
MsHvHc	900	0.0	39.1	49.1	10.0	0.1	42.3	57.6	5.1	5.5
HsLvLc	900	0.0	2.9	22.8	20.0	4.1	8.9	87.0	3.0	23.7
HsLvMc	900	0.5	3.5	15.8	12.3	0.6	56.5	42.9	1.7	13.2
HsLvHc	900	10.8	4.5	11.3	6.9	0.2	78.9	20.9	0.9	7.7

Model run name	Sustained pumping	Percent of water pumped by wells from boundary conditions	Ambient-Percent of inputs to surficial unit (layer 1) that leaks into upper till (layer 2) within local area	Stressed-Percent of inputs to surficial unit (layer 1) that leaks into upper till (layer 2) within local area	Pumping-induced increase in percent of inputs leaking into upper till (layer 2)	Percent of water entering buried sand unit from below	Percent of water entering buried sand unit through the side faces	Percent of water entering buried sand unit through the top face	Drawdown in layer 1 (surficial unit)	Drawdown in layer 3 (till)
	gpm	percent							feet	
HsMvLc	900	0.0	19.9	31.7	11.8	0.6	1.5	97.9	3.5	5.4
HsMvMc	900	0.0	22.2	33.5	11.3	0.2	15.0	84.8	3.3	5.2
HsMvHc	900	0.1	25.4	35.7	10.3	0.7	30.4	69.5	3.0	4.9
HsHvLc	900	0.0	33.1	41.6	8.5	0.1	1.7	98.1	4.9	5.4
HsHvMc	900	0.0	34.7	43.3	8.6	0.1	7.4	92.5	4.9	5.3
HsHvHc	900	0.0	39.8	48.6	8.8	0.0	17.2	82.8	4.8	5.2
BSkh_L	900	0.0	14.6	30.2	15.6	0.3	28.2	71.5	6.2	11.6
BSkh_H	900	0.0	19.9	33.1	13.2	0.2	37.5	62.3	3.7	4.4
LFtrlk	900	0.1	4.1	20.4	16.3	0.5	70.3	29.3	2.6	15.4
CRtrlk	900	0.0	23.3	35.6	12.3	0.1	19.7	80.2	6.7	8.0
Ppen_L	900	0.0	17.5	31.1	13.6	0.2	34.7	65.1	4.4	6.2
Ppen_H	900	0.0	17.5	31.1	13.6	0.2	34.7	65.1	4.4	6.3
SURF_L	900	0.0	39.0	60.4	21.3	0.3	49.0	50.7	13.3	14.0
SURF_H	900	0.0	6.3	14.1	7.8	0.1	26.3	73.5	1.4	3.8
TOTq_L	300	0.0	17.5	21.3	3.8	0.2	33.2	66.6	1.3	2.0
TOTq_H	2250	0.0	17.5	59.7	42.2	0.3	45.4	54.4	19.2	23.0
UTtk_L	900	0.0	20.1	32.7	12.7	0.2	30.4	69.4	4.5	6.0
UTtk_H	900	0.0	14.7	29.3	14.6	0.2	39.8	59.9	4.3	7.0