M.L. 2014, Chp. 226, Sec. 2, Subd. 03h Project Abstract
For the Period Ending June 30, 2017

PROJECT TITLE: Protecting the States Confined Drinking-Water Aquifers
PROJECT MANAGER: Jared Trost
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2014, Chp. 226, Sec. 2, Subd. 03h

APPROPRIATION AMOUNT: $ 394,000
AMOUNT SPENT: $ 393,600.21
AMOUNT REMAINING: $ 399.79

Overall Project Outcomes and Results

Confined (or buried) aquifers 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, buried aquifers are thought to be less susceptible to surface contamination, but may recharge very slowly and may be prone to unsustainable groundwater withdrawals. This study was completed to give insight to the susceptibility and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota. A combination of hydrologic field measurements, geochemical analyses, and modeling techniques were used to quantify the variability of hydrologic properties and flux of water through till confining units to buried aquifers at two representative sites in Minnesota. Glacial deposits of the Des Moines Lobe were characterized in Litchfield, Minnesota and glacial deposits of the Superior Lobe were characterized in Cromwell, Minnesota.

A conceptual understanding emerges from the field measurements at the two sites that till “layers” in the glacial deposits of the Des Moines and Superior Lobes in Minnesota are not really continuous layers, but rather a complex series of sediment mixtures with differing abilities to transmit water. The hydrologic field measurements and geochemical analysis demonstrated large variations in till confining unit properties over relatively small vertical and horizontal distances, underscoring the challenges of assessing the susceptibility and sustainability of groundwater resources in confined aquifer systems.

Many waters in Minnesota are under threat of nutrient contamination from anthropogenic activities such as row-crop agriculture. This study provided some evidence that till confining units may be effective at reducing the susceptibility of buried aquifers to nitrate contamination, but may be a source of phosphorus. Data from Litchfield show that chloride is present in elevated concentrations where nitrate is not, despite abundant agriculture in the surrounding area. This suggests that denitrification may be occurring within the till; previous studies have demonstrated denitrification in Des Moines lobe tills (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995). Phosphorus, though present at depth, particularly in Cromwell, is likely geologic rather than anthropogenic in origin.

The conceptual 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. Over long periods of time, pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients could induce flow that affects surface-water resources. The source of water entering a buried aquifer that is being pumped can be highly variable, depending on the overlying till vertical hydraulic conductivities and the lateral connectivity of buried aquifer to adjacent till and aquifers. A sensitivity analysis demonstrated that the simulation of the source of water to wells is most sensitive to the vertical hydraulic conductivity of the overlying till, the areal extent of the aquifer, and the connectivity of the horizontal hydraulic conductivity of geologic materials adjacent to the aquifer.

Project Results Use and Dissemination

As the result of this project, 4 publications were produced and 1 in preparation. A total of 9 presentations were given to audiences; 5 presentations at professional meetings and 4 public presentations.

Date of Report: August 11, 2017
Final Report
Date of Work Plan Approval: June 4, 2014
Project Completion Date: June 30, 2017
Does this submission include an amendment request? No

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

Project Manager: Jared Trost
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Location: Statewide

Total ENRTF Project Budget:

ENRTF Appropriation:	**$394,000.00**
Amount Spent:	**$393,600.21**
Balance:	**$ 399.79**

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 03h

Appropriation Language:

$394,000 the second year is from the trust fund to the Commissioner of Natural Resources for an agreement with the United States Geological Survey to test methods of defining properties of confined drinking water aquifers in order to improve water management. This appropriation is available until June 30, 2017, by which time the project must be completed and final products delivered.

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

II.PROJECT STATEMENT: Many glacial aquifers in Minnesota, used as sources of drinking water, are overlain by clayey glacial deposits (confining units, see figures). 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 assess hydraulic properties of the state's two major regional glacial confining units--the Des Moines and Superior lobe till confining units (see figures) by measuring detailed, site-specific information about protective confining units at two study sites that represent the state's most 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 effort will help to answer important questions about confining units and confined aquifers, including:

- *What are the pathways for water and contaminant movement through glacial confining units?*
- *What is the source of water replenishing glacial confined aquifers?*
- *How long does it take water to move along the flow pathways?*
- *How much water infiltrates into and recharges glacial aquifers?*
- *What are best estimates of long-term sustainable pumping from confined glacial aquifers used as sources of drinking water?*
- *How do properties of glacial confining units vary across the state?*

<u>Problem:</u> 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 confining units by mapping existing and newly collected data 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 and Superior lobe till deposits (see figures). 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 comprised 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 and 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 information to accurately evaluate contributing areas for wells completed in confined-drift aquifers are essential for the MDH's wellhead protection program because delineating and protection of these contributing areas is more complex for confined aquifers than for unconfined aquifers. Accurate simulation of infiltration through glacial till also is a critical component for calibration of 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 Minnesota Department of Natural Resources 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 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, Minnesota Pollution Control Agency (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 and map the continuity of the state's most important confining units--the Des Moines and Superior lobe confining units. The approach involves conducting two detailed field studies in areas representing each of these 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 will be a significant part of this study and will take place when the study begins. Study- site selection will be a collaborative effort with the Minnesota Department of Natural Resources, the Minnesota Geological Survey, and the Minnesota Department of Health. Study sites will be located near appropriate municipal production wells in areas with approved wellhead protection plans.

The objectives of the study are as follows:

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

III. PROJECT STATUS UPDATES:

Project Status as of December 31, 2014:

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 contract for technical assistance from the Minnesota Geological Survey was prepared. A Joint Funding Agreement was prepared and reviewed by USGS Headquarters and by the Minnesota Department of Natural Resources. A decision was made to contract with the USGS drilling group for test drilling and well installation. Meetings were held with staff from the Minnesota Geological Survey, the Minnesota Department of Health and the Minnesota Department of Natural Resources to discuss selection criteria for test sites. Limited costs were incurred during this period. The funding agreement with the Minnesota Department of Natural Resources was not signed until on November 4, 2014. Considerable, off-budget, time was spent in assessing potential study sites, sites based on information in well-head protection documents provided by the Minnesota Department of Health. Minnesota Department of Natural Resources staff assisted in technical evaluation of potential sites.

Amendment Request (12/31/2014)

This request includes a reduction in the budgets intended as contract-project support to the Minnesota Geological Survey (MGS). The MGS is unable to provide the level of support originally requested. Some of the work intended to be provided by the MGS will need to be accomplished by staff from the USGS.
The changes include:

- Budget reduction from $60,000 to $30,000 for MGS contract staff support and a corresponding increase in USGS staff salary support.
- Change in contract support for the MGS for in-state travel, from $5000 to $2,500 and a corresponding increase for in-state travel for USGS staff.
- Change contract support for the MGS for supplies and analytical costs from $1,000 to zero and a corresponding increase for equipment and supplies for the USGS.

Request approved by the LCCMR January 5, 2015

Project Status as of June 30, 2015:

A contract was awarded to the Minnesota Geological Survey (MGS) for technical assistance and for geological interpretation. A Joint Funding Agreement was approved by USGS Headquarters and by the Minnesota Department of Natural Resources. An agreement was completed to contract with the USGS drilling group (California Water Science Center) for test drilling and well installation because of the specialized nature of the drilling required. Study sites were selected in Litchfield and Cromwell, Minnesota and site permissions were obtained for access. Meetings were held with staff from the MGS, the Minnesota Department of Health and the Minnesota Department of Natural Resources to plan for data collection at each of the sites. Drilling and field instrumentation began in early June. However, limited cost have been billed to the project as of the date of this report.

A second-phase proposal was submitted as part of the 2016 LCCMR proposal process. The second phase would add to additional sites to the overall study. A total of four sites has been considered adequate to cover the variability of hydrologic conditions across the state. This was noted in the 2014 proposal. The second phase study would be similar to the current study but at 2 different site locations.

Amendment Request (6/30/2015)
This request eliminates objective 3 of the study. The objective is being eliminated because the Minnesota Department of Natural Resources (MDNR) was unable to fund the effort. There were no Trust Funds included in the work outlined under objective 3. This objective was to be completed with funding the MDNR and the USGS. Objective 3 was as follows:

- Develop a database of hydraulic information for till confining units throughout Minnesota.

Project Status as of December 31, 2015:

Well and piezometer installations were completed by the USGS Western Drilling Program crew. Wells and piezometers have been developed and finished. The sites are located near Litchfield and near Cromwell. In all, 19 well or piezometers, were completed. The Litchfield site is in a part of the state where Des Moines lobe glacial till is the principal glacial confining unit. The Cromwell site is located where the Superior lobe glacial till is the principal confining unit. Small-diameter observation well clusters, or piezometers, were installed in the confined-drift aquifers, the confining units overlying the confined aquifers, and in the surficial unconfined-drift aquifers. One well cluster, at each study site, is located in close proximity to the municipal water-supply well. The second of the well-cluster locations, at each study site, is located at some distance from the municipal-supply wells. Pressure transducers were installed in selected observation wells and piezometers to continuously measure water levels and hydraulic heads. Hydraulic, geochemical and hydraulic testing of soils and soil water is completed. These tests are being analyzed to determine geologic and hydraulic properties of the aquifers and confining beds.

Amendment Request (12/30/15)

1. This request further reduces the budget intended as contract support from the Minnesota Geological Survey (MGS). It includes reductions in both staff time and travel expense for MGS staff. This request reduces the amount of financial support planned to be provided by MGS staff and increases the budget for USGS travel and for analysis of groundwater samples at USGS contract labs. The change is requested because MGS staff were unable to schedule staff during some field activities due to the changing schedules of contract drill crews. USGS staff completed field work planned to have been done by MGS staff. These conflicts could not be avoided and were worked out successfully among MGS and USGS staff. The remaining tasks assigned to MGS for this project can be completed under the current contract with the University of Minnesota (MGS) and within this amended request. These changes result in a budget reduction from $30,000 for MGS contract staff support to $14,985. The funds were used to increase the travel budget by $6,815, and $8,200 was allocated for lab analytical expenses.The MGS travel contract for $2,500 was also reduced to $0; these funds were re-allocated for supplies.
2. Under activity 2, we stated that "Time of travel tests will be determined by conducting a tracer test. A conservative tracer such as potassium bromide will be applied within boreholes and monitored in underlying observation wells to evaluate infiltration rates." A tracer test will not be done for two reasons: (1) Preliminary analyses of slug test and groundwater chemistry data indicate that the travel times for an added tracer across the confining beds will be years longer than the project period and (2) we are already employing multiple methods to estimate the infiltration rates across the confining beds (modeling, analytical techniques, environmental tracers) and the tracer test would not not yield new information substantially different from what we will obtain from our other methods. This change does not require a change in the budget.
3. Personnel FTE and costs have been updated in the budget summary and workplan budget spreadsheet.

Amendment approved by LCCMR 1-25-2016

Amendment Request (5/24/16)

1. This request reduces the budget for contract support from the Minnesota Geological Survey (MGS) by $1,472.85 for a new total of $13,512.15. The MGS completed their data analysis and provided a report summarizing the results. They have issued their final invoice and completed their tasks for less than the budget established in the last amendment request. These funds were re-allocated to supplies.
2. Under activity 2, we state "A USGS Scientific Investigations Report will be published." In support of this publication effort, a budget of $9,000 was allocated for contract printing (expenses related to the production of the publication through USGS contract publishers). We are now confident that phase 2 of

this project will be funded and it will be more cost effective to publish just one report that summarizes the results from the phase 1 and phase 2 projects. The field methods and project design is the same for phase 1 and phase 2. As part of phase 1, we will still produce a draft report that summarizes the phase 1 results, but we will not incur the $9,000 publishing cost. The phase 2 project workplan has budget to cover the publication production expenses. Most of the $9,000 will be re-allocated for hiring a contractor to abandon the wells and piezometers installed during activity 1 ($8,000). The expenses for well installation took the entire contract drilling budget and so additional funds are necessary to abandon the wells and piezometers according to Minnesota Department of Health code. The remaining $1,000 will be used for supplies.

3. The cost of the transducers required for Activity 1 will be more than anticipated and the expense is incorrectly budgeted in Activity 2 rather than Activity 1. The following changes are requested: Increase the activity 1 Equipment/Tools/Supplies budget to $24,311.42, decrease the activity 2 Equipment/Tools/Supplies budget to $2,118.56.
4. The cost of consumable supplies and shipping was less than anticipated for activity 1 and can be reduced to $742.53. The cost of consumable supplies and shipping in support of water quality sampling for activity 2 will require more funds than are budgeted now; it is requested that this budget be increased to $1,500.
5. The laboratory costs for water quality analyses as part of phase 2 will be lower than originally budgeted; it is requested that the budget be reduced from $8,200 to $4,500. The Minnesota Department of Health and Iowa State University will be paying for some analyses from their own funds and the planned analyte list has changed from when the budget was developed. The new analytes are better suited to fulfill the objectives of this project. The funds will be re-allocated to supplies.
6. The timeline of several tasks have been adjusted to reflect the current deadlines.

Amendment approved by LCCMR 5-26-2016

Project Status as of June 30, 2016

The Minnesota Geological Survey completed their analysis and interpretation of the geologic samples collected during the drilling at the Litchfield and Cromwell sites. They have summarized their results in a report titled "Core Descriptions and Borehole Geophysics in Support of USGS Hydrologic Properties of Till Investigation, Litchfield and Cromwell, Minnesota". The report is available here: ftp://mgsftp2.mngs.umn.edu/pub4/outgoing/MGS_report_in_support_of_USGS_till_study_Phase_I.pdf. Continuous and discrete water level data were collected throughout the last reporting period. Groundwater samples were collected from 19 of the newly installed wells and piezometers in May 2016. These samples are presently being analyzed at the USGS National Water Quality Laboratory and the University of Waterloo Isotope Laboratory. Slug tests were completed in all 19 wells and piezometers. Aquifer hydrologic properties were quantified with analyses of slug test data. A draft report of the slug test analyses is complete and is in the USGS review process.

Project Status as of December 30, 2016

All water quality data from the sampling in May has been reviewed and approved.

Progress has been made on several of the final report products that will result from this project. The slug test report, which summarizes the hydrologic properties surrounding each of the 19 wells installed as part of this project, is still in the USGS review process. Alyssa Witt has written substantial portions of her thesis. This thesis summarizes the field drilling and sampling methods, the lab analytical methods, the properties of the geological materials determined from slug tests, pore-water chemistry, and groundwater chemistry. These data are being used to get point estimates of recharge rates through till and the susceptibility of the confined aquifers to human activities at the land surface. The thesis will comprise part of the final report from this project. The final report will also compare the point field observations with a MODFLOW groundwater flow model of each site. The model serves to test hypotheses about the variability of till properties. The models for the Litchfield and

Cromwell sites have been constructed based on the best available hydrologeologic information. They are now in the process of being refined and calibrated to reproduce observed field data.

Amendment Request (6/30/17)

1. This amendment is to increase the budget for well abandonment and activity 2 salary and decrease budgets for all other categories with remaining funds. The well abandonment cost is more than anticipated and the budget needs to be increased from $8,000 to $12,269.25 to seal the wells according to Minnesota well codes. Well abandonment is part of the activity 2 contract drilling, so we request that the activity 2 contract drilling budget be increased from $24,000 to $24,269.25.
2. All purchases of equipment, tools, and supplies have been completed and no more funds are needed for these expenses. We request that the activity 1 equipment budget be reduced from $24,311.76 to $24,163.09 and the activity 2 equipment budget be reduced from $2,118.56 to $0.00
3. All lab analyses have been completed and no more funds are needed for these expenses. We request that the activity 2 lab analysis budget be reduced from $4,500 to $3,813.62.
4. All travel is completed for activity 2 and the budgeted amount is more than the expenditures since the last billing period. We request that the activity 2 travel budget be reduced from $10,315 to $8,899.65.
5. Activity 2 USGS miscellaneous expenses were lower than estimated. We request that the activity 2 miscellaneous budget be reduced from $1,500 to $1,199.92.
6. ~~After all of these budget adjustments, an additional $399.79 remained to be re-allocated. We request that these funds be allocated to salary for hydrologic technicians.~~

Amendment approved by LCCMR 7-12-2017. Item 6 was not approved.

Project Status as of June 30, 2017
Alyssa Witt successfully defended her thesis, which is now in the process of being converted to a USGS Scientific Investigations Report. The Litchfield and Cromwell models are still undergoing calibration to reproduce field data. The review of the slug test report is on hold until field data from phase 2 is added.

Overall Project Outcomes and Results

Confined (or buried) aquifers 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, buried aquifers are thought to be less susceptible to surface contamination, but may recharge very slowly and may be prone to unsustainable groundwater withdrawals. This study was completed to give insight to the susceptibility and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota. A combination of hydrologic field measurements, geochemical analyses, and modeling techniques were used to quantify the variability of hydrologic properties and flux of water through till confining units to buried aquifers at two representative sites in Minnesota. Glacial deposits of the Des Moines Lobe were characterized in Litchfield, Minnesota and glacial deposits of the Superior Lobe were characterized in Cromwell, Minnesota.

A conceptual understanding emerges from the field measurements at the two sites that till "layers" in the glacial deposits of the Des Moines and Superior Lobes in Minnesota are not really continuous layers, but rather a complex series of sediment mixtures with differing abilities to transmit water. The hydrologic field measurements and geochemical analysis demonstrated large variations in till confining unit properties over relatively small vertical and horizontal distances, underscoring the challenges of assessing the susceptibility and sustainability of groundwater resources in confined aquifer systems.

The observations at the Litchfield site indicate that only limited portions of tills are aquitards that limit water flow and susceptibility to contamination for long periods of time. The till sequence at well nest LFO2 contained a zone of very low hydraulic conductivity whereas the till sequence at well nest LFO1, only about a 0.5 mi away from LFO2, lacked a such a feature. The estimated vertical travel time between the two sites differs by three orders of magnitude, from about 2 years to over 1,000 years. The LFO1 site had evidence of recent anthropogenic inputs to the buried aquifer whereas no evidence of anthropogenic inputs was observed at LFO2. The aquifer test, which measured hydrologic conductivity of a much larger volume than the slug tests, demonstrates that the average ability of the till to transmit water lies between the two extremes observed at LFO1 and LFO2.

Observations at Cromwell also demonstrated a complex sequence of variable till material. An overall upward gradient existed at this site, but gradient directions were variable within the till. The hydraulic gradient data and the ^3H data suggest that recharge to the buried 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 we 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 buried aquifer at the Cromwell site. The relatively high hydraulic conductivity estimates of the till and the similarity in water-level patterns observed throughout the Cromwell profile suggest there is no aquitard layer present like that at LFO2.

Many waters in Minnesota are under threat of nutrient contamination from anthropogenic activities such as row-crop agriculture. This study provided some evidence that till confining units may be effective at reducing the susceptibility of buried aquifers to nitrate contamination, but may be a source of phosphorus. Data from Litchfield show that chloride is present in elevated concentrations where nitrate is not, despite abundant agriculture in the surrounding area. This suggests that denitrification may be occurring within the till; previous studies have demonstrated denitrification in Des Moines lobe tills (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995). Phosphorus, though present at depth, particularly in Cromwell, is likely geologic rather than anthropogenic in origin.

The conceptual 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. Over long periods of time, pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients could induce flow that affects surface-water resources. The source of water entering a buried aquifer that is being pumped can be highly variable, depending on the overlying till vertical hydraulic conductivities and the lateral connectivity of buried aquifer to adjacent till and aquifers. A sensitivity analysis demonstrated that the simulation of the source of water to wells is most sensitive to the vertical hydraulic conductivity of the overlying till, the areal extent of the aquifer, and the connectivity of the horizontal hydraulic conductivity of geologic materials adjacent to the aquifer.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Select sites for detailed study that represent the primary glacial confining units in the state. Construct scientific boreholes and testing

Description: Two field study sites will be selected for detailed hydrologic investigation. One site will be located in a part of the state where Des Moines lobe glacial till is the principal glacial confining unit. The second site will be located where the Superior lobe glacial till is the principal confining unit. Study sites will be identified and selected in consultation with staff from the Minnesota Departments of Health and Natural Resources and the Minnesota Geological Survey. 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 Minnesota Department of Health. 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 close proximity to the municipal water-supply well. The second of the well-cluster location, at each study site, will be located at some distance from the municipal-supply wells. The exact locations of the well nests will be determined, after the study sites are selected, 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. They will be installed in the spring of 2015. Observation wells and piezometers will be installed in scientific boreholes after geophysical testing of the boreholes is completed. Pressure transducers will be installed in each of the observation wells and piezometers to continuously measure water levels and hydraulic head over the duration of the study. The identification and siting of study sites and well-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.

(As of December 30, 2016)
Summary Budget Information for Activity 1:

ENRTF Budget:	**$240,398.62**
Amount Spent:	**$240,398.62**
Balance:	**$ 0.00**

Activity Completion Date: September 2015

Outcome	Completion Date	Budget
1. Locate appropriate test sites near existing high-capacity municipal 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 and based on evaluation of local geological conditions.	**October 2014**	**$7,553**
2. Obtain site access and site-use permission. Obtain drilling permits and well variances if needed. Meet with city officials. Travel and reconnaissance of potential sites.	**December 2014**	**$ 5,000**
3. Install boreholes and instrument sites for hydraulic, geophysical and chemical tests to define hydraulic properties of confining units. Locate observation well sites. Install wells and using contract driller. Conduct geophysical surveys of boreholes. Install pressure transducers and water level recording equipment. Much of these expenses are associated with contract drilling.	**June 2016**	**$227,845.33**

Activity Status as of December 31, 2014 (Activity 1):

The proposal was selected by the Legislative and Citizens Commission on Minnesota Resources (LCCMR) and recommended for inclusion in a funding bill which passed the Minnesota House and Senate and was signed by Governor Dayton. Detailed project work plans and budgets were prepared and approved by the LCCMR. The USGS technical project proposal was prepared, reviewed by staff from the Minnesota Water Science Center, and reviewed and approved by the USGS Water Science Field Team and the Midwest Region. Project information was documented in the USGS Information Data System. A sole-source justification was prepared for technical assistance from the Minnesota Geological Survey. The funding allocated for the MGS had to be reduced at the request of MGS staff. A Joint Funding Agreement was prepared for review by Headquarters and by the Minnesota Department of Natural Resources. There have been delays in the review and completion of the Joint Funding Agreement and in approval of the sole-source contract.

A decision was made to use the USGS drilling contract group for test drilling and well installation. Meetings were held with staff from the Minnesota Geological Survey, the Minnesota Department of Health and the Minnesota Department of Natural Resources to discuss selection criteria for test sites. A decision was made to locate test sites around existing municipal wells that have prepared wellhead protection plans and in counties that have completed geologic atlases. Based on input from the Minnesota Department of Health, wellhead protection plans were reviewed for 30 municipalities. These were for municipalities having their public supply wells completed in confined-drift aquifers underlying confining units that are comprised of glacial tills having origins from the Superior or Des Moines Glacial lobes. Site information was reviewed that considered the thickness and hydrologic properties of confining units, site conditions and supply-well characteristics. The list was narrowed to 12 municipalities. Jim Berg (MNDNR) assisted with additional analyses that considered the degree of confinement of the aquifers in which the municipal wells were completed, based on stratigraphic analysis and water chemistry (tritium). At this time four sites remain in consideration. These include Buckman, Winsted, Litchfield, and Watertown. This list is being narrowed to two sites based on local site conditions and on information provided by the public water utilities. One site will be located in a part of the state where Des Moines lobe glacial till are the principal glacial confining unit. A second site will be located where the Superior lobe glacial till is the principal confining unit. At both study sites small-diameter observation well clusters, or piezometers, will be installed in the confined aquifer, the confining unit overlying the confined aquifer, and in the surficial unconfined 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 municipal water-supply well. The second well-cluster location, at each study site, will be located at some distance from the municipal-supply wells. The exact locations of the well nests will be determined, after the study sites are selected, 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 next three-month period of the study. They will be installed in the spring of 2015. Observation wells and piezometers will be installed in scientific boreholes after geophysical testing of the boreholes is completed. Pressure transducers will be installed in each of the observation wells and piezometers to continuously measure water levels and hydraulic head over the duration of the study

Limited costs were incurred during this period. The funding agreement, with the Minnesota Department of Natural Resources, was not signed until November 4, 2014. Considerable, off-budget, time was spent is assessing potential sites based on information in well-head protection documents provided by the Minnesota Department of Health. Minnesota Department of Natural Resources staff assisted in technical evaluation of potential sites.

