DEPARTMENT OF NATURAL RESOURCES

Ecological and Water Resources - Groundwater Technical Analysis

Aquifer Test Report

Date:	May 22, 2020
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Subject:	**Tim Nolte Aquifer Test: Permits 2017-4235, 2017-4236, 2017-4237**
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I hereby certify that this plan, document, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the laws of the state of Minnesota.

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Executive summary

An aquifer test was conducted for appropriation permit applications 2017-4235 (NW Irrigation well), 2017-4236 (Production well), and 2017-4237 (East Irrigation well) to evaluate the effects of high capacity pumping on nearby domestic wells, water resources and the area aquifers. The test highlights include:

- All three irrigation wells are completed in leaky confined aquifers affected by no-flow boundary conditions. The wells are capable of providing the requested rate and volume listed in the permit applications.
- Several nearby domestic wells are at high risk for well interference when the irrigation wells are pumped singularly or all at the same time.

- The effect of pumping the Northwest Irrigation well on the nearby surface water bodies cannot be evaluated at this time.
- The following is recommended:
    - Aquifer thresholds should be established for the Deep Observation well (841474) and the threshold formalized as a condition for both the Production and East Irrigation well permits (2017-4236 and 2017-4327 respectively).
    - The Deep Observation well should be monitored using a data logger. This monitoring should be formalized as a monitoring condition for permits 2017-4236 and 2017-4237.
    - The proposed irrigation wells should alternate pumping (wells should not pump at the same time) to mitigate risk to nearby domestic wells. If wells are allowed to pump at the same time, resulting in cumulative pumping impacts, several domestic wells will need to be replaced to avoid an out-of-water well interference.
    - Pump intakes should be lowered in the following domestic wells at risk from single production well pumping:
        - Nolte (714382)
        - Roggenkamf (552894)
        - Pickar (123614)
        - Rucks (727163)
    - Well construction information for eleven domestic wells without information should be collected by the permittee and provided to DNR. If information is unobtainable, then the well owners should be provided with information describing the well interference process and how to report an out-of-water well interference.
    - The August mean base flow analysis for the Redeye River should be requested from the DNR Water Monitoring and Surveys Unit. The impacts to the Redeye River from pumping the proposed irrigation wells can then be evaluated more completely.
    - An aquifer test or use-season test, designed by DNR, should be completed on the Northwest Irrigation well. The results from this test can be used to evaluate pumping impacts on nearby wetlands and the river and to verify the risk to domestic wells.
    - Monitoring of the Deep (841474) and Shallow (841475) Observation wells near the Production well (805421) should be conducted by the permittee following a DNR monitoring plan.
    - The rates and volumes pumped from all the proposed irrigation wells should be recorded for each irrigation cycle along with the exact pump on and off time for the first season. The data will be evaluated along with the monitoring information to validate the aquifer test findings and need for further monitoring.

Introduction

In December of 2017, Mr. Nolte (applicant) submitted three permit applications for wells (Table 1) to irrigate 303 acres of land (Figure 1). In May 2018, a petition requesting an Environmental Assessment Worksheet (EAW) be developed was forwarded to the MN Department of Natural Resources (DNR). The EAW was to address land conversion and chemical applications associated with Mr. Nolte's applications in and around the Pineland Sands area. DNR is developing an EAW to address these issues. A determination was made in January 2020 that an aquifer test would not be required as part of the EAW information requirements, however, the DNR's Ecological and Water Resources Groundwater Technical Unit recommended that the aquifer test requirement not be waived for the permit applications.

Table 1. Permit application information

Unique Well no.	Well Name	Application no.	Requested Pumping rate (gpm)	Requested Volume (million gallons per year)	Irrigated Acreage
805420	NW Irrigation Well	2017-4235	450	21.2	65
805422	East Irrigation Well	2017-4237	800	45	138
805421	Production Well	2017-4236	700	32.6	100

In January 2020, the applicant and his agent (Northwest AqwaTek Solutions-NWATS) requested that DNR provide aquifer test specifications in order to complete the aquifer test requirements for the three permit applications. The Pre-aquifer Test Specifications (Step 1 specifications) were provided to the applicant and his agent on January 28, 2020 (Yourd, 2020a). The applicant's agent (NWATS) supplied the information from the Step 1 specifications through a series of emails from March 3, 2020 through March 16, 2020. DNR developed the aquifer test design (Step 2 specifications) based on the submitted information, and sent the design to the applicant and his agent on March 18, 2020 (Yourd, 2020b). The aquifer test design instructed the applicant/agent to pump from the irrigation well associated with permit 2017-4235 (Unique Well 805421) at 800 gallons per minute (gpm) for a minimum of 4 days and up to 7 days and monitor the other two irrigation wells and several other wells in the area (Figure 1-Monitored Wells). The aquifer test monitoring was completed according to DNR specifications on 4/10/2020. Table 2 contains the list of wells monitored during the aquifer test along with their construction information. The Minnesota Permitting and Reporting System (MPARS, 2020) contains all well logs, emails, and information submitted for this aquifer test.

The purpose of this report is to present DNR's analysis and conclusions from the aquifer test and provide recommendations for permit decision makers.

Table 2: Monitored Wells

Well name	Unique well number	UTM Easting (m-NAD83 zone 15N)	UTM Northing (m-NAD83 zone 15N)	Ground Elevation (ft NAVD88)	Measuring Point (MP) Elevation (ft NAVD88)	Well Depth (ft below land surface-bLS)	Screened Interval (ft bLS)	Screen Elevation Top (ft NAVD88)	Well Depth Elevation (ft NAVD88)	Well Diameter (in)	Static Water Level (ft bMP*) (3/9/20)	Static Water Elevation (ft NAVD88)	Interpreted Aquifer
NW Irrigation Well	805420	348455.0152	5164837.638	1347.34	1349.04	140	105-140	1242.34	1207.34	12	2.77	1346.27	Browerville Sands 2 Aquifer
Caponera Well	728573	347425.7871	5162597.862	1367.87	1369.49	201	197-201	1170.87	1166.87	4	16.21	1353.28	Deep Browerville Sands 3 Aquifer
Eckenrude Well	421530	349008.6745	5162769.308	1344.53	1346.73	48	44-48	1300.53	1296.53	4	13.45	1333.28	Shallow confined Hewitt Sands 2 (Hsa2)
East Irrigation Well	805422	350464.5024	5163117.278	1337.73	1339.97	155	135-155	1202.73	1182.73	12	1.13	1338.84	Browerville Sands 3 Aquifer
Production Well	805421	349596.249	5163051.134	1343.05	1344.84	157	137-157	1206.05	1186.05	12	6.81	1338.03	Browerville Sands 3 Aquifer
Shallow Observation Well	841475	349535.3595	5163043.332	1340.66	1342.76	55	45-55	1295.66	1285.66	2	10.64	1332.12	Hewitt Sand Water Table
Deep Observation well	841474	349535.1633	5163047.686	1341.00	1342.9	155	147-155	1194	1186.00	4	5.2	1337.7	Browerville Sands 3 Aquifer

*bMP= below measuring point

Setting

The proposed Nolte irrigation fields and wells are located in the Pineland Sands area (Helgeson, 1977). The Pineland Sands area consists of a large surficial glacial outwash area containing an extensive unconfined (water table) aquifer (Helgeson, 1977) and several confined aquifers (Lusardi, 2016) within glacial till. Figure 2 shows the location of the irrigation wells with the surficial geology and nearby features.

Geology

The Pineland Sands region of Minnesota consists of 996 square miles of glacial deposits (outwash, till, and lacustrine deposits) in Becker, Cass, Hubbard, Todd and Wadena Counties (Reppe, 2005). The Nolte site is located towards the southern end of the Pineland Sands where the thickness of these glacial deposits is approximately 360 feet.

The geology of the proposed project area is described by Helgeson (1977) and the Wadena County Geologic Atlas (Lusardi and Marshall, 2016). The area consists of glacially deposited layers of sand and gravel (described as glacial outwash) separated by silt and clay layers (described as glacial till or paleo lake sediments). The deposits were from several different glaciation events during the Late Wisconsinan ice age.

The outwash sands and gravels at the land surface generally cover the entire Pineland Sands area with the exception of topographic highs of till deposits making up the drumlin fields. Till directly underlies the surficial outwash. Within the till deposits are several distinct layers of sands and gravels deposited as outwash from older glaciation events.

The bedrock underlying the confined aquifers consists of Paleoproterozoic slate and greywacke. The elevation of the bedrock ranges between 825 to 950 ft msl (Lusardi and Marshall, 2016) across the area. This type of bedrock does not provide useable quantities of water unless fractured and will not be discussed further.

Hydrogeology

There are two aquifer systems in the area (Eckman, 2002). The first is the unconfined (water table) aquifer located in the outwash at the land surface. This aquifer is commonly referred to as the Pineland Sands surficial aquifer. Surface water features in the Pineland Sands area have been shown to be directly connected to the unconfined aquifer (Helgeson 1977, LaBaugh et al 1981, and Walker, 2009). The second aquifer system consists of confined (buried) aquifers.

At the site, there is an unconfined aquifer and several buried outwash sand and gravel deposits separated by confining units of silt and clay (till). The buried outwash deposits make up the confined aquifers of the area (Lindgren, 2002). According to the Wadena County Geologic Atlas, the confined aquifers in the area tend to be discontinuous with varying vertical and horizontal interconnectivity. The uppermost confined aquifers are likely hydrologically connected (Lindgren, 2002). Geologic cross-sections constructed for part A of the Wadena County geologic atlas (Minnesota Geological Survey, 2016) indicate that the aquifers are of limited areal extent (Figures 3-5).

The Wadena County Geologic Atlas (Lusardi and Marshall, 2016) have identified the sand and gravel formations (outwash deposits) that make up identified and potential aquifers in both the unconfined and confined systems at the site. Although individual water bearing units are not identified in the Wadena County Geologic Atlas, aquifers are presumably associated with the coarser textured sands and gravels where many wells are completed. The geologic cross section C-C’ from this atlas (Figures 3 and 4) has identified the approximate elevations of these sand and gravel layers (aquifers) near the Northwest Irrigation well (805420). The geologic atlas supplemental cross section 25 shows similar sand and gravel layers (aquifers) near the remaining wells (Figures 3 and 5).

