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 This study was completed to give insight to the susceptibility and sustainability of the groundwater resources being withdrawn from confined aquifer systems in Minnesota.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?*

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

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 (δ^2H). 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 (^3H), and stable isotopes ($\delta^{18}O$ and δ^2H). Groundwater samples collected in May 2016 from piezometers in nest LFO1 were analyzed for enriched ^3H and stable isotopes ($\delta^{18}O$ and δ^2H) 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 δ^2H).

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 1×10^{-5} ft/d (4×10^{-6} m/d) for till. The geometric mean K values of till at LFO1 and LFO2 are 7×10^{-2} and 2×10^{-4} ft/d (2×10^{-2} and 6×10^{-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 1×10^{-2} ft/d (4×10^{-3} m/d) for till (table 5, table 6, fig. 10). The geometric mean K value for till is 6×10^{-2} ft/d (2×10^{-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.

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FIGURES

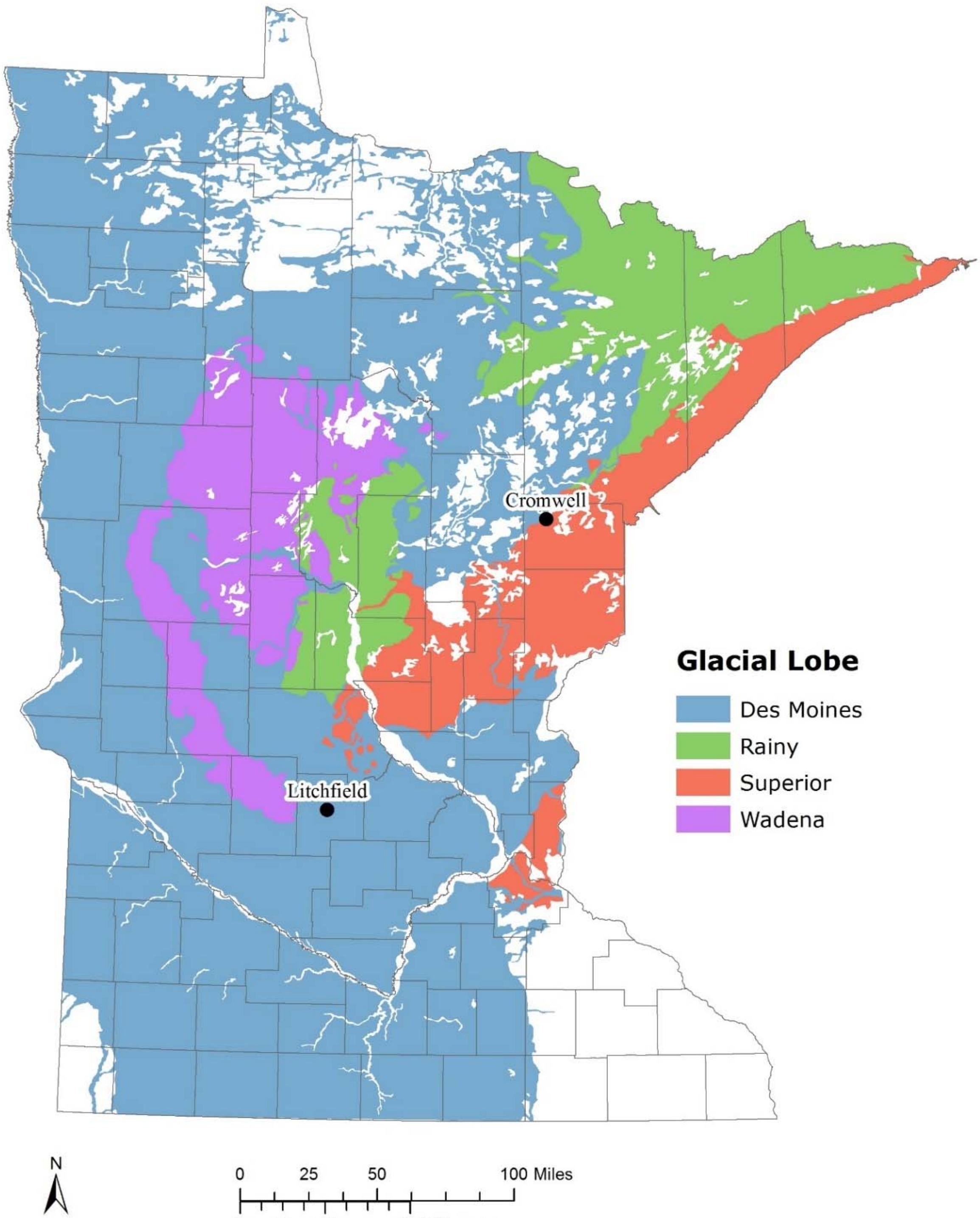

Figure 1. Map showing the extent of the major glacial lobe deposits in Minnesota (from Hobbs and Goebel, 1982) and the location of the Litchfield and Cromwell study sites.

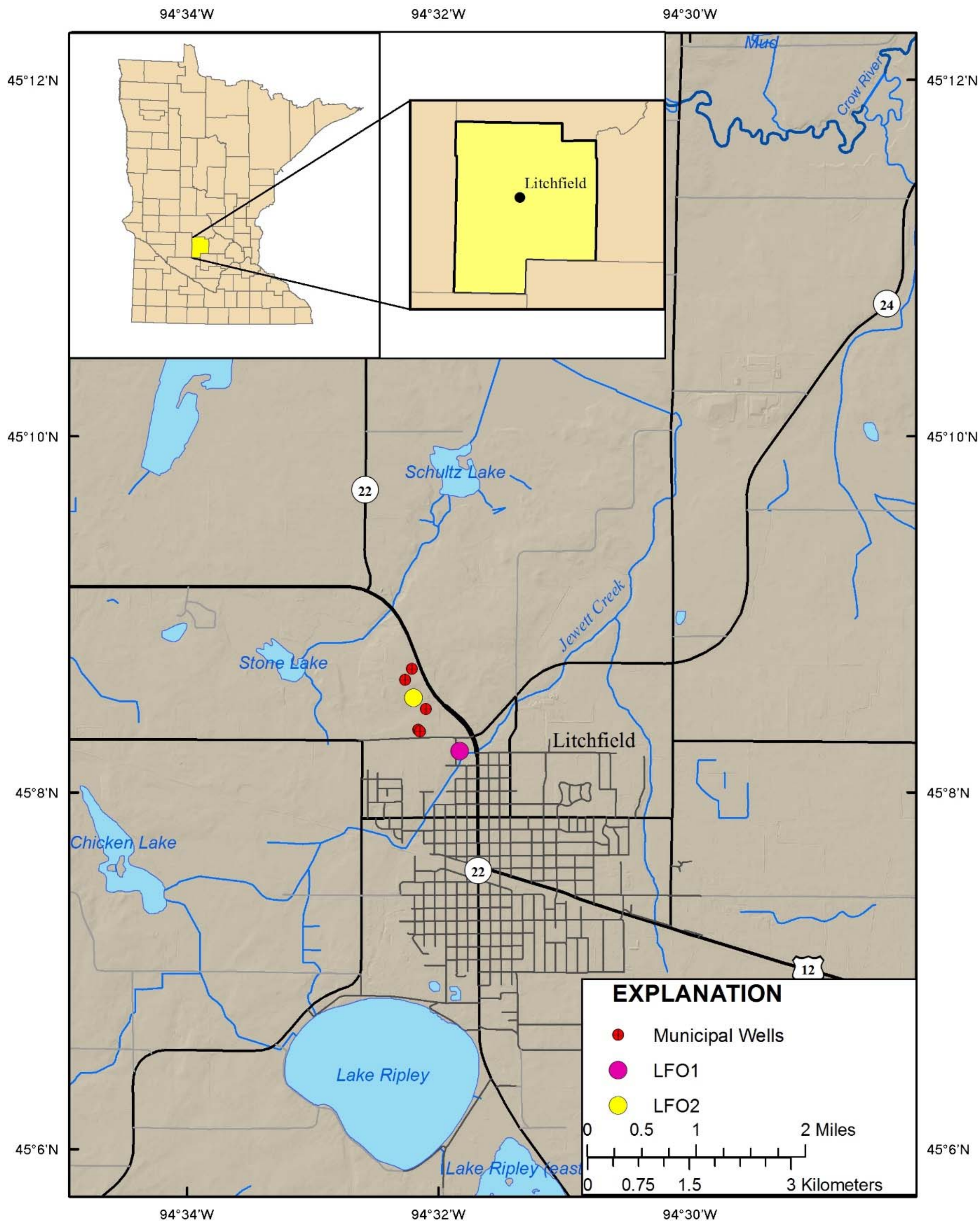

Figure 2. Map of the Litchfield study site.

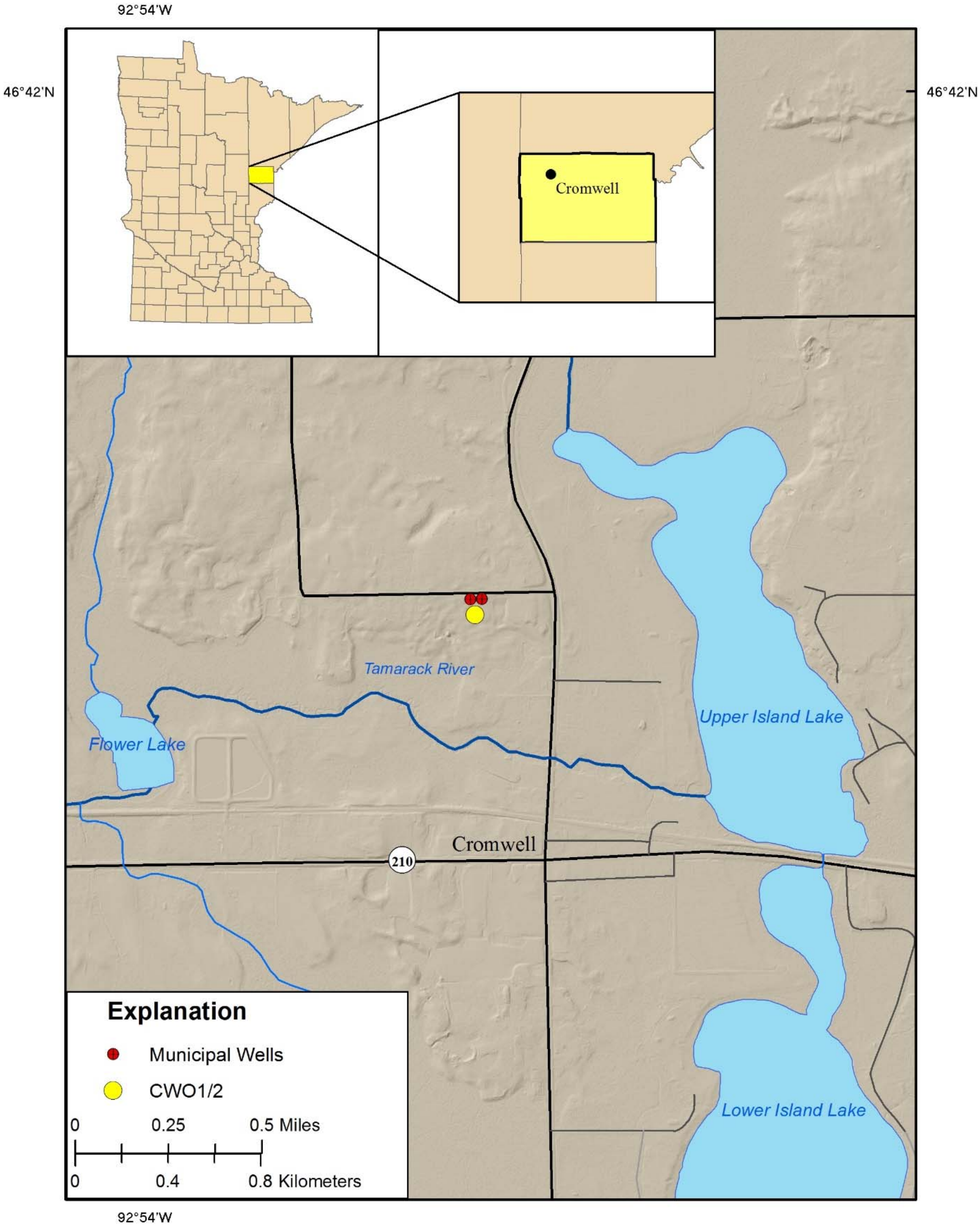

Figure 3. Map of the Cromwell study site.

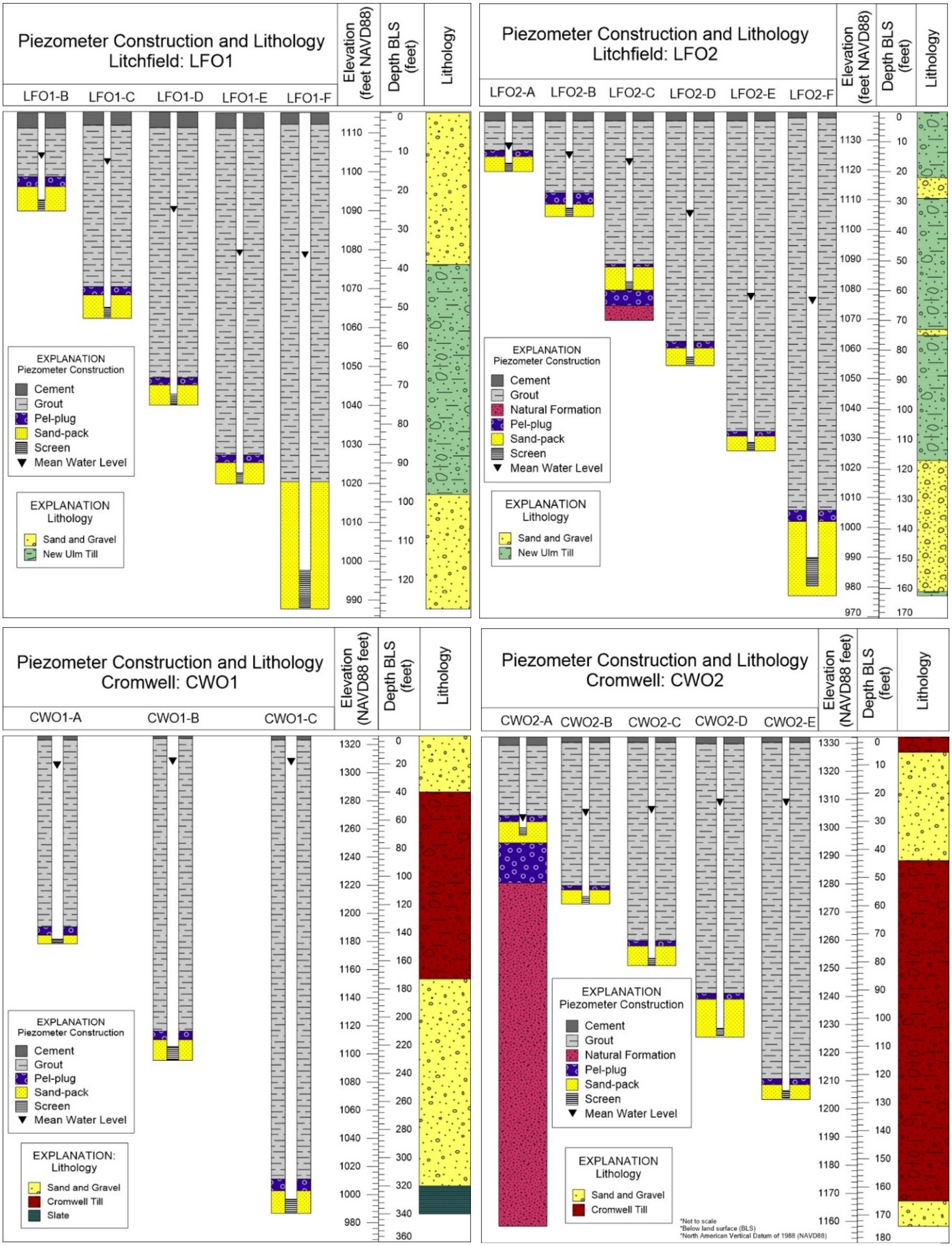

Figure 4. Piezometer construction and lithology diagrams for piezometer nests LFO1, LFO2, CWO1, and CWO2. Lithology summarized from Wagner and Tipping (2016).

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

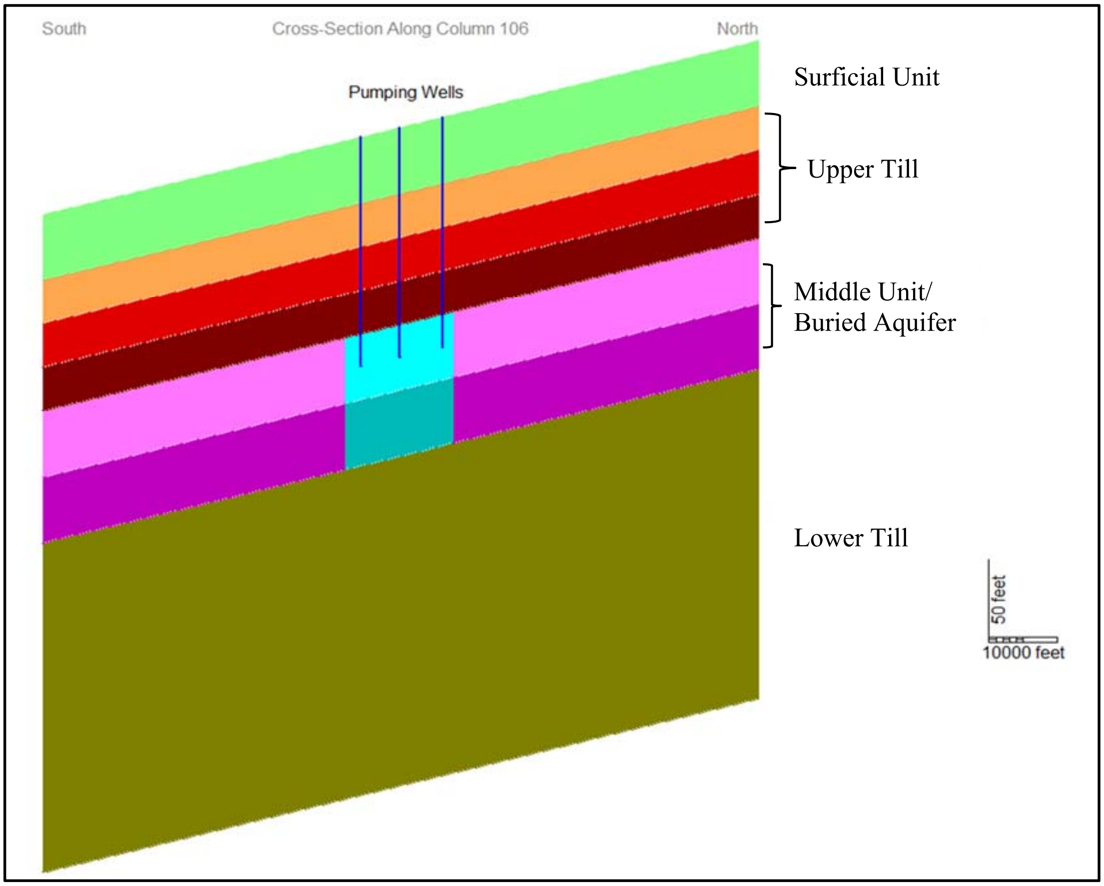

Figure 6. Cross-section view of the base conceptual groundwater-flow model.

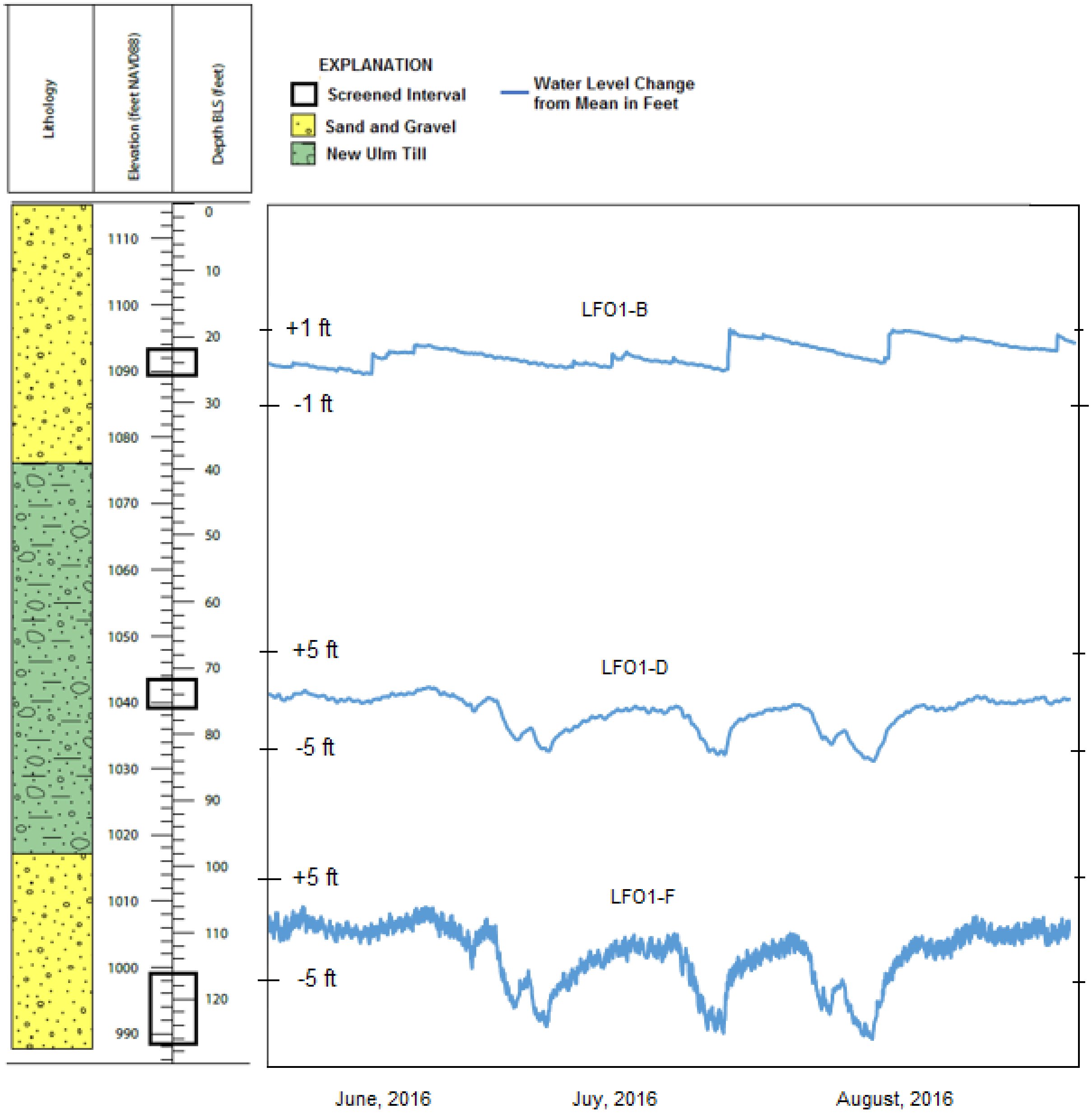

Figure 7. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Litchfield nest LFO1. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for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

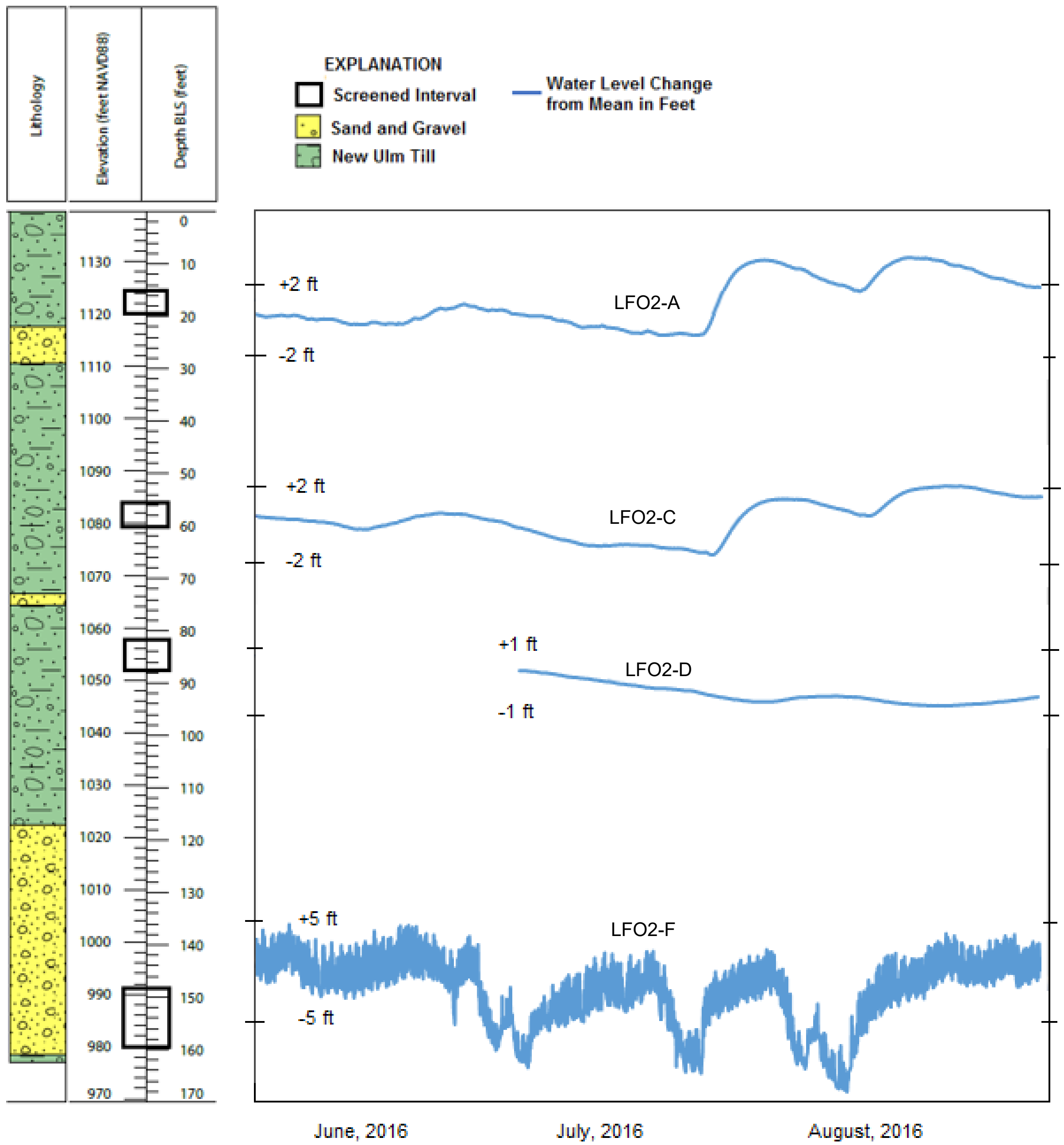

Figure 8. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Litchfield nest LFO2. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for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

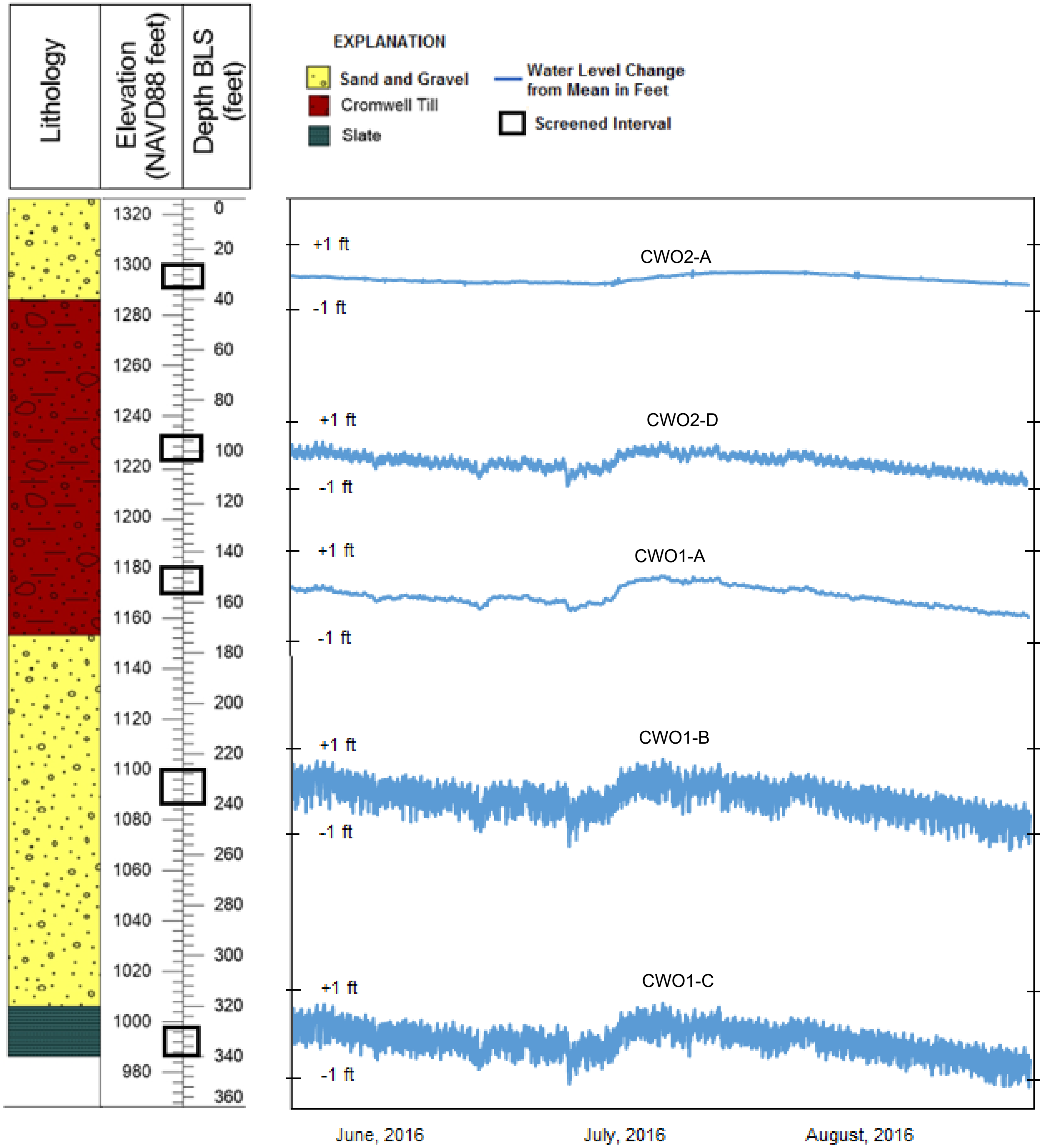

Figure 9. Lithology, screened intervals, and water level anomalies for piezometers containing transducers in Cromwell nest CWO1/2. Water-level anomalies are hourly measurement minus the long-term mean of each piezometer. Note that the scales differ by piezometer; this plot is intended to be used for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

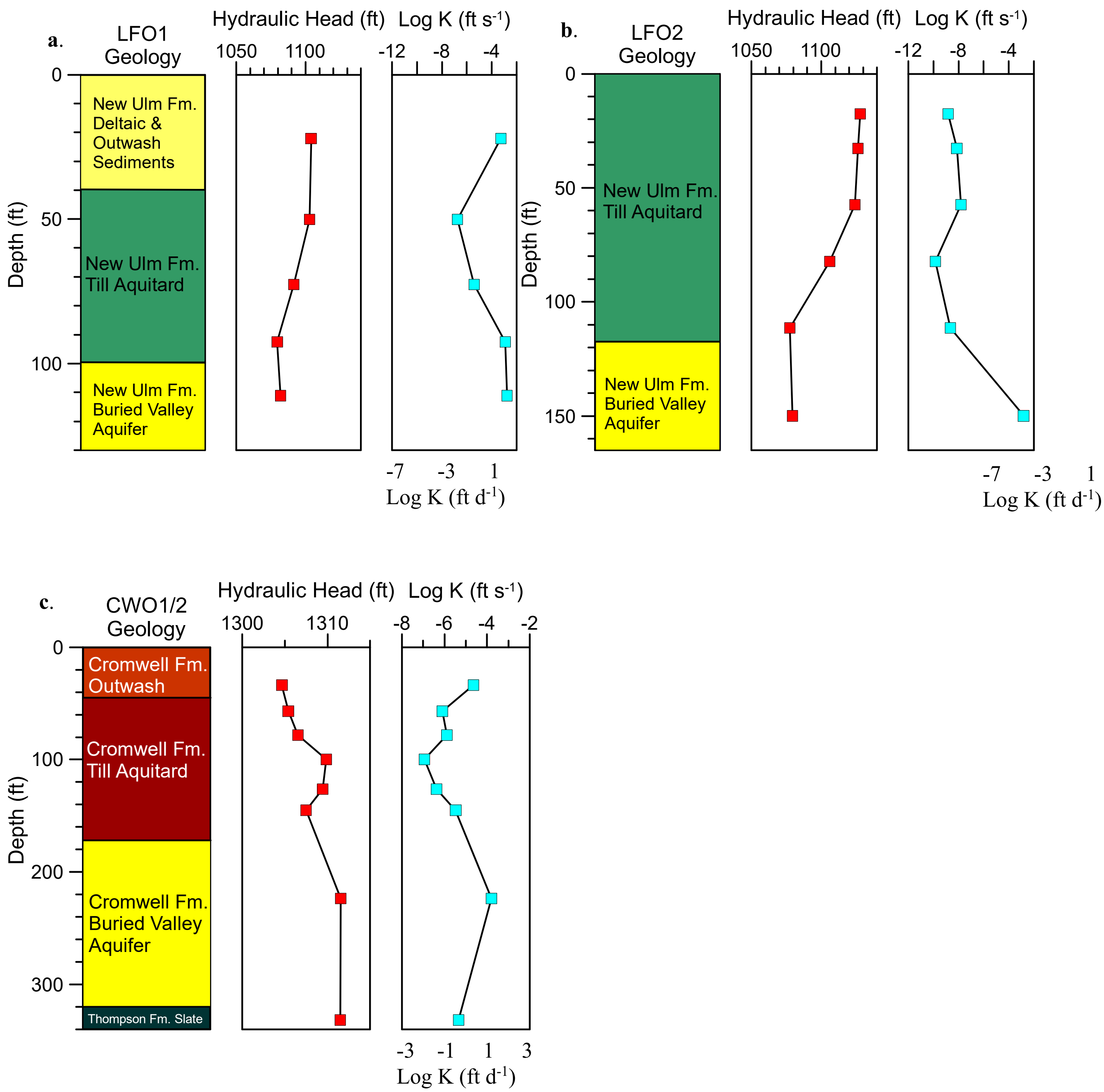

Figure 10. Generalized lithology, hydraulic head, and hydraulic conductivity (K) with depth at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and (c) Cromwell piezometer nest CWO1/2.

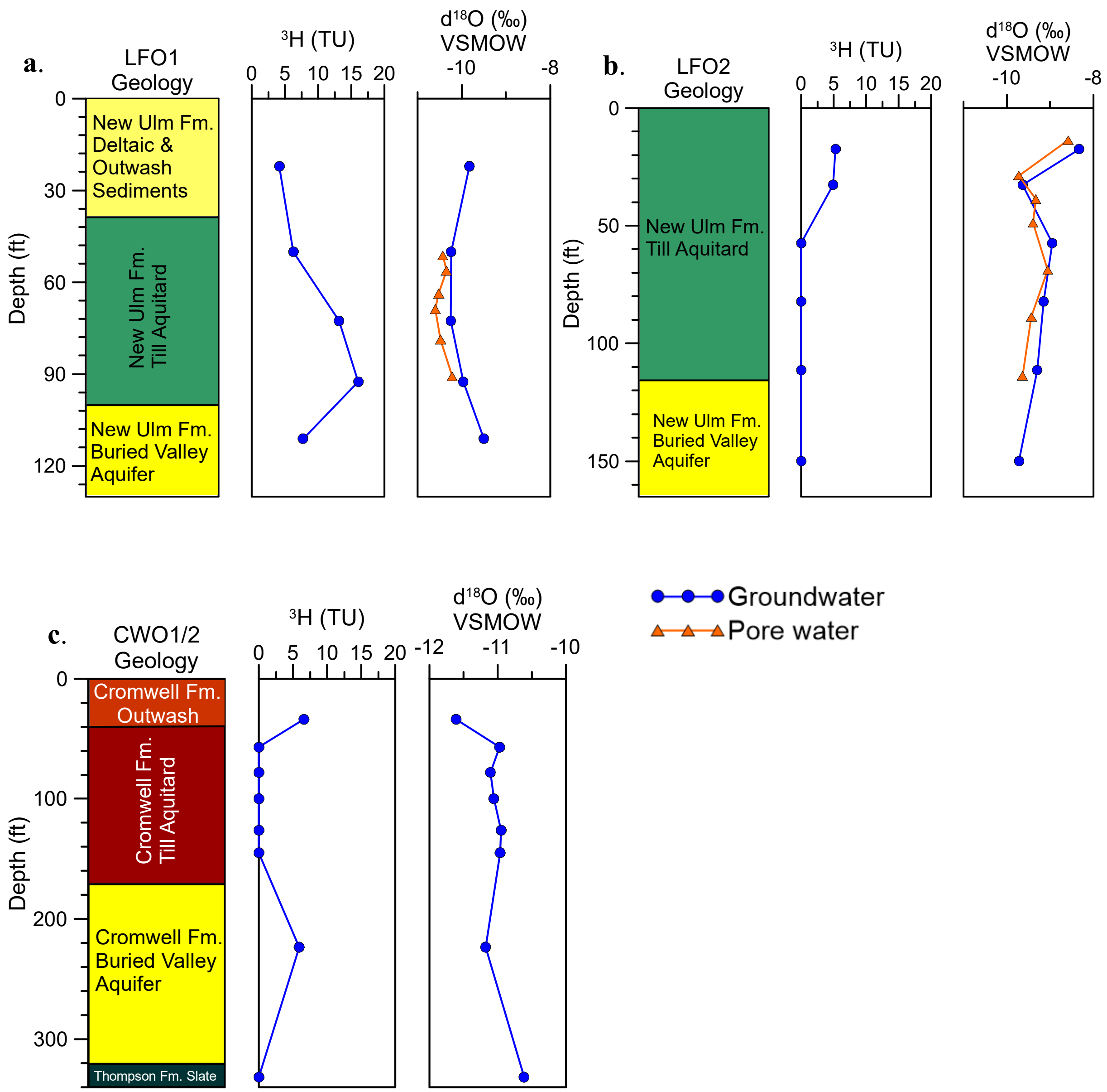

Figure 11. Generalized lithology and enriched tritium (^3H) and oxygen isotope (^{18}O) profiles determined from groundwater and pore-water samples at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and (c) Cromwell piezometer nest CWO1/2.

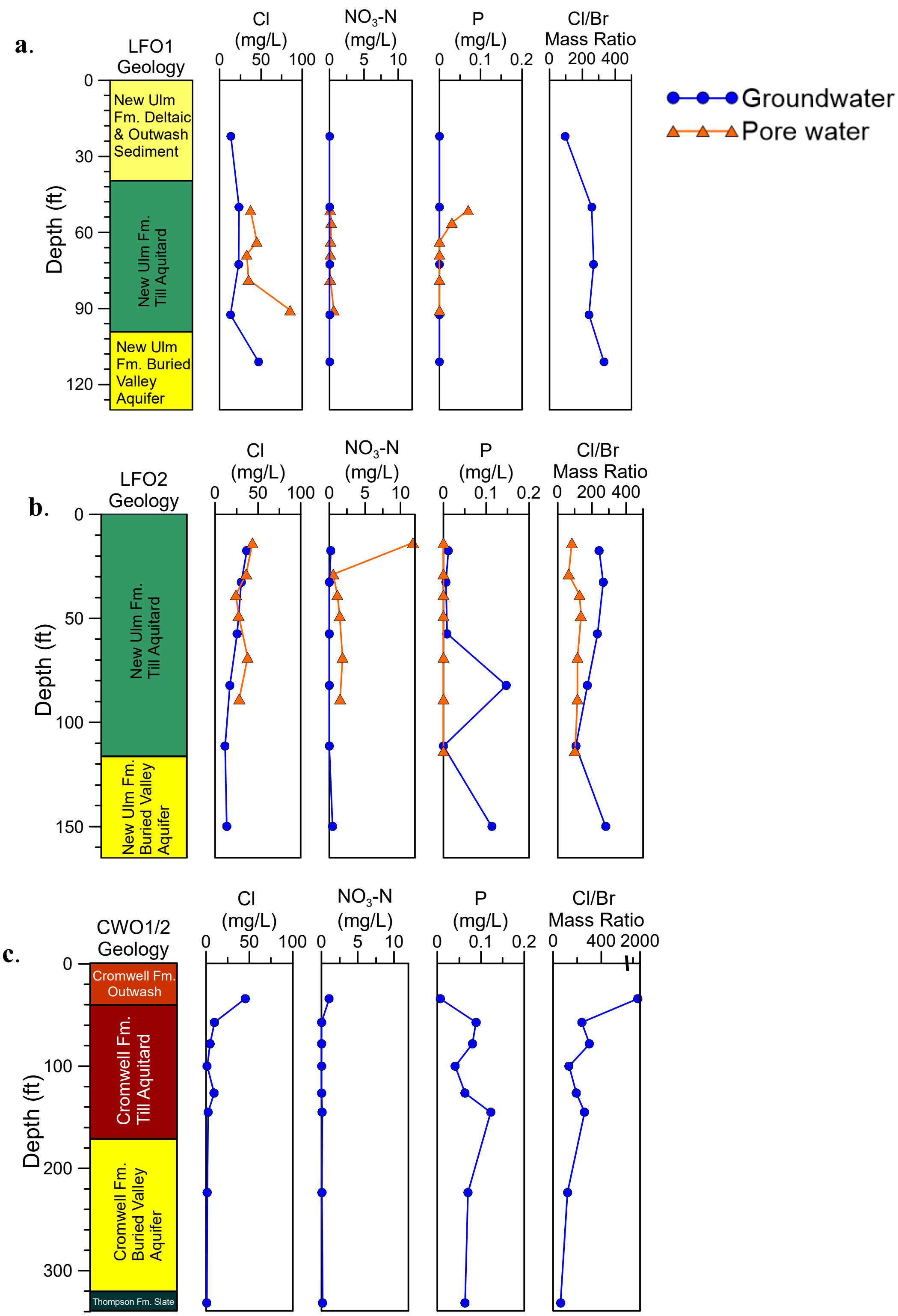

Figure 12. Generalized lithology, chloride (Cl) concentrations, nitrate (NO3) concentrations, phosphorus (P) concentrations, and chloride to bromide (Cl/Br) mass ratios determined from groundwater and pore-water samples at (a) Litchfield piezometer nest LFO1, (b) Litchfield piezometer nest LFO2, and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

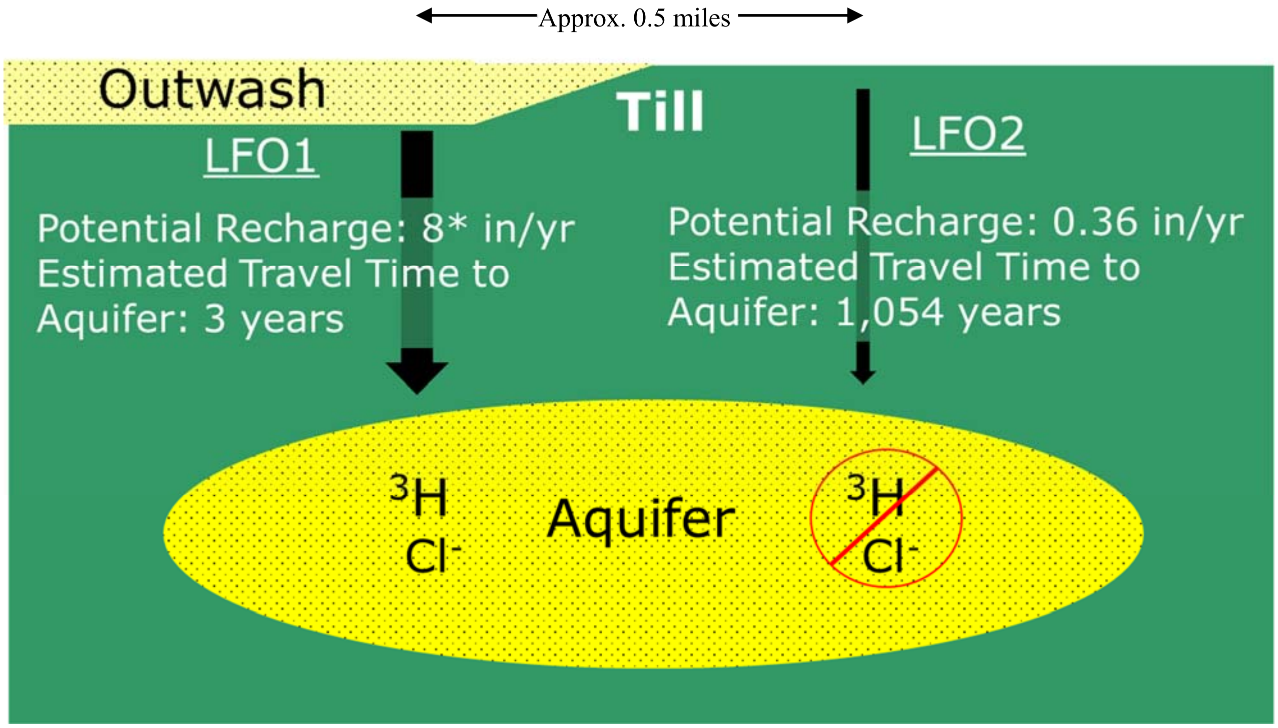

Figure 13. Graphical summary depicting the geologic, hydraulic, and geochemical results from piezometer nests LFO1 and LFO2 at the Litchfield, Minnesota study site. Chloride (Cl^-) and tritium (^3H) presence is indicated. [in/yr, inches per year]

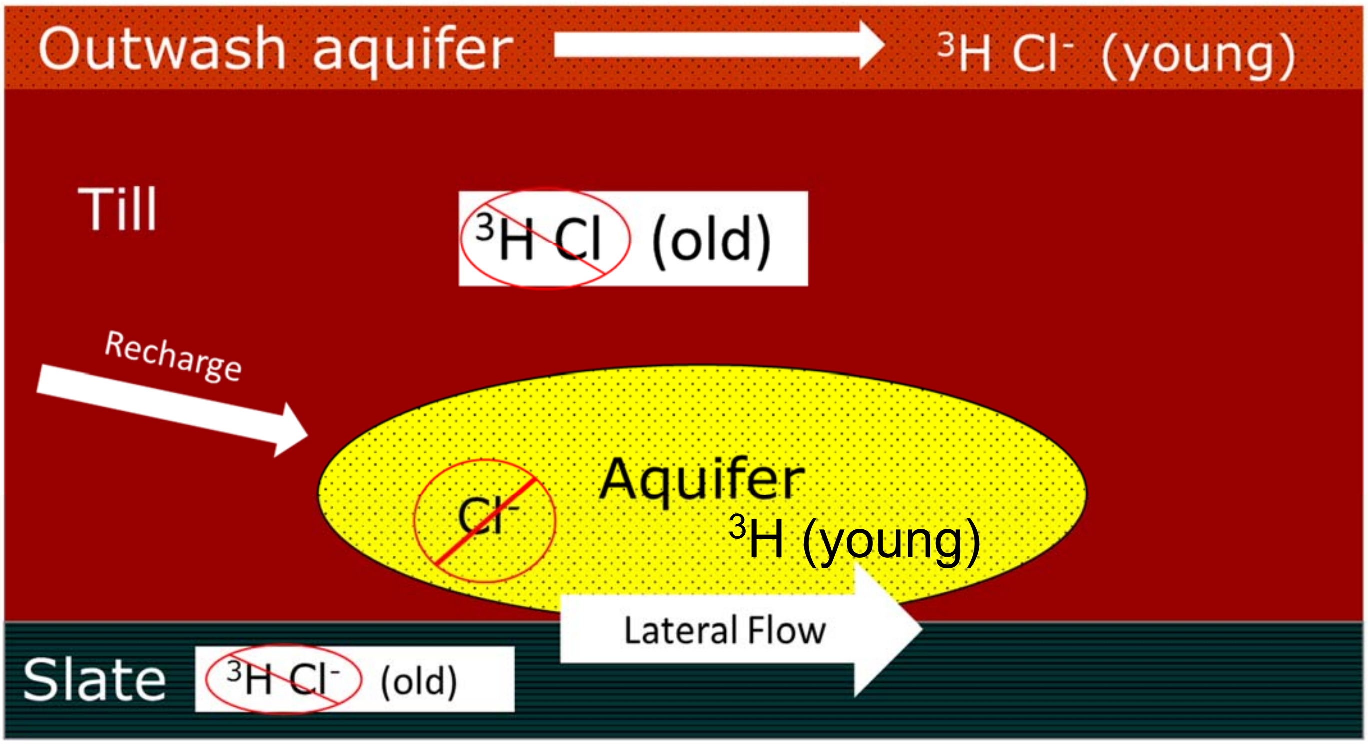

Figure 14. Graphical summary depicting the geologic, hydraulic, and geochemical results from piezometer nest CWO1/2 at the Cromwell, Minnesota study site. Chloride (Cl^-) and tritium (^3H) presence is indicated. Young and old refer to the apparent age of the groundwater based on tritium and chloride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

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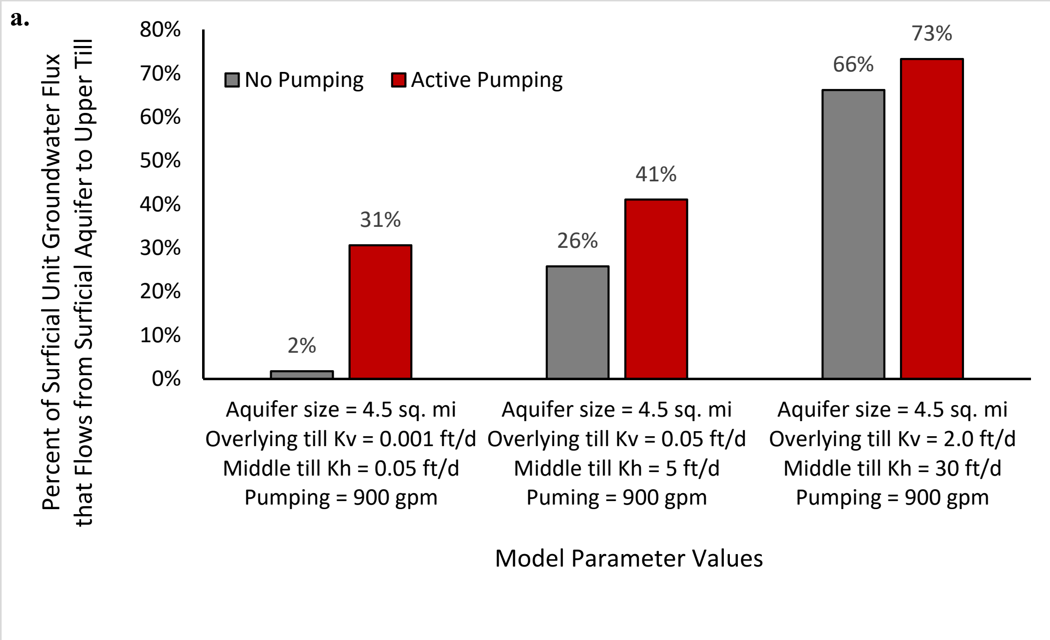


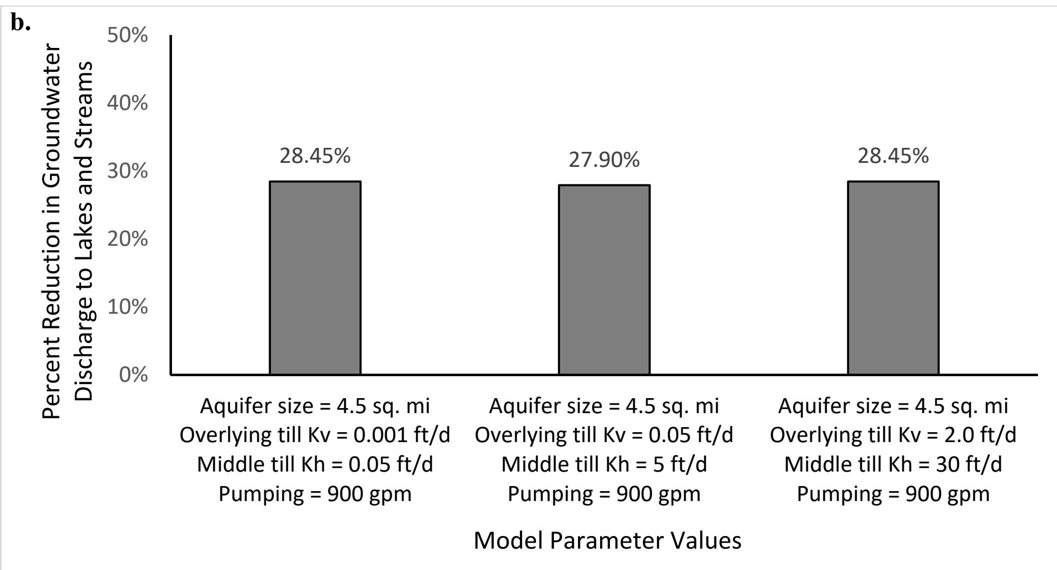


Figure 15. Bar graph of conceptual model output showing (a) the percent of groundwater recharge in the surficial aquifer (layer 1) that flows to the upper till unit (layer 2) under ambient and active pumping conditions. This graph shows the range of leakage with variations in aquifer size (sq. mi = square 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.

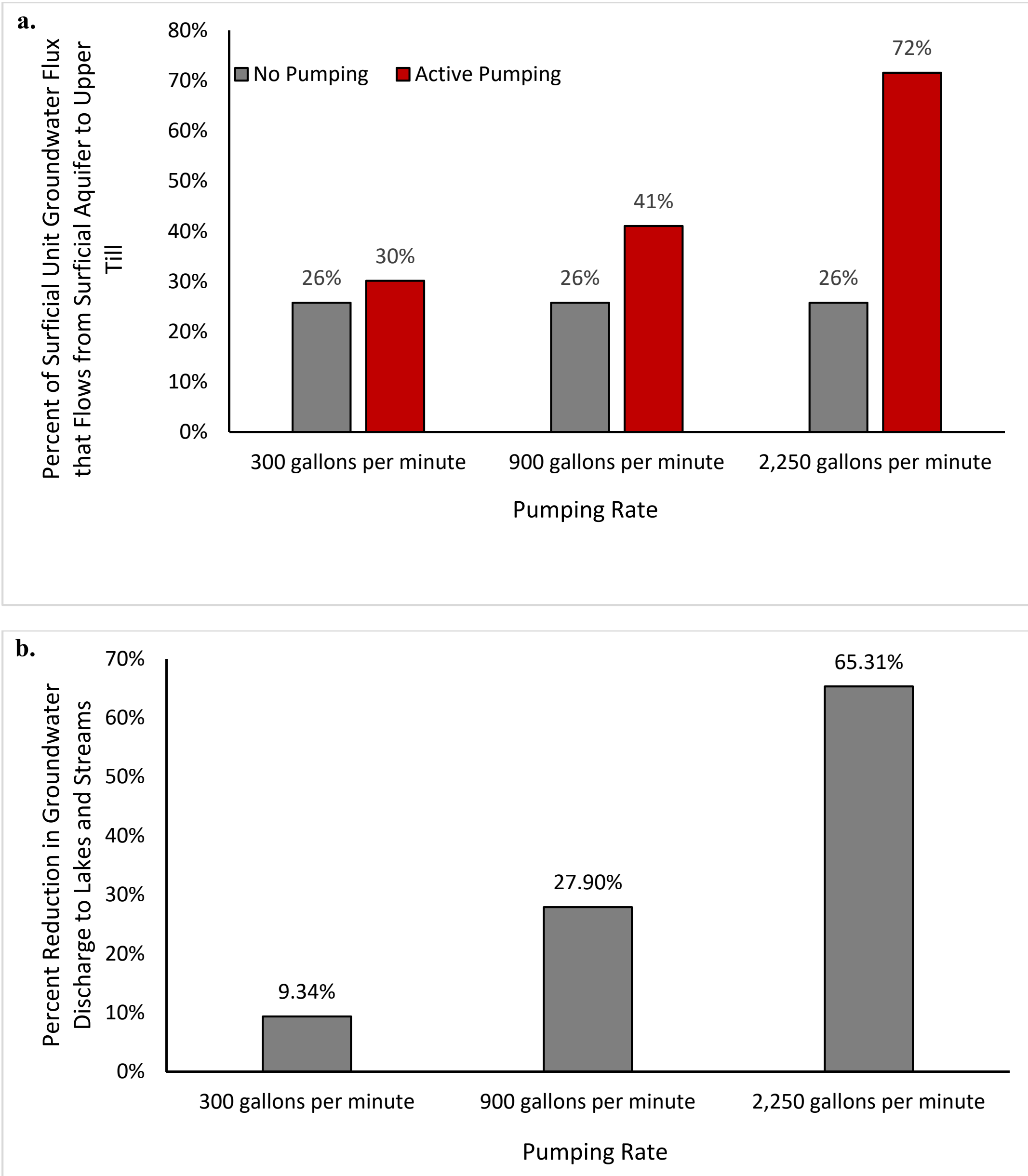


Figure 16. Bar graph of conceptual model output showing (a) the percent of groundwater recharge in the surficial aquifer (layer 1) that flows to the upper till unit (layer 2) under ambient and active pumping conditions. The leakage was determined within the 25-square mile local area shown in figure 5. 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.

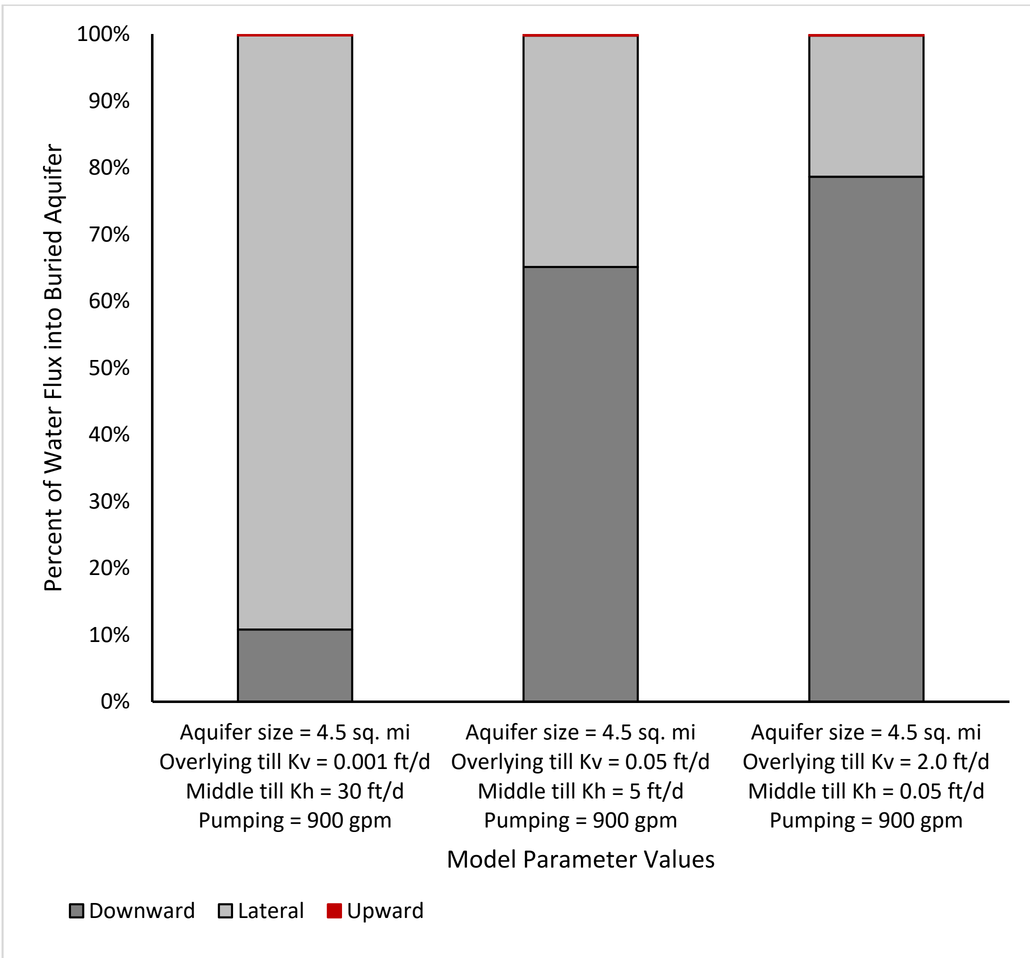


Figure 17. Bar graph of conceptual model output showing the percent of water entering the buried aquifer via downward flux from above, lateral flux from the sides, and upward flux from below. This graph shows the range of source water to wells due to variations in aquifer size (sq. mi = square miles),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

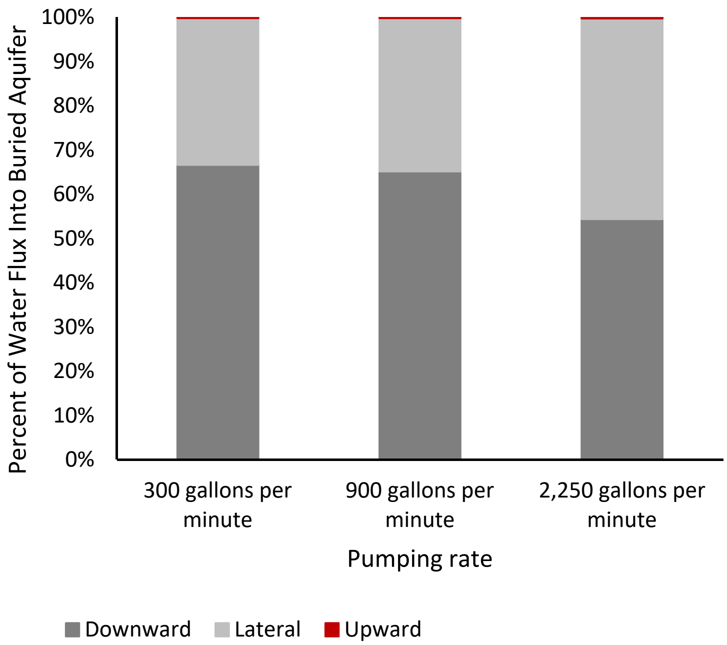


Figure 18. Bar graph of conceptual model output showing the percent of water entering the buried aquifer via downward flux from above, lateral flux from the sides, and upward flux from below with different pumping rates. All non-pumping model parameters were the base model values, as listed in table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

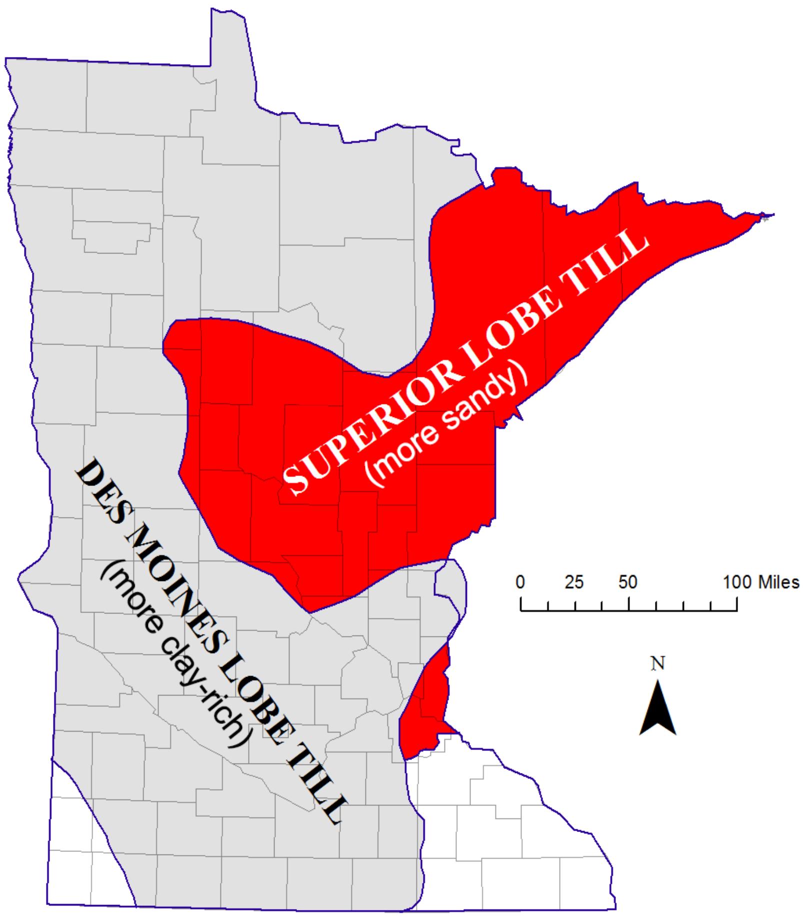
C. **Spending History:**

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

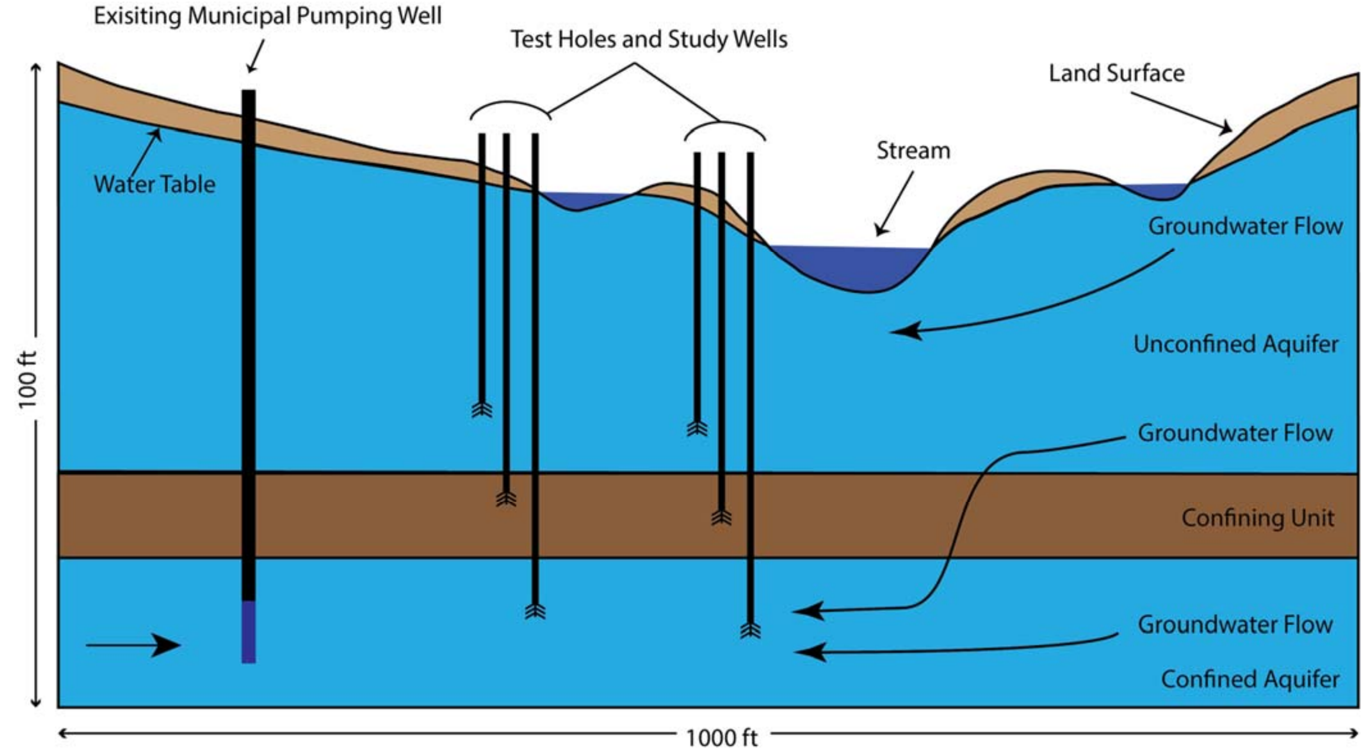
VIII. ACQUISITION/RESTORATION LIST: NA

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

Analysis of the Cromwell, Minnesota Well 4 (593593) Aquifer Test

CONDUCTED ON MAY 24, 2017

CONFINED QUATERNARY GLACIAL-FLUVIAL SAND AQUIFER

DEPARTMENT OF HEALTH

Analysis of the Cromwell, Minnesota Well 4 (593593) Aquifer Test Conducted on May 24, 2017

Minnesota Department of Health, Source Water Protection Program
PO Box 64975
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To obtain this information in a different format, call: 651-201-4700.

Upon request, this material will be made available in an alternative format such as large print, Braille or audio recording. Printed on recycled paper.

Contents

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Data Collection and Analysis

The constant-rate aquifer test performed at Cromwell 4 (593593) was conducted as described below. The test results are summarized in Table 1. The specifics of test location, scope, and timing are presented in Table 2, Table 3, and Table 4. Data were analyzed using standard methods cited in references. Individual analyses are presented the Figures 1-25 and are summarized in Table 5 and Table 6. Figures 26-44 include maps, comparison of manual and electronic data, and any other test documentation. Records of well construction are contained in Figures 45-54.

Description

Purpose of Test

The test of Cromwell 4 was conducted by the Minnesota Department of Health (MDH) Source Water Protection Unit as a small part of a longer-term project led by the United States Geological Survey (USGS). The overall purpose of the study is to assess the rates of groundwater recharge through low-conductivity glacial sediments at various sites in Minnesota.

Specific to Cromwell, eight observation wells were installed by the USGS in 2015. Water elevations were recorded on a one-hour interval in five of these wells for approximately one-year. The USGS had completed its data collection and was preparing to seal the observation wells. Prior to sealing the wells, notification was provided to the partner agencies relative to the completion of the work. At that time, staff in the Source Water Protection Unit recognized that this configuration of observation wells is nearly ideal for conducting a short-term constant-rate aquifer test that is designed to estimate vertical groundwater flow induced by pumping. Therefore prior to sealing the wells, MDH proposed to conduct tests that would complement the USGS data collection efforts.

Well Inventory

The well records are presented in Figures 45-54 and the well construction is summarized in Table 2. Detailed site plans are shown in Figure 26 and Figure 27.

Hydrogeologic Setting

These records were used to assess the hydrogeologic setting and identify the appropriate conceptual model for data analysis. A schematic section through the test site is shown on Figure 28 to illustrate the three layers that comprise the flow system; water table, aquitard, aquifer, and the construction of wells within these layers.

Other Interfering Wells

No other high capacity wells exist in the area to cause interference.

Test Setup

The USGS provided the pressure transducers and data loggers used for long-term monitoring, re-programmed to a one-minute interval. MDH hydrologists, Tracy Lund and Justin Blum, traveled to Cromwell on May 18, 2017 to assess site conditions and re-install the transducers to collect background water level and barometric data. At that time, the flowmeter-totalizer had been removed for cleaning and calibration. Mr. Tom Johnson, the water operator, indicated that the flowmeter would be returned to service shortly and the test was tentatively scheduled to begin on May 23, 2017.

Access to Cromwell 3 (519761) is restricted and the only means to measure the water level is via a bubbler-line. A transducer could be placed in Cromwell 4 to monitor water levels. A prior test of Cromwell 3 was conducted by the MDH in 2001. The location of the obwell nests relative to the PWS wells is slightly closer to Cromwell 4 than 3. The obwells constructed in the till are within 60 feet of Well 4 and are therefore more likely to respond to pumping. Because of these factors; access to the wells, prior tests, and the relative distance of the well nests, caused Cromwell 4 to be preferred for testing.

After the flowmeter was reinstalled, MDH staff mobilized for the test on May 24, 2017, arriving on-site at 10:00. The flow monitoring equipment and pump controls were inspected with the operator. Discussions with the operator indicated that the system demand is much smaller than the capacity of the well and water will have to be wasted during the 24-hour pumping phase. He considered putting a discharge control on one of the hydrants to drain the excess but opted to let the tower fill and overflow to the established drain. This presented no flooding or erosion hazard and did not require monitoring for concerns of public safety.

An MDH pressure transducer was installed in Cromwell 4; programmed to a 20 second interval, and scheduled to begin data collection 5/24/2017 at 12:00. Static levels were collected from all accessible wells prior to beginning the test. A transducer (in-line with a compressor) was attached to the Cromwell Well 3 bubbler-line to attempt to collect water levels.

Weather Conditions

Conditions were cool and rainy during background data collection. No appreciable precipitation occurred during pumping and recovery.

Discharge Monitoring

The totalizing flow meter was read manually to document the pumping rate. The operator flushed hydrants between 12:30 and 15:00, early in the pumping phase, putting some of the excess water to productive use.

Data Collection

The pump was started at 12:10:04 on 5/24/2017 by hand control. The compressor/transducer setup on Well 3 did not collect usable data. Water levels were collected manually from the accessible wells and data were downloaded to check the operation of the transducers.

It was found that the transducer in well USGS 2-E (773064) was set too deep in the well and did not collect usable data during background and early pumping. The submergence of the transducer was adjusted and a static collected at 15:30. Data collected after about 280 minutes of pumping (~18:00 on 5/24/2017) are valid. The transducers in all other observation wells appeared to functioning properly.

In the morning of 5/25/2017 distances from the pumped well to the observation wells and other features visible on aerial photos were measured with fiberglass tape. Data were downloaded from the transducers prior to end of pumping/start of recovery. Recovery began at 12:25:00 5/25/2017.

During the recovery period, over the Memorial Day weekend, the water operator agreed to manipulate the pump controls is such a way that Well 4 would not be pumped and Well 3 would be used to meet demand. Normal operation is to alternate the wells, accomplished by an automatic switch in the pump controls. Bypass of the switch provided data from short-term pumping of Well 3 to compare to that from the test of Well 4, just completed, see test 2613.

Data were downloaded on 5/30/2017 and water levels measured. The recovery-phase data from USGS 1-A was lost during the download process. Also, inspection of the data from Well 4 showed that the hydrant flushing caused anomalous changes in water level in the early part of the pumping-phase. Because of these problems, it was decided to perform a second, short-term constant-rate test, of Well 4 to attempt to collect additional early-time data from the pumped well and USGS 1-A. This test was run the same way as the earlier constant-rate test but for an abbreviated pumping period (345 minutes) with an overnight recovery. The final water levels were measured on 5/31/2017 and the equipment removed from the wells. Results of this short-term test are described in a separate document, see test 2619.

Qualitative Aquifer Hydraulic Response

Detailed site plans are shown in Figure 26 and Figure 27, identifying the wells and distances between the wells. A schematic cross section is provided for visual context of the test conditions, Figure 28. Comparison of manual and transducer data are shown Figure 29 through Figure 37. All but one well showed a response to pumping. USGS 2-A, constructed in the water table aquifer showed no response, as expected. The groundwater gradient is upward under 'static conditions,' including typical pumping to meet the system demand, Figure 38. The ambient difference in water elevation across the till at the well site is approximately 8.4 feet. Comparisons of water elevations between wells at the nests are shown on Figure 39 and Figure 40. From these comparisons, the more intensive pumping of this constant-rate test temporarily reversed the gradient within a short distance from the pumped well (~10 feet) and generated a strong signal for analysis of hydraulic properties.

The water elevations appear to trend upward over the data collection period. No appreciable change in water level can be attributed to changes in barometric pressure, Figure 41. The trend of the increase in water level shown on Figure 37was removed prior to analysis.

The only truly anomalous hydraulic responses were seen in wells USGS 2-B and 2-C, Figure 34 and Figure 35, respectively. These wells showed consistent, transient, reverse water level variation with the start of pumping of either Cromwell 3 or 4; conditions under which elevations would be expected to decrease. The reverse water variation also occurred at the end of the Cromwell 4 pumping phase. The magnitude of the response was about 0.1 foot and dissipated within about twenty minutes of the change in conditions. This phenomenon has been described in the literature as a poro-elastic response, Wolf (1970). Reverse water level fluctuations are characteristic of wells constructed in materials with a low conductivity and high elasticity (clay) that are in contact with materials of high conductivity and high compressive strength (sand). This condition is rarely observed and is the first time that it has been encountered (that we are aware of) in Minnesota. Because of this poro-elastic response, data from these wells are considered to be most representative of conditions within the till, relative to the response of other wells in this nest.

Within the aquifer itself, the simplifying assumptions of commonly used analysis techniques consider the movement of groundwater induced by pumping to be exclusively horizontal. In the case of this analysis, vertical head differences within the aquifer within 200 feet of the pumped well cannot be neglected. The pumping well is constructed with a twenty-foot screen, centered 55 feet below the top of the sand and gravel aquifer. The total thickness of the aquifer in this location is 145 feet. This type of well construction where the aquifer is screened over only a portion of the whole thickness is known as 'partially penetrating.' Because of this well construction, within small radial distances (tens of feet) from the pumped well, groundwater flow is spherical rather than horizontal; transitioning to horizontal with increasing radial distance. The rule of thumb (Hantush, 1964) for estimation of the radial distance at which this transition to horizontal flow is complete:

$$\mathrm{r_h} = 1.5 * (aquifer\ thickness) * (\frac{horizontal\ conductivity}{vertical\ conductivity})^{0.5}$$

Given the geometry of aquifer materials and well construction at this site; and, if there is no difference between horizontal and vertical hydraulic conductivity, then the minimum distance to the transition to horizontal flow is 217 feet. [In fluvial sediments, the vertical conductivity is normally smaller than the horizontal conductivity – increasing differences between these conductivities will produce a progressively larger radial distance of transition.] Both well nests are within this minimum distance and therefore the effects of partial penetration should be expected to be present.

The partially penetrating condition was verified in Aqtesolv, Figure 42, as being the result of spherical flow by the similarity of the slope of data to the diagnostic curve. A non-Theisian response was also seen by the approximate unit-slope of early-time data USGS 1-B, on a log-log plot before 200 minutes, Figure 43. The portion of the transient response before 200 minutes, dominated by spherical flow, should not be used for analysis by methods that do not incorporate partial-penetration.

An additional consideration for the analysis of aquifer properties is the decrease in conductivity at the top of a layer resulting from fluvial depositional processes. This is typically described as the 'fining upward' distribution of gain-size when looking at layers of sediment in cross-section. Because of this tendency, it is expected that the conductivity of the material at the top of the aquifer would be smaller than that at the level of the pumped-well screen or at the base of the aquifer.

This expectation is consistent with the remarkable similarity of the observed hydraulic response of USGS 1-B and 1-C, in the middle and at the base of the aquifer, Figure 43 and Figure 44. The similarity of response indicates a negligible contrast in horizontal and vertical conductivities for middle to lower parts of the aquifer. With regard to the response at the top of the aquifer, a smaller conductivity normally implies a larger drawdown. However, the drawdown at the top of the aquifer cannot be greater than that observed at USGS 1-B, at the level of the pumped-well screen within the aquifer. This represents a bounding condition on estimates of drawdown, useful to inform the analysis.