Activity Status as of June 30, 2015 (Activity 1):

The USGS technical project proposal was approved by the USGS Water Science Field Team and the USGS Midwest Region. Project information was documented in the USGS Information Data System. A contract for technical assistance from the Minnesota Geological Survey was awarded. A Joint Funding Agreement was approved but USGS Headquarters and by the Minnesota Department of Natural Resources.

A decision was made to use the USGS drilling contract group from the California Water Science Center because of the technical nature of drilling services required for this project. Meetings continued to be held with staff from the Minnesota Geological Survey, the Minnesota Department of Health and the Minnesota Department of Natural

Resources to complete selection of test-site locations. Based on input from the Minnesota Department of Health, wellhead protection plans were reviewed for 30 municipalities. These were for municipalities having their public supply wells completed in confined-drift aquifers underlying confining units that are comprised of glacial tills having origins from the Superior or Des Moines Glacial lobes. Site information was reviewed that considered the thickness and hydrologic properties of confining units, site conditions and supply-well characteristics.

Two field study sites were selected for detailed hydrologic investigation. One site is located in a part of the state where Des Moines lobe glacial till is the principal glacial confining unit (Litchfield). The second site (Cromwell) is located where the Superior lobe glacial till is the principal confining unit. At both study sites small-diameter observation well clusters, or piezometers, are being installed in the confined-drift aquifer, the confining unit overlying the confined aquifer, and in the surficial unconfined-drift aquifer. Two well-nest installations are located at each of the two study sites if funding allows. One well cluster, at each study site, will be located in close proximity to the municipal water-supply well. The second of the well-cluster location, at each study site, will be located at some distance from the municipal-supply wells. The exact locations and numbers of well nests is being determined, based on local site and access conditions, drilling costs, and on analysis of local groundwater pumping and hydrologic settings. Observation wells (completed in aquifers) and piezometers (completed in confining units) are being installed at this time. Work at Litchfield is completed. Wells and piezometers will be developed and pressure transducers will be installed in each of the observation wells and piezometers to continuously measure water levels and hydraulic head over the duration of the study. The identification and siting of study sites and well-nest locations involved a considerable amount of time and effort to ensure that the sites represent conditions typical for the primary confining units of the state.

Proposal submitted for phase two: A second-phase proposal was submitted as part of the 2016 LCCMR proposal process. The second phase would add two additional sites to the overall study. A total of four sites is considered adequate to cover the variability of hydrologic conditions across the state. The second phase also allowed our staff to demonstrate that the study approach was feasible during the first phase of the project. This was noted in the 2014 proposal. The second phase study would be similar to the current study but at 2 different site locations. The following test is extracted from the 2014 work plan: "Project Impact and Long-term Strategy: C. Long-Term Strategy and Future Funding Needs: Based on successful completion of this project, additional funding may be requested to supplement and to enhance data and information from this project."

Activity Status as of December 31, 2015

Well and piezometer installations were completed by the USGS Western Drilling Program crew. Wells and piezometers have been developed and completed. In all, 19 well or piezometers, were completed. The Litchfield site is in a part of the state where Des Moines lobe glacial till is the principal glacial confining unit. The Cromwell site is located where the Superior lobe glacial till is the principal confining unit. Small-diameter observation well clusters, or piezometers, were installed in the confined-drift aquifers, the confining units overlying the confined aquifers, and in the surficial unconfined-drift aquifers. One well cluster, at each study site, is located in close proximity to the municipal water-supply well. The second of the well-cluster locations, at each study site, is located at some distance from the municipal-supply wells. Pressure transducers were installed in selected observation wells and piezometers to continuously measure water levels and hydraulic heads.

Activity Status as of June 30, 2016

The necessary data documentation and data processing routines were established within USGS databases and related software. These tasks enable continuous water level data storage, quality assurance, and public availability according to USGS policies. The transducer sites were visited in January and April to download data stored on transducers and to field calibrate transducers.
Water level data for the Litchfield site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=093
Water level data for the Cromwell site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=017

Several wells at the Cromwell site had to be re-surveyed because its protective casing heaved due to frost. Survey showed actual well measuring points had moved very little. Phase 1 tasks are complete.

Activity Status as of December 30, 2016

The transducer sites were visited in October to download data stored on transducers and to field calibrate transducers.
Water level data for the Litchfield site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=093
Water level data for the Cromwell site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=017

Activity Status as of June 30, 2017

The transducer sites were visited in April to download data stored on transducers and to remove the transducers from the wells.
Water level data for the Litchfield site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=093
Water level data for the Cromwell site are available here:
http://groundwaterwatch.usgs.gov/countymap.asp?sa=MN&cc=017

Final Report Summary for Activity 1:

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

Br	Bromide
Cl	Chloride
CH_3CO_2	Acetate
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
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
S_2O_3	Thiosulfate
TU	Tritium units
USGS	United States Geological Survey
$\delta^{18}O$	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 (or buried) aquifers 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, buried aquifers are thought to be less susceptible to surface contamination, but may recharge very slowly and 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 buried aquifers. Buried glacial aquifers are used extensively for water supply in Minnesota. The primary objective of this study was to quantify the variability of hydrologic properties and flux of water through till confining units to buried aquifers at two representative sites in Minnesota using a combination of hydrologic field measurements, geochemical analyses, and modeling techniques. The results of this study give insight to the susceptibility and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota.

Study Site Selection

In this study, glacial deposits of the Des Moines Lobe and Superior Lobe were characterized in detail at two sites in Minnesota (fig. 1). The Litchfield site lies on Des Moines Lobe deposits in central Minnesota and the Cromwell site lies on Superior Lobe deposits in northeastern Minnesota (fig.1). These sites were selected to be representative of each major lobe. Several criteria were used to identify potential study locations. To be considered for the study, the sites had to have: (1) a small number of high-capacity pumping wells withdrawing water from a Quaternary buried artesian aquifer (Minnesota Geological Survey aquifer code QBAA); (2) the buried 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; and (5) information on the integrity of the high-capacity well construction. Sites meeting these minimum criteria were identified and then municipalities were contacted to gage their willingness in partnering with the USGS in the study. Litchfield and Cromwell met the selection criteria and were willing partners on the study.

Field Study Design and Piezometer Installation

Piezometer "nests" were installed 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 near 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 buried aquifer. The nest design has been commonly used to investigate hydrologic properties of tills (for example, Shaw and Hendry, 1998; Simpkins and Parkin, 1993). Two nests were installed at each site, one of which was "near" a municipal pumping center and one which was "far" from a municipal pumping center. However, as described below, the two Cromwell nests were merged into a single nest. The near and far nest design was intended to facilitate aquifer test analyses.

Two piezometer nests were established at the Litchfield site, LFO1 and LFO2. LFO1 consisted of five piezometers and was located approximately 1,500 feet from the nearest municipal pumping well. LFO2 consisted of six piezometers and was located within the city municipal well field and was approximately 500 feet from the nearest municipal well (fig. 2). Two piezometer nests were established at the Cromwell site, CWO1 and CWO2. CWO1 consisted of five piezometers and was located approximately 50 feet from the nearest municipal pumping well. CWO2 consisted of three piezometers and was located approximately 150 feet from CWO1 and the nearest municipal pumping well (fig. 3). CWO1 and CWO2 contain piezometers that are sequential in depth and are within 150 feet (ft) of each other so they will be referred to as one nest, CWO1/2, when discussing results. A total of 19 piezometers were installed between the three nests.

A hollow-stem auger rig was used for sediment core collection and installation of piezometers at nests LFO1, LFO2, and CWO2. 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 greatly slowed down the installation of piezometers at site CWO2, so a mud rotary rig was used to install the three piezometers at CWO1. Completion diagrams for each piezometer nest are shown in figure 4 and construction specifics are given in table 1. All 19 piezometers were developed by pumping to establish a good connection between the well screen and the surrounding geologic materials.

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.

Geologic Setting

The following is a summary of a detailed report produced during this study (Wagner and Tipping, 2016). Generalized lithologies are presented in figure 4.

Litchfield

At the Litchfield study site, till of the Villard Member of the New Ulm Formation overlies the buried-valley aquifer which is also part of the New Ulm Formation (Wagner and Tipping, 2016). The mean particle-size distribution of the till, determined from two continuous cores sampled typically at four foot intervals, was 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, 2005). The New Ulm Till at site LFO1 also had a proportionally greater sand component in the greater than (>) 2 mm matrix fraction, averaged across all samples, than that which was analyzed from the same formation at LFO2 (Wagner and Tipping, 2016). Sediment of the New Ulm Formation is yellow-brown and oxidized in the upper 15 ft (2.4 meters [m]), and grey brown and unoxidized below this depth. Carbonate clasts and a calcareous matrix are present throughout except in the top 3 ft (0.9 m) of LFO1. Fractures were described in LFO1 and LFO2 cores to depths of approximately 60 and 90 ft (18 and 27 m), respectively. Most lacked iron staining common to fracture surfaces in the equivalent till in Iowa (Helmke and others, 2005). Many may be artifacts of the coring process and subsequent unloading; however, Helmke and others (2005) found that many till fractures that were active in the transport process lacked Fe staining.

Sediment sequences differ between the LFO1 and LFO2 sites. At the LFO1 site, 12 ft (4 m) of fine-grained, sandy and silty deltaic and glaciolacustrine sediment with some gravel occurs above the till. Wagner and Tipping (2016) interpreted this to be 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 site LFO2, which lies at approximately 25 ft (8 m) higher elevation than LFO1 (Wagner and Tipping, 2016) – apparently too high to be influenced by the glacial lake. The sand and gravel aquifer unit begins at approximately 98 and 117 ft (30 and 36 m) below land surface at LFO1 and LFO2, respectively. Till thickness varies between the two piezometer nests. At nest LFO1 the till is approximately 60 ft (18 m) thick, and at LFO2 it is 115 ft (35 m) thick. The aquifer is approximately 44 ft (13 m) thick at site LFO2 and is underlain by Pre-Wisconsinan till of the Sauk Centre Member of the Lake Henry Formation (Meyer, 2015).

Cromwell

The stratigraphic sequence at the Cromwell study site is more complicated than that at the Litchfield study sites. Core samples were collected at piezometer nest CWO2; however, the high frequency of clasts greater than 2 inches (5 cm) in diameter interfered with the coring process and resulted in the collection of fewer core samples than expected. Core was not retrieved from nest CWO1, and the MGS reconstructed the geology through analysis of downhole gamma ray logs. Two glacigenic units were identified at the Cromwell site. Starting at the land surface, 6 ft (2 m) of silt loam till of the Alborn Member of the Aitkin Formation overlies 20 ft (6 m) of sand and gravel outwash of the Cromwell Formation deposited during the Automba Phase of the Superior Lobe. This unit is likely responsible for the hummocky topography at the site. Below the sand and gravel deposits lies 77 ft (23 m) of sandy loam to loam till with cross-stratified, fine to very coarse sand and gravel layers, which was also likely deposited during the Automba Phase. The buried-valley aquifer below this is a sand and gravel unit within the Cromwell Formation and it is underlain by Paleoproterozoic slate of the Thomson Formation (Boerboom, 2009).

Sediment of both the Cromwell Formation and the Aitkin Formation were both typically reddish-brown and a calcareous matrix was present in the core below 43.5 ft (13.3 m), suggesting a greater depth of leaching than till at the Litchfield study site and a lesser proportion of carbonate clasts. The Cromwell Formation till had a mean particle-size distribution of 57 percent sand, 31 percent silt, and 13 percent clay (Wagner and Tipping, 2016), which is about 8 percent more sand than the New Ulm till. The Aitkin Formation till was not analyzed for particle-size distribution.

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.

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 the state's most important confining units-- the Des Moines and Superior till confining units. The approach is to conduct two detailed field tests-- one each of two areas that represent the principal confining in the state. The field study sites are located adjacent to existing high-capacity municipal pumping wells to observe how pumping stress affects water movement based on properties of the confining beds. Scientific bore holes are being completed through the confining units and into the aquifers and confining units 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 test for example 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 all observations 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. Laboratory permeability tests also will be used to evaluate spatial variability in permeability. 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. Site-scale groundwater flow models will be used to simulate individual hydraulic tests and to test hypotheses regarding recharge through till. A draft USGS Scientific Investigations Report will be prepared and interim results will be presented in a final report to the LCCMR. The draft will go through the colleague and editorial review processes after the results from phase 2 of the project (project titled "Protection of State's Confined Drinking Water Aquifers – Phase II", funded in M. L. 2016) are available to be incorporated into the draft report. A USGS Scientific Investigations Report summarizing both phases of the project will be published in 2019.

Summary Budget Information for Activity 2: (December 30, 2016) **ENRTF Budget: $153,601.38**

Amount Spent: $ 153,201.59

Balance: $ 399.79

Activity Completion Date: September 2017

Outcome	Completion Date	Budget
1. Conduct hydraulic, geotechnical, geophysical and isotopic tests at each study site. Extensive field testing of geologic deposits. Water sampling. Hydraulic testing of aquifer responses to pumping. These tests are focused on determining hydraulic properties of geologic strata.	June 2016	$ 70,332.42
2. Analyze and interpret tests, define hydraulic properties and infiltration rates at each study site	December 2016	$ 30,000
3. Conduct conceptual groundwater modeling of pumping responses. This work will further quantify aquifer and confining bed properties.	April 2017	$ 25,000
4 Report on results. Prepare draft report.	June 2017	$ 16,000

5 Seal and abandon test wells according to state well code	May 2017	$ 12,269.25

Activity Status as of December 31, 2014:
No activity during this period.

Activity Status as of June 30, 2015

No activity during this period.

Activity Status as of December 31, 2015

Well and piezometer installations were completed by the USGS Western Drilling Program crew. Small-diameter observation well clusters, or piezometers, were installed in the confined-drift aquifers, the confining units overlying the confined aquifers, and in the surficial unconfined-drift aquifers. One well cluster, at each study site, is located in close proximity to the municipal water-supply well. The second of the well-cluster locations, at each study site, is located at some distance from the municipal-supply wells. Pressure transducers are being installed in selected observation wells and piezometers to continuously measure water levels and hydraulic heads. Hydraulic, geochemical and hydraulic testing of soils and soil water was completed. These tests will be used to determine geologic and hydraulic properties of the aquifers and confining beds.

Activity Status as of June 30, 2016

The Minnesota Geological Survey completed their analysis and interpretation of the geologic samples collected during the drilling at the Litchfield and Cromwell sites. They have summarized their results in a report titled "Core Descriptions and Borehole Geophysics in Support of USGS Hydrologic Properties of Till Investigation, Litchfield and Cromwell, Minnesota". The report is available here:
ftp://mgsftp2.mngs.umn.edu/pub4/outgoing/MGS_report_in_support_of_USGS_till_study_Phase_I.pdf.

Groundwater samples to be analyzed for major ions, nitrate, nitrite, ammonia, total phosphorus, and tritium content were collected from 14 wells and piezometers installed as part of this project; 8 at the Cromwell site and 8 at the Litchfield site. The 5 remaining wells and piezometers at the Litchfield site were also sampled, but will only be analyzed for tritium content. One duplicate sample and one blank sample were collected for quality assurance purposes.

Slug tests were completed in all 19 wells and piezometers installed as part of this project. During a slug test, an instantaneous change of water level is induced. As the water level returns back to the static condition, water levels are monitored through time to determine the near-well aquifer hydraulic conductivity. Field slug test data were analyzed using the Springer-Gelhar, KGS, or Butler methods. The AQTESOLV Program, version 4.5 was used to determine the best fit model to the water-level displacement versus time data for each well. A draft report of the slug test analyses is complete and is in the USGS review process.

Activity Status as of December 30, 2016

All water quality data from the sampling in May has been reviewed and approved.

Progress has been made on several of the final report products that will result from this project. The slug test report, which summarizes the hydrologic properties surrounding each of the 19 wells installed as part of this project, is still in the USGS review process. Alyssa Witt has written substantial portions of her thesis. This thesis summarizes the field drilling and sampling methods, the lab analytical methods, the properties of the geological materials determined from slug tests, pore-water chemistry, and groundwater chemistry. These data are being used to get point estimates of recharge rates through till and the susceptibility of the confined aquifers to human activities at the land surface. The thesis will comprise part of the final report from this project. The final report will also compare the point field observations with a MODFLOW groundwater flow model of each site. The model serves to test hypotheses about the variability of till properties. The models for the Litchfield and Cromwell sites have been constructed based on the best available hydrogeologic information. They are now in the process of being refined and calibrated to reproduce observed field data.

A draft purchasing agreement has been developed that enables the USGS to use a contract driller, licensed in Minnesota, to seal the 19 wells installed during this project.

Activity Status as of June 30, 2017
The Minnesota Department of Health has deployed transducers in the piezometers in Litchfield and Cromwell and is currently working to conduct a pump test in each of their aquifers. Tests results will be analyzed and incorporated into the modeling efforts for each location. After the completion of the pump tests, all piezometers will be sealed according to Minnesota regulations.

Final Report Summary for Activity 2

Methods

Hydrology

A variety of techniques were used to assess the hydrologic properties and leakage through till confining units at the two study sites: long-term water-level monitoring, slug tests, aquifer tests, and Darcian analyses 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 et al. 1976).

Long-term 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 (Kv) of till confining units (Cherry and others, 2006). Previous studies have used head variations in confined aquifers and aquitards induced by pumping over long-term time periods (years to decades) as evidence for extremely low aquitard Kv values (for example, Husain and others, 1998). Other studies have monitored hydraulic head in surficial aquifers and aquitard material to determine aquitard Kv values (for example, Keller and others, 1989).

Lab tests and slug tests are commonly used to assess the hydraulic properties of confining unit tills, but represent relatively small volumes of till. Vertical fractures or stratigraphic windows can be important transport features through till, but the results of laboratory measurements on core samples rarely reflect these features (Cherry and others, 2006). 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, 2006). Beyond potential identification of important transport features, slug tests have limited usefulness for determining the vertical hydraulic conductivity (Kv) of the till matrix because, in vertical holes, the slug response primarily depends on the horizontal component of the hydraulic conductivity (Cherry and others, 2006).

Aquifer tests designed with the specific purpose of determining till confining unit properties are another, larger-scale approach to estimating the vertical hydraulic conductivity 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, 2006). 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 aquitard and the pumped aquifer (Cherry and others, 2006). Several analytical methods, such as Neuman and Witherspoon (1972), exist to determine aquitard properties from properly executed aquifer tests.

Long-term water-level and precipitation monitoring

Water levels in the piezometers and municipal water supply wells were measured at discrete intervals by hand and logged hourly 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 buried aquifers. Manual water-level measurements were done with a Solinst or Keck electric tape or a steel tape between July 2015 and April 2017. Pressure transducers (OTT Orpheus Mini) recorded data in 12 piezometers between December 2015 and April 2017: LFO1-B, LFO1-D, LFO1-F, LFO2-A, LFO2-C, LFO2-D, LFO2-F, CWO1-A, CWO1-B, CWO1-C, CWO2-A, and CWO2-D. Precipitation was also monitored continuously with tipping bucket rain gages at LFO2-A and CWO2-A between December 2015 and April 2017. All discrete and continuous (hourly) water-level and precipitation data collected throughout this study were reviewed and approved according to various USGS groundwater technical policies, which are available at https://water.usgs.gov/admin/memo/GW. The data are available at https://waterdata.usgs.gov/nwis by searching for the USGS site identification numbers listed in table 1.

Slug tests

Rising and falling-head slug tests were conducted in each piezometer to estimate hydraulic conductivity (K). For each rising or falling head slug tests a solid PVC slug was rapidly added or removed from the piezometer and water level measurements were recorded either manually or with a pressure transducer. Slug tests results were analyzed with Aqtesolv using the most appropriate methods which included: KGS method, Butler method, and the Springer and Gelhar method.

Aquifer tests

Constant rate pumping tests were conducted at Litchfield and Cromwell to estimate the hydrologic properties of the aquifer and overlying till confining unit at both Litchfield and Cromwell sites. The Minnesota Department of Health Source Water Protection Unit carried out these tests. Detailed methods and documentation are available through the Minnesota Department of Health (Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b).

Recharge calculation

Potential recharge rates to the buried aquifer and the travel time through the till to the buried aquifer at each piezometer nest was calculated using the following equations:

$$Recharge\ to\ buried\ aquifer = -KIA$$

$$Travel\ time = \frac{n_e x}{KI}$$

where:

K = hydraulic conductivity
I = hydraulic gradient
A = Area
x = till thickness
n_e = effective porosity

Geochemical data collection

Groundwater samples from each piezometer were collected in July 2015 and May 2016 and analyzed to identify evidence of anthropogenic input, to estimate groundwater age, and to determine redox state at various depths within the confining unit and in the aquifer. Groundwater samples were collected in July 2015 from all nineteen piezometers and analyzed for common anions (bromide [Br], chloride [Cl], acetate [CH_3CO_2], fluoride [F], sulfate [SO_4], thiosulfate [S_2O_3]), nutrients (nitrite [NO_2], nitrate [NO_3], phosphate [PO_4]), and stable isotopes delta oxygen-18 ($\delta^{18}O$) and delta hydrogen-2 ($\delta^{2}H$). Groundwater samples were collected in May 2016 from piezometers in nests LFO2, CWO1, and CWO2 and analyzed for major anions (Br, Cl, F, SO_4), major cations (potassium [K], calcium [Ca], magnesium [Mg], manganese [Mn], sulfur [S], iron [Fe], sodium [Na]), nutrients (ammonia [NH_3], total phosphorus [P], NO_2, NO_3+NO_2), pH, total dissolved solids, enriched tritium (^{3}H), and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$). Groundwater samples collected in May 2016 from piezometers in nest LFO1 were analyzed for enriched ^{3}H and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) only. During the May 2016 sampling, additional quality assurance samples were collected at the Litchfield and Cromwell sites. One field inorganic blank sample was collected to verify that contamination was not being introduced during sample collection or lab analysis. One field replicate sample was collected to verify the repeatability of sample collection and lab analysis. 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).

Core samples collected during drilling in June and July 2015 were sent to the USGS California Water Science Center where a hydraulic press was used to extract pore fluid. The pore fluid from core samples was analyzed for pH, specific conductivity, common anions (F, bicarbonate [HCO_3], Cl, Br, SO_4, S_2O_3), nutrients (NO_2, NO_3, P), and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$).