Monitored Well Aquifer Classification

The Northwest Irrigation well was projected onto the fully interpreted cross section C-C’ of the atlas (Figures 3 and 4). The remaining wells were projected onto supplemental cross section 25 (Figures 3 and 5) of the atlas.

Cross section C-C’ (Figures 3 and 4) shows that the Northwest Irrigation well is likely completed within the Browerville Outwash 2 sand layer within the Browerville Formation. According to cross section C-C’, the Browerville Outwash 2 may be directly connected to the Browerville outwash 3 sand layer near the Northwest Irrigation well.

Supplemental cross section 25 (Figures 3 and 5) shows that the other two irrigation wells (805421 and 805422) and the Deep Observation well (841474) are completed within the Browerville Outwash 3 sand layer. Static water elevations in these three wells are very similar (Table 2).

The elevation of the screened formation and the static water levels within the Caponera (728573) domestic well indicate that this well is completed in the Browerville Outwash 3 aquifer, but is completed much deeper in the Browerville Outwash 3 than the pumped well. This well had a significantly higher water elevation than the other monitored wells.

The Shallow Observation well (841475) is completed within the unconfined aquifer. A projection of this well onto supplemental cross section 25 of the Geologic Atlas of Wadena County (Lusardi and Marshall, 2016) shows that this well is screened within the Hewitt Sands 2.

The Eckenrude (421530) well is completed in a shallow confined aquifer. The Geologic Atlas of Wadena County (Lusardi and Marshall, 2016) incorporated this well in the supplemental cross section 25 and showed it is screened within the Hewitt Sands 2. This cross section also suggests that it is connected to the unconfined aquifer near the Production well.

Table 2 contains the aquifer classification of each well based on the well’s completed depth and interpretation using the Wadena County Geologic Atlas (Lusardi, 2016).

DNR observation wells

The closest DNR observation well is well 80022 (unique number 244572), completed within the water table aquifer (Figure 1) approximately two miles from the pumped well (805421). Unfortunately, no recent water level data is available for this well at this time. There are no DNR water level observation wells completed within any of the confined aquifers within five miles of the irrigation wells.

Surface Water Features

The closest surface water body to the proposed appropriation is the Redeye River. The Redeye River (Public water inventory # 56079a) is located approximately 950 feet west southwest from the Production well and approximately 1960 feet southeast of the Northwest Irrigation well. The Redeye River is not a designated trout stream. Within one mile of the proposed project area, the Redeye River (AUID 07010107-503) is listed by the MPCA under Section 303d of the CWA as an Impaired Water for Escherichia coli, which includes the reach that is adjacent to the proposed project boundaries.

Because the aquifer test was to be conducted under frozen conditions, no plans were made to gage the river. Based on verbal communication with the consultant, it appears the river began to respond to spring melt and water levels rose in the river during the test, impacting the test results in the shallow wells. DNR maintains a gage on the Leaf River approximately 9 miles downstream from the Production well (Figure 2). Presumably, all streams in the immediate region will react similarly to spring melt. Therefore, this gaging site can be used qualitatively to evaluate stream changes at the site.

Nearby Wetlands

An unnamed public water wetland (#80008500) is 0.6 miles north of the East Irrigation well (805422). This unnamed public water wetland connects to a Wetland Conservation Act (1991) (WCA) regulated wetland located just north of the irrigated field for 2017-4237 and just east of the irrigate field for 2017-4236 (Figure 1). A Public Waters Inventory (PWI) wetland occurs to the south (PWI# 80008400) of the Production well and East Irrigation well. No special designations occur for these water bodies. In addition, the Redeye River is bordered by WCA regulated wetlands between the river and the irrigation wells.

Preliminary Understanding of the Groundwater Flow System

The area consists of variously interconnected unconfined and confined aquifer systems that vary in thickness across the area. In some places, the unconfined and shallower confined aquifer systems are directly connected. In other areas, they are connected only through leakage. The unconfined aquifer is directly connected to nearby surface water bodies.

Methods

The aquifer test was conducted as prescribed in the Step 2 aquifer test plan (Yourd 2020b). The Step 1 information was submitted in a series of emails prior to the Step 2 aquifer test plan and during its development. The final discharge location was approved by DNR just prior to the test start and is shown in Figure 1. Plywood was installed at the discharge point as an energy dissipation device. The flow meter (McCrometer SN 98-8-1067) was installed per the manufacturer’s specifications and a photo of the setup is located in Figure A-1 of Appendix A.

Groundwater Level Monitoring

Groundwater level monitoring followed the Step 2 aquifer test plan with the exception of minor gaps in data collection in some wells. These gaps did not affect the test results.

Wells monitored are listed in Tables 2 and 3. The equipment used in the monitoring, along with the dates and duration of monitoring are listed in Table 3. All loggers were set to measure water levels every minute. Figure 1 shows the location of the pumping well, observation wells, discharge point, and nearby resource features.

Table 3. Monitoring summary

Well name	Unique well number	Monitoring Start Date (Central Standard Time)	Monitoring End Date (Central Standard Time)	Monitoring Method, Instrument, Serial Number	Logger Depth (ft bMP)
NW Irrigation well	805420	3/9/2020	4/10/2020	Level Troll 400 SN 511918	13.17
Caponera well	728573	3/9/2020	4/10/2020	Level Troll 700 SN 674202	43.32
Eckenrude well	421530	3/9/2020	4/10/2020	Level Troll 400 SN 511737	27.18
East Irrigation well	805422	3/12/2020	4/10/2020	Level Troll 700 SN 413453	34.24
Production well	805421	3/17/2020	4/10/2020	Level Troll 700 SN 694302	118.0
Shallow Observation well	841475	3/9/2020	4/10/2020	Level Troll 700 SN 416859	43.62
Deep Observation well	841474	3/9/2020	4/10/2020	Level Troll 700 SN 659383	56.26

Aquifer Pumping Test

The aquifer pumping test generally adhered to the specifications of the Step 2 document (Yourd, 2020b). The following changes were made to the plan and approved by DNR:

- The initial pump start was on 3/24/20 10:00 CST. However, there was a leak in the piping flange adjacent to the irrigation well. The pump was shut off after 40 seconds of pumping at a rate of approximately 750 gpm. The leak was repaired. The Deep Obwell was fully recovered by 3/24/20 12:30 CST when the pumping phase began again.
- Following consultation, the DNR and the consultant agreed to continue the pumping phase of the test for 7 days.
- Barometric pressure was monitored with an Insitu rugged Barotroll (Serial number 651837) and placed in the NW Irrigation well (805420).
- A precipitation gage was installed on site approximately 20 feet northwest of the Deep Observation well. Daily precipitation was monitored from 3/24/20 to 4/10/20. Precipitation was minimal during the test and is shown in Figures 10 and 11.

Flow rate monitoring followed the Step 2 document guidance (Yourd, 2020b). The data is shown in the Table of Appendix A. The pumping rate stayed within 10% of the permit application rate of 800 gpm. A summary of the pumping data for the test is given in Table 4.

Table 4. Pumping Information

Well pumped	805421
Pump on (Date and Time)	3/24/20 12:30 CST*
Pump off (Date and Time)	3/31/20 12:30 CST*
Total pumping time (min)	10079.5
Total recovery time (min)	14555.5
Total volume pumped (galx100)	80308.5
Time-averaged pumping rate (gpm)	800

*central standard time

NWATS noted in an email on 3/27/20 that they observed that the Redeye River had risen 2 feet from the start of pumping on 3/24/20. This coincided with some water level increases in some of the monitored wells and the rising water levels in the Leaf River gage.

Results

Groundwater level monitoring was completed at all monitored wells and the hydrographs of the uncorrected and corrected data are presented in Figures 6-12. All logger data were corrected to manual water level data. Corrections were minimal.

Background Effects

The Production well, Deep Observation well and the Eastern Irrigation well were affected by rising antecedent regional groundwater levels. Removal of these pre-pumping background trends followed DNR standard procedures prior to analysis (Figures 6-8).

None of the wells reacted directly to precipitation measured on site. However, water levels in three wells (NW Irrigation, Shallow Observation, Eckenrude) did respond to rising water levels in the Redeye River (Figures 9 and 10; verbal communication NWATS). An existing river gage is available nine miles downstream on the Leaf River, a tributary to the Redeye River (Figure 2). This gage data was used to evaluate stream trends for the area. A comparison of this gage data with the well water level data shows that the water level rises in these wells coincided with the water level rises in the river stage (Figures 9 and 10). Water level rises in the Eckenrude and Shallow Observation wells were similar to the water level rise in the river. Therefore, it was assumed that any leakage effects due to pumping the Production well would be masked by the direct increases in aquifer water levels coinciding with the water level rise in the river. No further analysis of the Eckenrude and Shallow Observation well data was conducted.

In addition to the river effects, the Northwest Irrigation well had both an antecedent and a post recovery rising regional trend (Figure 9). The rising trend correlates to the rising water levels in the Redeye River and may include both river effects and regional trends. To address some of the impacts from these rising water level trends, the data from pre-pumping and post-recovery of the Northwest Irrigation well were fit with a linear trend line. This trend line was assumed to apply over the entire monitoring period in this well and cover all rising water level trends during the test. This trend over corrects the antecedent data and under corrects the post recovery data. However, it is the best available trend correction at this point for the aquifer test drawdown and recovery data without an on-site river gage. The equation for the trend line was used to correct the collected aquifer test data (depth to water) for this background trend.

Effect of Pumping during Aquifer Test

No drawdown was observed in the Shallow Observation well, the Eckenrude Domestic well or the Caponera Domestic well (Figures 10 and12). As discussed above, the Shallow Observation well and the Eckenrude Domestic well were highly impacted by the rising water levels in the Redeye River which may have masked any pumping effects. Drawdown was observed in the remaining monitored wells and is shown in Table 5.