Quantitative Analysis

Typically, an aquifer test characterizes the hydraulic properties of aquifer materials and if additional information can be extracted relative to the bounding aquitards; it is generally considered a 'bonus.' However, the primary question for this project is the assessment of the vertical movement of water in the till. Therefore, the goals of this project require a different approach.

The difference in water pressure across the aquitard drives the leakage through the till. The pressure at the top of the aquitard is well documented (USGS 2-A); but, is unknown at the base of the aquitard/top of aquifer. The uncertainty is the result of the effects of the partially-penetrating pumping well. Consequently, uncertainty in the drawdown at the boundary between the aquifer and till causes uncertainty in the leakage rate. Because of these complications, the analysis must proceed in stages and must be checked at each stage for consistency with the conceptual model of a partially penetrating well in a leaky-layered system.

The analysis process is broken into parts or steps that use different groups of wells to focus on how the aquifer works (conceptual models). Steps 1 through 4 lead to an assessment of representative (bulk) properties of the aquifer and aquitard. Step 5 is the analysis by the Neuman-Witherspoon method that emphasizes the impact of lithological variation within the till on hydraulic response and estimated aquifer properties. These different views of the data and how the aquifer works must converge to a set of relatively consistent aquifer properties for there to be some confidence in the test results.

Transient-Horizontal Flow

The hydraulics of a partially-penetrating pumping well has been developed in the literature with several published solutions. Some of these solutions have been implemented in the commercial aquifer test analysis software, Aqtesolv, (Duffield, 2007). This tool was used to simulate the aquifer response by a method that includes partial-penetration and leakage, a solution referenced to Hantush-Jacob (1955).

The base data set for the simulation included data from the pumped well and USGS 1-B. The goal of these simulations was to solve for reasonable aquifer properties and predict the drawdowns at the nest locations at the base of the till/top of the aquifer. The drawdown was simulated as 'virtual piezometers' at these locations. The solutions from these analyses uniformly produced very large transmissivity, small storativity, and large leakage factor, Figure 1. Well USGS 1-C was included in the solution shown on Figure 2. These simulations were not judged to be realistic because drawdowns at the virtual piezometers were uniformly smaller than that predicted by the response of the USGS obwells. It was found that inclusion of data from the pumped well was forcing an inappropriate solution.

The analysis based on data from only USGS 1-B is considered to be most reasonable to begin this process, Figure 3. This analysis produced aquifer properties that are in the reasonable range for transmissivity and storativity; including a vertical/horizontal conductivity ratio of ~0.5 and a leakage factor of ~360 feet (1/B = 2.8e-3). As the focus of this analysis is the properties of the till, the conductivity ratio and leakage factor are useful to simulate the effects of pumping at the base of the till at Nests 1 and 2. The transmissivity at the base of the till is expected to be in the range of 2,200 ft^2/day. And, based on this leakage factor, the X-axis intercept (semi-log plot of distance drawdown) is expected to be in the range of 400 feet (L * 1.12). Based on the aquifer properties from Figure 3, the drawdowns at the virtual piezometers are modeled to be in the range of 5 and 3 feet at Nests 2 and 1, respectively.

Steady-State Horizontal Flow

A distance-drawdown plot is used for the combined transient (Cooper-Jacob [1946]) and steady-state analysis (Hantush-Jacob [1955]), Figure 1 through Figure 4. This view of the aquifer response, based only on Cromwell 4 and USGS 1-B, produces a large transmissivity and large leakage factor (very low rate of leakage). The quantities are incorrect because the conceptual model is incomplete (no partial-penetration or anisotropy). The utility of this plot is that the slope of this regression defines the maximum drawdown in the aquifer system at any radial distance. Therefore, the estimated drawdown at Nest 2 cannot be greater than ~5.3 feet.

Steady-State Vertical Flow

At Cromwell, the till is quite leaky and all observation wells constructed within the till clearly responded to pumping. The number of observation wells at Nest 2 provides the most direct estimate of water pressure at the base of the till/top of the aquifer. The configuration of the well nest is analogous to test column of granular material in the laboratory where observation wells act as individual pitot tubes.

A linear regression of the observed drawdowns from the Nest 2 observation wells, after 1450 minutes of pumping and projected to 10,000 minutes, Figure 5. These values were used to estimate the possible drawdown at the base of the till, ranging from 4.8 to 5.8 feet, Figure 6. Lithological differences between USGS 2-D and USGS 2-E are the cause for this large range. The regressions that followed the trend of wells USGS 2-B and 2-C were favored because of reasons discussed above. Additionally, there are physical limits on the drawdown at the base of the till, as discussed above. The range of drawdown at Nest 2 from this analysis is consistent with that from the steady-state horizontal flow of approximately 5.3 feet.

The drawdown at Nest 1 can only be roughly estimated because a single observation well was constructed in the till, USGS 1-A. A similar regression to that described above was performed to estimate the drawdown at the base of the till at this Nest. Figure 7 shows these regressions at, 2.0 and 2.95 feet at 1450 minutes and 10,000 minutes, respectively. This is also consistent with the constraints on drawdown from Figure 4.

Steady-State Leakage Caused by Pumping

The consistency of these estimates was checked on a semi-log plot of distance-drawdown by comparing the slopes and X-axis intercepts, Figure 8 and Figure 9. These possible solutions produce a similar point of zero drawdown at 400 to 500 feet and reasonable transmissivities for aquifer materials at the base of the till. The storativity from these solutions is not valid because of the effects of partial penetration; however, these large values for storativity are reasonable with respect to the time that it takes for the response to pumping to propagate to the base of the till.

The leakage factor is essential for calculating the vertical conductivity of the till in combination with other parameters: transmissivity and aquitard thickness. Here, the notation for leakage factor, ‘L’ from Kruseman and de Ridder (1991) is used. The leakage factor from the steady-state Hantush-Jacob analysis is calculated as, $L = X_o / 1.12$. The equation for the vertical hydraulic resistance of the aquitard is, $c = L^2/T$ in units of days.

From these relationships, the vertical conductivity is calculated (in terms of L) as,

$k_V = b' / (L)^2 / T]$

As shown in Figure 9, the Hantush-Jacob analysis of distance-drawdown data produces,

$k_V = 130 / [(437)^2 * 2200] = 1.5$ ft/day.

Simultaneous Solution for Horizontal and Vertical Flow

The transient response of the observation wells constructed within the till can be analyzed by the Neuman-Witherspoon method. The responses at Nests 1 and 2 were analyzed separately and as a composite, Figure 11 through Figure 21.

The Nest 2 analyses, generally were consistent values for aquifer properties. The analysis of recovery data at Nest 2, Figure 17, produced the best match and results that most closely followed the analysis of USGS 1-B, Figure 3.

The Neuman-Witherspoon analyses from Nest 1, Figure 18 and Figure 19, produced a larger transmissivity and a larger vertical conductivity of the till. Figure 18 attempted to match the data from within the aquifer. The solution shown on Figure 19 was based on the single till observation well, USGS 1-A.

The composite analyses, matching all data from the obwells were lower quality matches and more variable results, Figure 20 and Figure 21.

Estimates of leakage factor from factor from the Neuman-Witherspoon analyses are reported as 1/B. This parameter is the same as the 'B' in 'r/B' from the steady-state Hantush-Jacob model, Walton (1960) normalized for radial distance. 1/B, is the inverse quantity, $L = (1/B)^{-1}$, and the vertical hydraulic resistance is expressed as, $1/c = (1/B)^2 * T$ in units of days^{-1}.

From these relationships, the vertical conductivity is calculated (in terms of 1/B) as,

$k_V = b' * [(1/B)^2 * T]$

As shown in Figure 17, the Neuman-Witherspoon analysis of data from Nest 2 produces,

$k_V = 130 * [(0.0017)^2 * 2300] = 0.86$ ft/day.

Heterogeneity in the properties of the till is indicated by the poor match of the response of USGS 1-E to the curves relative to the other wells in Nest 2, Figure 17. Examination of the slopes of the late-time data at the observation wells in the till shows that there is a marked similarity in the trends of USGS 1-A and USGS 2-E, Figure 22. Because of this similarity a separate Neuman-Witherspoon analysis was performed on only those wells, Figure 23. This analysis is a reasonable upper bound on the conductivity of the till, 4.1 ft/day.

Additional Analyses for Comparison to other Parts of the Dataset

Figure 24 and Figure 25 are recovery analyses for comparison to the short-term tests that were conducted after this test, see documents for tests 2613 and 2619.

Conclusion

The bulk aquifer and aquitard properties from this dataset are shown in Table 1, as derived from the analyses listed on Table 5 and Table 6. This test is a detailed examination of the properties of the till in a very small area. The large range of estimated aquifer properties result from both: the sub-set of the data to which an analysis method was applied, and natural lithological variation, particularly within the till.

The reported range of vertical conductivity of the till is from 0.85 to 4.1 ft/day. The low value, 0.85 ft/day, is from the response of wells at Nest 2, USGS 1-B, 1-C and 1-D.

However, the till contains significant heterogeneities and the vertical conductivity is significantly greater in some areas. Based on the responses at USGS 1-A and USGS 2-E, the largest credible value from this dataset is 4.1 ft/day. Because these wells are at both nests, it is likely that this analysis characterizes the till over a larger geographic extent than the analyses from the observation wells limited to Nest 2. Therefore, for modelling purposes it is unlikely that the low value is realistic and a more reasonable range of the bulk properties of the till is from 1.1 to 4.1 ft/day.

Acknowledgements

There have been few opportunities to collect this level of detailed hydraulic information for the analysis of rates of leakage through till. It is judged that this data collection effort and subsequent analysis was particularly successful, given the hydrogeologic setting and the normal challenges of adapting to field conditions. Credit for this success is due in large part to the active participation and support of Mr. Tom Johnson, water operator for the city of Cromwell. Thank you.

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Tables and Figures

Table 1. Summary of Results for Leaky Confined - Radial Porous Media Flow

Parameter	Value	Unit	Range Minimum	Range Maximum	+/- % variation
Top Stratigraphic Elev.	1152	feet (MSL)			
Bottom Stratigraphic Elev.	1007	feet (MSL)			
Transmissivity (T)	4,400	ft^2/day	1,000	5,700	
Aquifer Thickness (b)	145	feet	145	175	
Hydraulic Conductivity (k)	30	ft/day			
Ratio Vertical/Horizontal k[1]	0.5	0.00 %			
Primary Porosity (e_p)	0.25	0.00 %			
Storativity (S)	2.0e-4	dimensionless	1.0e-4	4.0e-4	
Characteristic Leakage (L)	500	feet	330	2610	
Hydraulic Resistance (c)	114	days	50	220	
Thickness of till (b')	130	feet			
Hydraulic Conductivity of till (k_V)	1.1	ft/day	0.8	4.1	

[1] Conductivity decreases to ~15 ft/day at top of aquifer (transmissivity, ~2,200 ft2/day)

Table 2. Aquifer Test Information

Information Type	Information Recorded
Aquifer Test Number	2612
Test Location	Cromwell 4 (593593)
Well Owner	City of Cromwell
Test Conducted By	MDH - T. Lund and J. Blum
Aquifer	QBAA
Confined / Unconfined	Confined
Date/Time Monitoring Start	05/18/2017 11:40
Date/Time Pump off Before Test	5/23/2017 4:31
Date/Time Pumping Start	5/24/2017 12:10:04
Date/Time Recovery Start	5/25/2017 12:25:00
Date/Time Test Finish	5/31/2017 11:00
Pumping time (minutes)	1454.93
Totalizer – end reading	106059750
Totalizer – start reading	105817400
Total volume (gallons)	242350 gallons
Nominal Flow Rate	167 (gallons per minute)
Number of Observation Wells	8 (see Table 3)

Table 3. Well Information

Well Name (Unique Number)	Easting Location, X[2] (meter)	Northing Location, Y[2] (meter)	Radial Distance (feet)	Ground Surface Elevation, GSE[3] (feet, MSL)	Measuring Point Description GSE+(stick-up) (feet, MSL)	Open Interval Top (feet, MSL)	Open Interval Bottom (feet, MSL)	Aquifer
Cromwell 4 (593593)	28.9	44.2	0.4	1328	~1329	1118	1098	QBAA
Cromwell 3 (519761)	62.5	45.3	112[4]	1328	~1330	1148	1138	QBAA
Nest 1								Till - QBAA - Bedrock
USGS C1-A (773071)	50.0	6.4	149.5	1326.3	1328.66+	1181.7	1178.9	Till – mid
USGS C1-B (773070)	48.8	6.3	147.8	1326.3	1328.62+	1105.4	1095.8	QBAA
USGS C1-C (773069)	47.3	6.4	145.6	1326.2	1328.78+	996.7	987.1	Thompson Fm.
Nest 2								Till - QWTA
USGS C2-A (773068)	40.6	54.0	53.9	1332.3	1334.67+	1300.0	1297.3	QWTA
USGS C2-B (773067)	40.6	56.1	58.8	1332.6	1334.98+	1275.9	1273.2	Till - top
USGS C2-C (773066)	42.2	54.0	57.7	1332.3	1334.71+	1253.6	1250.9	Till – mid top
USGS C2-D (773065)	39.1	54.0	50.9	1332.1	1334.58+	1228.5	1225.9	Till – mid
USGS C2-E (773064)	39.0	56.1	56.0	1332.4	1334.81+	1206.6	1204.0	Till - deep

[2] Local Datum
[3] Vertical Datum: NAV88
[4] Distance between well center, distance between outside of casing is 111 ft.

Table 4. Data Collection[5]

Data File Name: Well Name_Unique Number	Data Logger Type, SN:	Probe Id., Range (psi)	Install 1. Static WL[6]	Install 2. XD [7]Setting	Remove 3. Static WL	Remove 4. XD Setting	Diff. Static WL (1-3)	Diff. XD Setting (4-2)
Cromwell-4_593593	Troll 500 145815	17, 30 psi	15.86	12.55	15.39	13.30	0.47	0.75
Baro_data	Hermit 3000 45333	6, 15 psia						
1-A(773071)	OTT 382933		20.49	19.89	20.11	19.53	0.38	0.36
1-B(773070)	OTT 382932		16.12	15.34	15.31	14.60	0.81	0.74
1-C(773069)	OTT 382934		16.20	15.58	15.42	14.79	0.78	0.79
2-A(773068)	OTT 382929		29.69	29.04	29.48	28.70	0.21	0.34
2-B(773067)	OTT 382935		28.78	28.14	28.46	27.79	0.32	0.35
2-C(773066)	OTT 382936		26.95	26.46	26.52	26.07	0.43	0.39
2-D(773065)	OTT 382931		23.71	22.47	23.18	22.42	0.53	0.05
2-E(773064)	OTT 382937		25.15	37.16	23.65	35.60	1.5	1.56

[5] Notes about data collection: USGS transducers/loggers installed 5/18/2017, before 12:00 on 1-minute interval. Barometer recording from 5/18/2017 11:40 on 10-minute interval. Inspected C-3 setup for logging, no access to well except by existing bubbler line. C-4 access through submersible cap, transducer installed 5/24/2017. Initial setting of transducer in USGS 2-E (773064) too deep, device did not record usable data of background and early pumping. Transducer reset on 5/24/2017 15:28. Data not recovered from USGS 1-A logger during late pumping and recovery.

[6] WL = water level below measuring point, feet.

[7] XD = pressure transducer depth below water surface, feet.

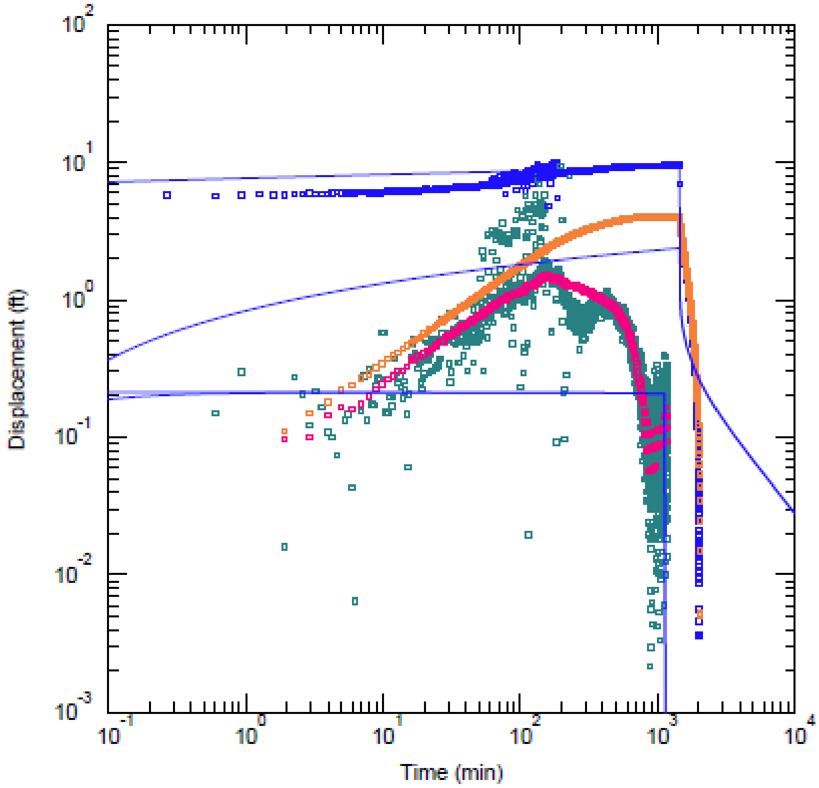
Table 5. Transient Analysis Results

Well Name (Unique Well No.)	Transmissivity, T (ft2/day)	Storativity, S (dimensionless)	Leakage Factor, L (feet)	Hydraulic Conductivity of Aquitard, kV (ft/day)	Analysis Method	Plot No. Remarks
C-4 (593593) 1-B (773070)	12,000	2.0e-5	150,000	7.0e-5	Hantush-Jacob	1. properties not credible for very leaky system
C-4 (593593) 1-B (773070) 1-C (773069)	17,000	3.5e-4	3,570	0.17	Hantush-Jacob	2. properties not credible for very leaky system
1-B (773070)	4,380	7.7e-3	330	2.6	Hantush-Jacob	3. kz/kr = 0.5, credible properties
C-4 (593593) 1-B (773070)	5,190	1.7e-4			Cooper-Jacob	4. properties not credible for very leaky system
Nest 2, all till obwell composite	2,200	5.0e-4	590	0.83	Neuman-Witherspoon	11. credible properties, consistent with plot 9, good match
2-B (770067)	2,300	3.0e-4	500	1.2	Neuman-Witherspoon	13.
2-C (770066)	2,300	5.0e-4	500	1.2	Neuman-Witherspoon	13.
2-D (770065)	1,800	1.9e-4	380	1.6	Neuman-Witherspoon	14.
2-E (770064)	2,300	5.0e-4	500	1.2	Neuman-Witherspoon	15.
Nest 2, till obwell composite, 2-D (770065) excluded from match	2700	3.0e-3	670	0.79	Neuman-Witherspoon	16.
Nest 2, till obwell composite recovery	2,300	4.0e-4	590	0.86	Neuman-Witherspoon	17. best match
C-4 (593593) 1-B (773070) 1-A (770071)	3,730	8.0e-4	1520	2.1	Neuman-Witherspoon	18.
1-A (770071)	3,550	1.2e-3	1960	1.2	Neuman-Witherspoon	19.
All till obwell composite	1,200	2.6e-3	145	7.4	Neuman-Witherspoon	20. properties not credible, too leaky
All well composite	2,790	2.9e-3	370	2.7	Neuman-Witherspoon	21.
1-A (770071) and 2-E (770064)	1590	5.0e-2	224	4.1	Neuman-Witherspoon	23. large credible k_V

Table 6. Steady-state Analysis Results

Transmissivity, T (ft^2/day)	Leakage Factor, L (feet)	Hydraulic Resistance, c (days)	Hydraulic Conductivity of Aquitard, k_v (ft/day)	Analysis Method	Plot No. Remarks
5,190	7,470	10,800	0.012	Hantush-Jacob	4. properties not credible for very leaky system
2,200	370	61	2.1	Hantush-Jacob	9. credible properties, consistent with plot 3
2,200	440	88	1.5	Hantush-Jacob	10. credible properties, consistent with plots 3 and 9

Figure 1. Solution of Aquifer Properties by Aqtesolv. Data from Cromwell 4 (593593) and USGS 1-B (773070)



WELL TEST ANALYSIS

Data Set: O:\...\00_Cromwell4.aqt
Date: 08/22/17 Time: 12:30:13

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0
1-B	140.5	0
1-C	140.4	0
2-B	0	54.8
2-C	0	53.2
2-D	0	46
2-E	0	51.7

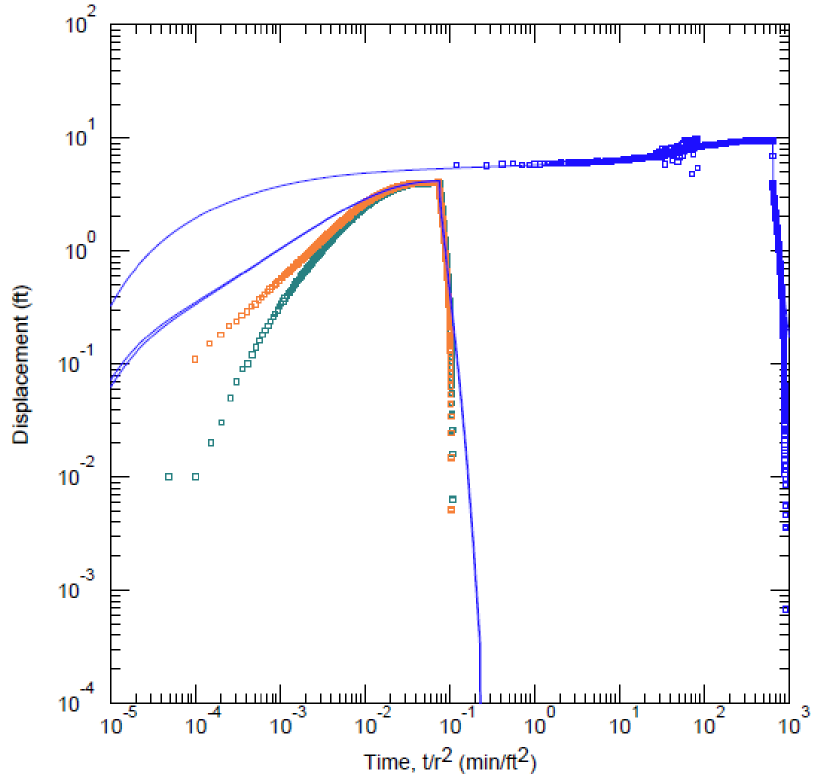
SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 1.204E+4 ft^2/day
S = 1.974E-5
1/B = 6.667E-6 ft^{-1}
Kz/Kr = 1.
b = 145. ft

L = 149,000 feet
kv = 130 * (6.7e-6)^2 * 12,000 = 7.0e-5 ft/day

Figure 2. Solution of Aquifer Properties by Aqtesolv. Showing Data from Cromwell 4 (593593), USGS 1-B (773070) and USGS 1-C (773071)



WELL TEST ANALYSIS

Data Set: O:\...\00_Cromwell4_nest-1_composite.aqt
Date: 08/22/17 Time: 12:36:55

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Cromwell 4	0	0
▫ 1-C	139	0
▫ 1-B	140.5	0
▫ 1-A	142	0

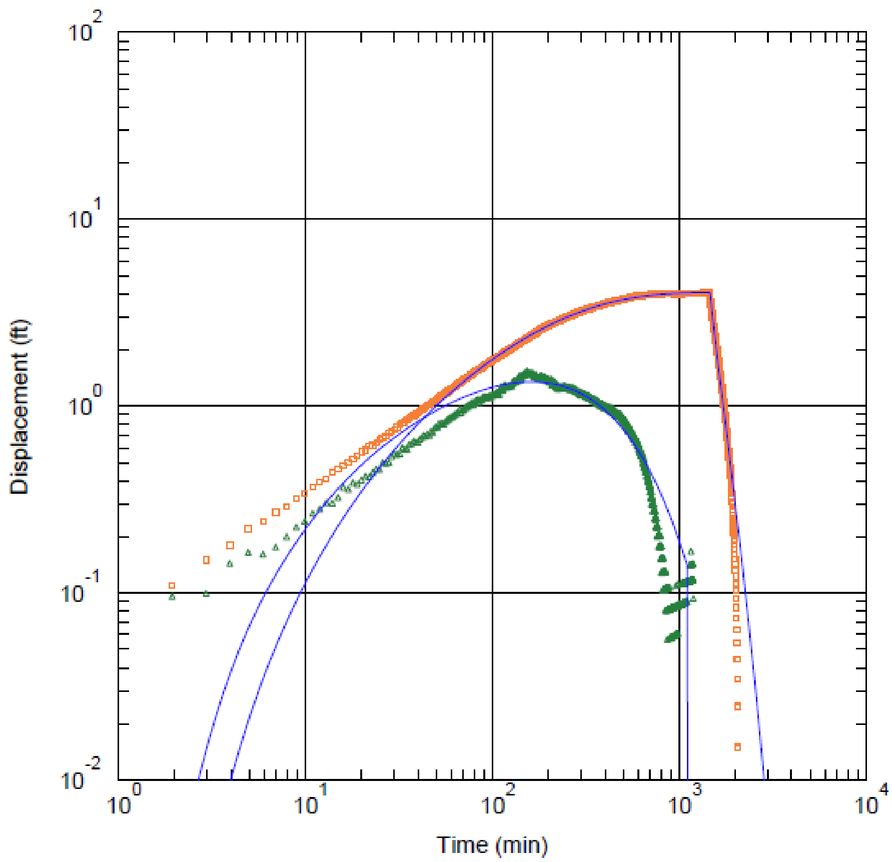
SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 1.695E+4 ft^2/day
S = 0.0003542
1/B = 0.0002804 ft^{-1}
Kz/Kr = 0.5
b = 145. ft

L = 10,800 feet
kv = 130 * (2.8e-4)^2 * 17,000 = 0.17 ft/day

Figure 3. Solution of Aquifer Properties by Aqtesolv. Data from USGS 1-B (773070) only



WELL TEST ANALYSIS

Data Set: O:\...\01_cromwell_nest-1-B_partial.aqt
Date: 08/22/17 Time: 12:33:33

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ 1-B	140.5	0

SOLUTION

Aquifer Model: Leaky

Solution Method: Hantush-Jacob

T = 4382.2 ft^2/day
r/B = 0.4231
b = 145. ft

S = 0.007766
Kz/Kr = 0.5

L = 333 Feet
k_v = 130 * (0.423/141)^2 * (4380 * 0.5) = 2.6 ft/day

Figure 4. Conventional Distance-drawdown Plot based on Cromwell 4 (593593) and USGS 1-B (773070)

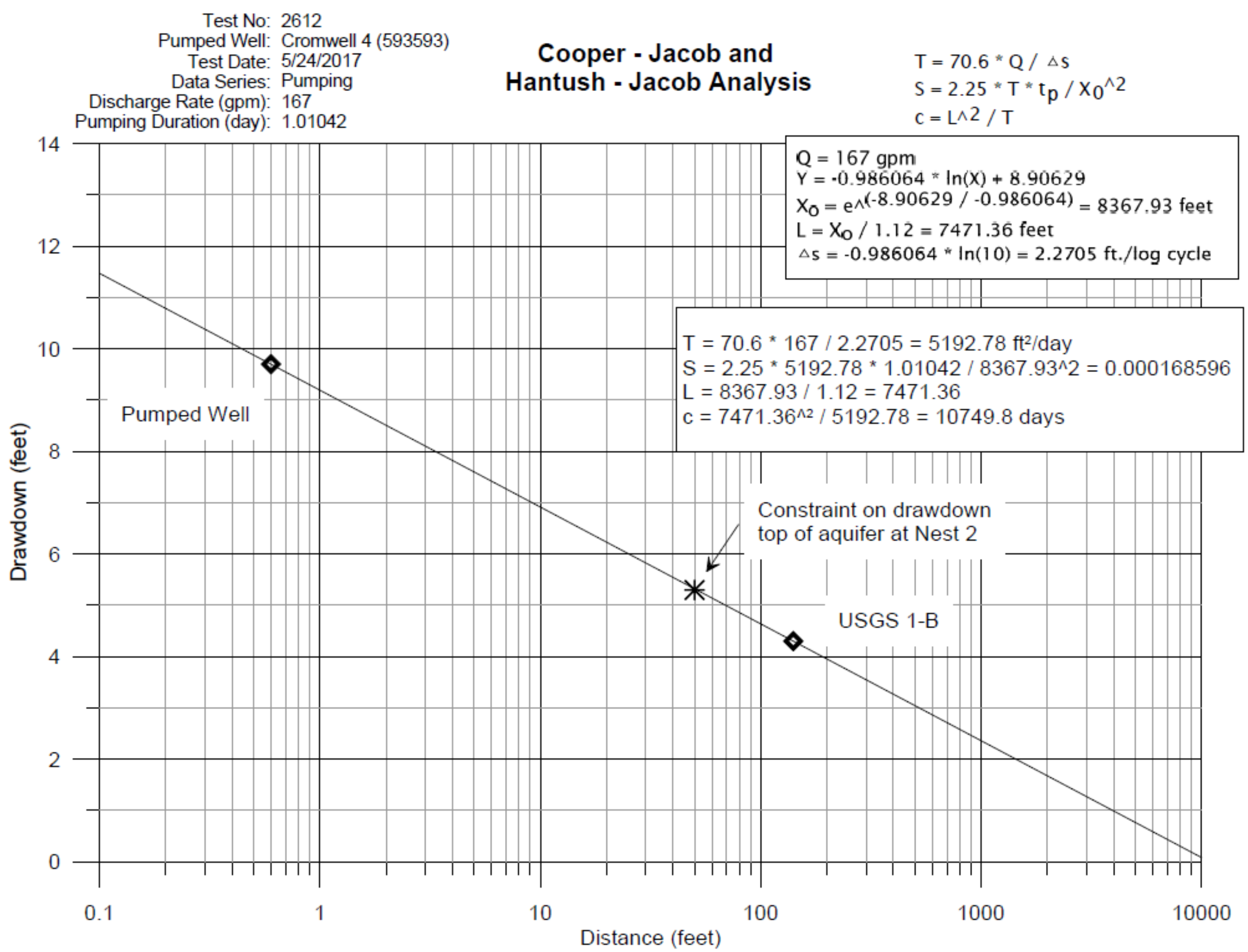


Figure 5. Drawdown at Nest 2 after 1450 minutes of pumping, projected to 10,000 minutes

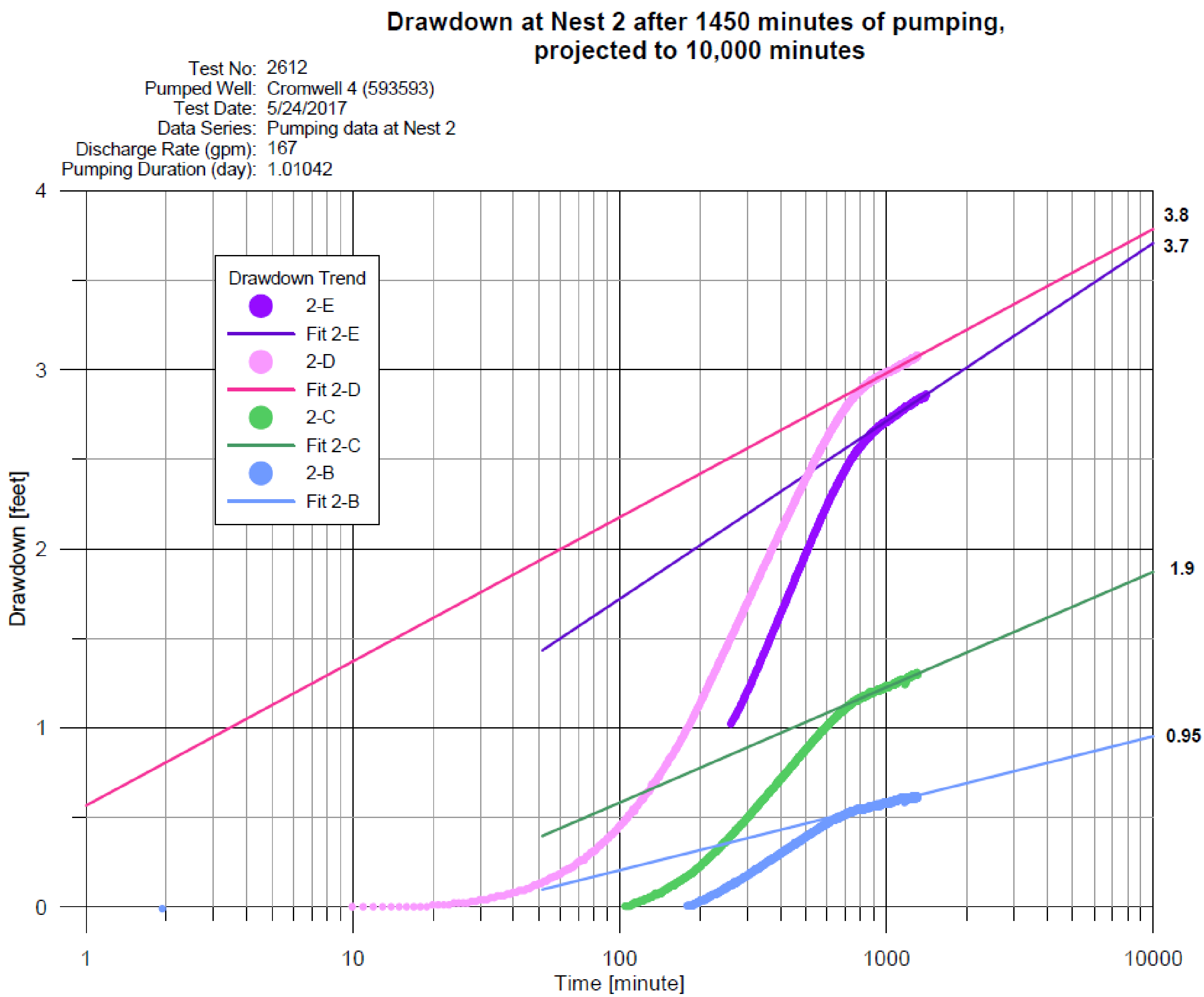


Figure 6. Groundwater Gradient at Nest 2 after 1450 Minutes of Pumping

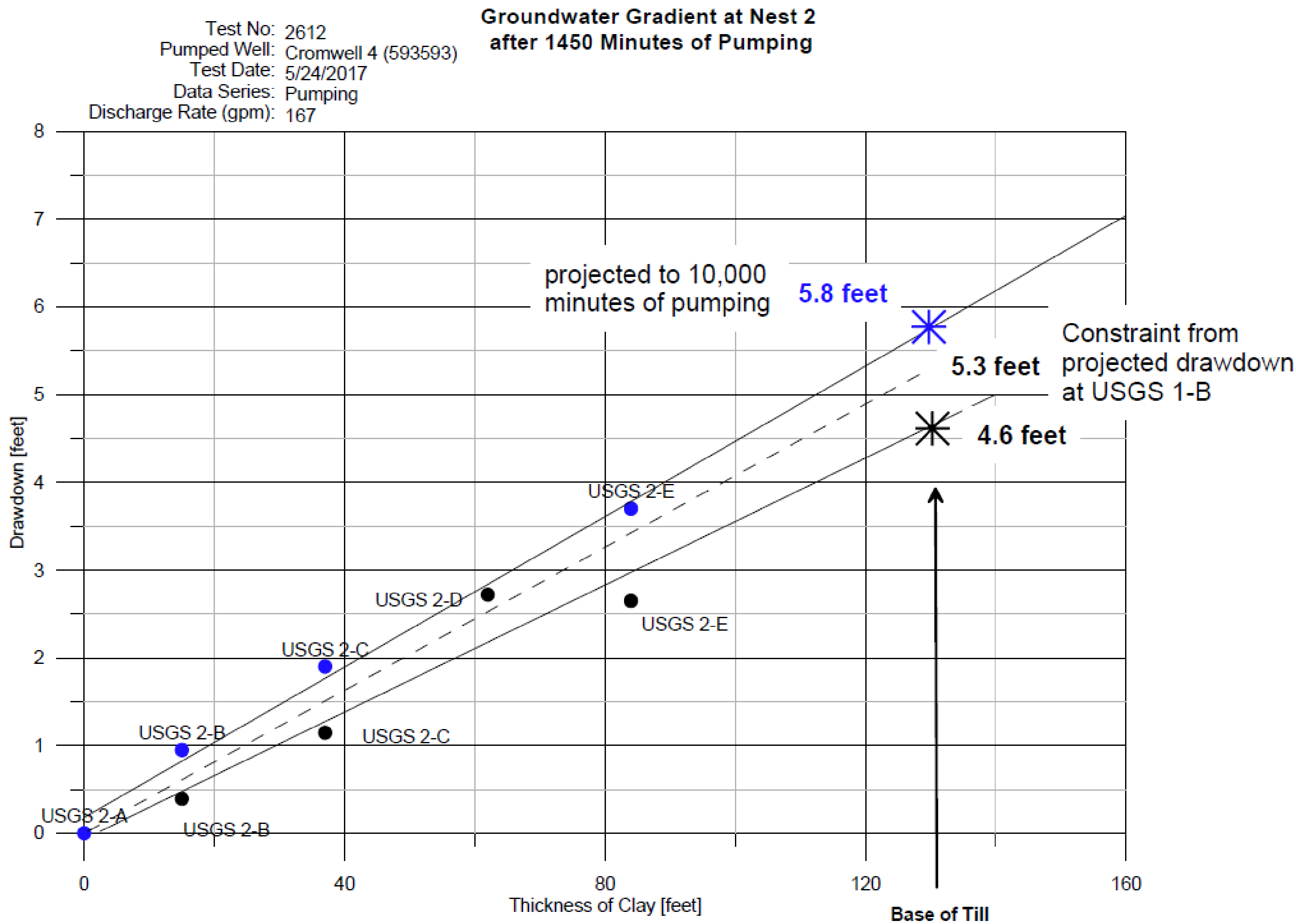


Figure 7. Drawdown at Nest 1 after 1450 minutes of pumping, projected to 10,000 minutes

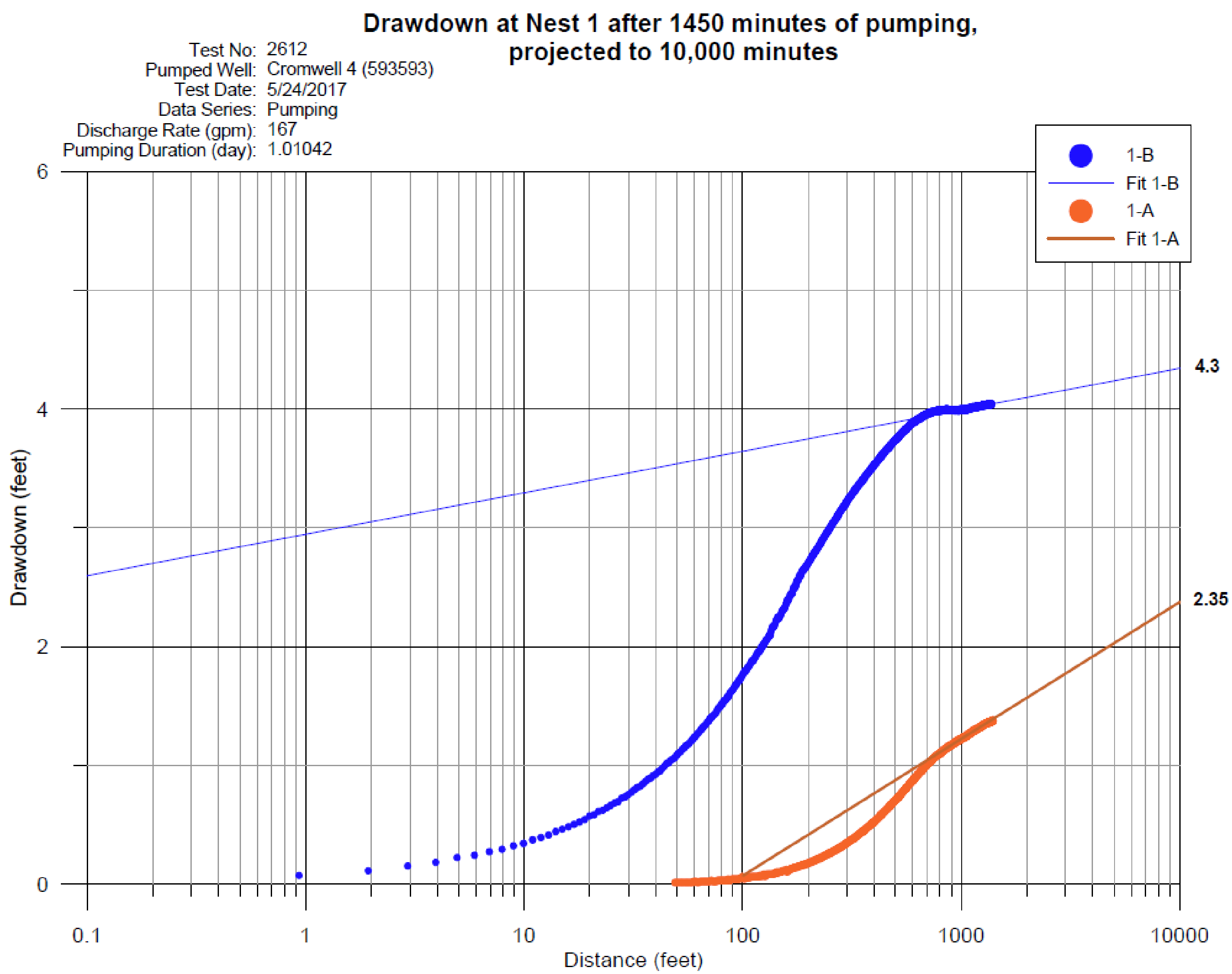


Figure 8. Groundwater Gradient at Nest 1 after 1450 Minutes of Pumping

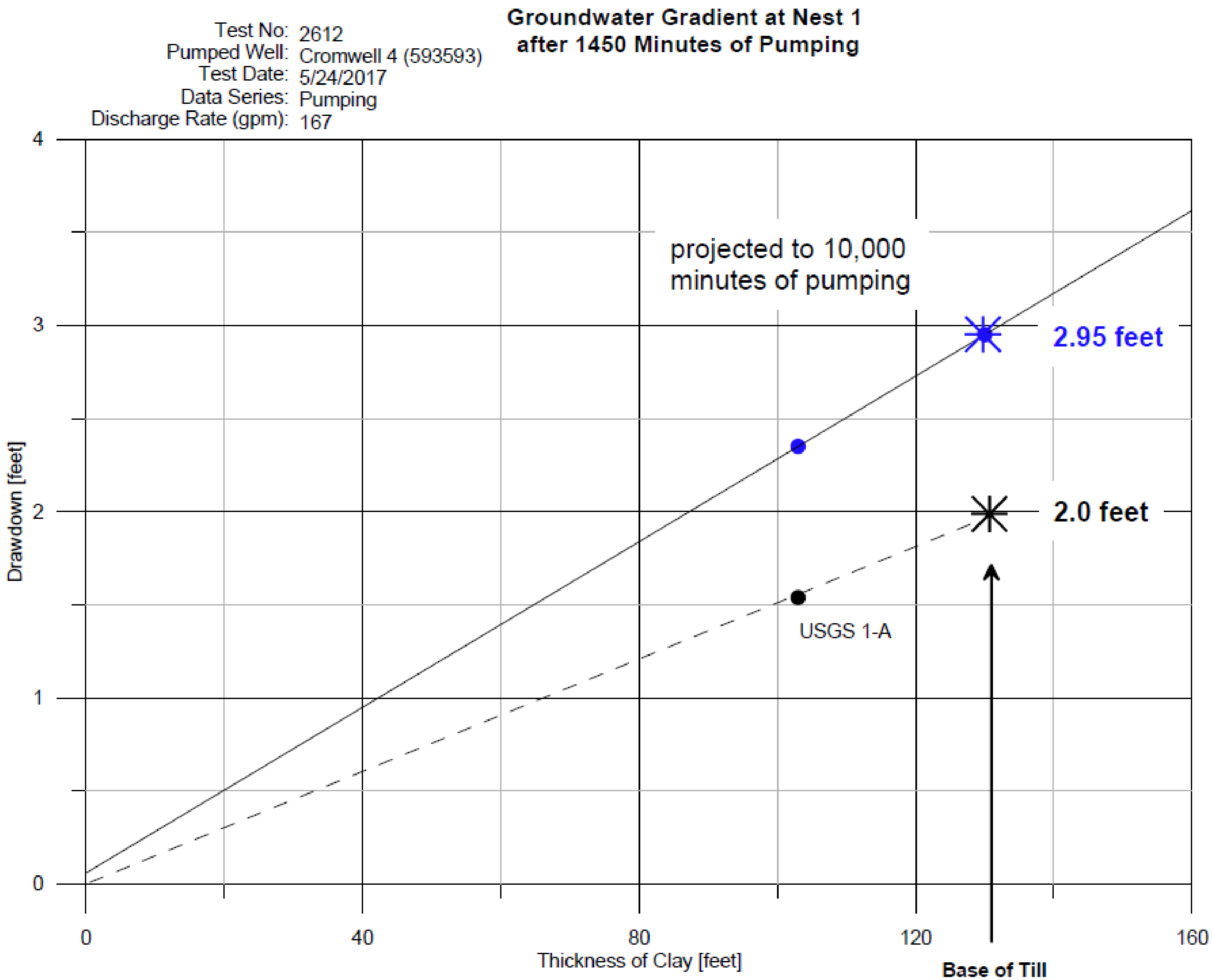


Figure 9. Comparison of Drawdowns at 1450 Minutes of Pumping at Nests 1 and 2, at Nase of Till, to that in Aquifer

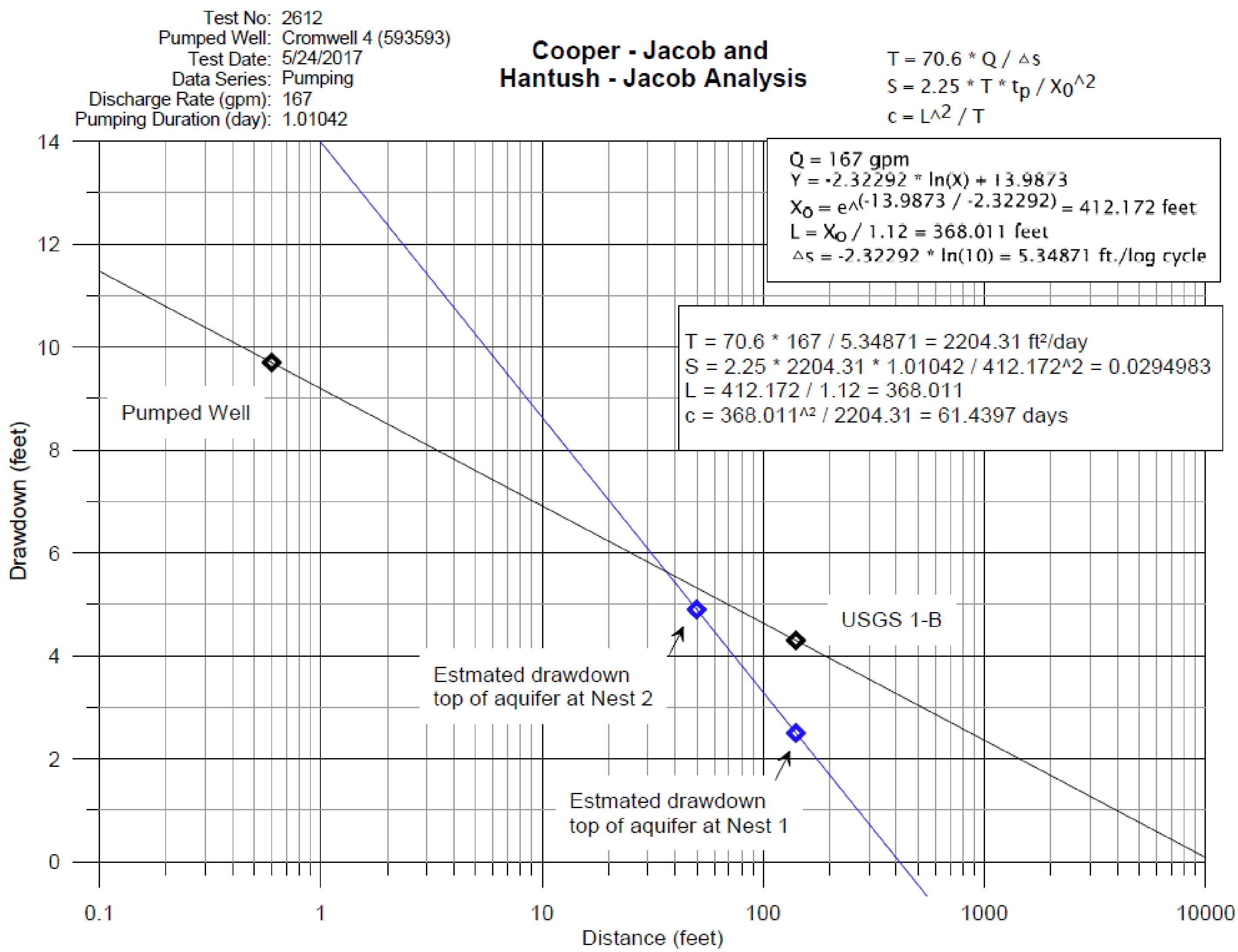


Figure 10. Comparison of Drawdowns at 10,000 Minutes of Pumping at Nests 1 and 2, at Base of Till, to that in Aquifer

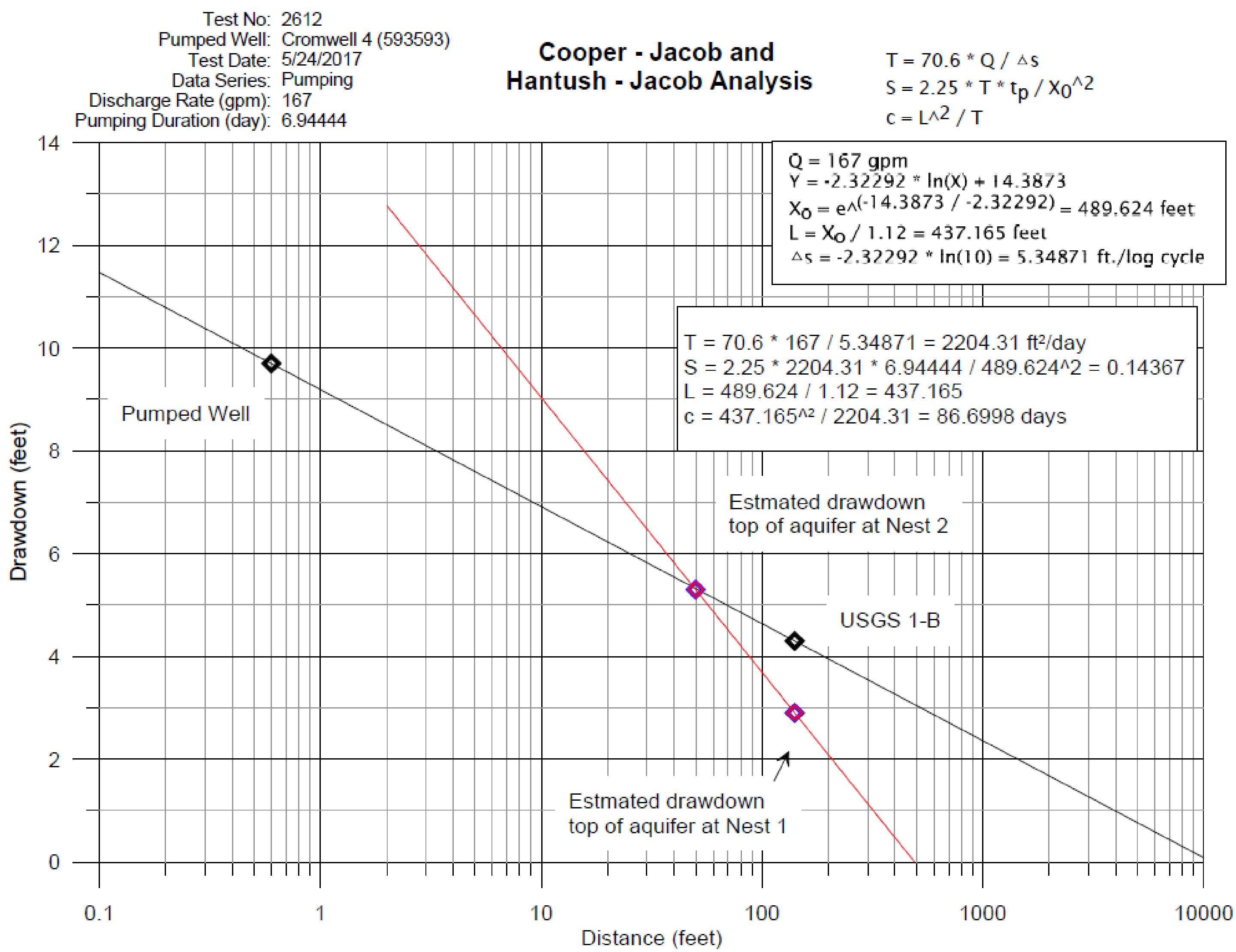
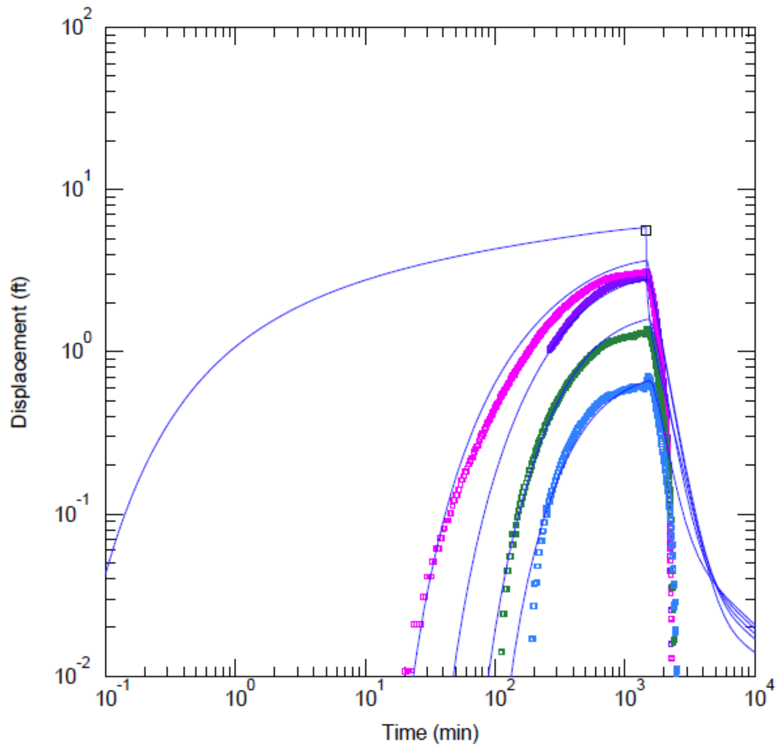


Figure 11. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-B, 2-C, 2-D, and 2-E



WELL TEST ANALYSIS

Data Set: O:\...\11_cromwell_nest-2_neuman.aqt
Date: 08/22/17 Time: 15:08:21

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ Nest 2	0	50
▫ USGS 2-E	51.7	0
▫ USGS 2-D	46	0
▫ USGS 2-C	53.2	0
▫ USGS 2-B	54.8	0

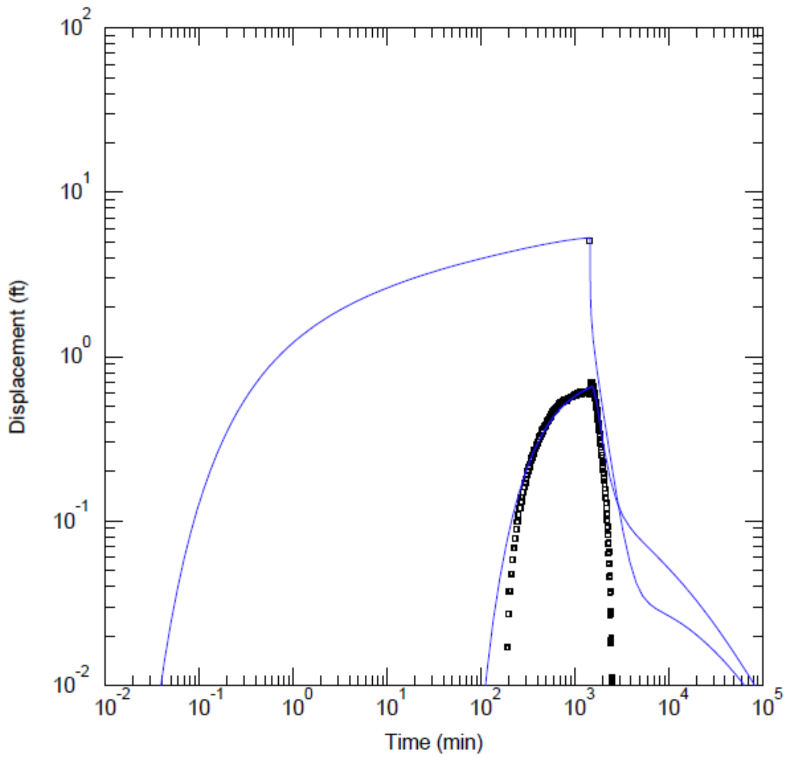
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2200. ft^2/day
1/B = 0.0017 ft^{-1}
T2 = 10000. ft^2/day
S = 0.0005
ß/r = 0.0021 ft^{-1}
S2 = 0.25

L = 590 feet
kv = 130 * (0.0017)^2 * 2200 = 0.83 ft/day

Figure 12. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-B only



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_2B.aqt
Date: 08/23/17 Time: 11:22:17

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-B	54.8	0

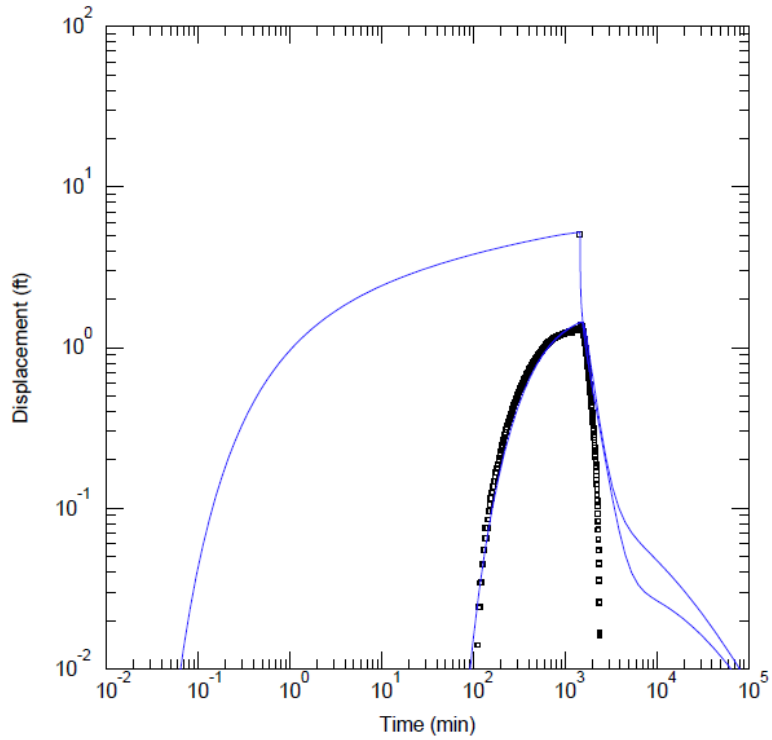
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2300. ft^2/day
1/B = 0.002 ft^{-1}
T2 = 2000. ft^2/day
S = 0.0003
ß/r = 0.0035 ft^{-1}
S2 = 0.25

L = 500
kv = 130 * (0.002)^2 * 2300 = 1.2 ft/day

Figure 13. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-B only



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_2C.aqt
Date: 08/23/17 Time: 11:23:18

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b'): 130. ft
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-C	53.2	0

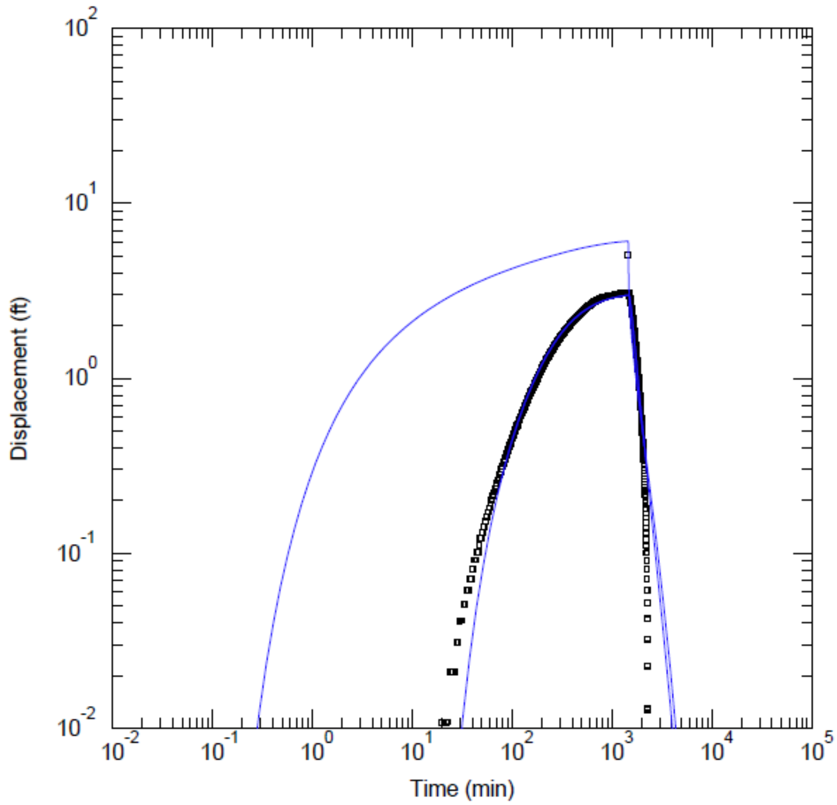
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2300. ft^2/day
S = 0.0005
1/B = 0.002 ft^{-1}
ß/r = 0.003 ft^{-1}
T2 = 2000. ft^2/day
S2 = 0.25

L = 500 Feet
k_v = 130 * (0.002)^2 * 2300 = 1.2 ft/day

Figure 14. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-C only



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_2D.aqt
Date: 08/23/17 Time: 11:24:59

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b'): 130. ft
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-D	46	0

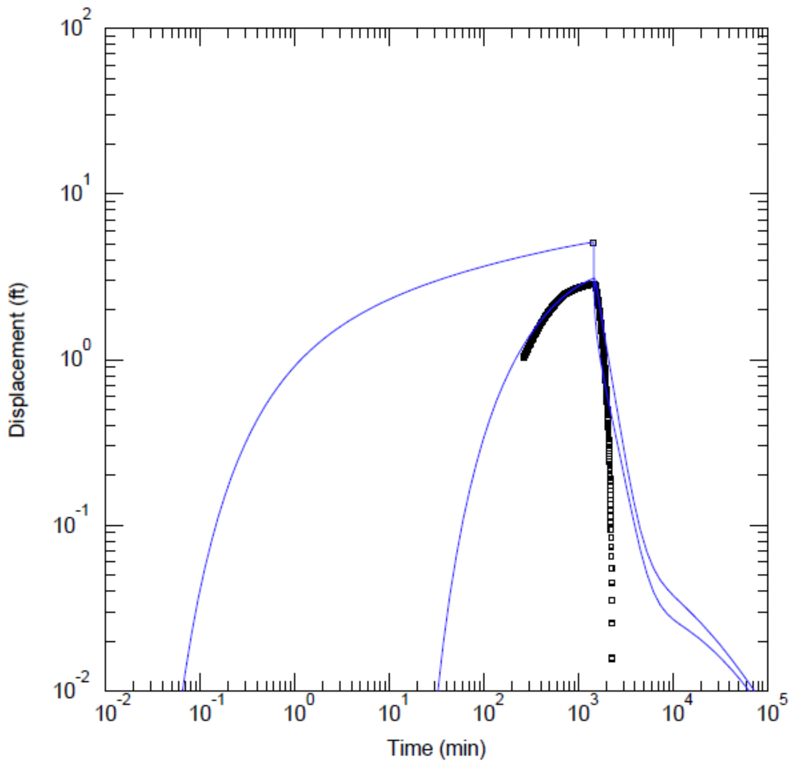
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 1800. ft^2/day
1/B = 0.002588 ft^{-1}
T2 = 1.44E+8 ft^2/day
S = 0.001862
ß/r = 0.001745 ft^{-1}
S2 = 1.

L = 380 feet
kv = 130 * (0.00259)^2 * 1800 = 1.6 ft/day

Figure 15. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-D only



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_2E.aqt
Date: 08/23/17 Time: 11:26:03

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-E	51.7	0

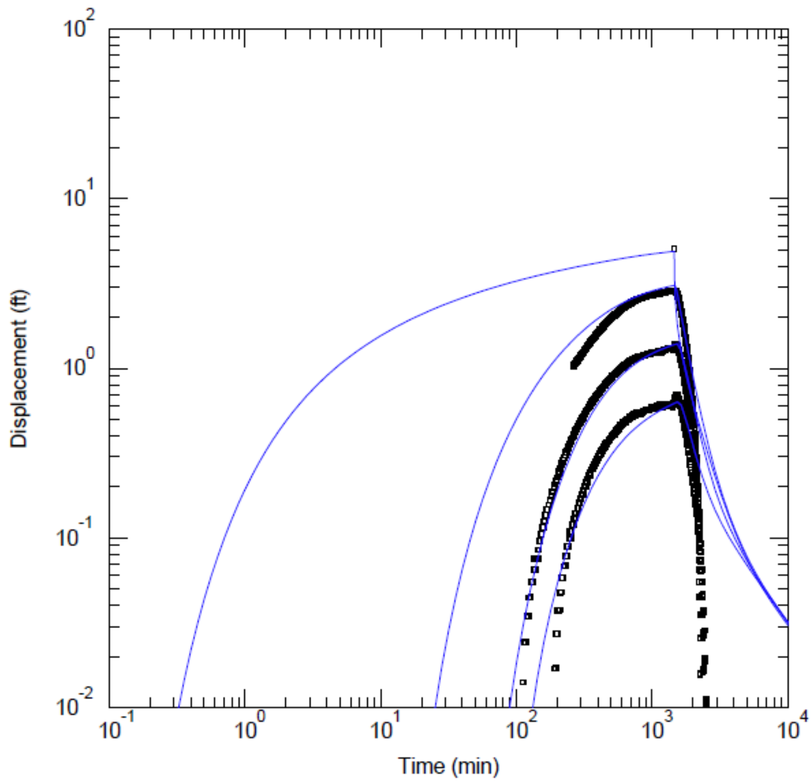
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2300. ft^2/day
1/B = 0.002 ft^{-1}
T2 = 2000. ft^2/day
S = 0.0005
ß/r = 0.0035 ft^{-1}
S2 = 0.25

L = 500 feet
kv = 130 * (0.002)^2 * 2300 = 1.2 ft/day

Figure 16. Solution of Aquifer Properties by Aqtesolv. Data from USGS 2-B, 2-C, and 2-E only



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_no2-D.aqt
Date: 08/22/17 Time: 14:45:40

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b'): 130. ft
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-E	51.7	0
▫ USGS 2-C	53.2	0
▫ USGS 2-B	54.8	0

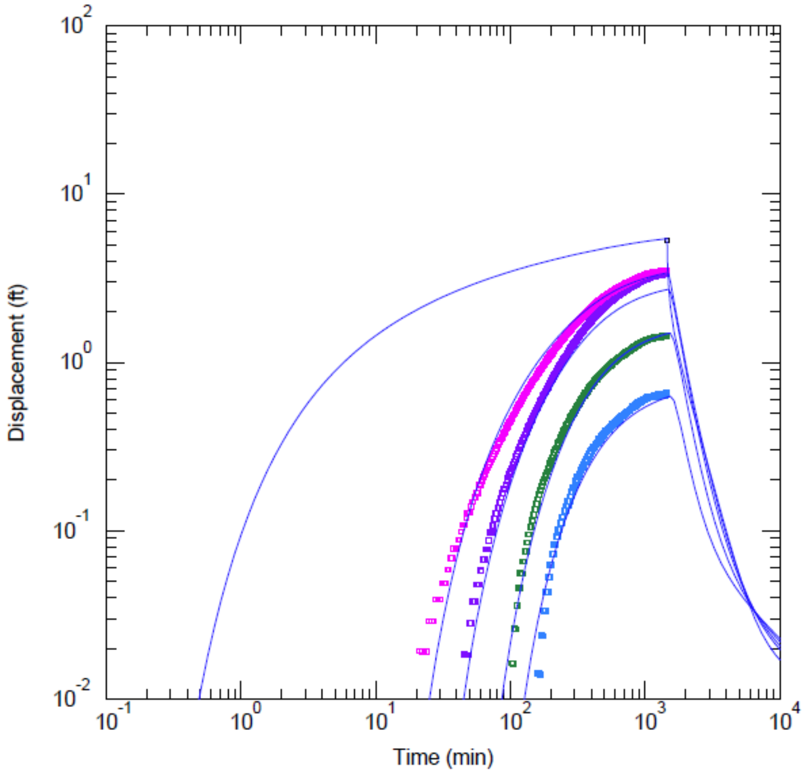
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2700. ft^2/day
S = 0.003
1/B = 0.0015 ft^{-1}
ß/r = 0.0007 ft^{-1}
T2 = 10000. ft^2/day
S2 = 0.03

L = 670 feet
kv = 130 * (0.0015)^2 * 2700 = 0.79 ft/day

Figure 17. Solution of Aquifer Properties by Aqtesolv. Recovery Phase Data from USGS 2-B, 2-C, 2-D, and 2-E



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-2_neuman_no2-D_recovery.aqt
Date: 08/21/17 Time: 08:14:53

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-E	51.7	0
▫ USGS 2-C	53.2	0
▫ USGS 2-B	54.8	0
▫ USGS 2-D	46	0

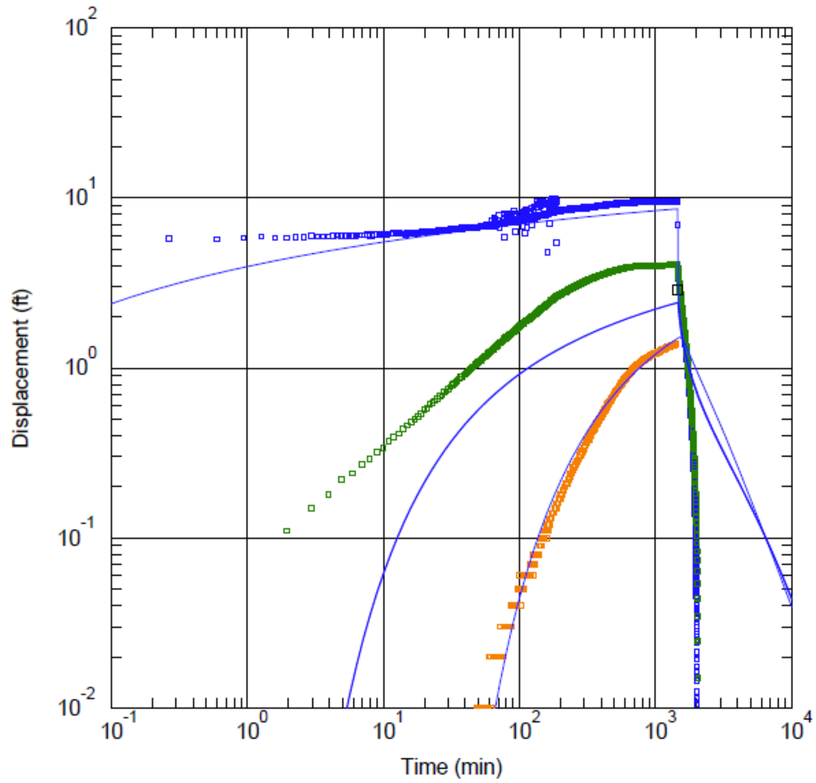
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2300. ft^2/day
1/B = 0.0017 ft^{-1}
T2 = 10000. ft^2/day
S = 0.004
ß/r = 0.0007 ft^{-1}
S2 = 0.2

L = 590 feet
kv = 130 * (0.0017)^2 * 2300 = 0.86 ft/day

Figure 18. Solution of Aquifer Properties by Aqtesolv. Match to Data from USGS 1-A, Data from USGS 1-B, and Cromwell 4



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-1_neuman.aqt
Date: 08/22/17 Time: 15:14:42

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Cromwell 4	0	0
▫ 1-B	140.5	0
▫ 1-A	142	0
□ Nest 1	141	0

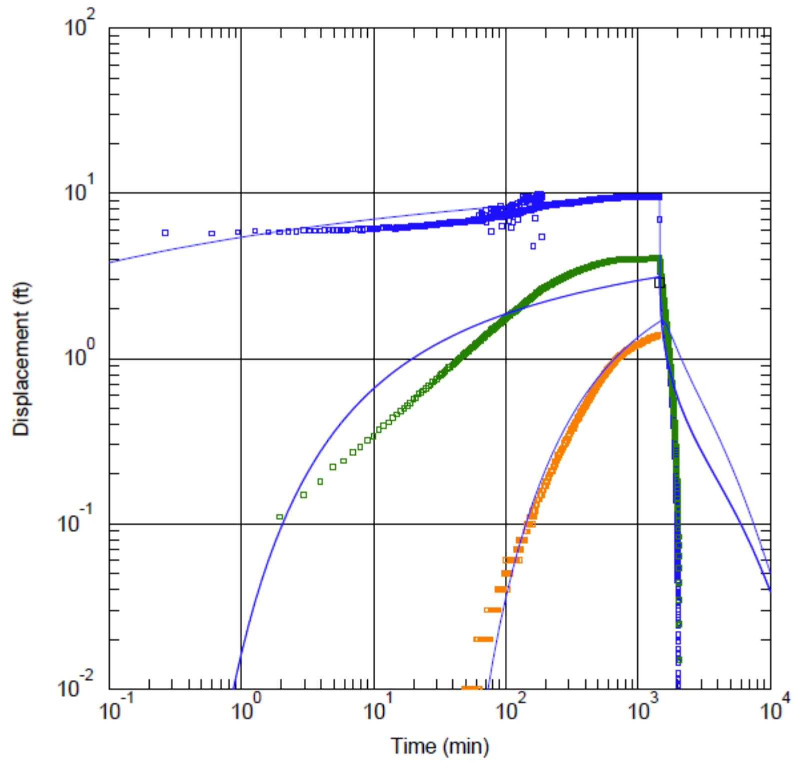
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 3731.6 ft^2/day
1/B = 0.0006568 ft^{-1}
T2 = 1.44E+8 ft^2/day
S = 0.008047
ß/r = 0.0001826 ft^{-1}
S2 = 1.