Groundwater modeling

It is challenging to assess the sustainability of groundwater withdrawals from buried aquifers because their hydrogeologic settings at locally relevant scales are highly uncertain. The field investigations at Litchfield and Cromwell established that the hydrologic properties of till overlying buried aquifers can be highly variable over short distances. Furthermore, the extent of buried aquifer systems and their connections to other aquifer systems are not well understood because of the complex glacial geologic history of Minnesota. The Minnesota Geological Survey has mapped buried aquifers (sand bodies) using the best available data (well logs from well installations) through the County Geologic Atlas Program, but even so, there are large uncertainties about the connectivity and extent of buried aquifer systems. The field studies 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 the source of water to wells in different hydrogeologic settings under varying groundwater withdrawal rates, a series of conceptual steady state groundwater-flow models were developed. The software package, Groundwater Vistas (Environmental Simulations Incorporated), was used to develop MODFLOW-2005 (Harbaugh, 2005) models for this analysis. The specific goals of the modeling exercise were to (1) develop a sense for the range of possible responses in surface-water and groundwater caused by pumping confined aquifers in a variety of hydrogeologic settings across Minnesota and (2) complete a sensitivity analysis to quantify the effects that variations in model parameter values have on the simulated source of water to buried aquifers.

The basic structure of the conceptual model is as follows (shown in figs. 5 and 6). The model domain was approximately 20 miles by 20 miles with a cell size of 500 ft by 500 ft (fig. 5). The model contained 7 layers: a surficial unit which contained several rivers and lakes, 3 layers of "upper" till which represented the confining unit, 2 layers that contained the buried sand aquifer and a "middle" unit, and a layer of "lower" till (fig. 6). The surficial unit was 40 ft thick, the three upper till layers were a total of 80 ft thick for all but one model run, the two layers comprising the buried aquifer and surrounding middle unit were 80 ft thick, and the lower unit was 200 ft thick (fig. 6). 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, 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.

Several model parameters were varied in the model scenarios (table 2). 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 2). The "base model" contained model parameter values that represented an approximate midpoint between observations at Litchfield and Cromwell. The upper and lower model parameter values are inclusive of Litchfield and Cromwell, typically extending slightly above and below observations at these sites.

Two response variables were extracted from model output and compared among the model runs: the source of water to buried aquifer and leakage of water from the surficial unit in layer 1 to the till in layer 2. For the source of water to the buried aquifer, the relative contributions of water entering the buried aquifer from above, lateral to, and below were compared among model runs. The leakage of water from the surficial unit in layer 1 to the till in layer 2 was quantified within a 5 mi by 5 mi "local area" (red outline in fig. 5) centered on the pumping wells and buried aquifer. The following equation was used to compute leakage as a percent of water fluxes in layer 1 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 1 to layer 2;

V_D = volume of water flowing downward from layer 1 to layer 2;

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

V_L = the net volume of lateral groundwater flow into and out of the local area; and

V_I = the volume of induced flow from local streams into layer 1 within the local area.

The recharge rate was fixed for all but one model run so increases in the percent of downward leakage indicates a 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. 5).

The percent change in the water entering the buried aquifer from the overlying till (downward flux) was compared to the percent change in the model parameter values listed in table 2. The relative percent sensitivity was calculated for each model parameter according to the following equation. All changes were relative to the base model.

$$Relative\ percent\ sensitivity = \frac{Percent\ change\ in\ downward\ flux}{|Percent\ change\ in\ model\ parameter\ value|} \times 100$$

Hydrogeology

Water Level Responses to Pumping and Weather

Piezometer nests LFO1 and LFO2 showed decreasing hydraulic head values with depth, providing evidence for a downward gradient (fig. 4, table 3, table 4). The continuous water levels data at LFO1 and LFO2 show varying responses to the municipal supply well pumping (figs. 7 and 8). In the two aquifer piezometers, LFO1-F and LFO2-F, a clear daily to sub-daily oscillation in water levels from the high-capacity wells is evident (figs. 7 and 8). LFO2 is the "near" nest and, as expected, LFO2-F shows a much larger oscillation from pumping than LFO1-F. Both buried aquifer piezometers show three large decreases in water level in June, July, and August of 2016. 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 buried aquifer system as the municipal wells.

Water-level changes from pumping stress are not apparent up through 30 ft of till at LFO2-D, suggesting there is an effective aquitard in the 30 feet of till between LFO2-F and LFO2-D (fig. 8). 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 good hydraulic connections through the till from 20 to 60 feet below land surface (fig. 8). 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 aquitard at LFO2 exists above and below LFO2-D and that at least the upper 60 feet of till are hydraulically connected.

A very different response exists at the far nest, LFO1 (fig. 7). LFO1-D is screened in till approximately 25 feet above the top of the buried aquifer and water level patterns in this piezometer closely resemble those observed in the buried aquifer. Even the daily oscillations from the cycling on and off of the Litchfield municipal wells are evident at LFO1-D, indicating a reasonable hydrologic connection from the aquifer through the bottom 25 feet of till. Water level patterns at LFO1-D bear a stronger resemblance to the buried aquifer than to the surficial aquifer, which is monitored by LFO1-B. Sharp water-level rises in LFO1-B are linked to rainfall events and (likely) rises in Jewett Creek, which is approximately 230 ft southeast of LFO1-B (fig. 2). Further time-series analysis is needed to determine if the pumping signal is apparent in the LFO1-B well. The till at LFO1 is only approximately 58 feet thick, and nearly half of this sequence is hydraulically well-connected between the top of the aquifer and LFO1-D.

The CWO1/2 nest demonstrated an upward gradient (fig. 4), and all of the continuously monitored piezometers showed similar seasonal patterns in water levels (fig. 9). Throughout the entire profile, from the surficial aquifer (CWO2-A) down to the bedrock (CWO1-C) an increase in water levels occurred July 8 – 15, 2016. This water-level rise was likely caused by a large rainfall event totaling 4.67 inches that fell at the site during July 7-13, 2016. Following this rise, water levels in all piezometers slowly declined through August, 2016. Daily oscillations in water levels from the Cromwell municipal wells are evident in the bedrock (CWO1-C), the buried aquifer (CWO1-B), and 2 till piezometers (CWO1-A and CWO1-D), but not in the surficial aquifer (CWO2-A). The till at CWO1/2 is about 130 ft thick, but the continuous water levels demonstrate that there is a hydraulic connection from the buried aquifer through at least the bottom 70 feet of the till.

Hydraulic Conductivity (K)

Slug tests indicate that values of K differ among the two study sites, primarily due to differences in particle size between the sandier and stonier Cromwell Formation till and the New Ulm Formation till. Only two piezometers were used to estimate the K value of till at nest LFO1. LFO1-E, which was intended to be screened solely in till, shows K values similar to sand and gravel units. The K values from this piezometer were omitted from the geometric mean calculation because of the possible connection with the aquifer. Results for K from five piezometers screened in the till at nest LFO2 were used to estimate the geometric mean K of the till.

Overall at the Litchfield study site, the values of K from slug tests range from 175 ft/d (53 m/d) for sand and gravel to 1 x 10^{-5} ft/d (4 x 10^{-6} m/d) for till. The geometric mean K values of till at LFO1 and LFO2 are 7 x 10^{-2} and 2 x 10^{-4} ft/d (2 x 10^{-2} and 6 x 10^{-5} m/d), respectively (table 5, table 6, fig. 10). These values for K are within previously observed values for Des Moines lobe till, although the K values at LFO1 were slightly higher than expected (Simpkins and Parkin, 1993; Helmke et al., 2005). A Mann-Whitney U test was applied to the Litchfield till data and showed a significant difference in the geometric mean K values of till between LFO1 and LFO2 at the 95 percent confidence level. The large difference in mean K values between the two study sites in Litchfield was unexpected. Although the difference could be due to a slightly higher sand content at LFO1 than LFO2 or be ascribed to till variability, the large three order of magnitude difference is more likely due to differences in till deposition between the sites or a greater influence of till fractures at LFO1.

The higher sand percentage in the Cromwell Formation till predicts that the K values there would be higher than the New Ulm Formation till. The K values in the Cromwell study site range from 16 ft/d (5 m/d) for sand and gravel to 1 x 10^{-2} ft/d (4 x 10^{-3} m/d) for till (table 5, table 6, fig. 10). The geometric mean K value for till is 6 x 10^{-2} ft/d (2 x 10^{-2} m/d) which is significantly different at the 95 percent confidence level from K values till at LFO2, but not the K values till at LFO1.

The slug tests that were completed in till piezometers measured the horizontal hydrologic properties of a small area of the till surrounding the sandpack, on the order of cubic meters (Bradbury and Muldoon, 1990). In contrast, the aquifer tests measured the response of tills to pumping of a small area of the till, on the order of hundreds of cubic meters. The aquifer test results demonstrate the hydrologic properties of tills that drive the observed responses. Table 6 shows the geometric mean hydraulic conductivity from both the slug tests and aquifer test, K values from the aquifer tests are higher which is a result of the scale dependency of K. Typically, the larger scale the test is, the higher the hydraulic conductivity.

Recharge through tills

Estimation of vertical recharge (leakage) to the underlying aquifer is complicated by the upward gradient at the Cromwell site, which precludes this calculation; i.e., there can be no route from water entering the land surface to the underlying aquifer at the piezometer nest location. Instead, groundwater moving laterally to this location from up gradient could be recharging this aquifer. The results obtained from our investigations could be useful in the next Wellhead Protection Plan update. Overall, it is clear that more research will be needed to determine the source and volume of recharge to this aquifer.

Where recharge (leakage) estimates are possible at the Litchfield study site due to predominantly downward vertical gradients, the different hydraulic gradient and K values at the two sites and lack of data on the exact size and extent of the buried aquifer of interest complicate direct application of Darcy's Law to the problem. The following calculations assume isotropy between horizontal and vertical hydraulic conductivities. The potential specific discharge or recharge flux (q) based on K and gradient data in the till at LFO1 and LFO2 is 78 and 0.34 in/year (198 and 0.85 cm/yr), respectively. A flux value of 78 in/year is not a realistic value of what is moving through the till, but a potential flux value. The mean average annual precipitation at the Litchfield site is approximately 30 in/year (Minnesota Department of Natural Resources, 2003); however, Smith and Westenbroek (2013) estimated recharge to the water table of between 4 and 8 inches per year in the vicinity of the site. Recharge to the aquifer in Litchfield was estimated from an aquifer extent of 3 mi^2 (7.8 km^2) from the MGS Meeker County sand distribution model (Meyer, 2015). Using the hydraulic characteristics of LFO1 (a less steep gradient and higher K values than LFO2) and an estimated specific discharge of 8 in/yr (20 cm/yr) based on recharge estimates done by Smith and Westenbroek (2013), an estimated 417 MGY would recharge the aquifer. This value is higher than the current municipal pumping rate of 340 MGY and suggests that those rates are sustainable. It also suggests that more contaminants can reach depth at this site. Using the hydraulic characteristics of the till at site LFO2 (lower K values and nearly double the gradient), a much lower recharge (leakage) volume of 17 MGY is estimated, which is well below the municipal pumping rate. In contrast to LFO1, this suggests that very little recharge from the ground surface reaches the aquifer (table 7). Based on the variability of the till hydrogeology at the two sites, and that these are point estimates, it is difficult to determine the recharge to the aquifer from these calculations. The high variability in K values and hydraulic gradients and uncertainty in aquifer and size make it difficult to estimate total recharge to the aquifer and thus predict its future sustainability. More detailed modeling analysis of the Litchfield and Cromwell study sites will reduce the uncertainty and provide a better estimation of recharge.

Groundwater age and travel time may be calculated from these same values for hydraulic gradient and K. At the Litchfield study site, based on vertical groundwater velocities of 7×10^{-2} ft/d and 3×10^{-4} ft/d (2×10^{-2} and 1×10^{-4} m/d) in LFO1 and LFO2, respectively, and assuming downward vertical flow in the till, groundwater age in the buried-valley aquifer ranges from about three to 1,054 years at LFO1 and LFO2, respectively (table 7). Groundwater recharge and age at the Cromwell study site could not be calculated by this method due to the upward-directed vertical gradients.

Groundwater Geochemistry and Water Quality

Stable Isotopes

During the Wisconsinan 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‰ (Remenda and others, 1994). Groundwater samples from each piezometer and pore water extracted from core samples were analyzed for $\delta^{18}O$ and δ^2H to determine whether the sites showed modern input values or glacial age pore fluid as seen in sequences of thick glacial till elsewhere (Simpkins and Bradbury, 1992). Results from nests LFO1 and LFO2 showed relatively uniform isotope values with depth, with mean $\delta^{18}O$ and δ^2H values of -9.53‰ (standard deviation = 0.55) and -65.87‰ (standard deviation = 4.30), respectively (fig. 11). Isotope values at LFO2 were slightly lower than those at LFO1. Assuming that modern precipitation input has a δ^2H value closer to -9.0‰, the LFO2 sites shows an incursion of recent precipitation in the top in the shallowest well, whereas the LFO1 site shows consistent values from top to bottom. Neither site shows evidence of the lower stable isotope values typically associated with glacial-age pore water, so groundwater in the till and the aquifer are likely not late Wisconsinan in age. This conclusion is consistent with the groundwater ages calculated using Darcy's Law. Stable isotope values from pore water are very consistent with the groundwater samples from piezometers. These data suggest that the groundwater values mostly reflect what is in the till, and not an artifact left from the drilling process.

Stable isotope values at CWO1/2 are consistently lower than LFO1/O2 with mean $\delta^{18}O$ and δ^2H values of -11.06‰ (standard deviation = 0.26) and -77.28‰ (standard deviation = 2.15), respectively. This is to be expected because fractionation increases with distance from the Gulf of Mexico and lower $\delta^{18}O$ and δ^2H values would occur at Cromwell because it is further north than the Litchfield site. The $\delta^{18}O$ values also lack a trend to lower values at depth, suggesting that groundwater in the till is also not late Wisconsinan in age.

Enriched Tritium

Enriched tritium (^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. If there are detectable levels of ^3H, then the water is considered "post-bomb" and likely recharged from the 1950's to the present. If there is no detectable tritium, then the water is considered "pre-bomb" and was likely recharged prior to the 1950's. ^3H analysis showed very different distributions at the three piezometer nests. Nest LFO2 shows a typical pattern for ^3H concentrations decline with depth in central Iowa (W.W. Simpkins, verbal communication, 2017), with a maximum value of 5.3 TU near the surface to below detection limit from about 60 ft (18 m) in depth down to the buried aquifer. Despite the classification scheme of Berg (2011), the ^3H found in the top two piezometers is likely recent recharge (based on precipitation samples in Ames, Iowa) and which is backed up by the $\delta^{18}O$ trend to higher values at the same depth. The lack of measureable ^3H below that suggests that groundwater is not only pre-bomb, but that the downward flux of water is quite small. Again, these data are consistent with the earlier Darcy's Law calculations.

Data from the LFO1 site suggests a different interpretation. At that piezometer nest, peak ^3H concentrations occur in the deepest piezometer in the till. The uppermost piezometer, which is screened in a surficial deltaic and outwash unit, shows a tritium concentration of 4.2 TU, which is suggestive of modern ^3H input. Tritium then increases with depth through the till to reach a peak of 16.1 TU in LFO1-E, then declining to 7.7 TU in LFO1-F, which is screened in the aquifer (fig. 11). The ^3H data are consistent with the lack of a significant trend in $\delta^{18}O$ with depth (i.e, groundwater is more recent at depth than at LFO2) and with the groundwater age estimates.

The upward gradient at the Cromwell study site suggests yet a different ^3H interpretation of the recharge (leakage) scenario for the buried-valley aquifer. Enriched ^3H activity of 5.9 TU occurs near the surface, with values below detection limit through the till and a modern concentration of 5.9 TU in the aquifer (fig. 11). This distribution suggests that groundwater is not moving vertically upward very quickly, because all the groundwater in the Cromwell Formation till is pre-bomb and is likely very old groundwater. The closeness of the ^3H activities in the buried-valley aquifer and the shallowest piezometer may be a coincidence, but may suggest that groundwater is recharged from a source area that is receiving recent recharge. Alternatively, Berg (2011) would suggest they are mixed-sources waters. It is also significant that the underlying slate aquifer shows a ^3H value that is pre-bomb, which would not be expected if the slate were actively recharging the buried aquifer above it. It is also noteworthy that the downward-directed hydraulic gradient between the slate and the buried valley aquifer is very slight, suggesting that flow could be horizontal along that boundary and thus suggest separate flow systems in the bedrock and the buried-valley aquifer. The hydraulic gradient data and the ^3H data suggest that recharge to the buried-valley aquifer at this location 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.

Chloride

Chloride concentrations in groundwater at the Litchfield study site ranged from 11 to 47 milligrams per liter (mg/L), which suggests loading of anthropogenic chloride into the aquifer. Background 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 > 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 15mg/L (Kelly et al., 2012). All three of the piezometer nests are next to roads where de-icing salts are applied and near agricultural areas where KCL fertilizer is likely applied. The groundwater flow system at each site determines the vertical penetration of contamination.

Groundwater at nest LFO2 showed a trend of decreasing Cl concentration with depth to values approaching background and near 11 mg/L, which would all be pre-bomb water and potentially the background concentration. The opposite trend is shown at piezometer nest LFO1 where Cl concentrations increase with depth (fig. 12). Both the Cl and ^3H data indicate substantial vertical penetration of recharge at the LFO1 site versus the LFO2 site. Pore-water Cl values were slightly higher than groundwater samples in nest LFO1 and showed an increase with depth, while pore water was nearly the same as groundwater in the LFO2 nest. All but one pore water analysis fell between 24 and 85 mg/L Cl, with an outlier at site LFO1 showing a concentration of 294 mg/L. That value was likely a lab contamination problem, and has been excluded from figure 12. In general, the groundwater was a reliable predictor of Cl in pore water. Chloride/bromide mass ratios in groundwater and pore water followed the same trend as Cl concentrations at the Litchfield study sites. Cl/Br ratios in groundwater samples and extracted pore water results ranged from 96 to 280 and 65 to 1360, respectively. These results also suggest anthropogenic influence on the groundwater from KCl fertilizers, de-icing road salts, and potentially sewage effluent at the LFO1 site due to its extremely large value (Katz et al., 2011).

The anthropogenic contamination results are quite different at the Cromwell study site. Piezometer nest CWO1/2, which has an upward-direct hydraulic gradient, shows that groundwater concentration of Cl and the Cl/Br mass ratio decreased with depth to near background values and ranged from 1.0 to 45.4 mg/L and 62.4 to 1845.1, respectively (fig. 12). These values indicated evidence of anthropogenic input near the surface in the shallow aquifer there, but not significantly in the underlying aquitard and aquifer. With the presumed water source containing little Cl coming upwards from below, the fact Cl or Cl/Br ratios are not large in the till confining unit section above it is consistent with ^3H and hydraulic gradient data.

Nitrate

Nitrogen fertilizers are the primary cause of increasing NO_3 concentrations in groundwater throughout the U.S. (Spalding and Exner, 1993; Sebilo et. al. 2013). Highest NO_3 concentrations were detected in groundwater at shallow depths at all sites with extremely low or undetectable concentrations occurring in deeper piezometers. Results from groundwater samples collected from piezometers at sites LFO1 and LFO2 showed that NO_3 ranged from 0 to 0.36 mg/L. These values are low for NO_3 concentrations in groundwater in aquitards in agricultural areas (Rodvang and Simpkins, 2001), which are usually 10 mg/L NO_3 or greater (Eidem et al. 1999). Results of pore water collected at the LFO1 and

LFO2 nests range from 0.6 – 11.7 mg/L. Results from nest CWO1/2 show NO_3 concentrations at 2.05 mg/L in groundwater in uppermost piezometer and concentrations below detection limit up to 0.03 mg/L below that depth (fig. 12). Based on studies elsewhere in the Des Moines lobe (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995), and data showing that Cl is present in large concentrations where NO_3 is not present, these relationships provide good evidence that denitrification is removing the NO_3 in the confining unit and the aquifer. 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 at the Litchfield and Cromwell sites also has the highest NO_2 concentration, which could indicate active denitrification and conversion of NO_3 to NO_2 as another intermediate step.

Phosphorus

Based on the vertical distribution of total P at the three sites and the groundwater flow systems and ages, there is little evidence of vertical penetration of total P from the surface into the subsurface. Phosphorus, derived from natural and anthropogenic sources, varies from 0.147 mg/L in groundwater at LFO2 to 0.123 mg/L in CWO1/2 (fig. 12). The median phosphorus concentration for buried Quaternary aquifers in Minnesota is 0.124 mg/L (Minnesota Pollution Control Agency, 1999). Concentrations of P 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 Fe-P minerals, releasing adsorbed P (Burkart et al., 2004).

The lack of evidence for vertical penetration may suggest that much of the total P may be geologic in origin, particularly in the CWO1/2 nest. The concentration of total P in groundwater at site LFO1 was less than 0.020 mg/L through the entire vertical profile. The concentration in extracted pore water decreases with depth and ranges from less than 0.020 to 0.070 mg/L. Total P concentration increases with depth in groundwater at site LFO2, and ranges from less than 0.003 to 0.147 mg/L, with the highest concentration occurring unexpectedly midway through the till. The concentration of total P in extracted pore water from LFO2 was below 0.020 mg/L for each sample and did not show the high concentration shown in the groundwater. The concentration of total P in groundwater at site CWO1/2 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 total P moving vertically in groundwater at these sites is lacking.

Field Study Summary

Observations at Litchfield suggest that only limited portions of tills at these sites are aquitards that limit water flow and susceptibility to contamination for long periods of time. The till sequence at well nest LFO2 contained a zone of very low hydraulic conductivity whereas the till sequence at well nest LFO1, only about a 0.5 mi away from LFO2, lacked a such a feature. The resulting differences in estimated recharge through the till and water quality are shown in figure 13. The estimated vertical travel time between the two sites differs by three orders of magnitude, from about 2 years to over 1,000 years. The LFO1 site had evidence of recent anthropogenic inputs to the buried aquifer whereas no evidence of anthropogenic inputs was observed at LFO2. The aquifer test, which measured hydrologic conductivity of a much larger volume than the slug tests, demonstrates that the average ability of the till to transmit water lies between the two extremes observed at LFO1 and LFO2.

Observations at Cromwell also demonstrated a complex sequence of variable till material. An overall upward gradient existed at this site, but gradient directions were variable within the till. The hydraulic gradient data and the ^3H data suggest that recharge to the buried 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 we observed near the water supply well may have little direct influence on the quality and quantity of water at Cromwell (fig. 14). Rather, the anthropogenic activities and geologic materials at a distal recharge area (yet to be defined) may affect the water observed in the buried aquifer at the Cromwell site. The relatively high hydraulic conductivity estimates of the till and the similarity in water-level patterns observed throughout the Cromwell profile suggest and no aquitard layer present like that at LFO2.

Groundwater Modeling

Effects of Pumping from Confined Aquifers on Surface-Water and Groundwater Resources

A series of model scenarios demonstrated that pumping groundwater from buried aquifers can affect surface-water resources, and the size of the effect varies according to the hydrogeologic setting and pumping rates. All the scenarios used as the basis for this discussion were steady-state models representing long-term average conditions. Figures 15a and 16a show the amount of water that leaked from the surficial aquifer into the upper till, as a percent of water fluxes in layer 1, under different hydrogeologic settings with and without pumping within the 5 mi by 5 mi local area (fig. 5). In the conceptual model (fig. 5), there are streams and a lake overlying the buried aquifer pumping center within the local area, figures 15b and 16b show the percent reduction in groundwater discharge to these streams and lakes caused by pumping the buried aquifer.