Table 5. Summary of observed drawdown and recovery

Well name	Unique well number	Static Water Elevation (ft NAVD88)	Corrected Deepest Pumping Elevation (ft NAVD88)	Corrected Recovery Elevation (ft NAVD88)	Total Drawdown (ft)	% Recovery on 4/10/20
NW Irrigation Well	805420	1346.342	1345.435	1346.813	0.907	152
Caponera Well	728573	1353.249	None Observed	NA	NA	NA
Eckenrude Well	421530	1333.280	None Observed	NA	NA	NA
East Irrigation Well	805422	1338.825	1315.658	1337.492	23.167	94
Production Well	805421	1337.026	1248.707	1336.123	88.319	99
Shallow Observation Well	841475	1332.240	None Observed	NA	NA	NA
Deep Observation Well	841474	1337.650	1292.029	1336.477	45.621	97

AQTESOLV analysis

The data from the Production well, the Deep Obwell, the East Irrigation well and the NW Irrigation well were analyzed using AQTESOLV Pro 4.5 (AQTESOLV, Duffield, 2007). The interim plots and more detailed analysis explanation are shown in Appendix B.

The data was first analyzed by diagnostic flow plots to determine the type of flow regime that may exist in the pumped aquifer per the recommended procedures for using AQTESOLV (Duffield, 2007). These flow plots showed that the data was affected by two no-flow boundaries and leakage into the pumped aquifer. The locations of the no-flow boundaries were estimated based on the timing of the observed boundary effects in the diagnostic flow plots and the geologic changes highlighted in the Wadena County Geologic Atlas (Lusardi, 2016).

The Theis (1935) confined aquifer solution was used to estimate the pumped aquifer parameters using the water level data collected in the wells completed in the pumped aquifer (Production well, Deep

Observation well, and East Irrigation well). The no-flow boundary conditions were then added as discussed above.

To account for the observed leakage effects in the diagnostic plots, the leaky confined Neuman-Witherspoon (1969) solution was used to analyze all the collected data. The shallow confined aquifer parameters can be obtained by applying this solution to data collected in an on-site monitoring well. However, there was no onsite shallow confined (Browerville Sands 2) monitoring well to calculate these parameters. Although the NW Irrigation well is completed in the Browerville Sands 2, it is located too far from the pumped well and was also impacted by the rising water levels in the Redeye River. Therefore, the shallower confined aquifer transmissivity (T) was estimated from the specific capacity data of the NW Irrigation well (Appendix B) using both the Cooley-Case (1973) and Hantush (1960) method followed by adjustment in AQTESOLV to fit the aquifer test data. The shallower confined aquifer storativity (S) was estimated as leaky confined (0.001 dimensionless) using literature values (Driscoll, 1968).

The Theis pumped aquifer T and S values, along with the estimated T and S values for the shallow confined aquifer, were used in AQTESOLV to estimate leakage parameters using the Neuman-Witherspoon (1969) solution. The final pumped aquifer storativity was visually adjusted in AQTESOLV to better match observed values. Figure 13 shows the final AQTESOLV report and Figure 14 shows the location of the no-flow boundaries. Table 6 shows the aquifer parameters obtained from this analysis.

The model does not fit the NW Irrigation well's aquifer test data well. This is likely due to the inability to remove the effects of the rising water levels in the Redeye River from the aquifer test data. In addition, the no-flow boundaries may not be accurately placed for this well. Further aquifer testing of this well would improve the understanding of the boundary locations, clarify leakage, and refine shallow aquifer parameters.

Table 6. Estimated parameters from AQTESOLV analysis

Well	Data analyzed	Solution	No-flow or recharge boundaries?	Transmissivity T (ft^2/day)	Storativity S (unitless)	Confining layer conductivity K' (ft/day)	Anisotropy ratio K_z/K_r (unitless)	Aquifer thickness b (feet)	Hydraulic conductivity K (ft/day)
Production well and East Irrigation well	All Data: 3/24/20 to 4/10/20	Neuman Witherspoon (1969)	2 parallel no-flow boundaries	3067	0.00001	0.00005	1	20	153
NW Irrigation well	Specific Capacity Test Data 9/23-9/26/2014	Cooley-Case (1973)	2 parallel no-flow boundaries	5000	0.001 (Driscoll 1986)	Not accurate from single well test	1	36	139

Refined Understanding of the Groundwater Flow System

The aquifer test demonstrated that pumping at the Production well caused drawdown in both the pumped aquifer (Deep Observation well and Eastern Irrigation well) and the shallow confined aquifer (NW Irrigation well). Two no-flow boundaries consistent with a channel aquifer affected the data. The shallow aquifers (Shallow Observation well, Eckenrude well and NW Irrigation well) are connected to the nearby Redeye River. This is consistent with the preliminary understanding of the groundwater flow system.

Water Use Sustainability and Potential Impacts

The aquifer parameters contained in Table 6 and the pumping schema outlined in Table 7 were used to estimate impacts to nearby domestic wells and resource features using forward modeling and the Neuman-Witherspoon solution in AQTESOLV (Duffield, 2007).

Potential for Well Interference

Domestic wells located between the two no-flow boundaries identified during the aquifer test and those located within 1 mile of the proposed irrigation wells were evaluated for well interference risk due to pumping one (singular) or all three (cumulative) proposed irrigation wells (Figure 14). Wells located outside of these boundaries would have reduced risk for interference from pumping these wells and to investigate cumulative pumping impacts would require incorporating other high volume appropriators' use. This is beyond the scope of this report.

DNR Permitting staff provided a list of 30 potential domestic wells not in Minnesota Well Index (MWI) that are within one mile of each permit application. This data, along with the MWI data, were used to evaluate domestic well interference risk from pumping one or all three irrigation wells associated with the permits listed in Table 1. Table 8 lists all the domestic wells evaluated along with known well construction information.

The majority of the domestic wells not in MWI had either no well information or were missing well information necessary (well depth, pump depth, etc.) to calculate risk. These wells are designated as "unknown risk" for interference and were not further evaluated. If information is obtained regarding these wells, the risk can be re-evaluated.

The remaining wells with known stratigraphy or well depth were evaluated using the Wadena County Geologic Atlas (Lusardi, 2016) supplemental stratigraphic cross section closest to each well. Each well's depth was calculated from the land surface elevation provided in the MWI (MGS and MDH, 2016) for that well or obtained from the 3 meter Digital Elevation Model LiDAR contours (MN DNR, 2012) using the well location. The aquifer for each domestic well was classified based on the stratigraphy shown on the well log and the well depth on the cross section. Wells with no stratigraphy were classified by depth only. If the aquifer classification could be either the "pumped aquifer" or "shallow confined aquifer," the more conservative pumped aquifer classification was used to calculate risk.

Wells completed in the unconfined (water table) aquifer were classified as low risk for well interference. These wells are indirectly connected to the pumped confined aquifers and the water level response to the aquifer test pumping was minimal. In addition, these wells are directly connected to the Redeye River. Therefore, unconfined aquifer response to pumping any of the proposed irrigation wells is likely to be mitigated by the Redeye River. The risk for well interference to these wells was not further evaluated.

For the remaining wells, drawdown from pumping each Production well individually was evaluated over a simulated irrigation season (April 1 to October 1) using the maximum requested pumping rates and volumes (MPARS) and the aquifer parameters described above. Each irrigation cycle was assumed to consist of application of one inch of water (Irrigation Box, 2020) followed by a period of no pumping. This resulted in 10 irrigation cycles, which were used in all forward modeling. Irrigation cycle information for each well is shown in Table 7. It should be noted that reducing the application rate to less than one inch per cycle or changing the efficiency of the irrigation would not substantively change the final estimated drawdown at each well as the total appropriation volumes remain the same.

Table 7: AQTESOLV Forward Solution Irrigation pumping cycles

Unique Well no.	Well Name	Application no.	Proposed Pumping rate (gpm)	Proposed Volume (million gallons per year)	Irrigated Acreage	Irrigation Cycle* (pumping days - non pumping days)	Number of Irrigation Cycles per Irrigation Season
805420	NW Irrigation	2017-4235	450	21.2	65	3-15	10
805422	East Irrigation	2017-4237	800	45	138	4-14	10
805421	Production Well	2017-4236	700	32.6	100	3-15	10

* assumes a conservative 1 inch application rate per irrigation cycle, all cycles the same in one season, 85% efficiency

The AQTESOLV parameters from the aquifer test on the Production well were assumed to apply to all three irrigation wells when pumped together. This would give a conservative risk analysis for the NW Irrigation well.

The NW Irrigation well is completed in the shallow confined aquifer (Browerville Sands 2). The connectivity of this aquifer to shallower aquifers (Hewitt Sands formation-confined or unconfined), or the pumped aquifer (Browerville Sands 3) was demonstrated in this aquifer test. Therefore it was assumed that any domestic well classified as being completed in any of these aquifers is in direct communication with the well being pumped. This does not take into account the unknown leakage that occurs into this aquifer and will result in a conservative risk analysis. The specific capacity test aquifer parameters calculated using AQTESOLV (Duffield, 2007) with the Cooley Case (1973) solution as described above and in Appendix B were used to predict risk from pumping this irrigation well alone. Boundary conditions discussed above were assumed to apply to the NW Irrigation well's shallow confined aquifer. This should be considered an estimate of risk only. A more precise risk for interference would require completion of an aquifer test using this well as a pumping well and installing and monitoring a nearby monitoring well nest.