L = 1520 feet
kv = 130 * (0.00066)^2 * 3730 = 0.21 ft/day

Figure 19. Solution of Aquifer Properties by Aqtesolv. Match to Data from USGS 1-A and Modeled Drawdown at the Base of Till, Data from USGS 1-B, and Cromwell 4



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-1_neuman_obws_only.aqt
Date: 08/22/17 Time: 09:35:30

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b'): 130. ft
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0
1-B	140.5	0
1-A	142	0
Nest 1	141	0

SOLUTION

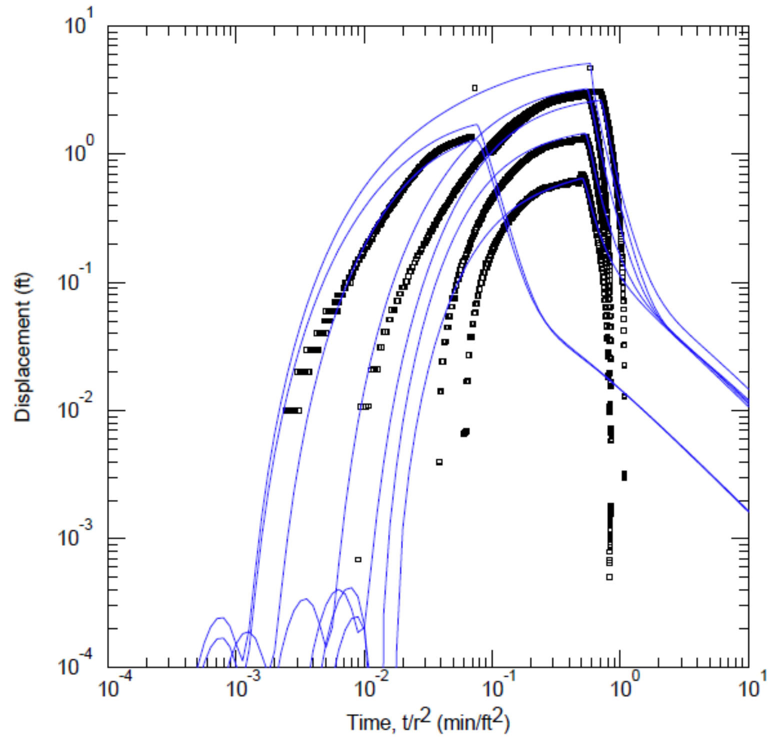
Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 3547.8 ft^2/day
S = 0.001231
1/B = 0.0005151 ft^{-1}
ß/r = 0.0003916 ft^{-1}
T2 = 2000. ft^2/day
S2 = 0.3

L = 1960 feet

kv = 130 * (0.00051)^2 * 3550 = 0.12 ft/day

Figure 20. Solution of Aquifer Properties by Aqtesolv. Match to Data from all USGS Observation Wells and Drawdown at the Base of Till at Nests 1 and 2



WELL TEST ANALYSIS

Data Set: O:\...\15_cromwell_nests1&2_neuman.aqt
Date: 08/22/17 Time: 15:22:35

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 0.5
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Nest 2	0	50
▫ USGS 2-E	51.7	0
▫ USGS 2-D	46	0
▫ USGS 2-C	53.2	0
▫ USGS 2-B	54.8	0
▫ USGS 1-A	142	0
▫ Nest 1	140.5	0

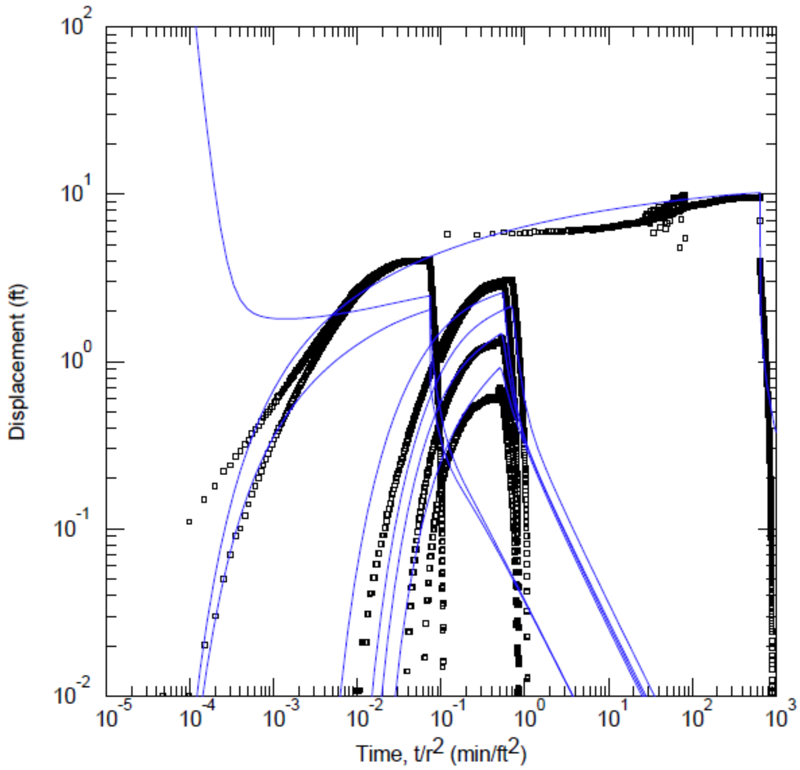
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

$T = 1204.1$ ft^2/day
$1/B = 0.006891$ ft^{-1}
$T2 = 10000.$ ft^2/day
$S = 0.02603$
$ß/r = 0.001982$ ft^{-1}
$S2 = 1.$

L = 145 feet
kv = 130 * (0.00689)^2 * 1200 = 7.4 ft/day

Figure 21. Solution of Aquifer Properties by Aqtesolv. Match to all data



WELL TEST ANALYSIS

Data Set: O:\...\cromwell4_neuman_composite_thick.aqt
Date: 08/21/17 Time: 13:22:20

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 20. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0
1-B	140.5	0
1-C	140.4	0
2-B	0	54.8
2-C	0	53.2
2-D	0	46
2-E	0	51.7

SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 2785.3 ft^2/day
1/B = 0.002969 ft^{-1}
T2 = 2200. ft^2/day
S = 0.00291
ß/r = 0.002176 ft^{-1}
S2 = 0.03

Figure 22. Similarity in Slope of 1-A and 2-E

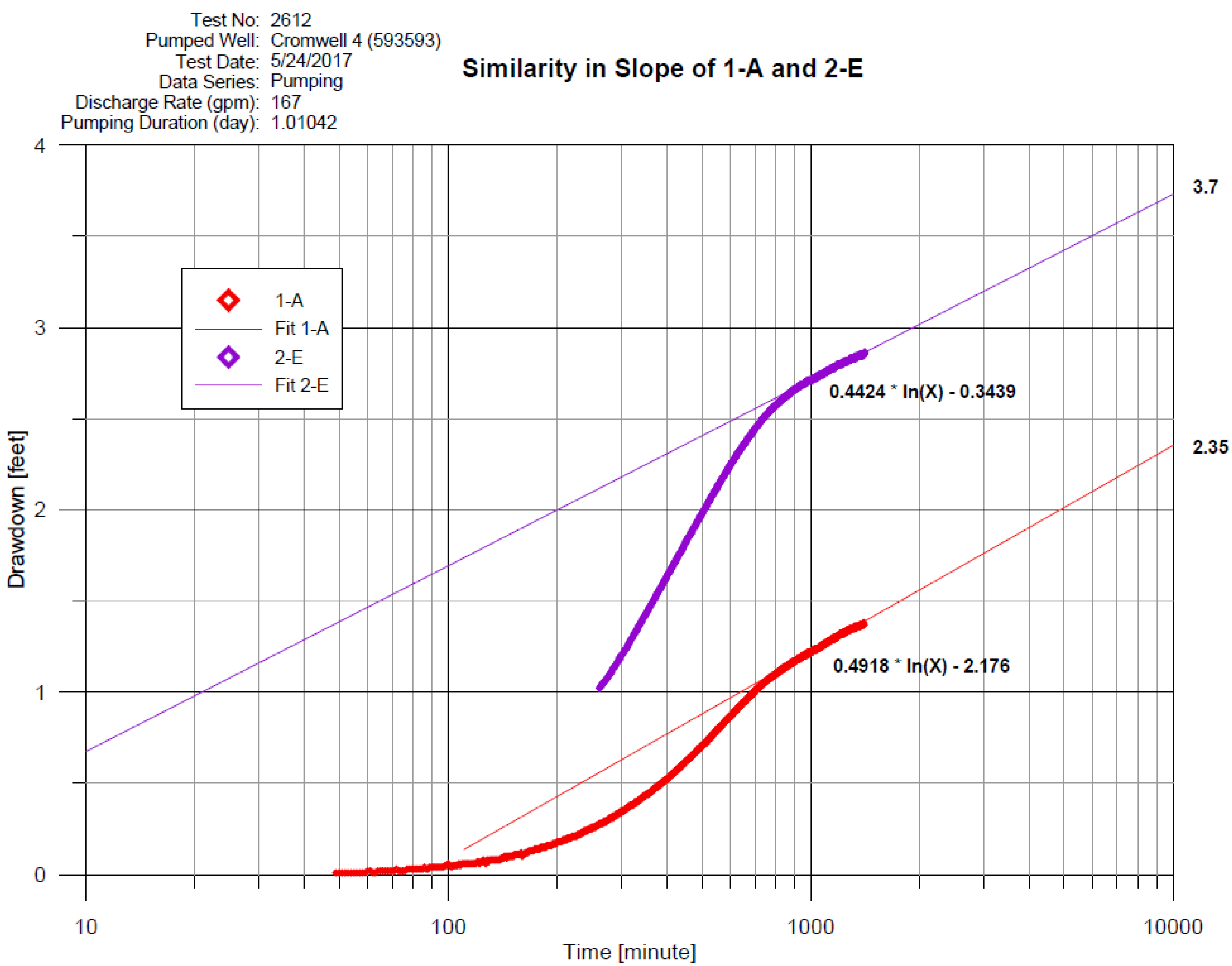
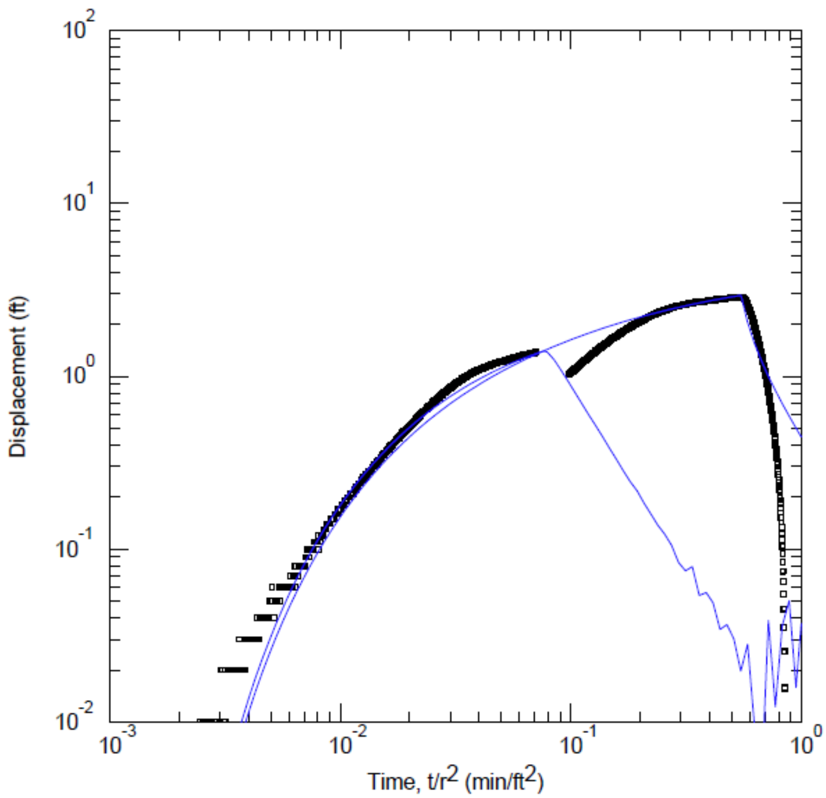


Figure 23. Solution of Aquifer Properties by Aqtesolv. Match to Data from USGS 1-A and USGS 2-E



WELL TEST ANALYSIS

Data Set: O:\...\24_cromwell4_1-A&2-E_neuman_composite.aqt
Date: 09/12/17 Time: 14:03:19

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 20. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ 1-A	140.6	0
▫ 2-E	0	51.7

SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 1589. ft^2/day
1/B = 0.004471 ft^{-1}
T2 = 10000. ft^2/day
S = 0.05497
ß/r = 7.276E-8 ft^{-1}
S2 = 0.3

L = 224 feet
kv = 130 * (0.00447)^2 * 1590 = 4.1 ft/day

Figure 24. Agarwal Analysis

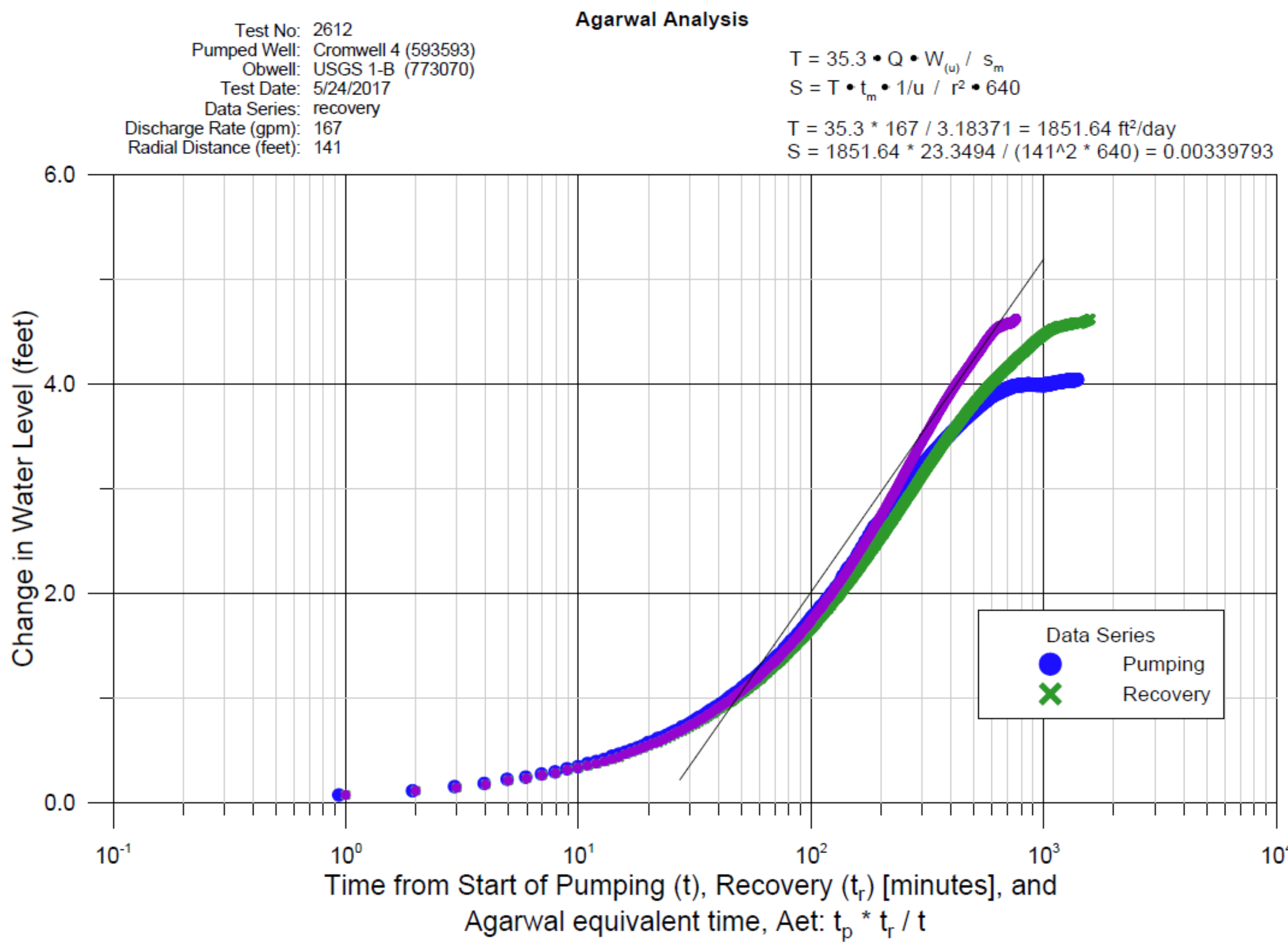
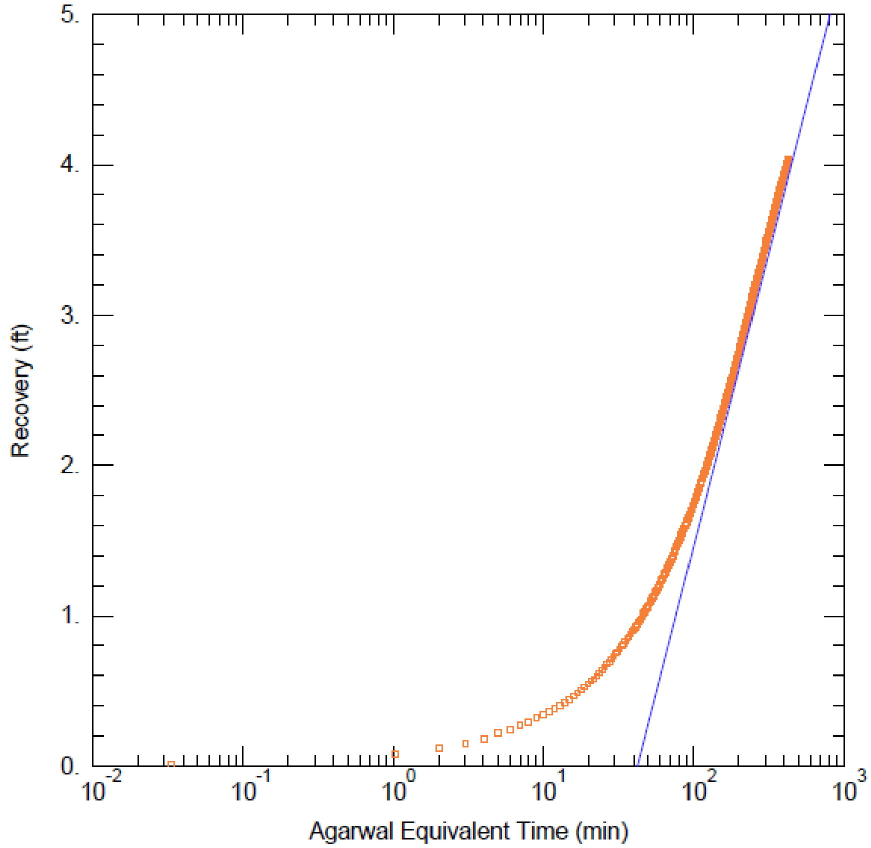


Figure 25. Solution of Aquifer Properties by Aqtesolv. Analysis of Recovery Data from Pumped Well



WELL TEST ANALYSIS

Data Set: O:\...\cromwell-4_nest-1-B_agarwal_theis.aqt
Date: 09/06/17 Time: 16:43:05

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
1-B	140.5	0

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob

T = 1511.4 ft^2/day S = 0.00504

Figure 26. Well Identification

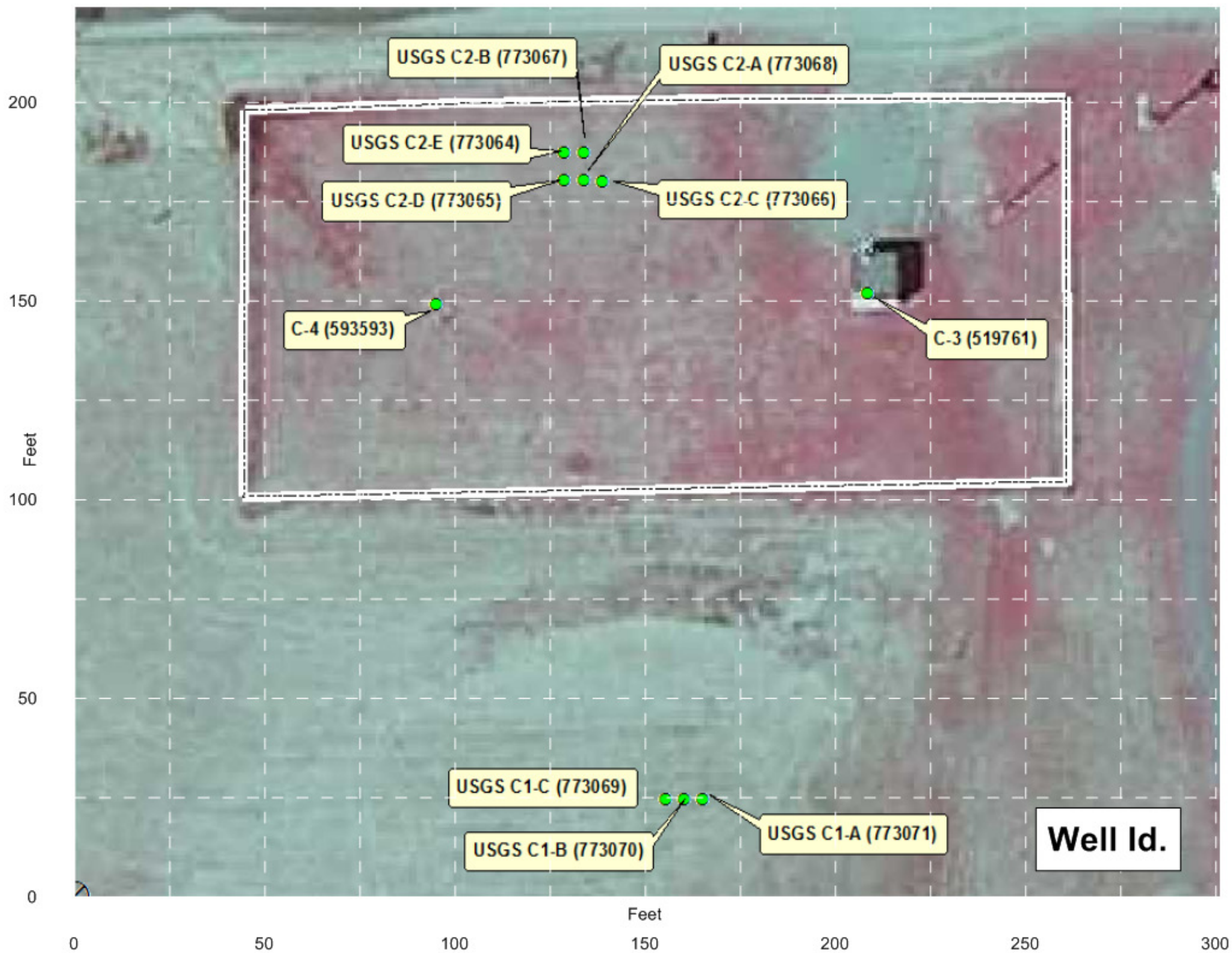


Figure 27. Distances between Wells and Well Nests

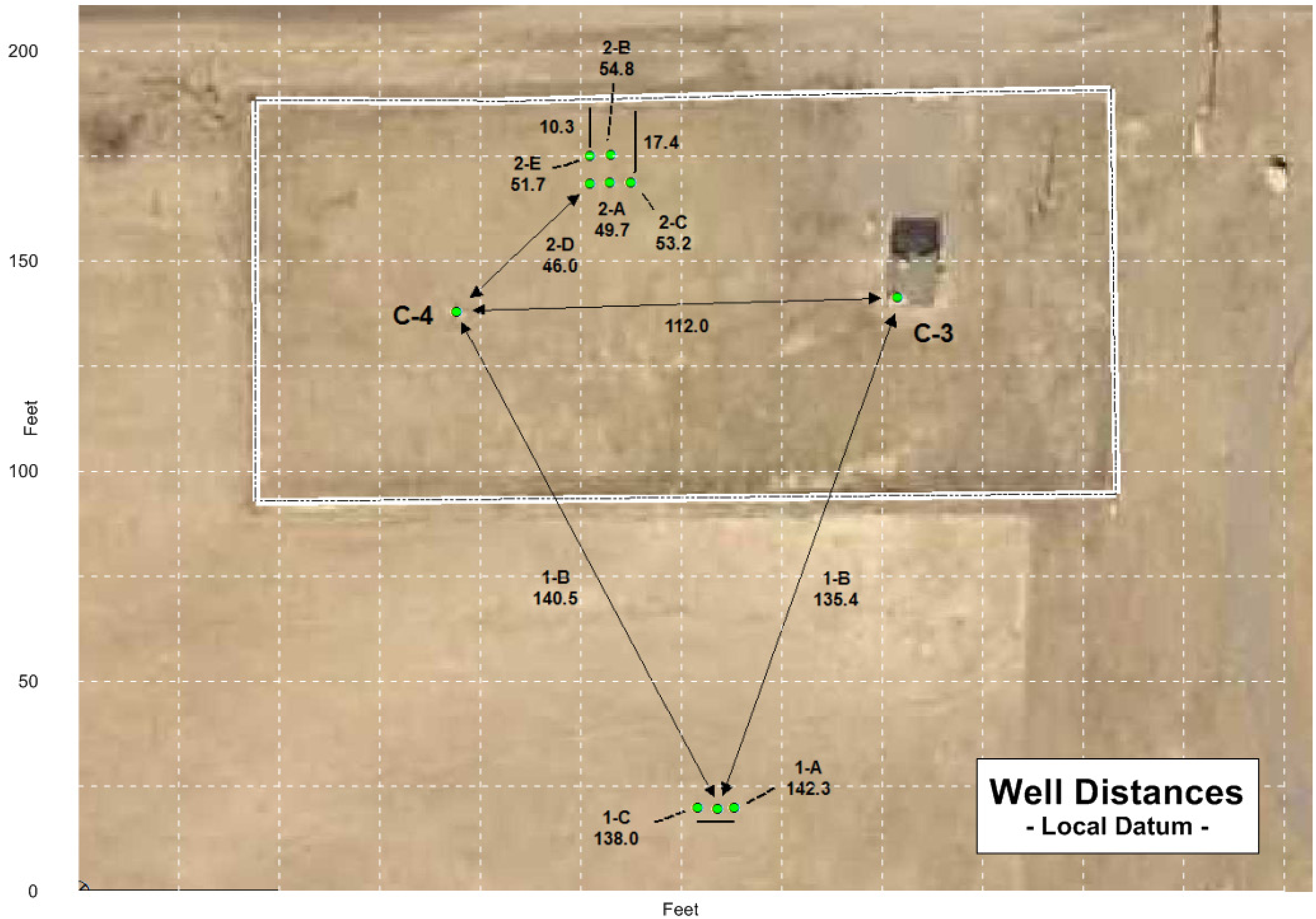
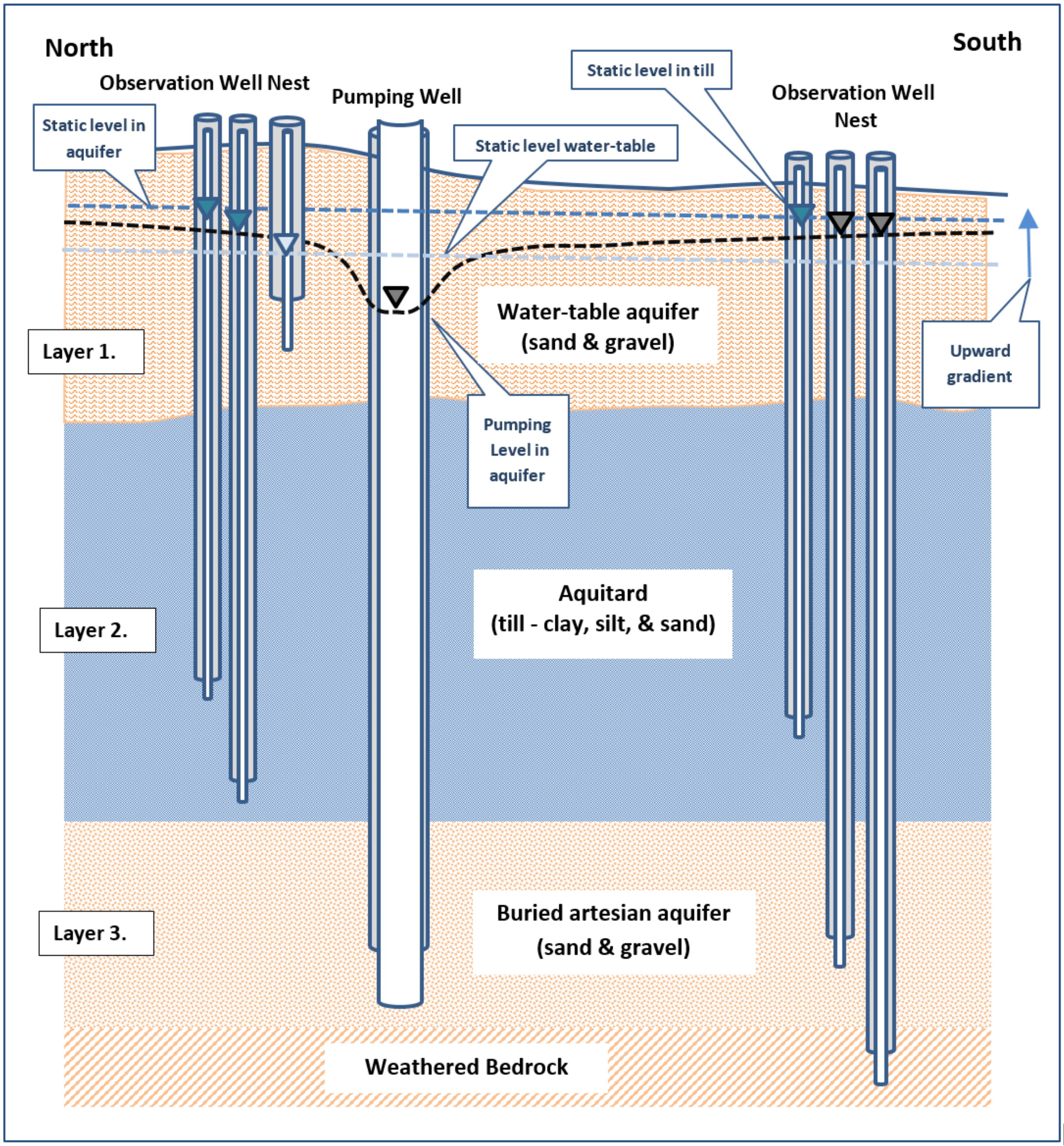


Figure 28. Schematic Section Across Site



Schematic Section

Figure 29. Time-series of Groundwater Elevation Collected at Cromwell 4.

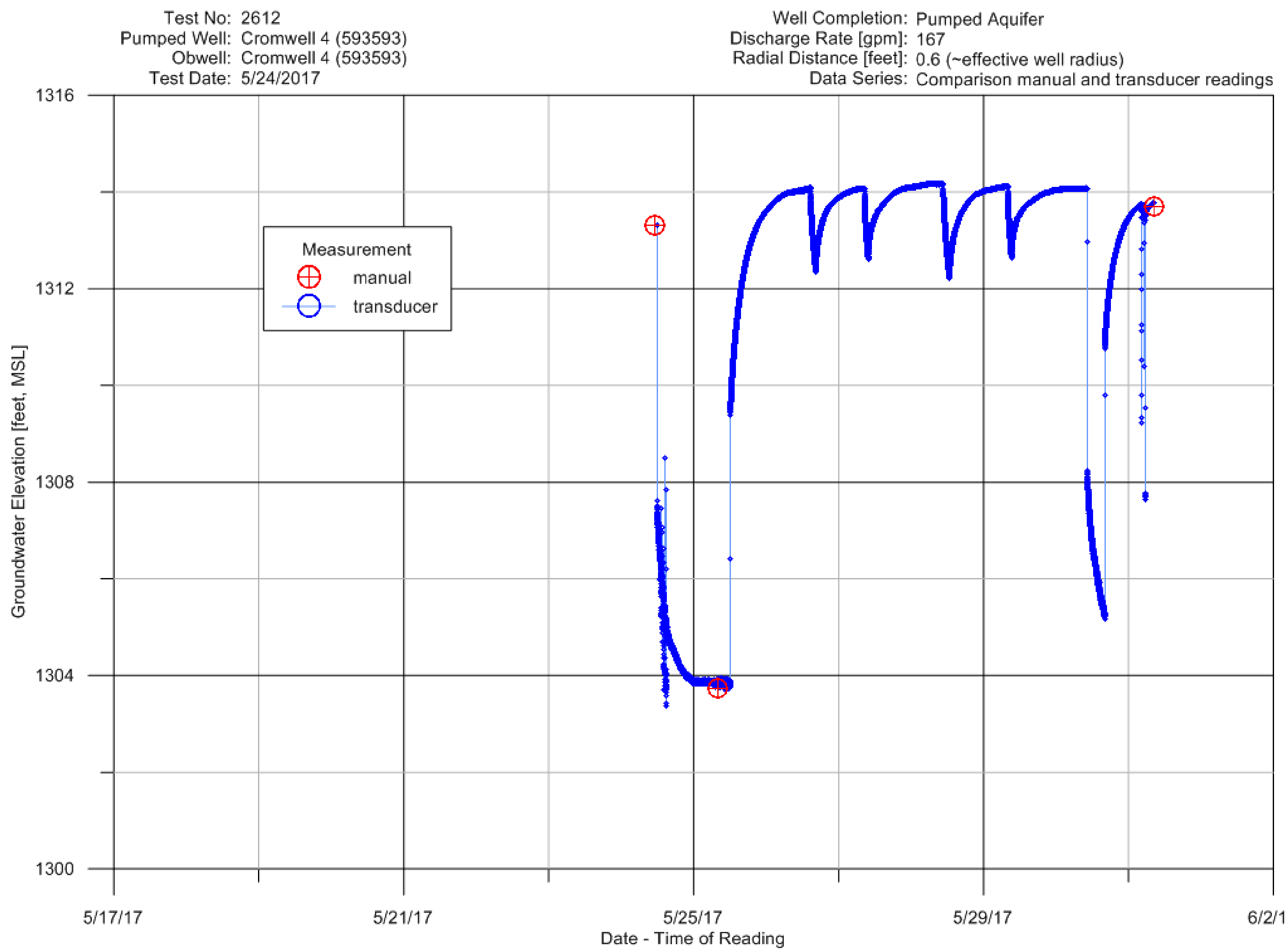


Figure 30. Time-series of Groundwater Elevation Collected at USGS 1-A.

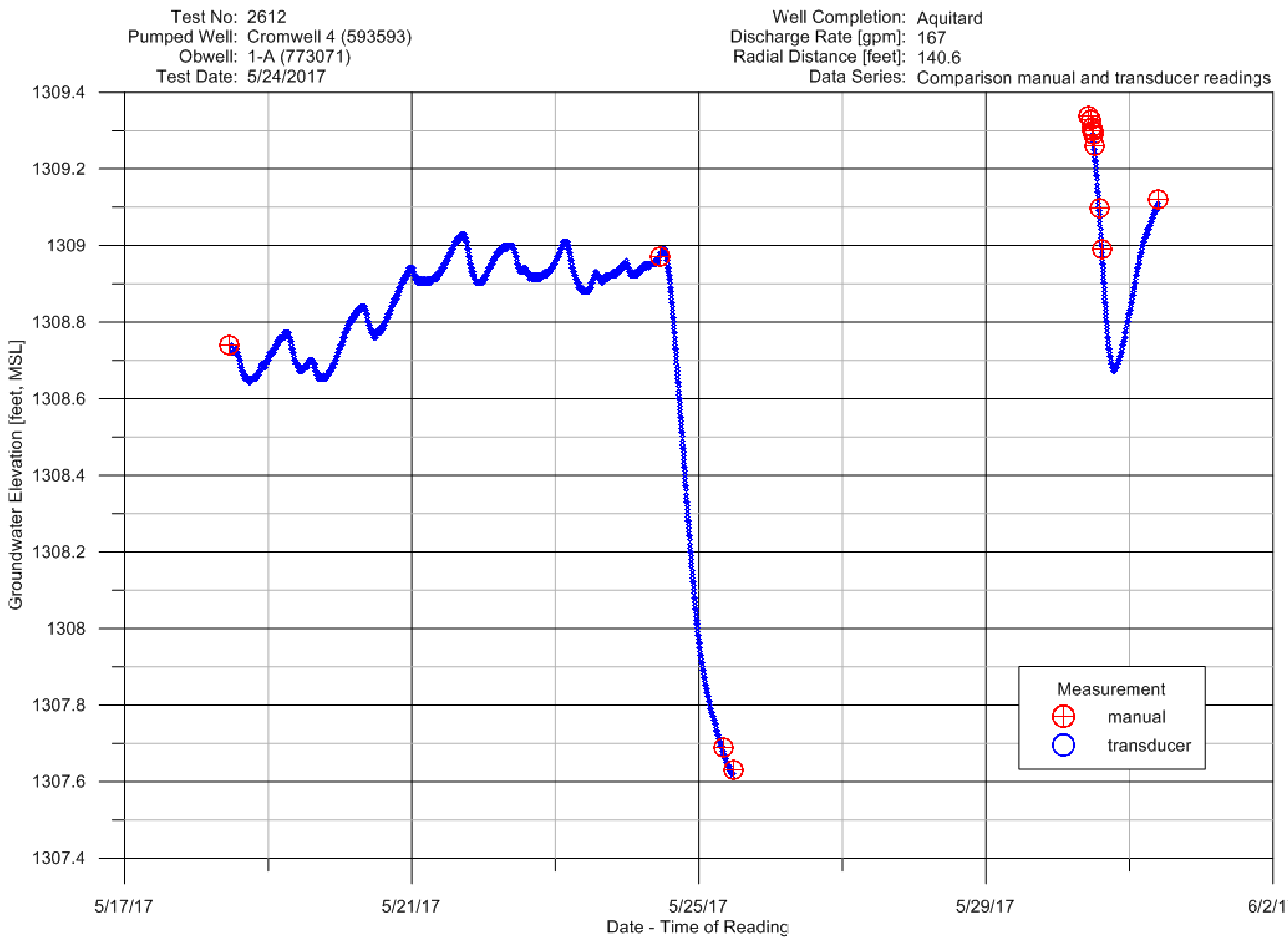


Figure 31. Time-series of Groundwater Elevation Collected at USGS 1-B

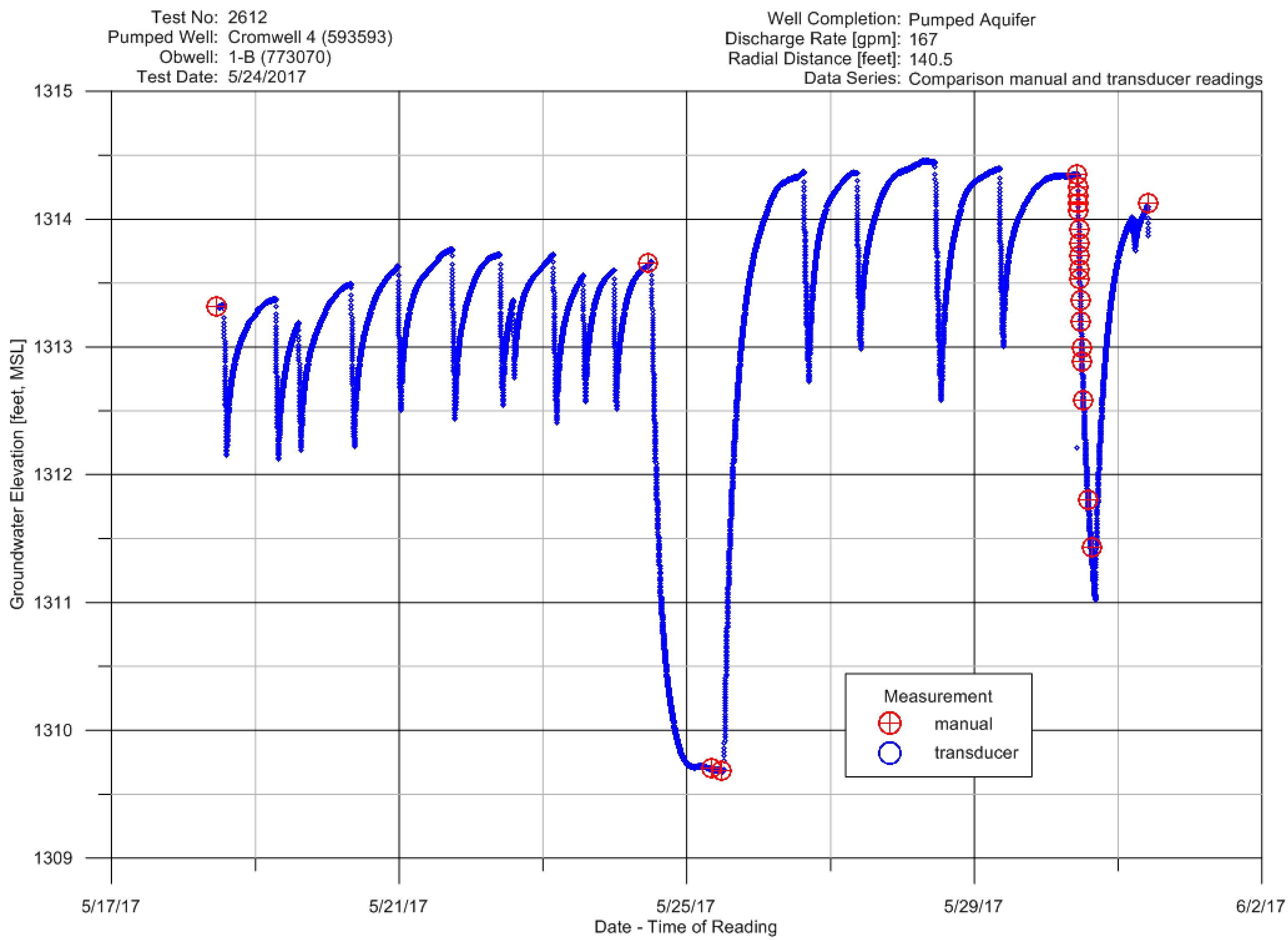


Figure 32. Time-series of Groundwater Elevation Collected at USGS 1-C

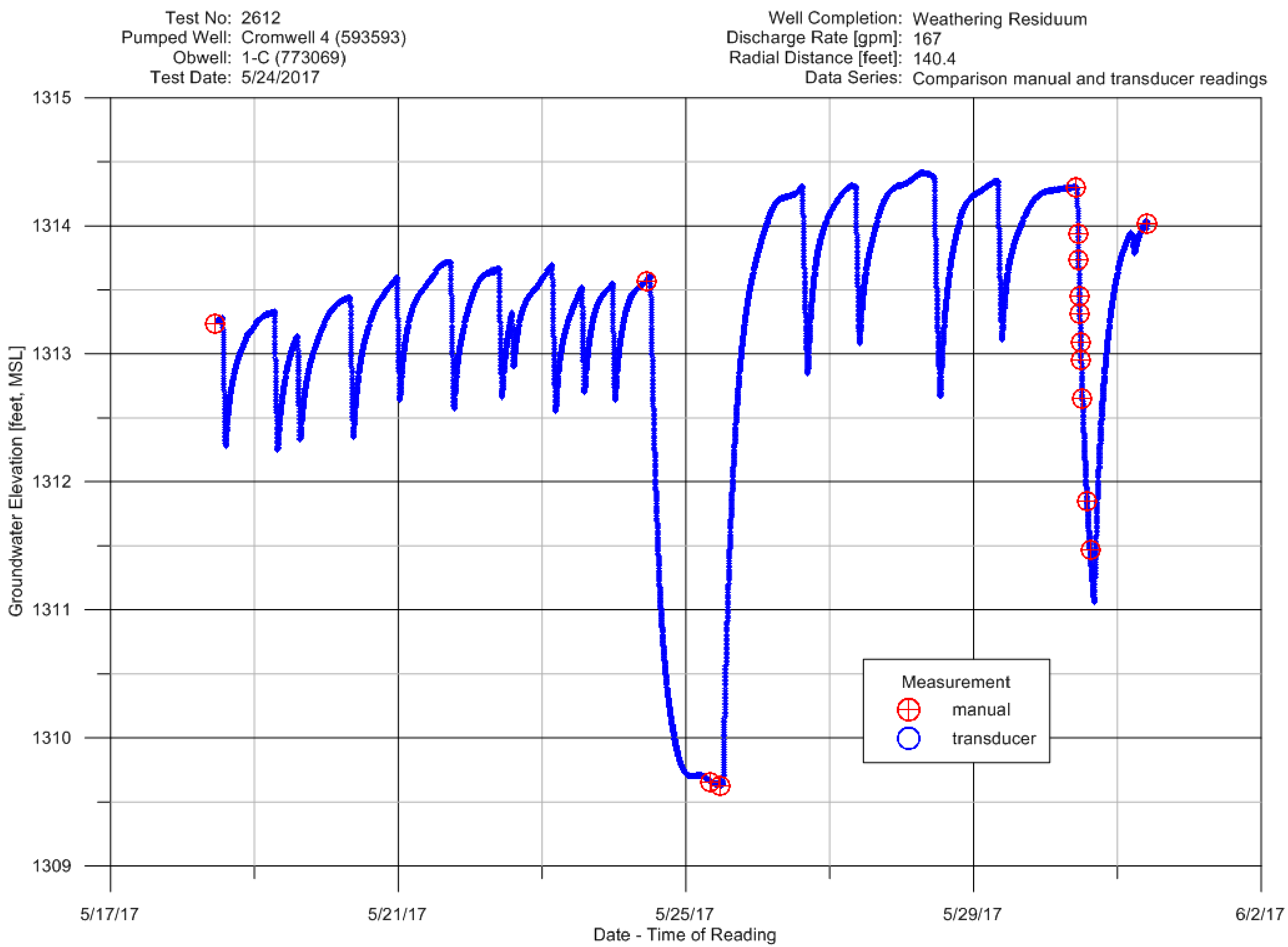


Figure 33. Time-series of Groundwater Elevation Collected at USGS 2-A

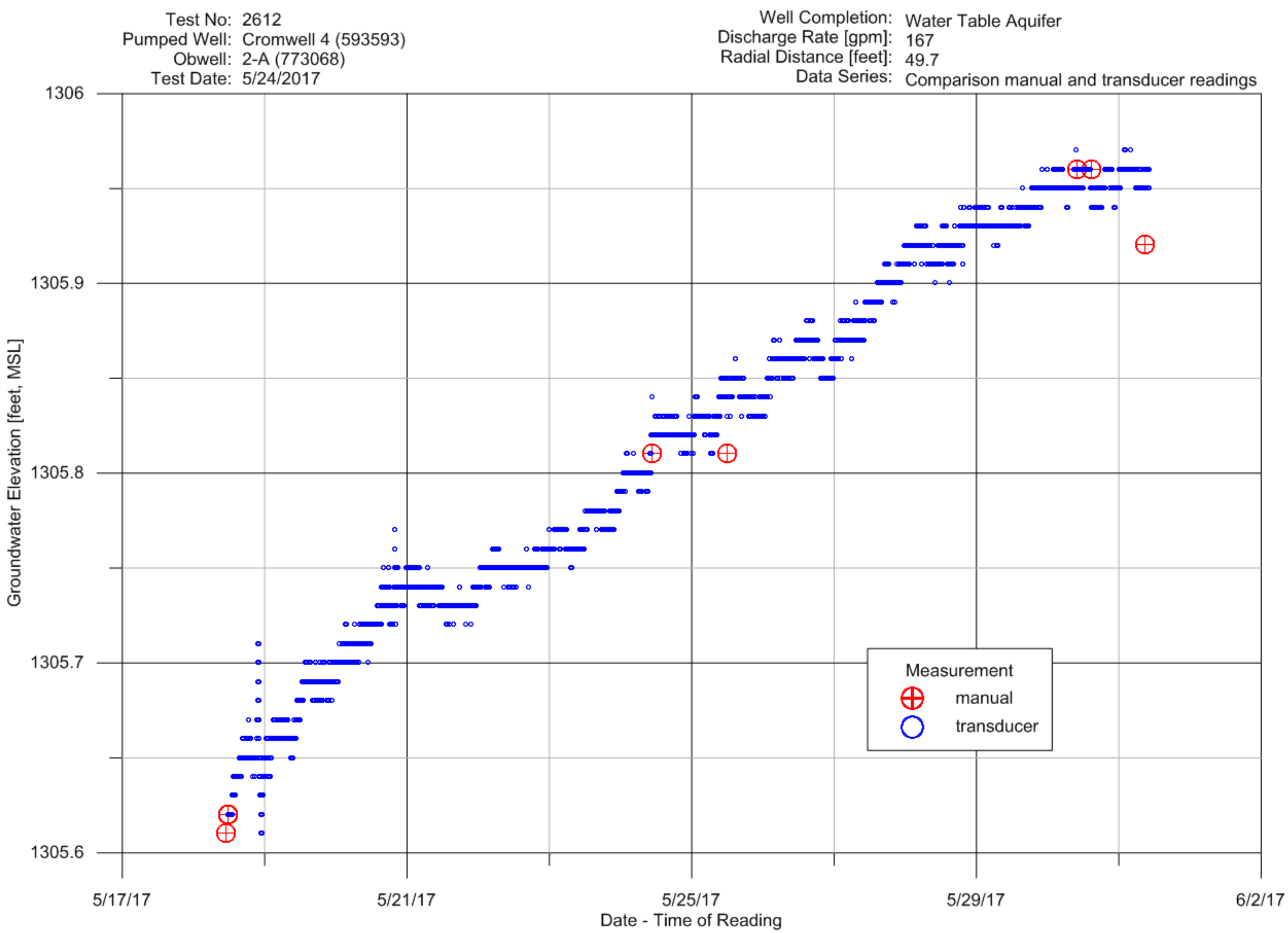


Figure 34. Time-series of Groundwater Elevation Collected at USGS 2-B

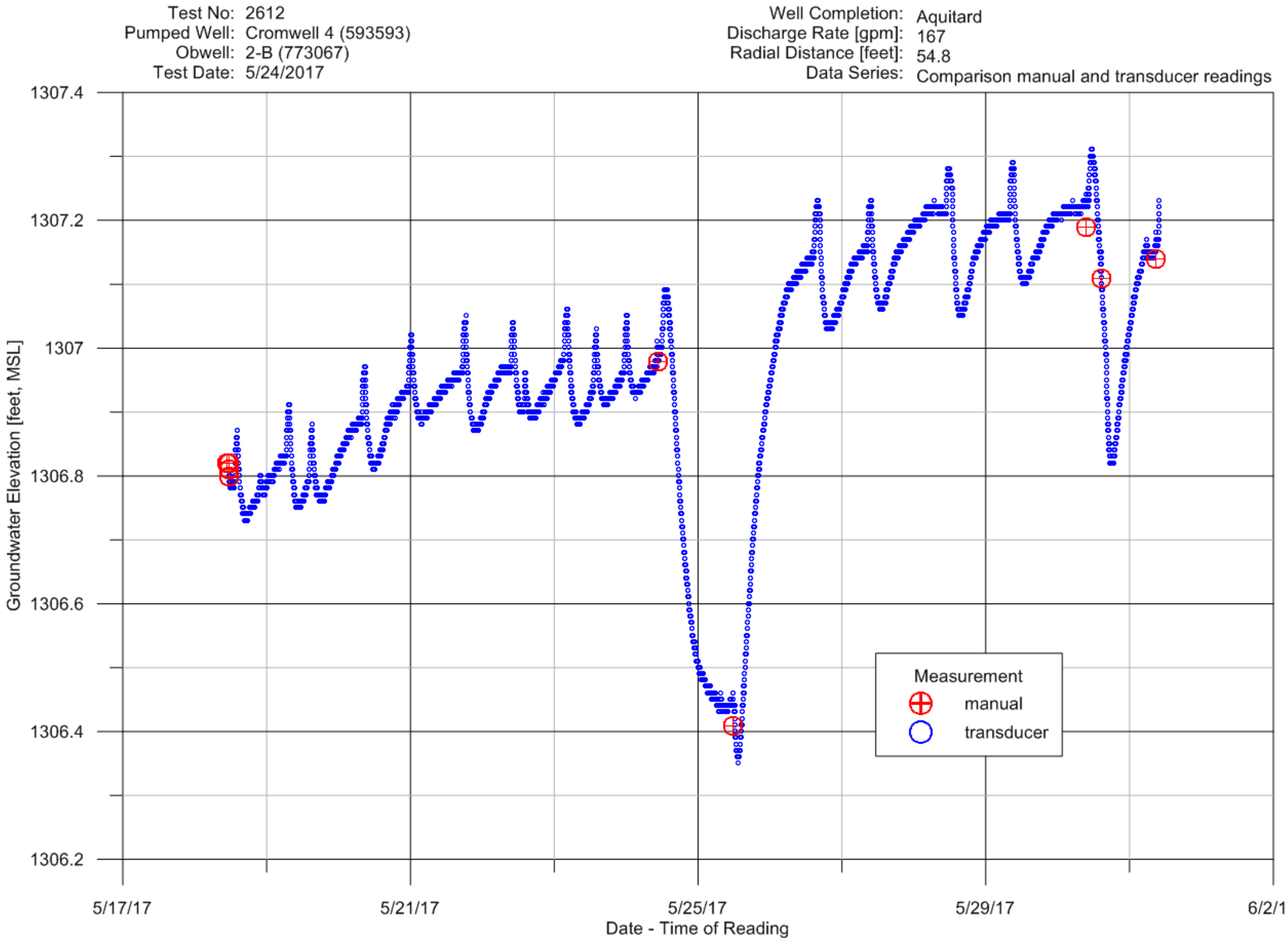


Figure 35. Time-series of Groundwater Elevation Collected at USGS 2-C

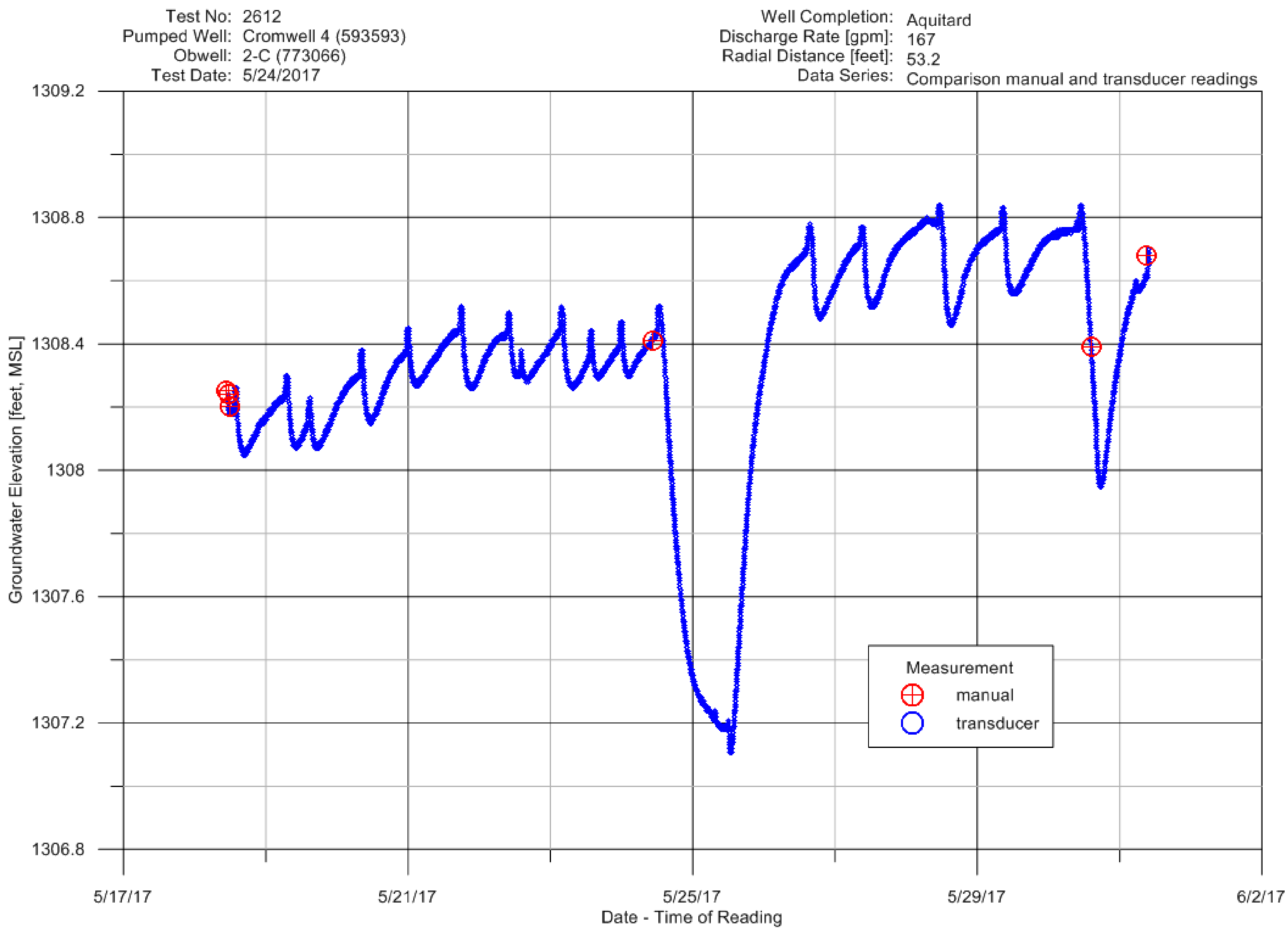


Figure 36. Time-series of Groundwater Elevation Collected at USGS 2-D

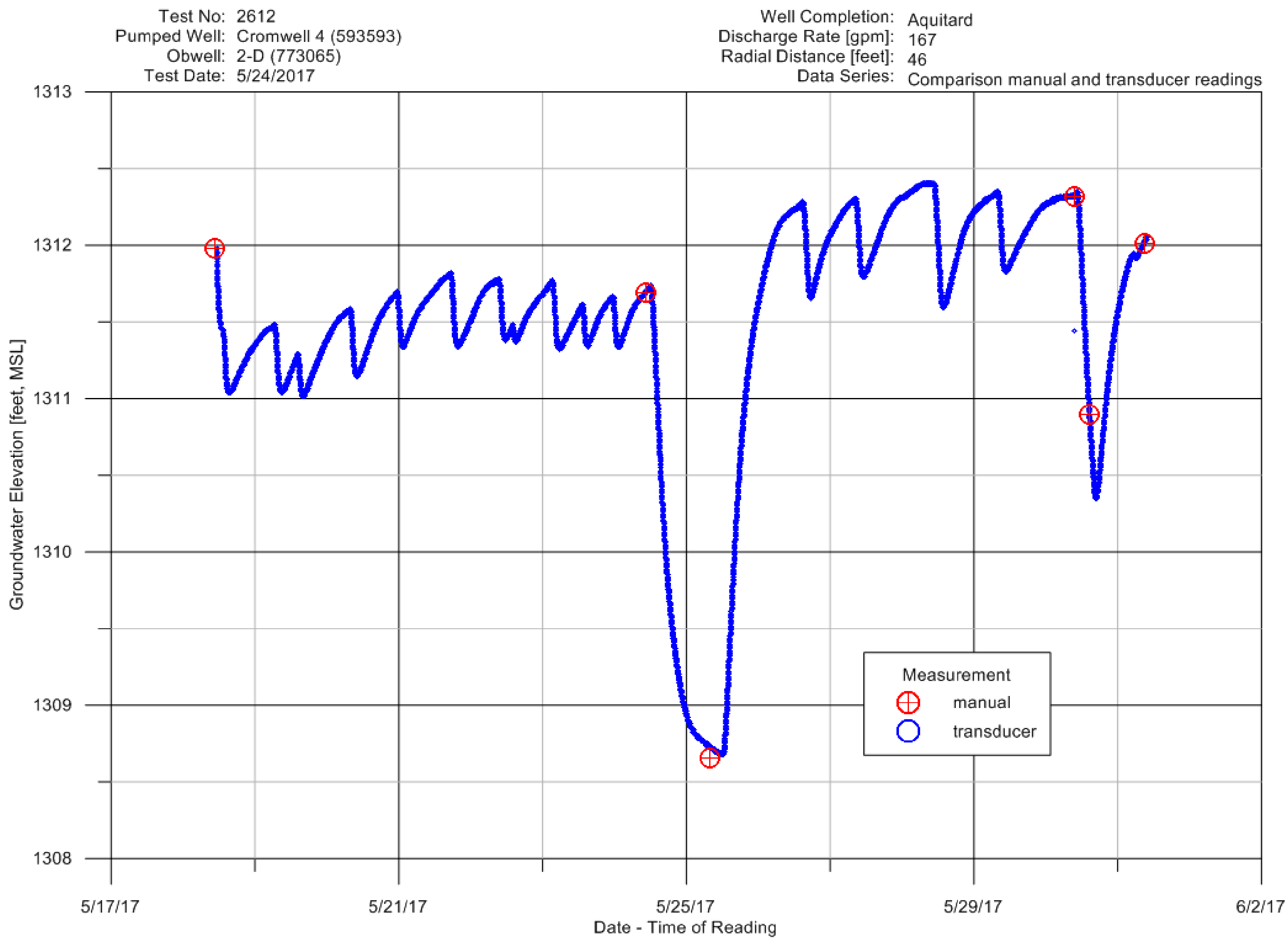


Figure 37. Time-series of Groundwater Elevation Collected at USGS 2-E

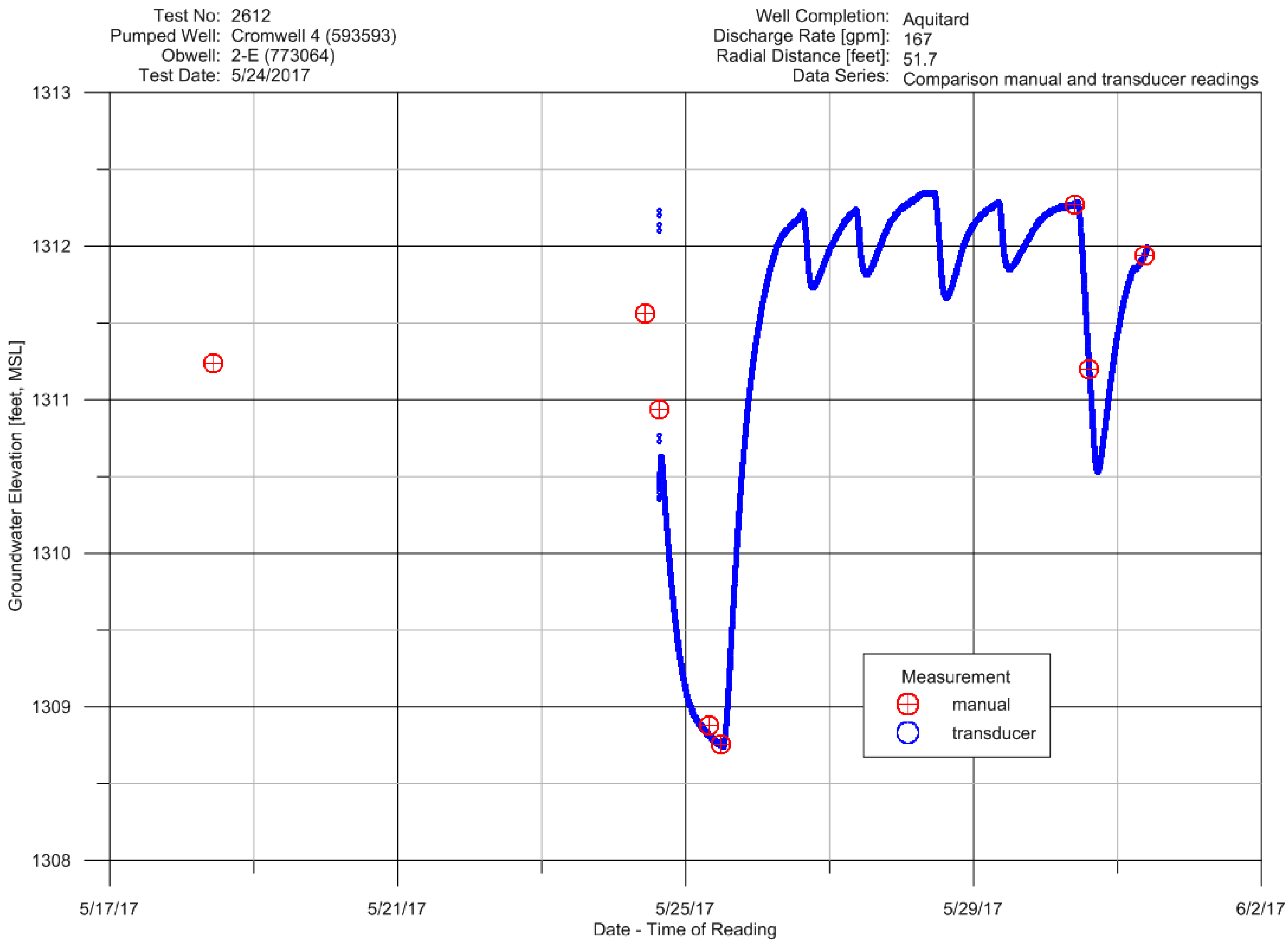


Figure 38. Time-series of Groundwater Elevation Collected at all Wells

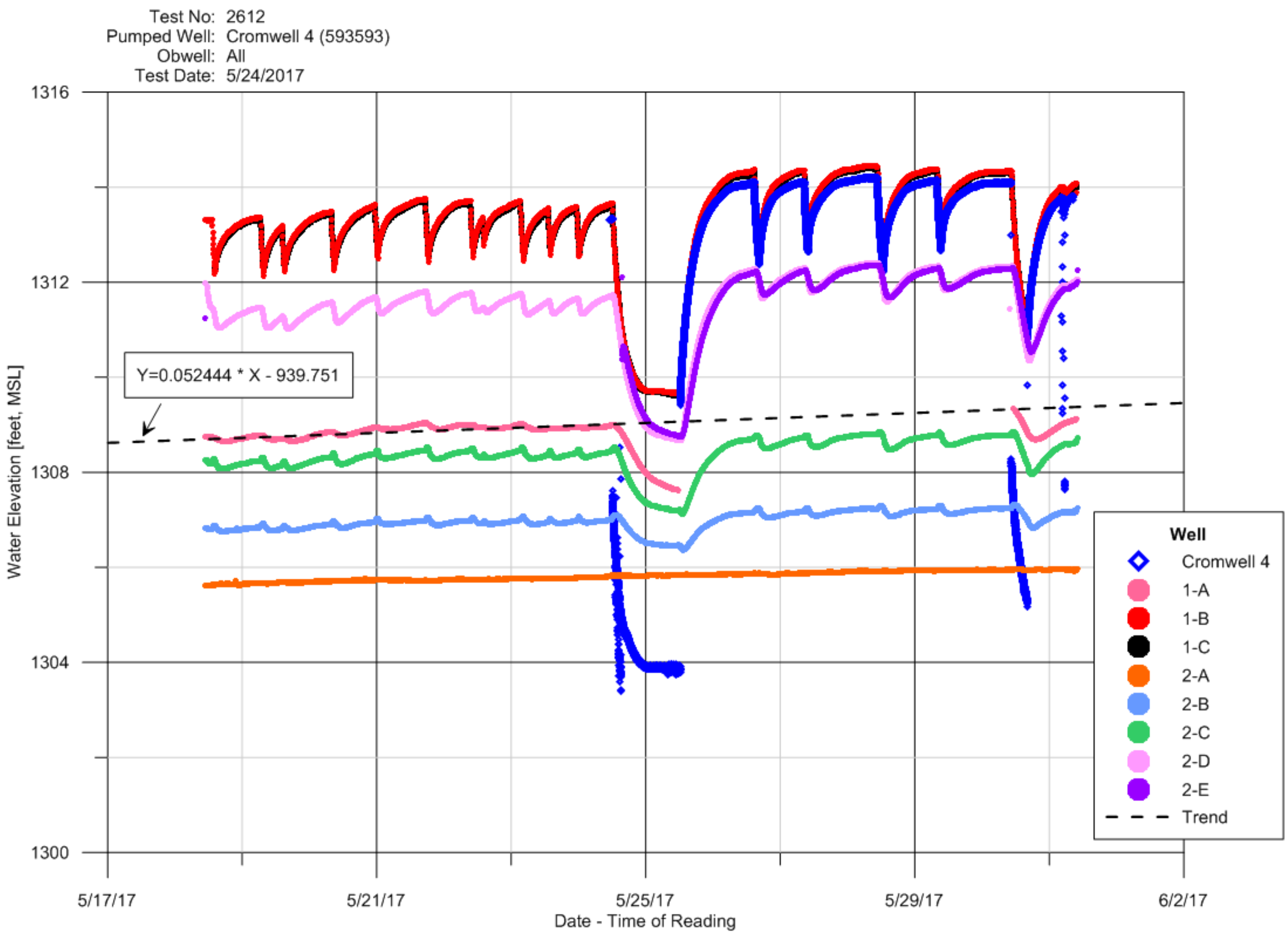


Figure 39. Time-series of Groundwater Elevation Collected at Cromwell 4 and Nest 1

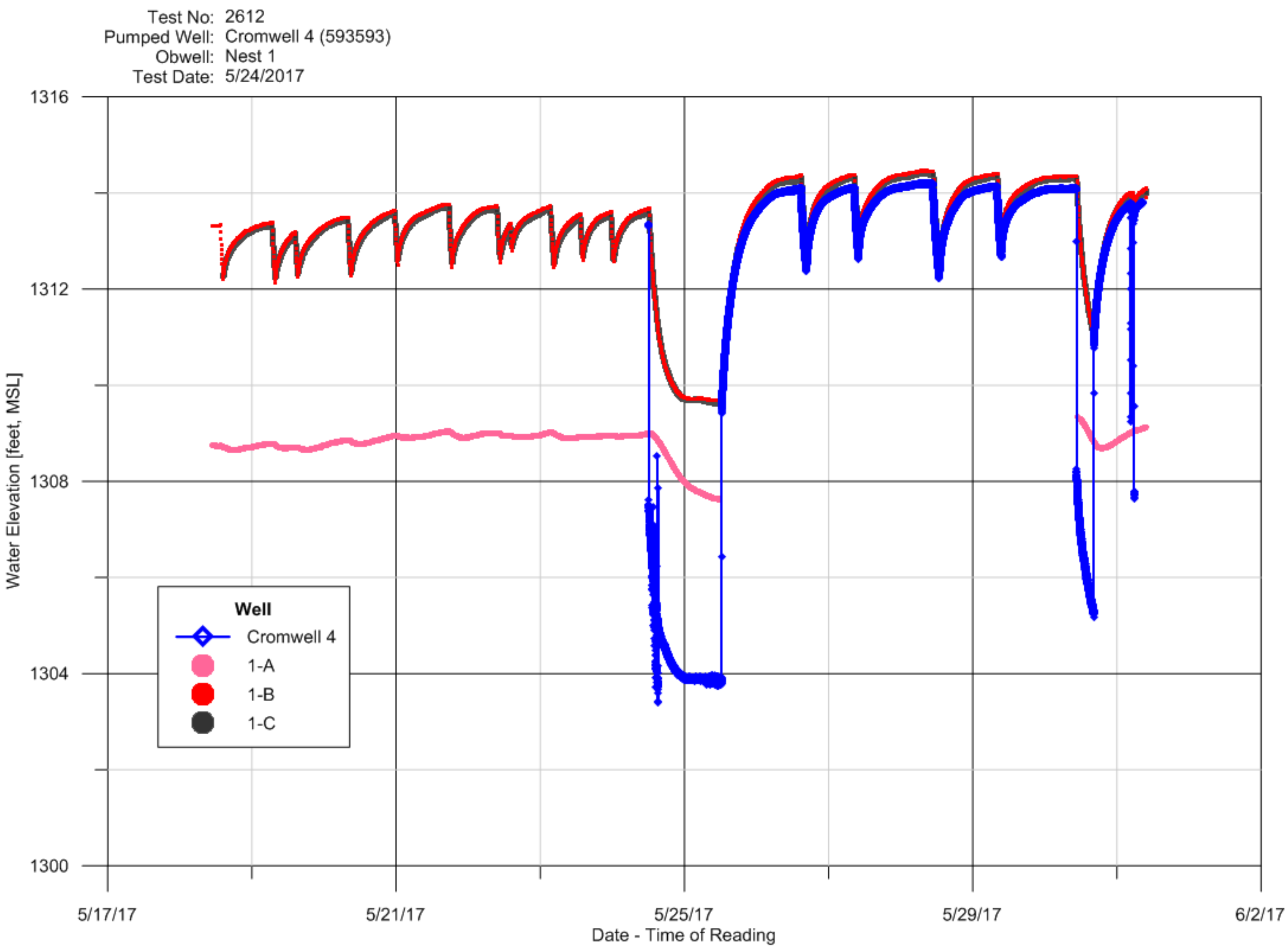


Figure 40. Time-series of Groundwater Elevation Collected at Cromwell 4 and Nest 2

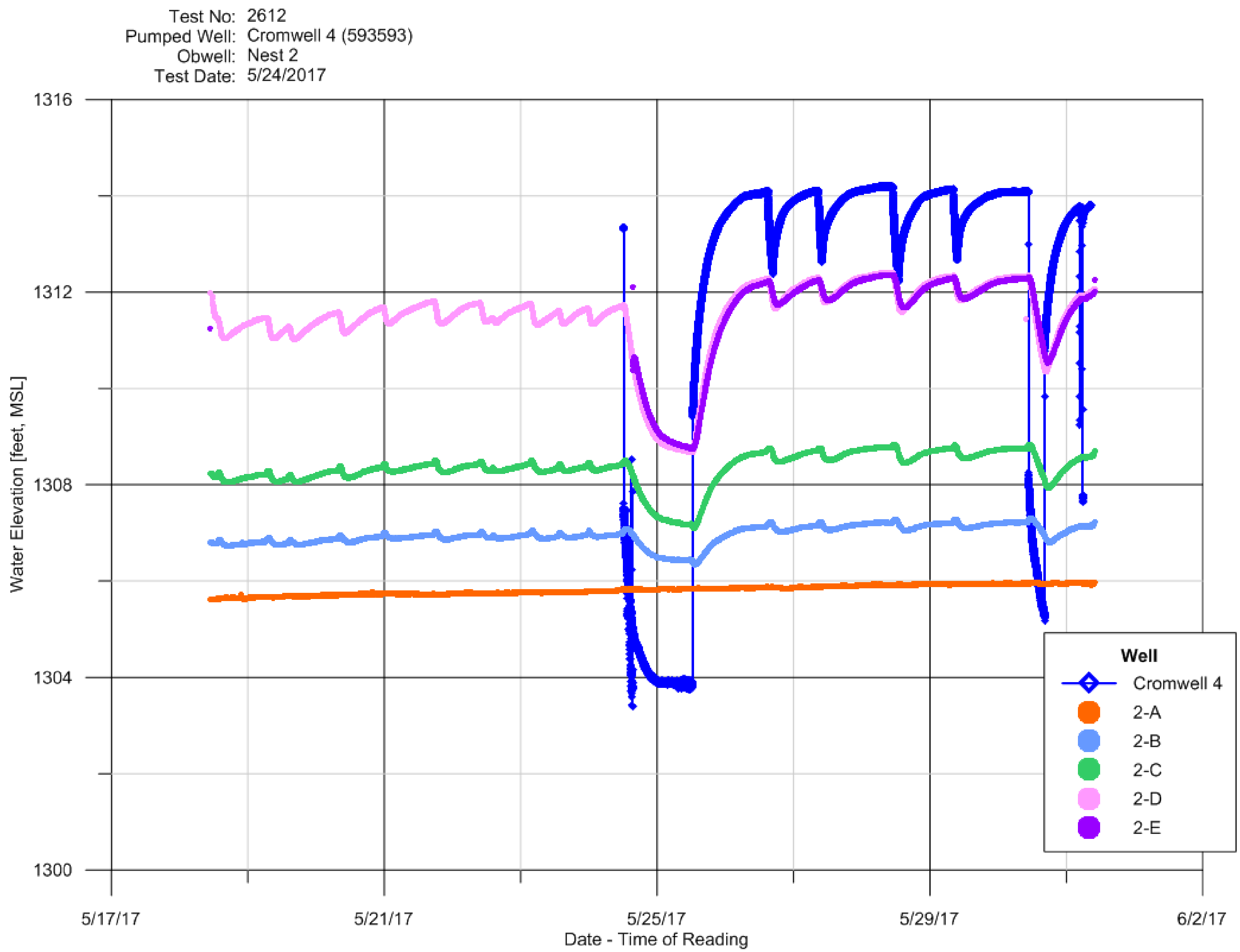


Figure 41. Time-series of Groundwater Elevation Collected at USGS 2-A and Barometric Pressure as Difference in Water Level

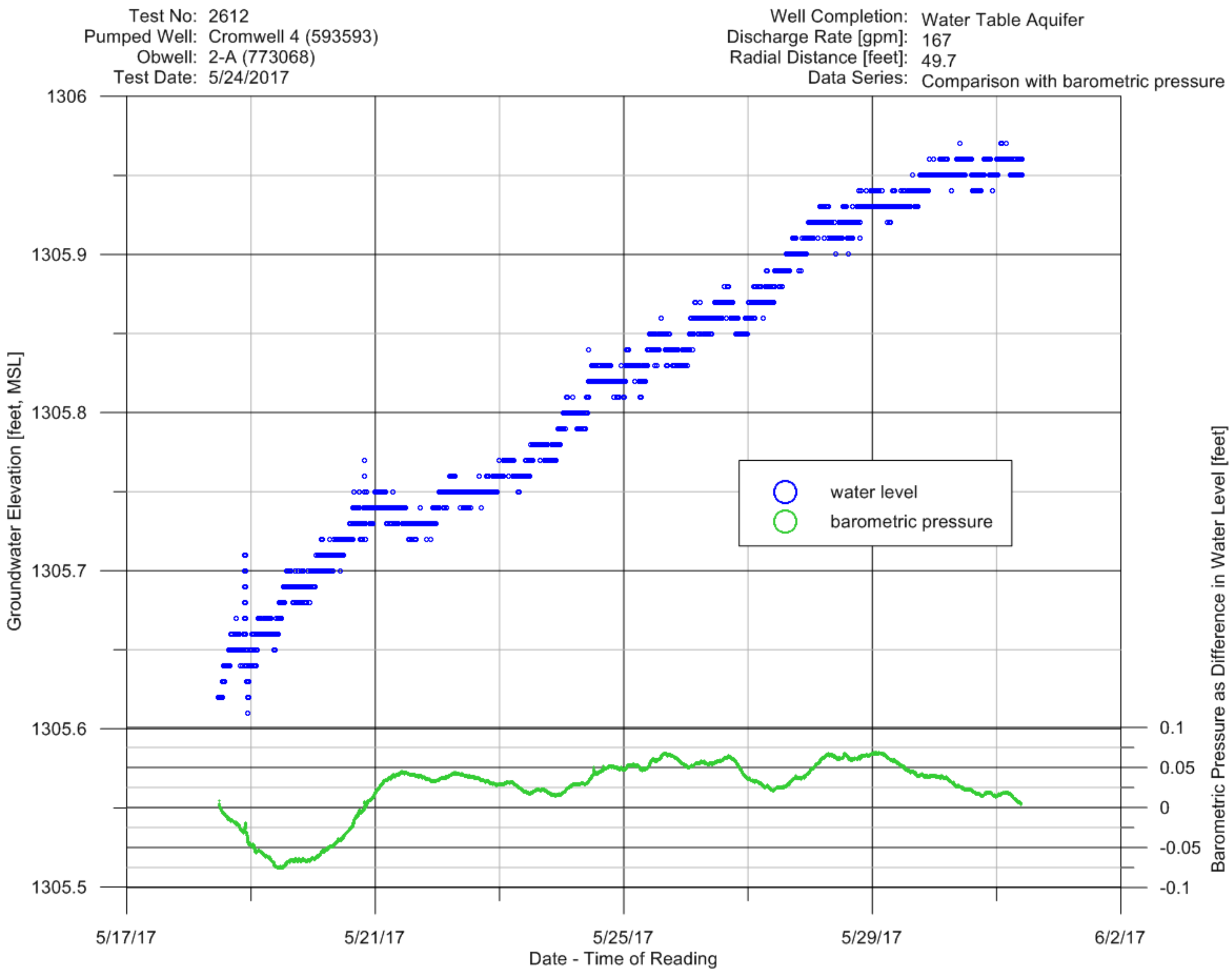
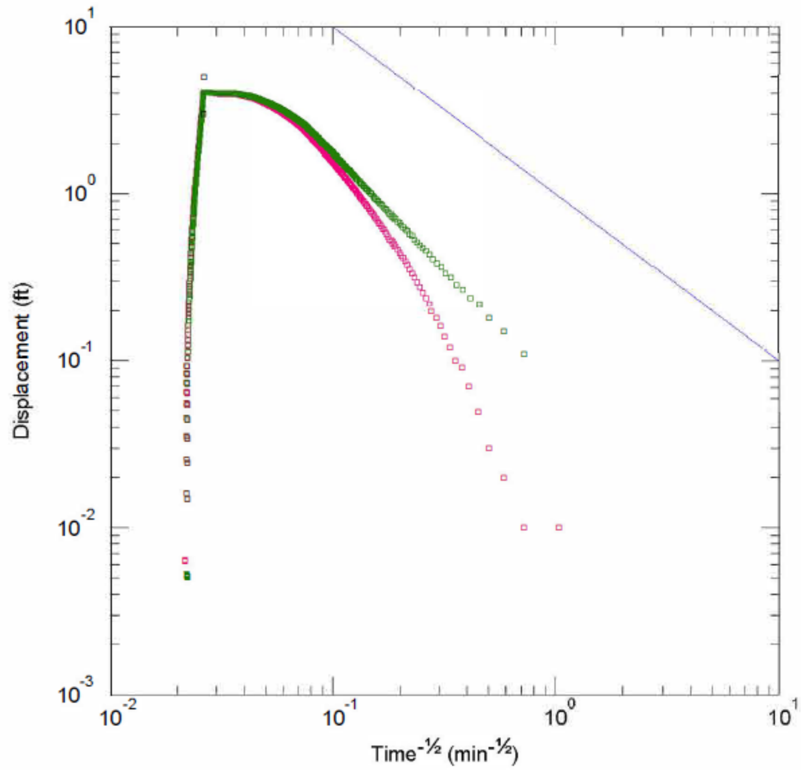


Figure 42. Aqtesolv plot of diagnostic slope for spherical flow and data from USGS 1-B and 1-C



WELL TEST ANALYSIS

Data Set: O:\...\cromwell_nest-1_hantush_partial_1-Bonly_spherical.aqt
Date: 08/18/17 Time: 16:44:40

PROJECT INFORMATION

Company: MDH
Client: City of Cromwell
Location: Cromwell 4
Test Well: C-4 (593593)
Test Date: 5/24/2017

AQUIFER DATA

Saturated Thickness: 145. ft
Aquitard Thickness (b'): 130. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 20. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Cromwell 4	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
1-C	139	0
1-B	140.5	0
1-A	142	0
Nest 1	141	0
Nest 2	0	50

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 1043.9 ft^2/day
1/B = 0.004064 ft^{-1}
C = 0. min^2/ft^5
S = 0.005146
Sw = 0.
P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min
$s(t) = 5.641E\text{-}19Q + 0.Q^2$
W.E. = 100.% (Q from last step)

Figure 43. Conventional log-log plot of drawdown and recovery at USGS 1-B with Walton (1960) leaky type-curve

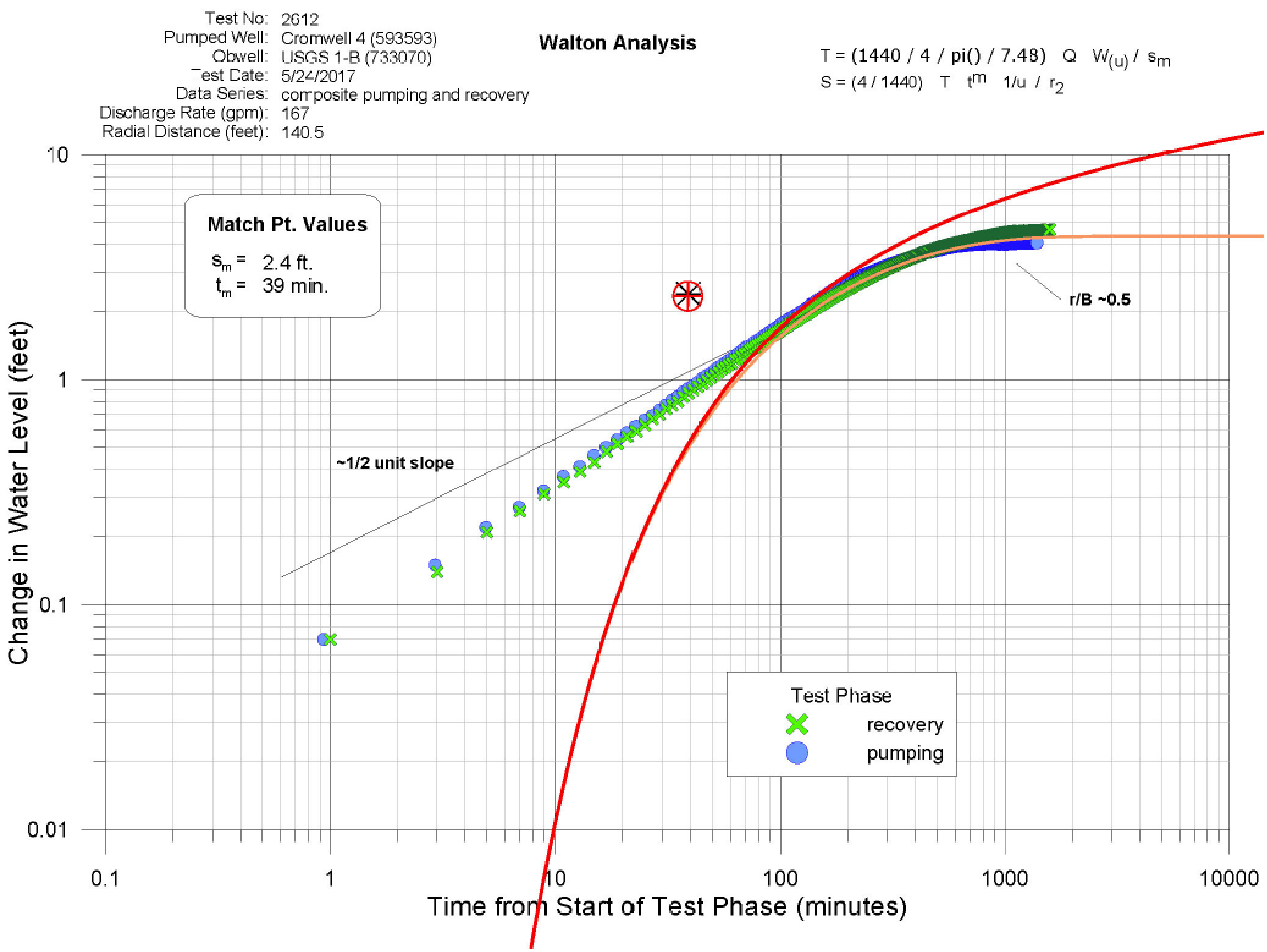


Figure 44. Conventional log-log plot of drawdown and recovery at USGS 1-C with Walton (1960) leaky type-curve

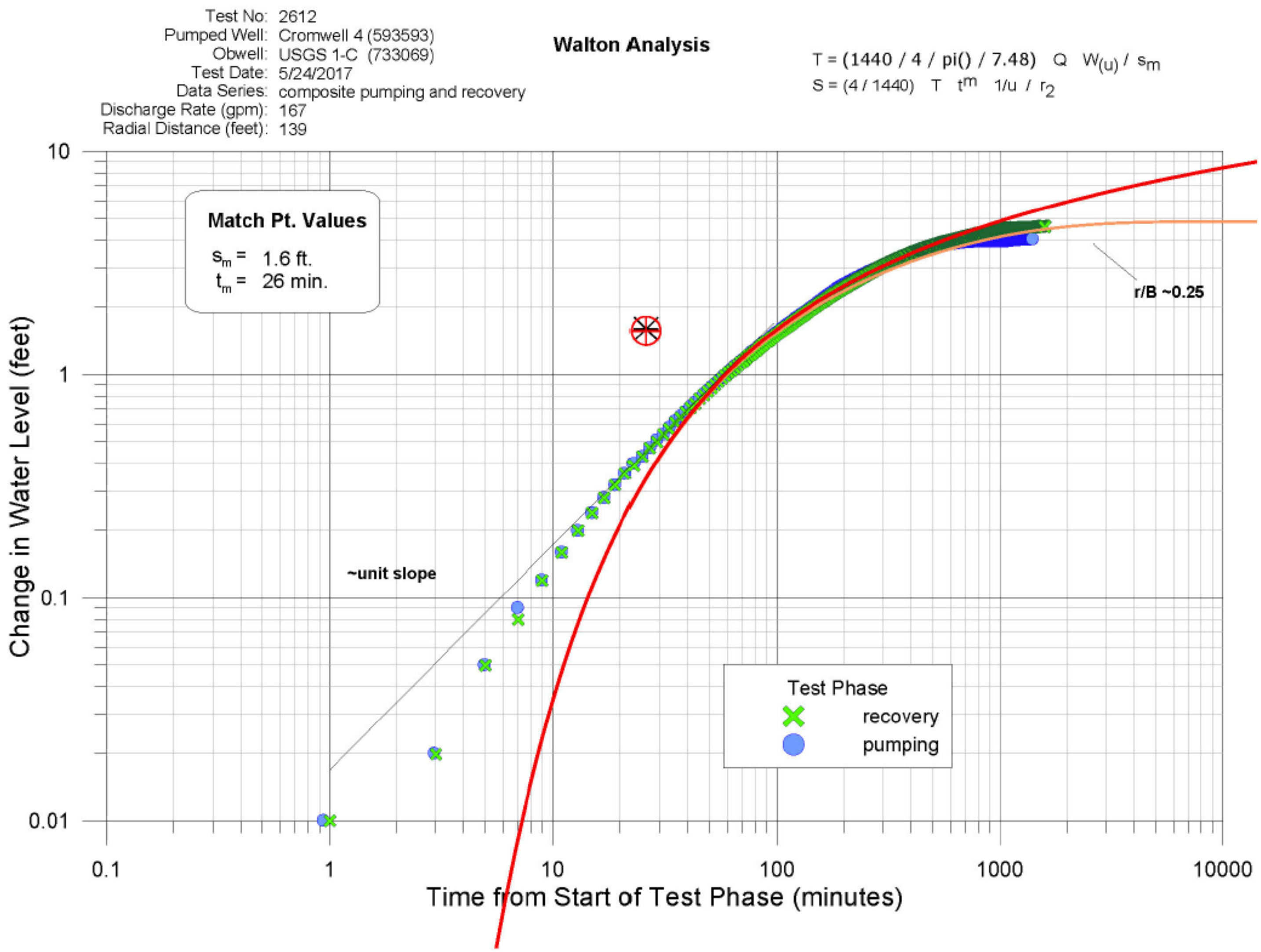


Figure 45. Well and Boring Report - Well 593593

Minnesota Unique Well Number

593593

County: Carlton
Quad: Cromwell
Quad ID: 226B

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date: 03/22/2000
Update Date: 03/10/2014
Received Date:

Well Name	Township	Range	Dir Section	Subsection
CROMWELL 4	49	20	W 33	CABABA

Elevation: 1329 Elev. Method: 7.5 minute topographic map (+/- 5 feet)

Address

Contact: P.O. BOX 74 CROMWELL MN 55726

Well: CROMWELL MN 55726

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
CLAY	0	5	BROWN	MEDIUM
SAND	5	40	BROWN	SOFT
CLAY	40	80	BROWN	MEDIUM
CLAY	80	175	GRAY	HARD
SAND/GRAVEL	175	200	GRAY	MEDIUM
SAND	200	240	GRAY	SOFT
SAND/GRAVEL	240	250	GRY/BLK	MEDIUM

Remarks

DRILLING METHOD: STAR DRILL.
LOCATION: VILLA VISTA CIRCLE

Well Depth: 250 ft. **Depth Completed:** 230 ft. **Date Well Completed:** 04/16/1999

Drill Method: Cable Tool Drill Fluid: Bentonite

Use: community supply(municipal) Status: Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type: Single casing Joint: Welded

Drive Shoe? Yes ☒ No ☐ Above/Below

Casing Diameter	Weight	Hole Diameter
8 in. To 210 ft.	28.5 lbs./ft.	14 in. To 230 ft.