The hydrogeologic setting and pumping caused large variations in the leakage from the surficial aquifer to the upper till unit. As vertical till hydraulic conductivity and middle unit horizontal hydraulic conductivity increased, the amount of leakage from the surficial aquifer to the upper till increased from two percent to 66 percent of water flux through the surficial unit (layer 1) even without pumping (gray bars in fig. 15a). With low vertical hydraulic conductivity of the till (layers 2 – 4) beneath the surficial unit (layer 1), lateral flow of groundwater through the surficial unit (layer 1) dominated the flow system, and only two percent of the groundwater leaked into the upper till unit (layer 2). With higher vertical conductivity of the till (layers 2 – 4) beneath the surficial unit (layer 1) leakage from layer 1 to layer 2 was a much more dominant flow path within the local area, accounting for 66 percent of layer 1 water flux prior to pumping stress.

Pumping at 900 gallons per minute (gpm) produced an increase in the leakage by variable amounts in the different hydrogeologic settings (fig. 15a). The largest pumping-induced change increased leakage from two percent to 31 percent with low vertical hydraulic conductivity of the overlying till (Kv = 0.001 ft/d) and low horizontal hydraulic conductivity (Kh) of the middle unit adjacent to the aquifer (Kh = 0.05 ft/d). The Kv of 0.001 ft/d and the 900 gpm pumping rate is comparable to the Litchfield site. In the more "leaky" system with higher vertical till hydraulic conductivities, pumping increased the leakage to till by only seven percent, from 66 to 73 percent of water flux through the surficial layer (fig. 15a).

Pumping induced a 28 percent reduction in groundwater discharge to lakes and streams for the three hydrogeologic settings in figure 15b. Despite the relative differences in the leakage as a percent of the overall flux through layer one (fig. 15a), the percent reduction in groundwater discharge to streams and lakes is similar in all three scenarios. In these scenarios, the vertical hydraulic conductivity of the till was varied simultaneously with the horizontal hydraulic conductivity of the middle unit adjacent to the buried aquifer. In a separate model scenario (not shown) where the overlying till unit (layer 2 – 4) is assigned a low vertical K (0.001 ft/d) and the middle unit adjacent to the buried aquifer is assigned a high horizontal K (30 ft/d), the reduction in groundwater discharge to streams and lakes induced by pumping within the local area is only about 9 percent.

These hydrogeologic scenarios demonstrate that over long periods of time, pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients induce flow that affects overlying surface-water resources.

Variations in the pumping rate caused large changes in the leakage from the surficial aquifer to the upper till unit and in the amount of groundwater discharge to streams and lakes. Figure 16 shows the change in leakage and the reduction in groundwater discharge to streams and lakes within the local area in the base model at 300 gpm, 900 gpm (comparable rate to Litchfield), and 2,250 gpm. At the 300 gpm pumping rate, pumping only increased the leakage by about 4 percent above ambient, but at the 2,250 gpm pumping rate, the leakage increased to 72 percent of water fluxes through the surficial unit (layer 1). These increases in downward leakage induced by pumping correspond with reductions in groundwater discharge to lakes and streams within the local area (fig 16b). Pumping at 300 gpm reduced groundwater discharge to streams and lakes by about 9 percent compared to ambient, but pumping at 2,250 gpm reduced groundwater discharge to streams and lakes by about 65 percent compared to ambient. These results indicate that the introduction pumping into a confined aquifer system can have a local effect on surface-water resources, and the size of that effect depends on the pumping rate. The 900 gpm rate is representative of the pumping rates in 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 is evident from the large summer drawdowns in the buried aquifer hydrographs (figs. 6 and 7) and from the aquifer test data (Minnesota Department of Health, 2017b). At the 900 gpm pumping rate, leakage into the upper till increased appreciably from 26 percent to 41 percent and the groundwater discharge to streams and lakes decreased by about 28 percent.

Source of Water to the Buried Aquifer

Figure 17 shows the range of responses from a series of model scenarios in which the vertical hydraulic conductivity of the overlying till and the horizontal hydraulic conductivity of the geologic material adjacent to the buried aquifer were varied. The relative amounts of water reaching a buried aquifer from above and laterally change drastically with variations in the hydrogeologic setting (fig. 17). Water entering the aquifer from the till below was less than 1 percent of the total flow in all three scenarios in (fig. 17). In one extreme case with low vertical hydraulic conductivity in the overlying till and high horizontal hydraulic conductivity in the materials adjacent to the buried aquifer, only about 11 percent of water entered the top of the buried aquifer while 89 percent entered the buried aquifer laterally from the sides. At the other extreme, 79 percent of water entered the buried aquifer from above and only 21 percent entered the buried aquifer from the sides in a setting with high vertical hydraulic conductivity in the overlying till and low horizontal hydraulic conductivity in the materials adjacent to the buried aquifer (fig. 17). In the base model with a vertical till conductivity between the values determined for Litchfield and Cromwell, most of the water (65 percent) entered through the top of the buried aquifer.

Changes to the pumping rate also have a moderate effect on the source of water reaching the buried aquifer. Figure 18 shows the changes in the source of water to a buried aquifer for the base model with pumping at 300, 900, and 2,250 gpm. At 300 and 900 gpm, the relative amounts of water entering the aquifer from above and laterally are very similar. At 2,250 gpm, there is an increase in the percent of water entering the aquifer from the sides and a corresponding decrease in percent of water entering from above. The total flux of water is higher under the 2,250 gpm pumping scenario, but where that water enters the buried aquifer is different compared to the lower pumping rates.

Sensitivity Analysis

A sensitivity analysis was completed to quantify the effects that variations in model parameter values have on the simulated source of water to buried aquifers. This sensitivity analysis provides insight about the relative value of different types of information. Highly sensitive parameters, those which, when changed, cause large changes in the simulated result, should be well informed by data collection efforts in order to maximize a model's ability to simulate observed conditions. The results of the sensitivity analysis can be used to guide data collection efforts in support of future site-specific models developed to evaluate the sustainability of groundwater withdrawals from buried aquifer systems. The relative sensitivities model of parameters to the downward flux of water are presented in table 8. The magnitude of the relative sensitivities are important. For example, a parameter with a relative sensitivity of -30 percent and one with 30 percent are equally sensitive; the -30 percent indicates a decrease in the simulated model result whereas the 30 percent indicates an increase in the simulated model result.

The most sensitive parameters were the vertical hydraulic conductivity (Kv) of the overlying till, the areal extent of the aquifer, and the horizontal hydraulic conductivity of the middle unit adjacent to the buried aquifer (table 8). Reducing the vertical hydraulic conductivity (Kv) of the overlying till from the base model value of 0.05 ft/d to 0.001 ft/d (representative of Litchfield till) caused a large reduction in the downward flux of water into the buried aquifer. For this range of Kv values, Kv was the most sensitive parameter. However, increasing the Kv from 0.05 to 2 ft/d (representative of Cromwell till) had little effect on the downward flux of water (table 8). The areal extent of the buried aquifer was a sensitive parameter both when increased and decreased. This is expected as the vertical thickness of the buried aquifer was held constant, and so increasing the areal extent provides a larger area on top of the buried aquifer for percolating water to enter relative to the sides of the aquifer. The next most sensitive parameter was the horizontal hydraulic conductivity (Kh) of the middle unit. A decrease in Kh from 5.0 ft/d to 0.05 ft/d caused a large increase in the downward flux of water into the buried aquifer. However, an increase in the Kh to 30 ft/d cause little change in the downward flux of water into the buried aquifer.

The thickness of the upper till, the total pumping rate, and the buried aquifer's horizontal hydraulic conductivity were moderately sensitive parameters (table 8). The downward flux of water into the buried aquifer was inversely related to the thickness of the till; i.e. increasing the till thickness resulted in decreased amounts of water entering the aquifer from directly above. The downward flux of water into the buried aquifer was also inversely related to the buried aquifer's horizontal hydraulic conductivity, and decreasing it caused a larger change in simulated results than increasing it. Increasing the pump rate resulted in a decrease in the percent of total leakage downward and an increase in lateral leakage. The downward flux of water into the buried aquifer from the overlying till was not affected by changes to the well screen length and the penetration of the well screen within the aquifer (table 8).

Modeling summary

The conceptual 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. Over long periods of time, pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients could induce flow that affects surface-water resources. The source of water entering a buried aquifer that is being pumped can be highly variable, depending on the overlying till vertical hydraulic conductivities and the lateral connectivity of buried aquifer to adjacent till and aquifers. A sensitivity analysis demonstrated that the simulation of the source of water to wells is most sensitive to the vertical hydraulic conductivity of the overlying till, the areal extent of the aquifer, and the connectivity of the horizontal hydraulic conductivity of geologic materials adjacent to the aquifer.

Summary and Conclusions

Confined (or buried) aquifers 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, buried aquifers are thought to be less susceptible to surface contamination, but may recharge very slowly and may be prone to unsustainable groundwater withdrawals. This study was completed to give insight to the susceptibility and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota. A combination of hydrologic field measurements, geochemical analyses, and modeling techniques were used to quantify the variability of hydrologic properties and flux of water through till confining units to buried aquifers at two representative sites in Minnesota. Glacial deposits of the Des Moines Lobe were characterized in Litchfield, Minnesota and glacial deposits of the Superior Lobe were characterized in Cromwell, Minnesota.

A conceptual understanding emerges from the field measurements at the two sites that till “layers” in the glacial deposits of the Des Moines and Superior Lobes in Minnesota are not really continuous layers, but rather a complex series of sediment mixtures with differing abilities to transmit water. The hydrologic field measurements and geochemical analysis demonstrated large variations in till confining unit properties over relatively small vertical and horizontal distances, underscoring the challenges of assessing the susceptibility and sustainability of groundwater resources in confined aquifer systems.

The observations at the Litchfield site indicate that only limited portions of tills are aquitards that limit water flow and susceptibility to contamination for long periods of time. The till sequence at well nest LFO2 contained a zone of very low hydraulic conductivity whereas the till sequence at well nest LFO1, only about a 0.5 mi away from LFO2, lacked a such a feature. The estimated vertical travel time between the two sites differs by three orders of magnitude, from about 2 years to over 1,000 years. The LFO1 site had evidence of recent anthropogenic inputs to the buried aquifer whereas no evidence of anthropogenic inputs was observed at LFO2. The aquifer test, which measured hydrologic conductivity of a much larger volume than the slug tests, demonstrates that the average ability of the till to transmit water lies between the two extremes observed at LFO1 and LFO2.

Observations at Cromwell also demonstrated a complex sequence of variable till material. An overall upward gradient existed at this site, but gradient directions were variable within the till. The hydraulic gradient data and the ^{3}H data suggest that recharge to the buried 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 we 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 buried aquifer at the Cromwell site. The relatively high hydraulic conductivity estimates of the till and the similarity in water-level patterns observed throughout the Cromwell profile suggest there is no aquitard layer present like that at LFO2.

Many waters in Minnesota are under threat of nutrient contamination from anthropogenic activities such as row-crop agriculture. This study provided some evidence that till confining units may be effective at reducing the susceptibility of buried aquifers to nitrate contamination, but may be a source of phosphorus. Data from Litchfield show that chloride is present in elevated concentrations where nitrate is not, despite abundant agriculture in the surrounding area. This suggests that denitrification may be occurring within the till; previous studies have demonstrated denitrification in Des Moines lobe tills (Simpkins and Parkin, 1993; Parkin and Simpkins, 1995). Phosphorus, though present at depth, particularly in Cromwell, is likely geologic rather than anthropogenic in origin.

The conceptual 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. Over long periods of time, pumping-induced hydraulic gradients can be established in buried aquifer systems and, even in low hydraulic conductivity tills, these gradients could induce flow that affects surface-water resources. The source of water entering a buried aquifer that is being pumped can be highly variable, depending on the overlying till vertical hydraulic conductivities and the lateral connectivity of buried aquifer to adjacent till and aquifers. A sensitivity analysis demonstrated that the simulation of the source of water to wells is most sensitive to the vertical hydraulic conductivity of the overlying till, the areal extent of the aquifer, and the connectivity of the horizontal hydraulic conductivity of geologic materials adjacent to the aquifer.

References

Berg, J.A. 2011. Plate 8 – Hydrogeologic cross sections. C-39 Geologic Atlas of Carlton County, Minnesota [Part B]. *Minnesota Department of Natural Resources, Ecological and Water Resources Division*. Retrieved from the MNDNR County Geologic Atlas Program, http://www.dnr.state.mn.us/waters/programs/gw_section/mapping/platesum/carlcga.html

Boerboom, Terrence J.. (2009). C-19 Geologic atlas of Carlton County, Minnesota [Part A]. Minnesota Geological Survey.Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/58760.

Bradbury, K.R., and M.A. Muldoon. 1990. Hydraulic conductivity determinations in unlithified glacial and fluvial materials. In *Ground water and vadose zone monitoring*. Edited by D.M. Nielsen and A.I. Johnson. Philadelphia, PA,: American Society for Testing and Materials:138-151

Burkart, M. R., W.W. Simpkins, A.J. Morrow, and J.M. Gannon. 2004. Occurrence of total dissolved phosphorus in unconsolidated aquifers and aquitards in Iowa. J*ournal of the American Water Resources Association*. 1319: 827–834.

Cherry, J.A., Parker, B.L., Bradbury, K.R., Eaton, T.T., Gotkowitz M.B., Hart, D.J., and Borchardt, M.A., 2006. *Contaminant Transport Through Aquitards: a State-of-the-science Review.*. AWWA Research Foundation. 126 p.

Eidem, J.M., W.W. Simpkins, and M.R. Burkart, 1999. Geology, groundwater flow, and water quality in the Walnut Creek watershed. *Jour. Environ. Qual.* 28:60-68.

Grisak, G.E., and J.A. Cherry. 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. *Canadian Geotechnical Journal,* 12:23-43.

Grisak, G.E., J.A. Cherry, J.A. Vonhof, and J.P. Blumele. 1976. Hydrogeologic and hydrochemical properties of fractured till in the interior plains region. Edited by R. F. Legget, editor. Royal Society of Canada, Ottawa. 304-335.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6- A16.

Hart, D. J., K. R. Bradbury, and M. B. Gotkowitz, 2008, Is one an upper limit for natural hydraulic gradients? *Groundwater* 46, no. 4: 518-520.

Helmke, M.F., W.W. Simpkins, and R. Horton. 2005. Fracture-controlled transport of nitrate and atrazine in four Iowa till units. *Jour. of Environ. Qual.* 34:227-236.

Hobbs, H.C.; Goebel, J.E.. (1982). S-01 Geologic map of Minnesota, Quaternary geology. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, Accessed November 22, 2017 at http://hdl.handle.net/11299/60085.

Howard, K.W.F. and Beck, P.J. 1993. Hydrogeochemical implications of groundwater contamination by road de-icing chemicals. J. Contam. Hydrol., 12: 245-268.

Husain, M.M., Cherry, J.A., Fidler, S., and Frape, S.K. 1998. On the long-term hydraulic gradient in the thick clayey aquitard in the Sarnia region, Ontario. *Canadian Geotechnical Journal,* 35:986-1003.

Katz, B. G., S. M. Eberts, and L.J Kauffman. 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. *Journal of Hydrology*. 397:151–166.

Keller, C.K., van der Kamp, G., and Cherry, J.A. 1989. Multiscale Study of the Permeability of a Thick Clayey Till. *Water Resources Research,* 25:2299-2317.

Kelly, W. R., S. V. Panno, K. Hackley, and W.R. Kelly. 2012. The Sources, Distribution, and Trends of Chloride in the Waters of Illinois. Illinois State Water Survey, Prarie Research Institute, Champaign, Illinois, p. 67 (March, Report No. B-74).

Meyer, Gary N., (2015). C-35, Geologic Atlas of Meeker County, Minnesota [Part A]. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/166576.

Minnesota Department of Health, 2017a, Analysis of the Cromwell, Minnesota Well 4 (593593) Aquifer Test. Accessed November 20, 2017 at http://www.health.state.mn.us/divs/eh/water/swp/maps/testcromwell.pdf.

Minnesota Department of Health, 2017b, Analysis of the Litchfield, Minnesota Well 2 (607420) Aquifer Test. Accessed November 20, 2017 at http://www.health.state.mn.us/divs/eh/water/swp/maps/testlitchfield.pdf.

Minnesota Department of Health, 2017c, Minnesota well index online. Access November 20, 2017 at https://apps.health.state.mn.us/cwi/.

Minnesota Department of Natural Resources, 2003, 1981-2010 Normal Annual Precipitation. Retrieved from the Minnesota Climatology Working Group, DNR Division of Ecological and Water Resources, http://climate.umn.edu/img/normals/precip/precip_norm_annual.htm

Minnesota Department of Natural Resources, 2017, Minnesota Water Use Data, ArcGIS Layer. Accessed November 20, 2017 at http://files.dnr.state.mn.us/waters/watermgmt_section/appropriations/mpars_wa_permits_installations_uses.zip.

Minnesota Pollution Control Agency, 1999, Phosphorous in Minnesotas Ground Water. Environmental Outcomes Division, Ground Water Monitoring & Assessment Program. https://www.pca.state.mn.us/sites/default/files/phospho.pdf

Neuman, S.P., and P.A. Witherspoon. 1972. Field determination of the hydraulic parameters of leaky multiple aquifer systems. *Water Resources Research,* 8:1284-1298.

Parkin, T.B. and W.W. Simpkins, 1995. Contemporary groundwater methane production from Pleistocene carbon. *Journal of Environmental Quality.* 24:367-372.

Remenda, V.H., Cherry, J.A. and Edwards, T.W.D., 1994. Isotopic composition of old ground water from Lake Agassiz: implications for late Pleistocene climate. *Science*, *266* (5193), p.1975.

Rodvang, S.J, and W.W. Simpkins. 2001. Agricultural contaminants in Quaternary aquitards: A review of occurrence and fate in North America. *Hydrogeology Journal*. 9:44-59.

Sebilo, M., B. Mayer, B. Nicolardot, G. Pinay, and A. Mariotti. 2013. Long-term fate of nitrate fertilizer in agricultural soils. *Proceedings of the National Academy of Sciences, USA.* 110:18185-18189

Shaw, R.J. and Hendry, M.J., 1998. Hydrogeology of a thick clay till and Cretaceous clay sequence, Saskatchewan, Canada. *Canadian Geotechnical Journal*, *35*(6), pp.1041-1052.

Simpkins, W.W. and Bradbury, K.R., 1992. Groundwater flow, velocity, and age in a thick, fine-grained till unit in southeastern Wisconsin. *Journal of Hydrology*, *132*(1-4), pp.283-319.

Simpkins, W.W. and Parkin, T.B., 1993. Hydrogeology and redox geochemistry of CH4 in a late Wisconsinan till and loess sequence in central Iowa. *Water Resources Research*, *29*(11), pp.3643-3657.

Simpkins, W.W. 2010. Nonpoint source contamination of a municipal water supply at the urban-agricultural interface. GSA Annual Meeting Abst. with Programs.

Smith, E.A., and Westenbroek, S.M., 2015, Potential groundwater recharge for the State of Minnesota using the Soil-Water-Balance model, 1996–2010: U.S. Geological Survey Scientific Investigations Report 2015–5038, 85 p., Also available at http://dx.doi.org/10.3133/sir20155038.

Spalding, R. F., and M.E. Exner. 1993. Occurrence of nitrate in groundwater – A Review. *Journal of Environmental Quality*. 22:392-402.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, accessed April 1, 2016, at https://water.usgs.gov/owq/FieldManual/.

Wagner, K. and Tipping, R., 2016, Core Descriptions and Borehole Geophysics in Support of USGS Hydrologic Properties of Till Investigation, Litchfield and Cromwell, Minnesota. Accessed November 20, 2017 at ftp://mgsftp2.mngs.umn.edu/pub4/outgoing/MGS_report_in_support_of_USGS_till_study_Phase_I.pdf.

Witt, A.N., 2017, Hydrogeological and geochemical investigation of recharge (leakage) through till aquitards to buried-valley aquifers in central and northeastern Minnesota. M.S. Thesis, Iowa State University, 168 p. Will be available here: http://lib.dr.iastate.edu/etd/.

FIGURES

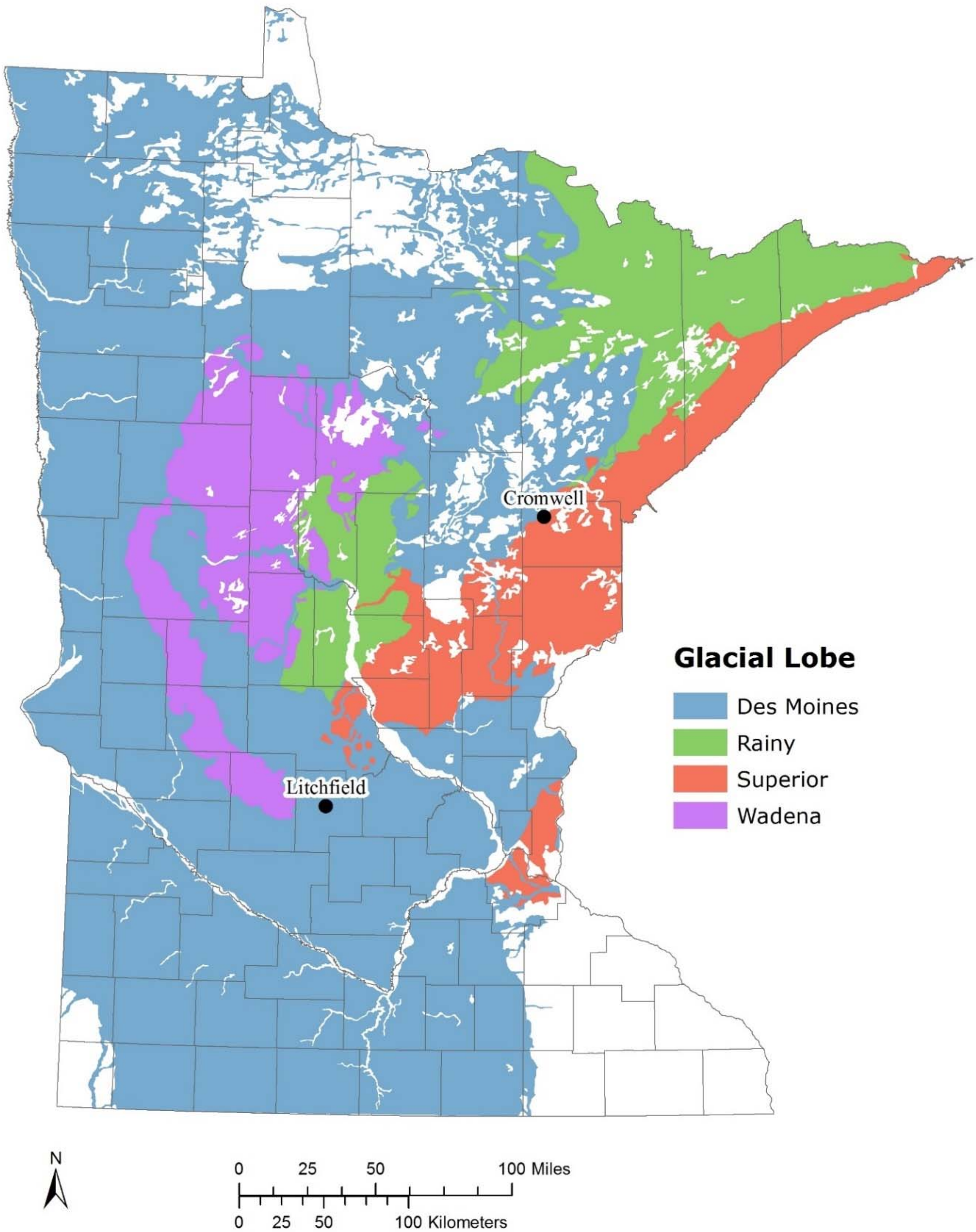

Figure 1. Map showing the extent of the major glacial lobe deposits in Minnesota (from Hobbs and Goebel, 1982) and the location of the Litchfield and Cromwell study sites.