Table 8: Domestic Well Information

Homeowner - Name	Unique Well Number	UTM X (m)	UTM Y (m)	Well Depth (ft)	Land Surface Elevation (NAVD88)	Well Depth Elevation (NAVD88)	Well Diam (in)	Static Water Level Depth (ft)	Static Water Level Elevation (ft NAVD88)	Drop Pipe Length (ft)	Pump Type	Available head in well (ft)	Available head above pump intake (ft)	Aquifer Classification
Tom Nelson	190935	350086	5164416	60	1352	1292	4	23	1329	Unknown	None Noted	37	Unknown	Unpumped Shallow Confined (Browerville Sands 1)
Brian Boe	695127	349316	5164434	49	1349	1300	4	12	1337	Unknown	None Noted	37	Unknown	Unpumped Shallow Confined (Browerville Sands 1)
Nolte	714382	349880	5164269	52	1366	1314	4	30	1336	35	submersible	22	5	Unpumped Shallow Confined (Browerville sSnds 1)
John Rucks	727163	349985	5164477	52	1365	1313	4	25	1340	40	submersible	27	15	Unpumped Shallow Confined (Browerville Sands 1)
Douglas Larson	153304	349595	5165882	115	1351	1236	4	4	1347	Unknown	None Noted	111	Unknown	Unpumped Shallow Confined (Browerville Sands 2)
Jake Nolte	828390	348575	5164267	50	1346	1296	4	7	1339	Unknown	None Noted	43	Unknown	Unpumped Shallow Confined (Hewitt Sands 1 or 2)
Bob Pickar	123614	349748	5162495	55	1336	1281	4	13	1323	Unknown	None Noted	42	Unknown	Unpumped Shallow Confined (Hewitt Sands 1 or 2)
Tappe Brothers LLC	none	350549	5161430	100	1356	1256	4		1356	80	submersible	100	80	Unpumped Shallow Confined (Hewitt Sands 2 or Browerville Sands 2)
Ludwig Roggenkamf	552894	351164	5162281	80	1345	1265	4	12	1333	40	submersible	68	28	Unpumped Shallow Confined (Hewitt Sands 2)
Robert/Dennis Graphenteen	789806	348566	5165808	115	1352	1237	4	6	1346	Unknown	None Noted	109	Unknown	Unpumped Shallow Confined or Pumped Aquifer (Browerville Sands 2 or 3)
Richard Theusch	794135	348574	5165289	128	1349	1221	4	1	1348	40	submersible	127	39	Pumped Confined (Browerville Sands 2 or 3)
Terry and Mary Tinnes	788841	349424	5165796	128	1351	1223	4	4.7	1346.3	60	submersible	123.3	55.3	Pumped Confined (Browerville Sands 2 or 3)
C/W (possibly mislocated based on scanned in well log)	825459	349801	5165822	120	1350	1230	4	5.5	1344.5	60	submersible	114.5	54.5	Pumped Confined (Browerville Sands 2 or 3)
Al Zdonowich	153343	349730	5165964	121	1349	1228	4	5.0	1344.0	Unknown	Unknown	116.0	Unknown	Pumped Confined (Browerville Sands 2 or 3)

Homeowner - Name	Unique Well Number	UTM X (m)	UTM Y (m)	Well Depth (ft)	Land Surface Elevation (NAVD88)	Well Depth Elevation (NAVD88)	Well Diam (in)	Static Water Level Depth (ft)	Static Water Level Elevation (ft NAVD88)	Drop Pipe Length (ft)	Pump Type	Available head in well (ft)	Available head above pump intake (ft)	Aquifer Classification
Karen Kutila	821041	351802	5164804	98	1340	1242	4	6.5	1333.5	60	submersible	91.5	53.5	Pumped Confined (Browerville Sands 2 or 3)
Duane Graba	807082	349941	5166223	126	1345	1219	4	5.0	1340.0	60	submersible	121.0	55.0	Pumped Confined (Browerville Sands 2 or 3)
Joyce Ashman	none	350915	5163296	12	Unknown	Unknown	Unknown	Unknown	Unknown	Not Reported	Unknown	Unknown	Unknown	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Larry Hayes	none	350381	5162605	19	1337	1318	Unknown	7	1330	2	Sand Point*	12	-5*	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Larry Hayes	none	350421	5162649	19	1337	1318	1.5	5.5	1331.5	2	Sand Point*	13.5	-3.5*	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Larry Hayes	none	350392	5162648	20	1338	1318	1.5	5.5	1332.5	2	Sand Point*	14.5	-3.5*	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Larry Hayes	none	350377	5162645	20	1338	1318	1.5	7	1331	2	Sand Point*	13	-5*	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Larry Hayes	none	350410	5162610	21	1337	1316	1.5	7	1330	2	Sand Point*	14	-5*	Unconfined (water table, Holocene surficial sands or Hewitt Sands 1)
Janice Jones	none	348760	5166234	15	1354	1339	2	Unknown	Unknown	3	Sand Point*	15	Unknown	Unconfined (water table, Holocene surficial sands)
Jason and Shawna Plautz	none	347494	5165923	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Gregg and Carol Seibert	none	347800	5166130	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
David and Sybil Whitaker	none	248691	5166121	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Dale and Vicki Hugget	none	349477	5166015	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Steven and Kathlene Connell	none	347978	5164604	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Kimberly Parkos	none	350862	5163966	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Jacqueline Lilleodden or Mark Hoskins	none	350827	5163473	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

Homeowner - Name	Unique Well Number	UTM X (m)	UTM Y (m)	Well Depth (ft)	Land Surface Elevation (NAVD88)	Well Depth Elevation (NAVD88)	Well Diam (in)	Static Water Level Depth (ft)	Static Water Level Elevation (ft NAVD88)	Drop Pipe Length (ft)	Pump Type	Available head in well (ft)	Available head above pump intake (ft)	Aquifer Classification
Jacqueline Lilleodden or Mark Hoskins	none	350789	5163272	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Ervin Leo Salo	none	351702	5162740	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Rhonda Robberstad	none	350883	5161886	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Marylou McDonald	none	350561	5161487	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

*Sand point wells reported by owner as having a pump intake less than the static water levels in the well
Green highlights indicate wells screened in unconfined (water table) aquifers that are classified as low risk.
Orange highlights indicate wells with unknown well construction information and unknown risk to well interference.

The AQTESOLV forward solution analysis predicts drawdown at each domestic well depending on which individual well, or all three wells, are pumping. The interference risk at a domestic well was estimated by subtracting this modeled drawdown from the available head above the pump intake or drop pipe length. It is assumed that a domestic well with ten feet of water above the pump intake will continue to serve as a water supply. If there has less than 10 feet of water remaining above the pump intake, then the well is considered at high risk. If the well has between 10 and 20 feet of water remaining above the pump intake, then the well is considered at moderate risk. If the well has greater than 20 feet of water above the pump intake, then the well is considered at low risk. The modeled drawdown was also compared to the available head in the domestic well (well depth minus static water level) and the well risk was further refined. If the pump intake was unknown, risk was estimated based only on well depth.

Drawdown predictions and risk for well interference are shown in Table 9 and include the following:

1. Pumping the **NW Irrigation well** does not result in Domestic well risk to interference. However, this risk analysis is an estimate only.
2. If pumping only the **Production well**:
    a. Two wells are at high risk for well interference: Nolte (714382) and John Rucks (727163). The Nolte (714382) well is owned by the applicant and presumably will be corrected by himself if needed. The John Rucks (727163) pump intake could be lowered to mitigate the interference risk if the pump is capable of pumping from a deeper depth.
    b. Two wells are at moderate risk for well interference: Bob Pickar (123614) and Ludwig Roggenkamf (552894). The Bob Pickar well has an unknown pump intake. Both wells have sufficient water in them, provided the pump intake is low enough in the well and the pump is capable of pumping at the deeper depth.
3. If pumping only the **East Irrigation well**:
    a. Two wells are at high risk for well interference: Nolte (714382-discussed in item 2 above) and the John Rucks (727163) well. The John Rucks (727163) pump intake could be lowered to mitigate the interference risk if the pump is capable of pumping at the deeper depth.
    b. Two wells are at moderate risk for well interference: Tom Nelson (190935) and Bob Pickar (123614). Both wells pump intake could be lowered to mitigate the interference risk if the pumps are capable of pumping at the deeper depth
4. If **all three irrigation wells** are pumped at the same time, nine wells are at high risk for well interference; Nolte (714382), John Rucks (727163), Ludwig Roggenkamf (552894), Richard Theusch (794135), Al Zdonowich (153343), Tom Nelson (190935), Brian Boe (695127), Jake Nolte (828390), and Bob Pickar (123614).
    a. Six of these wells have predicted drawdown greater than the well depth or very close to the bottom of the well: Tom Nelson (190935), Brian Boe (695127), Nolte (714382), John Rucks (727163), Jake Nolte (828390), and Bob Pickar (123614). These wells would need to be replaced with deeper wells to accommodate all three irrigation wells pumping at the same time.

5. Seven wells have an unknown pump intake depth. For these wells, well interference risk was estimated by well depth only. These wells include: Al Zdonowich (153343), Tom Nelson (190935), Brian Boe (695127), Jake Nolte (828390), Bob Pickar (123614), Douglas Larson (153304), Robert/Dennis Graphenteen (789806). The depth of the pump intake could increase or decrease this risk and could be determined by the applicant's well driller.

Table 9-Well Interference Risk

Homeowner - Name	Unique Well Number	Calculated Drawdown (ft) from pumping only Production Well	Calculated Drawdown (ft) from pumping only East Irrigation Well	Calculated Drawdown (ft) from pumping all 3 Irrigation Wells	Well Interference Risk from pumping Production well	Well Interference Risk from pumping East Irrigation Well	Well Interference Risk from pumping NW Irrigation Well	Well Interference Risk from pumping all three Irrigation wells
Nolte	714382	15.99	17.5	40.5	High	High	Low	High
John Rucks	727163	14.6	16.5	38.2	Moderate for well but pump intake needs to be lowered	Moderate for well but pump intake needs to be lowered	Low	High
Ludwig Roggenkamf	552894	13	18.9	34.8	Moderate for well but pump intake could be lowered	High but pump intake could be lowered	Low	High but pump intake could be lowered
Richard Theusch	794135	10.4	11	34.6	Low	Low	Low	High but pump intake could be lowered
Al Zdonowich	153343	9.3	10.6	28.3	Low for well but Unknown pump intake	Low for well but Unknown pump intake	Low for well but Unknown pump intake	High but pump intake unknown and could be low risk
Tom Nelson	190935	14.7	17	38.4	Low for well based on well depth but Unknown pump intake	Moderate for well, unknown pump intake	Low	High but unknown pump intake

Homeowner - Name	Unique Well Number	Calculated Drawdown (ft) from pumping only Production Well	Calculated Drawdown (ft) from pumping only East Irrigation Well	Calculated Drawdown (ft) from pumping all 3 Irrigation Wells	Well Interference Risk from pumping Production well	Well Interference Risk from pumping East Irrigation Well	Well Interference Risk from pumping NW Irrigation Well	Well Interference Risk from pumping all three Irrigation wells
Brian Boe	695127	15.3	15.3	40	Low for well based on well depth but Unknown pump intake	Low for well based on well depth but Unknown pump intake	Low for well based on well depth but Unknown pump intake	High but unknown pump intake
Jake Nolte	828390	14.9	14.2	42.3	Low for well but Unknown pump intake	Low for well but Unknown pump intake	Low for well but Unknown pump intake	High but unknown pump intake
Bob Pickar	123614	26	24	54.3	Moderate for well but pump intake is unknown	Moderate for well but pump intake is unknown	Low	High but unknown pump intake
Douglas Larson	153304	9.4	10.95	28.8	Low for well but Unknown pump intake	Low for well but Unknown pump intake	Low for well but Unknown pump intake	Low for well but Unknown pump intake
Robert/Dennis Graphenteen	789806	8.9	9.8	28.4	Low	Low	Low	Low for well but Unknown pump intake
Tappe Brothers LLC	none	13	17.4	33.9	Low	Low	Low	Low
Terry and Mary Tinnes	788841	9.5	10.9	29.1	Low	Low	Low	Low
C/W (possibly mislocated based on scanned in well log)	825459	9.6	11.2	29.1	Low	Low	Low	Low
Karen Kutila	821041	10.5	14.5	30.5	Low	Low	Low	Low
Duane Graba	807082	8.8	10.6	27.2	Low	Low	Low	Low

Surface Water Depletion

Figure 15 shows the location of the proposed irrigation wells and the nearby surface water features. The closest surface water feature to the Production wells is the Redeye River and its associated wetlands. Other nearby surface water features include both Public Water and Wetland Conservation Act regulated wetlands. This section contains a summary of the stream depletion calculations that are discussed in detail in Appendix C.