Open Hole: From ft. To ft.

Screen? ☒ Type: stainless Make: JOHNSON

Diameter	Slot/Gauze	Length	Set
8 in.	50	22 ft.	210 ft. 230 ft.

Static Water Level

21.2 ft. land surface Measure 04/16/1999

Pumping Level (below land surface)

23.5 ft. 5 hrs. Pumping at 310 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model

☒ Casing Protection ☒ 12 in. above grade

☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	70 Sacks	0 ft.	180 ft.

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed: 05/00/1999

Manufacturer's name: GRUNDFOS

Model Number: 150S75-4 HP: 7.5 Volt: 230

Length of drop pipe: 60 ft Capacity: 150 g.p. Typ: Submersible

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer: Quat. buried

Last Strat: sand +larger Depth to Bedrock ft

Located by: Minnesota Department of Health

Locate Method: Digitization (Screen) - Map (1:24,000)

System: UTM - NAD83, Zone 15, Meters X 508617 Y 5170337

Unique Number Verification Input Date 08/09/2000

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Renner E.H. Well	71015	PRAUGHT, V.

Minnesota Well Index Report 593593

Printed on 05/19/2017
HE-01205-15

Figure 46. Well and Boring Report - Well 519761

Minnesota Unique Well Number **519761**

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 03/04/1993
Update Date 03/10/2014
Received Date

Well Name	Township	Range	Dir Section	Subsection
CROMWELL 3	49	20	W 33	CABAAB

Elevation 1325 Elev. Method Calc from DEM (USGS 7.5 min or equiv.)

Address
Contact P.O. BOX 74 CROMWELL MN 55726
Well CROMWELL MN 55726

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SANDY CLAY	0	12	BROWN	MEDIUM
SAND WITH CLAY	12	30	BROWN	MEDIUM
SAND	30	55	BROWN	SOFT
FINE SAND	55	62	BROWN	SOFT
FINE SAND & ROCKS	62	90	BROWN	HARD
COARSE SAND	90	92	BROWN	SOFT
CEMENTED SAND &	92	112	BROWN	HARD
CEMENTED SAND &	112	132	BROWN	MEDIUM
CEMENTED SAND &	132	172	BROWN	MED-HRD
MIXED SAND	172	180	BROWN	SOFT
COARSE SAND	180	190	BROWN	SOFT

Remarks

Well Depth 190 ft. Depth Completed 190 ft. Date Well Completed 10/21/1992

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use community supply(municipal) Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint Welded
Drive Shoe? Yes ☒ No ☐ Above/Below 0 ft.

Casing Diameter Weight Hole Diameter
8 in. To 180 ft. 28.5 lbs./ft. 10 in. To 190 ft.

Open Hole From ft. To ft.

Screen? ☒ Type stainless Make COOK
Diameter Slot/Gauze Length Set
8 in. 25 10 ft. 180 ft. 190 ft.

Static Water Level
16 ft. land surface Measure 10/20/1992

Pumping Level (below land surface)
32.1 ft. 24 hrs. Pumping at 290 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	0	0 ft.	180 ft.

Nearest Known Source of Contamination
100 feet Southeas Direction Septic tank/drain field Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP 0 Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand-brown Depth to Bedrock ft
Located by Minnesota Department of Health
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508644 Y 5170337
Unique Number Verification Information from Input Date 10/18/1999

Angled Drill Hole

Well Contractor
Petersen Well Co. 69183 PETERSEN, D.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 519761 Printed on 05/19/2017 HE-01205-15

Figure 47. Well and Boring Report - Well 773071

Minnesota Unique Well Number **773071**

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/21/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO1-A	49	20	W 33	CABADB

Elevation 1325.9 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Contact 1220 VILLA COURT DR CROMWELL MN 55726
Well 1189 VILLA VISTA CI CROMWELL MN 55726
[illegible]ODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
GRAVEL WITH SAND &	0	8	BRN/RED	SOFT
SILT, SAND & CLAY W/	8	11	RED/BRN	MEDIUM
GRAVEL & SAND WITH	11	22	GRAY	MEDIUM
SAND & GRAVEL WITH	22	43	GRAY	MEDIUM
SAND WITH SILT &	43	101	RED/BRN	MEDIUM
SILT SAND CLAY	101	150	VARIED	MED-HRD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.
GAMMA & EM INDUCTION LOGGED 8-13-2015. LOGGED FOR USGS.

Well Depth	Depth Completed	Date Well Completed
150 ft.	147.97 ft.	07/21/2015

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use environ. bore hole Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 144. ft. 0.68 lbs./ft. 6.7 in. To 150 ft.

Open Hole From ft. To ft.
Screen? ☒ Type slotted pipe Make JOHNSON

Diameter	Slot/Gauze	Length	Set	
2 in.	10	2.8 ft.	144.5 ft.	147.3 ft.

Static Water Level
20.1 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 6.0 hrs. Pumping at 0.79 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	12 Sacks	2 ft.	144 ft.
concrete	3 Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508636 Y 5170295
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
US Geological Survey	1548	LEININGER, R.

Minnesota Well Index Report 773071 Printed on 05/19/2017 HE-01205-15

Figure 48. Well and Boring Report - Well 773070

Minnesota Unique Well Number

773070

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/21/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO1-B	49	20	W 33	CABADB

Elevation 1325.8 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Contact 1220 VILLA COURT DRIVE CROMWELL MN 55726
Well 1189 VILLA VISTA CI CROMWELL MN 55726
WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
GRAVEL WITH SAND &	0	8	BRN/RED	SOFT
SILT, SAND & CLAY	8	11	RED/BRN	MEDIUM
GRAVEL & SAND WITH	11	22	GRAY	MEDIUM
SAND & GRAVEL WITH	22	43	GRAY	MEDIUM
SAND WTH SILT AND	43	101	RED/BRN	MEDIUM
SILT, SAND, CLAY	101	173	VARIED	MED-HRD
SAND & GRAVEL	173	231	VARIED	MED-HRD

Well Depth 230.9 ft. **Depth Completed** 230.87 ft. **Date Well Completed** 07/20/2015

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 220. ft. 0.68 lbs./ft. 6.7 in. To 23.5 ft.

Open Hole From ft. To ft.
Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
2 in.	20	9.6 ft.	220.9 ft.	230.5 ft.

Static Water Level
16.7 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 3.9 hrs. Pumping at 1.35 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	12	Sacks	2 ft.	215.7 ft.
concrete	3	Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508635 Y 5170295
Unique Number Verification Information from Input Date 08/14/2015

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.
GAMMA & EM INDUCTION LOGGED 8-13-2015. LOGGED FOR USGS.

Angled Drill Hole

Well Contractor

US Geological Survey	1548	LEININGER, R.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773070 Printed on 05/19/2017 HE-01205-15

Figure 49. Well and Boring Report - Well 773069

Minnesota Unique Well Number

773069

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/21/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO1-C	49	20	W 33	CABADB

Elevation 1325.8 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Contact 1220 VILLA COURT DRIVE CROMWELL MN 55726

Well 1189 VILLA VISTA CI CROMWELL MN 55726

Stratigraphy Information 2380 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
GRAVEL WITH SAND	0	8	BRN/RED	SOFT
SILT, SAND & CLAY	8	11	RED/BRN	MEDIUM
GRAVEL & SAND W	11	22	GRAY	MEDIUM
SAND & GRAVEL WITH	22	43	GRAY	MEDIUM
SILT, SAND, CLAY	43	173	RED/BRN	HARD
SAND & GRAVEL	173	320	VARIED	MED-HRD
CLAY WITH SLATE	320	342	BLU/GRY	HARD

Remarks

SEE DRILLER LOG FOR DETAILED INFORMATION.
GAMMA & EM INDUCTION LOGGED 8-13-2015. LOGGED FOR USGS.

Well Depth	Depth Completed	Date Well Completed
342 ft.	339.59 ft.	07/18/2015

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use environ. bore hole Status Active

Well Hydrofractured? Yes [ ] No [X] From To

Casing Type Single casing Joint

Drive Shoe? Yes [ ] No [X] Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 330 ft. 0.68 lbs./ft. 6.7 in. To 340 ft.

Open Hole From ft. To ft.

Screen? [X] Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
2 in.	20	9.6 ft.	329.9 ft.	339.5 ft.

Static Water Level
16.7 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 3.9 hrs. Pumping at 1.48 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
[X] Casing Protection [X] 12 in. above grade
[ ] At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? [X] Yes [ ] No [ ] Not Specified

Material	Amount		From	To
bentonite	28	Sacks	2 ft.	324 ft.
concrete	3	Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? [ ] Yes [X] No

Pump [X] Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? [ ] Yes [X] No

Variance
Was a variance granted from the MDH for this well? [ ] Yes [X] No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508633 Y 5170295
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 LEININGER, R.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773069

Printed on 05/19/2017
HE-01205-15

Figure 50. Well and Boring Report - Well 773068

Minnesota Unique Well Number

773068

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO2-A	49	20	W 33	CABABA

Elevation 1332 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Well 1189 VILLA VISTA CI CROMWELL MN 55726
C/W 2280 WOODALE DR MOUNDS VIEW MN 55112
CROMWELL MN 55726

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
COARSE SAND &	0	8	RED/BRN	SOFT
SILTY SANDY CLAY	8	11	RED/BRN	HARD
SAND & GRAVEL	11	22	GRAY	HARD
SAND & GRAVEL	22	43	GRAY	HARD
CLAY W/SILT & SAND,	43	120	RED/BRN	HARD
SAND, SILTY WITH	120	174	BROWN	HARD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 174 ft. Depth Completed 35.17 ft. Date Well Completed 07/09/2015
Drill Method Auger (non-specified) Drill Fluid

Use environ. bore hole Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter 1.2 in. To 34.8 ft. Weight 0.74 lbs./ft. Hole Diameter 8.2 in. To 174 ft.

Open Hole From ft. To ft.
Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	32.5 ft.	35.1 ft.

Static Water Level
28.6 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 2.8 hrs. Pumping at 0.17 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified
Material Amount From To
well grouted, type unknown ft. ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand+silt-brown Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508625 Y 5170347
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773068 Printed on 05/22/2017
HE-01205-15

Figure 51. Well and Boring Report - Well 773067

Minnesota Unique Well Number

773067

County: Carlton
Quad: Cromwell
Quad ID: 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date: 08/14/2015
Update Date: 10/20/2015
Received Date:

Well Name	Township	Range	Dir Section	Subsection
CWO2-B	49	20	W 33	CABABA

Elevation 1332.2 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address
Well: 1189 VILLA VISTA CI CROMWELL MN 55726
Contact: 2280 WOODALE DR CROMWELL MN 55112

Stratigraphy Information CROMWELL MN 55726

Geological Material	From	To (ft.)	Color	Hardness
COARSE SAND &	0	8	RED/BRN	SOFT
SAND, SILTY WITH	8	11	RED/BRN	MEDIUM
GRAVEL & SAND,	11	22	DK. GRY	MEDIUM
SAND WITH SILT, MED.	22	40	DK. GRY	MEDIUM
SAND&GRVL POOR	40	43	DK. GRY	HARD
SILTY CLAY	43	61	RED/BRN	HARD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 60.5 ft. **Depth Completed** 59.62 ft. **Date Well Completed** 07/13/2015
Drill Method Auger (non-specified) **Drill Fluid**
Use environ. bore hole **Status** Active
Well Hydrofractured? Yes ☐ No ☒ From To
Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☐ Above/Below
Casing Diameter 1.2 in. To 56.8 ft. **Weight** 0.74 lbs./ft. **Hole Diameter** 8.2 in. To 60.5 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL
Diameter 1.2 in. Slot/Gauze 10 Length 2.7 ft. Set 57 ft. 59.6 ft.

Static Water Level
27.9 ft. land surface **Measure** 08/18/2015

Pumping Level (below land surface)
ft. 2.1 hrs. Pumping at 0.15 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	6	Sacks	2 ft.	55 ft.
concrete	1	Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508625 Y 5170349
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773067 Printed on 05/22/2017 HE-01205-15

Figure 52. Well and Boring Report - Well 773066

Minnesota Unique Well Number **773066**

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO2-C	49	20	W 33	CABAAB

Elevation 1331.9 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Well 1189 VILLA VISTA CI CROMWELL MN 55726

Contact 2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information CROMWELL MN 55726

Geological Material	From	To (ft.)	Color	Hardness
COARSE SAND &	0	8	RED/BRN	SOFT
SAND, SILTY WITH	8	11	RED/BRN	MEDIUM
GRAVEL & SAND,	11	22	DK. GRY	MEDIUM
SAND WITH SILT, MED.	22	40	DK. GRY	MEDIUM
SAND&GRVL, POOR	40	82	DK. GRY	HARD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth	Depth Completed	Date Well Completed
81.57 ft.	81.57 ft.	07/10/2015

Drill Method Auger (non-specified) **Drill Fluid**

Use environ. bore hole **Status** Active

Well Hydrofractured? Yes [ ] No [X] From To

Casing Type Single casing **Joint**
Drive Shoe? Yes [ ] No [ ] Above/Below

Casing Diameter **Weight** **Hole Diameter**
1.2 in. To 78.7 ft. 0.74 lbs./ft. 8.2 in. To 81.5 ft.

Open Hole From ft. To ft.

Screen? [X] **Type** slotted pipe **Make** ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	79.9 ft.	81.5 ft.

Static Water Level
26.5 ft. land surface **Measure** 08/18/2015

Pumping Level (below land surface)
ft. 12. hrs. Pumping at 0.3 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
[X] Casing Protection [X] 12 in. above grade
[ ] At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? [X] Yes [ ] No [ ] Not Specified

Material	Amount		From	To
bentonite	6	Sacks	2 ft.	73.5 ft.
concrete	1.5	Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? [ ] Yes [X] No

Pump [X] Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? [ ] Yes [X] No

Variance
Was a variance granted from the MDH for this well? [ ] Yes [X] No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat sand+silt-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508627 Y 5170347
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773066 Printed on 05/22/2017 HE-01205-15

Figure 53. Well and Boring Report - Well 773065

Minnesota Unique Well Number: **773065**

County: Carlton
Quad: Cromwell
Quad ID: 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date: 08/14/2015
Update Date: 10/23/2015
Received Date:

Well Name	Township	Range	Dir Section	Subsection
CWO2-D	49	20	W 33	CABABA

Elevation 1331.9 Elev. Method LiDAR 1m DEM (MNDNR)

Address
Well: 1189 VILLA VISTA CI CROMWELL MN 55726
Contact: 2280 WOODALE DR MOUNDS VIEW MN 55112
CROMWELL MN 55726

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
COARSE SAND &	0	8	RED/BRN	SOFT
SAND, SILTY W/CLAY	8	11	RED/BRN	MEDIUM
COARSE SAND &	11	22	DK. GRY	MEDIUM
SAND W/ SILT, MED.	22	40	DK. GRY	MEDIUM
SAND&GRVL POOR	40	43	DK. GRY	HARD
SILTY CLAY	43	108	RED/BRN	HARD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.
CORE TAKEN FROM O FT. TO 107 FT. AS PART OF USGS TILL STUDY.

Well Depth 107.5 ft. **Depth Completed** 106.45 ft. **Date Well Completed** 06/29/2015
Drill Method: Auger (non-specified) Drill Fluid:

Use: environ. bore hole Status: Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type: Single casing Joint
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter: 1.2 in. To 103. ft. Weight: 0.74 lbs./ft. Hole Diameter: 8.2 in. To 107. ft.

Open Hole From ft. To ft.
Screen? ☒ Type: slotted pipe Make: ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	103.8 ft.	106.4 ft.

Static Water Level
23.4 ft. land surface Measure 08/18/2015

Pumping Level (below land surface)
ft. 1.1 hrs. Pumping at 0.33 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	9	Sacks	2.5 ft.	92 ft.
concrete	2	Sacks	ft.	2.5 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508624 Y 5170347
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773065 Printed on 05/22/2017 HE-01205-15

Figure 54. Well and Boring Report - Well 773064

Minnesota Unique Well Number

773064

County Carlton
Quad Cromwell
Quad ID 226B

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/23/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
CWO2-E	49	20	W 33	CABABA

Elevation 1331.9 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Well 1189 VILLA VISTA CI CROMWELL MN 55726
Contact 2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information CROMWELL MN 55726

Geological Material	From	To (ft.)	Color	Hardness
COARSE SAND &	0	8	RED/BRN	SOFT
SAND, SILTY W/CLAY	8	11	RED/BRN	MEDIUM
GRAVEL & SAND	11	22	DK. GRY	MEDIUM
SAND W/SILT MED. TO	22	40	DK. GRY	MEDIUM
SAND & GRVL POOR	40	43	DK. GRY	HARD
SILTY CLAY	43	120	RED/BRN	HARD
SILTY SANDY CLAY	120	130	DK. BRN	HARD

Well Depth 129.5 ft. Depth Completed 128.65 ft. Date Well Completed 07/12/2015

Drill Method Augar (non-specified) Drill Fluid

Use environ. bore hole Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint

Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight Hole Diameter
1.2 in. To 125. ft. 0.74 lbs./ft. 8.2 in. To 129. ft.

Open Hole From ft. To ft.

Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	126 ft.	128.6 ft.

Static Water Level
23.9 ft. land surface Measure 08/18/2015

Pumping Level (below land surface)
ft. 3.9 hrs. Pumping at 0.4 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	8	Sacks	2 ft.	24.1 ft.
concrete	2	Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay- Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 508624 Y 5170349
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.
CORE TAKEN FROM 108 FT. TO 120.5 FT. AS PART OF USGS TILL STUDY.

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773064 Printed on 05/22/2017 HE-01205-15

Analysis of the Litchfield, Minnesota Well 2 (607420) Aquifer Test

CONDUCTED ON JUNE 29, 2017

CONFINED QUATERNARY GLACIAL-FLUVIAL SAND AQUIFER

DEPARTMENT OF HEALTH

Analysis of the Litchfield, Minnesota Well 2 (607420) Aquifer Test Conducted on June 29, 2017

Minnesota Department of Health, Source Water Protection Program
PO Box 64975
St. Paul, MN 55164-0975
651-201-4700
health.drinkingwater@state.mn.us
www.health.state.mn.us/divs/eh/water/swp

To obtain this information in a different format, call: 651-201-4700.

Upon request, this material will be made available in an alternative format such as large print, Braille or audio recording. Printed on recycled paper.

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Data Collection and Analysis

The constant-rate pumping test of Litchfield 2 (607420) was conducted as described below. The representative aquifer properties are summarized in Table 1. The specifics of test location, scope, and timing are presented in Table 2 and Table 3. The associated data files and a comparison of manual and transducer measurements are presented in Table 4. The results of analyses are presented in Appendix 1 and are summarized in Table 5. The analyses used standard methods, cited in references. The figures include maps, field notes, other documentation, and records of well construction.

Description

Purpose of Test

The test of Litchfield 2 was conducted by the Minnesota Department of Health (MDH) Source Water Protection Unit as a small part of a long-term project that was led by the United States Geological Survey (USGS). The overall purpose of the study was to assess the rates of groundwater recharge through low-conductivity glacial sediments (till) at various sites in Minnesota.

Specific to Litchfield, nine observation wells were installed by the USGS in 2015. Water elevations were recorded on a one-hour interval in seven of these wells for approximately one-year. The USGS had completed its data collection and was preparing to seal the observation wells. Prior to sealing the wells, notification was provided to the partner agencies relative to the completion of the work. At that time, staff in the Source Water Protection Unit recognized that this configuration of observation wells is nearly ideal for conducting short-term constant-rate aquifer tests on Public Water Supply (PWS) wells so as to estimate vertical groundwater flow. Therefore prior to sealing the wells, MDH proposed to conduct tests that would complement the USGS data collection efforts.

Well Inventory

The well records are presented in Figures 46-62 and the well construction is summarized in Table 22. The site plan is shown in Figure 16.

Hydrogeologic Setting

A schematic section (geologic cross-section) through the test site is shown on Figure 17 to illustrate the three layers that comprise the flow system; water table, aquitard, aquifer, and the construction of wells within these layers.

Other Interfering Wells

Other high capacity wells exist in the area that may cause interference. These wells are associated with the First District dairy processing in the center of Litchfield (to the south of the wellfield), and the Desens crop irrigation well (to the east of the wellfield). Several smaller domestic and non-community supply wells exist in the area. However, based on previous testing these smaller wells are not judged to present significant interference. Mr. Desens was contacted prior to the test to gain access to the observation well on his property. This well contains a transducer and water level data over the test period was obtained with the assistance of Minnesota Department of Natural Resources (MDNR).

Test Setup

The USGS provided the pressure transducers and data loggers used for long-term monitoring, re-programmed to a one-minute interval. MDH hydrologists, Justin Blum and Luke Pickman, traveled to Litchfield on June 13, 2017 to assess site conditions and re-install the transducers to collect background water level and barometric data. Transducers were placed in all existing observation wells, with the exception of USGS 2-E.

Access to Litchfield 2 is provided by a 0.75-inch polyethylene tube. The restricted diameter of this tube did not allow a transducer to be placed in the well to monitor water levels even though manual measurements were easily made. The three additional PWS wells in the wellfield; 3, 4 and 5, are similarly constructed and equipped. A prior test of Litchfield 2 was conducted by a geotechnical consultant (ECAD, 1998) and the observation well from that testing still exists a short distance from Well 2. Because of these factors; access to the wells, prior tests, and the relative distance of the observation wells, Litchfield 2 was selected to be the pumping well for this test.

The water operator, Mr. Herb Watry, was not comfortable with a standard test schedule; 24-hours of rest, 24-hours of pumping and 24-hours of recovery, because of system water demand and the limitations of the city water treatment plant. Extensive discussions with the operator indicated that an abbreviated pumping and recovery period of 4 to 6 hours each was possible and would still provide sufficient capacity. On that basis, the test was tentatively scheduled to begin on June 23, 2017. However, a major storm event on June 22, 2017 and various other public works projects caused the start of testing to be put off for a week. Other preparations for the test continued; on June 22, 2017 an acoustic water level sensor was installed in Litchfield 2, and the transducer in the Desens observation well was set up on a five-minute interval with the assistance of MDNR staff.

Weather Conditions

Conditions were warm and mostly dry during background data collection. Rain events greater 0.2-inches were recorded on June 22th and 27th at the Litchfield Waste Water Treatment Plant. No appreciable precipitation occurred during the pumping and recovery periods of June 29th to June 30th, 2017.

Discharge Monitoring

The pumping rates of the wells were reported by the Litchfield water treatment plant SCADA system. This was supplemented by manual readings of the totalizing flow meter on the Well 2 discharge line.

Data Collection

MDH personnel mobilized for the test on 6/29/2017, arriving on-site at 11:00. Upon arrival, the system was not in a 'rest' state; Litchfield Wells 3 and 5 were pumping, and Wells 2 and 4 were off. [Well 4 remained out of service for repairs until 7/6.] Wells 3 and 5 were turned off at 12:16:30 to place the wellfield into a limited recovery. The Litchfield 2 pump was started at 6/29/2017 14:03:30 by hand control through the SCADA system. Water levels were collected manually from Litchfield Wells 3, 4, and 5 from 12:00 until 15:00. The operator turned off the Litchfield 2 pump at 20:00 and all city wells remained off until 6/30/2017 06:00. At that time the system was critically short of water and Wells 2, 3, and 5 were pumped intensively over the next day to restore reserve capacity.

The USGS transducers remained in the wells until 7/10/2017 when static levels were measured and all equipment was removed. Data were attempted to be downloaded from the transducers at Nest 2 prior to equipment removal but difficulties connecting to the data loggers caused the equipment to be pulled before downloading. Data from the Desens obwell was downloaded on 7/13/2017 by MDNR staff. (personal communication, Ari Berland, MDNR)

The comparisons of manual and transducer measurements are presented in Figures 15 through 33. Only one well saw a decline in water level below the transducer setting, USGS 1-E, Figure 26, affecting data collection after 7/6/2017. The batteries of the acoustic transducer in Litchfield 2 failed during the extended recovery period and data after 7/7/2017 were not recorded. However, the MDH transducer in the Litchfield monitoring well continued to function over the monitoring period to provide a continuous record at that location.

Time signatures of the data files were checked against the computer clock after the equipment was removed from the wells. It was found that the USGS data logger clocks lost between 40 and 58 seconds, an average of 50 seconds, over the 28-day data collection period. This small and nearly uniform time shift was judged to not strongly affect data over the short, 14-hour, test period. Otherwise, the USGS loggers performed as expected and the equipment was returned to the USGS Mounds View office on 7/11/2017.

After the test was complete, precipitation records from the WWTP were obtained and the operator generated reports from the SCADA system for daily pumping from the wells. The daily pumping totals were compared to readings from the totalizing flowmeter on Well 2. There is a significant difference in flow volume between these two sources. The SCADA average cumulative volume reported for Well 2 was 710 gpm. The reading from totalizer, 46 minutes after the start of pumping, was 787 gpm. The appropriate value to use for the analysis was evaluated by comparison to results from the 1998 test of Litchfield 2, ECAD - test 2209. The larger rate produced comparable transmissivity values to the earlier test and is considered to be more accurate.

Qualitative Aquifer Hydraulic Response

A general site plan is shown in Figure 16, identifying the wells monitored for this test. Distances between the pumping and observation wells are presented in Table 3. A schematic cross section is provided for visual context of the test conditions, Figure 17. Comparison of manual and transducer data are shown in, Figures 18 through 33, documenting the proper functioning of the equipment.

The differences between pre and post-test manual and transducer water levels from wells completed in the pumped aquifer were consistent, indicating little effect of cable stretch, transducer 'drift,' or other common problems. This was not the case for observation wells constructed in till, particularly in Nest 2, where static water levels were disturbed by installation of the transducers. The instrumentation displaced water in the well casings similar to a 'slug' injection. This disturbance dissipated over a time interval that varied according to the hydraulic conductivity of the materials in which the wells are constructed; from seconds to greater than 20 days. The USGS had analyzed these 'slug' tests during earlier parts of this study; therefore, additional slug analyses were not performed on this dataset.

The groundwater elevations in both nests showed a downward gradient, as expected, Figure 34 and Figure 35. There was a clear signal in all wells completed in the aquifer caused by the pumping of Litchfield 2, Figure 36 and Figure 37. As for the response in the till observation wells, the effects of pumping of Litchfield 2 was seen only at Nest 1, Figure 34. No response was seen in any of the till observation wells at Nest 2, Figure 35.

The possible influence on groundwater elevation from barometric pressure changes was evaluated, Figure 40. Barometric pressure varied little over the pumping test period. The range around the mean pressure was +/- 0.03 psi with a small upward trend of 0.05 psi. This variation is considered to have a negligible effect on water elevation and the data were not corrected for barometric efficiency.

Long-term trends in groundwater elevation were evaluated. The groundwater elevation in the shallow water-table observation well, USGS 1-B declined about 0.5 foot over the monitoring period, Figure 23. At Nest-2, the decline in well USGS 2-A was about 2 feet, Figure 28. The declines differed between the well nests; at Nest 1 the decline was linear, whereas Nest 2 saw a curvilinear decline – similar to a stream recession curve. The overall decrease in groundwater elevation at the water table appears to be an area-wide trend.

The vertical groundwater gradient is uniformly downward over the test area. At Nest 1, to the south of the wellfield, the ambient groundwater elevation difference is approximately 25 feet. During the test this difference increased by about 1 foot. Therefore, the incremental difference in the volume of leakage through the till as the result of this test is small relative to the ambient leakage.

Precipitation events are associated with small increases in groundwater elevation at both Nests 1 and 2, Figure 41. At Nest 2, the changes in elevation are seen to propagate downward, decreasing in magnitude with depth, in wells 2-B, 2-C, and 2-D, Figure 29, Figure 30, and Figure 31. This relationship holds true for Nest 1 also but is less pronounced, Figure 24 and Figure 25. The trend in the pumped aquifer is less clear because of the cycling of many pumping wells; but, groundwater elevation was relatively stable until 7/5/2017.

During the extended monitoring period, between 7/5 and 7/8/2017, groundwater elevation in the aquifer declined up to 10 feet, starting to recover on 7/9/2017, Figure 36. This event affected all wells constructed in the aquifer nearly equally. It was not associated with a marked increase in pumping from the Litchfield wellfield, Figure 42. The SCADA system reported an increase in total pumping volume over that period of about ten percent above average. Nor was it associated with any changes in flow from the First District dairy processing; as the waste water flow from that facility to the Litchfield WWTP was within the normal range over that time and no additional pumping was reported from First District wells. (personal communication, M. Geers, city of Litchfield and R. Albrecht, First District, Inc.) It was clearly not associated with pumping of the Desens irrigation well as that well remained off until about 7/12, after the time that water elevations had started to recover, Figure 33. The small differences in the response of the Desens obwell relative to other wells in the aquifer are probably associated with the return to service of Well 4, Figure 43 and Figure 44. Because of the magnitude and uniform effect of this change in water elevation, it can only be caused by a large discharge located at a large distance; greater than 2000 gpm, and at one mile or greater distance. During this analysis, the mystery of the source of this disturbance was referred to MDNR as it clearly has area-wide significance.

Subsequent discussions with the USGS verified that similar declines had occurred the previous year, Figure 45. In 2016, three episodes of water elevation decline similar in magnitude to that observed during this test occurred during the summer months, June, July and August. Comparison of these declines in water elevation to records of precipitation showed that they only occurred during dry times and on two occasions the recovery coincided with rain events. The declines are not strongly related to local pumping because the magnitude of the cycling of local wells is consistent throughout the year. Because these declines 1) regularly occur only in the summer months, 2) start during dry periods, and 3) recover after significant rainfall events, leads to the conclusion that they are the result of cumulative effects of area-wide irrigation pumping.

Quantitative Analysis

Traditional aquifer test analysis utilizes two main types of simple inverse models, transient and steady-state, see: selected references. When both types of models are used for the analysis (data permitting) - the aquifer hydraulic response may be proved consistent from the two perspectives and uncertainty in hydraulic properties is reduced.

Conceptual Model

The conceptual model for this test is of a layered leaky aquifer system with the majority of wells completed in two of three layers, as per the schematic section, Figure 17. The layers have distinctly different hydraulic characteristics. The first layer is composed of glacial drift and alluvium, which contains the water table. The second layer is the till which provides hydraulic confinement and recharge by leakage to the third layer. The third layer is the hydraulically-confined glacial outwash aquifer in which the production wells are constructed.

For the analysis of the confining layer data, it is preferred initially to use the simplest approach so as to introduce as few degrees of freedom as possible. The conceptual model of flow through the till is each well nest is analogous to a column of permeable material in the laboratory and flow is steady-state. For analysis of aquifer properties, the steady-state conceptual model leakage of a two-layer system is used [de Glee (1930) and Hantush-Jacob (1955)]. There is assumed to be no change in storage in these steady-state models. Transient analysis by the Neuman-Witherspoon (1969) method was also done for comparison, as data permitted.

Pumped Aquifer

Analyses are presented in Figures 1 through 10. Adjustments to the data were made prior to analysis to account for the effects of the short rest period before the start of pumping and the abbreviated duration of the test. The first adjustment is made to estimate the impact of previous pumping/recovery cycles by superposition, Figure 16. This correction was applied to the drawdown of each well for the composite transient analyses, Figures 17 through 21.

The recovery period was 10-hours in length and therefore is a bit higher quality. The transient distance drawdown analysis (t/r^2), Figure 7, used recovery data. However, the duration of the 10-hour recovery was not long enough for steady-state conditions to develop. Therefore, recovery data were projected to 10,000 minutes, Figure A1-8, for the steady-state analyses, Figure 9 and Figure 10.

Aquifer transmissivity is best represented by the distance-drawdown analyses between 8,800 to 11,000 ft2/day. The storativity (dimensionless) is in the range of 5.5e-5 at the Nest 2 site to as large as 2.0e-4 at nest 1, to the south of the wellfield. This variation in storativity corresponds to the relative conductivity of the till at the well nests. No wells showed a leaky response, as expected, and the corresponding leakage factor from the steady-state analyses is quite large, approximately 22,000 feet. Comparison of these results to those of the earlier aquifer test shows that the transmissivity and storativity are within the same range but the characteristic leakage factor from the earlier test was significantly smaller. [This may be due in part to a bias in the earlier analysis which used drawdown values after only 1440 minutes of pumping. It also was the result of choices to weight proximal wells more heavily to the fit rather than more distant wells. The uncertainty of the leakage factor from that analysis was quite large.]

There are differences between the response to pumping and recovery for USGS 1-F and Desens Obwell, Figure 5 and Figure 6, that are not seen in the response of wells located within the wellfield. It is believed that these differences are the result of interference from other, more distant, pumping wells. The effect of the differences causes an increase in uncertainty of hydraulic properties at these wells, +/- 30% of the nominal values which are presented on the figures and Table 5.

Aquitard (Confining) Layer

Analyses are presented in Figures 11 – 15. The assessment of the vertical hydraulic conductivity of the till at Nests 1 and 2 depends on the observed response to pumping. There was no observed response to pumping at Nest 2 and the analysis is therefore limited. The observed response to pumping at Nest 1 is shown on Figure 11as four series:

1) pumping,
2) recovery,
3) recovery projected to 1000 minutes, and
4) that caused by the 'unknown pumping.'

The short-term differences in water level caused by pumping are best fit by a log function. As the well nest is expected to react linearly, as a hydraulic column in the laboratory; this indicates that the duration of pumping was insufficient for the system to reach equilibrium. The recovery data projected to 10,000 minutes may be used, as that response was linear, but limited to only two wells. The strongest linear signal was caused by the 'unknown pumping' 7/5 through 7/8/2017. These data indicate that only the deeper observation wells; USGS 1-E, 1-D, and possibly 1-C, may provide a reasonably linear relationship of clay thickness vs. water level change. As water levels drew down below the transducer in USGS 1-E, an estimate of the water level was made from the consistent difference between USGS 1-E and 1-F of 0.6 feet, Figure 26.

Note that on Figure 11, the intersection of all regressions at ~0 feet of drawdown is much less than the full thickness of the till. Therefore, the true thickness of competent till as a confining layer is not its full lithological thickness at the Nest 1 site. It appears that the effective thickness is approximately 48 to 50 feet.

The composite leaky analysis, Figure 12, used the parameter estimation tool in Aqtesolv for the data from the wellfield area. The data from wells 1-F and Desens Obwell plot significantly below the other wells. This indicates that the transmissivity and/or leakage is different for the wells not matched. This is additional confirmation that the aquitard is more permeable in the area near Nest 1.

The Neuman-Witherspoon analysis of recovery data from Nest 1, Figure 13, produces a kV of the aquitard of 1.8e-2 ft/day. However, the match is poor because the test was not conducted long enough to generate a strong signal. Also, this initial analysis assumed that the thickness of the aquitard is 63 feet rather than that from the well records (114 feet). The smaller effective aquitard thickness from Figure 11 can be verified with this model. On Figure 14, the match to data from well 1-E is much improved if an aquitard thickness of 50 feet is used, with no other change in parameters.

The analysis of the data associated with this abbreviated constant-rate test is limited because of the relatively small signal that only affected wells 1-E and 1-D. However, a very strong signal was generated by the disturbance after 7/5/2017 19:00, Figure 43. Unfortunately, no facts are available to verify the well location(s) or pumping rate(s) that may have caused the disturbance. Modeling the impact of the observed response has inherent uncertainties but is a worthwhile check on the aquitard properties, if only because of the strength of the signal.

If aquifer properties are reasonably consistent in this area, the effects of the 'unknown pumping' well at Nest 1 may be modeled in Aqtesolv. Assuming a well located approximately 8000 feet from Nest 1 and discharging at a rate of 2300 gpm for 5000 minutes, a steady-state model provides similar aquifer properties: T – 9,000 ft2/day, S - 5e-5, and L - 20,000 feet. These assumptions were then used as the basis for a Neuman-Witherspoon analysis of the data after 7/5/2017 19:00, Figure 15. The match was quite good to data from all observation wells in the till: 1-E (estimated), 1-D, and 1-C. The k_V of the aquitard was smaller, 1.0e-3 ft/day, than that calculated from the test of Litchfield 2, Figure 14, but not out of the reasonable range. For comparison, this value is essentially the same as than that from the steady-state analyses, Figure 9 and Figure 10.

Because no response was observed at the Nest 2 site, the k_V of the aquitard is at least one order of magnitude smaller than that at Nest 1, at most 1.0e-4 ft/day or smaller.

Conclusion

The hydraulic properties of the two-layer aquifer and aquitard system are shown in Table 1. These values are a summary of the analyses listed on Table 5. The large range of estimated aquifer properties shown are the result of both the sub-set of the data to which an analysis method was applied and natural lithological variation - particularly within the till.

The bulk aquifer properties were within the expected range given the prior test of Litchfield 2 in 1998. The leakage factor from this test was larger (a lower rate of leakage) than that from the earlier test, with better documentation and a much more robust analysis.

The interesting aspect of these data is that the more conductive portion of the aquitard (Nest 1) appears to dominate the bulk hydraulic response, as represented by the steady-state analyses.

Acknowledgements

There have been few opportunities to collect this level of detailed hydraulic information for the analysis of rates of leakage through till. The test conducted at the Litchfield municipal wellfield described here was successful not simply because of the efforts of MDH but also for the work of many, over decades. This analysis drew heavily on previous testing of Litchfield Well 2 in 1998, data collected by the USGS in 2015 and 2016, the work of MDNR with irrigators in the area, as well as other sources. It is an example of how success may

sometimes result from being there to gather information, taking advantage of coincidental and uncontrolled field conditions, rather than the 'proper conduct' of an aquifer test.

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Tables and Figures

Table 1. Summary of Results for Leaky Confined - Radial Porous Media Flow

Parameter	Value	Unit	Range Minimum	Range Maximum	+/- % variation
Top Stratigraphic Elev.	1015	feet (MSL)	1008	1022	
Bottom Stratigraphic Elev.	986	feet (MSL)	978	986	
Transmissivity (T)	9,000	ft2/day	7,000	14,500	
Aquifer Thickness (b)	29	feet	30	44	
Hydraulic Conductivity (k)	310	ft/day	155	310	
Ratio Vertical/Horizontal k (k_V/K_R)	1	0.00 %			
Primary Porosity (ep)	0.25	0.00 %			
Storativity (S)	7.5e-5	dimensionless	5.5e-5	3.3e-4	
Characteristic Leakage (L)	21,000	feet	5,000	24,100	
Hydraulic Resistance (c)	44,400	days	2,800	63,500	
Thickness of till (b')	50	feet	48	130	
Hydraulic Conductivity of till (k_V)	1.0e-3	ft/day	< 1.0e-4	2.0e-2	

Table 2. Aquifer Test Information

Information Type	Information Recorded
Aquifer Test Number	2617
Test Location	Litchfield 2 (607420)
Well Owner	City of Litchfield
Test Conducted By	MDH - J. Blum and J. Woodside
Aquifer	QBAA
Confined / Unconfined	Confined
Date/Time Monitoring Start	06/13/2017 12:10
Date/Time Pump off Before Test	06/29/2017 12:16:30
Date/Time Pumping Start	06/29/2017 14:03:30
Date/Time Recovery Start	06/29/2017 20:00:00
Date/Time Test Finish	7/13/2017 14:35
Pumping time (minutes)	1454.93
Totalizer – end reading	not recorded
Totalizer – start reading	122,434,800
Total volume (gallons)	280,060 gallons
Nominal Flow Rate	787 (gallon per minute)
Number of Observation Wells	8 (see Table 3)

Table 3. Well Information

Well Name (Unique Number)	Easting Location, X[1] (meter)	Northing Location, Y[1] (meter)	Radial Distance (feet)	Ground Surface Elevation, GSE[2] (feet, MSL)	Measuring Point Description GSE+(stick-up) (feet, MSL)	Open Interval Top (feet, MSL)	Open Interval Bottom (feet, MSL)	Aquifer
Wellfield								
Litchfield 2 (607420)	613	481.6	1	1120	1124.35 e	1013	988	QBAA
L-MW (607417)	607.8	496.1	51	1120	1123.7	1001.2	996.2	QBAA
Litchfield 3 (632077)	674.4	711.6	781	1123.2	1127.2	1018	990	QBAA
Litchfield 4 (632078)	538.4	1129.6	2140	1126	1130	1026	1002	QBAA
Litchfield 5 (764258)	466.1	1014.9	1815	1149	1153	1015.5	990.5	QBAA
Desens, D. (800011)	1384.7	947.7	2958	1128.4	1129.4 e	980.4	970.4	QBAA
Nest 1								
USGS 1-B (773062)	1021.8	265.5	1517	1114.5	1118.23	1092.1	1089.2	QWTA
USGS 1-C (773060)	1019.2	267.5	1506	1114.8	1118.35	1064.6	1061.7	Till
USGS 1-D (773059)	1020.4	267.5	1510	1114.7	1118.25	1042.3	1039.4	Till
USGS 1-E (773058)	1021.8	267.5	1514	1114.5	1118.07	1022.1	1019.2	Till
USGS 1-F (773057)	1020.4	265.6	1513	1114.7	1118.1	996.7	987.2	QBAA
Nest 2								
USGS 2-A (773056)	559.8	844	1202	1139.6	1142.82	1122.5	1119.6	QWTA
USGS 2-B (773055)	559.8	842.9	1198	1139.2	1142.24	1106.9	1104.1	Till
USGS 2-C (773054)	561.3	844	1201	1139.4	1142.41	1082.4	1079.6	Till
USGS 2-D (773053)	559.7	841.6	1194	1139.2	1142.15	1058.1	1058.1	Till
USGS 2-E (773052)	561.4	842.9	1197	1139.3	1142.46	1028.3	1025.5	QBAA
USGS 2-F (773051)	561.4	841.6	1193	1139.3	1142.37	986.8	976.9	QBAA

[1] Local Datum
[2] Vertical Datum: NAV88

Table 4. Data Collection

Data File Name: Well Name_Unique Number	Data Logger Type, SN:	Probe Id., Range (psi)	Install 1. Static WL[3]	Install 2. XD[4] Setting	Remove 3. Static WL	Remove 4. XD Setting	Diff. Static WL (1-3)	Diff. XD Setting (4-2)
L-2_(607420)	Acoustic transducer		50.29	49.64	71.04[5]			
Baro_data	Hermit 3000 45333	6, 15 psia						
L-Ob(607417)	Troll 500 145815	17, 30 psi	46.50	61.59	59.70	48.54	-13.2	-13.04
USGS-1-B(773062)	OTT 382929		13.55	12.96	14.17	12.33	-0.62	-0.63
USGS-1-C(773060)	OTT 382931		14.61	13.97	15.46	14.83	0.78	0.79
USGS-1-D(773059)	OTT 382935		28.77	28.30	32.75	32.34	-3.98	4.04
USGS-1-E(773058)	OTT 382934		38.04	37.52	45.29	39.60[6]	-0.21	--
USGS-1-F(773057)	OTT 382937		38.20	37.11	45.45	44.88	7.25	7.77
USGS-2-A(773056)	OTT 382927		13.99	14.19	16.09	16.23	-2.1	2.04
USGS-2-B(773055)	OTT 382932		14.99	16.09	16.39	18.72	1.4	0.35
USGS-2-C(773054)	OTT 382930		17.87	16.06	19.02	18.59	-2.15	2.52
USGS-2-D(773053)	OTT 382933		35.19	34.07	35.90	35.38	-0.71	1.31
USGS-2-E(773052)	None installed		64.36		71.33			
USGS-2-F(773051)	OTT 382938		65.43	64.88	70.88	70.01	-5.45	5.13

[3] WL = water level below measuring point, feet.
[4] XD = pressure transducer depth below water surface, feet.
[5] Pump running
[6] Transducer set above water surface in well at removal

Table 5. Transient Analysis Results

Well Name (Unique Well No.)	Transmissivity, T (ft2/day)	Storativity, S (dimensionless)	Leakage Factor, L (feet)	Hydraulic Conductivity of Aquitard, kV (ft/day)	Analysis Method	Figure No. Remarks
L-2 (607420)	3,440	NA[7]	NA	NA	Theis	2. poor match, T not credible
L-MW (607417)	8,600	2.5e-4	NA	NA	Theis	3. good match
USGS 2-F (773051)	14,700	5.5e-5	NA	NA	Theis	4. good match to pumping data
USGS 1-F (773057)	14,700	3.3e-4	NA	NA	Theis	5. divergence between pumping and recovery data – uncertainty in T & S values +/- 30%
Desens (800011)	14,300	1.5e-4	NA	NA	Theis	6. divergence between pumping and recovery data – uncertainty in T & S values +/- 30%
Aquifer, composite	10,000	1.1e-4	NA	NA	Theis - t/r2	7. good match, inefficiency of pumped well causes divergence from Theis-curve
Aquifer, composite	9,170	2.0e-4			Cooper – Jacob	9. representative bulk aquifer properties
Aquifer, composite	11,000	9.5e-4	20,000	1.4e-3	Hantush-Jacob - t/r2	12. Aqtesolv solution - match to L-MW and USGS 2-F
Nest 1, composite	14,000	1.0e-4	6,700	2.0e-2	Neuman-Witherspoon	13. aquitard thickness of 63 feet - poor match
Nest 1, composite	10,800	1.2e-4	5,500	1.8e-3	Neuman-Witherspoon	14. aquitard thickness of 50 feet - better match to USGS 1-E
Nest 1, composite	8,000	7.4e-5	10,800	1.0e-3	Neuman-Witherspoon	15. aquitard thickness of 50 feet - good match to all till wells

Table 6. Steady-state Analysis Results

Transmissivity, T (ft^2/day)	Leakage Factor, L (feet)	Hydraulic Resistance, c (days)	Hydraulic Conductivity of Aquitard, k_v (ft/day)	Analysis Method	Plot No. Remarks
9,170	24,100	63,500	7.9e-4	Hantush-Jacob	9. representative bulk aquifer properties
8,830	22,000	54,800	9.0e-4	De Glee	10. representative bulk aquifer properties

[7] Not Applicable

Figure 1. Adjustments for pumping-phase data

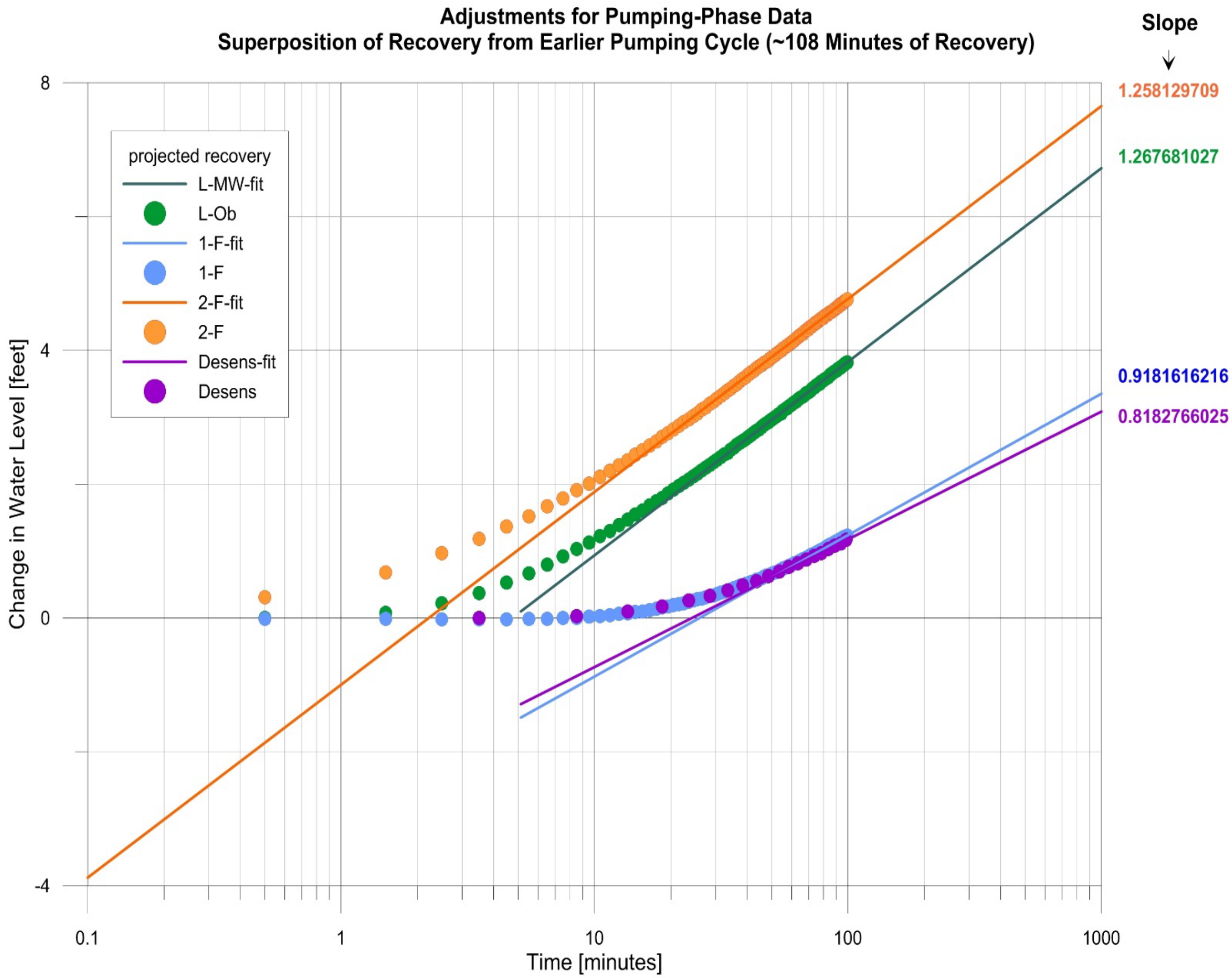


Figure 2. Theis (1935) analysis of pumping and recovery data from Litchfield 2 (607420)

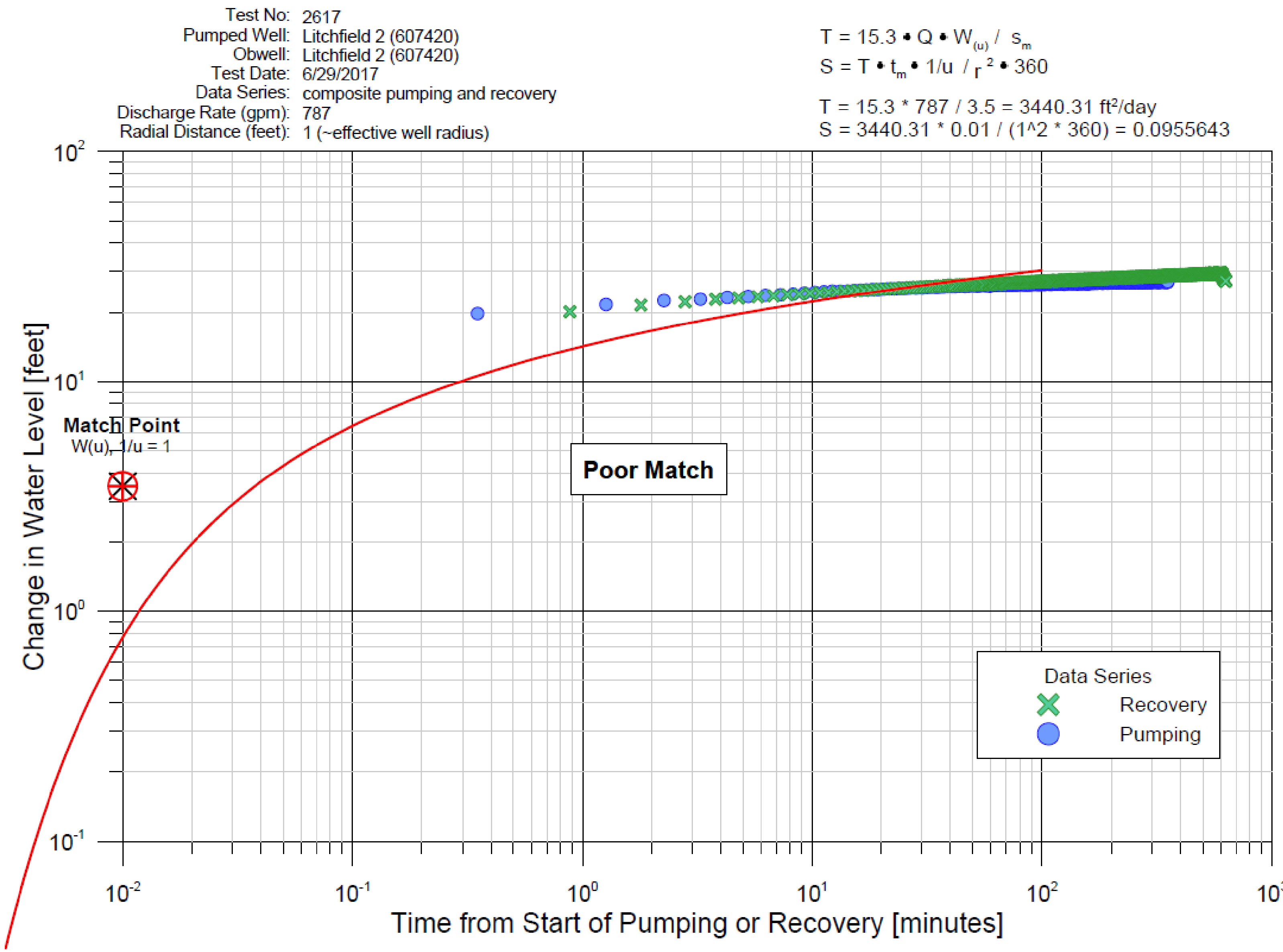


Figure 3. Theis (1935) analysis of pumping and recovery data from Litchfield MW (607417)

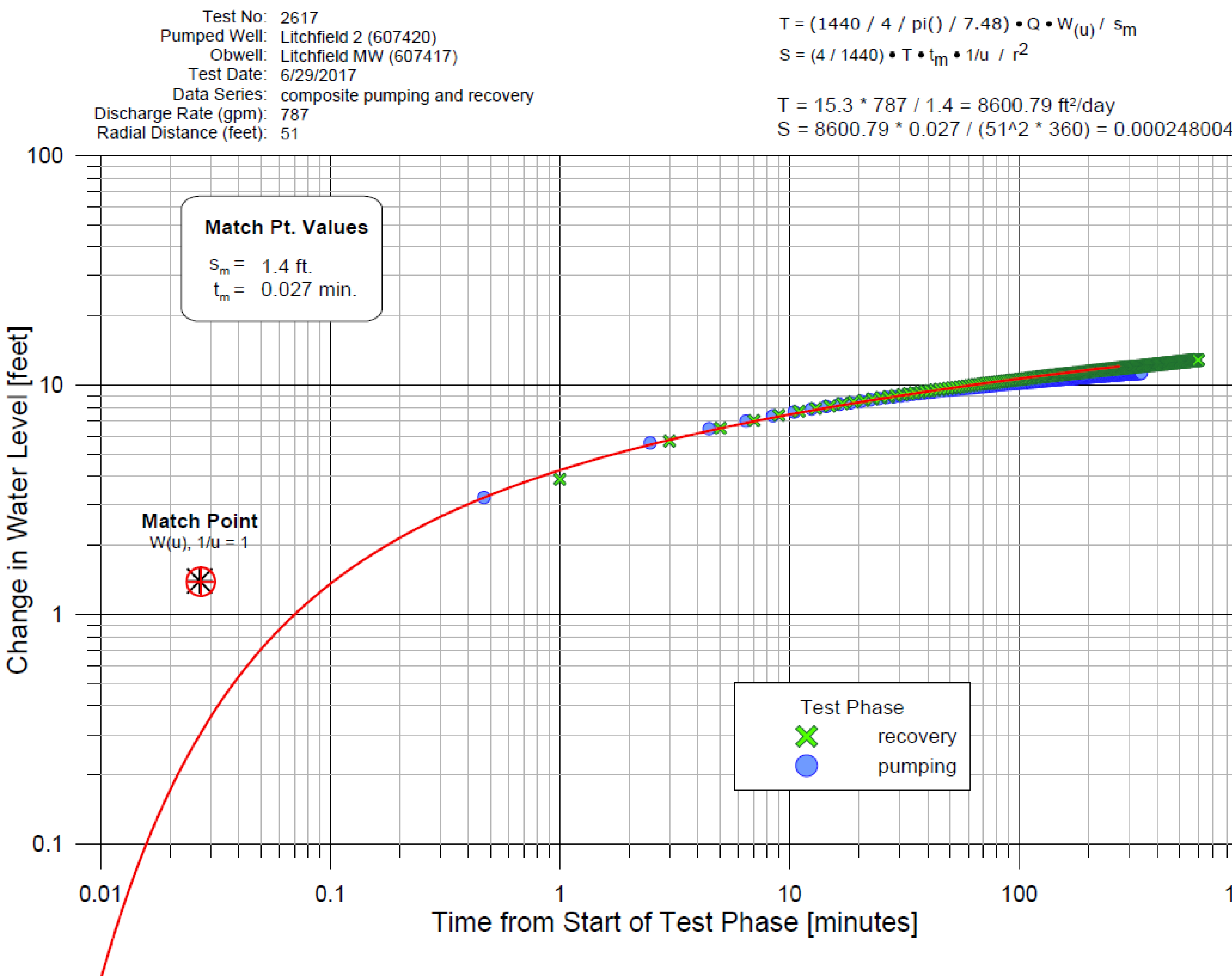


Figure 4. Theis (1935) analysis of pumping and recovery data from USGS 2-F (773051)

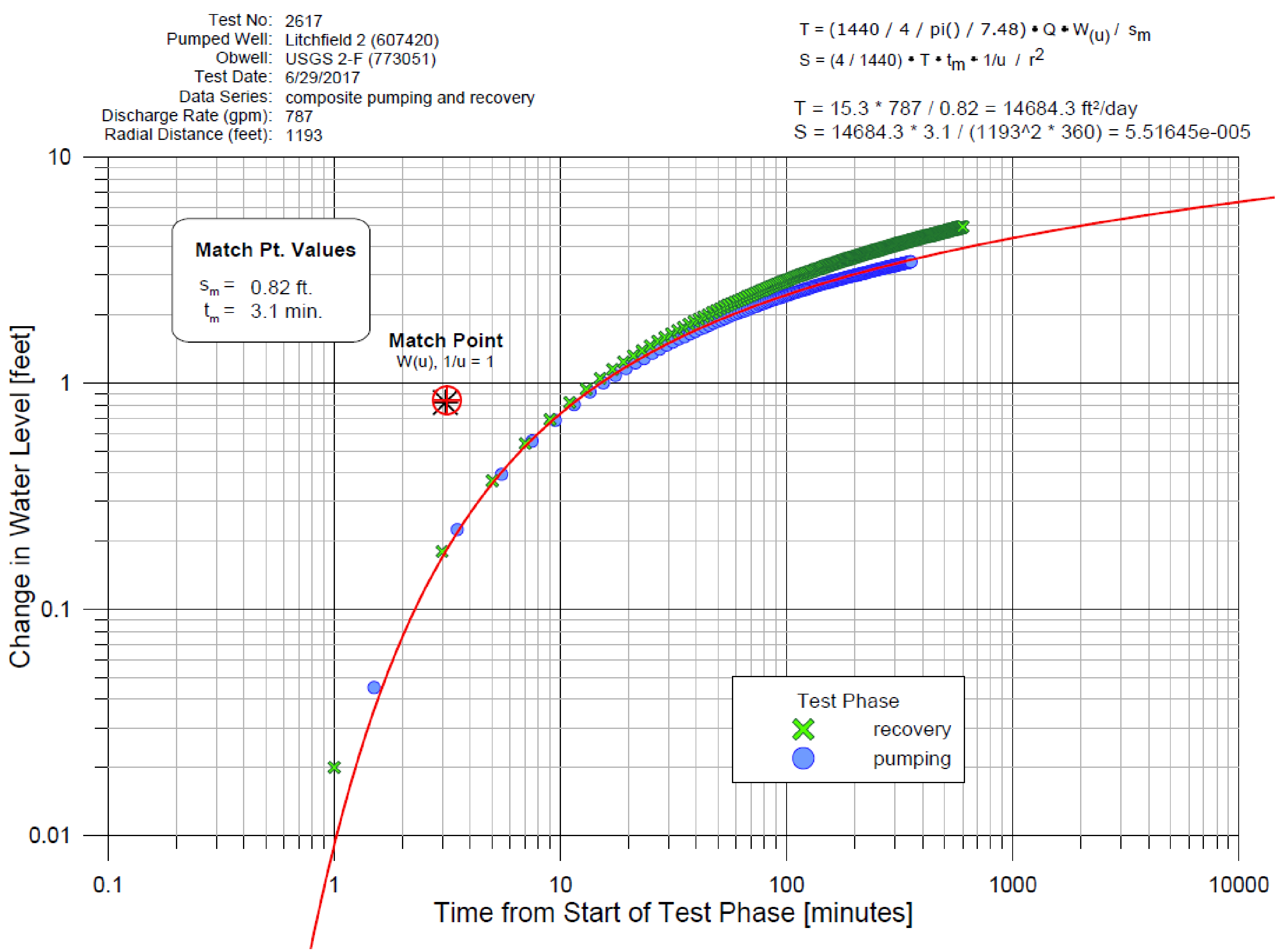


Figure 5. Theis (1935) analysis of pumping and recovery data from USGS 1-F (773057)

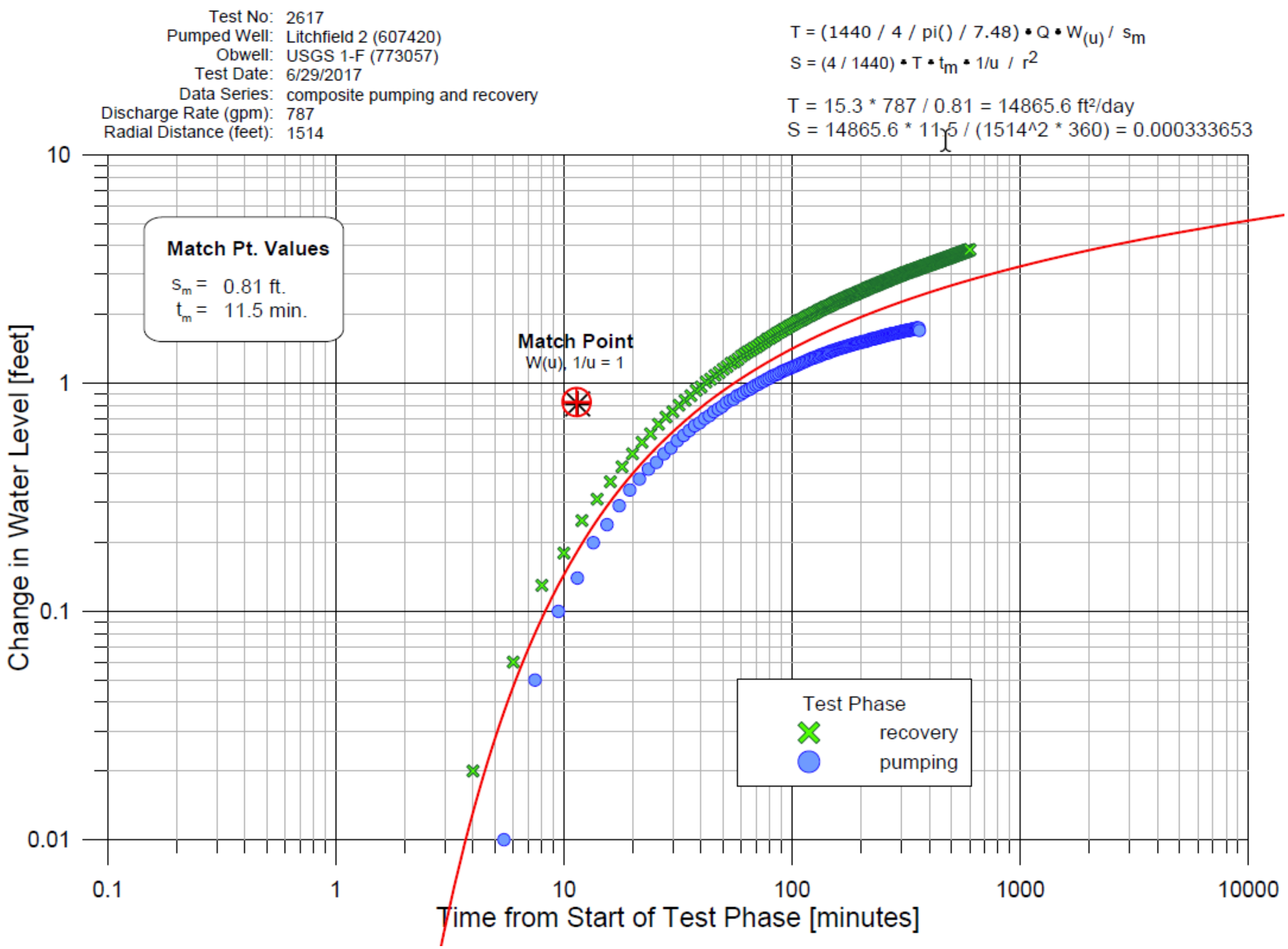


Figure 6. Theis (1935) analysis of pumping and recovery data from Desens (800011)