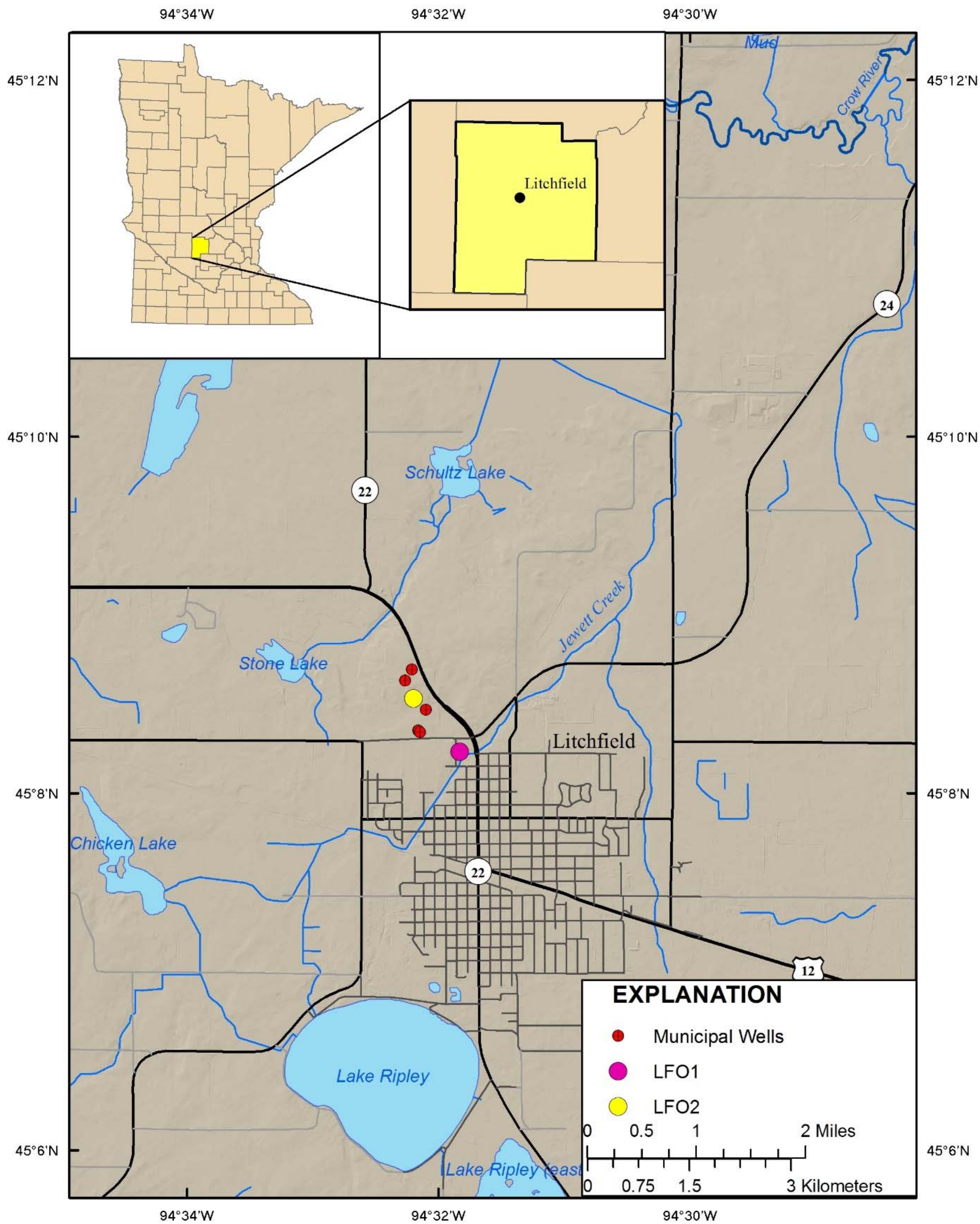

Figure 2. Map of the Litchfield study site.

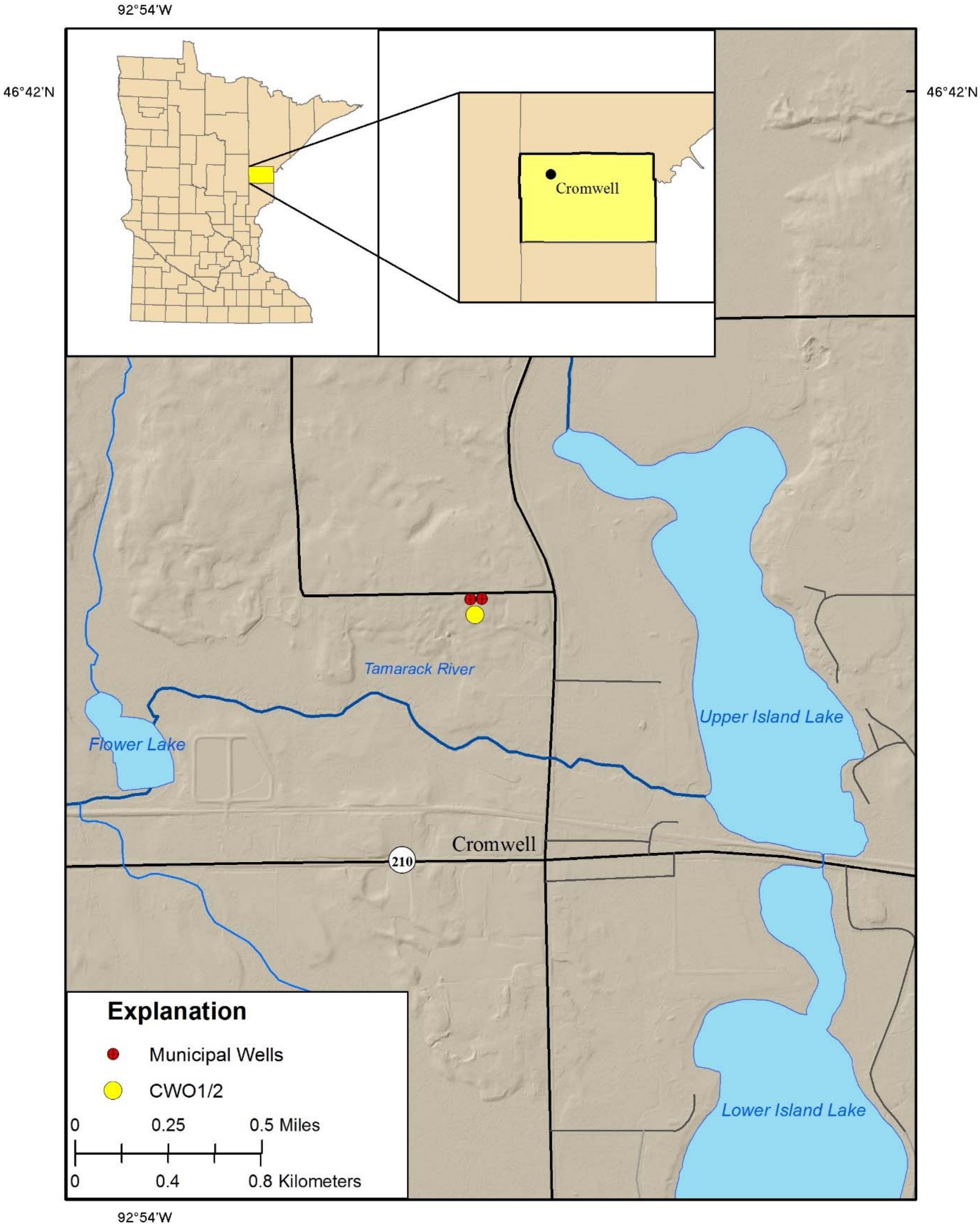

Figure 3. Map of the Cromwell study site.

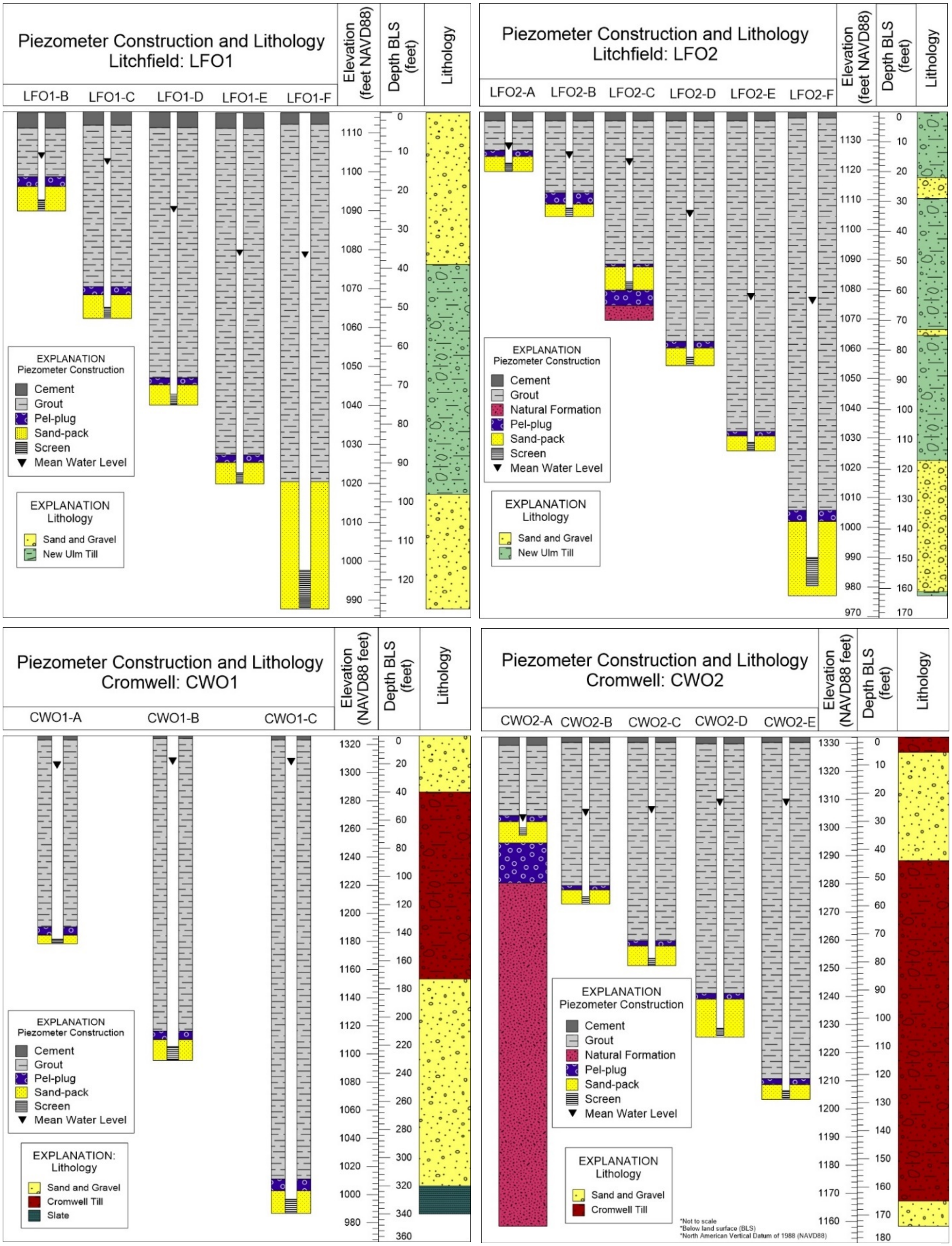

Figure 4. Piezometer construction and lithology diagrams for piezometer nests LFO1, LFO2, CWO1, and CWO2. Lithology summarized from Wagner and Tipping (2016).

Figure 5. Aerial view of the base conceptual groundwater-flow model.

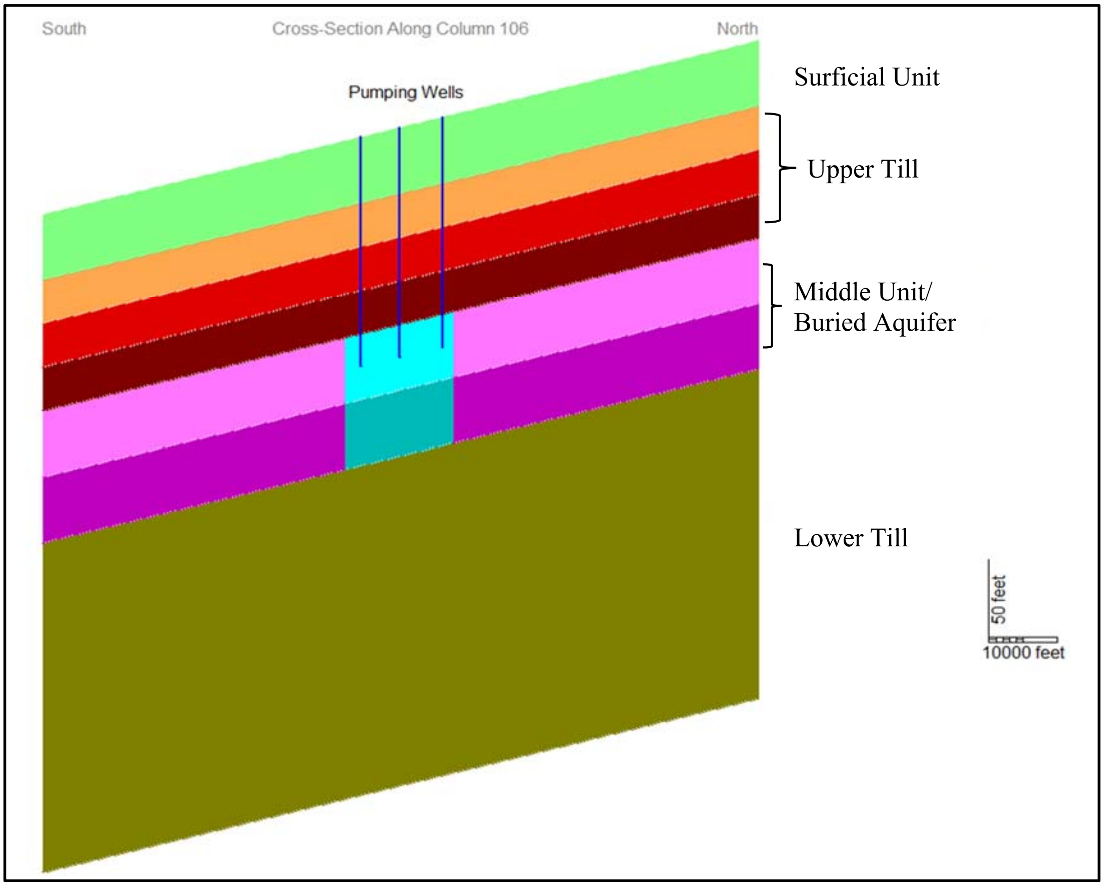

Figure 6. Cross-section view of the base conceptual groundwater-flow model.

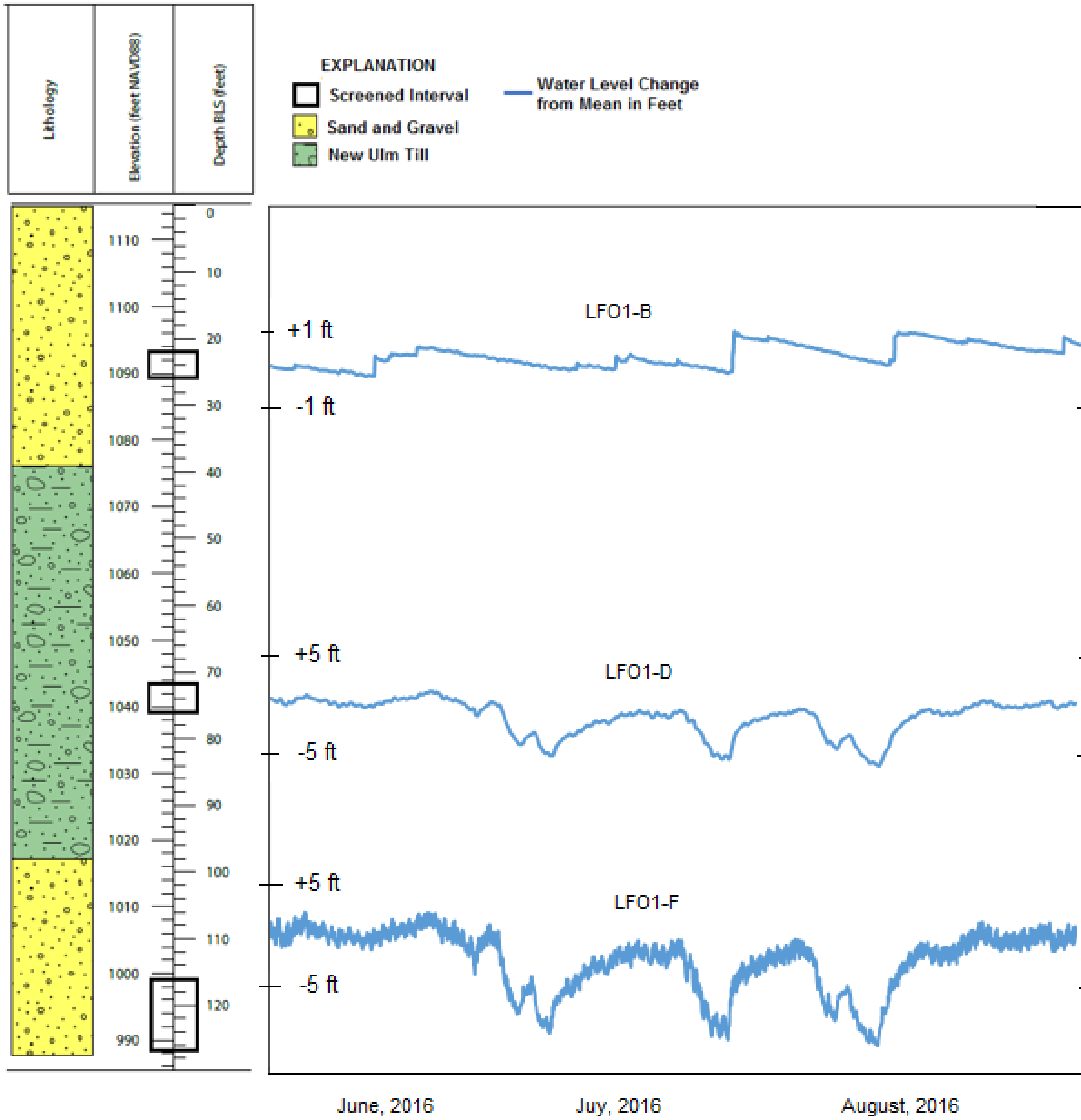

Figure 7. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Litchfield nest LFO1. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for visualizing patterns in water-level variations through time by depth but not for assessing the magnitude of those changes.

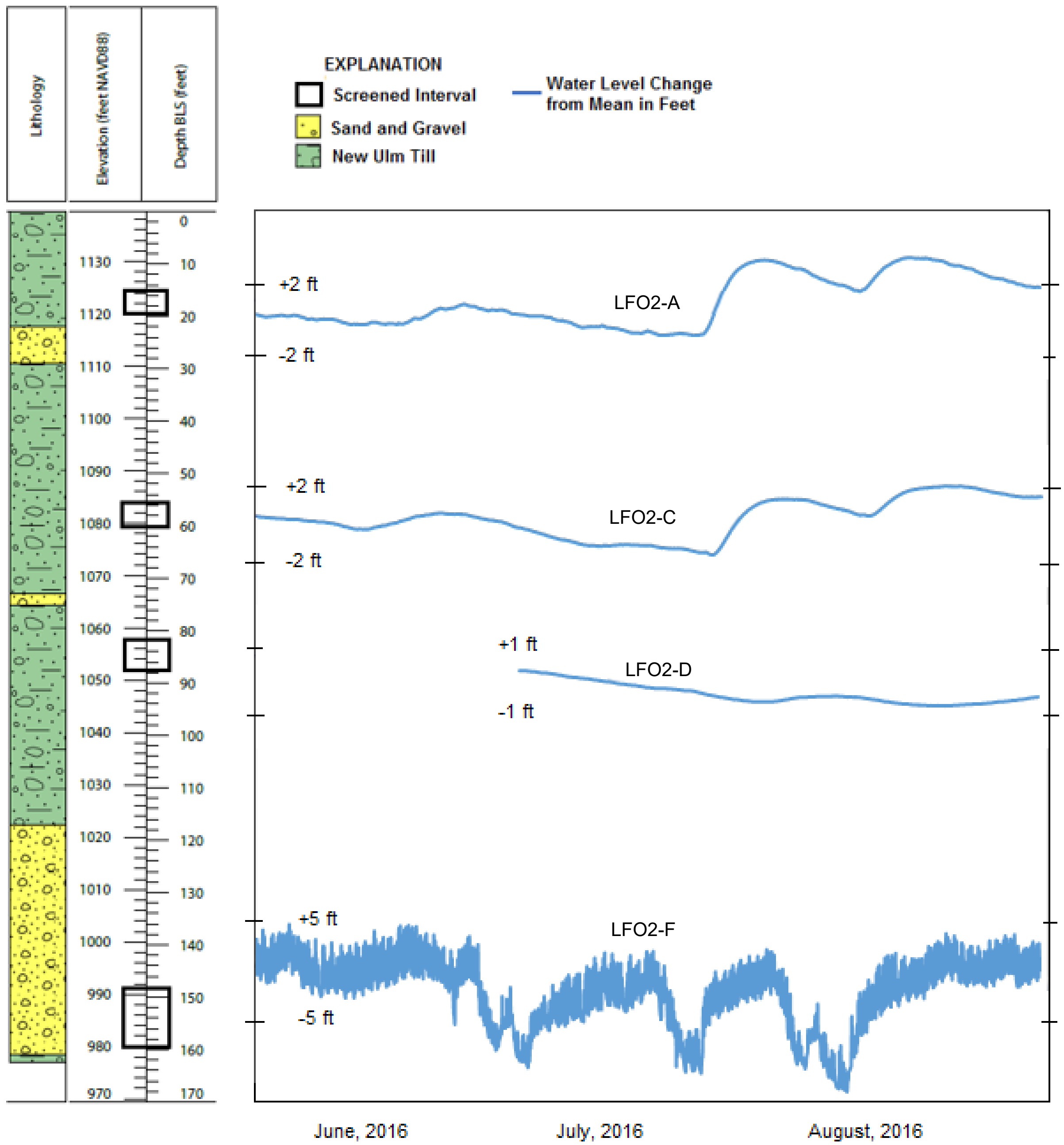

Figure 8. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Litchfield nest LFO2. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for visualizing patterns in water-level variations through time by depth but not for assessing the magnitude of those changes.