Nearby wetlands

The water table (unconfined aquifer) is highly connected to the surface water features in this area. Analyses by Stark et al (1994), Helgesen (1977), LaBaugh et al (1981), Siegel (1980) and Walker et al (2009), have shown that the water table aquifer and surface water are interconnected in the Pineland Sands area and both are heavily dependent on recharge from precipitation. The combination of melting snow entering the water table and the subsequent flow of meltwater into the Redeye River caused the water levels to increase. Since the river is directly connected to the unconfined aquifer, the rise in river water levels and the melting of snow caused an increase in water levels in the unconfined aquifer of approximately 1 foot. This increase in water levels masked any drawdown signature from the aquifer test. Therefore, it is not expected that the Production well or East Irrigation well will significantly impact surficial water features that are connected directly to the Redeye River such as the nearby wetlands.

The NW Irrigation well is completed in a shallower confined aquifer (Browerville Sands 2). The 2019 land imagery data shows the Redeye River is located closer to this well than the public watercourse delineation (MNDNR, 2017). This well's aquifer responded immediately to rising water levels in the Redeye River and associated wetlands. Its connectivity to other nearby wetlands (and associated unconfined aquifer) farther away from the river is unknown. The impact of pumping of this well on these wetlands is not calculable without site-specific aquifer parameters derived from an aquifer test that measures leakage from the unconfined system into the Browerville Sands 2 aquifer.

Redeye River

Stream depletion of the Redeye River was calculated using the aquifer parameters discussed above and the permit application information shown in Table 1. The depletion estimates were calculated based on aquifer types as described below.

Production and East Irrigation wells - Browerville Sands 3

For the Production and East Irrigation wells, the Dudley Ward-Lough (2011) solution method was used to calculate possible stream depletion after one irrigation cycle, 14 days of continuous pumping, and from a single irrigation season of 60 days. This solution method matches the site's hydrogeology near these wells where the pumped aquifer is a semi-confined aquifer in a two-layer leaky confined aquifer system. The solution method calculated a maximum of 0.04 and 0.03 cubic feet per second depletion of the Redeye River from the East irrigation and the Production well respectively. Although there is not an August base flow analysis available for the Redeye River, this amount of stream depletion is not likely to negatively impact the flow in the Redeye River.

Northwest Irrigation Well - Browerville Sands 2

For the NW Irrigation well, the Hunt (1999) method of analysis was used to estimate stream depletion using the aquifer parameters derived using the specific capacity test data from this well. The specific capacity data is limited but is the best data available.

The Hunt (1999) method provides estimated stream depletion rate after 7 days, 30 days, 150 days and 365 days. The assumptions associated with this method matches the observed hydrogeology near this well where the aquifer is assumed to be connected to the Redeye River. This solution method estimated a maximum stream flow depletion of approximately 1 cfs (27 Liters/second) over one year. An August mean base flow (low flow value) for the Redeye River is not available. It is unknown if this estimated amount of depletion will negatively impact this river. This depletion rate can be compared to the August mean baseflow for the Redeye River once it becomes available.

An aquifer test using this well as a pumping well, a nearby nest of monitoring wells (one completed in the pumped aquifer and one completed in the unconfined aquifer) along with a stream gage in the river would be needed to provide better estimates of stream flow depletion. It is possible that a use-season test at the NW Irrigation well with an installed river gage would provide adequate information to evaluate this well's impact on the Redeye River.

Safe Yield and Historic/Projected Water Levels

For confined aquifers, the DNR has established a two-tiered aquifer protection threshold system to ensure the long-term viability of the pumped aquifer and to prevent exceedance of the aquifer safe yield as defined by MN Rule 6115.0630 Definitions Subps.15 and 16. These thresholds allow for appropriation from the aquifer, but establishes minimum water level elevations to be maintained as a safeguard to protect the structural integrity of the aquifer itself. Threshold elevations are usually set in observation wells completed in the source aquifer rather than pumped wells.

The first threshold is set at an elevation that is 50% of the pre-pumping available head above the top of the aquifer. The second is a water level elevation associated with 25% of the pre-pumping available head above the aquifer. If water levels drop to the 50% threshold, pumping will need to be evaluated and a possible reduction in rate and volume may be required. At the 25% threshold, pumping would need to cease to prevent exceeding the safe yield for the artesian aquifer. If more than one aquifer is impacted by pumping, then thresholds are set similarly in the other aquifers.

Production well and East Irrigation well (Browerville Sands 3 Aquifer)

The thresholds for the aquifer supplying water to the Production and East Irrigation wells were calculated using the static water level elevation measured in the Deep Observation Well on 3/9/20 by the applicant's consultant, the land surface elevation at the well surveyed by the applicant's surveyor, and the Deep Observation well log. The information is shown in Table 10 and Figure 16.

Table 10: Browerville Sands 3 Aquifer* Threshold Calculations

Parameter	Elevation (ft NAVD 88)	Depth to water bMP (Ft)
Static Water Elevation on 3/9/20 (ft NAVD88)	1337.7	5.2
Top of Aquifer Elevation from well log (ft NAVD88)	1206	135
50 % threshold (ft NAVD88)	1275.2	66
25 % threshold (ft NAVD88)	1238.93	104

**As monitored by the Deep Observation Well*

Water levels in the Deep Observation well during the Production well aquifer test dropped to an elevation of 1292.07 feet as measured by the data logger. This shows that after pumping seven days, the Production well did not breach the 50% threshold for the Browerville Sands 3 aquifer at the site. Pumping the Production well **alone** for a typical 3-day-irrigation cycle is not expected to breach the 50% threshold for the Browerville Sands 3 aquifer.

The forward solution modeling described above and in Appendix B was used to evaluate water levels in this aquifer when both the East Irrigation and the Production well are pumping. This model calculates that water levels in the Browerville Sands 3 aquifer are expected to drop 70 feet if both wells are pumping. This is equivalent to an elevation of 1271 ft. This is 4 feet above the 50% threshold and could be an indication that pumping both wells simultaneously may adversely impact the aquifer over time, especially if both wells pump at the same time. However, if the wells are not pumped together and are not pumped for over seven days at a time, it is unlikely that this threshold will be breached.

It is recommended that the East Irrigation and Production wells alternate pumping (both should not pump at the same time). In addition, monitoring of the Deep and Shallow Observation wells should be conducted when pumping either well. The rates and volumes pumped from both the East and Production wells should be recorded for each irrigation cycle. The monitoring data and the pumping information should be submitted to DNR after the irrigation season ends each year. This data can be compared to the thresholds shown in Table 10.

Northwest Irrigation well (Browerville Sands 2 Aquifer)

Safe yield cannot be accurately analyzed for the Browerville Sands 2 aquifer because there is not an aquifer test or monitoring well associated with the NW Irrigation well aquifer. It is recommended that either an aquifer test or a use-season test over one irrigation season be conducted on the NW Irrigation well.

If conducted, the aquifer test should consist of using this well as a pumping well, installation of a nearby monitoring well nest (one completed in the pumped aquifer and one completed in the unconfined aquifer) and installation of a stream gage in the river. This test could provide better estimates of leakage, stream flow depletion and impacts on the source aquifer.

Alternatively, a use-season test can be conducted. Similar to the aquifer test, a nest of observation wells should be installed near the NW Irrigation well (one well completed in the pumped aquifer and one completed in the unconfined aquifer). The wells should be monitored during the irrigation season along with exact pumping information. The production well must be equipped with a properly installed flow meter. Pumping information should include each irrigation cycle's time on and time off, along with flow meter readings at the beginning and end of each irrigation cycle. The data should be provided to DNR at the end of the irrigation season and will be used to estimate the impacts from pumping this well on the nearby water resources and the source aquifer.

Conclusion

DNR found that the aquifer test results showed:

- The Production well and East Irrigation well are completed within the confined Browerville Sands 3 aquifer.
- The NW Irrigation well is completed within the shallower confined Browerville Sands 2 aquifer.
- Both confined aquifers are leaky confined aquifers.
- Aquifer testing indicates the Browerville Sands 3 aquifer is a channelized sand and gravel aquifer with at least two no-flow (barrier) boundaries. These boundaries also likely apply to the Browerville Sands 2 aquifer but further testing would be needed to confirm this.
- One domestic well (Nolte 714382) is at high risk and two wells (Roggenkamf 552894 and Pickar 123614) are at moderate risk for well interference from pumping the Production well alone. This moderate risk could be mitigated by lowering the pump intake in these wells.
- Three domestic wells (Nolte 714382, Rucks 727163, and Roggenkamf 552894) are at high risk and two wells are at moderate risk (Nelson 190935 and Pickar 123614) for well interference from pumping the East Irrigation well alone. This risk could be mitigated by lowering the pump intake in these wells.
- Several nearby domestic wells are at high risk for well interference if all three irrigation wells pump at the same time. The increased high risk could be mitigated by either alternating the pumping of the wells (i.e., don't pump all wells at the same time) or by replacing the at risk wells with deeper wells and pumps set lower in the wells.
- Eleven domestic wells (Plautz, Seibert, Whitaker, Hugget, Connell, Parkos, Lilleodden, Hoskins, Salo, Robberstad, and McDonald) are at unknown well interference risk from pumping any of the proposed irrigation wells. Well construction information from these wells is missing but could be evaluated if provided.
- Seven domestic wells (Ashman, five Hayes wells, and Jones-no unique numbers) are at low well interference risk from pumping any of the proposed irrigation wells. These wells are completed in the unconfined aquifer and pumping impacts would be minimal.
- Stream depletion of the Redeye River was modeled at 0.04, 0.03 and 1 cfs from pumping the East Irrigation, Production well and NW Irrigation well respectively. It is unknown if this amount of

stream depletion, in particular that from the NW irrigation well, would negatively impact the Redeye River without the August mean base flow analysis for this river.