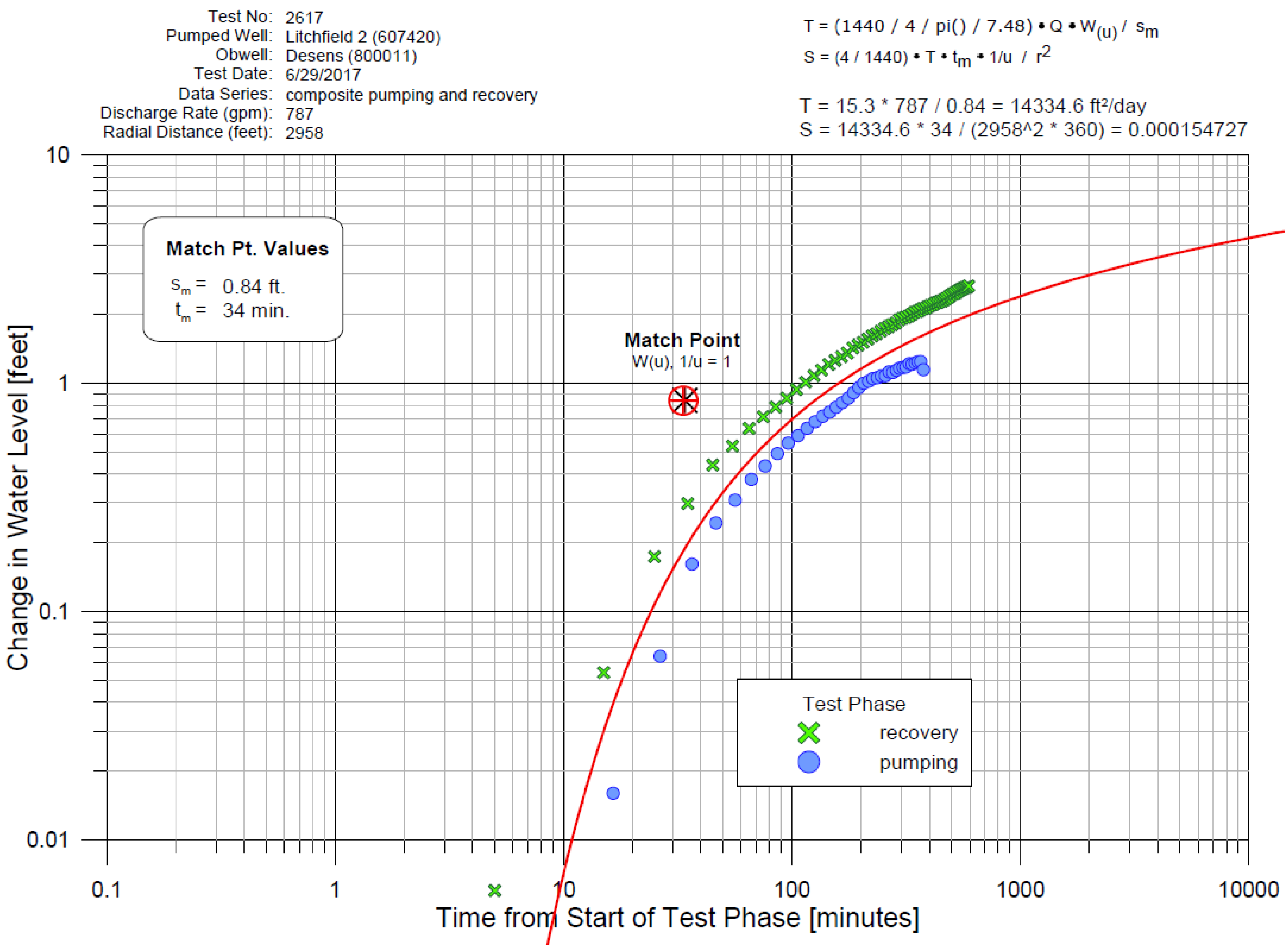


Figure 7. Theis (1935) composite (t/r²) analysis of recovery data

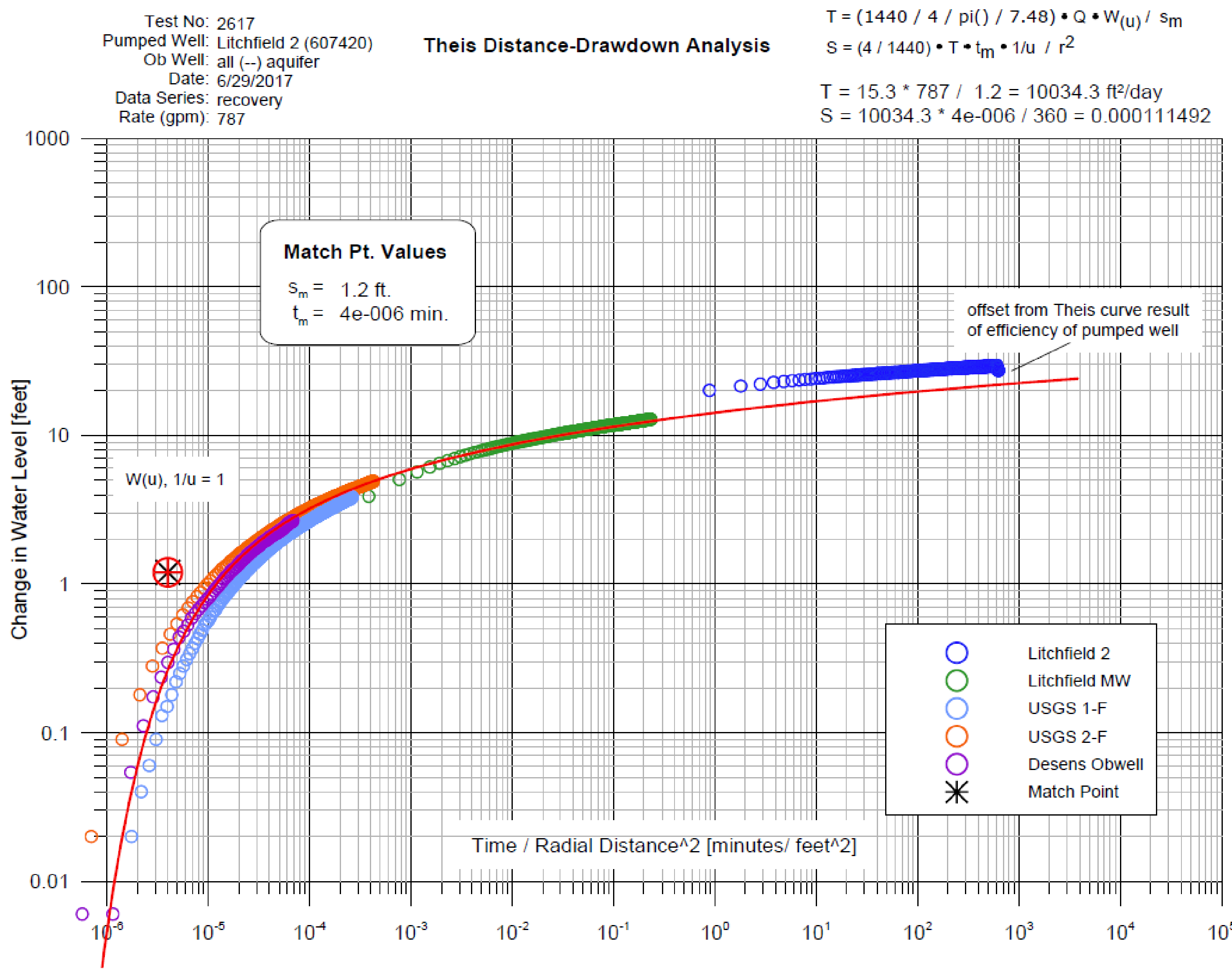


Figure 8. Projected recovery to 10,000 minutes for steady-state analysis

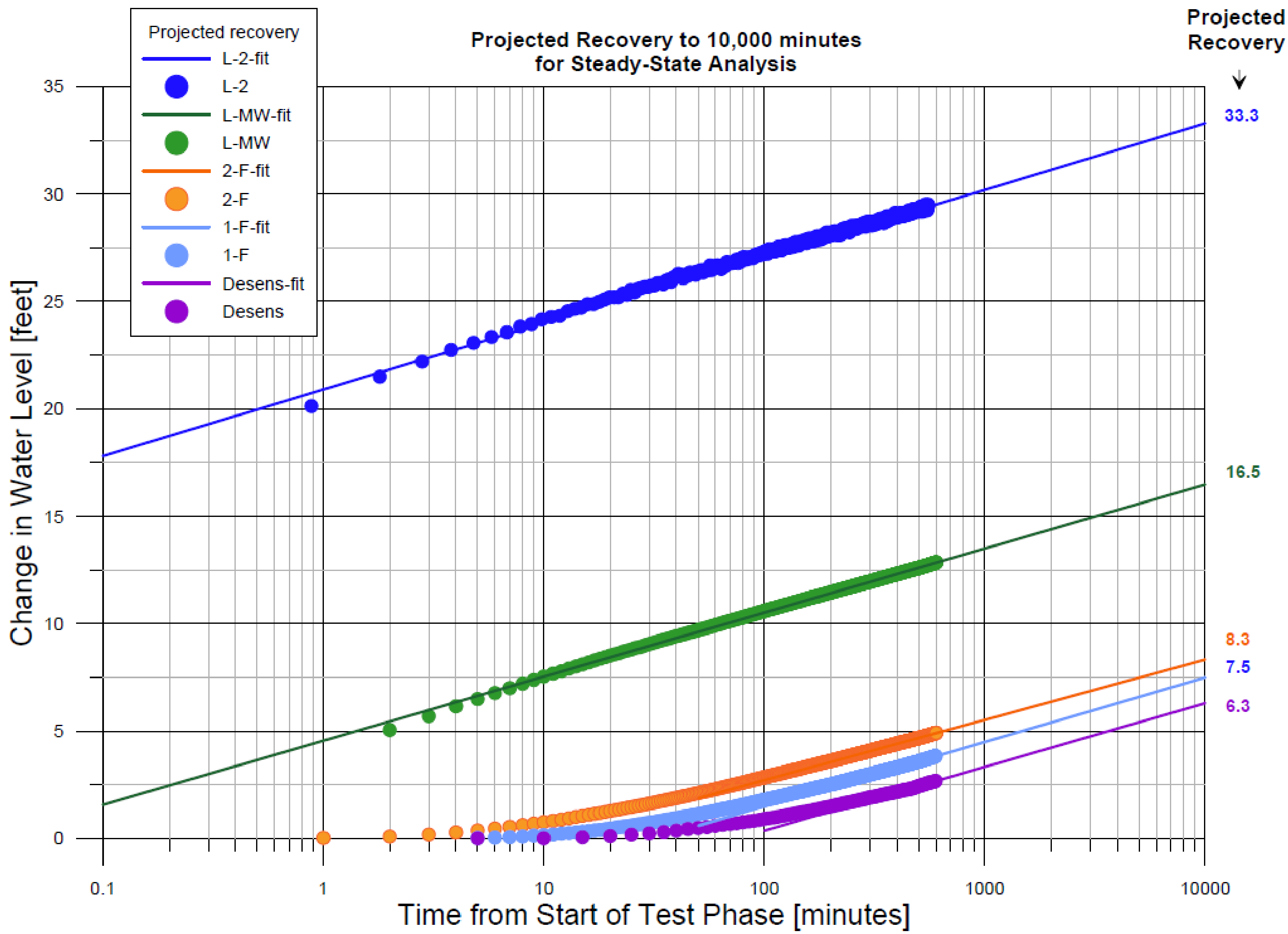


Figure 9. Cooper-Jacob (1946) transient and Hantush-Jacob (1955) steady-state analyses

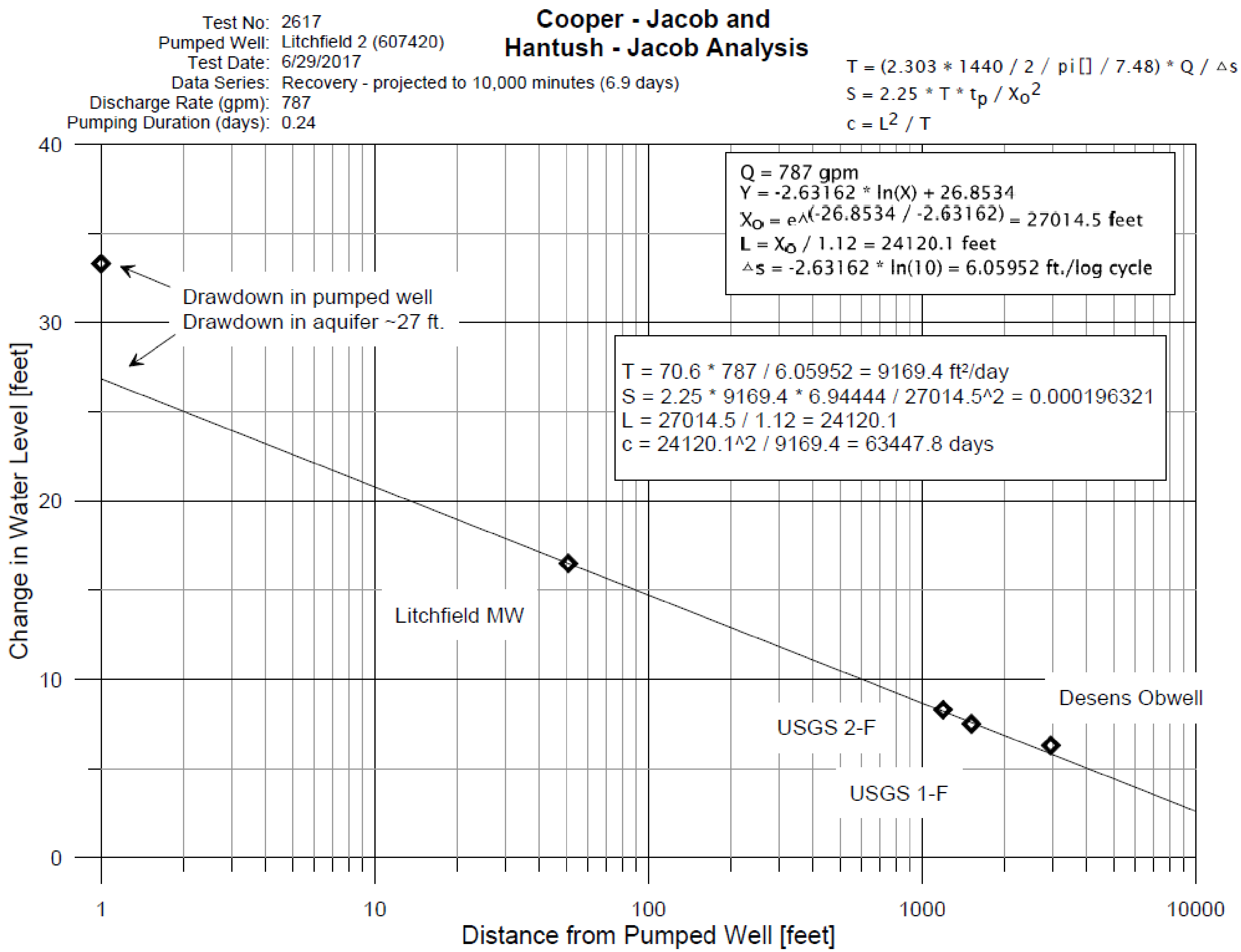


Figure 10. de Glee (1930) steady-state analysis

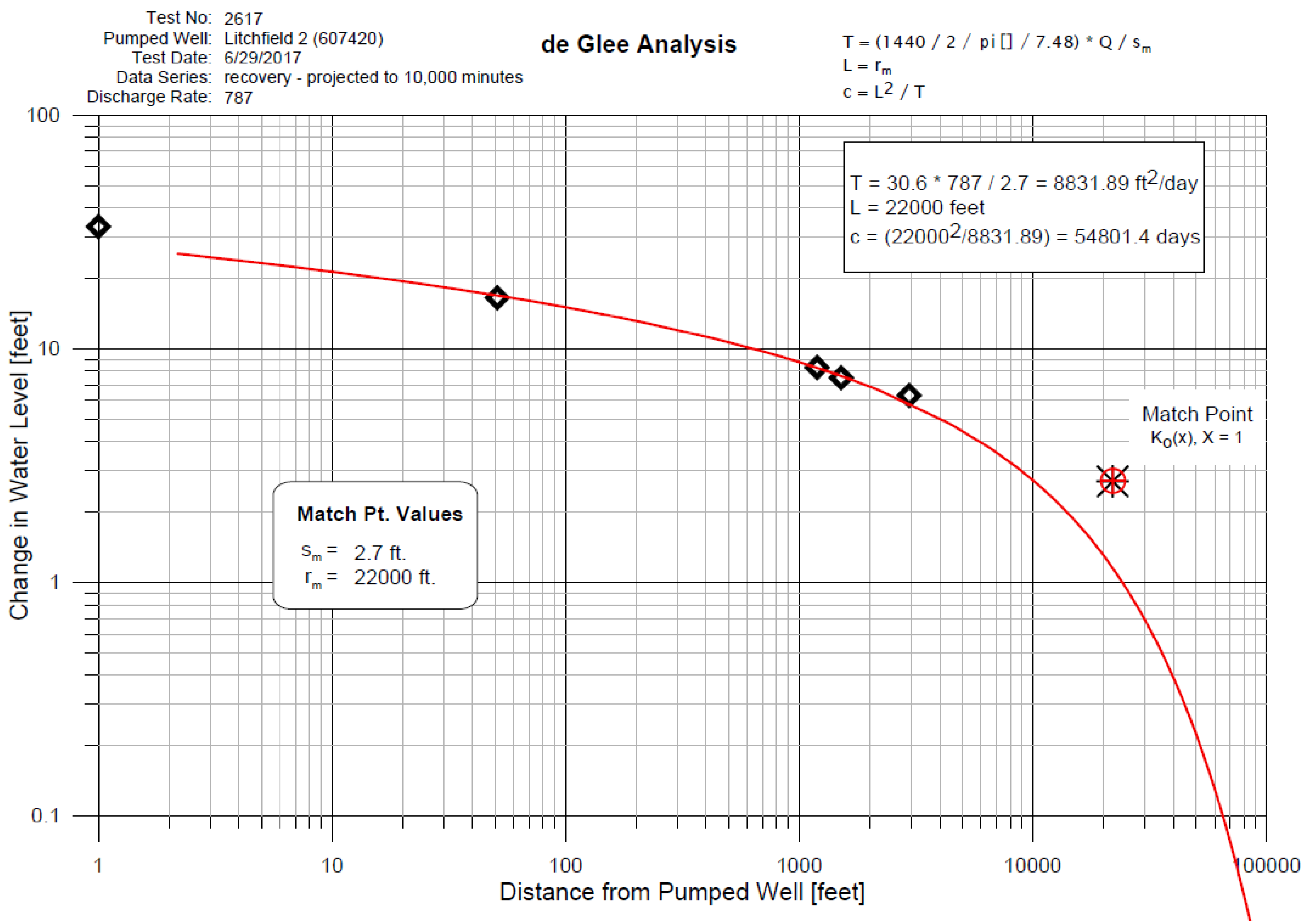


Figure 11. Difference in water level at USGS Nest-1 during pumping and recovery

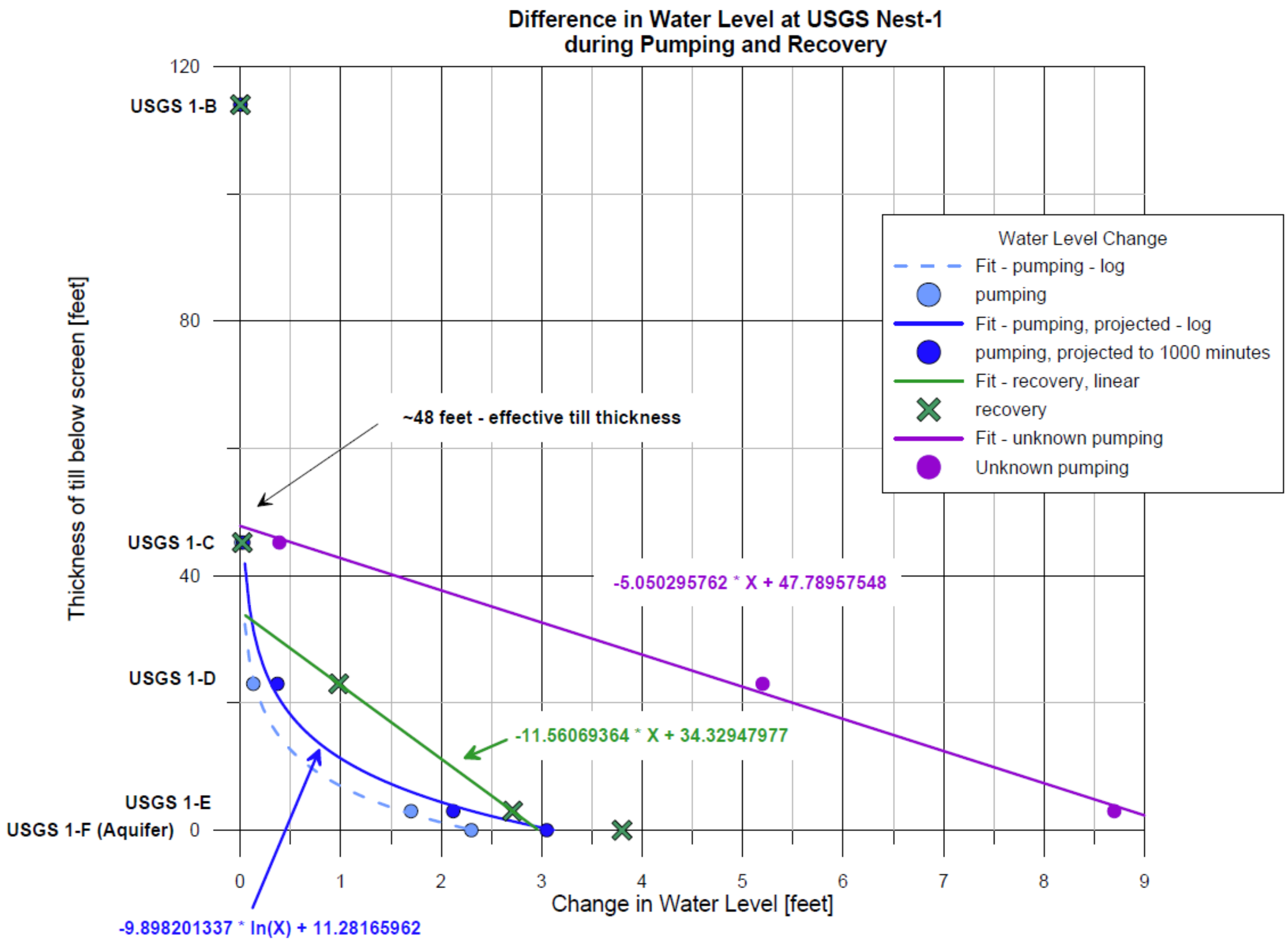
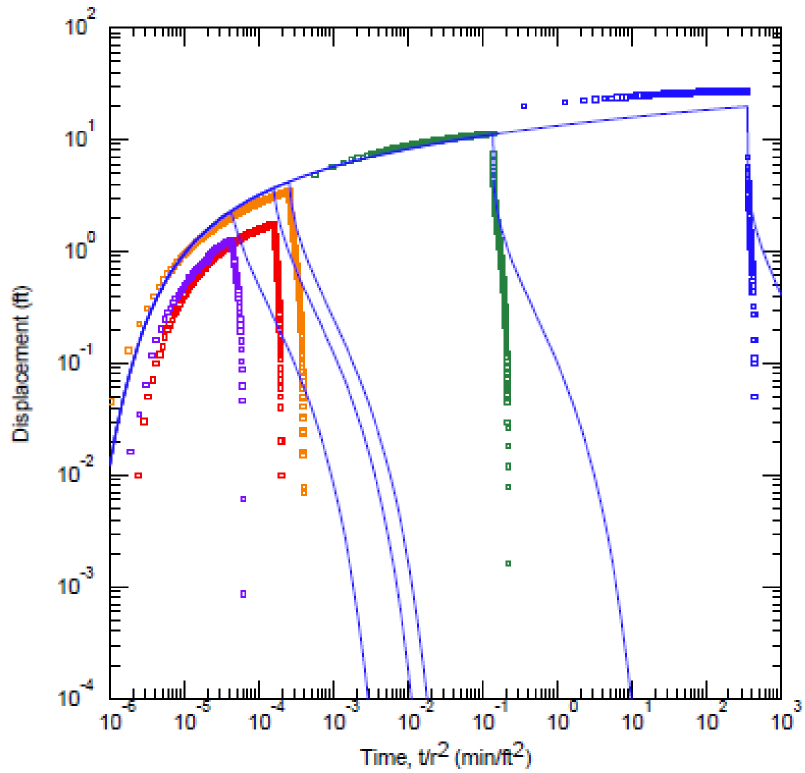


Figure 12. Aqtesolv composite (t/r2). Hantush-Jacob (1955) model



WELL TEST ANALYSIS

Data Set: O:\...\litchfield_aquifer_composite.aqt
Date: 08/28/17 Time: 15:35:03

PROJECT INFORMATION

Company: MDH
Client: City of Litchfield
Location: Litchfield 2
Test Well: L-2 (607420)
Test Date: 6/29/2017

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
2	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
2	0	0
MW	0	51
USGS 1-F	0	-1513
USGS 2-F	0	1193
Desens	2958	0

SOLUTION

Aquifer Model: Leaky

Solution Method: Hantush-Jacob

T = 1.1E+4 ft^2/day

S = 9.5E-5

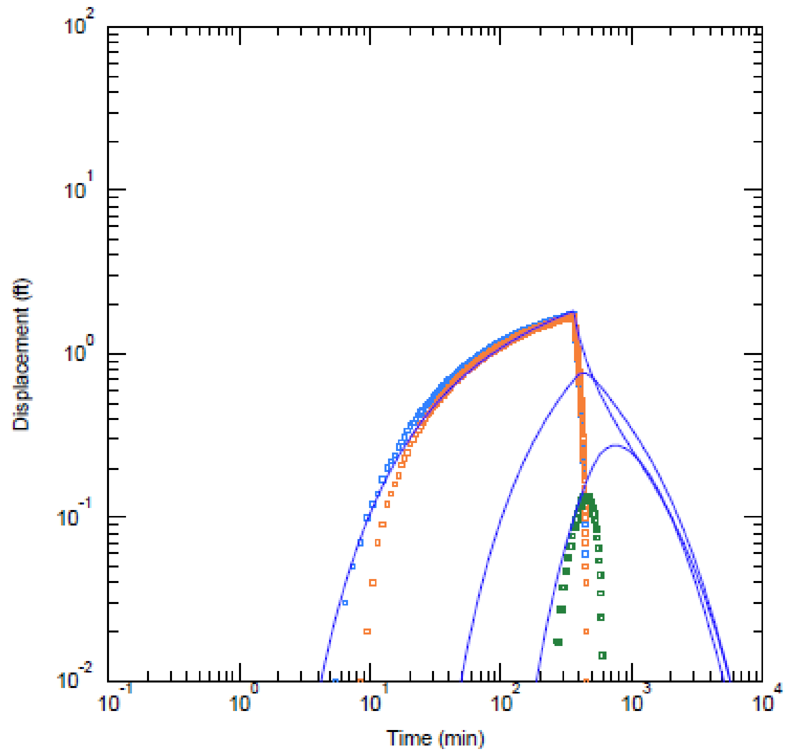
1/B = 5.0E-5 ft^{-1}

Kz/Kr = 1.

b = 6.944 ft

L = 20,000 feet
kV = 0.00005 * 11,000 * 50 = 0.0014 ft/day

Figure 13. Aqtesolv analysis of data from Nest 1 wells, Neuman-Witherspoon (1969) model. Till thickness 63 feet.



WELL TEST ANALYSIS

Data Set: O:\...\13_litchfield_nest-1_neuman.aqt
Date: 08/29/17 Time: 12:24:43

PROJECT INFORMATION

Company: MDH
Client: City of Litchfield
Location: Litchfield 2
Test Well: L-2 (607420)
Test Date: 6/29/2017

AQUIFER DATA

Saturated Thickness: 30. ft
Aquitard Thickness (b'): 63. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
2	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
USGS 1-F	0	-1513
USGS 1-E	0	-1514
USGS 1-D	0	-1510

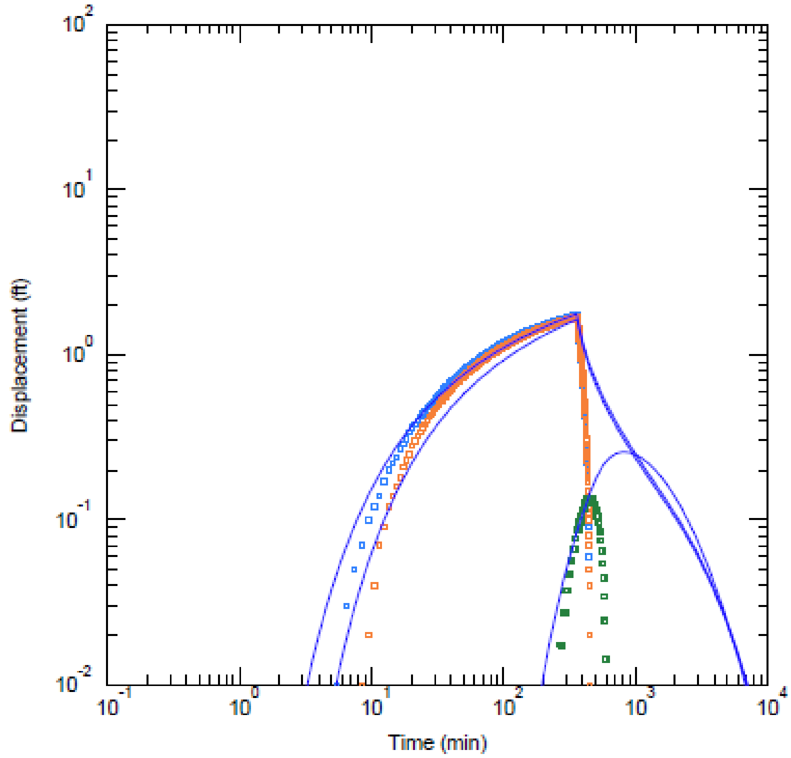
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 10000. ft^2/day
1/B = 0.0002082 ft^{-1}
T2 = 1000. ft^2/day
S = 0.00015
ß/r = 0.0001731 ft^{-1}
S2 = 1.

L = 5,000 feet
kV = 0.0002 * 10,000 * 50 = 0.02 ft/day

Figure 14. Aqtesolv analysis of data from Nest 1 wells, Neuman-Witherspoon (1969) model. Till thickness 50 feet



WELL TEST ANALYSIS

Data Set: O:\...\14_litchfield_nest-1_neuman_thickness.aqt
Date: 08/29/17 Time: 12:19:34

PROJECT INFORMATION

Company: MDH
Client: City of Litchfield
Location: Litchfield 2
Test Well: L-2 (607420)
Test Date: 6/29/2017

AQUIFER DATA

Saturated Thickness: 30. ft
Aquitard Thickness (b'): 50. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
2	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
USGS 1-F	0	-1513
USGS 1-E	0	-1514
USGS 1-D	0	-1510

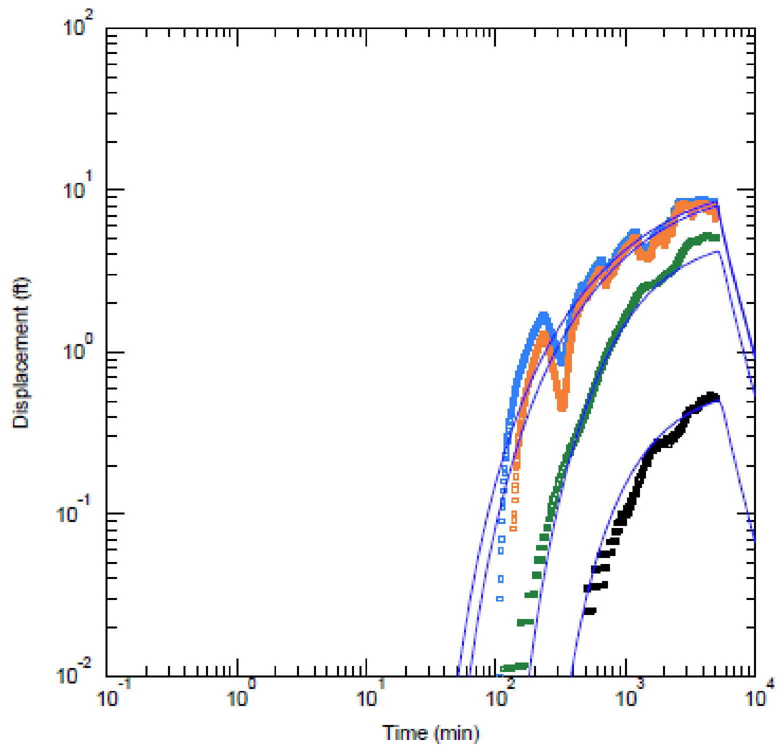
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 1.08E+4 ft^2/day
1/B = 0.0001825 ft^{-1}
T2 = 1000. ft^2/day
S = 0.00012
ß/r = 0.0001939 ft^{-1}
S2 = 1.

L = 5,500 feet
k_V = 0.0001825 * 10,800 * 50 = 0.018 ft/day

Figure 15. Aqtesolv analysis of data from Nest 1 wells, Neuman-Witherspoon (1969) model. Drawdown from unknown pumping wells.



WELL TEST ANALYSIS

Data Set: O:\...\15_litchfield_unkpump_nest-1_neuman.aqt
Date: 08/29/17 Time: 12:16:07

PROJECT INFORMATION

Company: MDH
Client: City of Litchfield
Location: Litchfield 2
Test Well: L-2 (607420)
Test Date: 6/29/2017

AQUIFER DATA

Saturated Thickness: 30. ft
Aquitard Thickness (b'): 50. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
UnkPump	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
USGS 1-F	8000	0
USGS 1-E	8000	0
USGS 1-D	8000	0
USGS 1-C	8000	0

SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 8000. ft^2/day
1/B = 5.0E-5 ft^{-1}
T2 = 10000. ft^2/day
S = 7.38E-5
ß/r = 9.198E-6 ft^{-1}
S2 = 1.

L = 20,000 feet
k_v = 0.00005 * 8000 * 50 = 0.001 ft/day

Figure 16. Well Location Map: well name and Minnesota unique well number

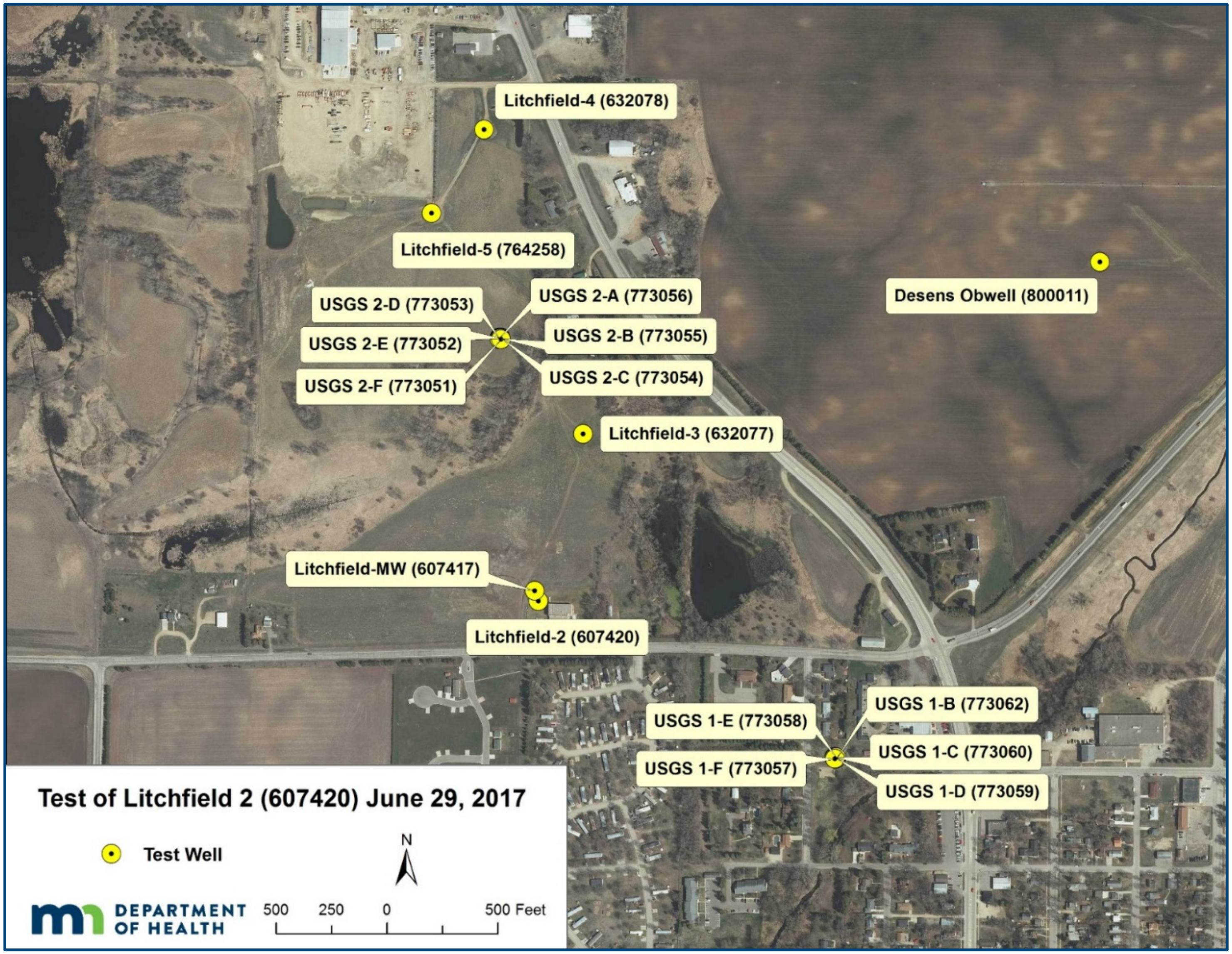


Figure 17. Schematic Section

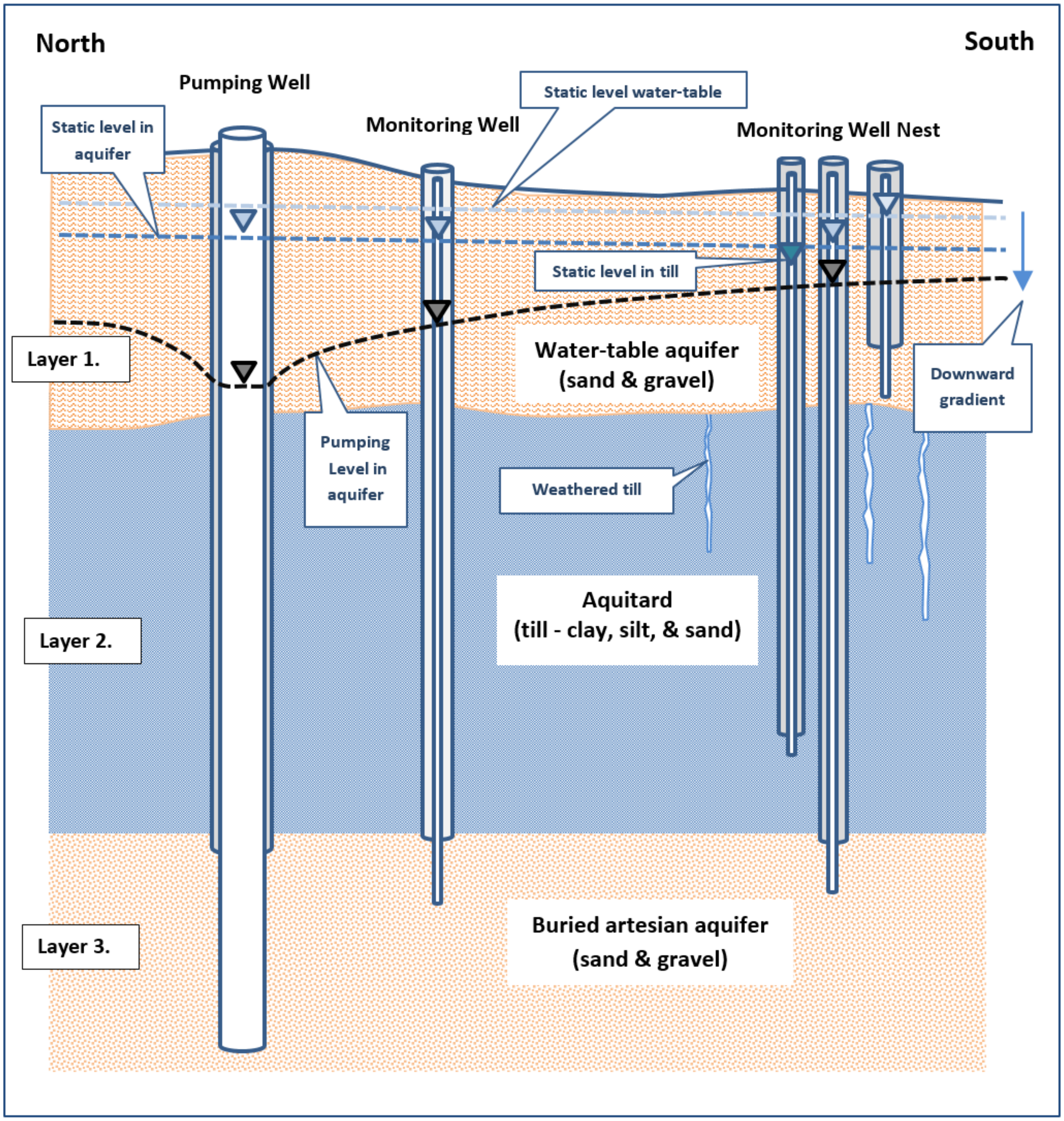


Figure 18. Depth to Water from Top of Casing at Litchfield 2 (607417), Both Manual and Electronic Measurements

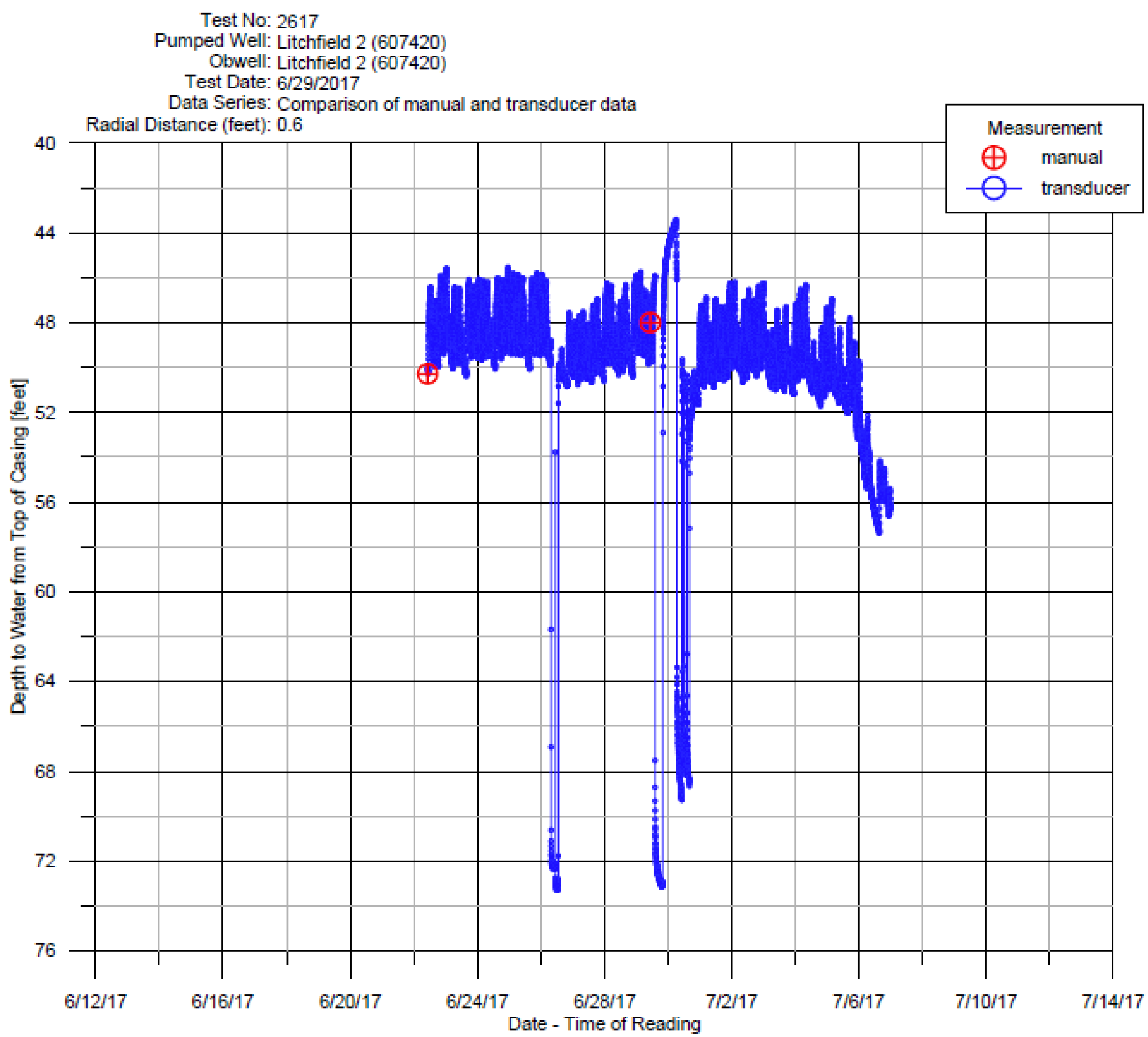


Figure 19. Depth to Water from Top of Casing at Litchfield MW (607420), Both Manual and Electronic Measurements

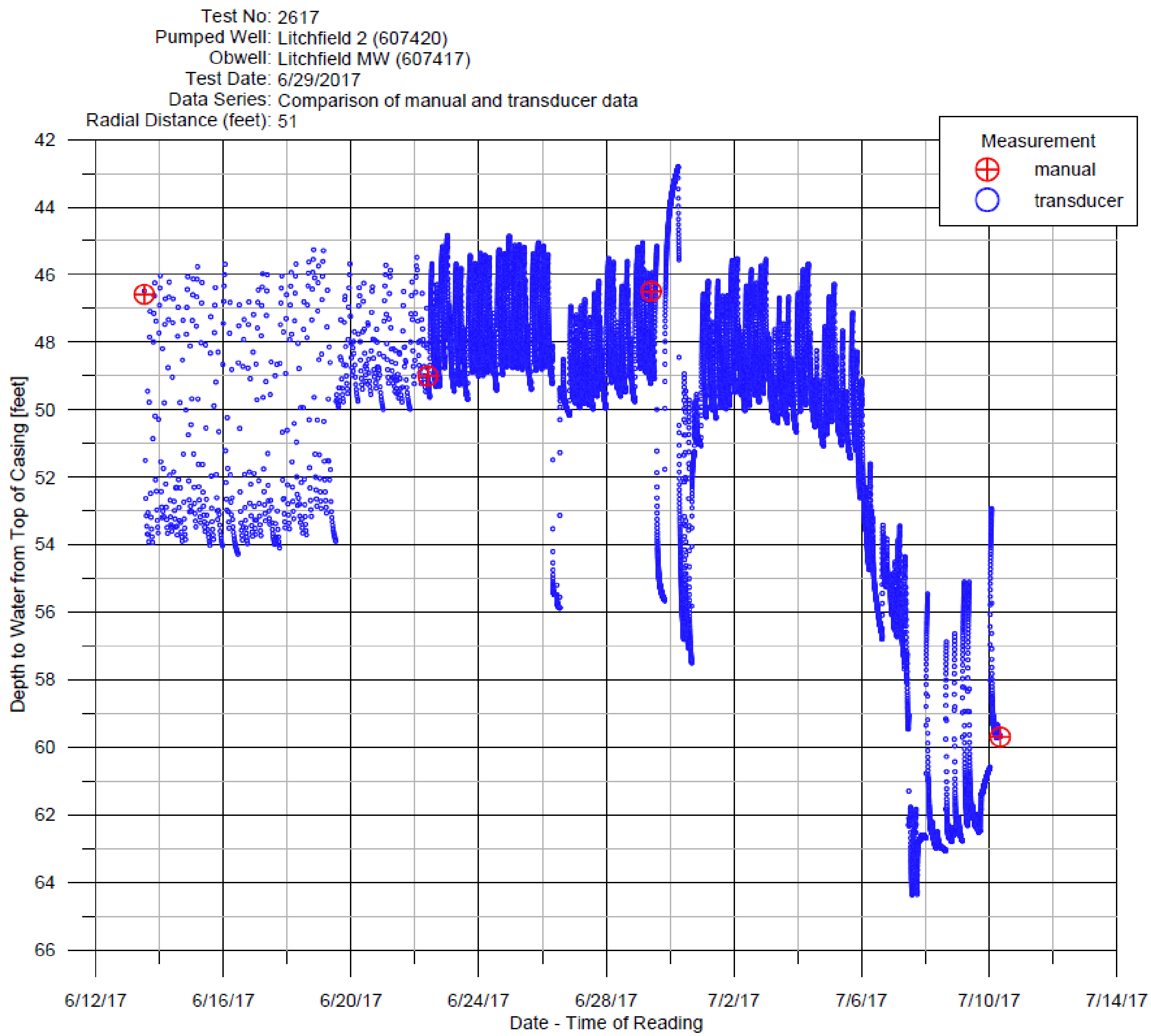


Figure 20. Depth to Water from Top of Casing at Litchfield 3 (632077), Manual Measurements

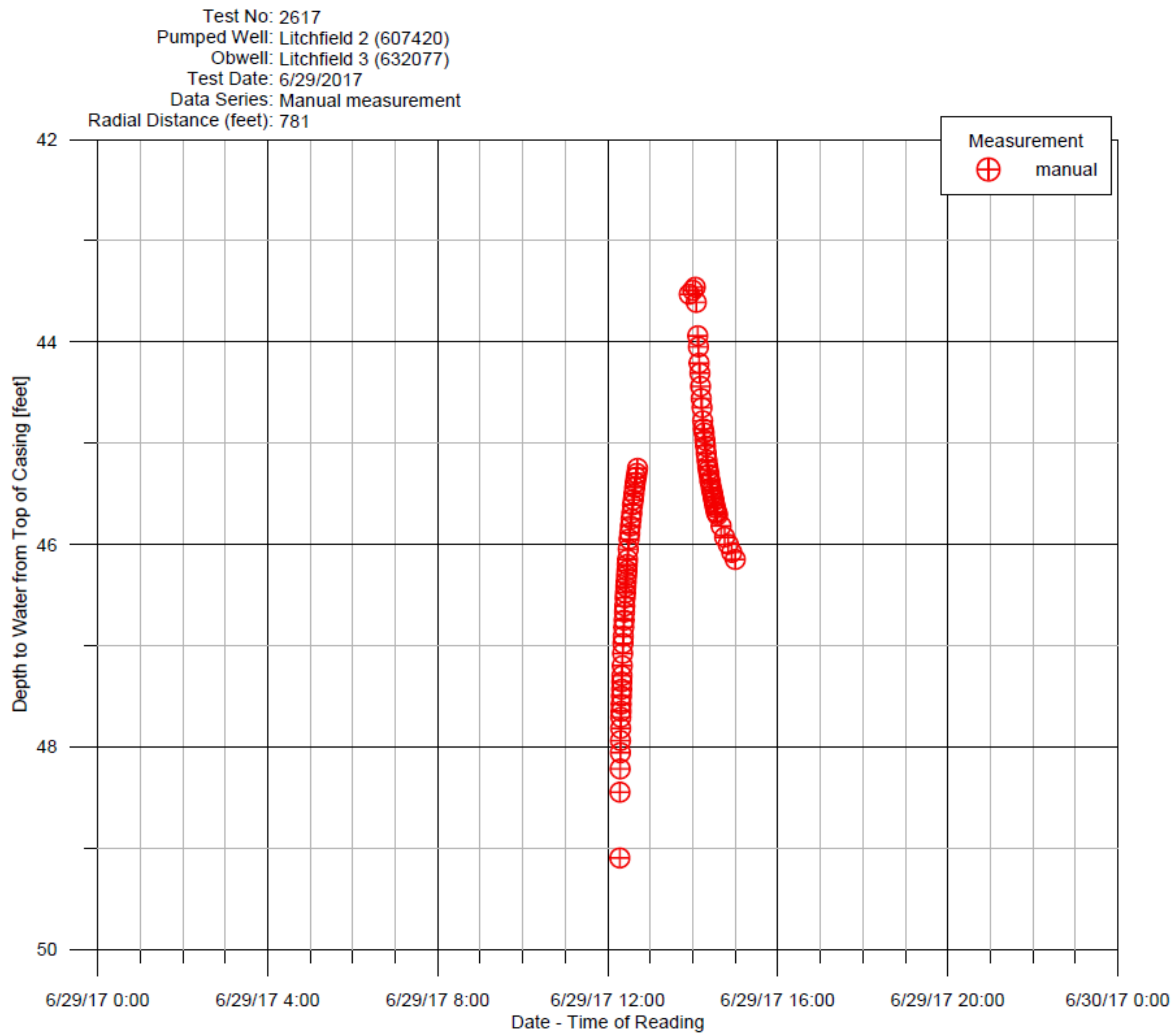


Figure 21. Depth to Water from Top of Casing at Litchfield 4 (632078), Manual Measurements

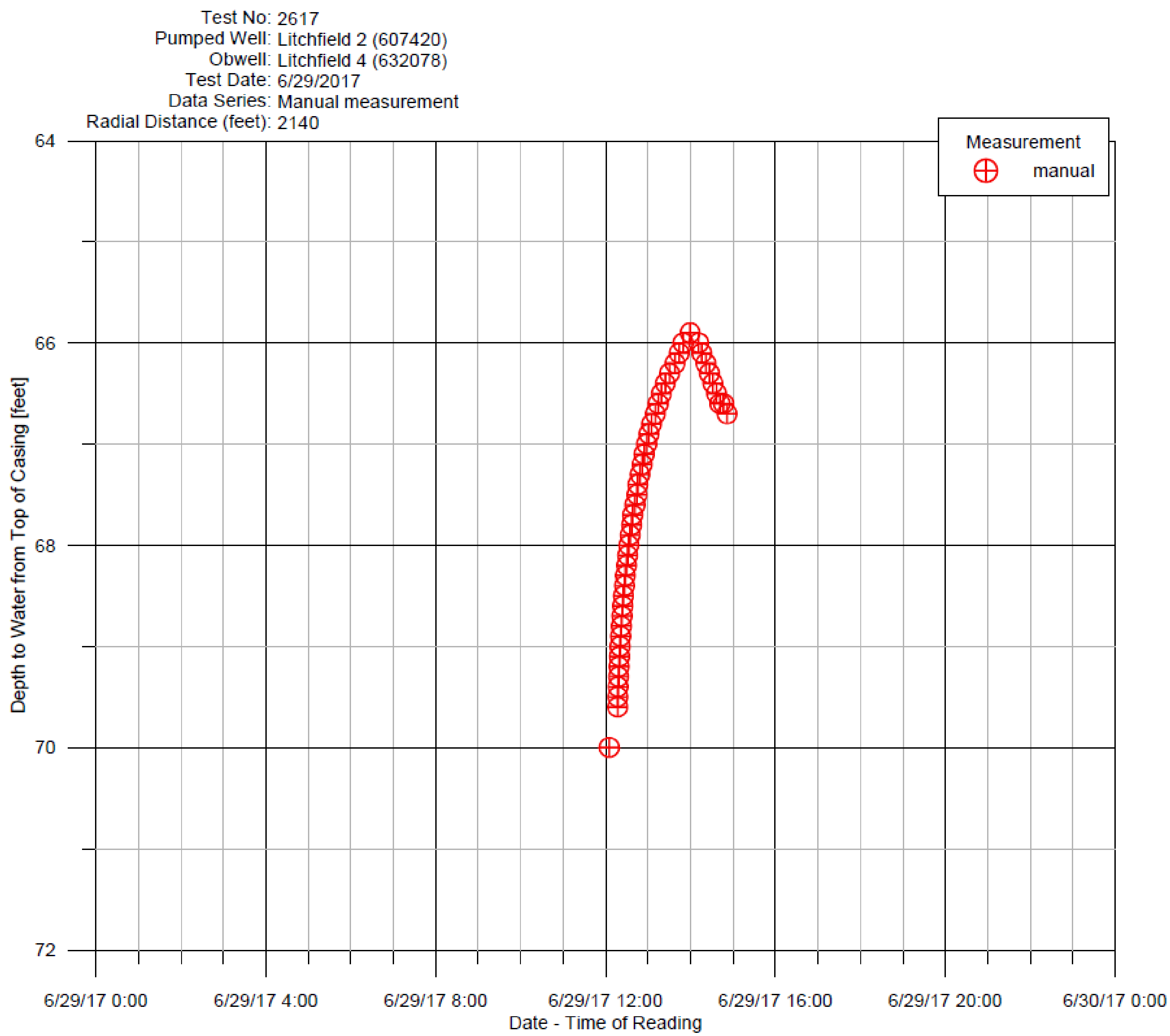


Figure 22. Depth to Water from Top of Casing at Litchfield 5 (764258), Manual Measurements

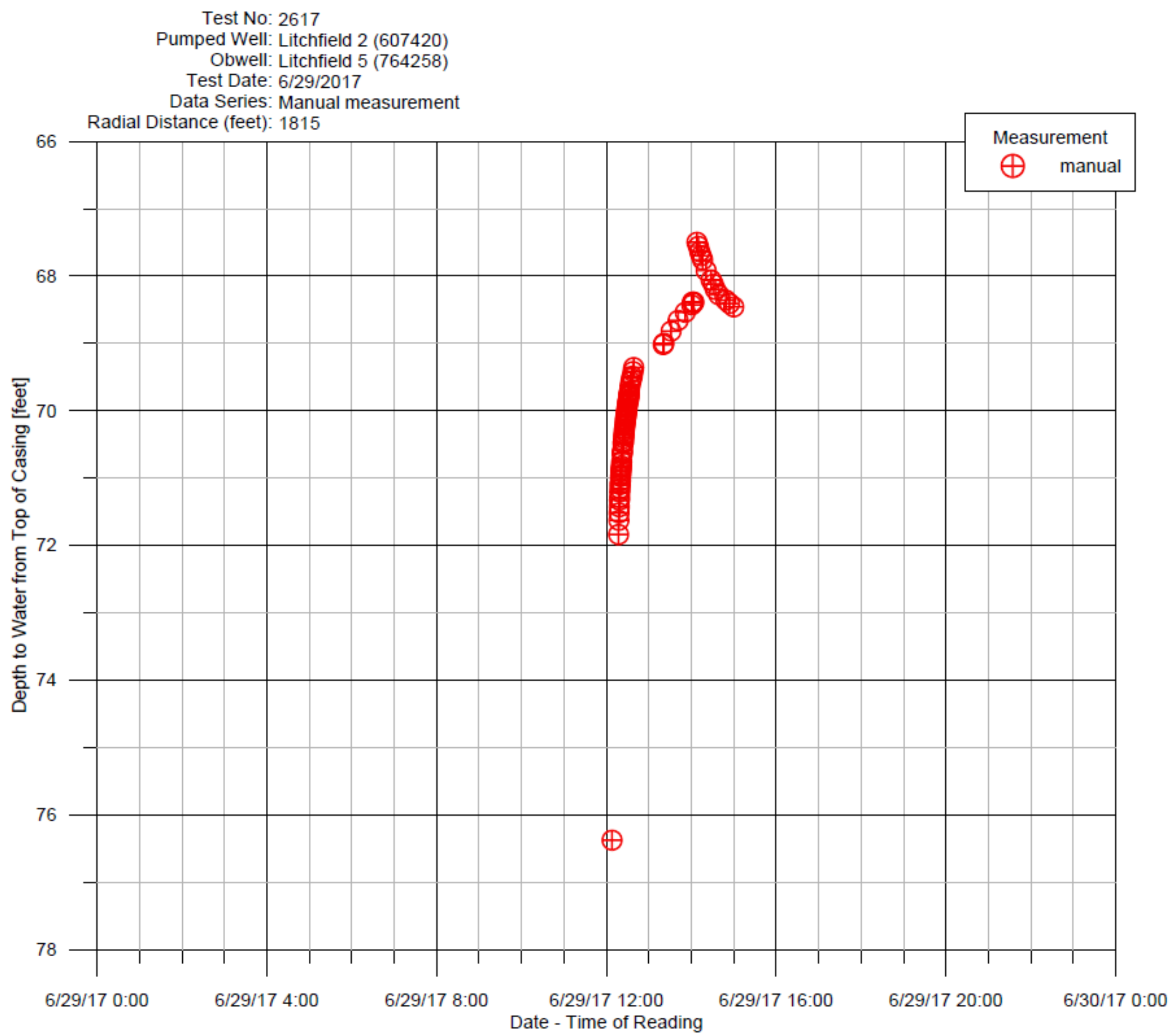


Figure 23. Depth to Water from Top of Casing at USGS 1-B (773062), Both Manual and Electronic Measurements

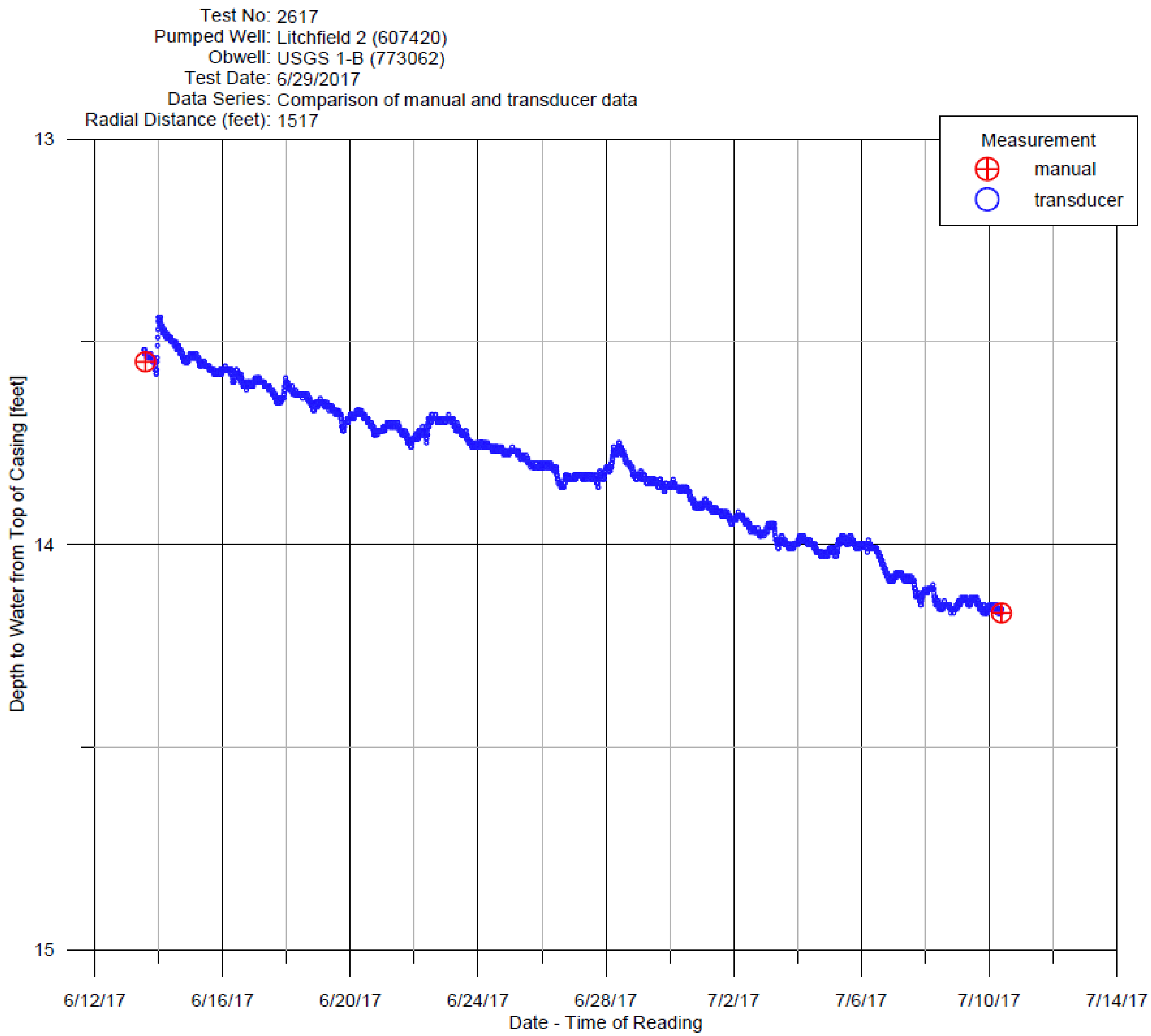


Figure 24. Depth to Water from Top of Casing at USGS 1-C (773060), Both Manual and Electronic Measurements

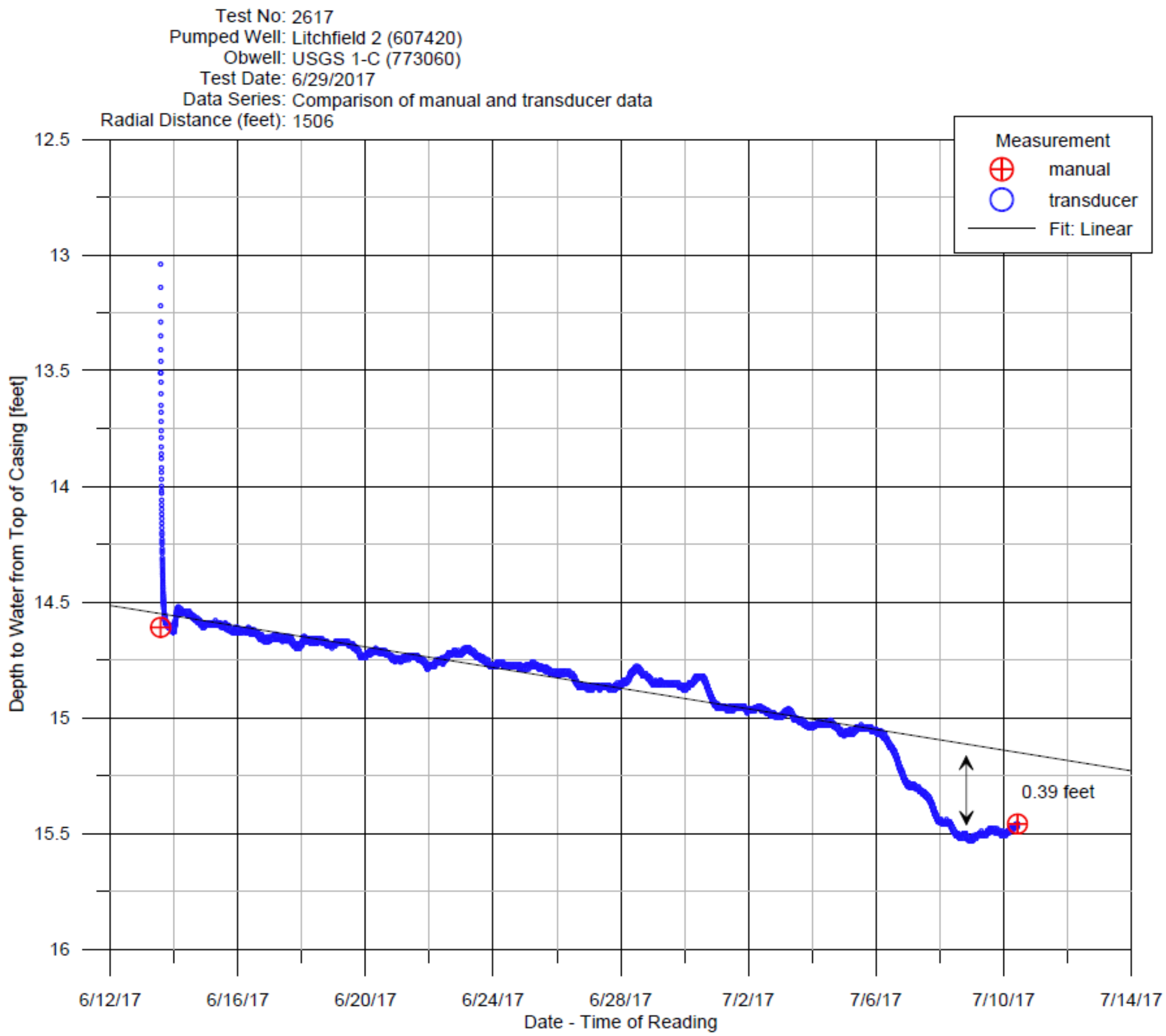


Figure 25. Depth to Water from Top of Casing at USGS 1-D (773059), Both Manual and Electronic Measurements

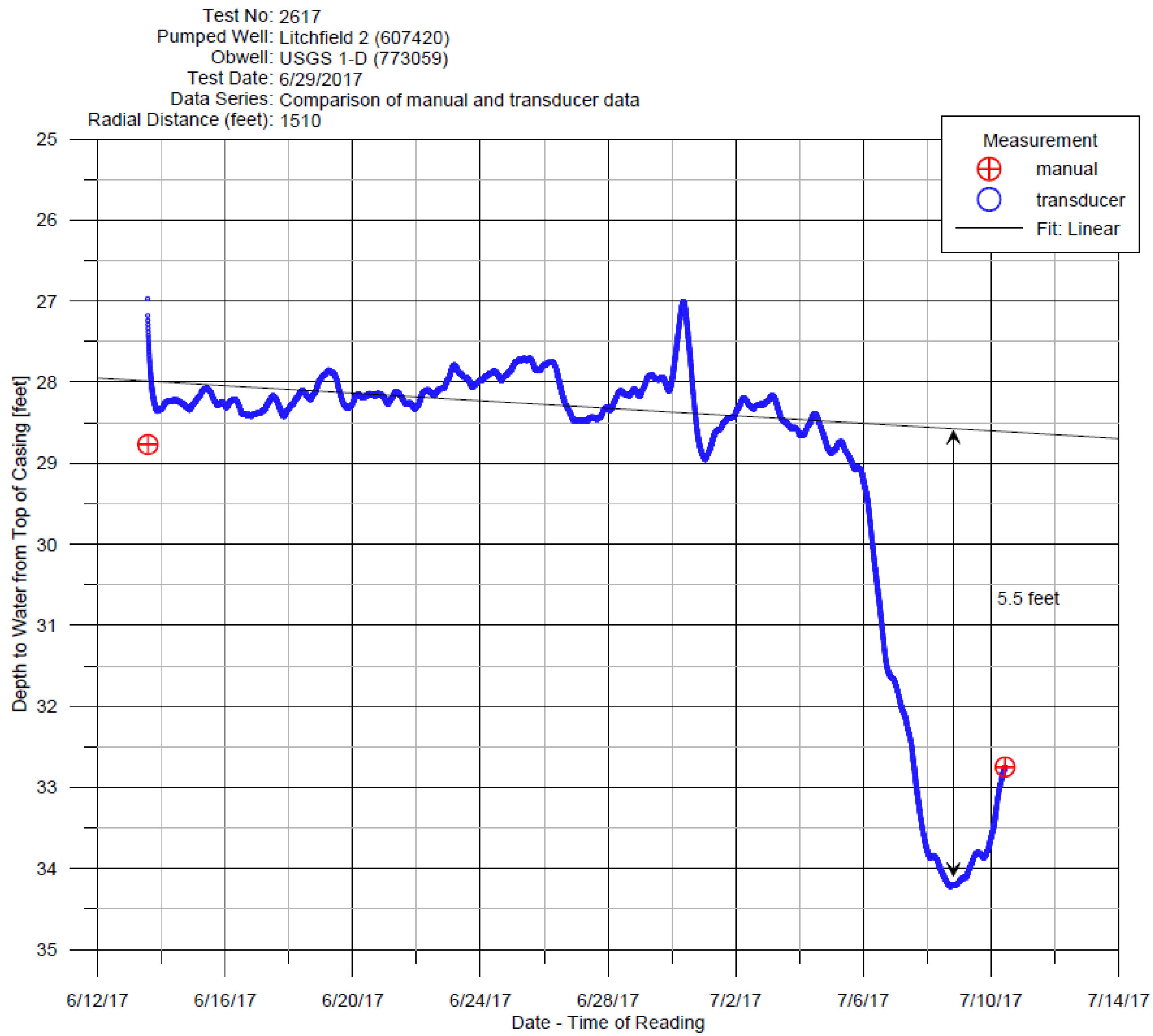


Figure 26. Depth to Water from Top of Casing at USGS 1-E (773058), Both Manual and Electronic Measurements

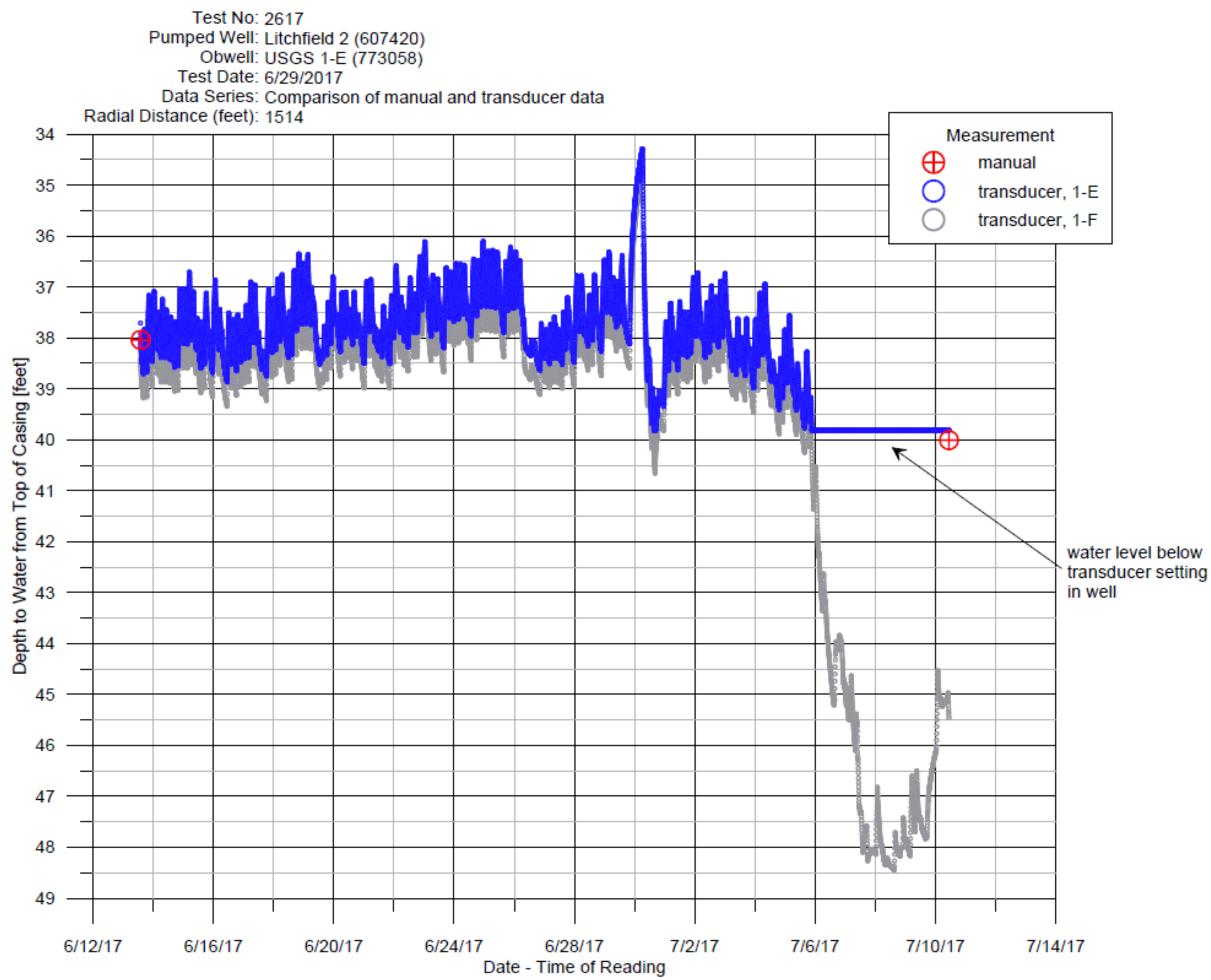


Figure 27. Depth to Water from Top of Casing at USGS 1-F (773057), Both Manual and Electronic Measurements

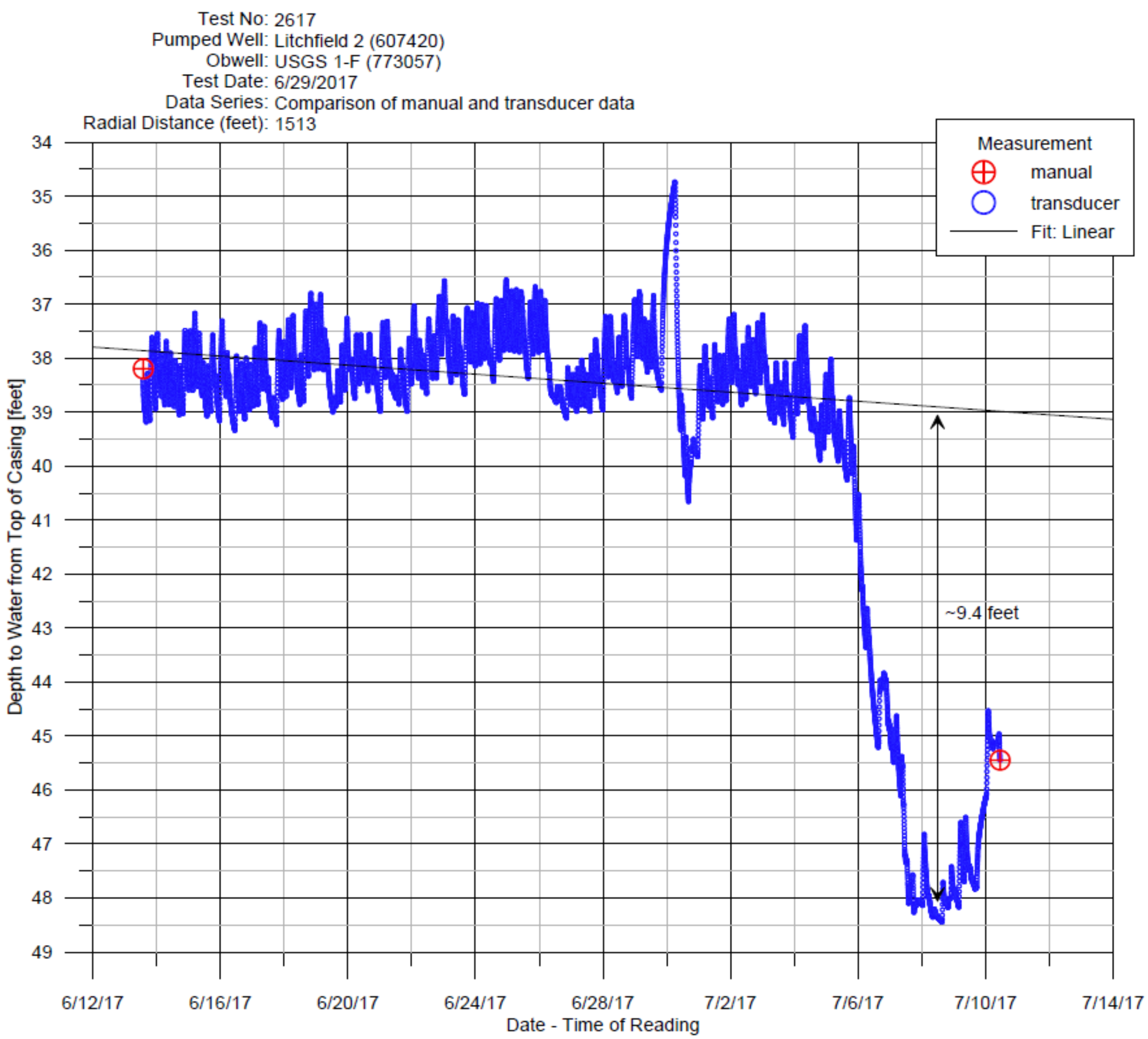


Figure 28. Depth to Water from Top of Casing at USGS 2-A (773056), Both Manual and Electronic Measurements

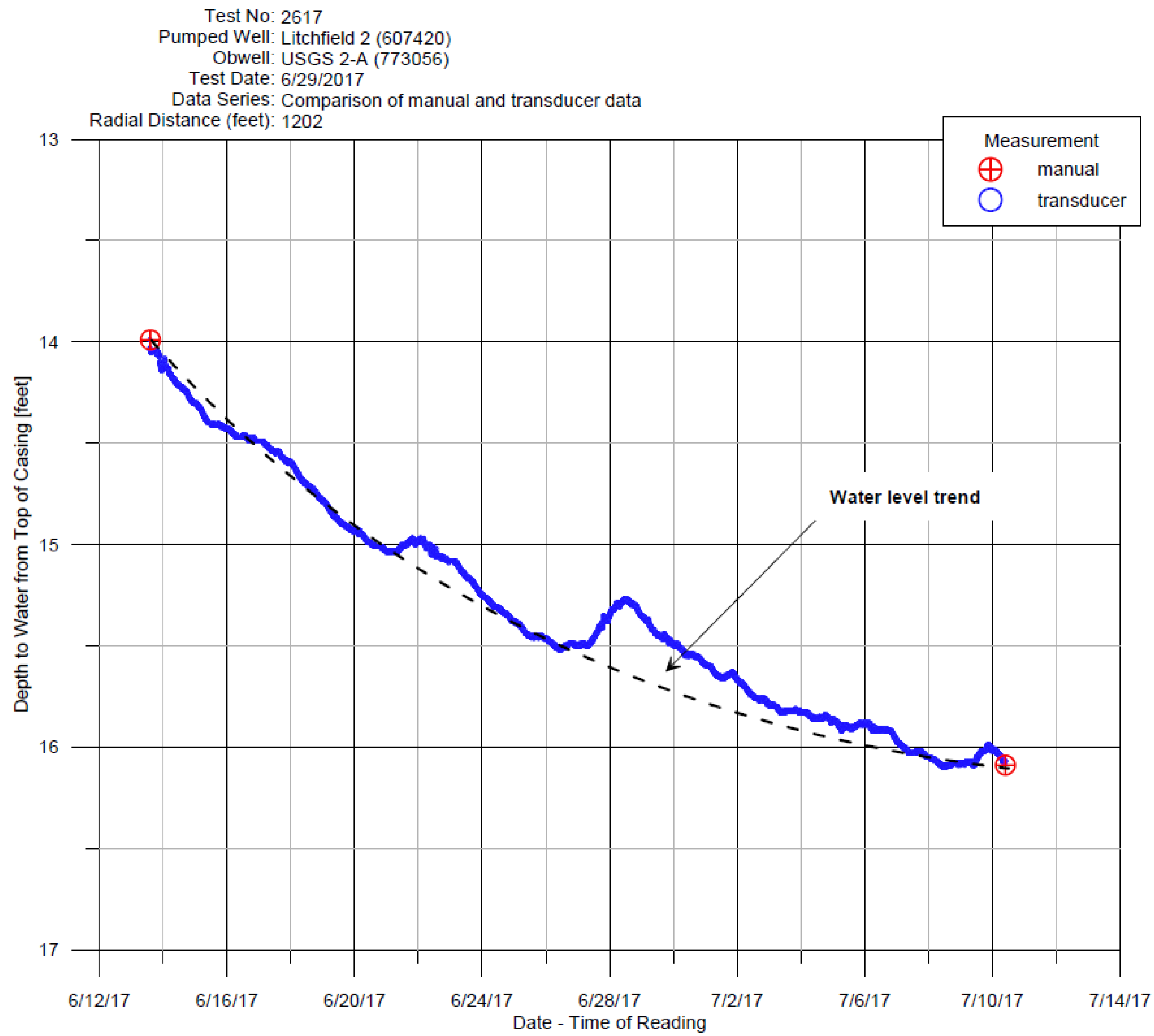


Figure 29. Depth to Water from Top of Casing at USGS 2-B (773055), Both Manual and Electronic Measurements