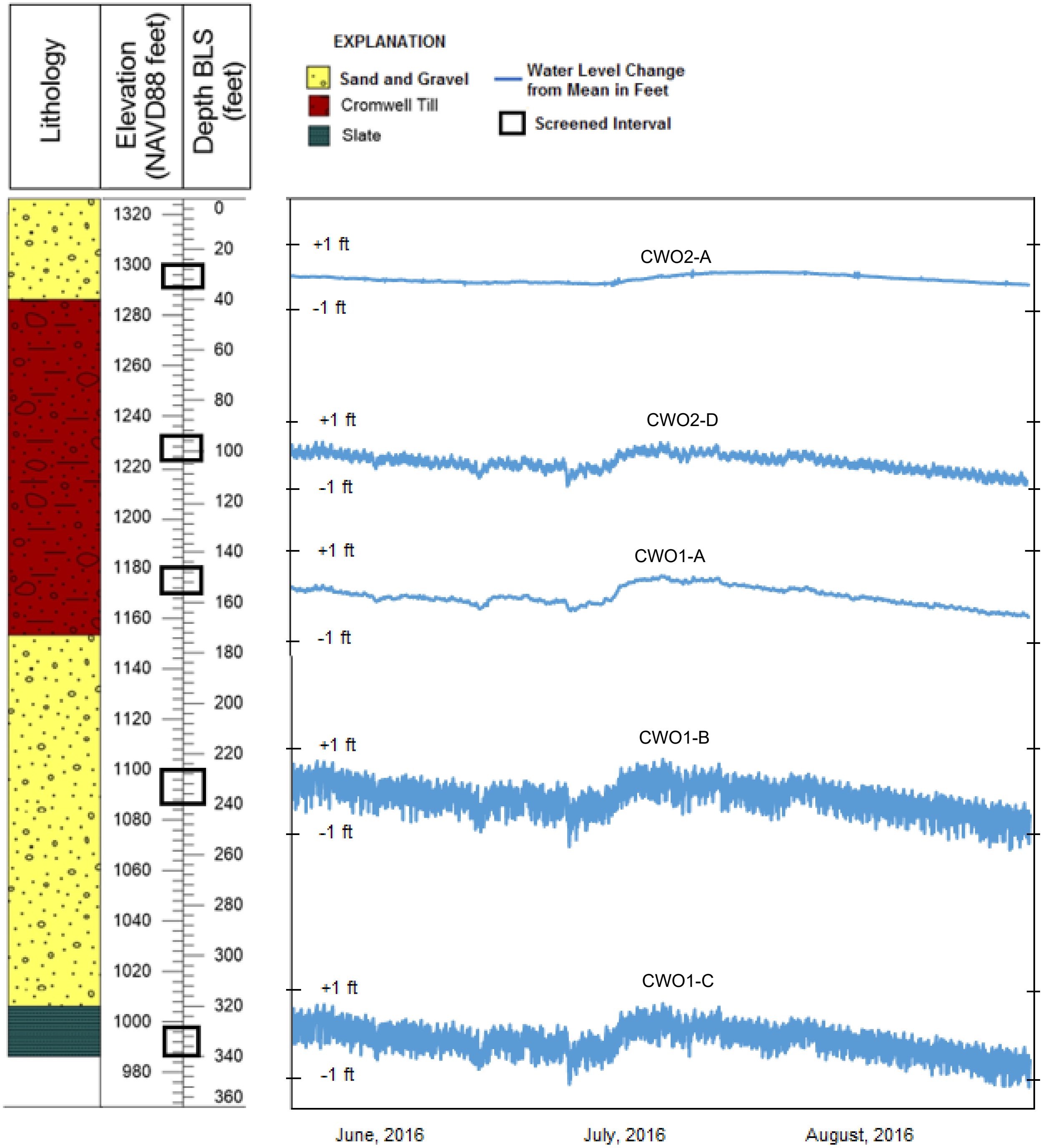

Figure 9. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Cromwell nest CWO1/2. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for visualizing patterns in water-level variations through time by depth but not for assessing the magnitude of those changes.

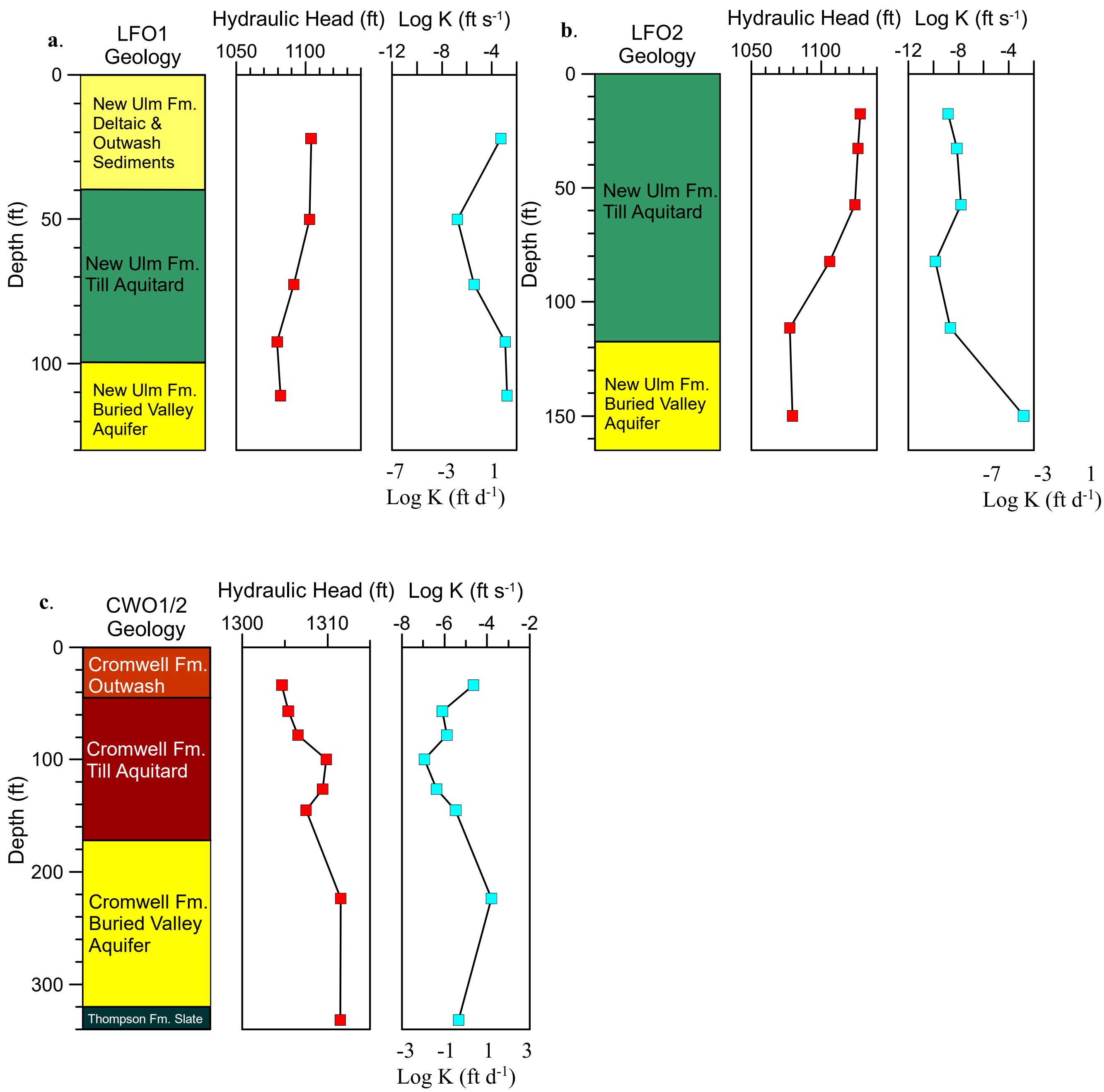

Figure 10. Generalized lithology, hydraulic head, and hydraulic conductivity (K) with depth at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and (c) Cromwell piezometer nest CWO1/2.

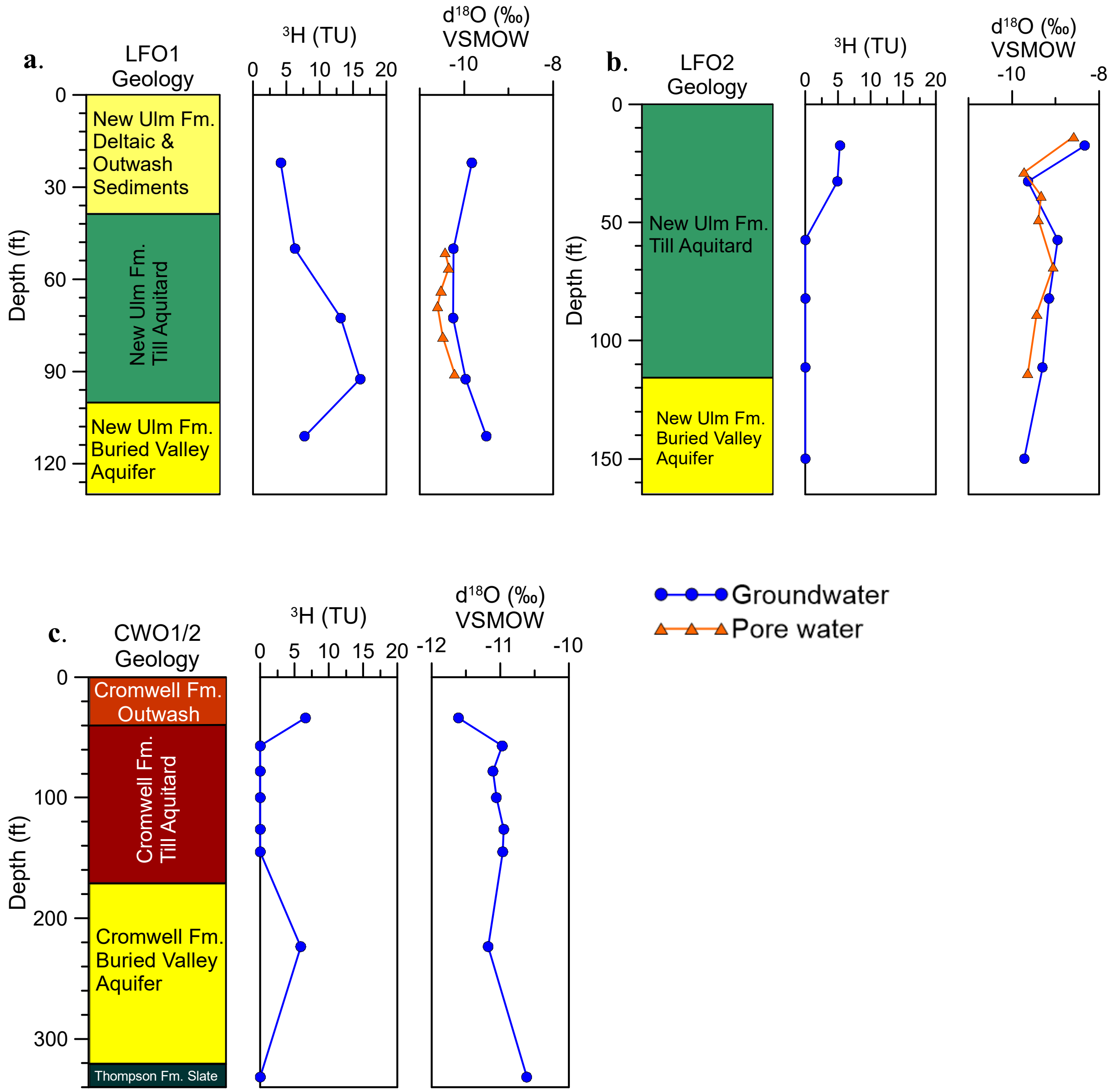

Figure 11. Generalized lithology and enriched tritium (^{3}H) and oxygen isotope (^{18}O) profiles determined from groundwater and pore-water samples at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and (c) Cromwell piezometer nest CWO1/2.

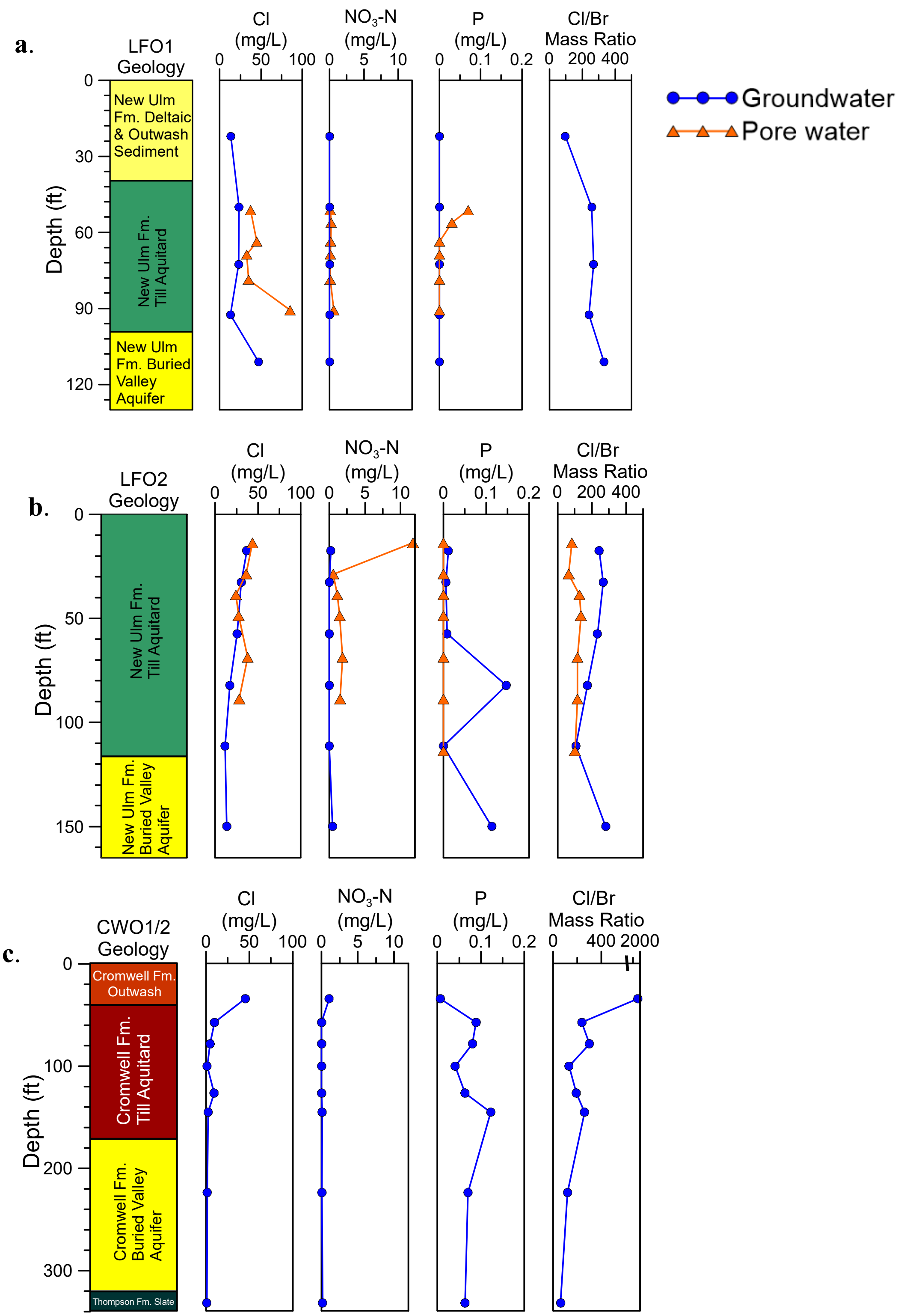

Figure 12. Generalized lithology, chloride (Cl) concentrations, nitrate (NO3) concentrations, phosphorus (P) concentrations, and chloride to bromide (Cl/Br) mass ratios determined from groundwater and pore-water samples at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and (c) Cromwell piezometer nest CWO1/2.

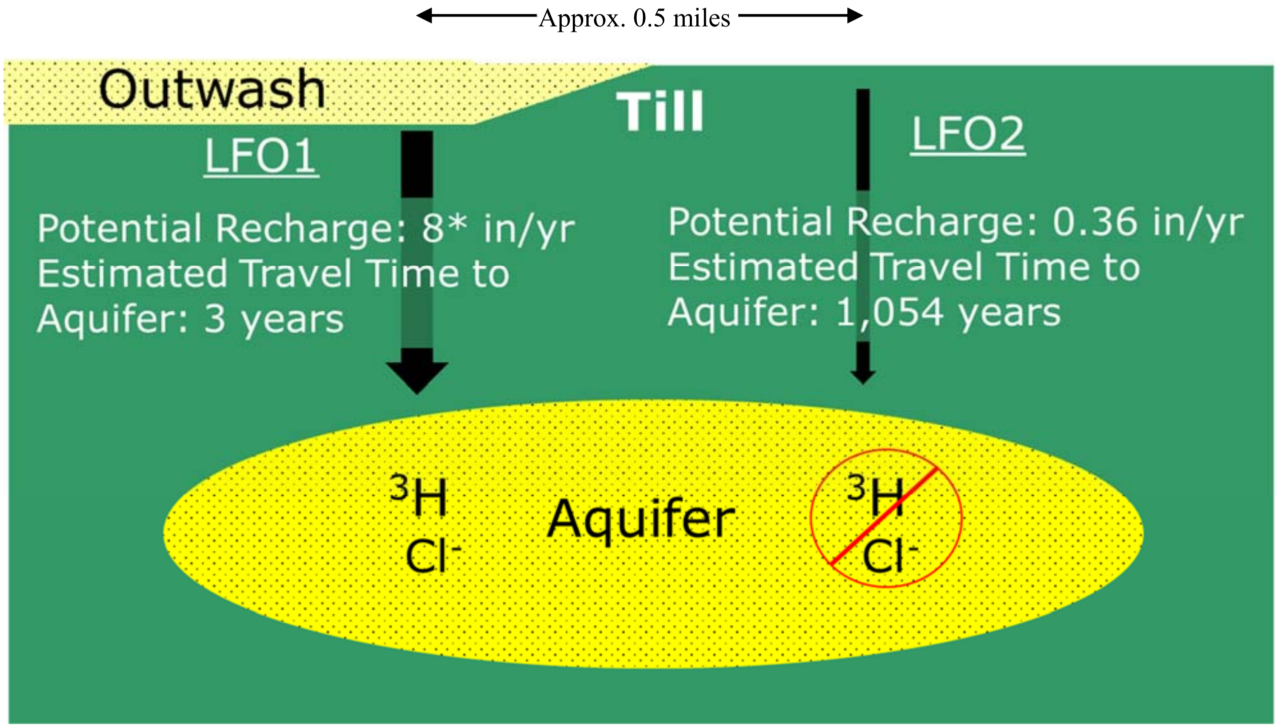

Figure 13. Graphical summary depicting the geologic, hydraulic, and geochemical results from piezometer nests LFO1 and LFO2 at the Litchfield, Minnesota study site. Chloride (Cl^-) and tritium (^3H) presence is indicated. [in/yr, inches per year]

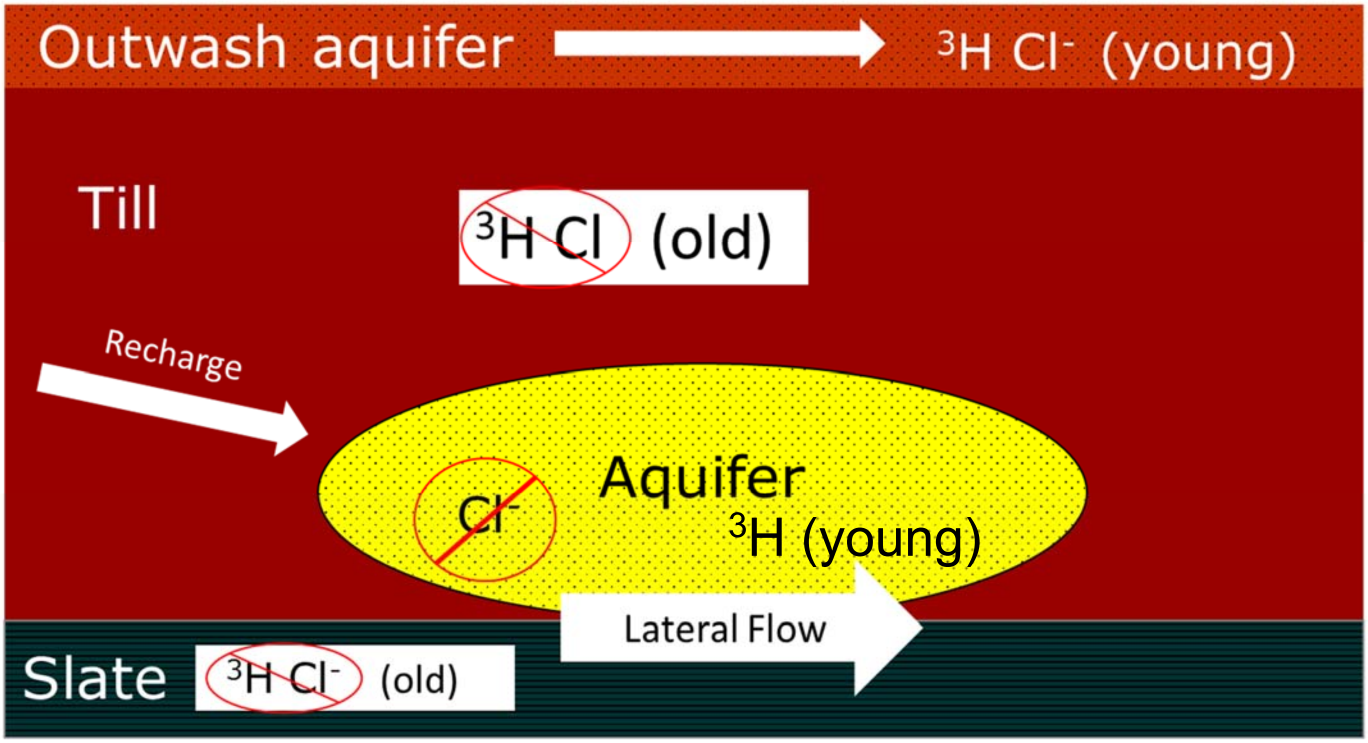

Figure 14. Graphical summary depicting the geologic, hydraulic, and geochemical results from piezometer nest CWO1/2 at the Cromwell, Minnesota study site. Chloride (Cl^-) and tritium (^3H) presence is indicated. Young and old refer to the apparent age of the groundwater based on tritium and chloride concentrations; young water has been exposed to the atmosphere after the 1950s, old water reached groundwater prior to the 1950s