- It is not expected that the East Irrigation well and the Production well pumping will impact nearby wetlands when pumping.
- The NW Irrigation well impacts on nearby wetlands could not be evaluated due to a lack of high quality aquifer parameters for the Browerville Sands 2 aquifer. An aquifer test or irrigation season use and monitoring would help evaluate potential impacts to surface water features.

Recommendations

Recommendations include:

- The August mean base flow analysis should be requested from the DNR Water Monitoring and Surveys Unit. The impacts to the Redeye River from pumping the proposed irrigation wells can then be re-evaluated.
- An aquifer test or use-season test should be completed on the Northwest Irrigation well. This information would also help refine evaluation of impacts on nearby domestic wells, wetlands, the Redeye River and the source aquifer. This would require:
    - Installation of a flow meter capable of measuring rate (gallons per minute) and volume (total gallons pumped) on the Northwest Irrigation well.
    - Recording pump operation details, including date and time of pump on and off, pumping rate and pumping volume for each irrigation cycle.
    - The installation of a nest of observation wells near the Northwest Irrigation well; one well completed in the source aquifer, the other completed in the unconfined aquifer. The wells would need to be surveyed to NAVD88 (vertical) and NAD83 zone 15 N meters (horizontal) and instrumented with data loggers set to take water levels every minute.
    - The installation of a stream gage in the Redeye river near the site. The gage would need to collect both stage and flow readings and be surveyed to NAVD88 (vertical) and NAD83 zone 15 N meters (horizontal).
    - DNR would provide or need to approve a detailed test plan for this work.
- Establish the two-tier aquifer threshold (Table 10) as a permit condition for both the Production well and East Irrigation well permits. The Deep Observation well (841474) should be used to monitor these thresholds for the Browerville Sands 3 aquifer.
- Monitoring, using data loggers, of the Deep (841474) and Shallow (841475) Observation wells near the Production well should be conducted hourly, and the data submitted via email to DNR at: Region1_WaterData.dnr@state.mn.us
- The rates and volumes pumped from both the East and Production wells should be recorded for each irrigation cycle along with the exact pump on and off time for the first season. The monitoring data and the pumping information should be submitted to DNR after the irrigation season ends.

The data will be evaluated to validate the aquifer test findings and need for further detailed pumping date/times.

- An operational plan to mitigate the highest well interference risk should be developed. This plan should include alternate pumping schedules (i.e., wells should not pump at the same time). If an operational plan is not developed, the following wells need to be replaced at a deeper depth to avoid an out-of-water domestic well interference:
  - Tom Nelson (190935)
  - Brian Boe (695127)
  - Nolte (714382)
  - John Rucks (727163)
  - Jake Nolte (828390)
  - Bob Pickar (123614)
- The following wells need to be modified (pump intakes should be lowered) to address single irrigation well pumping impacts:
  - Nolte (unique #714382)
  - Roggenkamf (unique #552894)
  - Pickar (unique #123614)
  - Rucks (unique #727163)
- Well construction information for the eleven domestic wells without information should be collected by the permittee and provided to MNDNR. If information is unobtainable, then the well owners should be provided with information on reporting well interference.

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List of Figures

Figure 1. Location Map for Permit Applications 2017-4235, 4236, 4237

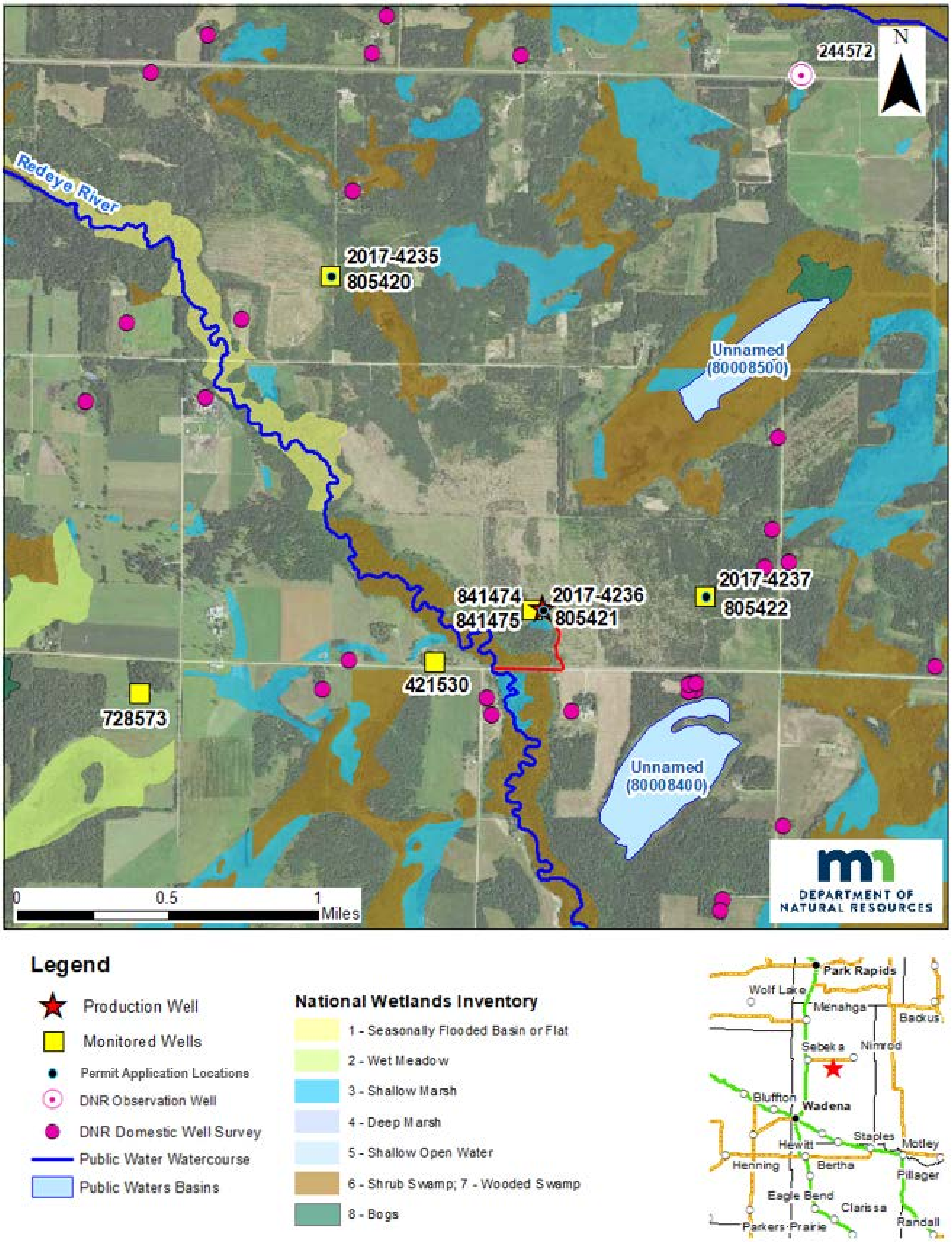


Figure 2. Surficial geology of Wadena County, MN (modified after Lusardi and Marshall, 2016)

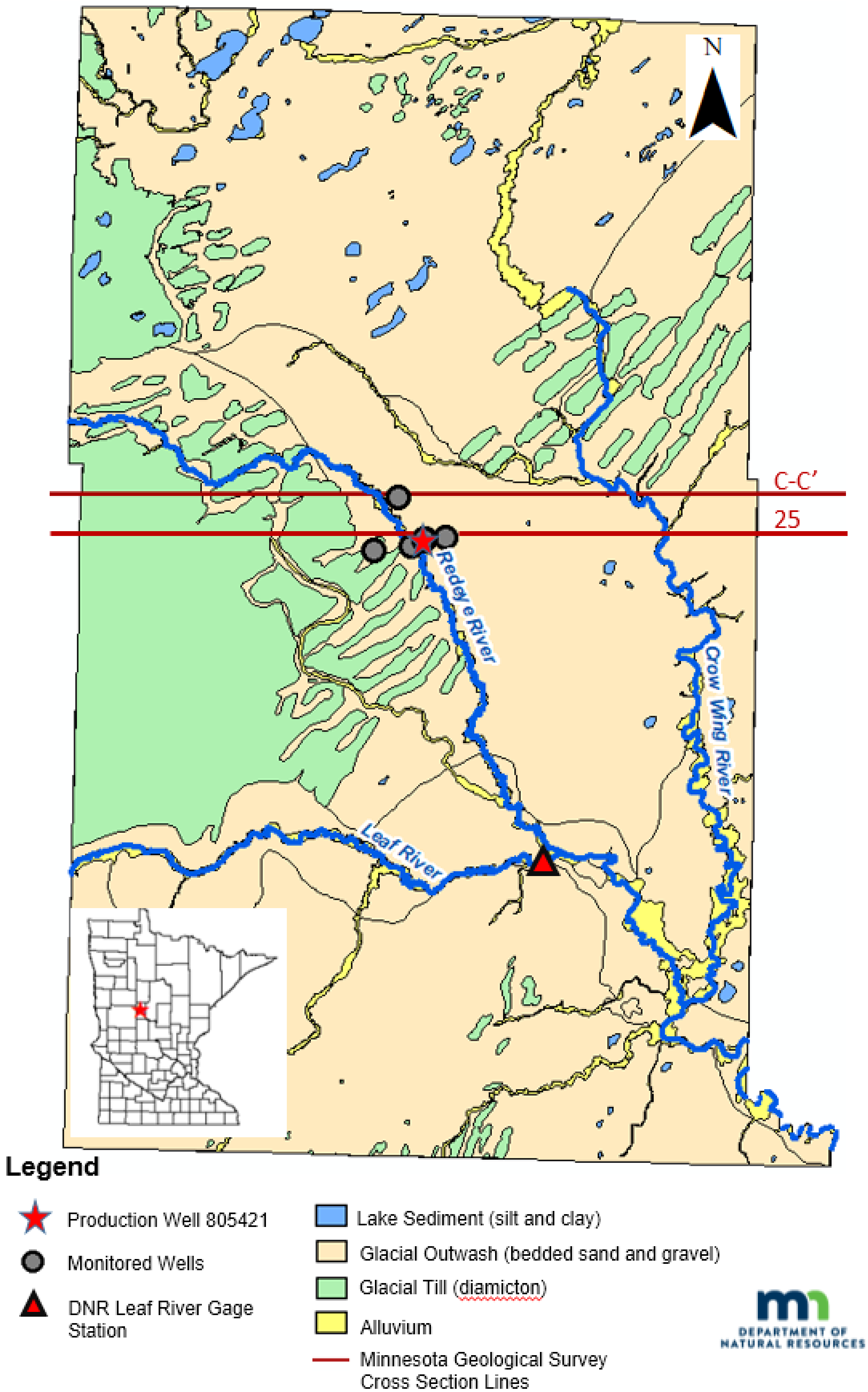


Figure 3. Legend for County Geologic Atlas Cross Sections (Lusardi, 2016)