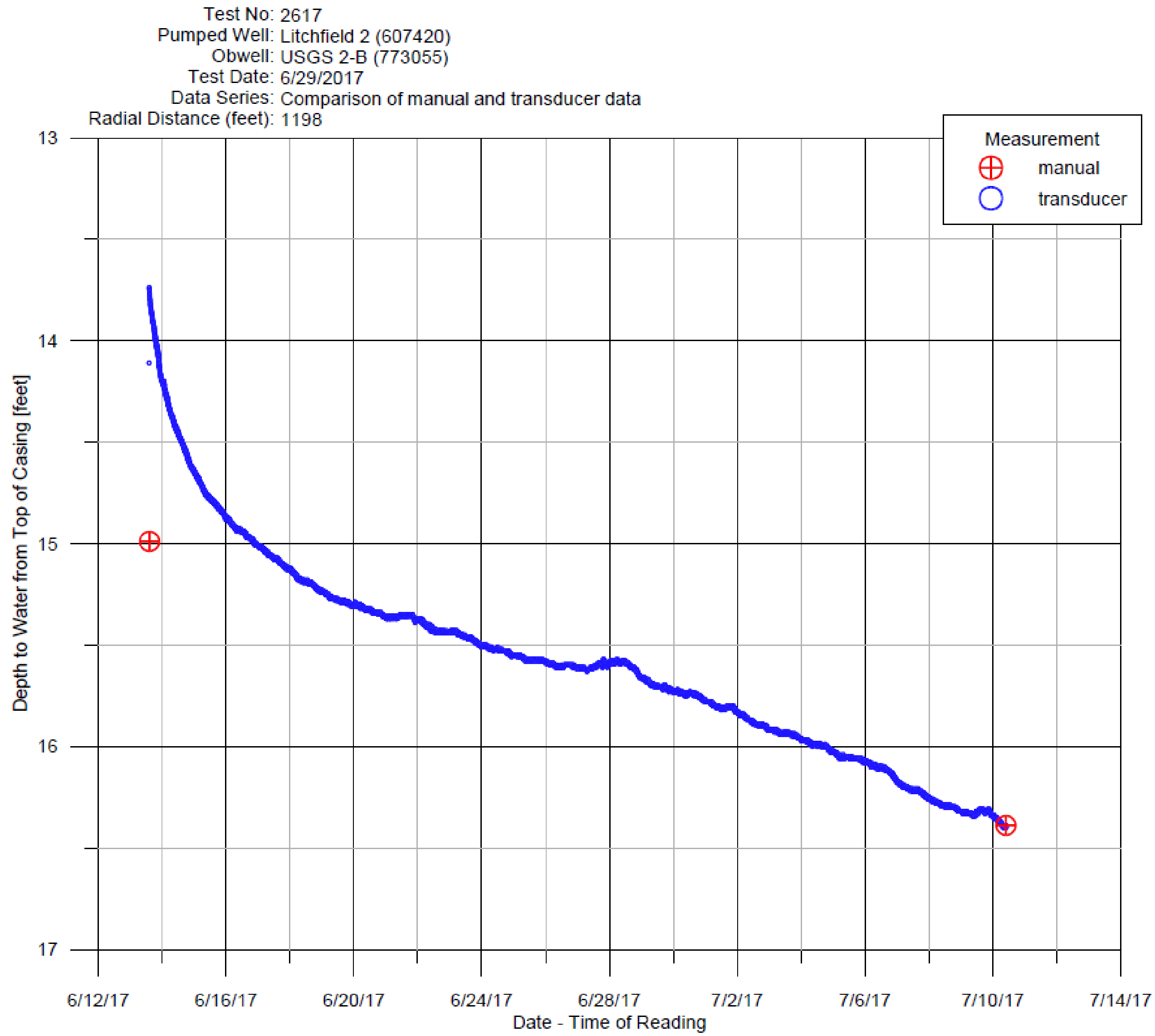


Figure 30. Depth to Water from Top of Casing at USGS 2-C (773054), Both Manual and Electronic Measurements

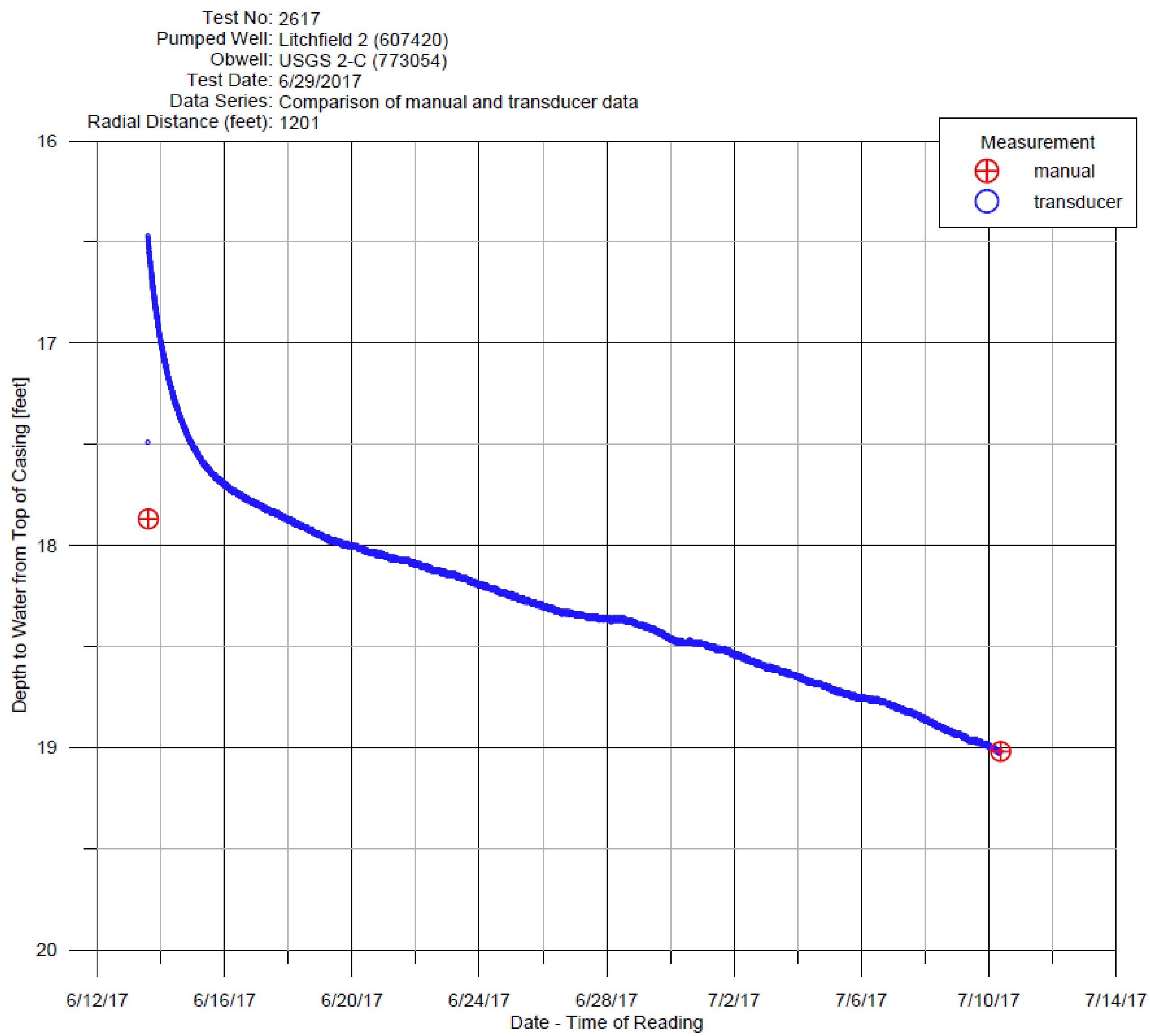


Figure 31. Depth to Water from Top of Casing at USGS 2-D (773053), Both Manual and Electronic Measurements

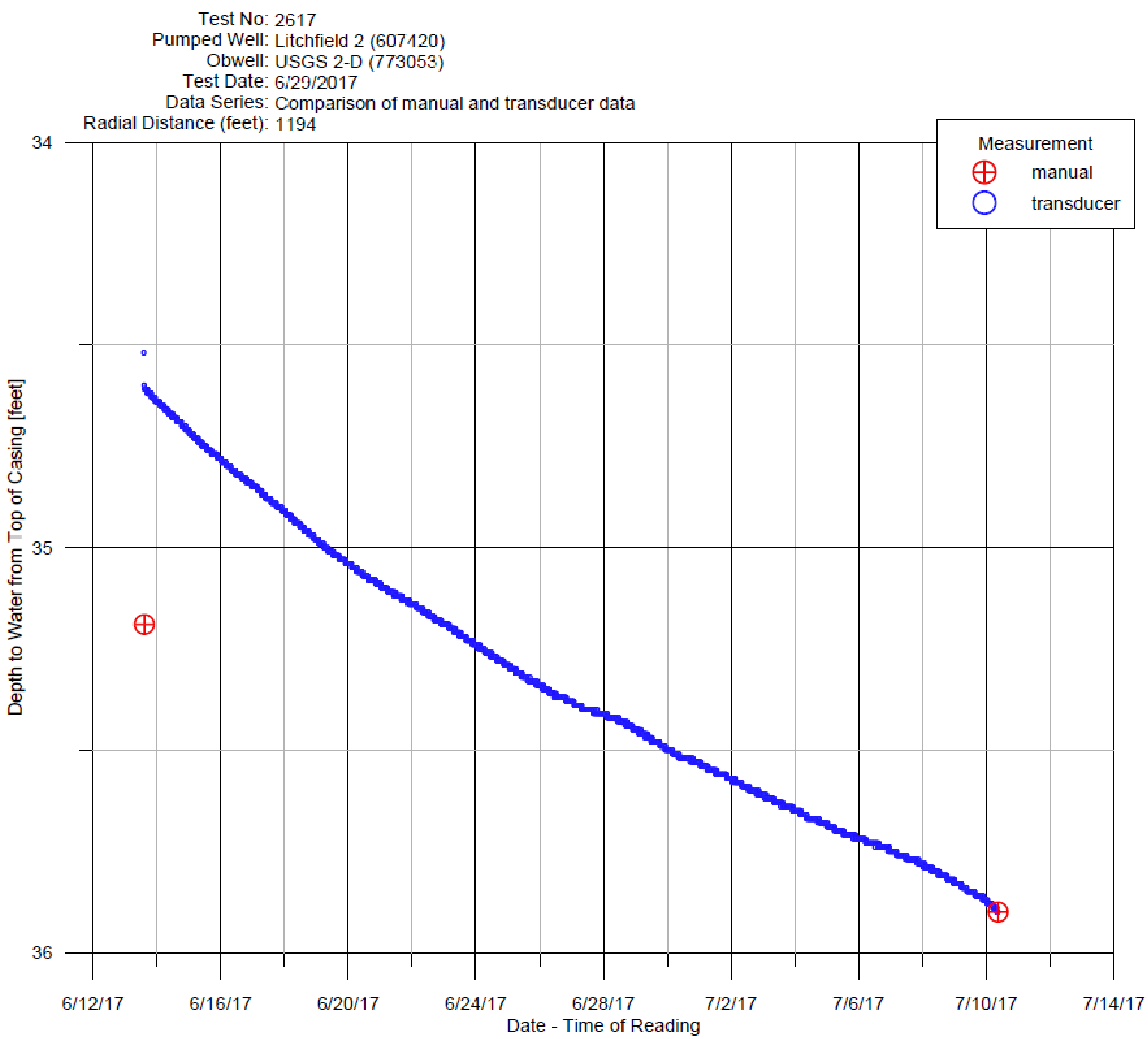


Figure 32. Depth to Water from Top of Casing at USGS 2-F (773051), Both Manual and Electronic Measurements

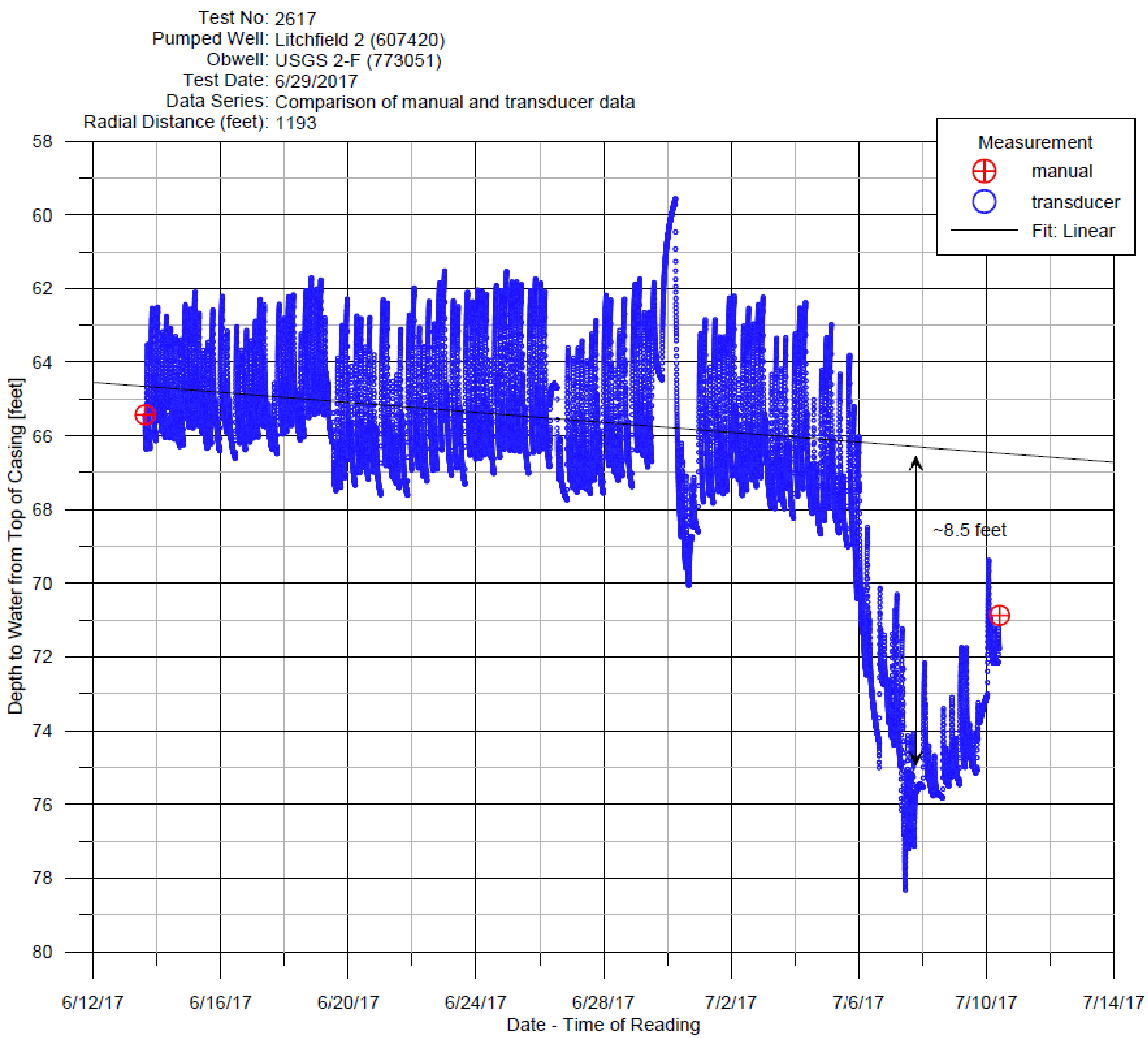


Figure 33. Depth to Water from Top of Casing at Desens Observation (800011), Both Manual and Electronic Measurements

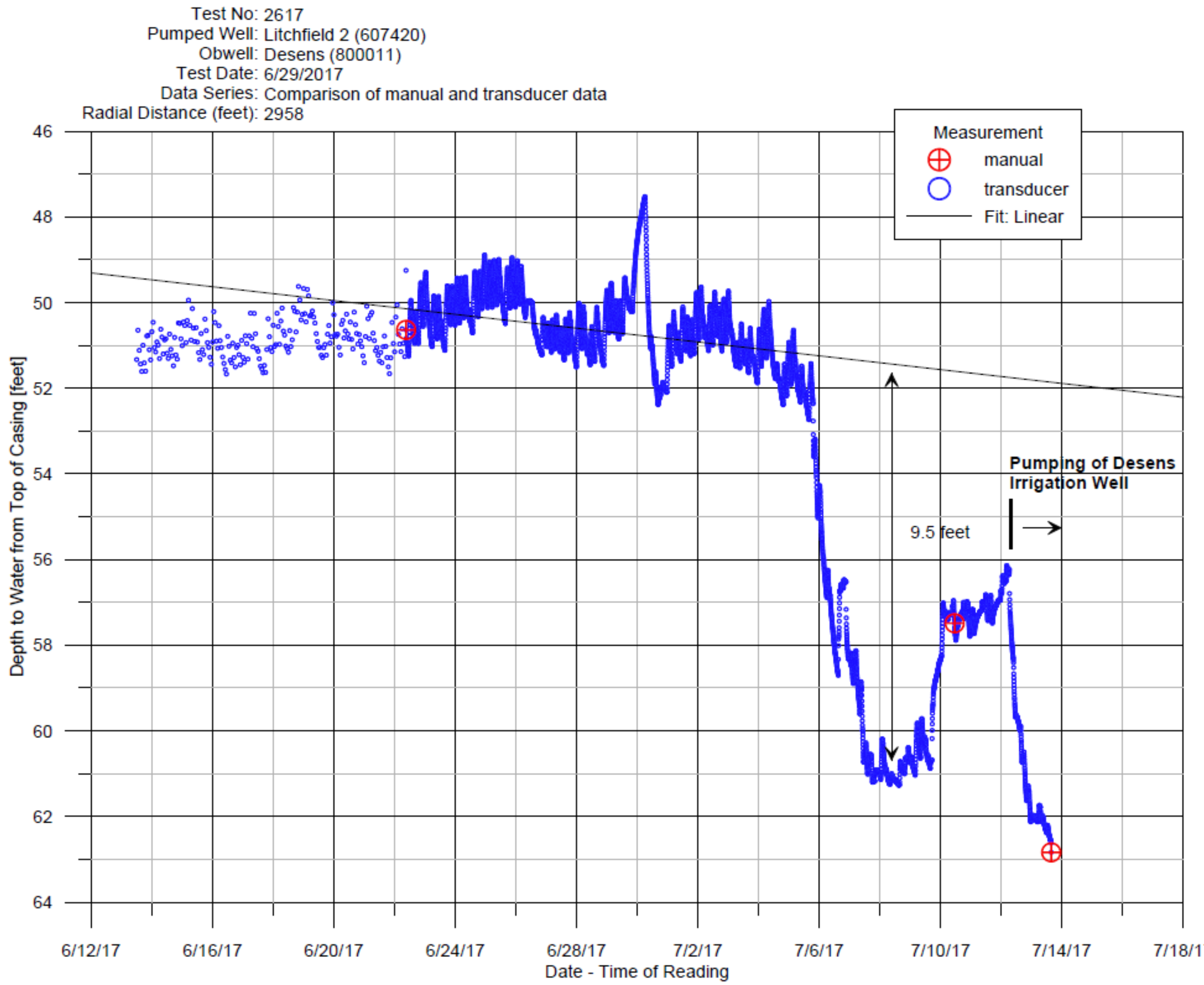


Figure 34. Groundwater elevation at Litchfield-2 and Nest 1

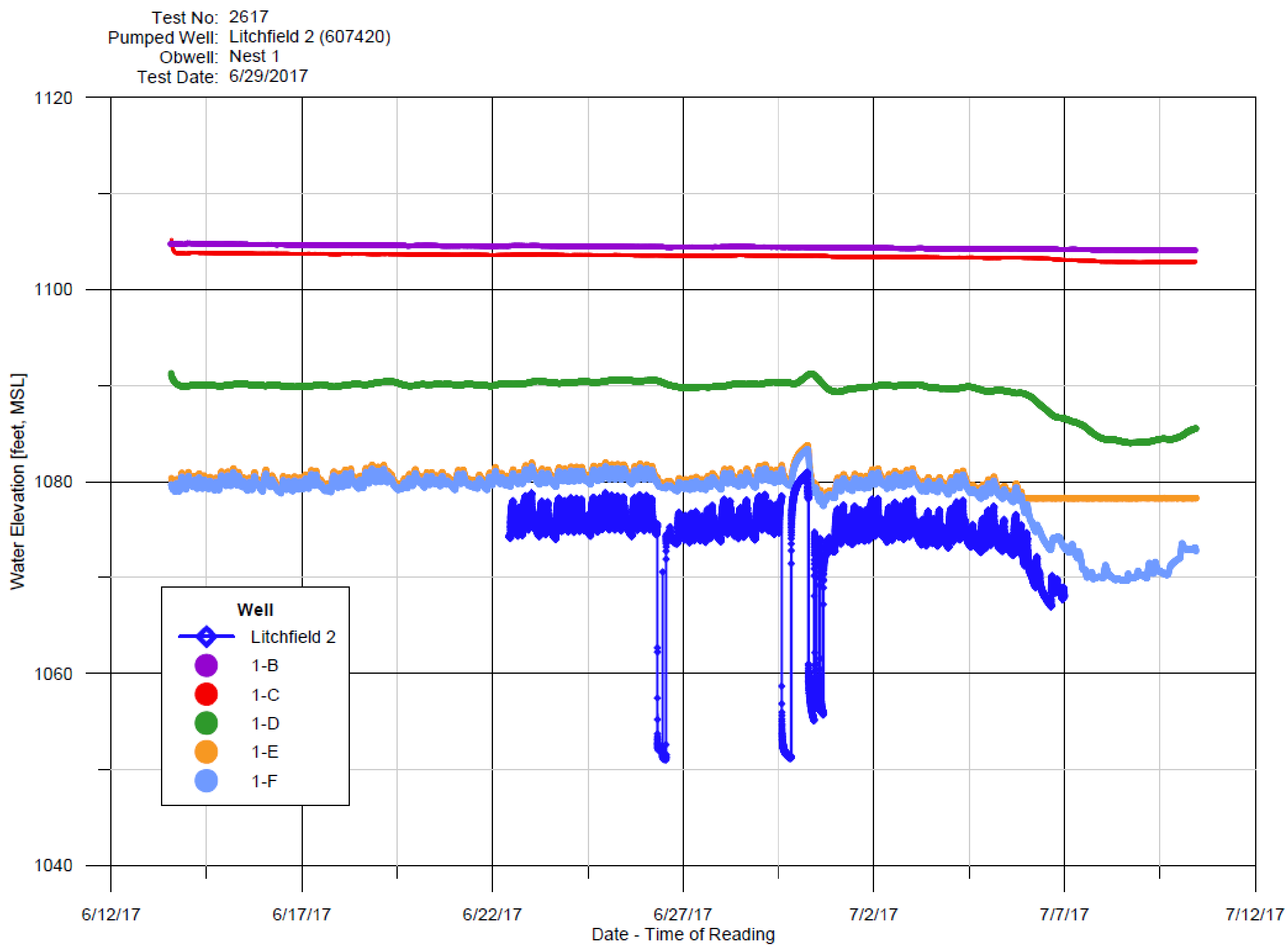


Figure 35. Groundwater elevation at Litchfield-2 and Nest 2

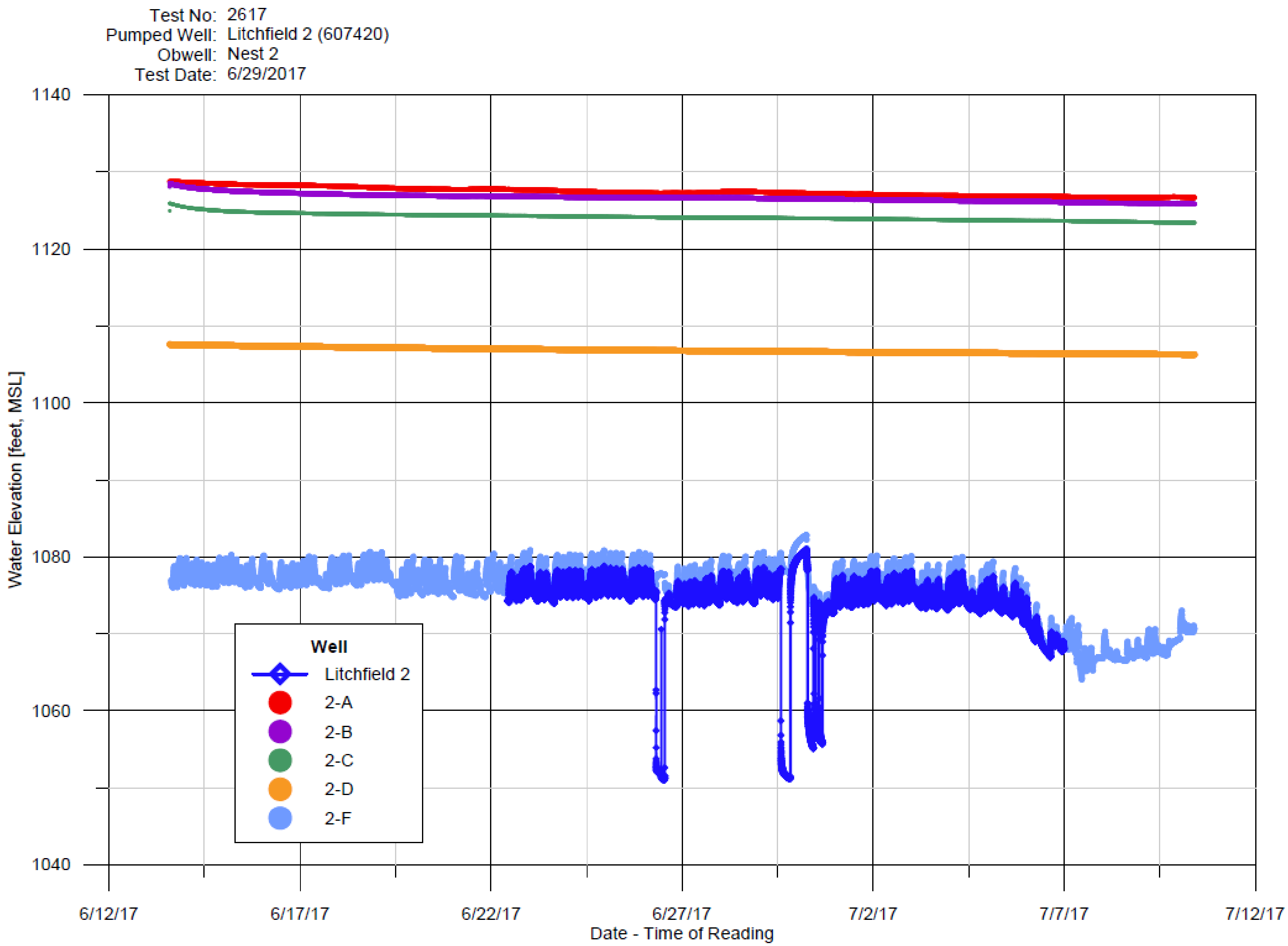


Figure 36. Groundwater elevation at Litchfield-2 and Observation Wells Constructed in Aquifer, All Data

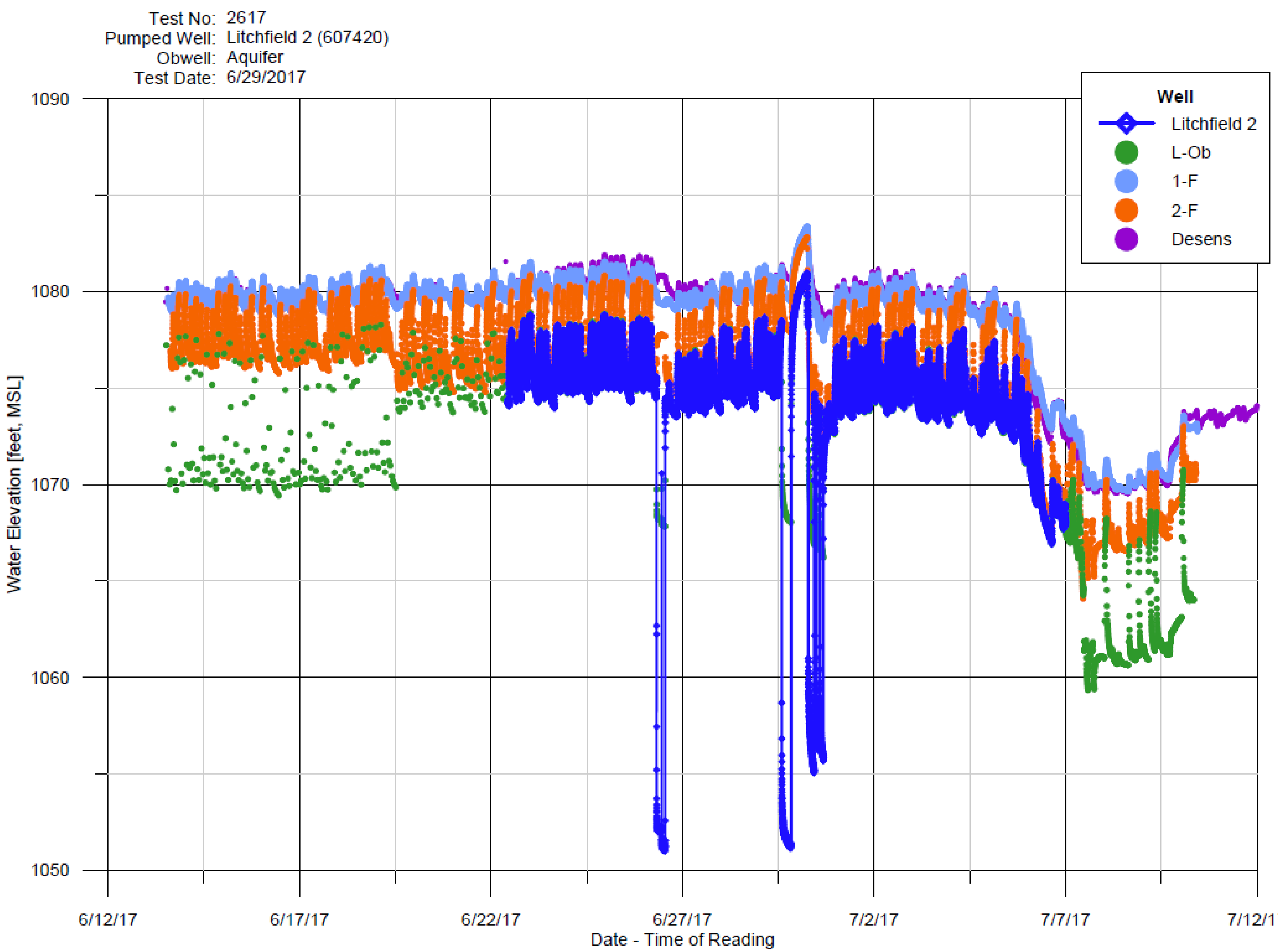


Figure 37. Groundwater elevation at Litchfield-2 and Observation Wells, Test Period

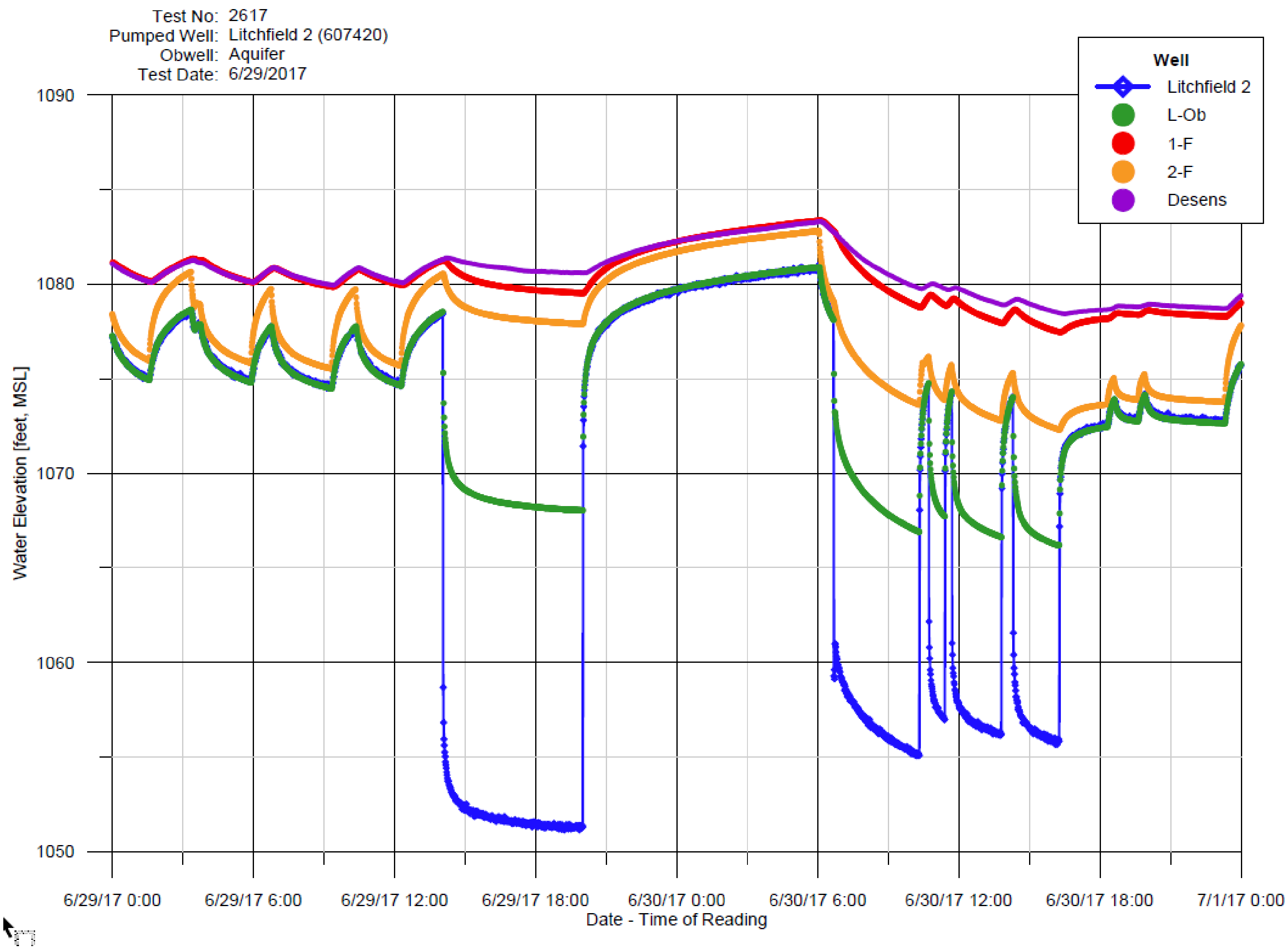


Figure 38. Groundwater elevation at Litchfield-2 and Nest 1, Test Period

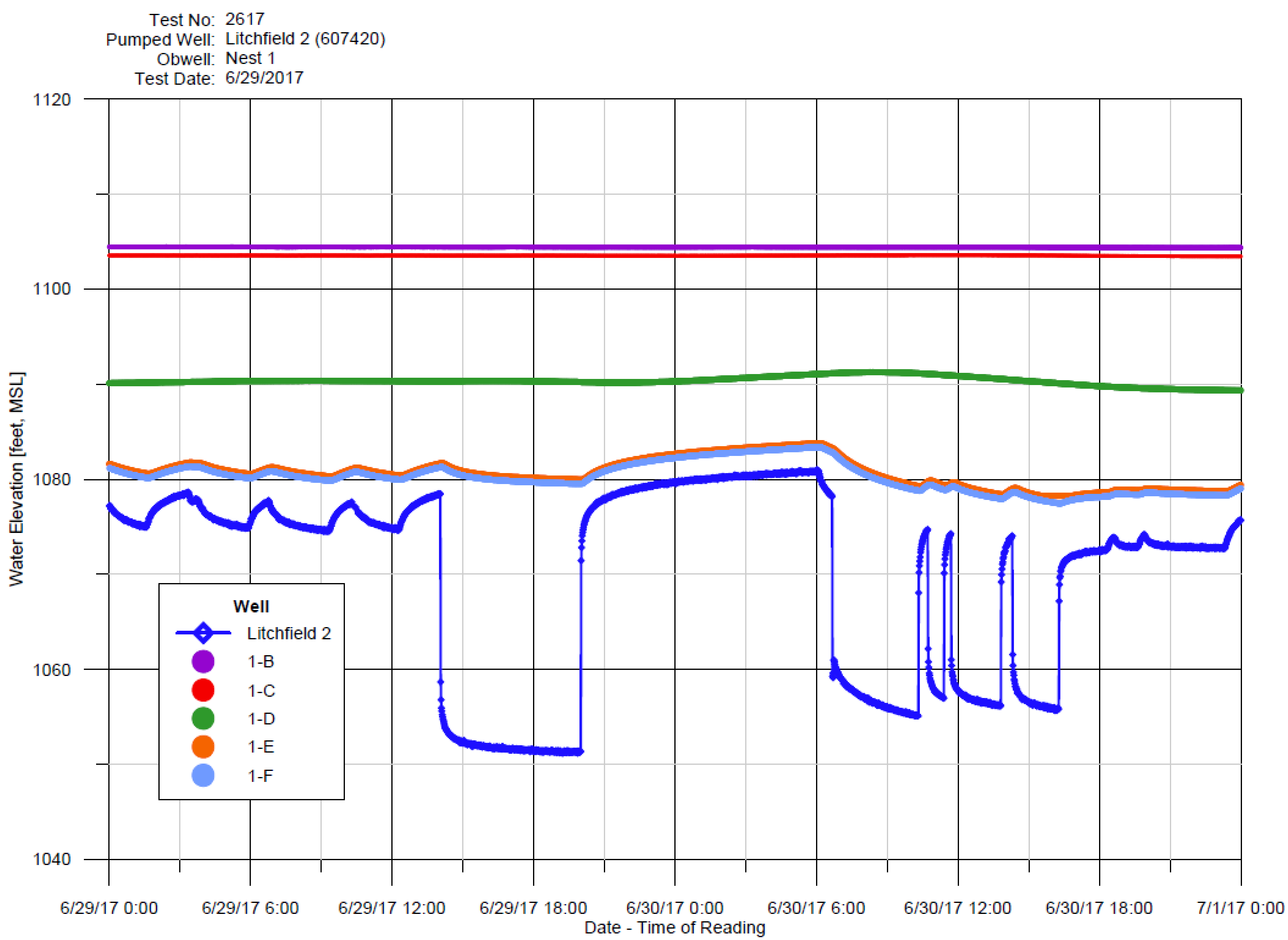


Figure 39. Groundwater elevation at Litchfield-2 and Nest 2, Test Period

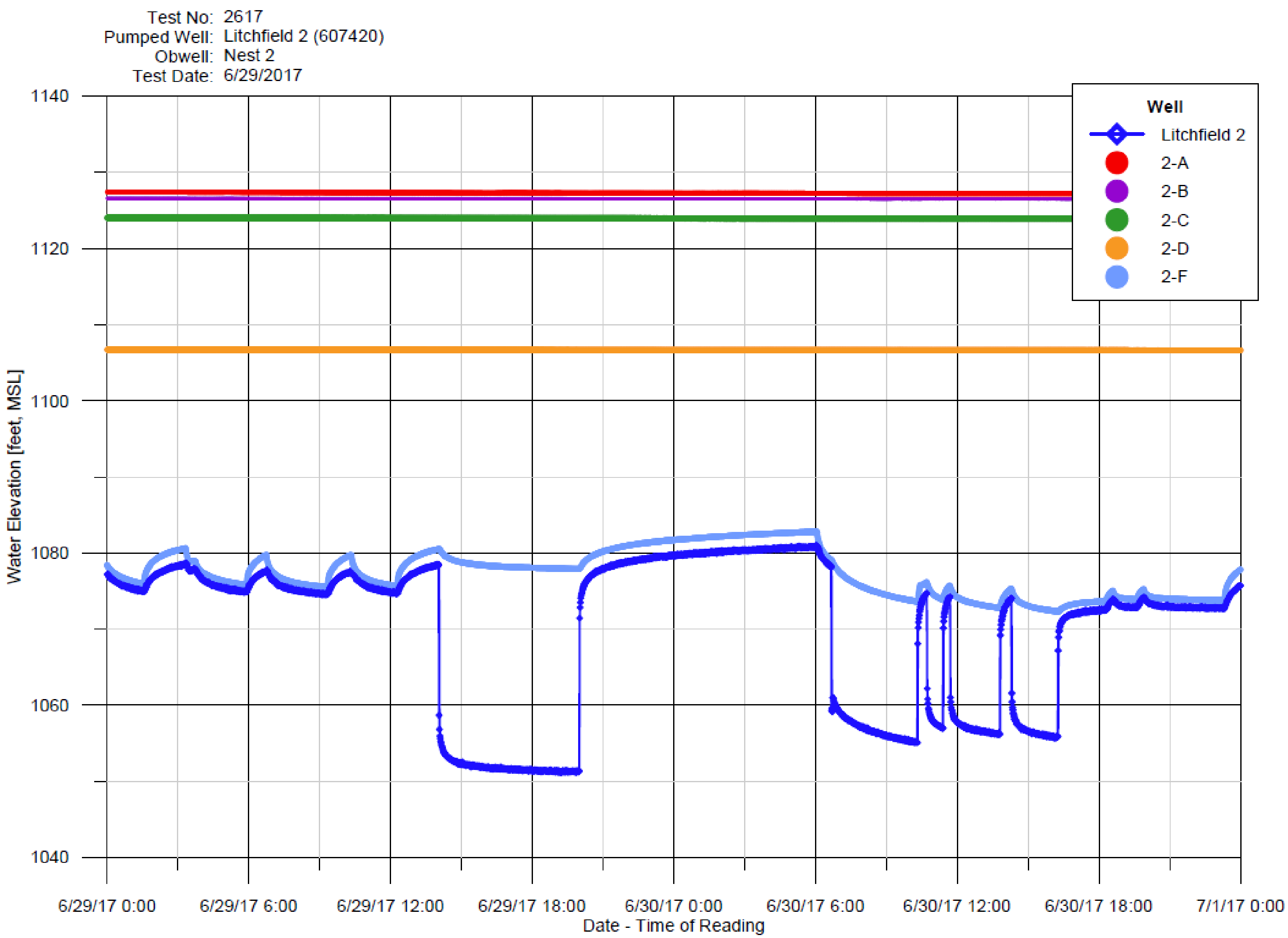


Figure 40. Groundwater Elevation in Aquifer Compared to Barometric Pressure, Test Period

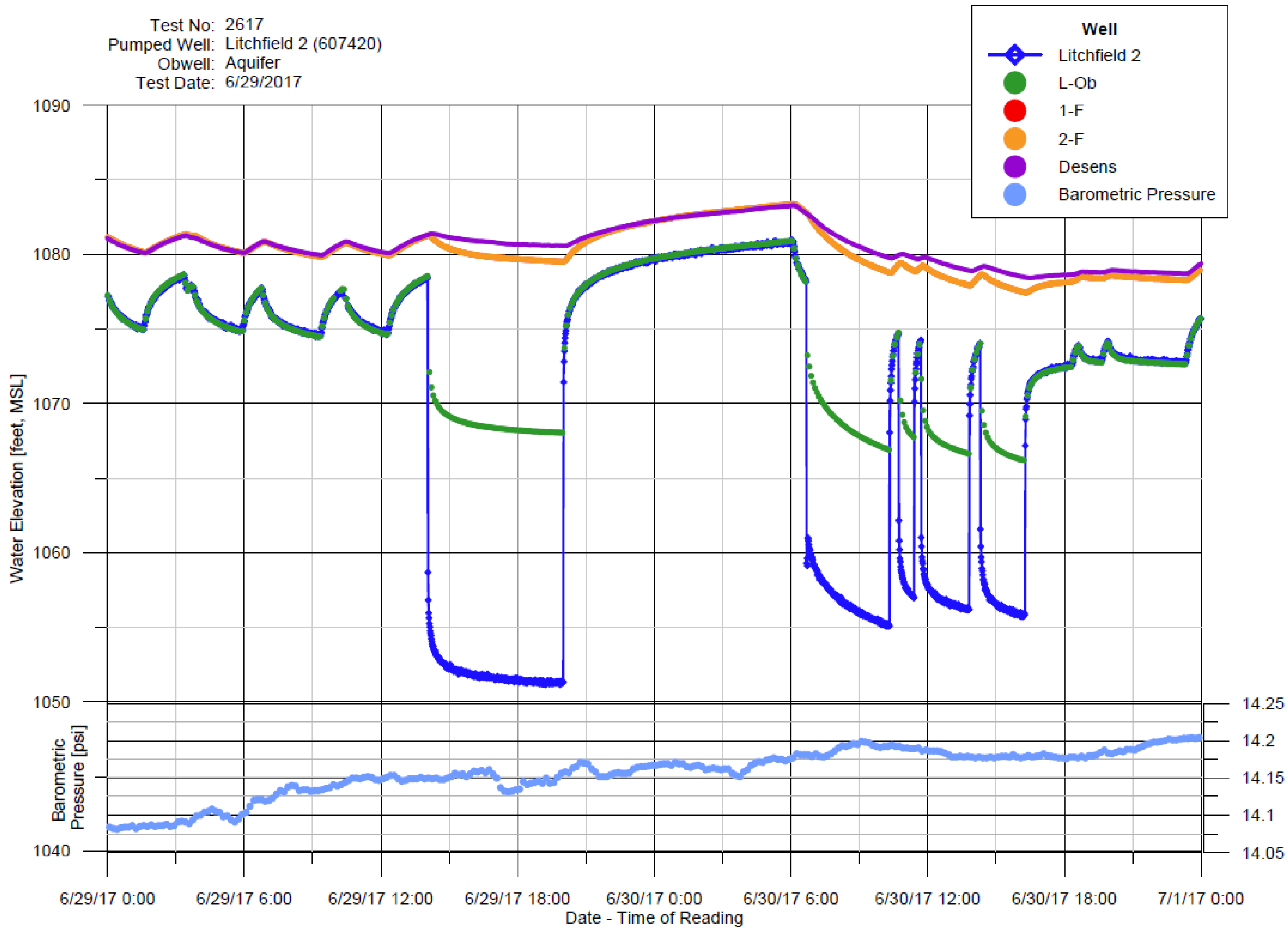


Figure 41. Depth to Water in Water-Table Wells Compared to Rainfall Events

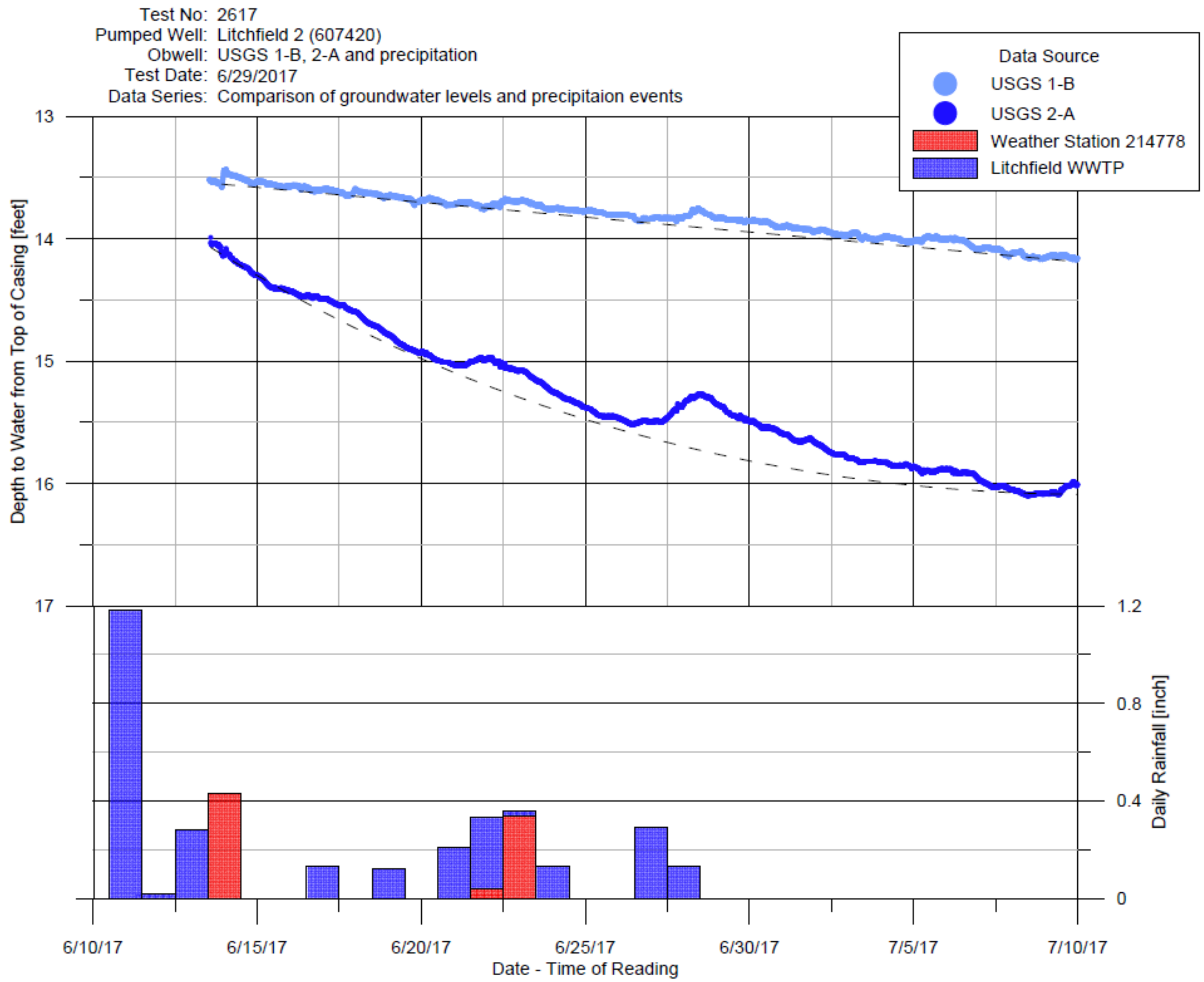


Figure 42. Daily Pumping Volume from Community Supply Wells, June 1, to July 10, 2017

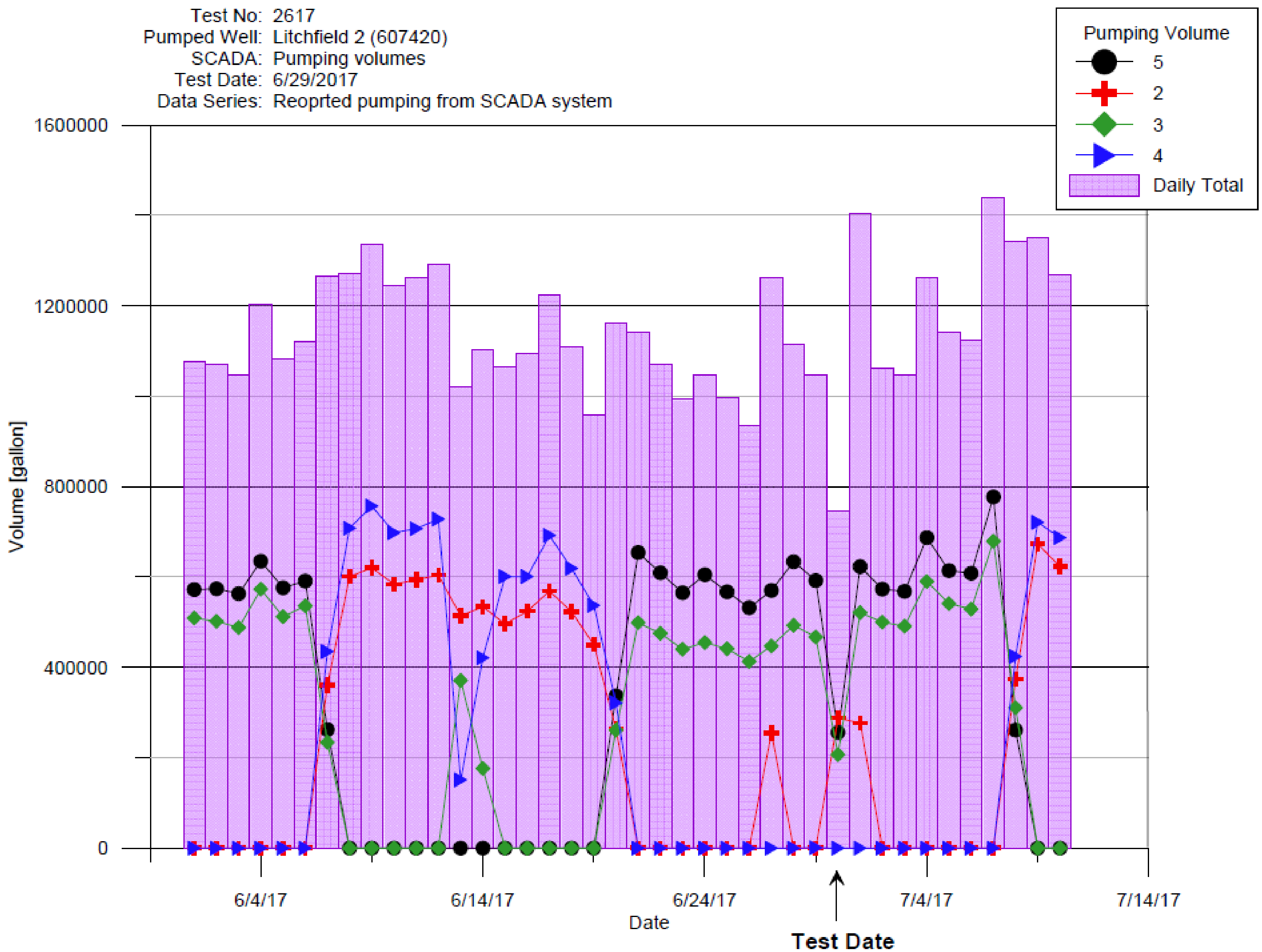


Figure 43. Expanded View of Groundwater Elevation in Aquifer Wells from July 2 to July 11, 2017

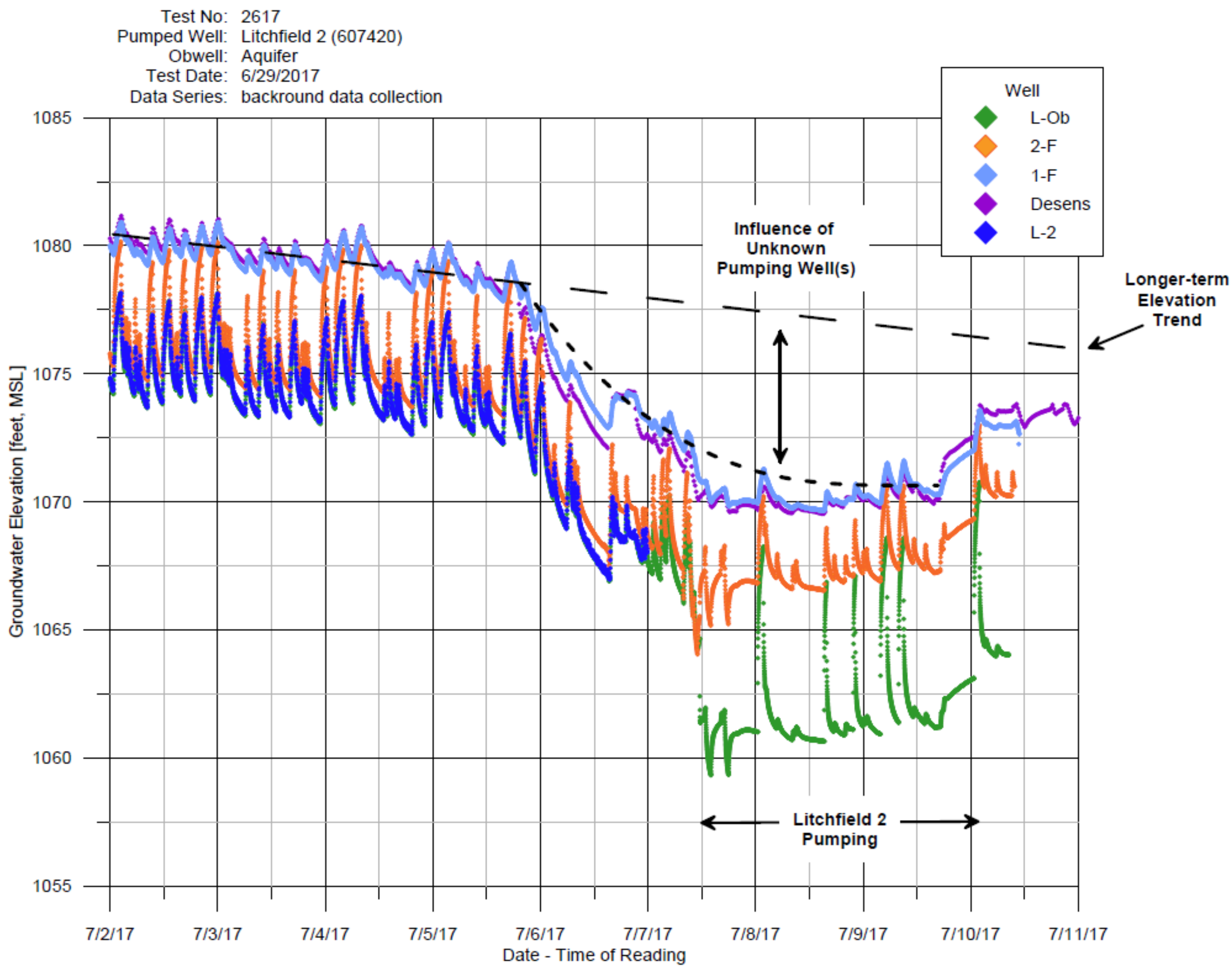


Figure 44. Local Effects of Community Supply Wells from July 5 to July 11, 2017

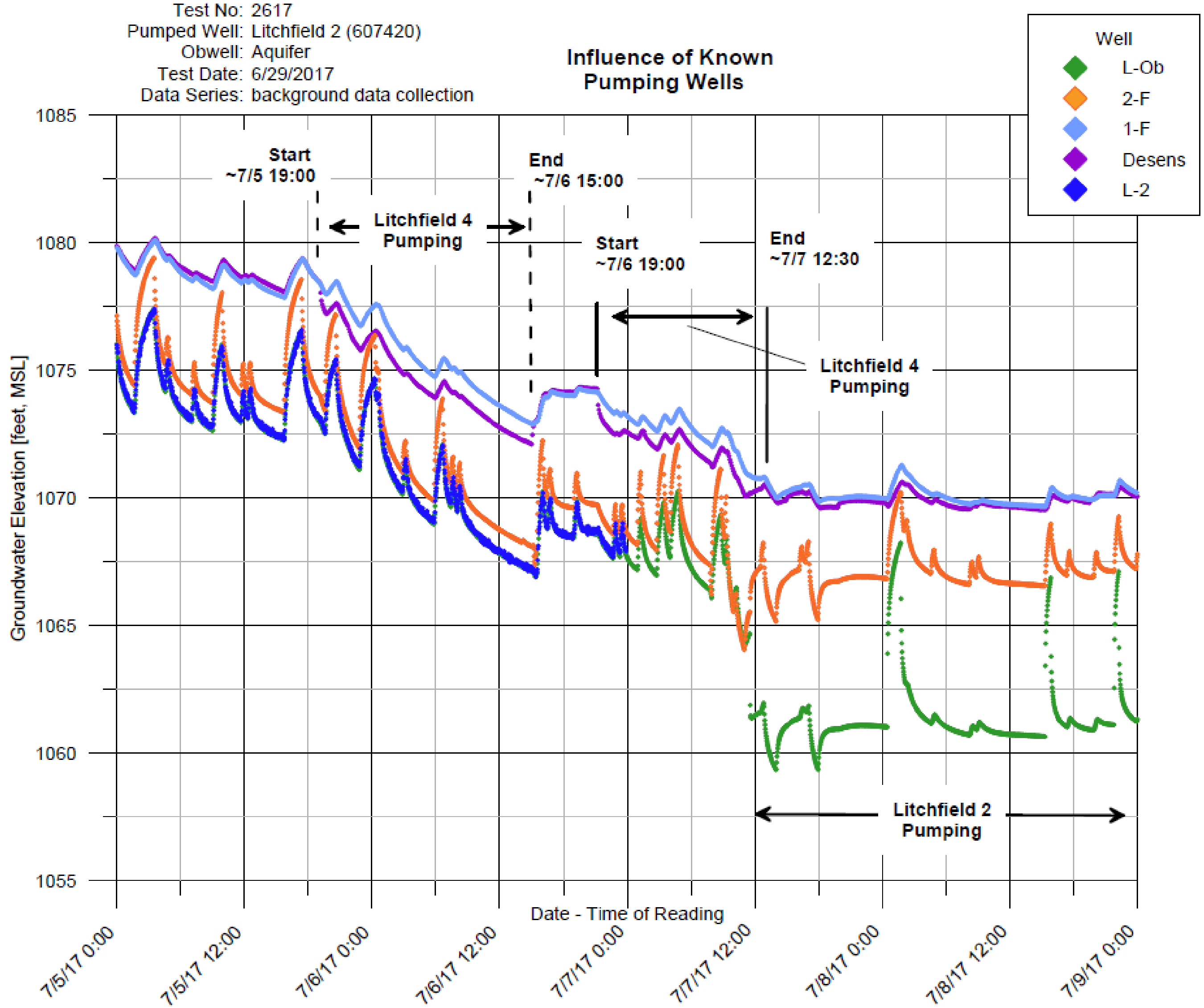


Figure 45. Groundwater Elevation at USGS 2-F (773051) Compared to Rainfall Events, Summer of 2016

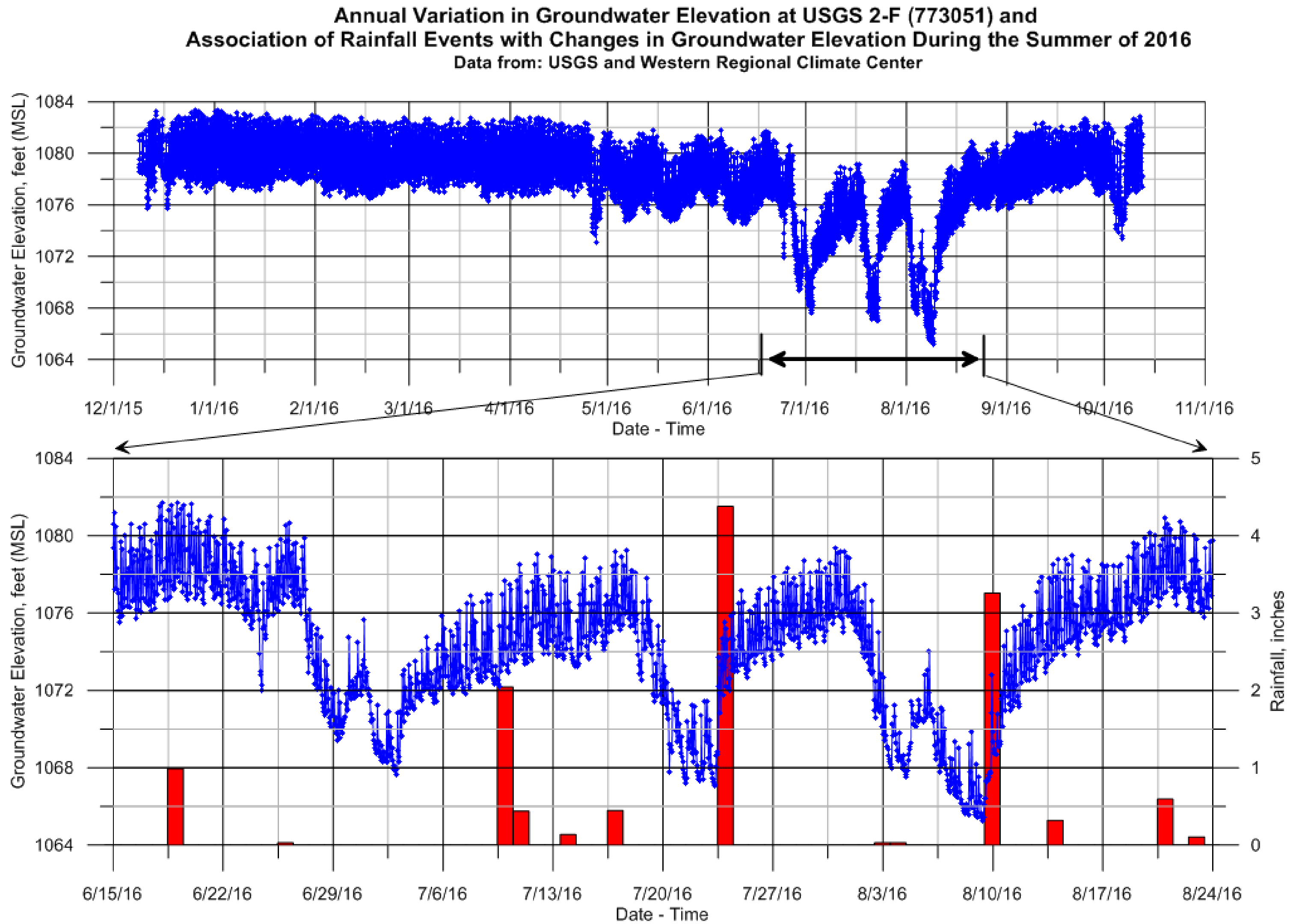


Figure 46. Well and Boring Report - Litchfield 2 (607420)

Minnesota Unique Well Number
607420

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 03/23/1999
Update Date 06/16/2017
Received Date

Well Name	Township	Range	Dir Section	Subsection
LITCHFIELD 2	119	31	W 2	CDCDAA

Elevation 1120 Elev. Method 7.5 minute topographic map (+/- 5 feet)

Address

Contact 126 MARSHALL AV N LITCHFIELD MN 55355
Well LITCHFIELD MN 55355

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
CLAY	0	24	BROWN	
CLAY	24	29	GRAY	
SAND & GRAVEL	29	35	BROWN	
CLAY	35	65	GRAY	
SAND & GRAVEL	65	71	BROWN	
CLAY	71	105	GRAY	
SAND & GRAVEL	105	134	BROWN	
CLAY	134	134	GRAY	

Remarks
MDH AQUIFER TEST, 20017

Well Depth	Depth Completed	Date Well Completed
134 ft.	132 ft.	02/19/1998

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use community supply(municipal) Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
12 in. To 107 ft. lbs./ft. 18 in. To 134 ft.

Open Hole From ft. To ft.

Screen? ☒ Type stainless Make JOHNSON
Diameter Slot/Gauze Length Set
12 in. 115 25 ft. 107 ft. 132 ft.

Static Water Level
42 ft. land surface Measure 02/19/1998

Pumping Level (below land surface)
132 ft. 7.5 hrs. Pumping at 1000 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
neat cement	85	Sacks	0 ft.	87 ft.
high solids bentonite	50	Sacks	87 ft.	132 ft.
			ft.	ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat clay-gray Depth to Bedrock ft
Located by Minnesota Department of Health
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379247 Y 4999548
Unique Number Verification Information from Input Date 09/19/2000

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Traut M.J. Well Co.	71536	ROBBIE/DON

Minnesota Well Index Report 607420

Printed on 06/19/2017
HE-01205-15

Figure 47. Well and Boring Report - Litchfield 3 (632077)

Minnesota Unique Well Number **632077**

County: Meeker
Quad: Litchfield
Quad ID: 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date: 03/22/2000
Update Date: 03/10/2014
Received Date:

Well Name	Township	Range	Dir Section	Subsection
LITCHFIELD 3	119	31	W 2	CDABDC

Elevation: 1126 — Elev. Method: 7.5 minute topographic map (+/- 5 feet)

Address
Contact: 126 MARSHALL AV N LITCHFIELD MN 55355
Well: LITCHFIELD MN 55355

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL	0	2	BLACK	
CLAY	2	18	YELLOW	
CLAY	18	98	GRAY	
DIRTY SAND	98	106	GRAY	
SAND	106	117	GRAY	
SAND COARSER	117	130	GRAY	
SAND FINER	130	136	GRAY	
CLAY	136	140	GRAY	

Remarks
GAMMA LOGGED 10-5-1999 BY SUMMIT.

Well Depth	Depth Completed	Date Well Completed
140 ft.	136 ft.	12/09/1999

Drill Method: Non-specified Rotary — Drill Fluid: Bentonite

Use: community supply(municipal) — Status: Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type: Single casing — Joint: Welded
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter: 12 in. To 108 ft. — Weight: 49.5 lbs./ft. — Hole Diameter: 18 in. To 140 ft.

Open Hole: From ft. To ft.
Screen? ☒ Type: stainless — Make: JOHNSON

Diameter	Slot/Gauze	Length	Set
12 in.	70	28 ft.	108 ft. 136 ft.

Static Water Level
43.6 ft. mll — Measure 11/22/1999

Pumping Level (below land surface)
65.5 ft. 20 hrs. Pumping at 750 g.p.m.

Wellhead Completion
Pitless adapter manufacturer: MONITOR — Model: 7PS1214WBW
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information — Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	3 Cubic yards	12 ft.	98 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed — Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock — Aquifer: Quat. buried
Last Strat: clay-gray — Depth to Bedrock ft
Located by: Minnesota Department of Health
Locate Method: GPS SA Off (averaged)
System: UTM - NAD83, Zone 15, Meters — X 379308 Y 4999778
Unique Number Verification — Input Date 09/19/2000

Angled Drill Hole

Well Contractor

L.t.p. Enterprises, Inc.	91686	VERDECK, D.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report — 632077 — Printed on 06/12/2017 HE-01205-15

Figure 48. Well and Boring Report - Litchfield 4 (632078)

Minnesota Unique Well Number
632078

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 03/22/2000
Update Date 03/10/2014
Received Date

Well Name	Township	Range	Dir Section	Subsection
LITCHFIELD 4	119	31	W 2	CABACB

Elevation 1149 Elev. Method 7.5 minute topographic map (+/- 5 feet)

Address
Contact 126 MARSHALL AV N LITCHFIELD MN 55355
Well LITCHFIELD MN 55355

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL SILTY	0	1	BLACK	
SANDY CLAY/GRAVEL	1	10	BROWN	
CLAY SANDY/PEBBLES	10	42	GRAY	
SANDY CLAY/SAND	42	48	GRAY	
SANDY CLAY/PEBBLES	48	97	GRAY	
SANDY CLAY	97	113	BROWN	V.SOFT
SANDY CLAY/PEBBLES	113	121	GRAY	
SAND & GRAVEL	121	128	GRAY	
SAND & GRAVEL	128	136	GRAY	
SAND & GRAVEL	136	146	GRAY	
SANDY CLAY/PEBBLES	146	150	GRAY	
CLAY	150	159	GRAY	

Remarks
BOTTON 12 FT. OF HOLE GROUTED W/HIGH SOLIDS.

Well Depth 159 ft. Depth Completed 147 ft. Date Well Completed 12/09/1999
Drill Method Non-specified Rotary Drill Fluid Bentonite
Use community supply(municipal) Status Active
Well Hydrofractured? Yes ☐ No ☐ From To
Casing Type Single casing Joint Welded
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight: 12 in. To 123 ft. 49.5 lbs./ft.
Hole Diameter: 18 in. To 147 ft.; 6.2 in. To 159 ft.

Open Hole From ft. To ft.
Screen? ☒ Type stainless Make JOHNSON

Diameter	Slot/Gauze	Length	Set	
12 in.	70	24 ft.	123 ft.	147 ft.

Static Water Level
61.2 ft. land surface Measure 12/08/1999

Pumping Level (below land surface)
77.8 ft. 21 hrs. Pumping at 750 g.p.m.

Wellhead Completion
Pitless adapter manufacturer MONITOR Model 7PS1214WBW
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	4.5 Cubic yards	8 ft.	113 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat clay-brown Depth to Bedrock ft
Located by Minnesota Department of Health
Locate Method GPS SA Off (averaged)
System UTM - NAD83, Zone 15, Meters X 379172 Y 5000196
Unique Number Verification Input Date 09/19/2000

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
L.t.p. Enterprises, Inc.	91686	VERDECK, D.

Minnesota Well Index Report 632078 Printed on 06/19/2017 HE-01205-15

Figure 49. Well and Boring Report - Litchfield 5 (764258)

Minnesota Unique Well Number **764258**

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 01/29/2009
Update Date 04/16/2015
Received Date 01/21/2009

Well Name	Township	Range	Dir Section	Subsection
LITCHFIELD 5	119	31	W 2	CABCCA

Elevation 1152 Elev. Method 7.5 minute topographic map (+/- 5 feet)

Address

Contact 126 MARSHALL AV NE LITCHFIELD MN 55355
Well LITCHFIELD MN 55355

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL	0	1	BLACK	
SANDY CLAY	1	2	BROWN	
SANDY CLAY WITH	2	7	YELLOW	
SANDY CLAY	7	11	TAN	
SANDY CLAY WITH	11	14	GRAY	
SANDY CLAY-SAND &	14	20	GRAY	
SANDY CLAY	20	36	GRAY	
SANDY CLAY WITH	36	47	GRAY	
SANDY CLAY WITH	47	121	GRAY	
SOFT SANDY CLAY	121	123	BROWN	SOFT
SANDY CLAY WITH	123	125	GRAY	
COARSE SAND AND	125	128	VARIED	
SANDY CLAY	128	131	GRAY	
SAND WITH CLAY	131	135	GRAY	
SAND SOME PEA ROCK	135	144	GRAY	MEDIUM
FINER SAND	144	147	GRAY	
COARSE SAND-	147	158	VARIED	
GRAVEL	158	162	VARIED	
SANDY CLAY	162	165	GRAY	

Remarks

Well Depth	Depth Completed	Date Well Completed
165 ft.	161.5 ft.	10/30/2008

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use community supply(municipal) Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
12 in. To 136. ft. 0 lbs./ft. 18 in. To 165 ft.

Open Hole From ft. To ft.
Screen? ☒ Type stainless Make JOHNSON

Diameter	Slot/Gauze	Length	Set
12 in.	60	25 ft.	136.5 ft. 161.5 ft.

Static Water Level
70.4 ft. land surface Measure 08/12/2008

Pumping Level (below land surface)
88.5 ft. 24 hrs. Pumping at 900 g.p.m.

Wellhead Completion
Pitless adapter manufacturer MONITOR Model 9PS1214
☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	4.5 Cubic yards	10 ft.	126.5 ft.

Nearest Known Source of Contamination
0 feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☐ Not Installed Date Installed 10/30/2008
Manufacturer's name GRUNDFOS
Model Number 800S400- HP 40 Volt 460
Length of drop pipe 120 ft Capacity 800 g.p. Typ Submersible

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat clay+sand-gray Depth to Bedrock ft
Located by Minnesota Department of Health
Locate Method GPS SA Off (averaged)
System UTM - NAD83, Zone 15, Meters X 379100 Y 5000084
Unique Number Verification Input Date 11/13/2008

Angled Drill Hole

Well Contractor

LTP Enterprises, Inc.	2157	THEISEN, R.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 764258 Printed on 06/12/2017 HE-01205-15

Figure 50. Well and Boring Report - Litchfield-MW (607417)

Minnesota Unique Well Number
607417

County: Meeker
Quad: Litchfield
Quad ID: 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date: 04/22/2003
Update Date: 08/18/2014
Received Date:

Well Name	Township	Range	Dir Section	Subsection
LITCHFIELD MW 119	31	W 2		CDCADB

Elevation: 1123.2 Elev. Method: Surveyed

Address

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SANDY CLAY	0	22	BROWN	
CLAY	22	29	GRAY	
SAND & GRAVEL	29	37	BROWN	
CLAY	37	40	GRAY	
SAND	40	45	BROWN	
ROCK	45	47	BLK/WHT	
CLAY	47	72	GRAY	
SAND & GRAVEL	72	76	BROWN	
CLAY	76	107	GRAY	
SAND & GRAVEL	107	130	BROWN	

Remarks
WELL OBS #1

Well Depth: 130 ft. Depth Completed: 127 ft. Date Well Completed: 12/18/1997
Drill Method: Auger (non-specified) Drill Fluid: Bentonite
Use: monitor well Status: Active
Well Hydrofractured? Yes ☐ No ☒ From To
Casing Type: Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below
Casing Diameter: 2 in. To 122 ft. Weight: lbs./ft. Hole Diameter: 6.5 in. To 130 ft.
Open Hole From ft. To ft.
Screen? ☒ Type: stainless Make: JOHNSON
Diameter: 2 in. Slot/Gauze: 10 Length: 10 ft. Set: 122 ft. 127 ft.

Static Water Level
40 ft. land surface Measure 12/18/1997

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified
Material: high solids bentonite Amount: 7 Sacks From: 3 ft. To: 120 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer: Quat. buried
Last Strat: sand +larger-brown Depth to Bedrock ft
Located by: Minnesota Geological Survey
Locate Method: Digitization (Screen) - Map (1:24,000)
System: UTM - NAD83, Zone 15, Meters X 379227 Y 4999595
Unique Number Verification: Info/GPS from data Input Date 10/22/1998

Angled Drill Hole

Well Contractor
Traut M.J. Well Co. 71536 ROBBIE & DON
Licensee Business / Lic. or Reg. No. / Name of Driller

Minnesota Well Index Report 607417
Printed on 06/19/2017
HE-01205-15

Figure 51. Well and Boring Report - USGS 1-B (773062)

Minnesota Unique Well Number

773062

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO1-B	119	31	W 11	ABACBB

Elevation 1114.5 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Contact 126 MARSHALL AV N LITCHFIELD MN 55355

Well 982 MILLER AV N LITCHFIELD MN 55355

Stratigraphy Information 2800 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
SAND, WELL SORTED	0	12	GRAY	SOFT
SAND WELLSORTED	12	14	GRAY	SOFT
SAND, WELL SORTED,	14	19	GRAY	SOFT
SAND, MED. TO	19	25	GRAY	SOFT

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 25.27 ft. **Depth Completed** 25.27 ft. **Date Well Completed** 06/12/2015

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing **Joint** Glued

Drive Shoe? Yes ☐ No ☒ **Above/Below**

Casing Diameter 1.2 in. To 22.4 ft. **Weight** 0.74 lbs./ft. **Hole Diameter** 8.2 in. To 25.2 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	22.4 ft.	25 ft.

Static Water Level
11 ft. land surface **Measure** 08/17/2015

Pumping Level (below land surface)
ft. 3.7 hrs. Pumping at 0.21 g.p.m.

Wellhead Completion
Pitless adapter manufacturer **Model**
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	1.67	Sacks	4.5 ft.	19.2 ft.
concrete	2	Sacks	ft.	4.5 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat sand+silt-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379655 Y 4999332
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773062 Printed on 06/19/2017 HE-01205-15

Figure 52. Well and Boring Report - USGS 1-C (773060)

Minnesota Unique Well Number

773060

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO1-C	119	31	W 11	ABACBB

Elevation 1114.8 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Contact 126 MARSHALL AV N LITCHFIELD MN 55355

Well 982 MILLER AV N LITCHFIELD MN 55355

Stratigraphy Information 2360 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
SAND, WELL SORTED	0	12	GRAY	SOFT
SAND WELL SORT	12	14	GRAY	SOFT
SAND, WELL SORTED,	14	19	GRAY	SOFT
SAND, MED. TO	19	22	GRAY	SOFT
SAND, MEDIUM WELL	22	43	GRAY	SOFT
SILT & CLAY WITH	43	53	GRAY	MEDIUM

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION

Well Depth 53.1 ft. Depth Completed 53.1 ft. Date Well Completed 06/12/2015

Drill Method Augur (non-specified) Drill Fluid

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint Glued

Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
1.2 in. To 50.2 ft. 0.74 lbs./ft. 8.2 in. To 53 ft.