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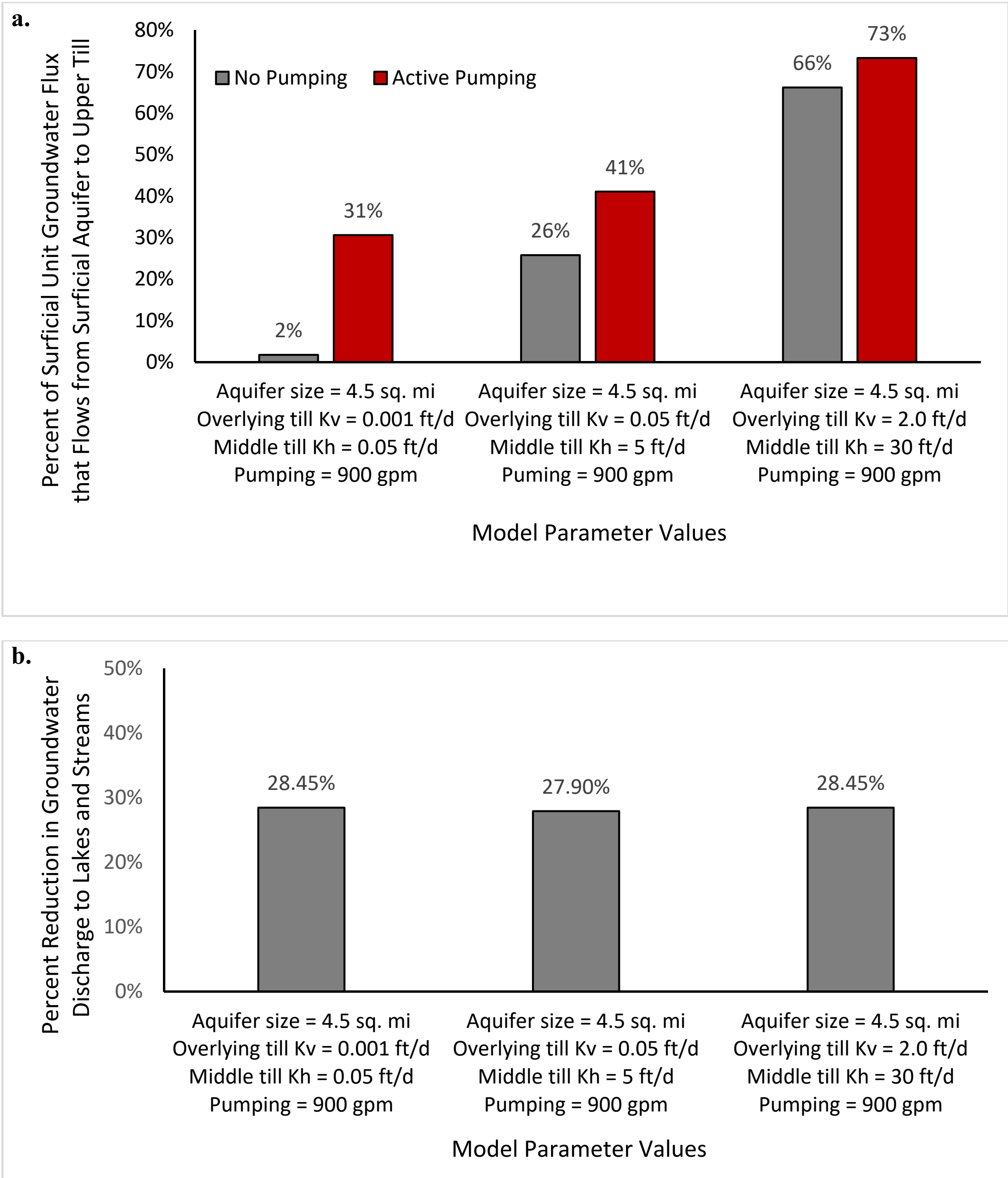
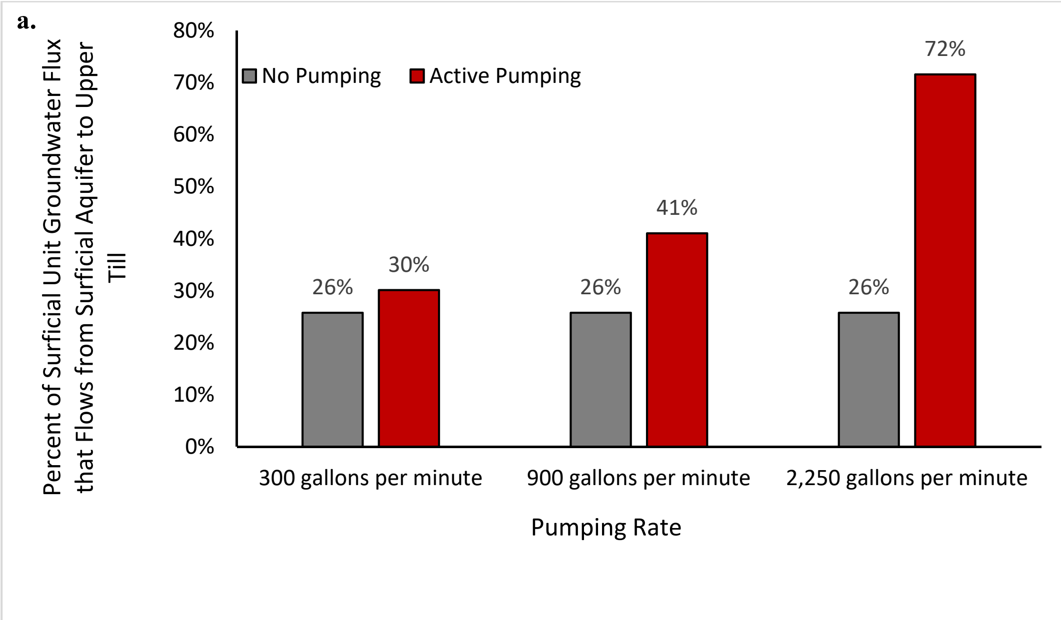


Figure 15. Bar graph of conceptual model output showing (a) the percent of groundwater recharge in the surficial aquifer (layer 1) that flows to the upper till unit (layer 2) under ambient and active pumping conditions. This graph shows the range of leakage with variations in aquifer size (sq. mi = square miles), vertical hydraulic conductivity (Kv) of overlying till, and horizontal hydraulic conductivity (Kh) of middle till unit adjacent to buried aquifer. This was determined within the 25-square mile local area shown in figure 5. (b) The percent reduction in groundwater discharge to lakes and streams from ambient to pumping conditions.



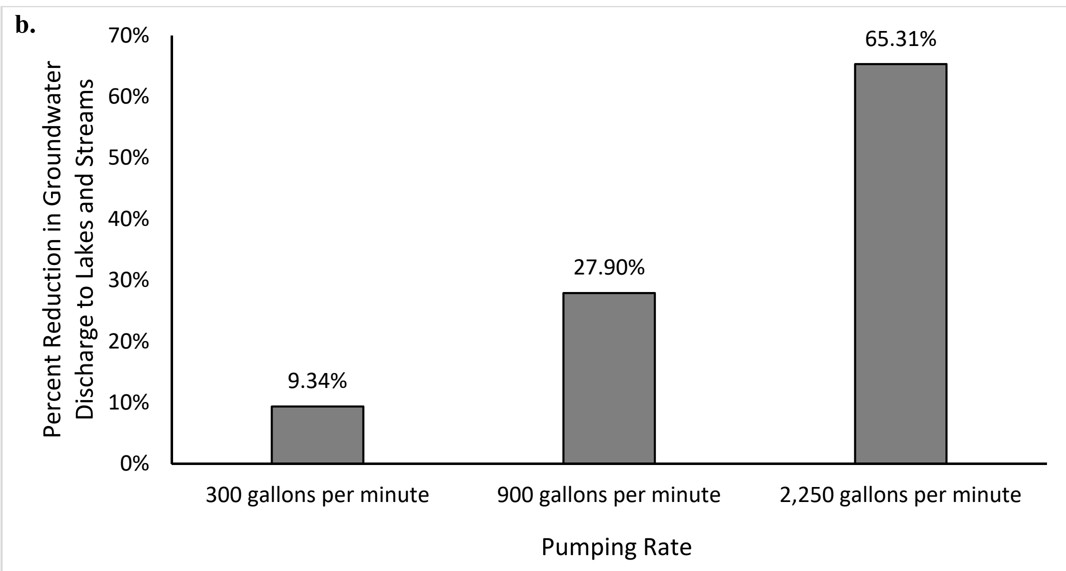


Figure 16. Bar graph of conceptual model output showing (a) the percent of groundwater recharge in the surficial aquifer (layer 1) that flows to the upper till unit (layer 2) under ambient and active pumping conditions. The leakage was determined within the 25-square mile local area shown in figure 5. All non-pumping model parameters were the base model values, as listed in table 2. (b) The percent reduction in groundwater discharge to lakes and streams from ambient to pumping conditions.

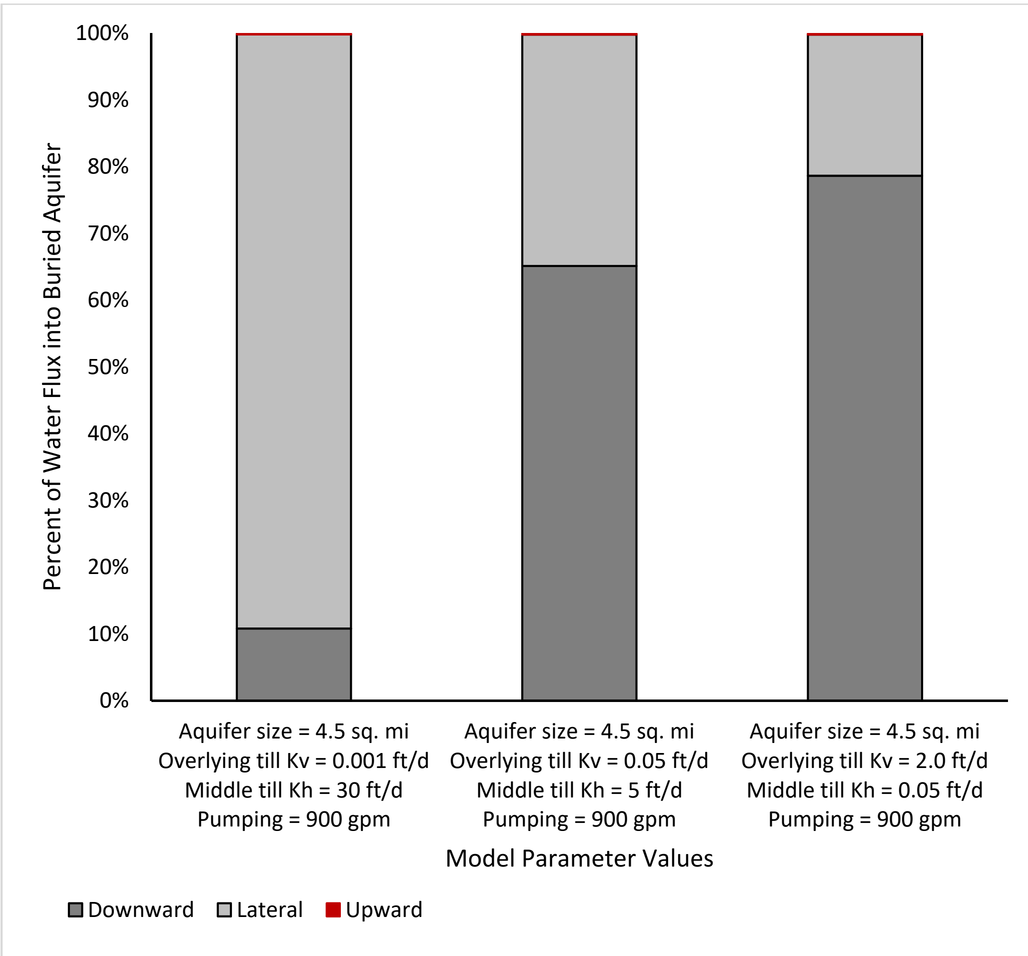


Figure 17. Bar graph of conceptual model output showing the percent of water entering the buried aquifer via downward flux from above, lateral flux from the sides, and upward flux from below. This graph shows the range of source water to wells due to variations in aquifer size (sq. mi = square miles), vertical hydraulic conductivity (Kv) of overlying till, and horizontal hydraulic conductivity (Kh) of middle till unit adjacent to buried aquifer.

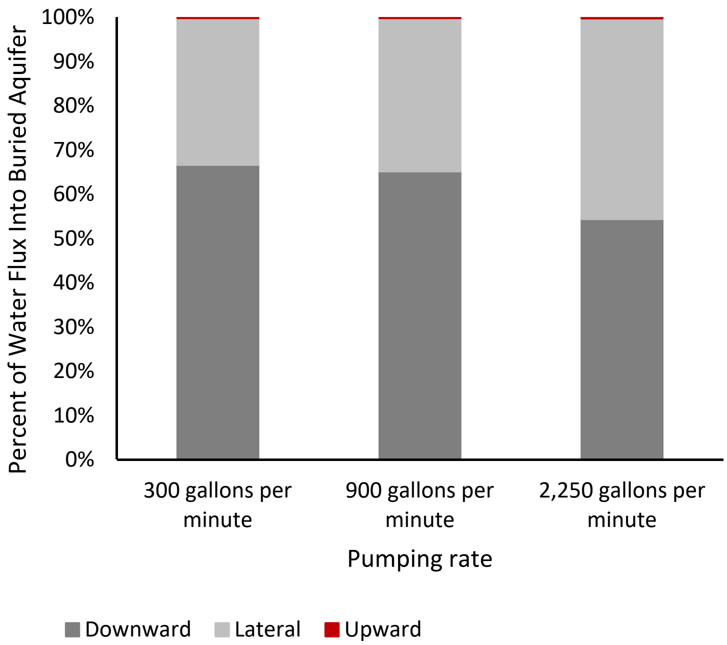


Figure 18. Bar graph of conceptual model output showing the percent of water entering the buried aquifer via downward flux from above, lateral flux from the sides, and upward flux from below with different pumping rates. All non-pumping model parameters were the base model values, as listed in table 2.

TABLES

Table 1. Piezometer names, locations, and construction information.

[ft, feet; in, inches; ft BLS, feet below land surface; ft NAVD88, feet above North American Datum of 1988]

Piezometer Name	USGS Site ID	Latitude	Longitude	Land Surface Elevation (ft NAVD88)	Drill Depth (ft BLS)	Borehole Diameter (in)	Pressure Transducer
LFO1-B	450814094315001	45°08'14"	94°31'50"	1115.22	25.5	8.25	Y
LFO1-C	450814094315002	45°08'14"	94°31'50"	1115.45	53.1	8.25	N
LFO1-D	450814094315003	45°08'14"	94°31'50"	1115.34	75.5	8.25	Y
LFO1-E	450814094315004	45°08'14"	94°31'50"	1115.15	96	8.25	N
LFO1-F	450814094315006	45°08'14"	94°31'50"	1115.19	127.7	8.25	Y
LFO2-A	450832094321201	45°08'32"	94°32'12"	1139.45	20	8.25	Y
LFO2-B	450832094321202	45°08'32"	94°32'12"	1139.29	35.5	8.25	N
LFO2-C	450832094321203	45°08'32"	94°32'12"	1139.72	70	8.25	Y
LFO2-D	450832094321204	45°08'32"	94°32'12"	1139.18	86	8.25	Y
LFO2-E	450832094321205	45°08'32"	94°32'12"	1139.64	114	8.25	N
LFO2-F	450832094321206	45°08'32"	94°32'12"	1139.47	162.5	8.25	Y
CWO1-A	464110092531401	46°41'10"	92°53'14"	1326.28	150	6.75	Y
CWO1-B	464110092531402	46°41'10"	92°53'14"	1326.29	231	6.75	Y
CWO1-C	464110092531403	46°41'10"	92°53'14"	1326.25	340	6.75	Y
CWO2-A	464112092531401	46°41'12"	92°53'14"	1332.28	174	8.25	Y
CWO2-B	464112092531402	46°41'12"	92°53'14"	1332.59	60.5	8.25	N
CWO2-C	464112092531403	46°41'12"	92°53'14"	1332.33	82	8.25	N
CWO2-D	464112092531404	46°41'12"	92°53'14"	1332.13	107.5	8.25	Y
CWO2-E	464112092531405	46°41'12"	92°53'14"	1332.44	129.5	8.25	N

Table 1. continued.

Piezometer Name	Casing Diameter (in)	Screen Diameter (in)	Screen Slot Size	Screen Openings (in)	Screen Length (ft)	Screened Interval (ft BLS)
LFO1-B	1.25	1.25	10	0.01	2.66	22.40 - 25.06
LFO1-C	1.25	1.25	10	0.01	2.66	50.23 - 52.89
LFO1-D	1.25	1.25	10	0.01	2.66	72.40 - 75.06
LFO1-E	1.25	1.25	10	0.01	2.66	92.41 - 95.07
LFO1-F	2.04	2.04	20	0.02	9.62	117.5 - 127.12
LFO2-A	1.25	1.25	10	0.01	2.66	17.12 - 19.78
LFO2-B	1.25	1.25	10	0.01	2.66	32.26 - 34.92
LFO2-C	1.25	1.25	10	0.01	2.66	56.97 - 59.63
LFO2-D	1.25	1.25	10	0.01	2.66	82.27 - 84.93
LFO2-E	1.25	1.25	10	0.01	2.66	110.95 - 113.61
LFO2-F	2.04	2.04	20	0.02	9.62	149.56 - 159.18
CWO1-A	2.04	2.04	10	0.01	2.8	144.56 - 147.36
CWO1-B	2.04	2.04	20	0.02	9.62	220.91 - 230.53
CWO1-C	2.04	2.04	20	0.02	9.62	329.63 - 339.25
CWO2-A	1.25	1.25	10	0.01	2.66	32.30 - 34.96
CWO2-B	1.25	1.25	10	0.01	2.66	56.75 - 59.41
CWO2-C	1.25	1.25	10	0.01	2.66	78.70 - 81.36
CWO2-D	1.25	1.25	10	0.01	2.66	103.58 - 106.24
CWO2-E	1.25	1.25	10	0.01	2.66	125.78 - 128.44

Table 2. Model parameters that were varied in the conceptual groundwater model scenarios.

Model Parameter Value	Units	Low Parameter Value	Base Model Parameter Value	High Parameter Value	Source(s) that informed model property values
Vertical hydraulic conductivity (K_v) of upper till and lower unit	feet per day	0.001	0.05	2	Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b
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	Meyer, 2015; Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b
Buried sand body (aquifer) size	mile x mile	1.0 x 0.5	3.0 x 1.5	5.0 x 2.5	Meyer, 2015
Buried sand body (aquifer) horizontal hydraulic conductivity (K_h)	feet per day	30	100	400	Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b
Thickness of upper till	feet	40	80	160	Wagner and Tipping, 2016; Witt, 2017
Total pumping rate	gallons per minute	300	900	2250	Minnesota Department of Natural Resources, 2017
Screen length and penetration of pumping wells	screen length and location in aquifer	40 foot screen in lower aquifer layer	40 foot screen in upper aquifer layer	80 foot screen across both aquifer layers (full penetration)	Minnesota Department of Health, 2017c
Kh of top model layer; Kv of of top model layer; recharge rate	feet per day; feet per day; inches per year	5.0; 0.5; 2.0	70; 7.0; 0.4	400; 40; 8.0	Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b; Witt, 2017
Transmissivity of buried sand body (aquifer); upper till Kv	feet2 per day; feet per day	4400; 0.6769	8,000; 0.05	8,990; 0.0016	Minnesota Department of Health, 2017a; Minnesota Department of Health, 2017b; Witt, 2017

Table 3. Average water-level values in each piezometer.

[ft BLS, feet below land surface; ft NAVD88, feet above North American Datum of 1988]

Piezometer Name	Average Water Level (ft NAVD88)	Average Water Level (ft BLS)
LFO1-B	1103.94	11.28
LFO1-C	1102.99	12.46
LFO1-D	1091.30	24.04
LFO1-E	1079.50	35.65
LFO1-F	1081.83	33.36
LFO2-A	1128.00	11.45
LFO2-B	1126.36	12.93
LFO2-C	1123.98	15.74
LFO2-D	1106.12	33.06
LFO2-E	1077.43	62.21
LFO2-F	1079.28	60.19
CWO2-A	1304.66	27.62
CWO2-B	1305.40	27.19
CWO2-C	1306.54	25.79
CWO2-D	1309.87	22.26
CWO2-E	1309.46	22.98
CWO1-A	1307.49	18.79
CWO1-B	1311.53	14.76
CWO1-C	1311.51	14.74

Table 4. Mean vertical hydraulic gradients between the uppermost and lowermost screens at each piezometer nest.

[ft BLS, feet below land surface; ft NAVD88, feet above North American Datum of 1988]

Site Name	**Overall Hydraulic Gradient**	**Direction**	**Upper Screen Midpoint (ft BLS)**	**Lower Screen Midpoint (ft BLS)**	**Upper Mean Water Level (ft NAVD88)**	**Lower Mean Water Level (ft NAVD88)**
LFO1	0.22	Downward	1091.49	992.88	1103.94	1081.83
LFO2	0.36	Downward	1121.00	985.01	1128.00	1079.28
CWO1/2	0.02	Upward	1298.65	991.81	1304.66	1311.51

Table 5. Mean hydraulic conductivity (K) values from slug tests, lithology, and Formation for each piezometer.
[ft/d, feet per day]

Piezometer	Mean K (ft/d)	Lithology	Formation Name
LFO1-B	4.30E+01	silty to coarse sand	New Ulm
LFO1-C	1.70E-02	till	New Ulm
LFO1-D	3.50E-01	till	New Ulm
LFO1-E	8.60E+01	till/sand and gravel	New Ulm
LFO1-F	1.70E+02	sand and gravel	New Ulm
LFO2-A	8.60E-05	till	New Ulm
LFO2-B	6.00E-04	till	New Ulm
LFO2-C	1.70E-03	till	New Ulm
LFO2-D	1.20E-05	till	New Ulm
LFO2-E	1.70E-04	till	New Ulm
LFO2-F	8.60E+01	sand and gravel	New Ulm
CWO1-A	2.60E-01	till	Cromwell
CWO1-B	1.70E+01	sand and gravel	Cromwell
CWO1-C	4.30E-01	slate	Thomson
CWO2-A	1.70E+00	sand and gravel	Cromwell
CWO2-B	6.90E-02	till	Cromwell
CWO2-C	8.60E-02	till	Cromwell
CWO2-D	8.60E-03	till	Cromwell
CWO2-E	3.50E-02	till	Cromwell

Table 6. Comparison of hydraulic conductivities determined with slug tests and aquifer tests at the Litchfield and Cromwell sites.

[<, less than]

Site	Test Type	Till Hydraulic Conductivity in feet per day		
		Minimum	Maximum	Geometric Mean
Litchfield	LFO1 slug test	0.02	0.4	0.08
	LFO2 slug test	0.00001	0.002	0.0002
	Aquifer test	<0.0001	0.02	0.001
Cromwell	CWO1/2 slug test	0.0086	0.26	0.054
	Aquifer test	0.8	4.1	1.1

Table 7. Hydraulic characteristics at sites LFO1 and LFO2 and estimated age in years, specific discharge, and estimated vertical recharge through the till at each site.

[i, hydraulic gradient; ft/s, feet per second; ft, feet; n_e, effective porosity; mi^2, square miles; in/yr, inches per year; 10^6 gallons/year, millions of gallons per year]

Site Name	Overall *i*	Till Geometric Mean (K) ft/s	x (ft)	n_e	A (mi^2)	Max Age (years)	q (in/yr)	Q (10^6 gallons/year)
LFO1	0.22	8E-07	60	0.25	3	3	8*	417
LFO2	0.36	2E-09	115	0.25	3	1054	0.34	18

*Value based on average yearly precipitation in central Minnesota.

Table 8. Relative percent sensitivity of downward flux into the buried aquifer for model parameters that were increased or decreased from the base model value.