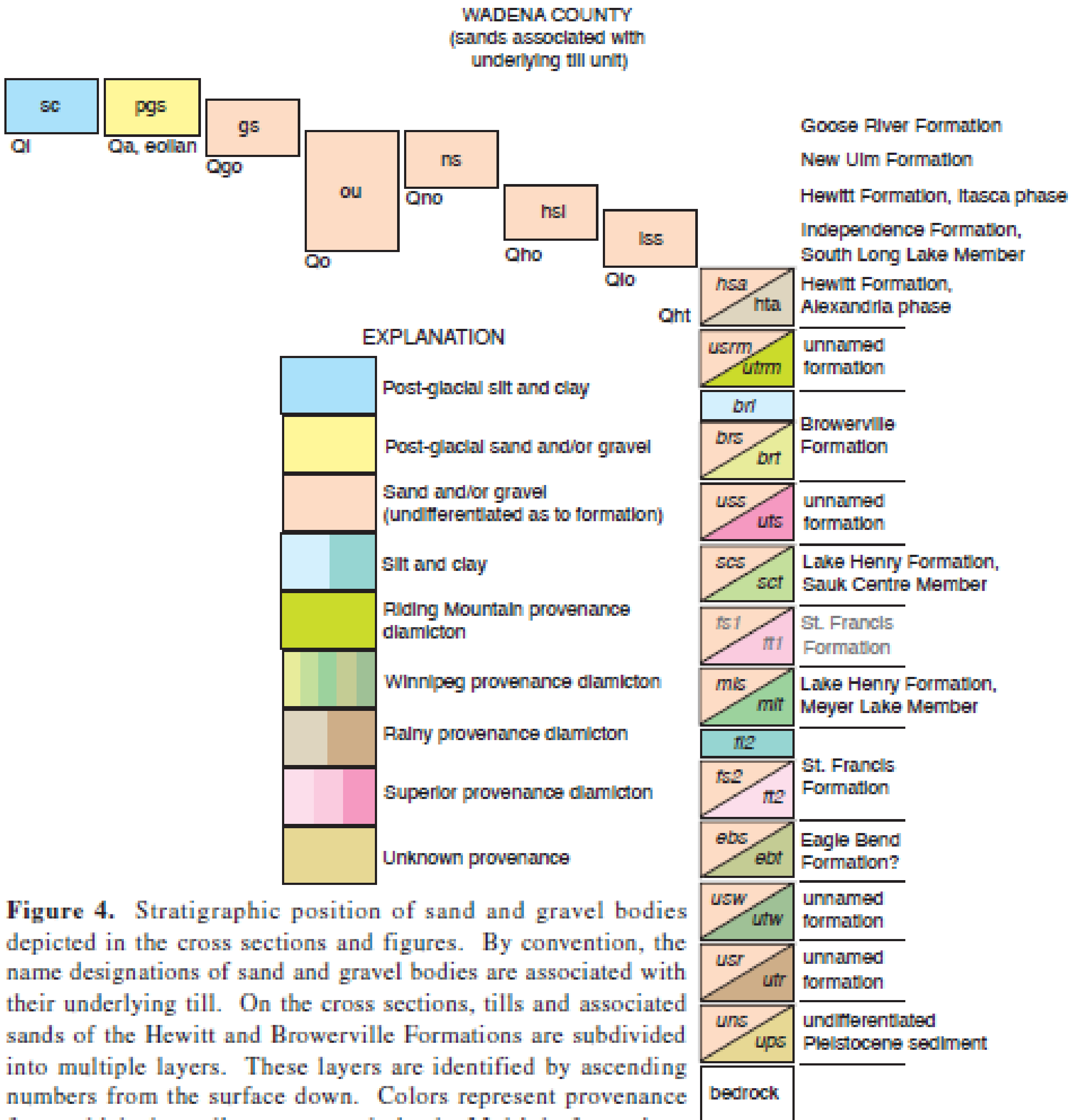
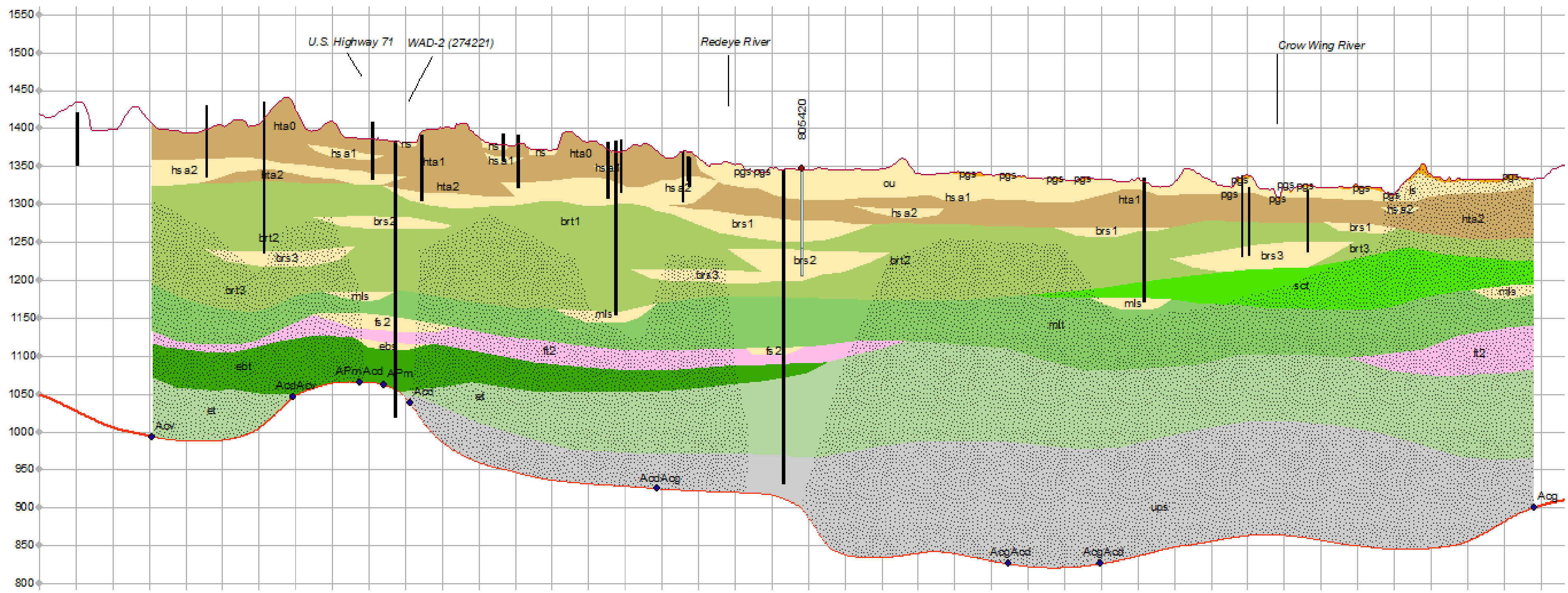