Open Hole From ft. To ft.

Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	50.2 ft.	52.8 ft.

Static Water Level
12.5 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 1.9 hrs. Pumping at 0.21 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	3.5 Sacks	3.5 ft.	4.7 ft.
concrete	2.5 Sacks	ft.	3.5 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379653 Y 4999334
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773060 Printed on 06/19/2017 HE-01205-15

Figure 53. Well and Boring Report - USGS 1-D (773059)

Minnesota Unique Well Number
773059

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO1-D	119	31	W 11	ABACBB

Elevation 1114.7 Elev. Method LiDAR 1m DEM (MNDNR)

Address
Contact 126 MARSHALL AV N LITCHFIELD MN 55355
Well 982 MILLER AV N LITCHFIELD MN 55355
Stratigraphy Information 2980 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
SAND, WELL SORTED	0	12	GRAY	SOFT
SAND WELL SORT	12	14	GRAY	SOFT
SAND, MEDIUM WELL	14	19	GRAY	SOFT
SAND, MED. TO	19	22	GRAY	SOFT
SAND, MEDIUM WELL	22	43	GRAY	SOFT
SILT & CLAY WITH	43	76	GRAY	MEDIUM

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth	Depth Completed	Date Well Completed
75.5 ft.	75.27 ft.	06/11/2015

Drill Method Auger (non-specified) Drill Fluid

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint Glued
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
1.2 in. To 72.4 ft. 0.74 lbs./ft. 8.2 in. To 75.5 ft.

Open Hole From ft. To ft.
Screen? ☒ Type slotted pipe Make ENVIRONMENTAL
Diameter Slot/Gauze Length Set
1.2 in. 10 2.7 ft. 73.4 ft. 75 ft.

Static Water Level
25.8 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 3.6 hrs. Pumping at 0.2 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
cuttings	5	4 ft.	70.2 ft.
concrete	2.5	ft.	4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379654 Y 4999334
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773059 Printed on 06/19/2017
HE-01205-15

Figure 54. Well and Boring Report - USGS 1-E (773058)

Minnesota Unique Well Number
773058

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO1-E	119	31	W 11	ABACBB

Elevation 1114.5 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Contact 126 MARSHALL AV N LITCHFIELD MN 55355
Well 982 MILLER AV N LITCHFIELD MN 55355
2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SAND, WELL SORTED,	0	12	GRAY	SOFT
SAND, WELL SORTED,	12	14	GRAY	SOFT
SAND, MEDIUM WELL	14	19	GRAY	SOFT
SAND, MED. TO	19	22	GRAY	SOFT
SAND, MEDIUM WELL	22	43	GRAY	SOFT
SILT & CLAY WITH	43	95	GRAY	SFT-HRD

Remarks
SEE DRILLER LOG FOR DETAILED INFORMATION.

Well Depth 95.3 ft. **Depth Completed** 95.28 ft. **Date Well Completed** 06/10/2015

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☒ **Above/Below**

Casing Diameter 1.2 in. To 92.4 ft. **Weight** 0.74 lbs./ft. **Hole Diameter** 8.2 in. To 95 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	92.4 ft.	95 ft.

Static Water Level
36.3 ft. land surface **Measure** 08/17/2015

Pumping Level (below land surface)
ft. 11. hrs. Pumping at 0.28 g.p.m.

Wellhead Completion
Pitless adapter manufacturer **Model**
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	7	Sacks	4 ft.	89.5 ft.
concrete	2.5	Sacks	ft.	4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed **Date Installed**
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock **Aquifer** Quat. buried
Last Strat pebbly sand/silt/clay-gray **Depth to Bedrock** ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379655 Y 4999334
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773058 Printed on 06/19/2017 HE-01205-15

Figure 55. Well and Boring Report - USGS 1-F (773057)

Minnesota Unique Well Number

773057

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/22/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO1-F	119	31	W 11	ABACBB

Elevation 1114.7 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Contact 126 MARSHALL AV N LITCHFIELD MN 55355
Well 982 MILLER AV N LITCHFIELD MN 55355
[illegible]WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
WELL SORT, SAND,	0	12	GRAY	SOFT
SAND WELL SORT	12	14	GRAY	SOFT
SAND, MEDIUM WELL	14	19	GRAY	SOFT
SAND, MED. TO	19	22	GRAY	SOFT
SAND, MEDIUM WELL	22	43	GRAY	SOFT
SILT & CLAY W/ SAND	43	98	GRAY	SFT-HRD
SAND & GRAVEL,	98	130	GRAY	MEDIUM

Well Depth 130 ft. **Depth Completed** 127.46 ft. **Date Well Completed** 06/15/2015

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☒ **From** **To**

Casing Type Single casing **Joint** Glued

Drive Shoe? Yes ☐ No ☒ **Above/Below**

Casing Diameter 2 in. To 118 ft. **Weight** 1.02 lbs./ft. **Hole Diameter** 8.2 in. To 130 ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.9 in.	20	9.6 ft.	118 ft.	127.4 ft.

Static Water Level
36.6 ft. land surface **Measure** 08/17/2015

Pumping Level (below land surface)
ft. 2.9 hrs. Pumping at 1.11 g.p.m.

Wellhead Completion
Pitless adapter manufacturer **Model**
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	9	Sacks	3.4 ft.	95 ft.
concrete	2.5	Sacks	ft.	3.4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock **Aquifer** Quat. buried
Last Strat sand+larger-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379654 Y 4999332
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.
GAMMA & EM INDUCTION LOGGED 6-24-2015. LOGGED FOR USGS.

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773057

Printed on 06/19/2017
HE-01205-15

Figure 56. Well and Boring Report - USGS 2-A (773056)

Minnesota Unique Well Number

773056

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 09/09/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO2-A	119	31	W 2	CACDBD

Elevation 1139.6 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Well 61656 270TH ST LITCHFIELD MN 55355

Contact 126 MARSHALL AV N LITCHFIELD MN 55355

Stratigraphy Information 2860 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
SILT&CLAY W/SAND,	0	20	GRAY	MEDIUM

Remarks

SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 20 ft. Depth Completed 19.99 ft. Date Well Completed 06/24/2015

Drill Method Augar (non-specified) Drill Fluid

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint Glued

Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight: 1.2 in. To 17.1 ft. 0.74 lbs./ft.

Hole Diameter: 8.2 in. To 20 ft.

Open Hole From ft. To ft.

Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	17.1 ft.	19.7 ft.

Static Water Level

17.3 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)

ft. 1.2 hrs. Pumping at 0.08 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model

☒ Casing Protection ☒ 12 in. above grade

☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	2	Sacks	3 ft.	15 ft.
concrete	1.5	Sacks	ft.	3 ft.

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer Quat. buried

Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft

Located by Minnesota Geological Survey

Locate Method Digitization (Screen) - Map (1:24,000)

System UTM - NAD83, Zone 15, Meters X 379193 Y 4999910

Unique Number Verification Information from Input Date 09/09/2015

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
US Geological Survey	1548	HUCKABY, J.

Minnesota Well Index Report 773056

Printed on 06/12/2017
HE-01205-15

Figure 57. Well and Boring Report - USGS 1-F (773057)

Minnesota Unique Well Number
773055

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 09/09/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO2-B	119	31	W 2	CACDBD

Elevation 1139.2 Elev. Method LiDAR 1m DEM (MNDNR)

Address
Well 61656 270TH ST LITCHFIELD MN 55355
Contact 126 MARSHALL AV N LITCHFIELD MN 55355
2880 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SILT&CLAY W/SAND,	0	36	GRAY	MEDIUM

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 35.5 ft. Depth Completed 35.13 ft. Date Well Completed 06/24/2015
Drill Method Auger (non-specified) Drill Fluid
Use monitor well Status Active
Well Hydrofractured? Yes [ ] No [X] From To
Casing Type Single casing Joint Glued
Drive Shoe? Yes [ ] No [ ] Above/Below
Casing Diameter 1.2 in. To 32.3 ft. Weight 0.74 lbs./ft. Hole Diameter 8.2 in. To 35.5 ft.

Open Hole From ft. To ft.
Screen? [X] Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	32.2 ft.	34.9 ft.

Static Water Level
23.8 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 1.4 hrs. Pumping at 1.43 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
[X] Casing Protection [X] 12 in. above grade
[ ] At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? [X] Yes [ ] No [ ] Not Specified

Material	Amount		From	To
bentonite	4	Sacks	3 ft.	30.5 ft.
concrete	1.5	Sacks	ft.	3 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? [ ] Yes [X] No

Pump [X] Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? [ ] Yes [X] No

Variance
Was a variance granted from the MDH for this well? [ ] Yes [X] No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379193 Y 4999909
Unique Number Verification Information from Input Date 09/09/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773055 Printed on 06/12/2017
HE-01205-15

Figure 58. Well and Boring Report - USGS 2-C (773054)

Minnesota Unique Well Number **773054**

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/20/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO2-C	119	31	W 2	CACDBD

Elevation 1139.4 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Well 61656 270TH ST LITCHFIELD MN 55355
Contact 126 MARSHALL AV N LITCHFIELD MN 55355
2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SILT & CLAY W/SAND,	0	70	GRAY	MEDIUM

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 70 ft. **Depth Completed** 59.84 ft. **Date Well Completed** 06/22/2015
Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☒ From To
Casing Type Single casing **Joint** Glued
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Casing Diameter 1.2 in. To 57 ft. **Weight** 0.74 lbs./ft. **Hole Diameter** 8.2 in. To 70 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	56.9 ft.	59.6 ft.

Static Water Level
31.8 ft. land surface **Measure** 06/22/2015

Pumping Level (below land surface)
ft. 1.2 hrs. Pumping at 0.14 g.p.m.

Wellhead Completion
Pitless adapter manufacturer **Model**
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	7	Sacks	3 ft.	54.7 ft.
concrete	2	Sacks	ft.	3 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed **Date Installed**
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock **Aquifer** Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379195 Y 4999910
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
US Geological Survey	1548	HUCKABY, J.

Minnesota Well Index Report 773054 Printed on 06/12/2017 HE-01205-15

Figure 59. Well and Boring Report - USGS 2-D (773053)

Minnesota Unique Well Number **773053**

County: Meeker | Quad: Litchfield | Quad ID: 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date: 08/14/2015
Update Date: 10/20/2015
Received Date:

Well Name	Township	Range	Dir Section	Subsection
LFO2-D	119	31	W 2	CACDBD

Elevation 1139.2 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address
Well: 61656 270TH ST LITCHFIELD MN 55355
Contact: 126 MARSHALL AV N LITCHFIELD MN 55355
2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SILT& CLAY W/SAND,	0	80	GRAY	MEDIUM
SAND& CLAY W/SAND,	80	86	GRAY	HARD

Remarks
SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth 85.5 ft. **Depth Completed** 81.14 ft. **Date Well Completed** 06/23/2015
Drill Method Auger (non-specified) **Drill Fluid**
Use monitor well **Status** Active
Well Hydrofractured? Yes ☐ No ☒ From To
Casing Type Single casing **Joint** Glued
Drive Shoe? Yes ☐ No ☐ Above/Below
Casing Diameter 1.2 in. To 81.1 ft. **Weight** 0.74 lbs./ft. **Hole Diameter** 8.2 in. To 85.5 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** slotted pipe **Make** ENVIRONMENTAL
Diameter 1.2 in. Slot/Gauze 10 Length 2.7 ft. Set 81.1 ft. 81.1 ft.

Static Water Level
78 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 1.4 hrs. Pumping at 0.1 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	6.5	Sacks	3 ft.	78.5 ft.
concrete	1.5	Sacks	ft.	3 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379193 Y 4999908
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
US Geological Survey	1548	HUCKABY, J.

Minnesota Well Index Report 773053 Printed on 06/12/2017 HE-01205-15

Figure 60. Well and Boring Report - USGS 2-E (773052)

Minnesota Unique Well Number

773052

County: Meeker
Quad: Litchfield
Quad ID: 125A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date: 08/14/2015
Update Date: 10/20/2015
Received Date:

Well Name	Township	Range	Dir Section	Subsection
LFO2-E	119	31	W 2	CACDBD

Elevation: 1139.3 Elev. Method: LiDAR 1m DEM (MNDNR)

Address

Well: 61656 270TH ST LITCHFIELD MN 55355

Contact: 126 MARSHALL AV N LITCHFIELD MN 55355

Stratigraphy Information: 2280 WOODALE DR MOUNDS VIEW MN 55112

Geological Material	From	To (ft.)	Color	Hardness
SILT&CLAY W/SAND,	0	80	GRAY	MEDIUM
SILT&CLAY W/SAND,	80	114	GRAY	HARD

Remarks

SEE DRILLERS LOG FOR DETAILED INFORMATION.

Well Depth: 113.9 ft. Depth Completed: 113.82 ft. Date Well Completed: 06/20/2015

Drill Method: Auger (non-specified) Drill Fluid:

Use: monitor well Status: Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type: Single casing Joint: Glued

Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter: 1.2 in. To 111 ft. Weight: 0.74 lbs./ft. Hole Diameter: 8.2 in. To 113. ft.

Open Hole: From ft. To ft.

Screen? ☒ Type: slotted pipe Make: ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	2.7 ft.	110.9 ft.	113.6 ft.

Static Water Level

95.6 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)

ft. 0.6 hrs. Pumping at 0.47 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model

☒ Casing Protection ☒ 12 in. above grade

☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	Sacks	3 ft.	108.6 ft.
concrete	Sacks	ft.	3 ft.

Nearest Known Source of Contamination

feet Direction Type

Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed

Manufacturer's name

Model Number HP Volt

Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer: Quat. buried

Last Strat: pebbly sand/silt/clay-gray Depth to Bedrock ft

Located by: Minnesota Geological Survey

Locate Method: Digitization (Screen) - Map (1:24,000)

System: UTM - NAD83, Zone 15, Meters X 379195 Y 4999909

Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor

US Geological Survey	1548	HUCKABY, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 773052

Printed on 06/12/2017
HE-01205-15

Figure 61. Well and Boring Report - USGS 2-F (773051)

Minnesota Unique Well Number

773051

County Meeker
Quad Litchfield
Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 08/14/2015
Update Date 10/23/2015
Received Date

Well Name	Township	Range	Dir Section	Subsection
LFO2-F	119	31	W 2	CACDBD

Elevation 1139.3 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Well 61656 270TH ST LITCHFIELD MN 55355

Contact 126 MARSHALL AV N LITCHFIELD MN 55355
2280 WOODALE DR MOUNDS VIEW MN 55112

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SILT&CLAY W/SAND,	0	80	GRAY	MEDIUM
SILT&CLAY W/SAND,	80	117	GRAY	HARD
SAND & GRAVEL,	117	161	GRAY	HARD
SILT&CLAY W/SAND,	161	163	GRAY	HARD

Remarks

SEE DRILLERS LOG FOR DETAILED INFORMATION.
GAMMA & INDUCTION LOGGED 8-19-2015. LOGGED FOR USGS.

Well Depth	Depth Completed	Date Well Completed
162.5 ft.	162.42 ft.	06/18/2015

Drill Method Auger (non-specified) Drill Fluid

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint Glued
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight
2 in. To 152. ft. 1.02 lbs./ft.

Open Hole From ft. To ft.

Screen? ☒ Type slotted pipe Make ENVIRONMENTAL

Diameter	Slot/Gauze	Length	Set	
1.9 in.	20	9.6 ft.	152.4 ft.	162 ft.

Static Water Level
61 ft. land surface Measure 08/17/2015

Pumping Level (below land surface)
ft. 6.4 hrs. Pumping at 0.86 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	10 Sacks	2 ft.	137 ft.
concrete	2 Sacks	ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000)
System UTM - NAD83, Zone 15, Meters X 379195 Y 4999908
Unique Number Verification Information from Input Date 08/14/2015

Angled Drill Hole

Well Contractor
US Geological Survey 1548 HUCKABY, J.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 773051

Printed on 06/19/2017
HE-01205-15

Figure 62. Well and Boring Report - Desens Observation (800011)

Minnesota Unique Well Number **800011**

County Meeker | Quad Litchfield | Quad ID 125A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 01/13/2014
Update Date 08/26/2014
Received Date 10/02/2013

Well Name	Township	Range	Dir Section	Subsection
DESEN, DOUG	119	31	W 2	DACAAC

Elevation 1128.4 **Elev. Method** Surveyed

Address

Contact 28003 620TH AV LITCHFIELD MN 55355
Well 620TH AV LITCHFIELD MN 55355

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL	0	3	BLACK	SOFT
CLAY	3	5	BROWN	SOFT
GRAVEL	5	9	BROWN	SOFT
CLAY	9	112	GRAY	MED-HRD
DIRTY GRAVEL	112	117	GRAY	SOFT
CLAY	117	120	GRAY	SFT-MED
SAND/GRAVEL	120	158	GRAY	SOFT
CLAY/GRAVEL	158	158	GRAY	SOFT

Remarks
DRILLERS: STEVE WEISBRICH & DREW BATES.

Well Depth	Depth Completed	Date Well Completed
158 ft.	158 ft.	07/29/2013

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use monitor well Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint Glued
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 148 ft. lbs./ft. 6.2 in. To 158 ft.

Open Hole From ft. To ft.
Screen? ☒ Type plastic Make JOHNSON

Diameter	Slot/Gauze	Length	Set
2 in.	10	10 ft.	148 ft. 158 ft.

Static Water Level
59.8 ft. land surface Measure 07/29/2013

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite			4 ft.	142 ft.
neat cement	2	Sacks	ft.	4 ft.

Nearest Known Source of Contamination
900 feet West Direction Septic tank/drain field Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat pebbly sand/silt/clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:12,000)
System UTM - NAD83, Zone 15, Meters X 380018 Y 5000014
Unique Number Verification Info/GPS from data Input Date 08/18/2014

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Mark J Traut Wells, Inc.	1404	STEVE/DREW

Minnesota Well Index Report 800011 Printed on 06/12/2017 HE-01205-15

Minnesota Geological Survey
Harvey Thorleifson, Director

CORE DESCRIPTIONS AND BOREHOLE GEOPHYSICS IN SUPPORT OF USGS HYDROLOGIC PROPERTIES OF TILL INVESTIGATION,

LITCHFIELD AND CROMWELL, MINNESOTA

Kaleb Wagner and Robert Tipping, *Minnesota Geological Survey, 2609 Territorial Road, St. Paul MN, 55114, USA*.

March 2016

Funded through the Environment and Natural Trust Fund as recommended by the Legislative and Citizens Commission on Minnesota Resources (LCCMR).

Contents

Executive summary

This report summarizes the contributions of the Minnesota Geological Survey to Phase I of an ongoing study – Environmental and Natural Resources Trust Fund (ENRTF), M.L. 2014, Chp. 226, Sec. 2, Subd. 03h, led by the United States Geological Survey (USGS) Minnesota Water Science Center, which seeks to further knowledge on the sources and rates of recharge to confined aquifers. Geologic cores from sites in Litchfield and Cromwell Minnesota were described both in the field and in the laboratory, and then archived at the Minnesota Department of Natural Resources core repository in Hibbing, Minnesota. Core sediments were described systematically in terms of grain size and sorting, texture, structure, Munsell color, level of consolidation, carbonate content of matrix, and clast lithological assemblage. Textural characterization included collection of 72 bulk sediment samples for particle-size analysis from the three cores at approximate 4' intervals to detect textural deviations between core sediments at each site, and to determine the degree of internal compositional variation. Borehole geophysical logs were collected for all drill holes of adequate diameter, including gamma, electromagnetic induction, spontaneous potential and resistivity logs.

Sediments in the two cores (LF01, LF02) acquired from Litchfield, MN chronicle the incursion of the Des Moines Lobe of the Laurentide Ice Sheet (LIS) into south-central Minnesota, and its subsequent demise during the Late Wisconsinan glacial episode. Recent work documents large-scale reorganizations of ice flow during the late last glacial within catchment areas of the Des Moines Lobe in southern Saskatchewan and Manitoba (Ross et al., 2009; O'Cofaigh et al., 2010), and these shifts are likely linked, in combination with local factors, to subtle variations in till texture, colour and visible clast lithologies documented down-core in LF01 and LF02. In Cromwell, core materials recovered from CW02 detail lobate interactions of the LIS in north-eastern Minnesota throughout the Late Wisconsinan glacial episode. Glacial tills and associated glaciolacustrine and glaciofluvial meltwater deposits of the St. Croix and Automba phases of the Superior Lobe are lithostratigraphically assigned to the Cromwell Formation (Wright et al., 1970; Johnson et al., 2016).

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Introduction

Confined aquifers set within glacigenic valley-fill sequences are an important source of drinking water for residents in many areas of Minnesota. Generally, these sequences are comprised of packages of low-permeability glacial tills and fine-grained glaciolacustrine sediments (i.e., potential aquitards) which overlie and/or encompass high permeability glaciofluvial outwash sands and gravels (i.e., potential aquifers). Confining units in these systems act as crucial elements by protecting underlying confined aquifers from land-surface contamination, but rates and sources of recharge to these aquifers remain poorly-understood. Estimations of aquifer connectivity within buried-valley sequences in Minnesota are confounded by significant variability in the hydraulic properties of glacial sediments across the state, much of which is attributable to the differing substrates and dynamics of the various ice lobes that deposited them. The ability to accurately characterize these properties has considerable implications for groundwater modeling, which is commonly used to inform policy and planning decisions. This report summarizes the contributions of the Minnesota Geological Survey to Phase I of an ongoing study, led by the United States Geological Survey Minnesota Water Science Center, which seeks to further knowledge on the sources and rates of recharge to confined aquifers set within buried-valley sequences in Minnesota.

Methods

Texture data and core analysis

Unlithified Quaternary age sediments were collected on-site between 06/09/2015 and 06/26/2015 at Litchfield (cores LF01, LF02) and Cromwell, MN (core CW02) by hollow-stem coring and extruded into polyethelene casing and transported to Minnesota Geological Survey (MGS) facilities for cutting, description, sampling, and packaging. Each 5’ interval was scored along the outer edge of the casing with a circular saw, and the core materials split using a standard mason’s chisel and rubber mallet. Unsampled splits were shipped to the DNR Drill Core Library at Hibbing, MN for archiving. Core sediments were described systematically in terms of grain size and sorting, texture, structure, Munsell color, level of consolidation, carbonate content of matrix, and clast lithological assemblage.

72 bulk sediment samples were collected for particle-size analysis from the three cores at approximate 4’ intervals, with higher sampling density near lithostratigraphic contacts, in order to detect textural deviations between core sediments at each site, and to determine the degree of internal compositional variation. Individual bulk sediment samples ranged in mass between ~150 and 200 g. Particle-size analysis was carried out by laboratory staff at MGS facilities and was conducted in two stages, broadly following ASTM D 422 procedural standards (Standard Test Method for Particle-Size Analysis of Soils): Dry sieving of the $< 4.0\ \varphi$ (> 0.63 mm) fraction, and hydrometer analysis of the $> 4.0\ \varphi$ (< 0.63 mm) fraction.

Prior to fines separation, samples were manually crushed, and 50 g of the > 4.0 φ (< 0.63 mm) fraction from each sample (in batches of 20) was weighed and placed into a 250 mL beaker, and the remaining portion of the raw sample archived. 150 mL of 40 g/L sodium pyrophosphate dispersant solution was added to each beaker and the slurries were stirred using a metal spatula and left to settle for 24 hours. A 1 L control cylinder was prepared for each test with 150 mL of 40 g/L sodium pyrophosphate and 850 mL of deionized water. Sediment mixtures were washed from 250 mL beakers into metal stirring cups using deionized water and placed on a mechanical mixer for 1 minute. After mixing, each sample was transferred to a 1 L settling cylinder and deionized water was added to make up the slurry to 1 L. ASTM 152H hydrometers were placed in both sample settling cylinders and the blank cylinder, and the meniscus correction factor calculated for each apparatus. Prior to measurement, samples were mixed and re-suspended for 1 minute using a metal plunger. Thermometers were placed in each cylinder, and temperature and hydrometer readings taken from both the blank and sample cylinders at 2 minutes following re-suspension, and thereafter at 2 hours. Wet Munsell color was obtained from each cylinder during particle sedimentation. The rate of particle settling was estimated using Stokes Law, which assumes that a solid, perfectly spherical particle of radius r and density ρs will settle downward through a fluid of density ρl at a calculable rate.

Following hydrometer testing, the < 4.0 φ (> 0.63 mm) sample fraction was isolated and retained by wet sieving. Retained fractions were transferred to beakers for drying on a hot plate. Dry sieving was then carried out using a stack of mesh sieves with apertures ranging from -1.0 φ (2 mm) to 4.0 φ (0.63 mm) (US Mesh #10 – 230). Dried samples were transferred to a sieve stack, loaded onto a RoTap® sieve-shaker, and mechanically agitated for 5 minutes to facilitate particle sorting. After shaking, the contents of each sieve were collected and their mass measured to three decimal places using a digital weigh scale. Percentages derived from hydrometer readings for particle fractions up to 4.0 φ (0.63 mm) were combined with dry sieving data for the 0 – 4.0 φ range, which returned baseline textural profiles for each sample.

Borehole geophysics

Litchfield observation wells LFO1-F and LFO2-F were logged using EM-Induction and Gamma sondes on June 24, 2015. Litchfield LFO2-F was re-logged using the EM-Induction sonde, with an adjustment to narrow the tool diameter, on August 19, 2015, in an attempt to reach the bottom of the hole. Cromwell observation wells CWO1-A, CWO1-B, and CWO1-C were logged using EM-Induction and Gamma sondes on August 13, 2015. Logging was conducted in holes having 2 inch diameter plastic casing inserted into 6 inch diameter holes. Fluid in the holes was aquifer water. Logging sondes and software used are manufactured by Century Geophysical Corporation, Tulsa Oklahoma. The EM-Induction sonde, tool type code 9512A, serial number 2704, is owned by the USGS; the Gamma sonde, tool type code 9060A, serial number 202 is owned by the MGS. Logging rates are shown in Table 1.

Table 1. Logging rates for Litchfield and Cromwell borehole geophysical logs.

Hole name	EM-Induction rate (ft/min)	Gamma rate (ft/min)
Litchfield LFO1-F	5	10
Litchfield LFO2-F	5	15
Cromwell CWO1-A	16	22
Cromwell CWO1-B	16	16
Cromwell CWO1-C	15	15

Results

Core descriptions and textural analysis

Logging and analysis of core materials revealed interpretable successions of glacially-derived sediments at each of the three sites (Appendix A). Core CW02 is capped by ~ 5.5' of Alborn Member diamicton (*Qat*) of the Aitkin Formation (*QAIA*), overlying ~ 20' of Cromwell Formation (*QCMU*) sand and gravel and ~ 76.5' of subjacent *QCMU* diamicton. ~ 7.5' of sand and gravelly sand overlies ~ 8.5' of finer-grained sand and silt at surface in core LF01, all of which rests on ~ 70' of alternating sandy loam (*Nva*), to loam (*Nvt*) textured diamicton of the Villard Member, New Ulm Formation (*QNVT*). Similarly, core LF02 is comprised of a thick (~ 113.5') package of unsorted sediments with variable textures (*Nva*, *Nvt*), intercalated with thin (≤ 7.5') glaciofluvial sequences and occasional sand stringers, flow noses and lenses. Bulk sample grain size distributions are presented in Table 2. See Appendix A for sample stratigraphic context.

Table 2. Bulk grain size distributions for Cromwell and New Ulm Tills from cores LF01, LF02 and CW02.

	Cromwell Till (QCMU)			**New Ulm Till (QNVT)**			**All**		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Mean	0.57	0.31	0.13	0.49	0.33	0.18	0.5	0.32	0.17
Median	0.56	0.31	0.13	0.47	0.33	0.18	0.48	0.33	0.18
Mode	0.56	0.33	0.14	0.47	0.34	0.18	0.47	0.33	0.18
St. Dev	0.03	0.02	0.02	0.06	0.04	0.03	0.06	0.04	0.04

Sample values are plotted in terms of their relative proportions of sand (0.063 – 2.00 mm), silt (0.002 – 0.063 mm), and clay (< 0.002 mm) for grouped units interpreted as glacial till, glaciolacustrine, and fine-grained ice-contact deposits (i.e., potential aquitards, *Group A*) in Fig.1[A], and grouped proglacial deltaic, outwash, and undifferentiated glaciofluvial deposits (i.e., potential aquifers, *Group B*) in Fig.1[B]. *QCMU* units within *Group A* (retrieved from core CW02) are relatively coarse-grained and exclusively exhibit sandy loam matrix textures.

Conversely, *QNVT* units within *Group A* (retrieved from cores LF01 and LF02) are, on average, finer-grained, and display predominantly loam, with minor skew towards sandy loam, matrix textures. *QCMU* units within *Group B* also plot with higher sand proportions and appear better-sorted than those of *QNVT*.

Comparison of grain size distributions (Fig.2) for *till samples only* confirms the existence of two separate populations, correlative with formations *QCMU* vs. *QNVT*. Density plots (shown along the diagonal in Fig.2) indicate that most of the variability between sampled tills is contained within the clay component (both within and between formations), though significant overlap occurs within the silt size-fraction. High negative correlation exists between sand and clay fractions within the sample distribution (as evidenced by the tightly-constrained negative slope on the sand vs. clay cross-plot), implying sufficient mixing and homogenization (i.e., a lack of bimodal till texture). *QNVT* tills exhibit slightly greater proportions of silt and clay, but moderately lesser proportions of sand compared to *QCMU* tills, in terms of all three measures of central tendency (Fig.3).

12 of 17 samples collected from core CW02 returned textural profiles inconsistent with their logged deposit-type (see Appendix A.1). Six of these samples (CW02/02-07) extracted in sequence from intervals logged as proglacial outwash (with the exception of CW02/02, interpreted as Alborn Member till of the Aitkin Formation) yielded uncharacteristically loamy textures, whereas 6 samples (CW02/10-15) obtained from intervals logged as glacial till yielded anomalously high sand and low fines percentages (with the exception of CW02/10 which ran high silt and clay). Our best judgment determined that samples were misordered at some unidentified stage during texture processing, and further, that interval CW02/2-07 corresponds to CW02/12-15 and *vice versa*. Samples are treated as such in all analyses presented here. Resampling of the archived core split has been completed and sample reprocessing for grain-size analysis is currently underway.

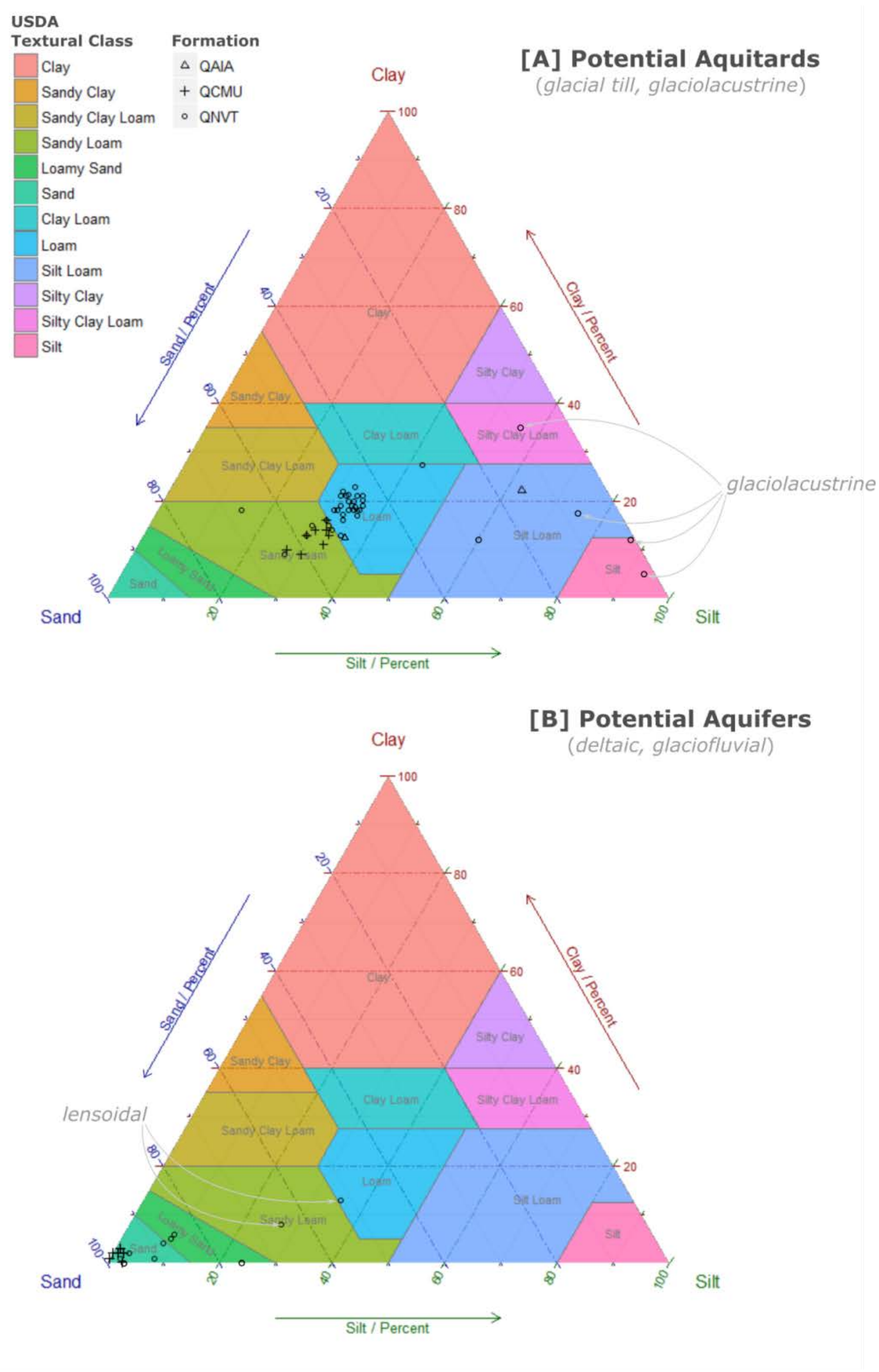


Figure 1. Ternary diagrams showing results of sample particle-size analysis from cores LF01, LF02, and CW02 for grouped units interpreted as: [A] glacial till, glaciolacustrine, and fine-grained ice-contact deposits (i.e., potential aquitards), and [B] grouped proglacial deltaic, outwash, and undifferentiated glaciofluvial deposits (i.e., potential aquifers). Classification and nomenclature follows United States Department of Agriculture (USDA) textural soil classification. QAIA = Aitkin Formation, Alborn Member, QCMU = Cromwell Formation, QNVT = New Ulm Formation, Villard Member.

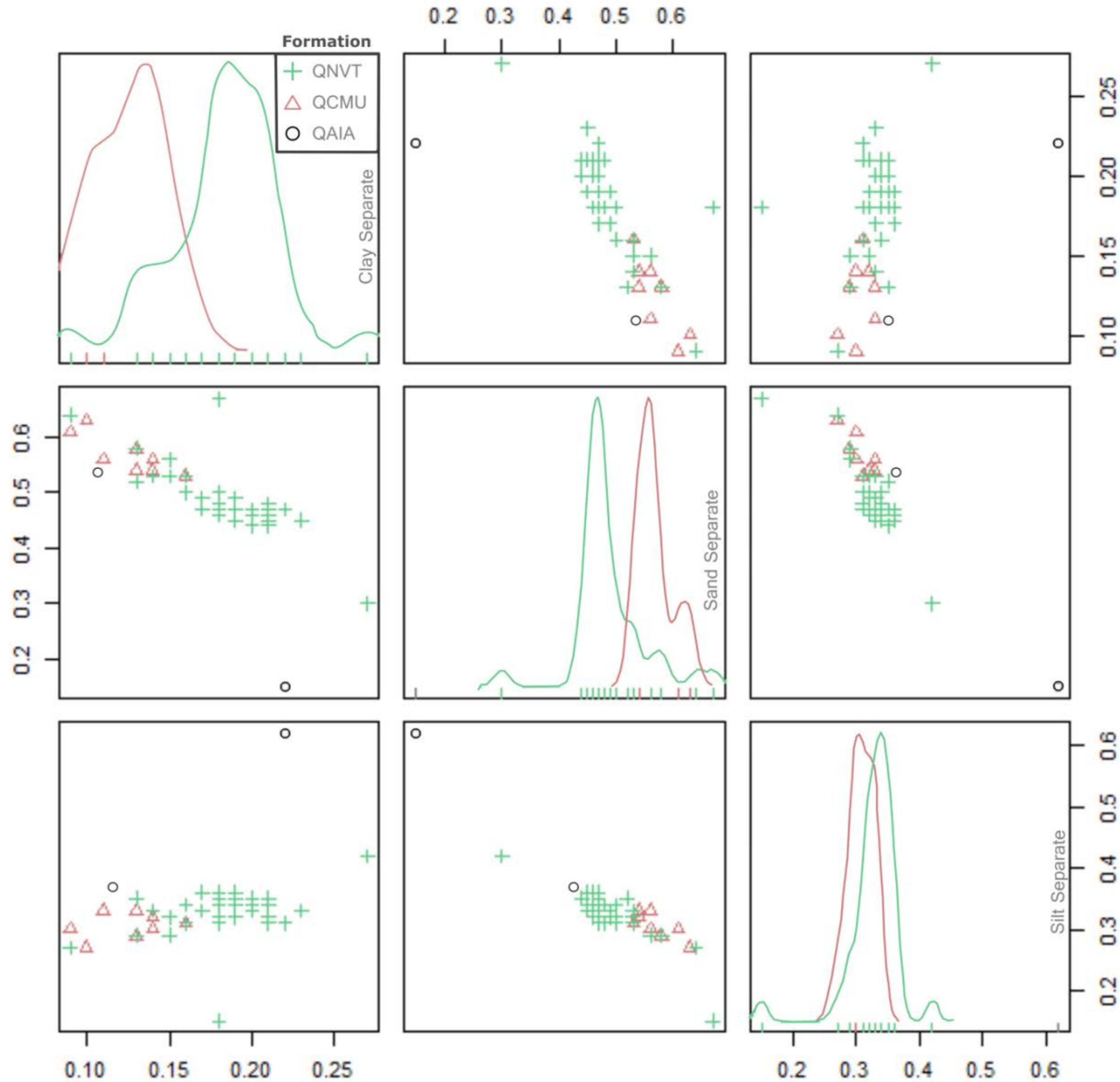
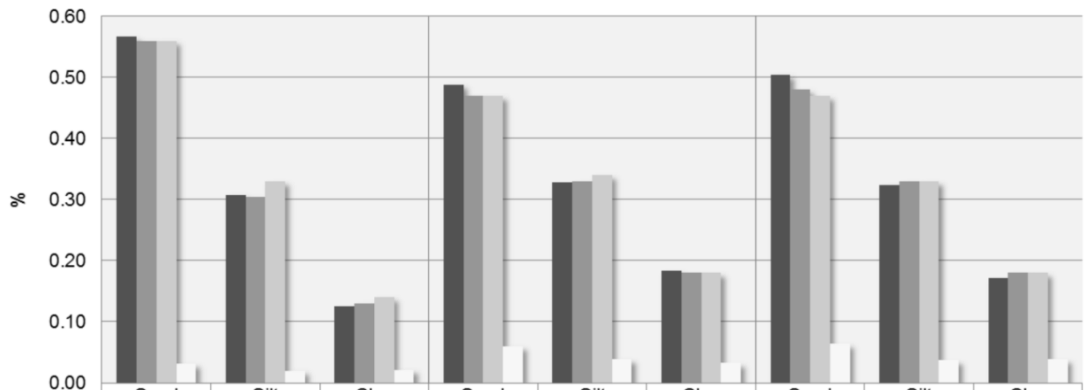


Figure 2. Scatterplot matrix depicting the relationship between sand, silt, and clay separates for till samples obtained from cores LF01, LF02, and CW02, grouped by lithostratigraphic formation. Sample density by particle-size fraction is shown along the diagonal for clay (left column), sand (middle column), and silt (right column). QAIA = Aitkin Formation, Alborn Member, QCMU = Cromwell Formation, QNVT = New Ulm Formation, Villard Member.



	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
	Cromwell Till (QCMU)			New Ulm Till (QNVT)			All		
Mean	0.57	0.31	0.13	0.49	0.33	0.18	0.50	0.32	0.17
Median	0.56	0.31	0.13	0.47	0.33	0.18	0.48	0.33	0.18
Mode	0.56	0.33	0.14	0.47	0.34	0.18	0.47	0.33	0.18
St. Dev	0.03	0.02	0.02	0.06	0.04	0.03	0.06	0.04	0.04

Figure 3. Central tendency statistics for sand, silt, and clay separates of till samples obtained from cores LF01, LF02, and CW02, grouped by lithostratigraphic formation. Two samples of the Alborn Member of the Aitkin Formation collected from core CW02 are not shown. * = sample has been reassigned to an interpreted depth due to inconsistency between texture result and sampled deposit-type. See Results section for details.

Borehole geophysics

Major hydrogeologic factors that can affect EM response are dissolved solids concentrations in the groundwater and silt and clay content (Williams et al., 1993). In general, boreholes logged using the EM-Induction sonde as part of this investigation have similar patterns in conductivity and gamma logs; increases in conductivity correspond to increasing gamma, likely due to increasing silt and clay content. Deviations from this pattern may correspond to changes in groundwater chemistry. Deviation depth intervals from Cromwell observation well cluster 1 (Figure 4) and Litchfield observation wells LFO1-F and LFO2-F (Figure 5) identify zones where changing dissolved solids concentrations may be occurring. Wells in Cromwell observation cluster 1 are closely spaced and deviation depth intervals roughly correspond in the upper 100 feet, particularly at depths 18 to 26 feet bgs and 60 to 70 feet bgs.(Figure 4). Deviation depth intervals in Litchfield LFO1-F and LFO2-F correspond to thick sand and gravel intervals in the bottom of the holes (Figure 5) and likely represent water chemistry differences in the confined aquifer from water in overlying fine-grained sediment.

During the June 24, 2015 logging of LFO2-F, the EM-Induction sonde stopped at 153 feet below the ground surface prior to logging, approximately 10 feet above the completed hole depth. The EM-Induction sonde has a larger diameter than the Gamma sonde and may have become stuck in a section of the casing that was not plumb. LFO2-F was re-logged using the EM-Induction sonde on August 19, 2015, this time with several wraps of electrical tape removed from the lower portion of the sonde to reduce tool diameter. The sonde again stopped at 153 feet below the ground surface,

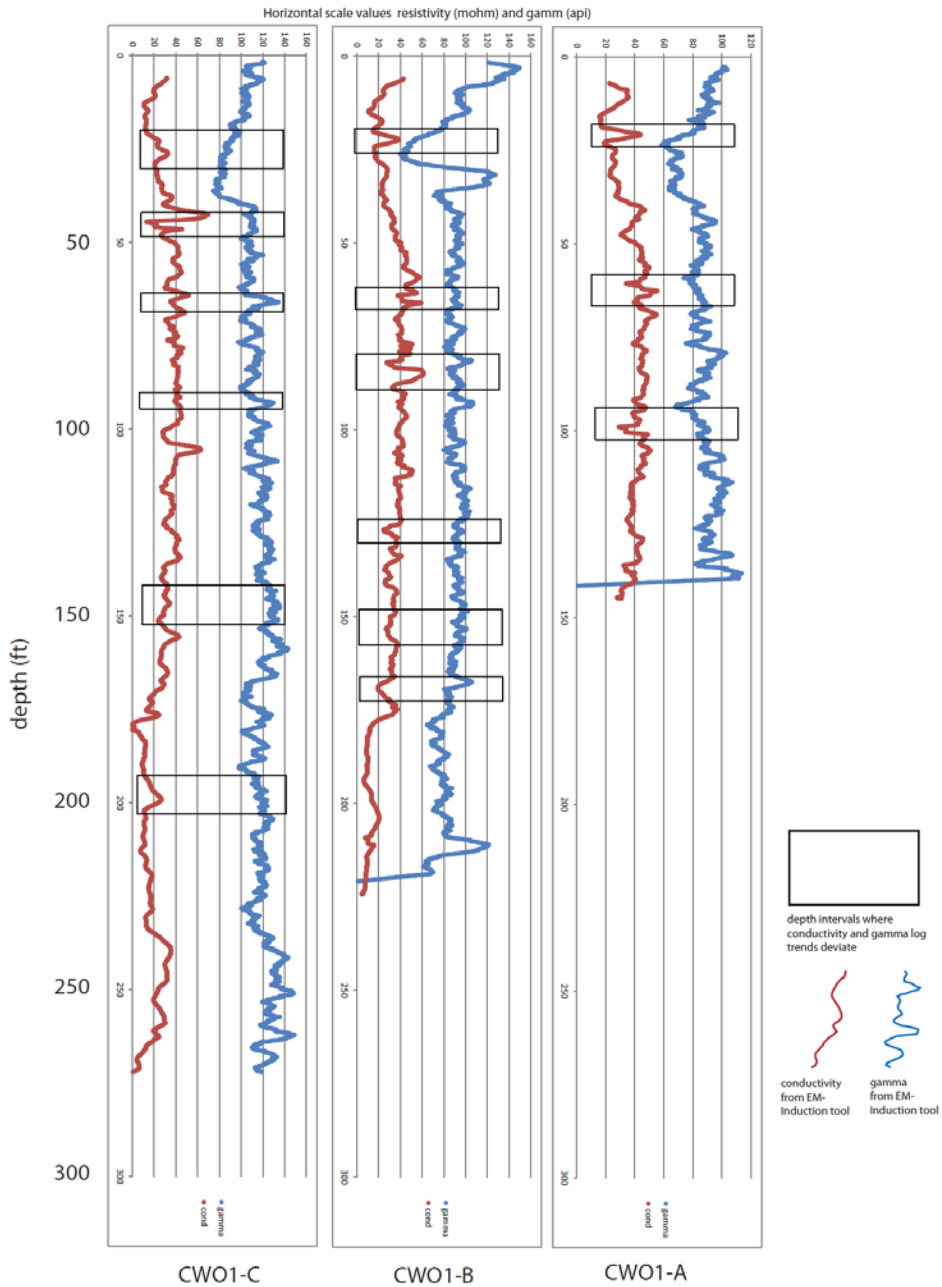


Figure 4. Qualitative identification of depth intervals where conductivity and gamma trends deviate, Cromwell observation well cluster 1. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

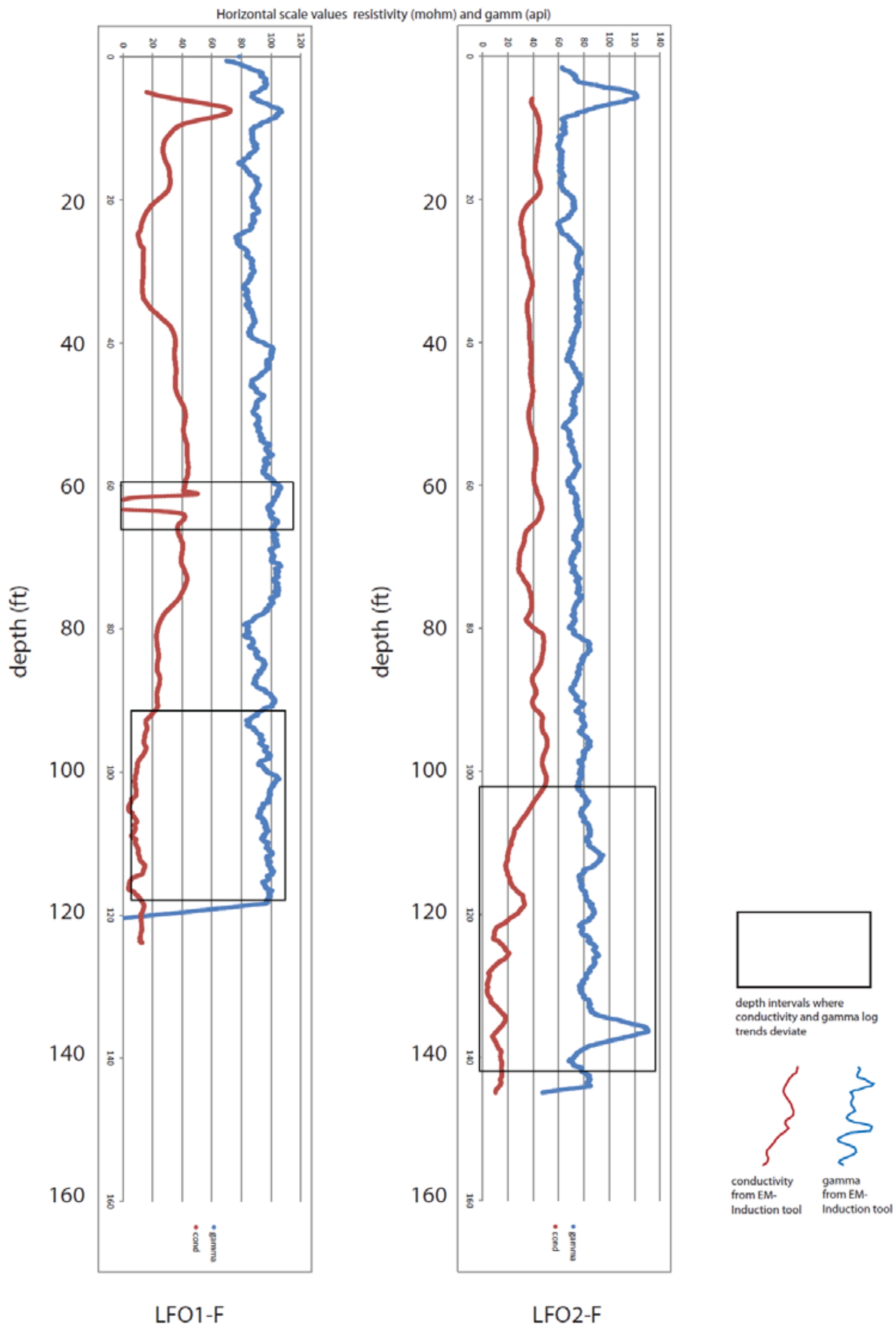


Figure 5. Qualitative identification of depth intervals where conductivity and gamma trends deviate, Litchfield observation wells LFO1-F and LFO2-F. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

resulting in no EM-induction record for the lower 10 feet of LFO2-F. EM-Induction and Gamma logs are included in Appendix B.

Prior to this investigation, borehole geophysical work by MGS has not included the EM-Induction sonde. The interpretation presented here is qualitative, and would benefit from review by USGS staff more familiar with EM-Induction logs. We see value in continued use of this sonde, recognizing casing material restrictions.

Discussion

Litchfield

Sediments encountered in the two cores (LF01, LF02) acquired from Litchfield, MN chronicle the incursion of the Des Moines Lobe of the Laurentide Ice Sheet (LIS) into south-central Minnesota, and its subsequent demise during the Late Wisconsinan glacial episode. During this stage, ice advanced out of Manitoba and Saskatchewan from the northwest, occupying the present-day Red River Valley, moving through Meeker County, and reaching as far south as Des Moine, Iowa by 14 ka BP (Clayton and Moran, 1982). The Des Moines Lobe represented the outlet of several dynamically-coupled ice streams (Patterson, 1997; Jennings, 2006) that eroded, incorporated, and transported materials from two broad source areas up-ice, conventionally referred to as "Riding Mountain" (northwest) and "Winnipeg" (north) provenances, the former of which is enriched proportionally with up to 50% higher gray Cretaceous Pierre shale content in the very-coarse sand (1-2 mm) fraction (Lusardi et al., 2011). The Villard Member of the New Ulm formation (*QNVT*) predominantly reflects a mixed Winnipeg provenance. Within the geographic boundaries of its occurrence, it has an average crystalline/carbonate/shale composition of .52/.31/.17 (Johnson et al., 2016). The reduced shale content, and the sandier texture compared to the Heiberg Member – the coeval and laterally stratigraphic equivalent member of the New Ulm Formation (the surface unit as little as 5 miles south and west of Litchfield (Meyer, 2015a)) – suggests that multiple ice sheds contributed distinctive lithological signatures to tills of the Des Moines Lobe, and impacted its dynamics, with the ice stream depositing the Villard Member having emerged from the north, and overridden and incorporated sandy materials of the Alexandria moraine complex in west-central Minnesota (Hobbs and Goebel, 1982). As this ice stream outlet thinned, it was partially captured by a second and buttressing outlet to the southwest that deposited the Heiberg Member till, shifting ice flow towards the northeast across most of Meeker County, and enabling ice to overtop the St. Croix moraine, thus spawning the Grantsburg Sublobe (Lusardi et al., 2011). The Villard Member in south-central Minnesota has not been directly dated, however, it is assumed correlative with the event that formed the Pine City moraine in east-central Minnesota between approximately 12 ka

^{14}C yr BP (14 ka cal yr BP; Wright and Rubin, 1956; Clayton and Moran, 1982) and 13 ka BP (16 ka cal yr BP; Jennings et al., 2013).

Recent work documents large-scale reorganizations of ice flow during the late last glacial within catchment areas of the Des Moines Lobe in southern Saskatchewan and Manitoba (Ross et al., 2009; O'Cofaigh et al., 2010), and these shifts are likely linked, in combination with local factors, to subtle variations in till texture, colour and visible clast lithologies documented here down-core in LF01 and LF02. The observed increase in felsic igneous lithologies, the introduction of sparse Late Precambrian North Shore Volcanic Group (NSVG) red volcanics, and the associated proportional reduction of carbonates (Paleozoic limestone and dolostone) incorporated as clasts within till at the base of both cores, indicate local incorporation of older Rainy provenance materials, most likely till and/or outwash of the underlying Hewitt Formation (including deposits of the Alexandria moraine complex) deposited by the Wadena Lobe early in the Late Wisconsinan. The sustained presence of Cretaceous shale corroborates that this is indeed a mixed-provenance unit, as the pure Hewitt Formation is devoid of this lithology. At both sites, it is inferred that all changes in the nature of the tills reflect variability within a single member (i.e., units *nvt, nva* of the Villard Member) of the New Ulm formation driven by fluctuating ice stream dynamics and interactions at the ice-bed interface, rather than oscillations between members (i.e., Villard vs. Heiberg), as mean sand, silt, and clay proportions of all *QNVT* tills shown here are within 1 standard deviation of values reported by workers in surrounding counties for the Villard Member of the New Ulm Formation (e.g., Lusardi, 2009; Lusardi et al., 2012, Meyer, 2015b). Systematic counts of the very coarse sand (1-2 mm) fraction were not completed for this study, but would be the preferred method of establishing a basis for this argument, as discrete members of the New Ulm Formation retain well-understood and distinctive lithologic assemblages (Johnson et al., 2016), and exhibit unique areal distributions on bivariate plots comparing % sand and % shale (Harris, 1998). Down-hole 1-2 mm grain counts were completed by the MGS on samples from a rotary-sonic core (MS-3) drilled 0.17 miles west of LF02 in support of the Meeker County Geological Atlas (Meyer, 2015b), and all tills described there from the surface to a depth of 134 ft. were interpreted as Villard Member of the New Ulm Formation.

The uppermost sands and gravelly sands encountered at surface in LF01 are interpreted as deltaic sediments deposited as interflow and underflow plumes into Glacial Lake Litchfield II (GLL II) (represented in the sediment archive in LF01 from 12-20.5'), which formed following recession from a late-stage re-advance of the Des Moines Lobe, when drainage was blocked to the north by stagnant ice, and to the east, by the western margin of the Grantsburg Sublobe in Wright County (Meyer, 2015a). The thin outwash sequence bounded by till, present from 21.75-28' in core LF02, possibly marks the position of this re-advance in the local stratigraphy. Though the difference in surface elevation between LF01 and LF02 is minor (< 25 ft.), the latter boring is sited on a till knob which evidently escaped inundation by the lake body, suggesting GLL II was relatively shallow and possibly short-lived.

Cromwell

Core materials recovered from CW02 detail lobate interactions of the LIS in north-eastern Minnesota throughout the Late Wisconsinan glacial episode. During the St. Croix phase, the first of multiple, successively less-expansive configurations of the Superior Lobe recognized within the Late Wisconsinan, ice (sourced from the Labrador-Québec divide centered south of Ungava Bay) occupied the Lake Superior lowland and advanced – confluently with the Rainy Lobe – south into west-central and south-central Minnesota, culminating in the deposition of the St. Croix moraine between 15 and 20 ka cal yr BP (Wright, 1972; Clayton and Moran, 1982; Johnson and Mooers, 1988). Subsequently, the Superior Lobe contracted back into the Lake Superior basin, fronted by networks of small proglacial lakes depositing fine sands, silts and clays which were later incorporated into the basal deposits of a second Superior Lobe advance (The Automba Phase) ~13.5 – 14 ka cal yr BP, which generated the Mille Lacs Moraine along its westernmost extent (Wright, 1972).

Glacial tills and associated glaciolacustrine and glaciofluvial meltwater deposits of the St. Croix and Automba phases of the Superior Lobe are lithostratigraphically assigned to the Cromwell Formation (*QCMU*; Wright et al., 1970; Johnson et al., 2016). Materials of this formation are present in core CW02 from 8.5' through to the base (120'), and consist of ~ 76.5' of subglacial till overlain by a ~ 20' sequence of variously graded and stratified proglacial outwash. Large (≤ 17 ft.) and frequent intervals of core loss and/or zero recovery in CW02 preclude detailed consideration of the glacial stratigraphy at this location; in particular, because differentiation of Automba and St. Croix phase deposits based on texture or lithology is problematic and generally relies on stratigraphic sense. This difficulty is exacerbated by a lack of confidence in sample texture results (see Results above). Though no formal assignment is offered here, the entire package of sediments below 8.5' is assumed Automba Phase in origin, in keeping with more regional subsurface mapping completed by the MGS for the Carlton County Geologic Atlas (Hobbs and Knaeble, 2009; Knaeble and Hobbs, 2009), including description of a rotary-sonic core (Unique #: 257600) drilled to 162 ft. depth 2.5 miles north of CW02. This package is hence interpreted as a continuous record marking sedimentation during a single phase of advance (subglacial till) and retreat (proglacial outwash over subglacial till) of the Superior Lobe. Assuming correct reassignment of misordered samples to depth, mean sand proportions of *QCMU* tills derived here are within 2 standard deviations, silt proportions within 3 standard deviations, and clay values equivalent to those reported by Hobbs and Knaeble (2009).

The Cromwell Formation in CW02 is capped by ≥ 5.5' of distinctive reddish-brown (5YR 4/4 – 7.5YR 4/4) silty diamicton interpreted as the Alborn Member of the Aitkin Formation (*QAIA*). The Aitkin Formation includes all deposits associated with the St. Louis Sublobe of the Koochiching Lobe, which advanced from the northwest as a piedmont glacier into glacial lakes Aitkin I and Upham I that formed following retreat of the Superior Lobe from its maximum Automba Phase configuration ~12.5 ka ^{14}C yr BP (~15 ka cal yr BP) (Jennings et al., 2013). The prominent red color and silt loam to clay loam texture of the Alborn Member derives from incorporation of fine-grained Glacial Lake Upham I sediments and underlying Automba Phase deposits. It exists at surface as only a narrow (1-8 miles wide) rim which demarcates the boundary of the St. Louis Sublobe beyond the former extent of Glacial Lake Upham II, which formed following the sublobe's collapse (Johnson et al., 2016). Two samples of Alborn Member till retrieved at surface from core CW02 diverge widely in terms of texture (again, assuming correct reassignment of misordered samples to depth). Clear indications of pedogenesis, including leaching, oxidation, root infiltration, fines translocation and ped development through the 0-1.5 ft. interval, and the presence of a platy, illuviated, argillic horizon from 3.5-5.5 ft. suggest extensive modification by soil-forming processes, and hence, that a representative sample of Alborn Member till was not obtained. Consequently, these samples are not isolated for comparison in Fig.3. It is important to note that the assignment of this uppermost diamicton in CW02 to the Alborn Member is somewhat tenuous, given the misassignment of textures to depth intervals, and the tendency for soil-forming processes to sufficiently alter Cromwell Formation tills such that they may be texturally indistinguishable from those of the Alborn Member (Alan Knaeble, pers comm.). Hobbs and Knaeble (2009) depict the surface unit at site CW02 as Cromwell Formation till (*Qat*), however this assessment was based locally on a hand sample obtained from a surface exposure, and thus did not account for the underlying ~20 ft. of sorted outwash deposits, which are considered here as a significant bounding unit between formations. The Alborn Member is construed as relatively patchy in the mapping of Hobbs and Knaeble (2009) and exists at surface as close as 3 miles east of CW02.

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Appendices: Logging and analysis of core materials and borehole geophysical logs

Appendix A – Logging and analysis of core materials

Appendix A.1 Textural analysis

Q#	Sample	Top (f)	Bot. (f)	Sand Separate	Silt Separate	Clay Separate	Gravel Fraction	Deposit Type	Leached	Dry Color	Wet Color	Formation
00Q0045274	CW02/01	1	1.5	0.52	0.37	0.12	0.13	Soil Modified Till	Y	7.5YR 4/4	10YR 4/4	QAIA
	CW02/10*	4	4.5	0.15	0.62	0.22	0.01	Soil Modified Till	Y	5YR 4/4	5Y 4/4	QAIA
	CW02/11*	8.5	10.5	0.97	0.01	0.02	0.01	Outwash	Y	10YR 4/4	10YR 5/8	QCMU
	CW02/12*	15	15.5	0.96	0.02	0.02	0.08	Outwash	Y	10YR 4/4	10YR 6/6	QCMU
	CW02/13*	19	19.5	0.97	0.01	0.03	0.26	Outwash	Y	10YR 3/4	2.5Y 7/6	QCMU
	CW02/14*	22	22.5	0.98	0	0.02	0	Outwash	Y	10YR 5/3	2.5Y 7/6	QCMU
	CW02/15*	27	27.5	0.99	0	0.01	0.11	Outwash	Y	7.5YR 3/2	2.5Y 8/2	QCMU
	CW02/08	44	44.5	0.54	0.33	0.13	0.09	Till	N	5Y 4/2	5Y 4/4	QCMU
	CW02/09	48.5	50	0.53	0.31	0.16	0.13	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/02*	54	54.5	0.63	0.27	0.1	0.19	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/03*	63	63.5	0.61	0.3	0.09	0.34	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/04*	66.5	67	0.58	0.29	0.13	0.1	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/05*	81.5	82	0.56	0.3	0.14	0.16	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/06*	94	94.5	0.56	0.3	0.14	0.16	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/07*	106	106.5	0.54	0.32	0.14	0.14	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/16	108.5	109	0.56	0.33	0.11	0.08	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/17	119.5	120	0.56	0.33	0.11	0.1	Till	N	7.5YR 3/2	5Y 4/4	QCMU
00Q0045272	LF01/01	6	6.25	0.97	0.03	0	0	Deltaic	Y	2.5Y 7/2	2.5Y 7/8	QNVT
	LF01/02	10	10.25	0.97	0.03	0	0.01	Deltaic	N	2.5Y 5/4	2.5Y 7/8	QNVT
	LF01/03	13	13.25	0.76	0.24	0	0	Deltaic	N	2.5Y 5/2	2.5Y 6/8	QNVT
	LF01/04	16	16.25	0.03	0.9	0.07	0	Glaciolacustrine	N	2.5Y 5/3	2.5Y 4/4	QNVT
	LF01/05	16.5	16.75	0.02	0.93	0.05	0	Glaciolacustrine	N	2.5Y 5/3	10YR 3/4	QNVT
	LF01/06	19.5	20	0.01	0.87	0.12	0	Glaciolacustrine	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/07	39.5	40	0.3	0.42	0.27	0.02	Till	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/08	43.5	43.75	0.09	0.56	0.35	0.03	Ice Contact	N	2.5Y 6/2	2.5Y 5/2	QNVT
	LF01/09	46	46.25	0.52	0.35	0.13	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/10	52	52.25	0.58	0.29	0.13	0.22	Till	N	2.5Y 5/2	2.5Y 5/2	QNVT
	LF01/11	53	53.25	0.48	0.34	0.18	0.06	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/12	55	55.25	0.46	0.34	0.2	0.09	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/13	58	58.25	0.46	0.36	0.18	0.03	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/14	62	62.25	0.45	0.36	0.19	0.06	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/15	65	65.25	0.47	0.36	0.18	0.1	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/16	72	72.25	0.47	0.32	0.21	0.07	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/17	75	75.25	0.45	0.33	0.23	0.08	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/18	78	78.25	0.65	0.27	0.08	0.02	Lensoidal	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/19	80.5	81	0.85	0.09	0.06	0.07	Glaciofluvial	N	2.5Y 4/2	2.5Y 5/2	QNVT

	LF01/20	81.5	81.75	0.88	0.08	0.04	0.28	Glaciofluvial	N	2.5Y 4/2	2.5Y 5/4	QNVT
	LF01/21	81.75	82	0.67	0.15	0.18	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/22	84	84.25	0.95	0.03	0.02	0	Glaciofluvial	N	2.5Y 5/2	10YR 6/4	QNVT
	LF01/23	84.25	85	0.56	0.29	0.15	0.03	Till	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/24	90	90.5	0.53	0.33	0.14	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
00Q0045273	LF02/01	3	3.5	0.5	0.34	0.16	0.05	Till	N	2.5Y 5/4	10YR 6/6	QNVT
	LF02/02	6.5	7	0.47	0.33	0.2	0.05	Till	N	2.5Y 4/4	10YR 6/6	QNVT
	LF02/03	12.5	13	0.47	0.35	0.18	0.05	Till	N	2.5Y 4/4	10YR 6/6	QNVT
	LF02/04	16.5	17	0.44	0.35	0.2	0.07	Till	N	2.5Y 4/2	2.5Y 4/4	QNVT
	LF02/05	18.5	18.75	0.52	0.35	0.13	0	Lensoidal	N	2.5Y 6/4	2.5Y 5/6	QNVT
	LF02/06	21	21.5	0.45	0.34	0.21	0.1	Till	N	2.5Y 3/1	2.5Y 4/4	QNVT
	LF02/07	24.5	25	0.97	0.02	0.01	0.01	Glaciofluvial	N	2.5Y 5/3	2.5Y 7/6	QNVT
	LF02/08	27	27.5	0.91	0.08	0.01	0.05	Glaciofluvial	N	2.5Y 4/1	2.5Y 5/4	QNVT
	LF02/09	30.5	31	0.53	0.31	0.16	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/10	33.5	34	0.49	0.32	0.19	0.05	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/11	38	38.5	0.5	0.31	0.18	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/12	42	42.5	0.49	0.33	0.17	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/13	46.5	47	0.46	0.32	0.21	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/14	50	50.5	0.46	0.34	0.2	0.28	Till	N	5Y 3/1	2.5Y 4/2	QNVT
	LF02/15	54	54.5	0.46	0.36	0.18	0.05	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/16	58	58.5	0.46	0.34	0.2	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/17	61	61.5	0.47	0.31	0.22	0.08	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/18	65	65.5	0.5	0.32	0.18	0.11	Till	N	2.5Y 3/2	2.5Y 4/2	QNVT
	LF02/19	68	68.5	0.47	0.33	0.2	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/20	73	73.25	0.64	0.27	0.09	0.08	Till	N	2.5Y 4/2	2.5Y 4/2	QNVT
	LF02/21	75.5	76	0.53	0.32	0.15	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/22	80.5	81	0.48	0.34	0.18	0.11	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/23	84.5	85	0.47	0.32	0.21	0.05	Till	N	2.5Y 3/2	2.5Y 4/2	QNVT
	LF02/24	88	88.5	0.47	0.36	0.17	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/25	93	93.5	0.47	0.35	0.19	0.03	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/26	97.5	98	0.48	0.31	0.21	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/27	102	102.5	0.44	0.35	0.21	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/28	106	106.5	0.47	0.34	0.19	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/29	107.25	107.5	0.87	0.09	0.05	0.58	Glaciofluvial	N	2.5Y 5/2	2.5Y 6/2	QNVT
	LF02/30	112	112.5	0.58	0.29	0.13	0.06	Till	N	5Y 3/1	2.5Y 4/2	QNVT

Appendix A.2 Description and correlation of log units

Description of Log Units

QUATERNARY

Wisconsinan Episode

New Ulm Formation

Villard Member

nd — DELTAIC - Interbedded very fine grained to very coarse grained sand and very fine to medium gravels

ns — GLACIOLACUSTRINE - Very fine to fine grained sand interbedded with very fine grained silt to sandy silt.

nvt — LOAMY TILL - Loam textured, unsorted sediment (diamicton).

nva — SANDY LOAM TILL - Loam to sandy loam textured, unsorted sediment (diamicton).

ng — OUTWASH - Massive to planar parallel to cross stratified fine to very coarse sand and very fine to coarse gravel.

Aitkin Formation

Alborn Member

Qat — SILT LOAM TILL - Predominantly silt loam to clay loam textured, unsorted sediment (diamicton).

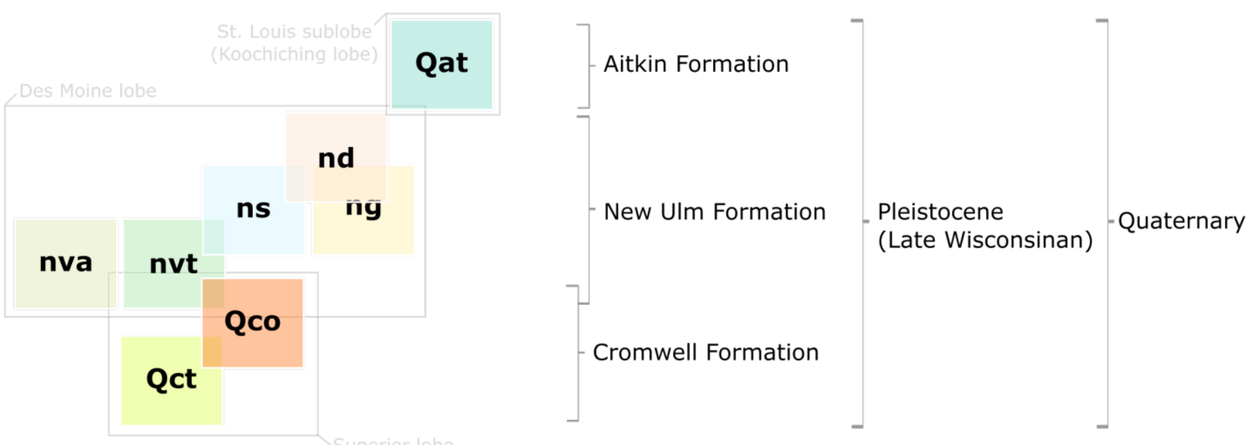
Cromwell Formation

Automba and/or St. Croix Phase

Qco — OUTWASH - Massive to planar parallel to cross stratified fine to very coarse sand and very fine to coarse gravel.

Qct — SANDY LOAM TILL - Sandy loam to loam textured, unsorted sediment (diamicton).