Property	Units	Base Model Parameter Value	Adjustment Type	Adjusted Model Parameter Value	Relative Percent Sensitivity for the downward flux of water into buried aquifer
Vertical hydraulic conductivity (K_v) of upper till and lower unit	feet per day	0.05	decrease	0.001	-59.7
			increase	2	0.2
Lateral connectivity of buried aquifer to adjacent till and aquifers (represented as horizontal hydraulic conductivity [K_h] of middle unit)	feet per day	5	decrease	0.05	29.4
			increase	30	-5.4
Buried sand body (aquifer) size	square miles	4.5	decrease	0.5	-29.9
			increase	12.5	14.6
Buried sand body (aquifer) horizontal hydraulic conductivity (Kh)	feet per day	100	decrease	30	13.9
			increase	400	-1.4
Thickness of upper till	feet	80	decrease	40	13.2
			increase	160	-8
Total pumping rate (sum of 3 wells)	gallons per minute	900	decrease	300	3.5
			increase	2250	-11
Screen length and penetration of pumping wells	feet	40	different location in aquifer	40	NA
			increase	80	0

Activity 3 has been canceled

This activity has been canceled because the Minnesota Department of Natural Resources staff decided that funds were not available. There are no direct implications on the overall project or on ENRTF funds

Final Report Summary: NA

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 December 31, 2017

Status as of December 31, 2014:
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. The detailed progress proposal was approved by technical specialists from the USGS.

Status as of June 30, 2015
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.

Status as of December 31, 2015
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.

Status as of June 30, 2016

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. The following is a list of presentations made by project team member and graduate student, Alyssa Witt:

- March 7th, 2015: Presentation given at Iowa State University Graduate Student Seminar
- July 29th, 2015: Short presentation given at the Villa Vista care center in Cromwell. Villa Vista is a nursing home behind the study site.
- October 9th, 2015: Cromwell-Wright School Environmental Day: outdoor learning day for students ranging from grade 7-12. A 20-30 minute summary of the project was given to approximately 8 groups of students throughout the day.
- November 4, 2015: Poster presentation at Geological Society of America meeting in Baltimore, Maryland. Abstract available here: https://gsa.confex.com/gsa/2015AM/webprogram/Paper269887.html
- March 5, 2016: Presentation given at Iowa State University Graduate Student Seminar
- April 20, 2016: Poster presentation at spring meeting of the Minnesota Groundwater Association

An abstract about the project has been submitted for the upcoming Minnesota Water Resources Conference to be held in October 2016.

Status as of January 13, 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. The following is a list of presentations made by project team member and graduate student, Alyssa Witt:

- October 18, 2016: Oral presentation titled “Estimating Groundwater Recharge to Buried Aquifers” was given at the Minnesota Water Resources Conference in St. Paul, Minnesota. Co-authors were Jared Trost and Jim Stark of the USGS.
- November 16, 2016: Poster presentation titled “Estimating Groundwater Recharge to Buried-Valley Aquifers Underlying the Des Moines and Superior Lobes in Minnesota” was given at the Minnesota Groundwater Resources Association meeting in St. Paul, Minnesota.

Final Report Summary for Dissemination:

Publications in prep or produced:

Minnesota Department of Health, 2017a, Analysis of the Cromwell, Minnesota Well 4 (593593) Aquifer Test. Accessed November 20, 2017 at http://www.health.state.mn.us/divs/eh/water/swp/maps/testcromwell.pdf.

Minnesota Department of Health, 2017b, Analysis of the Litchfield, Minnesota Well 2 (607420) Aquifer Test. Accessed November 20, 2017 at http://www.health.state.mn.us/divs/eh/water/swp/maps/testlitchfield.pdf.

Trost, J.J., Witt, A.N., Simpkins, W., Maher, A., Stark, J., Robinson, S. Hydrologic Properties of and Infiltration Through Glacial Till Confining Units of Minnesota. U.S. Geological Survey Scientific Investigations Report. *In prep (will be published after the completion of phase 2)*

Wagner, K. and Tipping, R., 2016, Core Descriptions and Borehole Geophysics in Support of USGS Hydrologic Properties of Till Investigation, Litchfield and Cromwell, Minnesota. Accessed November 20, 2017 at ftp://mgsftp2.mngs.umn.edu/pub4/outgoing/MGS_report_in_support_of_USGS_till_study_Phase_I.pdf.

Witt, A.N., 2017, Hydrogeological and geochemical investigation of recharge (leakage) through till aquitards to buried-valley aquifers in central and northeastern Minnesota. M.S. Thesis, Iowa State University, 168 p. Will be available online eventually here: http://lib.dr.iastate.edu/etd/

Presentations at professional meetings:

Witt, A.N. and Simpkins, W.W., Investigating Groundwater Recharge to Buried Valley Aquifers in Minnesota using Pore Water Geochemistry in Till Aquitards. November 4, 2015, Geological Society of America fall meeting, Baltimore, Maryland. Abstract: https://gsa.confex.com/gsa/2015AM/webprogram/Paper269887.html

Witt, A.N. and Simpkins, W.W., Estimating Groundwater Recharge to Buried Aquifers. April 20, 2016, Minnesota Groundwater Association spring meeting, St. Paul, Minnesota.

Witt, A.N., Simpkins, W.W., Trost, J., Stark, J., Estimating Groundwater Recharge to Buried Aquifers. October 18, 2016. Minnesota Water Resources Conference, St. Paul, Minnesota

Witt, A.N., Simpkins, W.W., Estimating Groundwater Recharge to Buried-Valley Aquifers Underlying the Des Moines and Superior Lobes in Minnesota. November 16, 2016, Minnesota Ground Water Association fall meeting, St. Paul, Minnesota.

Witt, A.N., Protecting the State's Confined Drinking-Water Aquifers. July 13, 2017,Minnesota Pollution Control Agency Water Issues Talk, St. Paul, Minnesota.

Other public presentations:

Witt, A.N, Estimating Groundwater Recharge to Buried Valley Aquifers Underlying the Des Moines and Superior Lobes in Minnesota. March 7, 2015, Iowa State University Department of Geological and Atmospheric Sciences Graduate Student Seminar, Ames, Iowa.

Witt, A.N., Presentation. July 29, 2015, Villa Vista Care Center Cromwell, Minnesota.

Witt, A.N, Presentation. October 9, 2015, Cromwell-Wright School Environmental Day, Cromwell, Minnesota.

Witt, A.N, Estimating Groundwater Recharge to Buried Valley Aquifers Underlying the Des Moines and Superior Lobes in Minnesota. March 6, 2016, Iowa State University Department of Geological and Atmospheric Sciences Graduate Student Seminar, Ames, Iowa.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Explanation
Personnel:	$197,000	Studies Chief, GS13, (Project management, oversight supervision and technical review) (one person at 4%) (Benefits are 22%, Salary is 78%)-$21,100; USGS Project Chief (GS-11) (one person at 23 % FTE for 3 years, benefits are 27% salary is 73%)-$65,300; Admin Support, (2 people, each at 1.7 percent FTE for each of 3 years) (benefits are 31 %, salary is 69 %) -$9,900; USGS Hydrologic Technician (GS-11) (one person at 16% for each of 3 years) (benefits are 24%, salary is 76%)-$40,300; additional technicians (1 at 5 % FTE for 3 years, 2 at 1 % FTE for 3 years) (benefits are 24%,

		salary is 76%)-$10,300; student employee (GS5) (benefits are 18%, salary is 82%)-$20,100; USGS Groundwater Specialist: (1 person at 3% FTE for 3 years) (benefits are 24%, salary is 76%)-$15,600; USGS Water Quality Specialist (GS13) (1 person at .5 % FTE for three years),(Benefits are 27%, salary is 73%)-$1800; USGS Spatial analysis and modeling specialist, (1 person at 0.4% FTE for 3 years) (beneifts are 27%, salary is 73%)-$1,600; IT technicians (2 people at 0.5 % FTE each for 3 years) (benefits are 22%, salary is 78%)-$3,500; USGS database administrator (1 person at 2 % FTE for 3 years) (benefits are 22%, salary is 78%)-$7,500
Professional/Technical/Service Contracts:	$155,595.02	- Minnesota Geological Survey: support of glacial geologic interpretation and well siting; well cutting interpretation; analysis of fractures patterns in glacial till; stratigraphic analysis for well completing; support of hydraulic, chemical, and geophysical testing; and contributions to final report as co-authors (includes salaries, supplies, and travel) - Drilling contracts: drilling, well installation, well sealing, and abandonment. -Chemical analyses of water samples at USGS contract laboratories ($4,500)
Equipment/Tools/Supplies:	$24,562.88	Field supplies and data collection: pumps, pressure transducers, electronic recording devices, well packers, well casing, and shelters.
Travel Expenses in MN:	$14,899.65	Travel and lodging while working at field sites and attending local meetings
Other: See detailed budget	$1,942.45	Postage and shipping, expendable supplies and materials.
TOTAL ENRTF BUDGET:	**$ 394,000**	

Add or remove rows as needed

Explanation of Use of Classified Staff: Not applicable

Explanation of Capital Expenditures Greater Than $5,000: Not applicable

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.4

Number of Full-time Equivalents (FTE) Estimated to Be Funded through contracts with this ENRTF Appropriation: 0.18

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
USGS cost-share funds	$148,200	$77,280	All activities—USGS administrative and indirect costs
Total	$148,200	$77,280	

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

Name	Affiliation	Role
James Walsh *	Minnesota Department of Health	Site selection—data support
Steve Robertson *	Minnesota Department of Health	Site selection—data support
Perry Jones	United States Geological Survey	Borehole testing; report, data base
Michael Menheer	United States Geological Survey	Drilling support and data collection
Lisa Syde-Hagen	United States Geological Survey	Administrative Support
Angela Hughes	United States Geological Survey	Administrative Support
John Bumgarner	United States Geological Survey	Site selection, hydraulic testing
Tony Runkle	Minnesota Geological Survey	Glacial Stratigraphy-Hydraulic testing, Reporting
Bob Tipping	Minnesota Geological Survey	Glacial stratigraphy- Hydraulic Testing, Reporting
Jan Faltisek*	Minnesota Department of Natural Resources	Regional hydrogeological analyses

* Participation as collaborator and advisor not receiving ENRTF funding

B. 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. Finally, the LCCMR project meshes seamlessly with Activity 3 focused on compilation and mapping statewide variability in hydrogeological properties of the Des Moines and Superior Lobe confining unit using existing data. These two related efforts represent major steps toward defining the hydrogeological properties of the important protective Des Moines and Superior 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. Based on successful completion of this project, additional funding may be requested to supplement and to enhance date and information from this project.

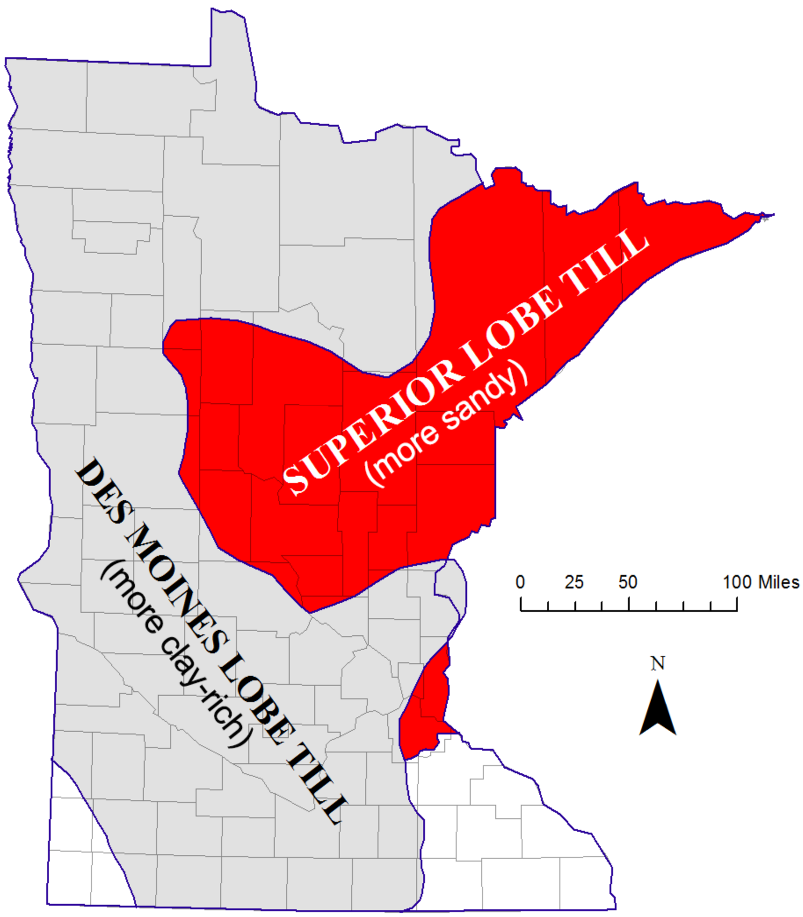
***C.* Spending History:**

Funding Source	**M.L. 2008 or FY09**	**M.L. 2009 or FY10**	**M.L. 2010 or FY11**	**M.L. 2011 or FY12-13**	**M.L. 2013 or FY14**
LCCMR-ENRTF	NA	NA	NA	NA	NA
USGS Cooperative Water Program	NA	NA	NA	NA	NA
MDNR Clean Water Fund	NA	NA	NA	NA	NA

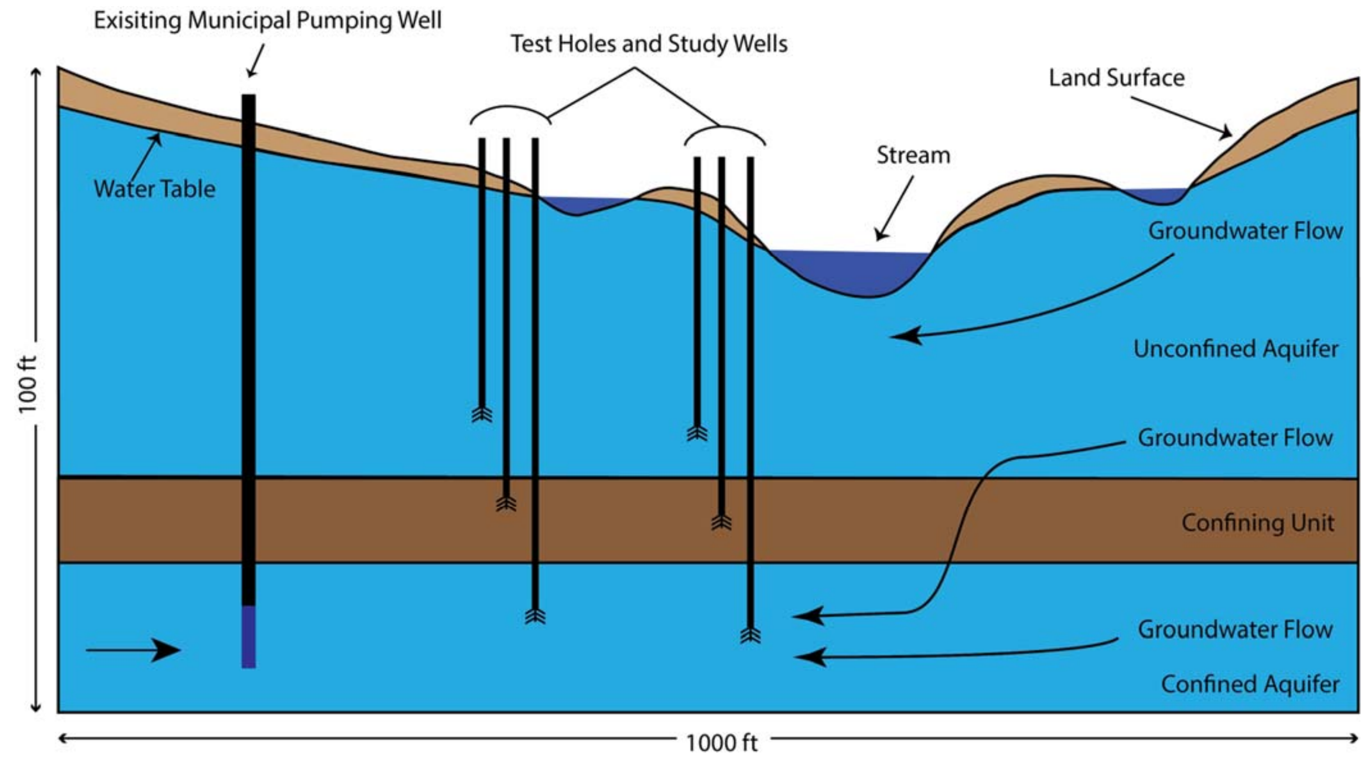
VIII. ACQUISITION/RESTORATION LIST: NA

IX. VISUAL ELEMENT or MAP(S): Shown below

Extent of Major Glacial Confining Units (Till)



Conceptualized graphic showing extent of the Des Moines lobe glacial till (gray) and the Superior lobe glacial till (red).



Conceptual model of land surface, glacial unconfined aquifer, confining unit (brown) and confined aquifer with production well.

X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: NA

XI Research Addendum: This proposal is being completed in great details. The detailed proposal will be revised based on USGS peer review comments. The proposal will then be approved by the USGS and added to this document. The expected date of proposal approval is April 30, 2014.

XII. REPORTING REQUIREMENTS:

Ti**meLine Requirements:** This project would run from July 2014 through June 2017. This timeline would include two field seasons (2015 and 2016). Quarterly written progress reports will be provided to project partners. Final reports and manuscripts will be submitted by June 30, 2017 with publication by January 1, 2018.

Period work plan status update reports will be submitted no later than 12/31/14, 06/15/15, 12/31/15, 06/30/16, and 12/31/16. A final report and associated products will be submitted between June 30 and August 15, 2017

Environment and Natural Resources Trust Fund
M.L. 2014 Project Budget

Project Title: Protection of State's Confined Drinking Water Aquifers
Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 03h
Project Manager: Jared Trost
Organization: U. S. Geological Survey.
M.L. 2014 ENRTF Appropriation: $ *394,000*
Project Length and Completion Date: 3 years--July 2014 through June 2017
Date of Report: June 30, 2017

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	**Revised Activity 1 Budget 6/16/2017**	**Amount Spent as of 6/30/2017**	**Activity 1 Balance as of 6/30/2017**	**Revised Activity 2 Budget 6/16/2017**	**Amount Spent as of 6/30/2017**	**Activity 2 Balance as of 6/30/2017**	**TOTAL BUDGET REVISED as of 6/16/2017**	**TOTAL BALANCE as of 6/30/2017**
BUDGET ITEM								
Personnel overall (wages and benefits)	$ 92,000.00	$ 92,000.00	$ -	$ 105,000.00	$ 105,000.00	$ -	$ 197,000.00	$ -
Studies Chief, GS13, (Project management, oversight supervision and technical review) (one person at 4%) (Benefits are 22%, Salary is 78%)-$21,100								
USGS Project Chief , (GS-11) (one person at 23 % FTE for 3 years, benefits are 27% salary is 73%)-$65,300								
Admin Support, (2 people, each at 1.7 percent FTE for each of 3 years) (benefits are 31 %, salary is 69 %) - $9,900								
USGS Hydrologic Technician (GS-11) (one person at 16% for each of 3 years) (benefits are 24%, salary is 76%)-$40,300; additional technicians (1 at 5 % FTE for 3 years, 2 at 1 % FTE for 3 years) (benefits are 24%, salary is 76%)-$10,300; student employee (GS5) (benefits are 18%, salary is 82%)-$20,100								
USGS Groundwater Specialist (1 person at 3% FTE for 3 years) (benefits are 24%, salary is 76%)-$15,600								
USGS Water Quality Specialist (GS13) (1 person at .5 % FTE for three years),(Benefits are 27%, salary is 73%)-$1800								
USGS Spatial analysis and modeling specialist, (1 person at 0.4% FTE for 3 years) (beneifts are 27%, salary is 73%)-$1,600								
IT technicians (2 people at 0.5 % FTE each for 3 years) (benefits are 22%, salary is 78%)-$3,500								
USGS database administrator (1 person at 2 % FTE for 3 years) (benefits are 22%, salary is 78%)-$7,500								
Professional/Technical/Service Contracts								
MGS (Minnesota Geological Survey) (staff support --Drs Runkle and Tipping). Support of glacial geologic interpretation and well siting. Well cutting interpretation. Analysis of fractures patterns in glacial till. Stratigraphic analysis for well completing. Support of hydraulic, chemical and geophysical testing. Contributions to final report as co-authors. Comment:The December 30,2015 ammendment request includes a reduction in the budget intended as contract support provided by the Minnesota Geological Survey (MGS). This request reduces the amount of support planned to be provided by MGS staff and increases staff funds for USGS staff. These conflicts could not be avoided and were work worked out successfully among MGS and USGS staff. In addition, remaining tasks assigned to MGS for this project can be completed under the current contract with the University of Minnesota.	$7,493.00	$7,493.00	$ -	$6,019.15	$6,019.15	$ -	$ 13,512.15	$ -

MGS (Minnesota Geological Survey travel, in-state) Vehicle mileage and lodging at field sites and for local meetings- Comment:(The December 30,2015 ammendment request includes a reduction in the budget for travel by the Minnesota Geological Survey (MGS). This request reduces the amount of travel support planned to be providedto MGS staff and increases travel funds for USGS staff. These conflicts could not be avoided and were work worked out successfully among MGS and USGS staff. These changes result in a budget reduction for MGS contract staff and a corresponding increase in USGS staff salary support.)	$0.00	$0.00	$ -	$0.00	$0.00	$ -	$ -	$ -
MGS (Minnesota Geological Survey) supplies for water sampling and hydraulic testing supplies and analytical costs -$1,000	$0.00	$0.00	$ -	$0	$0	$ -	$ -	$ -
Contract printing (contract fees for USGS reports: includes editing and preparation for electronic printing and distribution)- $9,000.	$0.00	$0.00	$ -	$0.00	$0.00	$ -	$ -	$ -
Contract drillers: Drilling, well installation, well sealing and abandonment. This work will be done by a private drilling contrrator through a bidding process.- $126,000.	$110,000.00	$110,000.00	$ -	$28,269.25	$28,269.25	$ -	$ 138,269.25	$0.00
USGS contract lab: chemical analyses of groundwater samples	$0.00	$0.00	$ -	$3,813.62	$3,813.62	$ -	$ 3,813.62	$ -
Equipment/Tools/Supplies: USGS miscellaneous field equipment and supplies for data collection, Pumps, pressure transducers, electronic recording devices, well packers, well casing and shelters. None of these individually exceed $5,000	$24,163.09	$24,163.09	$ -	$399.79	$0.00	$ 399.79	$ 24,562.88	$399.79
Travel expenses in Minnesota: USGS travel and lodging expense in Minnesota include mileage charges for government vehicles, lodging and meal expenses while working at field sites. Lodging and mileage expenses while attending local meetings.	$6,000.00	$6,000.00	$ -	$8,899.65	$8,899.65	$ -	$ 14,899.65	$ -
Other: USGS miscellaneous supplies, equipment and shipping. Miscellaneous required purchases, postage and FedEx shipping, expendable supplies and materials	$742.53	$742.53	$ -	$1,199.92	$1,199.92	$ -	$ 1,942.45	$ -
COLUMN TOTAL (partial)	$240,398.62	$240,398.62	$0.00	$153,601.38	$153,201.59	$399.79	$394,000.00	$399.79