Correlation of Log Units

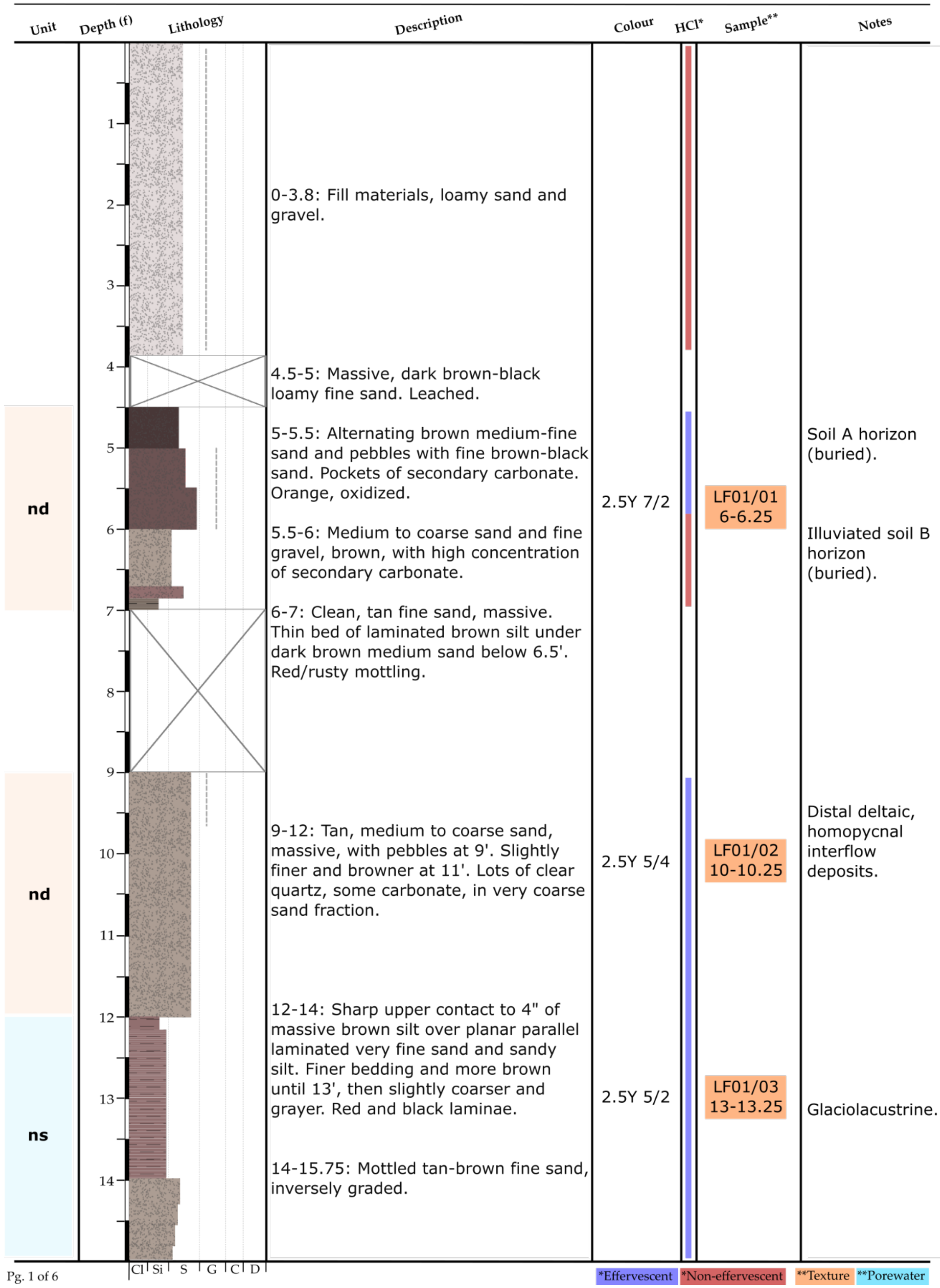


Appendix A.3 Core descriptions

LF01 – Graphical log

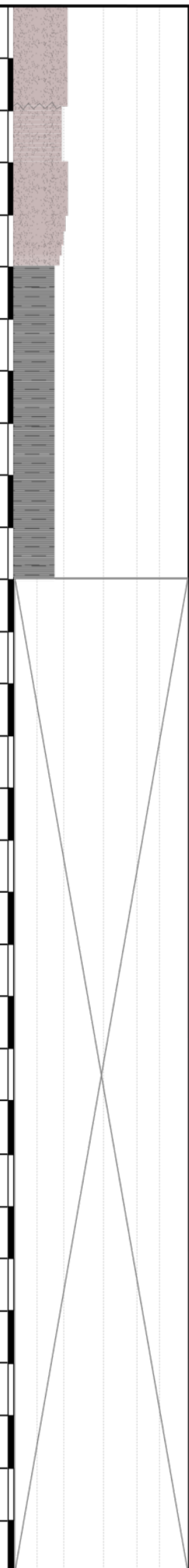
Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
ns	16–29		15.75-16.5: Planar parallel to ripple laminated tan-brown very fine sand and silt. Black laminae of silt @ 16'. Vaguely scoured contact to overlying massive brown fine sand.	2.5Y 5/3		LF01/04 16-16.25	Glaciolacustrine.
			16.5-17.5: Brown silt with very fine black laminae at depth. Inverse grading towards gradational lower contact.	2.5Y 5/3		LF01/05 16.5-16.75	
			17.5-20.5: Grey microlaminated clay-rich silt, relatively dense.	2.5Y 4/1		LF01/06 19.5-20	

Cl Si S G C D

*Effervescent *Non-effervescent **Texture **Porewater

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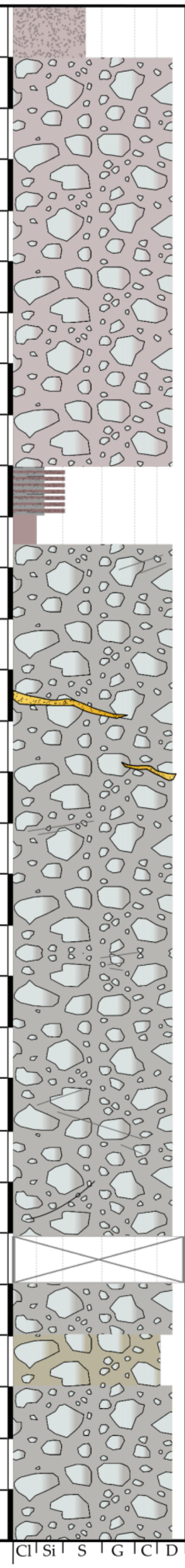
CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



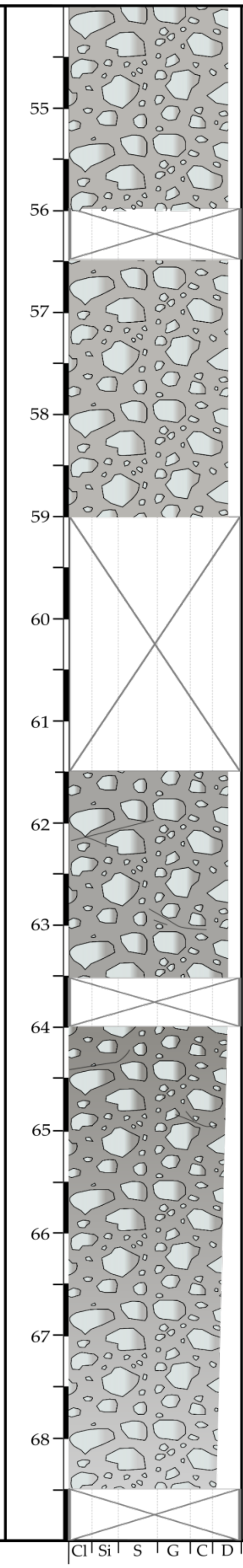
Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
nvt	39-39.5	39-39.5: Deformed brown, medium sand.				No core recovered from 30-39'.
nvt	39.5-43.5	39.5-43.5: Massive, matrix-supported diamicton. Moderately clast-rich. Clasts mostly subrounded, mostly carbonates, very fine to medium gravel-size. Gray-brown loam matrix. Granular structure. Deformed light grey banding @ 39.5'. More compact below 40'. Stringers of grey very fine sand @ 41'. Mixing of brown and dark brown matrices below 41.5'.	2.5Y 4/1		LF01/07 39.5-40	Ablation till, Riding Mountain-Winnipeg Provenance.
nvt	43.5-44	43.5-44: Alternating dry gray silt and dark brown fine sand.	2.5Y 6/2 (silt)		LF01/08 43.5-43.75	Depression hollow ponding.
nvt	44-44.25	44-44.25: Massive brown clay.				
nva	44.25-52	44.25-52: Relatively dense, grey, massive, matrix-supported diamicton. Sandy loam matrix. Frequent fractures, some with light brown or rust coloured fine sandy skins/infills. Some fracturing, probably an artefact of coring and exhumation/expansion. Very fine to medium gravel-sized clasts, mostly subrounded but vary to subangular. Felsics, mafics, carbonate, shale present; perceived increase in shale content with depth. Higher proportion of medium gravel-sized clasts below 50'.	2.5Y 3/1		LF01/09 46-46.25; 51-51.5	Subglacial till, Riding Mountain-Winnipeg provenance.
nva	52-52.25	52-52.25: Carbonate-cemented, light brown, compact, fine sandy loam diamicton.	2.5Y 5/2		LF01/10 52-52.25	
nva	52.25-54	52.25-54: Similar diamicton to 44.25'+, less fractured.	2.5Y 3/1		LF01/11 53-53.25	

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes

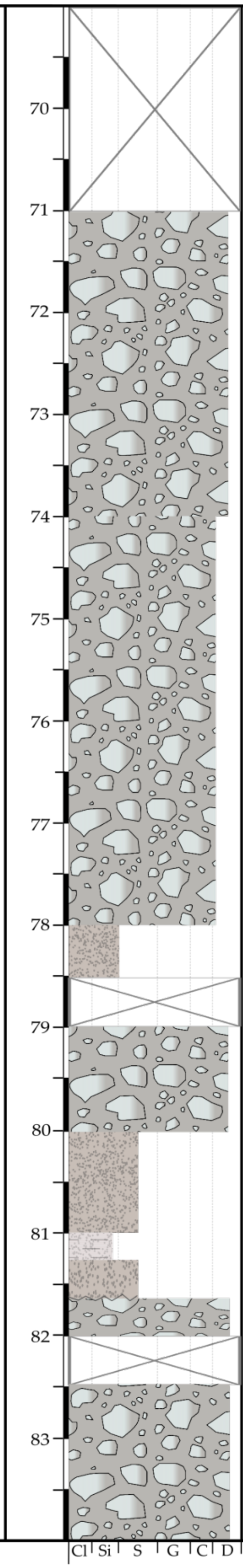


Unit	Depth (f)	Description	Colour	Sample**	Notes
nvt	54-59	54-59: Similar diamicton as above, but with apparent higher proportion of felsic lithologies. Several clasts around 55' are partially disintegrated and have highly weathered rinds.	2.5Y 3/1; 2.5Y 3/1	LF01/12 55-55.25; 56-56.5; LF01/13 58-58.25	Subglacial till, Riding Mountain-Winnipeg Provenance.
nvt	61.5-63.5	61.5-69: Very dense brown to grey-brown, massive, matrix-supported diamicton. Loam matrix; fines with depth, grading to siltier loam texture. Subtle colour change from grey-brown to grey with depth. Subhorizontal fractures (exhumation related?) from 61.5-65'. Very fine to coarse gravel-sized subangular to subrounded clasts. High proportion of carbonate clasts. Some shale, though visibly lower proportion than above, or perhaps just fewer large shale clasts. Chert @ 62'.	2.5Y 3/1	LF01/14 62-62.25; 63.5-64	
nvt	64-69		2.5Y 3/1	LF01/15 65-65.25; 68.5-69	Subglacial till, Riding Mountain-Winnipeg provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

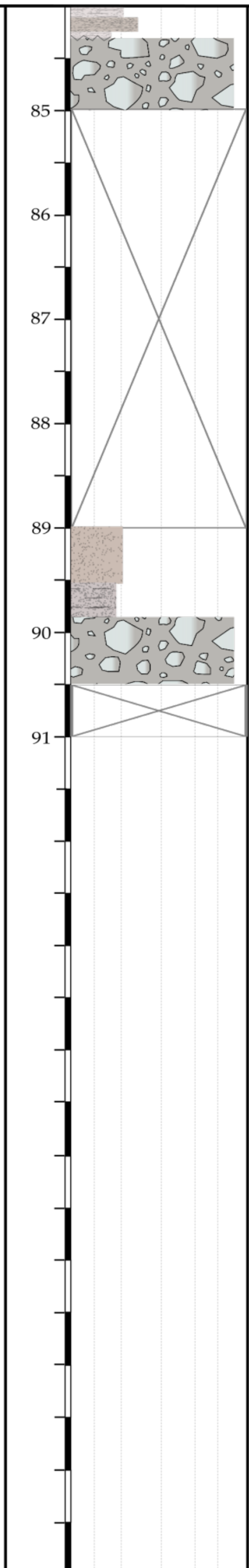


Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
nvt	71.5-74	71.5-74: Overconsolidated grey, massive, matrix-supported diamicton with loam matrix. Extremely dense. Many potassium feldspars. Increase in felsic igneous lithologies overall. Pink argillyte @72' - potentially Superior basin sourced.	2.5Y 3/1	Effervescent	LF01/16 72-72.25	Subglacial till and basal sorted sediment deposits, Riding Mountain-Winnipeg provenance; local incorporation of Rainy provenance materials.
nvt	74-78.25	74-78.25: Similar diamicton as above, but with siltier loam matrix. High proportion of carbonate and pink felsic igneous (possibly a few reds) lithologies, visible shale. Large (7 cm a-axis) chert clast at 76.5'. Very fine gravel-sized clasts of cherty lithologies common in this interval.	2.5Y 3/1	Effervescent	LF01/17 75-75.25	
nvt	78.25-78.5	78.25-78.5: Light brown, well-sorted fine sand, probably lensoidal.	2.5Y 3/1	Effervescent	LF01/18 78-78.25; 78.5-79	
nvt	79-80	79-80: Similar diamicton as 71.5'+.		Effervescent		
nvt	80-81	80-81: Well-sorted light brown medium sand.	2.5Y 4/2 (m. sand)	Effervescent	LF01/19 80.5-81	
nvt	81-81.25	81-81.25: Bedded grey very fine sand and silt.	2.5Y 3/1	Effervescent	LF01/20 81.5-81.75	
nvt	81.25-81.5	81.25-81.5: Poorly-sorted fine to very coarse sand and very fine to fine gravel. Carbonate-rich.		Effervescent	LF01/21 81.75-82	
nva	81.5-84	81.5-84: Overconsolidated grey, massive, matrix-supported diamicton. Extremely dense. Sandy loam matrix with obvious textural change from above diamicton. Scoured upper contact.		Effervescent		

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nva	84–85		84-84.25: Massive, grey silty very fine sand over brown medium sand. No apparent structure. Drilling issues encountered at this depth, possible that this could be slough from uphole (?).	2.5Y 5/2	Effervescent	LF01/22 84-84.25	
			84.25: Water saturated grey sandy silt, mixed with underlying diamict; either drilling slough or an erosive contact.	2.5Y 4/1		LF01/23 84.25-85	
			84.25-85: Grey, overconsolidated, massive, matrix-supported diamicton. Coarse-grained sandy loam matrix texture. Very fine to medium gravel-sized subangular to subrounded clasts. Carbonate and shale present but clearly in lower proportions than uphole. Proportionally more felsic igneous lithologies. Purplish-red rhyolite and vesicular basalt indicative of local incorporation of northeastern-sourced/Northshore lithologies.				Subglacial till and basal sorted sediment deposits, Riding Mountain-Winnipeg provenance; local incorporation of Rainy provenance materials.
nva	89–90.5		89-89.75: Massive grey to light brown medium sand grading at depth to grey sandy silt.		Effervescent		
			89.75-90.5: Similar diamicton as 84.25'+.	2.5Y 3/1		LF01/24 90-90.5	
						90.5-91 (Porewater)	

Depth scale: 85, 86, 87, 88, 89, 90, 91

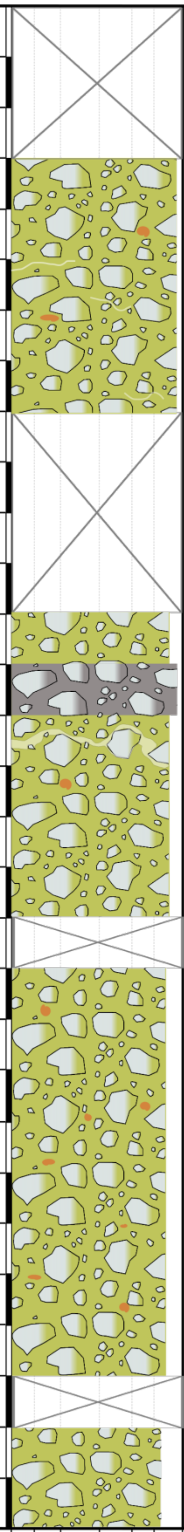
Grain size scale: Cl Si S G C D

*Effervescent *Non-effervescent **Texture **Porewater

LF02 – Graphical log

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



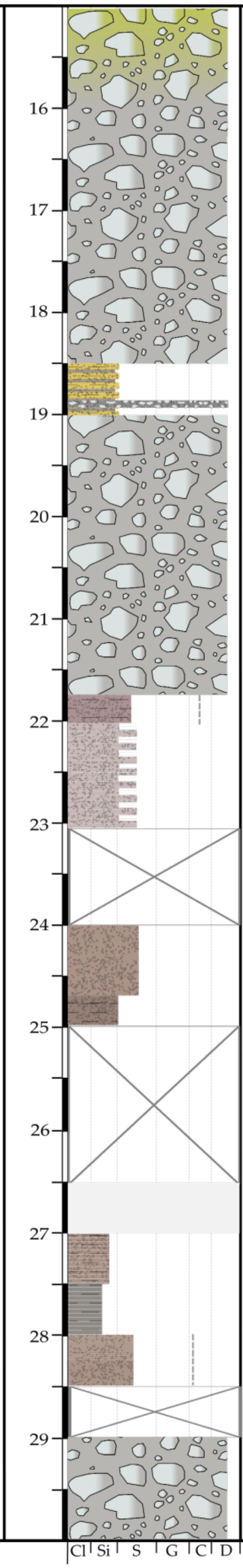
Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
	0-1.5					
nva	1.5-4	1.5-4: Oxidized olive to yellow-brown, massive, matrix-supported diamicton. Loam matrix. Moderately clast-rich; felsics and mafic igneous/carbonate/ weathered shale. Granular structure. Clear stringers of secondary carbonate. Red ochre spots present throughout. Clasts mostly subrounded but vary to subangular. Several broken-up, weathered micaceous granites.	2.5Y 4/4	Effervescent	LF02/01 3-3.5	Soil-modified ablation (?) till, Riding Mountain-Winnipeg provenance.
	4-6					
nva	6-6.5	6-6.5: Similar diamicton as 1.5'+ but very dessicated. Poor recovery.		Effervescent		
nvt	6.5-7	6.5-7: Dark gray, massive, matrix-supported diamicton. Coarse grained, friable. Possibly mixed with slough (?).	2.5Y 4/4	Effervescent	LF02/02 6.5-7	
nvt	7-9	7-9: Similar diamicton as 1.5'+, but finer matrix, and more clast-rich, with more visible shale present. Accumulation of secondary carbonate @ 7.25'. Frequent broken-up, weathered micaceous granites.		Effervescent		
	9-9.5					
nvt	9.5-13.5	9.5-13.5: Similar diamicton as 7'+, but lacks secondary carbonate. Frequent red ochre spots.	2.5Y 4/4	Effervescent	LF02/03 12.5-13	Ablation (?) till, Riding Mountain-Winnipeg provenance.
	13.5-14				13.5-14	
nvt	14-15			Effervescent		

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

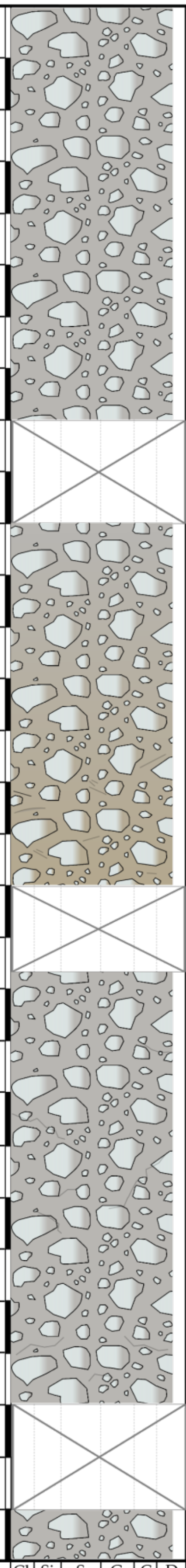
Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nvt	14-16.3		14-16.3: Yellow-brown oxidized massive, matrix-supported diamicton. Sandy loam matrix with granular structure. Grades to unoxidized grey-brown colour at base.		Effervescent		Ablation (?) till, Riding Mountain-Winnipeg provenance.
nvt	16.3-18.5		16.3-18.5: Same as above, but unoxidized and grey. Red rusty precipitate along cracks. Rich in shale. Fining matrix with depth, grading to sandy clay loam at base.	2.5Y 4/2	Effervescent	LF02/04 16.5-17	
nvt	18.5-19		18.5-19: Alternating planar parallel laminated yellow-brown very fine sand and grey-brown silty very fine sand. Capped by rusty bedding @ 18.5'. 1.5" thick dark grey massive, matrix-supported diamict inclusion with sandy clay loam matrix at 18.75'.	2.5Y 6/4	Effervescent	LF02/05 18.5-18.75	
nvt	19-21.75		19-21.75: Dark grey, overconsolidated, massive, matrix-supported diamicton. Sandy clay loam matrix. High fissility with a platy breakage structure. Subangular to subrounded carbonates, felsic and mafic igneous. Some visible shale, but proportionally less than above. Purple basalt @ 20'.	2.5Y 3/1	Effervescent	LF02/06 21-21.5	
ng	21.75-23.1		21.75-23.1: Brown silty sand and gravel over light brown oxidized planar parallel bedded sand, alternating between fine and medium grain size. Several thin beds of black medium sand.		Effervescent		
ng	24-25		24-25: Moderately well-sorted, massive, brown medium sand over 3" of dark brown silty sand at base. Quartz and carbonate-rich.	2.5Y 5/3	Effervescent	LF02/07 24.5-25	Proglacial outwash.
	26.5-27		26.5-27: Drilling slough.				
ng	27-28.5		27-28.5: Brown very fine bedded sandy silt over bedded grey silt over poorly sorted fine to coarse brown sand with occasional fine subrounded gravels. Sand is bedded in upper 3", massive below.	2.5Y 4/1	Effervescent	LF02/08 27-27.5; 28.5-29 (Porewater)	
nva	29-				Effervescent		



*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nva	31, 32, 33, 34		29-38.5: Overconsolidated, grey, massive, matrix-supported diamicton. Loam to sandy loam matrix, siltier pockets in places. Clast-rich in upper 1', less so at depth. Primarily subrounded clasts, includes carbonate and relatively low amounts of visible shale. Red volcanic at 33'. Fractured in places. Platy structure and browner matrix below 36.5'.	2.5Y 3/1; 2.5Y 3/1		LF02/09 30.5-31; LF02/10 33.5-34	
nva	35, 36, 37, 38			2.5Y 4/2		LF02/11 38-38.5; 38.5-39	Subglacial till, Riding Mountain-Winnipeg provenance; variable mixing with Rainy provenance materials.
nva	39, 40, 41, 42, 43, 44		39.3-48.5: Compact, dark grey, massive, matrix-supported diamicton. Loam to sandy loam matrix with granular structure. Fractured throughout, especially 41.4-43.5'; may be due to exhumation and/or core splitting, except 46' where fine brown sand infills voids. Many very fine to fine gravel-sized carbonate clasts throughout. Most larger clasts are subrounded felsic igneous lithologies (e.g., pink granite @ 45'). Shale present but appears less frequently with depth. Several red lithologies pulled from core (e.g., purple basalt @ 40').	2.5Y 3/1		LF02/12 42-42.5; 43.5-44	
nva							

Cl Si S G C D

*Effervescent *Non-effervescent **Texture **Porewater

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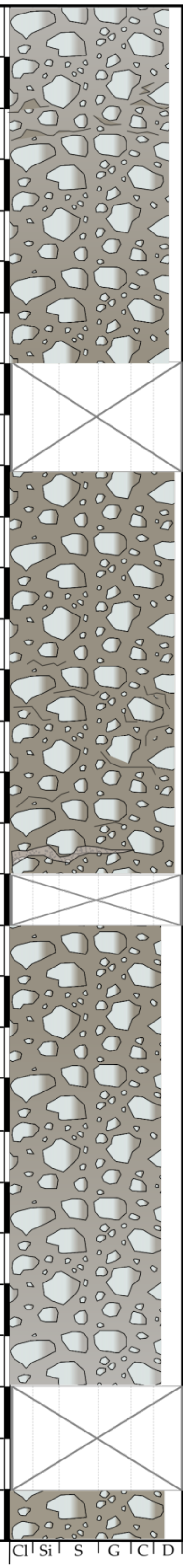
CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Depth (f): 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59



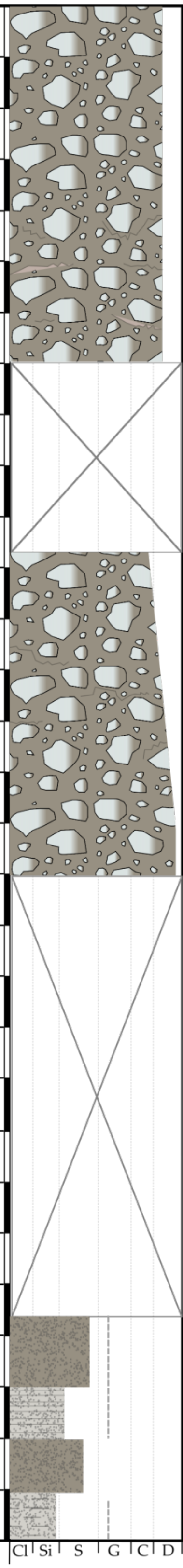
Unit	Description	Colour	HCl*	Sample**	Notes
nvt		2.5Y 3/1		LF02/13 46.5-47	
				48.5-49	
nvt	49.6-53.5: Similar diamicton as 39.3'+, but slightly browner and finer-grained loam matrix texture. More dense than above. High fracture density from 51.5-53.5'. Large greywacke clast (3" a-axis) @ 52'. Sub-horizontal stringer of light brown-grey very fine sand @ 53.5'.	5Y 3/1		LF02/14 50-50.5; 53.5-54	Subglacial till, Riding Mountain-Winnipeg provenance.
nvt	54-61.5: Similar diamicton as 49.6'+. Less fractured. Dominance of felsic igneous and carbonate lithologies, some shale. Lignite @ 55.5'. Becomes browner and matrix is siltier @ 59.5'.	2.5Y 3/1; 2.5Y 3/1		LF02/15 54-54.5; LF02/16 58-58.5; 58.5-59	
nvt					

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nvt	61–63		61.5-65.3: Grey-brown, overconsolidated, massive, matrix-supported diamicton. Loam matrix. Many carbonates, felsic and mafic igneous lithologies, some shale. Most clasts subangular to subrounded. Fractured throughout, some with rusy skins.	2.5Y 3/1	Effervescent	LF02/17 61-61.5 (Texture)	
	64					63.5-64 (Porewater)	
	65		65.3-65.5: Lag of coarse sand, mixed with diamicton. Possibly drilling-induced.	2.5Y 3/2		LF02/18 65-65.5 (Texture)	
nvt	66–68		65.5-73: Similar diamicton as 61.5'+. Matrix coarsens with depth to sandy loam and becomes more compact. No obvious change in lithological assemblage, but becomes slightly greyer/less brown. Fewer fractures towards base.	2.5Y 3/1	Effervescent	LF02/19 68-68.5 (Texture); 68.5-69 (Porewater)	Subglacial till, Riding Mountain-Winnipeg provenance.
	69–72						
ng	73–74		73-75: Inversely graded sequence; very poorly sorted brown loamy coarse sand and very fine to fine gravel, grading to faintly stratified grey fine sand with occasional very fine to fine gravel, over sharp transition to brown, well sorted medium sand, over scoured contact to grey very fine sand and silt with occasional very fine to fine gravel.	2.5Y 4/2 (v.f. sand)	Effervescent	LF02/20 73-73.25 (Texture)	



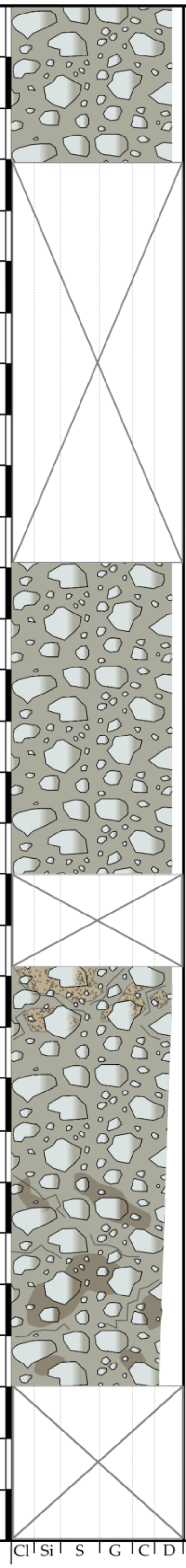
*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
nva	76		2.5Y 3/1		LF02/21 75.5-76	
	77–80	75-83.5: Massive, grey-brown matrix-supported diamicton. Very compact. Loam matrix. Very similar to 49.6'+.				
nva	81–83		2.5Y 3/1		LF02/22 80.5-81.5	Subglacial till, Riding Mountain-Winnipeg provenance.
	84				83.5-84	
nvt	85–88	84.4-84.7: Light brown fine to medium sand coating fragments of diamict; could be related to drilling issues and barrel removal at this depth.	2.5Y 3/2		LF02/23 84.5-85	
		84.7-88.5: Similar diamicton as 75'+. Matrix fines downwards and becomes browner in places. Fissile, platy breakage structure around 85'. Several angular clasts, though these are mostly shale. Otherwise lithologically similar to above. Higher fracture density from 86.5-88.5'. Lignite @ 87'. Mixed with light brown very fine sand from 91.5-92' - possibly dried slurry from top of barrel.	2.5Y 3/1		LF02/24 88-88.5	
	89				88.5-89	

Lithology:

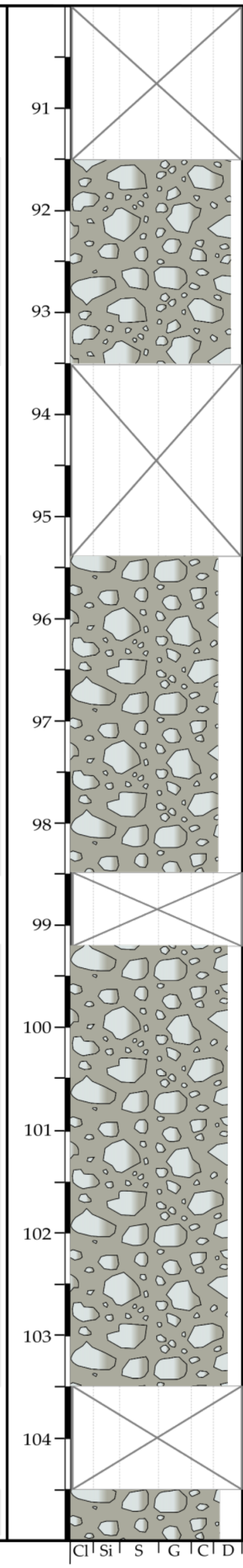


*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
nvt	92–93.5	92-93.5: Similar diamicton as 84.7+'.	2.5Y 3/1	Effervescent	LF02/25 93-93.5; 93.5-94	
nvt	95.4–98.5		2.5Y 3/1	Effervescent	LF02/26 97.5-98; 98.5-99	Subglacial till, Riding Mountain-Winnipeg provenance.
nvt	99.2–103.5	95.4-106.5: Grey, massive, matrix-supported diamicton. Overconsolidated. Variably-textured loam matrix, finer-grained below 104.2'. Granular breakage structure. Frequent very fine to fine gravel-sized carbonate clasts; fewer large clasts. Most clasts subangular to subrounded. Some carbonates have a rusty coating. Some shale present. Possibly less felsic igneous lithologies than above. Sandy lens @ 103'. More fissile from 102.5-103'.	2.5Y 3/1	Effervescent	LF02/27 102-102.5; 103.5-104	
nvt	104.5–			Effervescent		

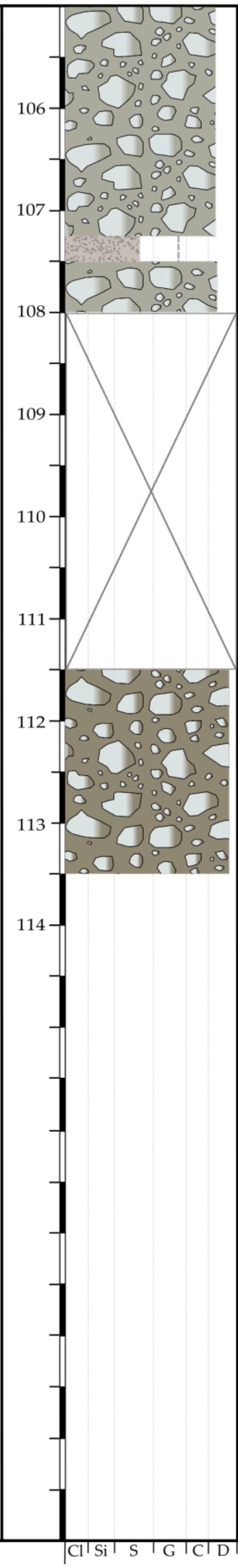


*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nvt	106–108		106.5-107.5: Similar diamicton as 95.4'+, with loam matrix. Large disintegrated grey shale clast @ 107'. Very poorly sorted, light brown, carbonate-rich fine to coarse sand and very fine to medium subangular gravels from 107.25-107.5'. Some red volcanics present.	2.5Y 3/1; 2.5Y 5/2	Effervescent	LF02/28 106-106.5; LF02/29 107.25-107.5; 108.5-109	Subglacial till, Riding Mountain-Winnipeg provenance.
	108–111		107.5-113.5: Similar diamicton as 95.4'+, but with noticeably coarser and browner matrix. A couple of large (2"+) clasts present. Predominantly carbonate lithologies. Shale present.				
nva	111.5–113.5			5Y 3/1	Effervescent	LF02/30 112-112.5	

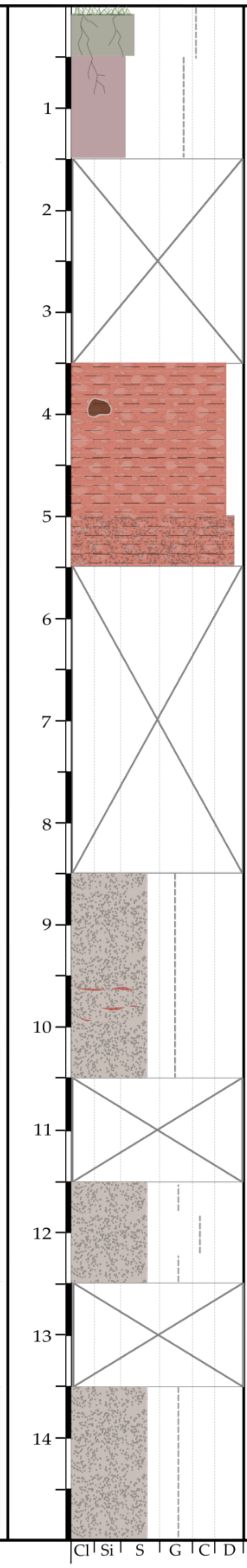


*Effervescent *Non-effervescent **Texture **Porewater

CW02 – Graphical log

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
Qat	0-1.5	0-0.5: Topsoil; brown loam with occasional angular gravels. Roots penetrate to ~0.7'. 0.5-1.5: Reddish-brown soil modified silt loam with fine gravels and occasional up to medium gravels.	7.5 YR 4/4		CW02/01 1-1.5	Soil A horizon.
Qat	3.5-5.5	3.5-5.5: Vaguely-stratified oxidized reddish-brown to orange-brown silt loam diamicton, becomes sandier below 5 ft. 1" diameter dark brown clay ball inclusion @ 4'. Occasional very coarse sand to fine gravels strewn throughout. Several cobble-sized angular clasts @ 4.5'. Colour change to olive brown @ 5.25'.	5 YR 4/4		CW02/02 4-4.5	Subglacial till, Mixed Superior-Winnipeg provenance.
Qco	8.5-12.5	8.5-12.5: Poorly sorted, tan to light brown massive sand and gravel. Predominantly medium sand, but ranging from fine to very coarse. Fine to medium subrounded gravels; felsic, mafic and red volcanics, and metasedimentary lithologies. Some rusted cemented layering below 9.5'. Occasional very coarse gravels to fine cobbles, some rounded to well-rounded. Becomes cobbly/gravelly @ 12', then better sorted medium to very coarse sand below, though sands are very loose and likely experienced mixing and/or settling in core liner.	10 YR 4/4		CW02/03 8.5-10.5	Proglacial outwash, Superior provenance.
Qco	13.5-15.5	13.5-15.5: Fine tan to brown sand with lesser medium to very coarse sand and occasional subrounded to rounded gravels. Varied lithologies, some iron fm., vesicular basalt. Sand becomes mostly coarse to very coarse @ 15'.				

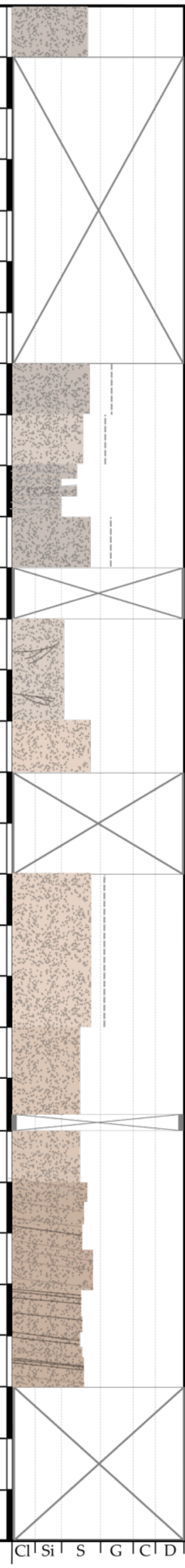
*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Colour	HCl*	Sample**	Notes
Qco	15–15.5	10 YR 4/4	Non-effervescent	CW02/04 15-15.5	
Qco	18.5–20.5	10 YR 3/4 (c. sand)	Non-effervescent	CW02/05 19-19.5	
Qco	21–22.5	10 YR 5/3	Non-effervescent	CW02/06 22-22.5	Proglacial outwash, Superior provenance.
Qco	23.5–26		Non-effervescent		
Qco	26–28.5		Non-effervescent	CW02/07 27-27.5	

Depth (f): 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29



Description

18.5-19: Vaguely stratified dark brown medium sand. Moderately well-sorted, but with coarse to very coarse sand and occasional fine gravel. 1 or 2 coarse subrounded gravels. Predominantly clear quartz, other felsics igneous, some reds in sand fraction.

19-19.5: Poorly-sorted fine to very coarse sand and fine to medium gravel. Lighter in overall colour than above, but more visible mafic component. Low recovery.

19.5-20.5: Brown medium sand with occasional subhorizontal bedding with brown, well-sorted very fine sand, grading into very poorly-sorted fine to very coarse sand and fine to medium subangular to subrounded gravel below 20'. Rich in darks, reds.

21-22: Very well-sorted light brown fine sand with occasional black ripples.

22-22.5: Sharp upper contact; lighter brown to tan medium to coarse sand. Moderately well-sorted. Massive.

23.5-25: Very poorly-sorted fine to very coarse sand and gravel. Dominated by coarse to very coarse sand and fine gravel. Poor recovery.

25-26.5: Well sorted, massive, brown medium sand. Increase in clear quartz from above.

26.5-28.5: Stratified brown sand. Beds vary from medium to very coarse sand, and 3" to <0.5" in thickness. Frequent dark black layers of fine sand. Apparent ~10 degree dip but could be drilling induced.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

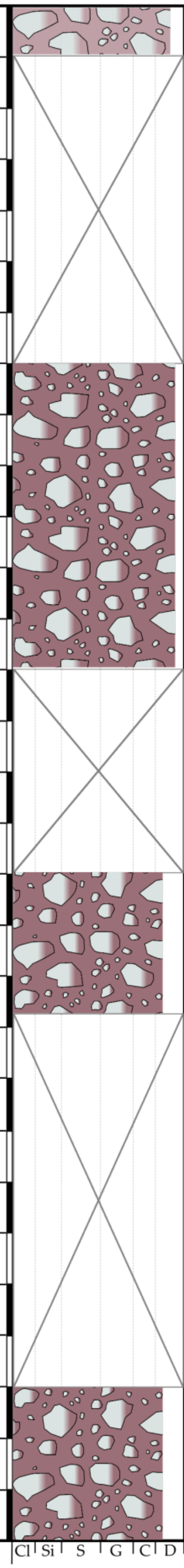
Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct	43.5-44.5	Cl Si S G C D	43.5-44.5: Massive, purplish-red, faintly stratified, matrix-supported diamicton. Sandy loam matrix. Granular breakage structure. Stratified black residue present beneath weathered mafics. Several large (2"-3") subangular and subrounded mafics.	5 YR 4/2	Effervescent	CW02/08 44-44.5	Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct	46, 47, 48						
Qct	49, 50, 51		44.5-60.5: Reddish-brown, relatively compact, massive, matrix-supported diamicton. Sandy loam matrix, granular structure. Moderately clast-rich; subangular to subrounded fine to very coarse gravels. Many metasedimentary lithologies including slate and greywacke. Lesser red volcanic component. Rare to absent light felsic igneous component. Apparent well-developed clast macrofabrics in places. Matrix texture is slightly finer grained from 44.5-45.5'. Silt siltier from 53.5-54' and 58.5-60.5'. Fewer large clasts, more felsic igneous and more rounded clasts below 58.5'.	7.5 YR 3/2		CW02/09 48.5-50	Subglacial till, Superior provenance.
	52, 53						
Qct	54			7.5 YR 3/2		CW02/10 54-54.5	
	55, 56, 57, 58						
Qct	59						



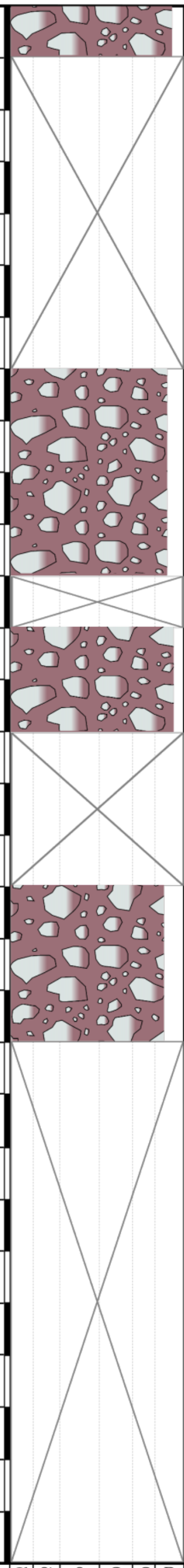
*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
Qct	60-60.5			Effervescent		
Qct	63.5-65.5	63.5-70: Similar diamicton as 44.5'+, but with more variable matrix texture and more clast-rich. Clasts are mostly subrounded fine to medium gravel-sized felsic igneous, dark metasedimentary and red volcanic lithologies. Lignite @ 67'. Very moist and sandy from 63.5-64'. More compact below 64'.	7.5 YR 3/2	Effervescent	CW02/11 63.5-64; 65.5-66	Subglacial till, Superior provenance.
Qct	66-67		7.5 YR 3/2	Effervescent	CW02/12 66.5-67; 67-67.5	
Qct	68.5-70			Effervescent		

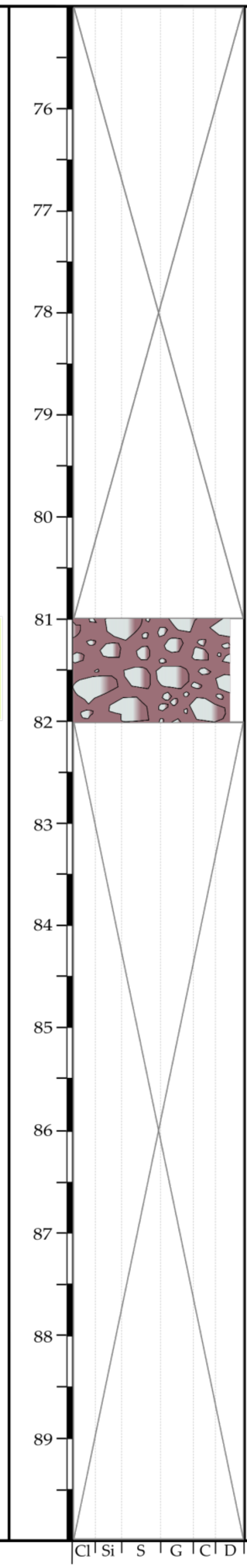
Depth scale: 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74



*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

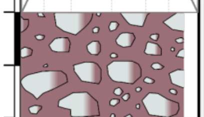


Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct	81-82		81-82: Similar to 63.5+. Reddish-brown to reddish-grey, massive, matrix-supported diamicton. Sandy loam matrix. Relatively clast-poor in this interval. Similar lithological assemblage as above.	7.5 YR 3/2		CW02/13 81.5-82	Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

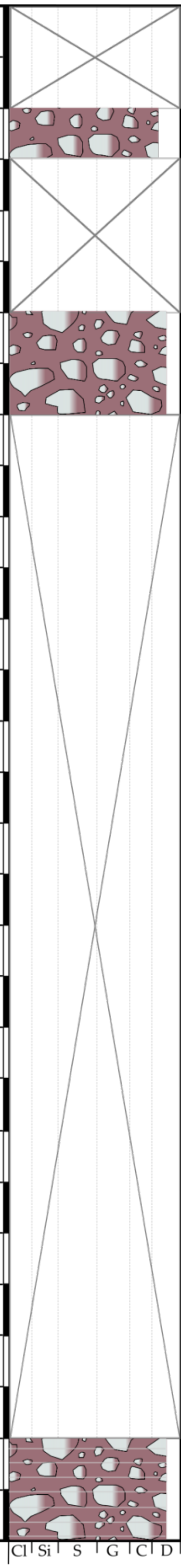
Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
	91						
	92						
	93						
Qct	94		93.5-94.5: Similar to 81'+. Matrix has slightly redder hue and siltier texture. Very coarse gravel-sized broken-up slate clast @ 94.5'.	7.5 YR 3/2		CW02/14 94-94.5	Subglacial till, Superior provenance.
	95						
	96						
	97						
	98						
	99						
	100						
	101						
	102						
	103						
	104						

Cl Si S G C D

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Depth (f)	Description	Colour	HCl*	Sample**	Notes
Qct	106–106.5	106-106.5: Reddish-brown to reddish-grey, massive, matrix-supported diamicton. Sandy loam matrix. Coarse gravel-sized (3" a-axis) well-rounded metasedimentary clasts @ 106'. Same lithological assemblage as above (red volcanics and metasedimentary rocks dominant). Slightly redder matrix hue than above.	7.5 YR 3/2	Effervescent	CW02/15 106-106.5; 106.5-107	Subglacial till, Superior provenance.
Qct	108–109	108-109: Similar diamicton as 106'+ with slightly sandier matrix. Retains red hue.	7.5 YR 3/2	Effervescent	CW02/16 108.5-109	
Qct	119–120	119-120: Similar diamicton as 108'+, but very faintly stratified. Apparent well-developed clast macrofabrics ~ parallel to sense of stratification.	7.5 YR 3/2	Effervescent	CW02/17 119.5-120; 120-120.5	Subglacial till, Superior provenance.

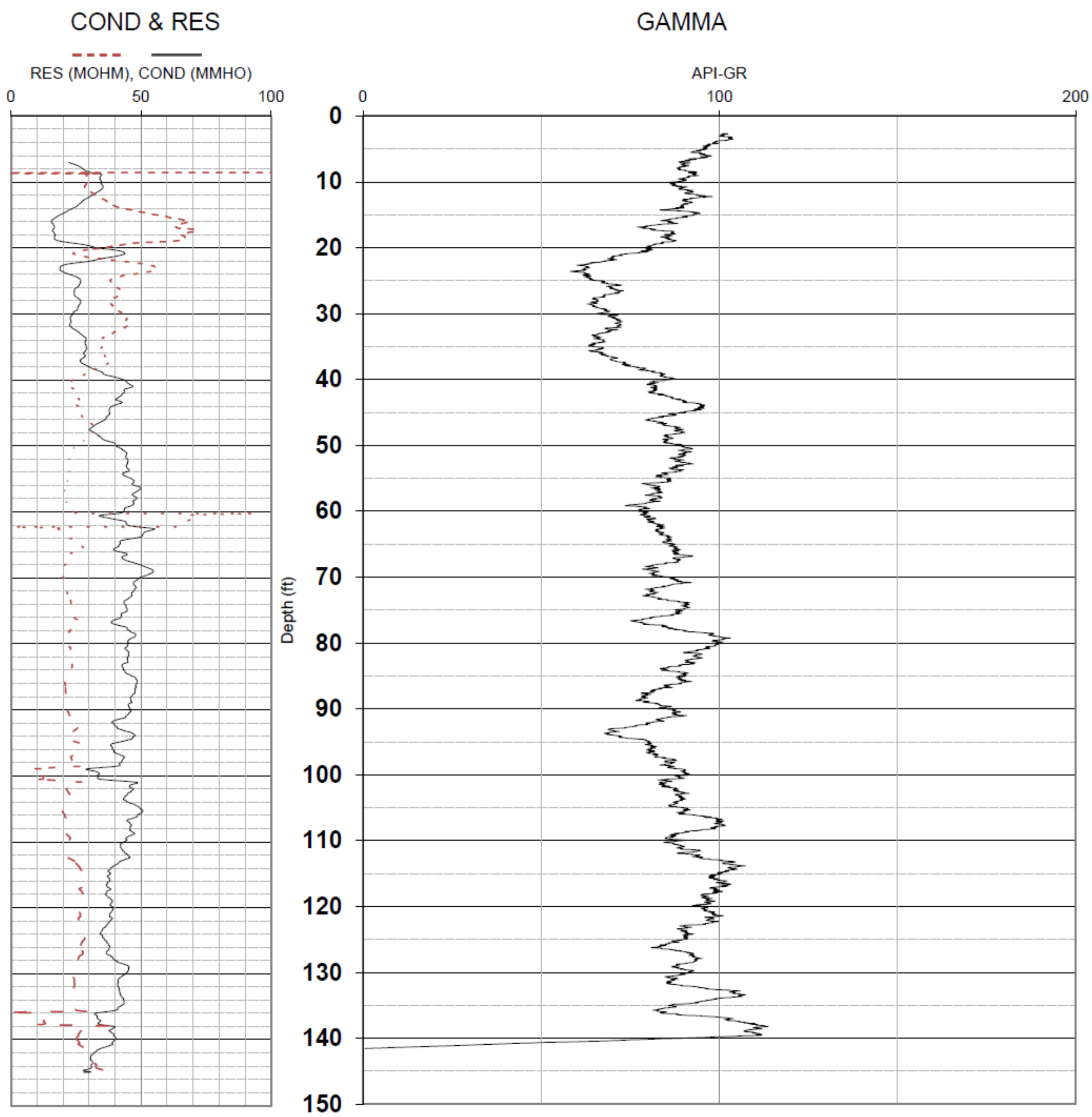
*Effervescent *Non-effervescent **Texture **Porewater

Appendix B – Borehole geophysical logs

EM Induction Log – CWO1A

Unique Number: **CW01A_em_induction.xlsx**

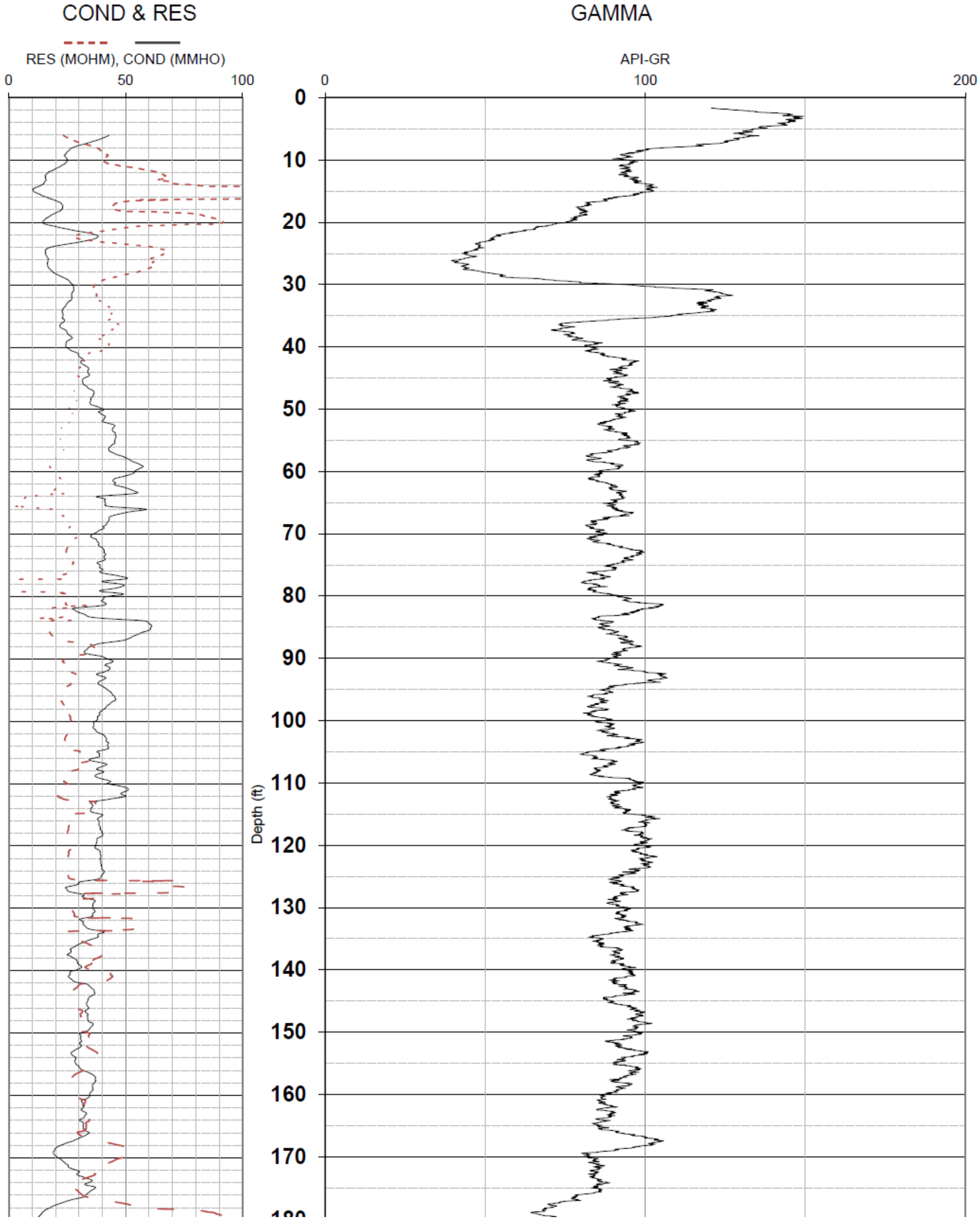
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

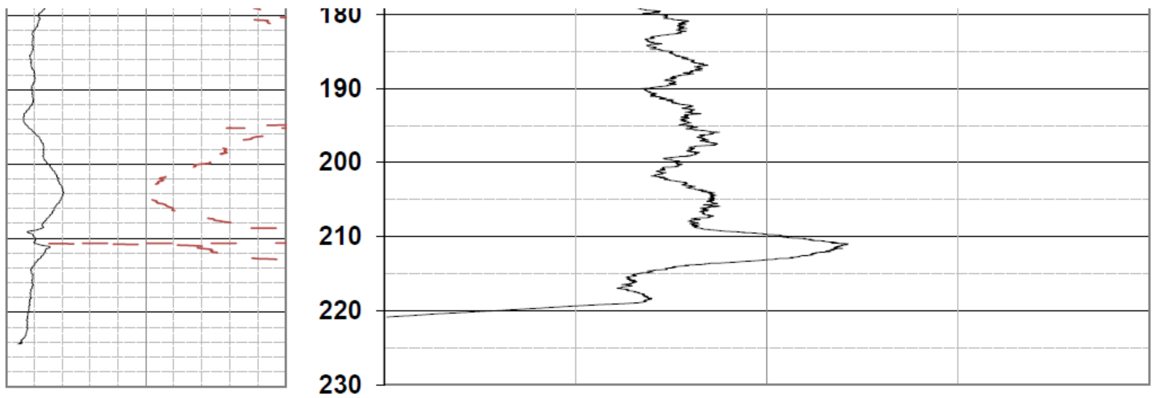


EM Induction Log – CWO1B

Unique Number: **CW01B_em_induction.xlsx**

Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

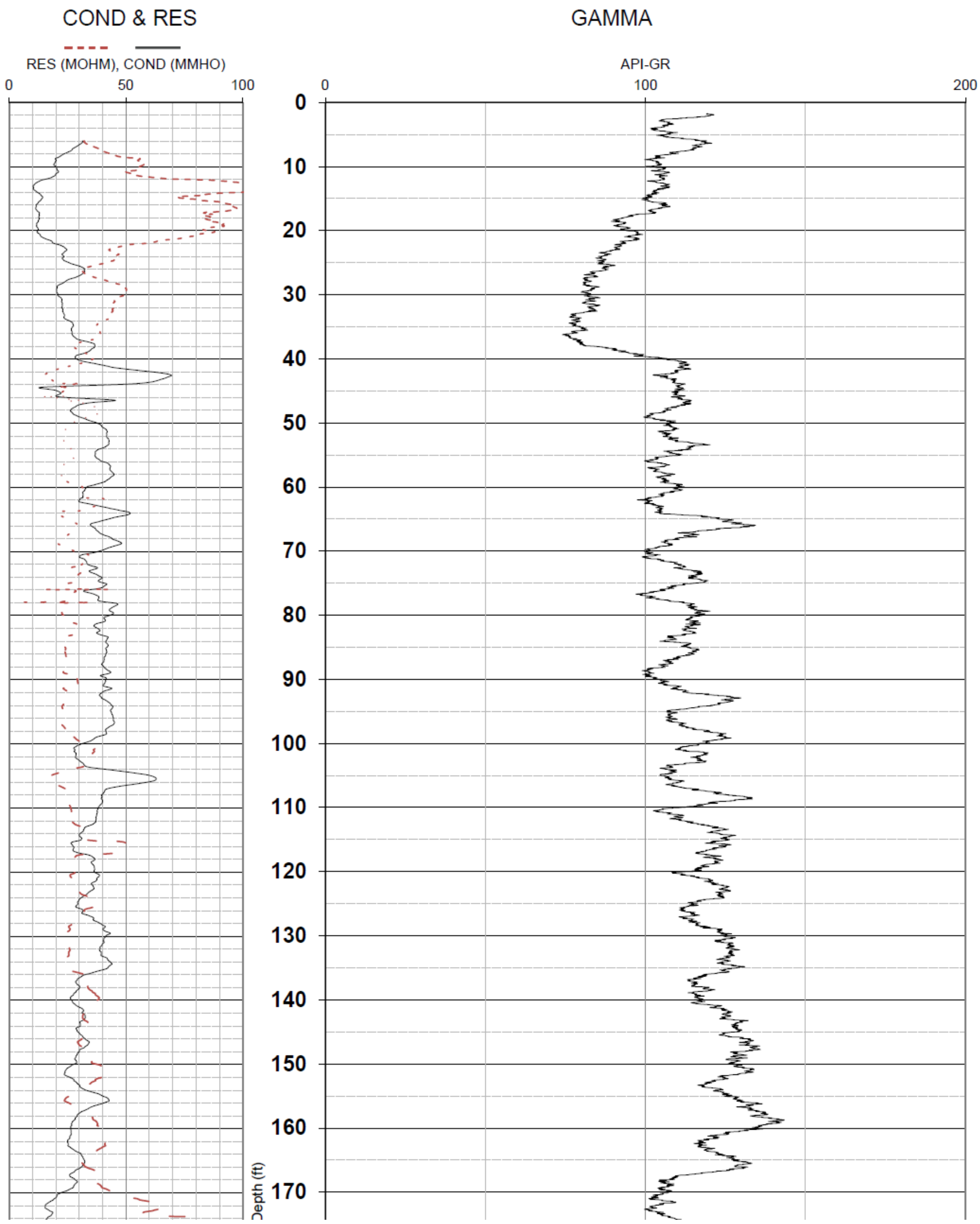


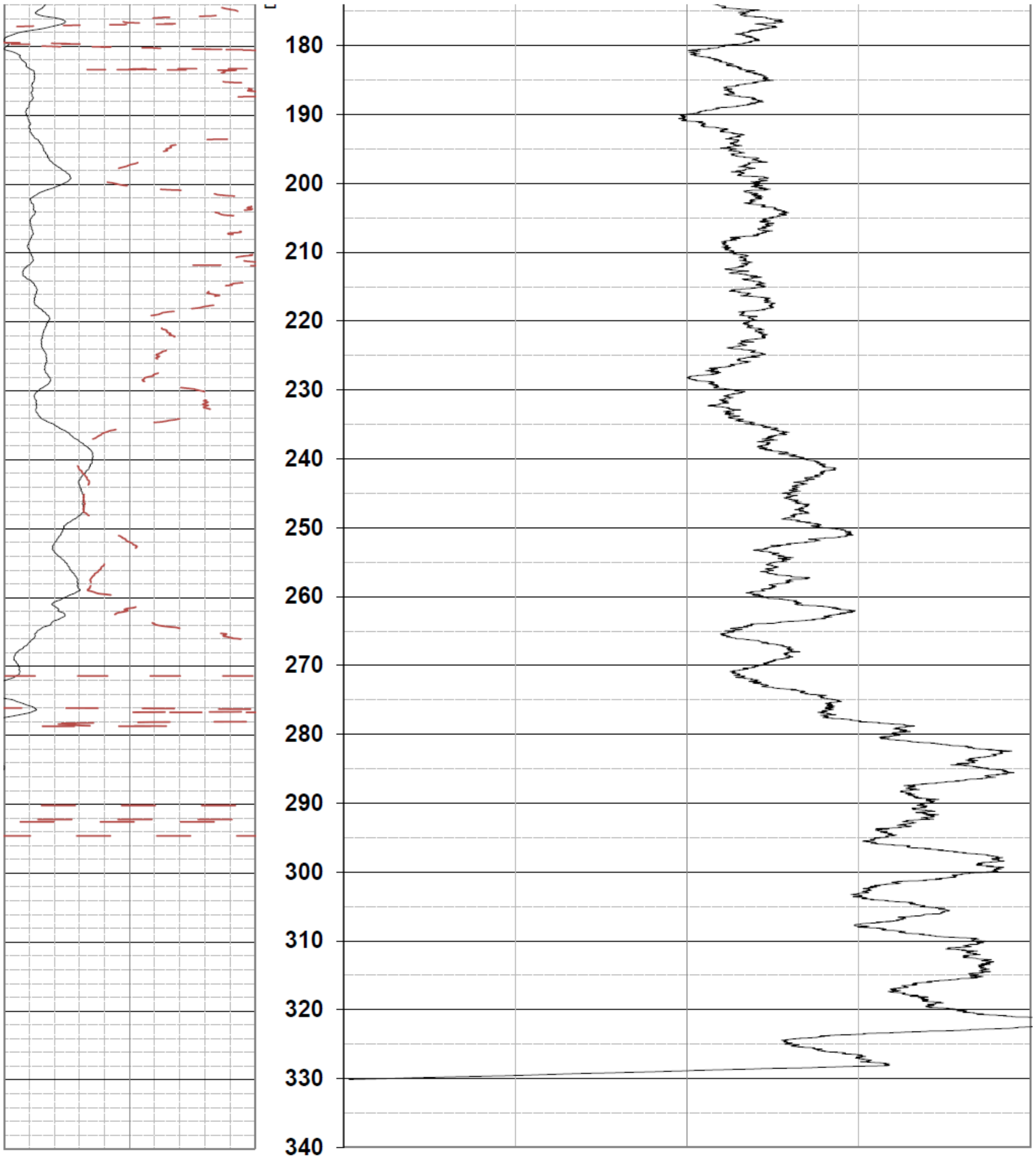

180
190
200
210
220
230

EM Induction Log – CWO1C

Unique Number: **CW01C_em_induction.xlsx**

Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

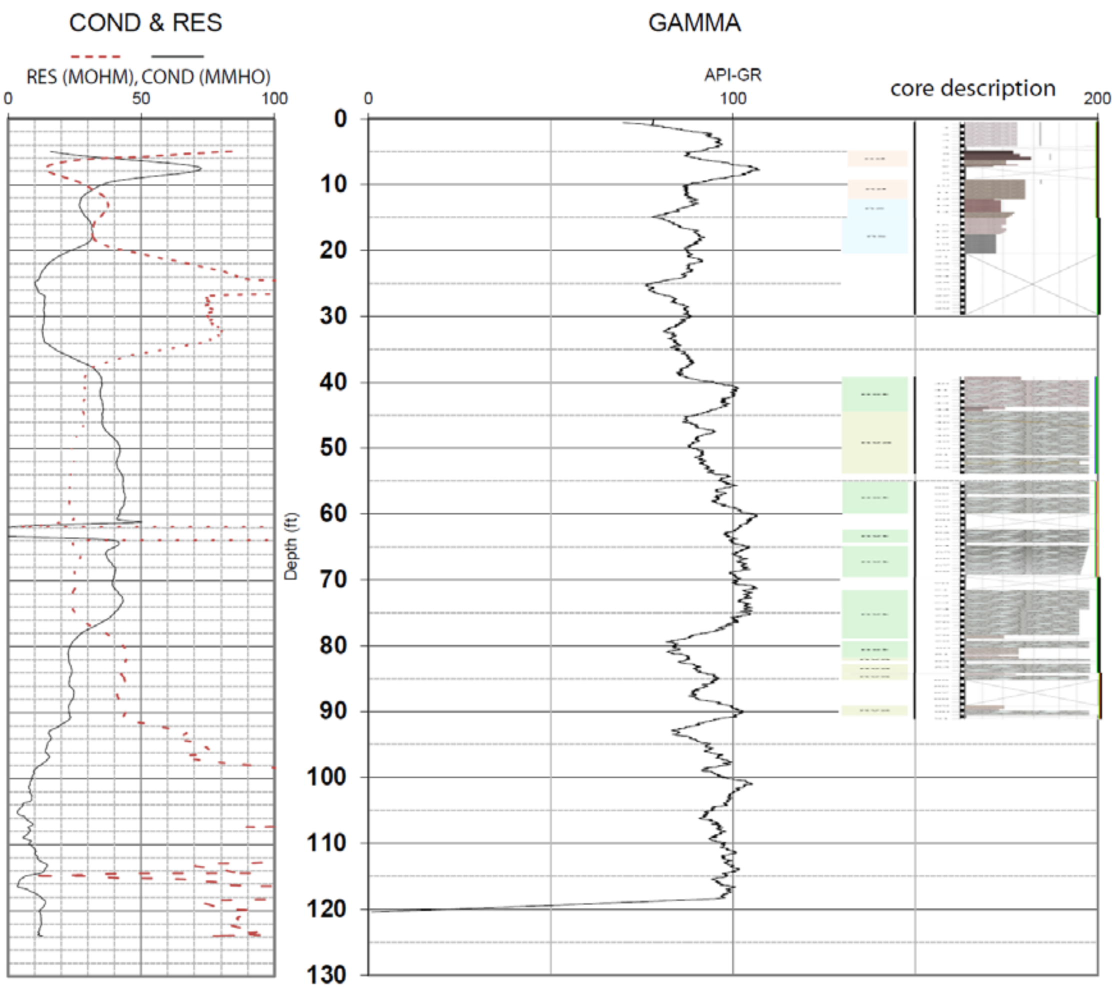



180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340

EM Induction Log with core description (see Appendix A) – LFO1F

Unique Number: **LFO1F_em_induction.xlsx**

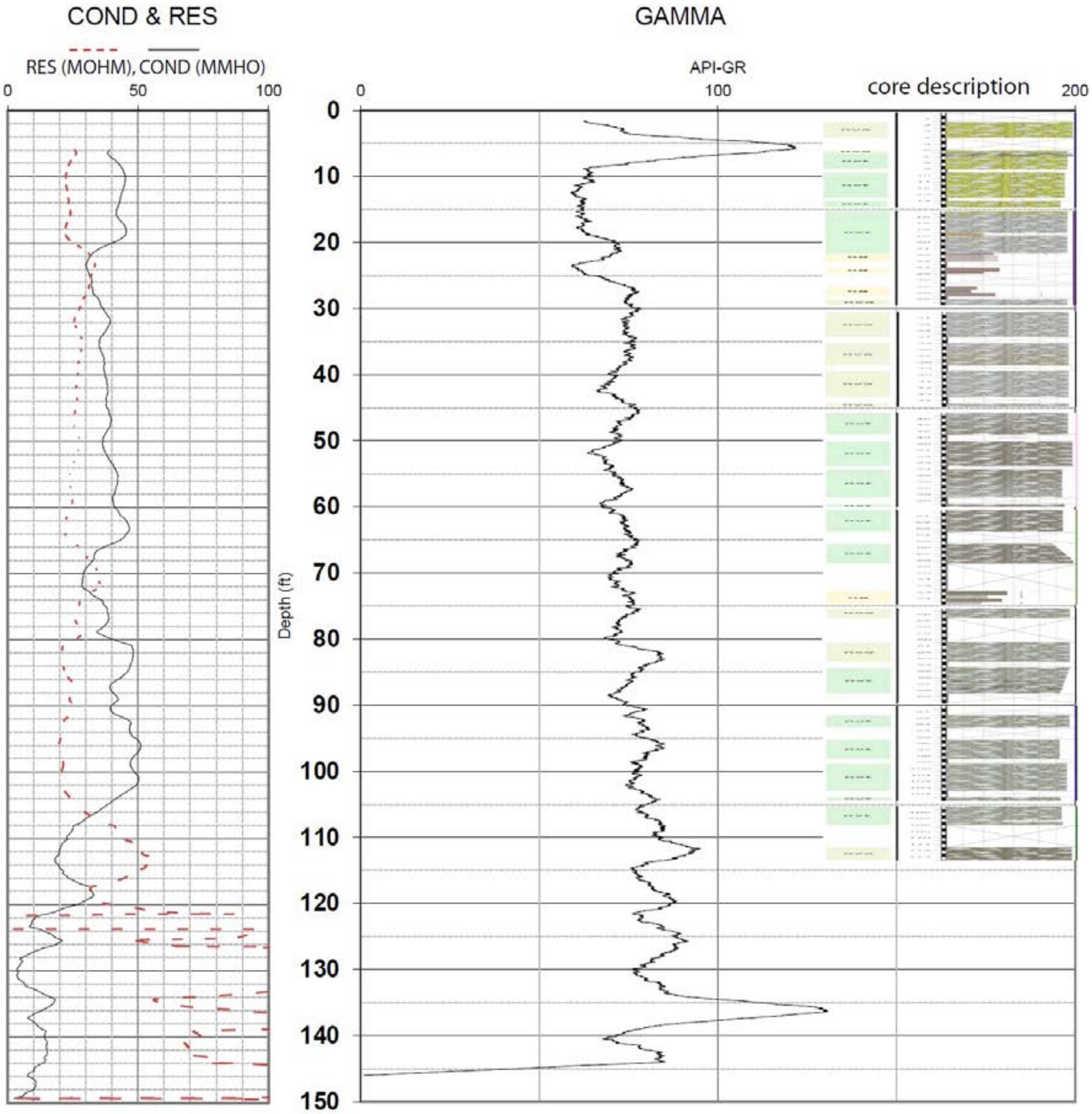
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969



EM Induction Log with core description (see Appendix A) – LFO2F, first run

Unique Number: **LFO2F_em_induction.xlsx**

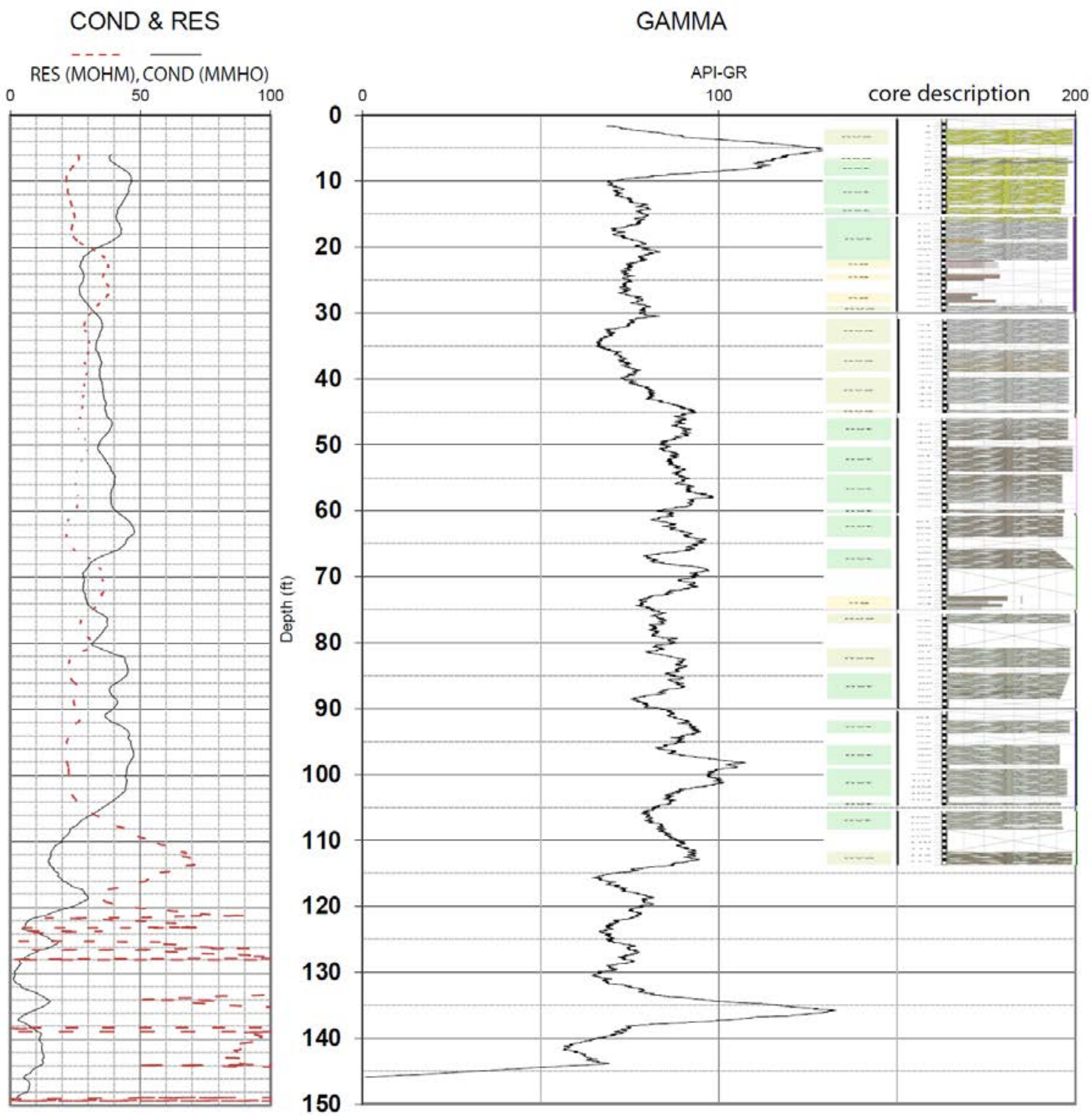
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969



EM Induction Log with core description (see Appendix A) – LFO2F, second run

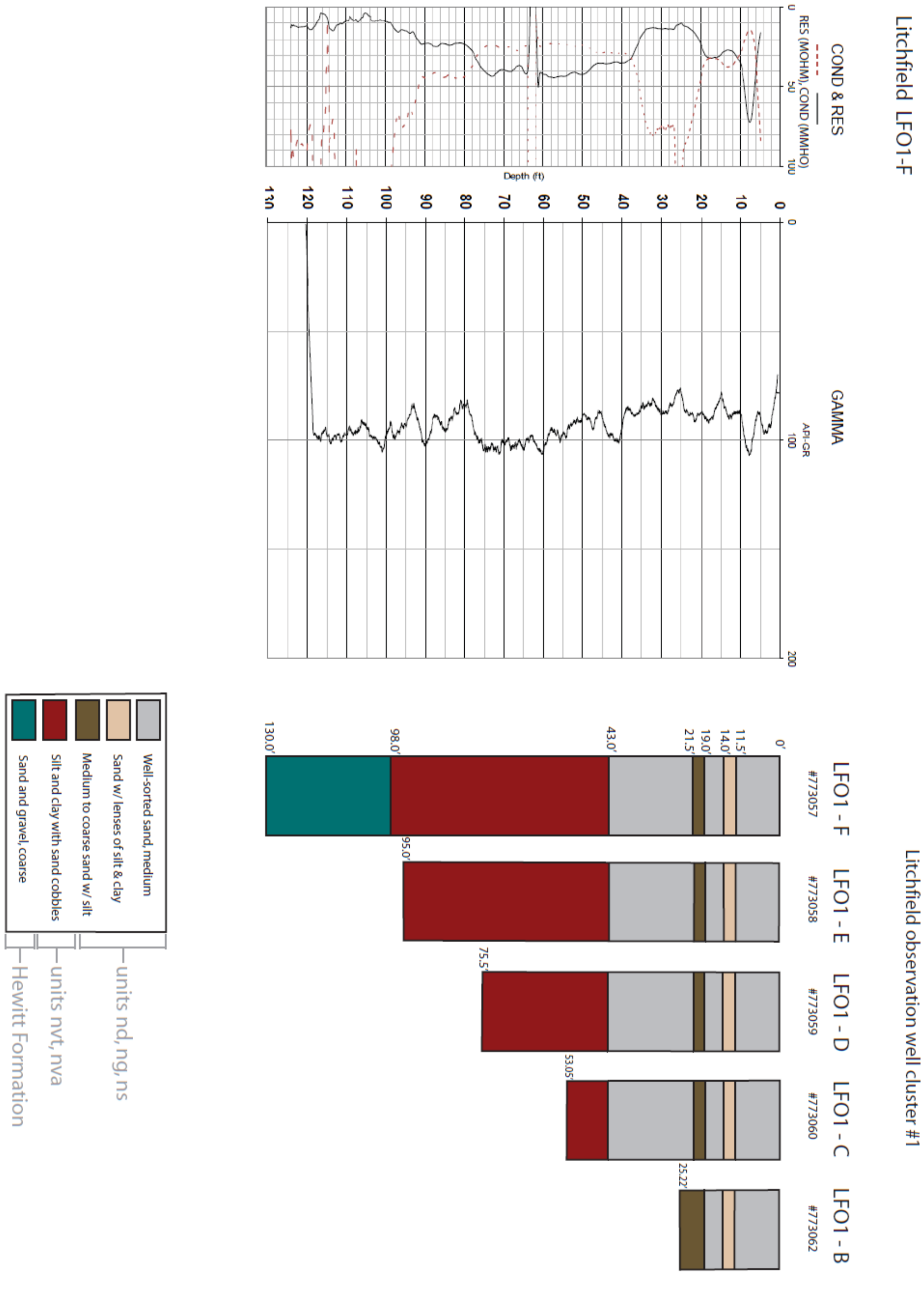
Unique Number: **LFO2F_em2_induction.xlsx**

Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

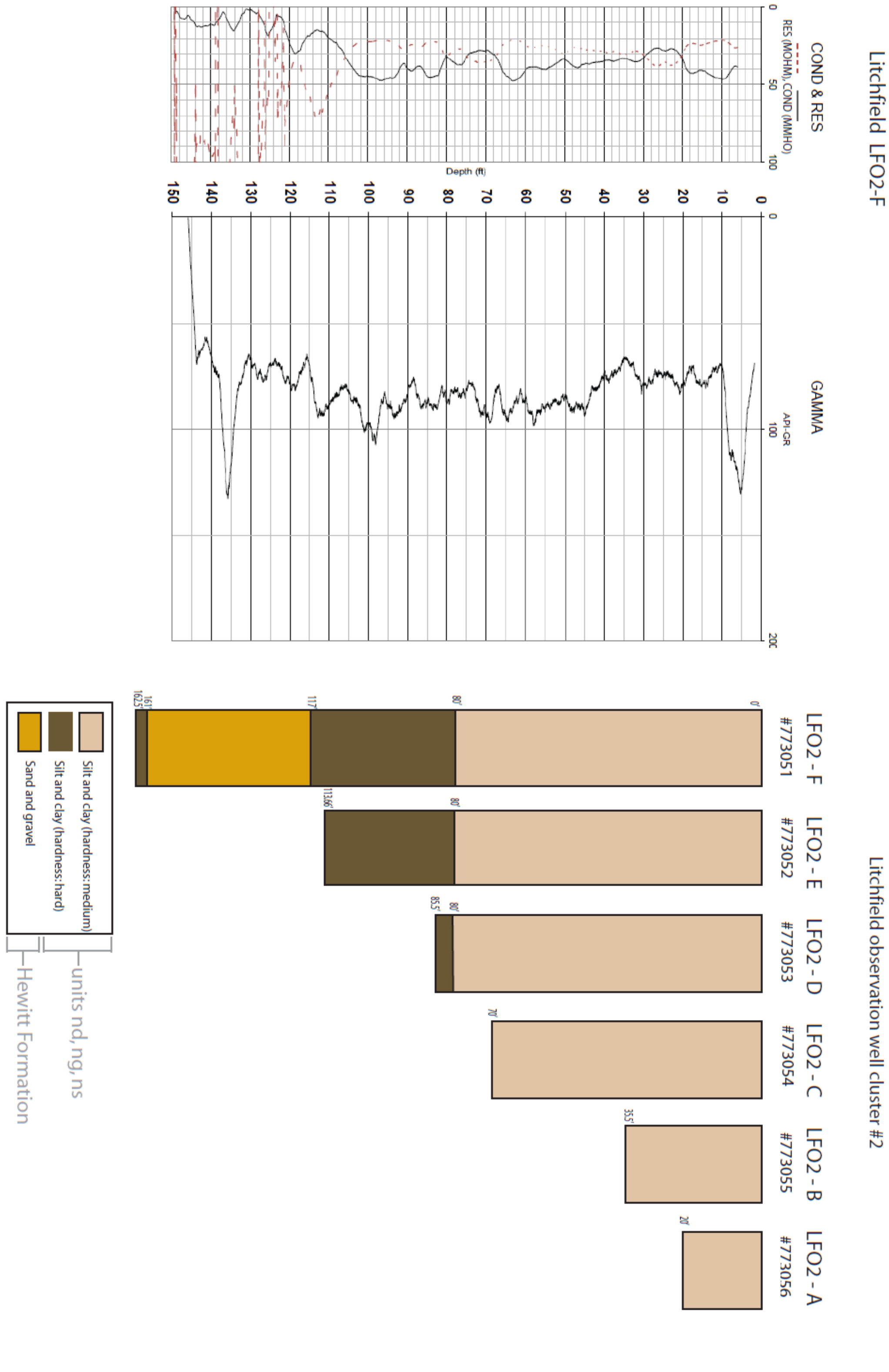


Appendix C – Generalized borehole lithostratigraphy and borehole geophysical logs

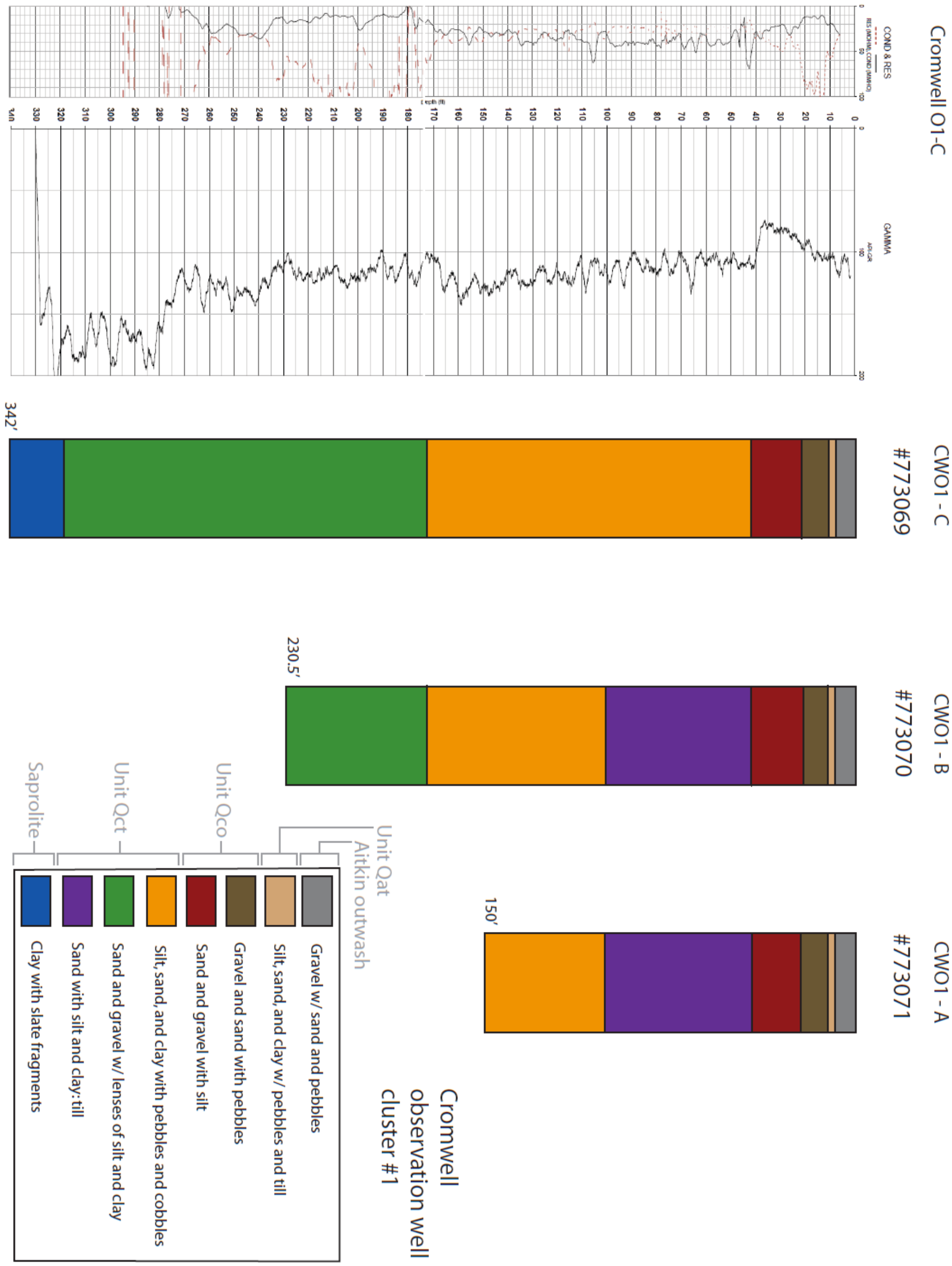
Litchfield observation well cluster 1



Litchfield observation well cluster 2



Cromwell observation well cluster 1



Cromwell observation well cluster 2 (EM-induction log from cluster 1, CWO1-A)