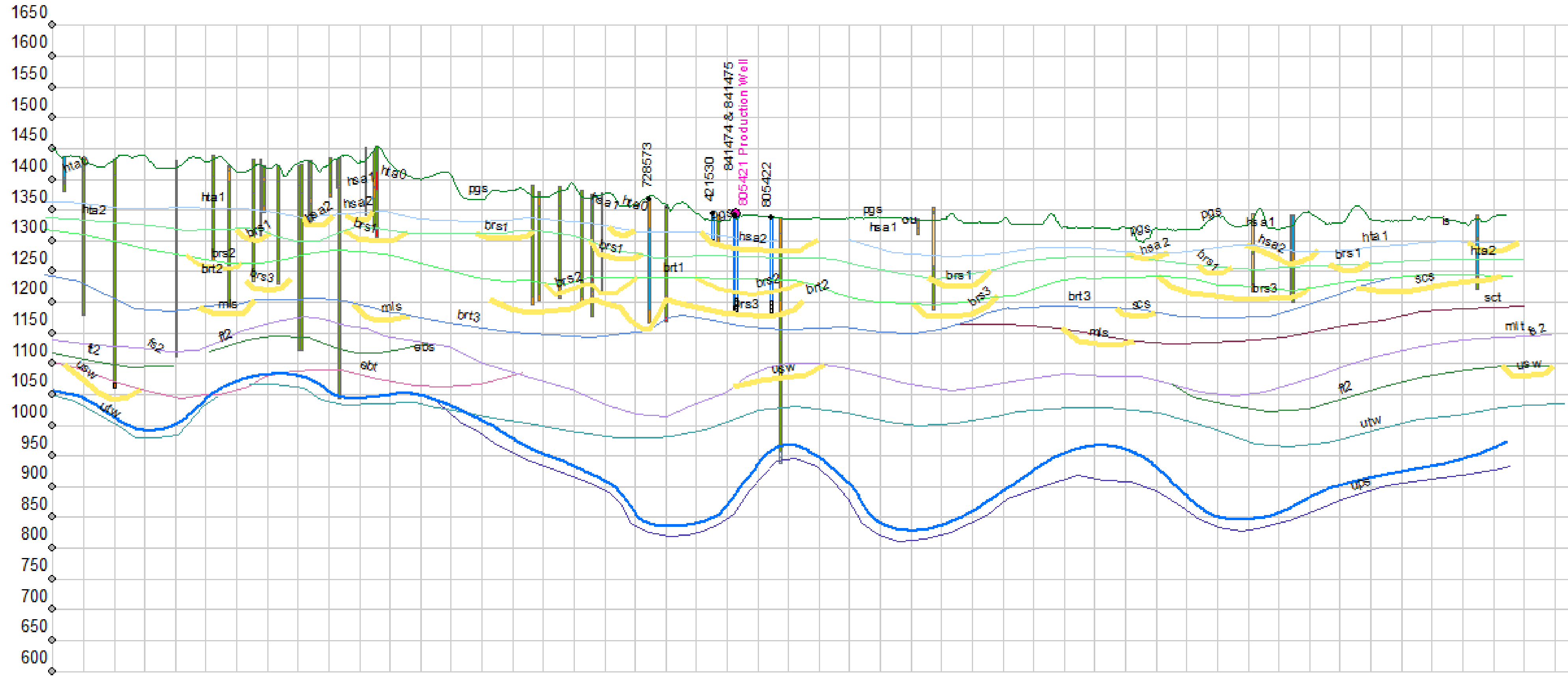
Figure 4. Stratigraphic position of sand and gravel bodies depicted in the cross sections and figures. By convention, the name designations of sand and gravel bodies are associated with their underlying till. On the cross sections, tills and associated sands of the Hewitt and Browerville Formations are subdivided into multiple layers. These layers are identified by ascending numbers from the surface down. Colors represent provenance from which the sediments were derived. Multiple formations from the same provenance are distinguished by shades of the base color. Gray text indicates units found in the regional stratigraphy but not encountered in drill holes in Wadena County. Associated surficial map unit labels are shown, where appropriate, beneath the stratigraphic unit boxes and labels.

Figure 4. Wadena County Geologic Atlas Cross Section C-C’



Elevation (ft MSL) on Y axis, Distance (50 meter squares) on X axis. Refer to Figure 3 for legend.

Figure 5. Wadena County Geologic Atlas Cross Section 25



Elevation (ft MSL) on Y axis, Distance (50 meter squares) on X axis. Refer to Figure 3 for legend.

Figure 6. Production Well 805421 Hydrograph

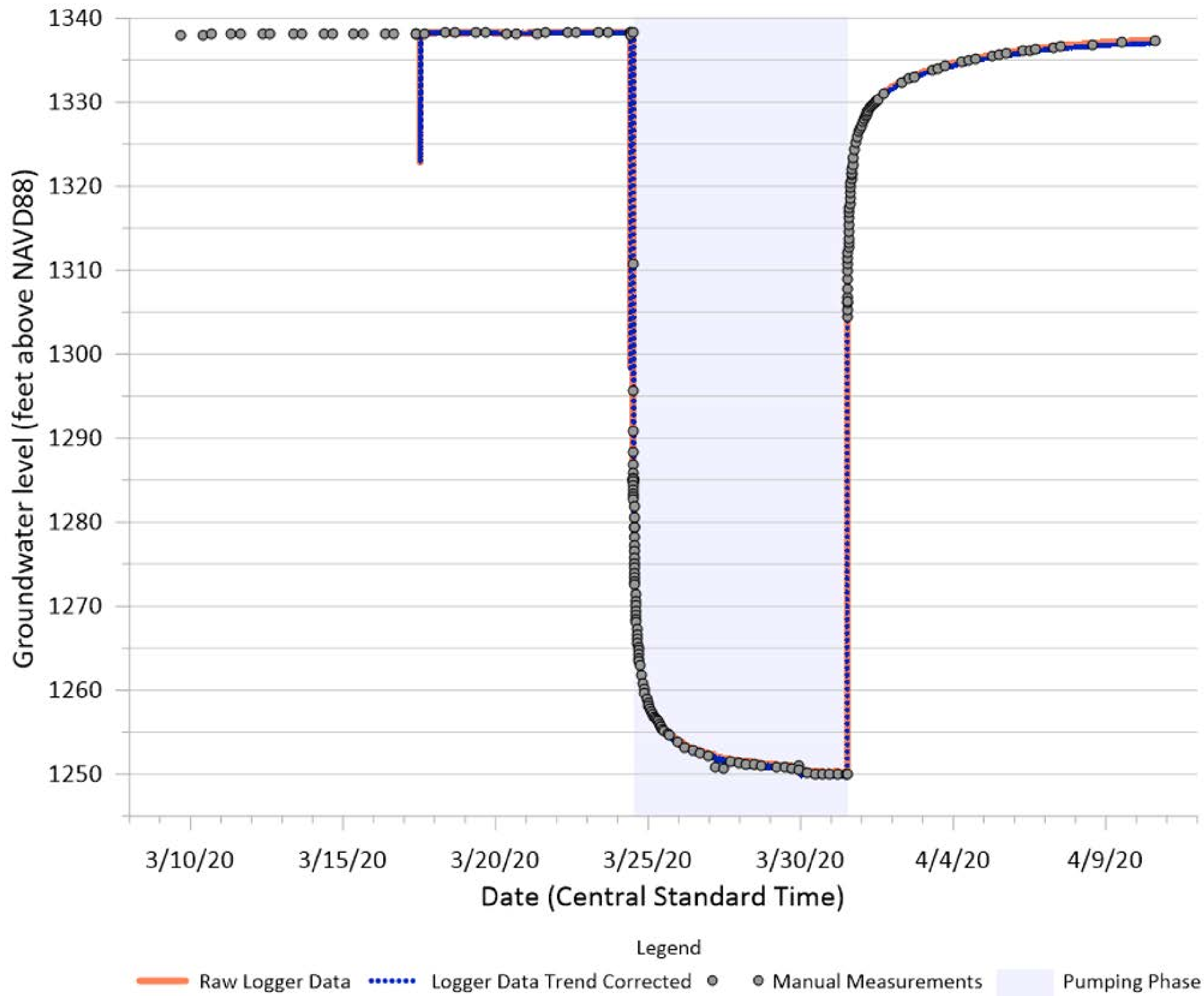
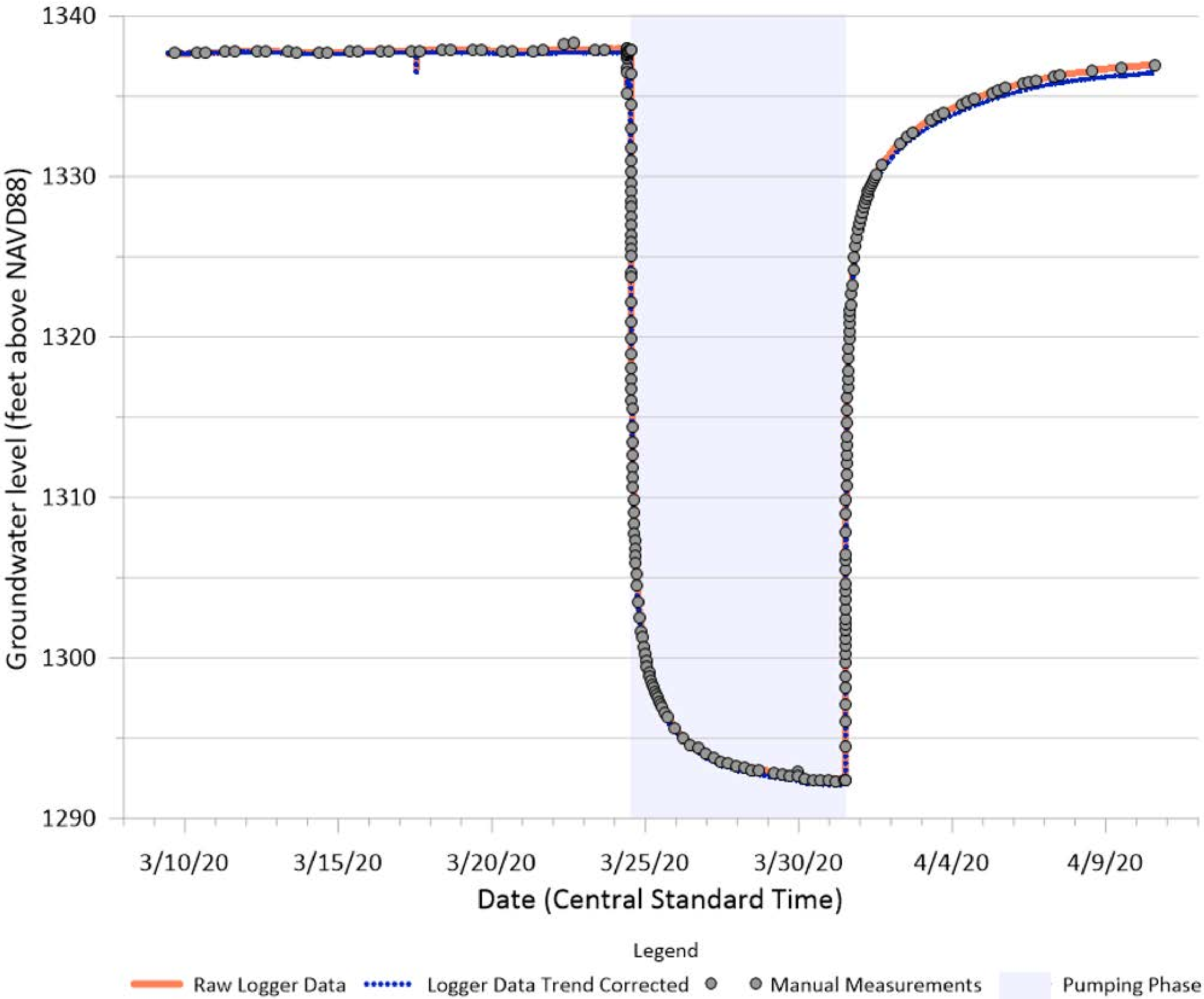


Figure 7. Deep Observation Well 841475 Hydrograph



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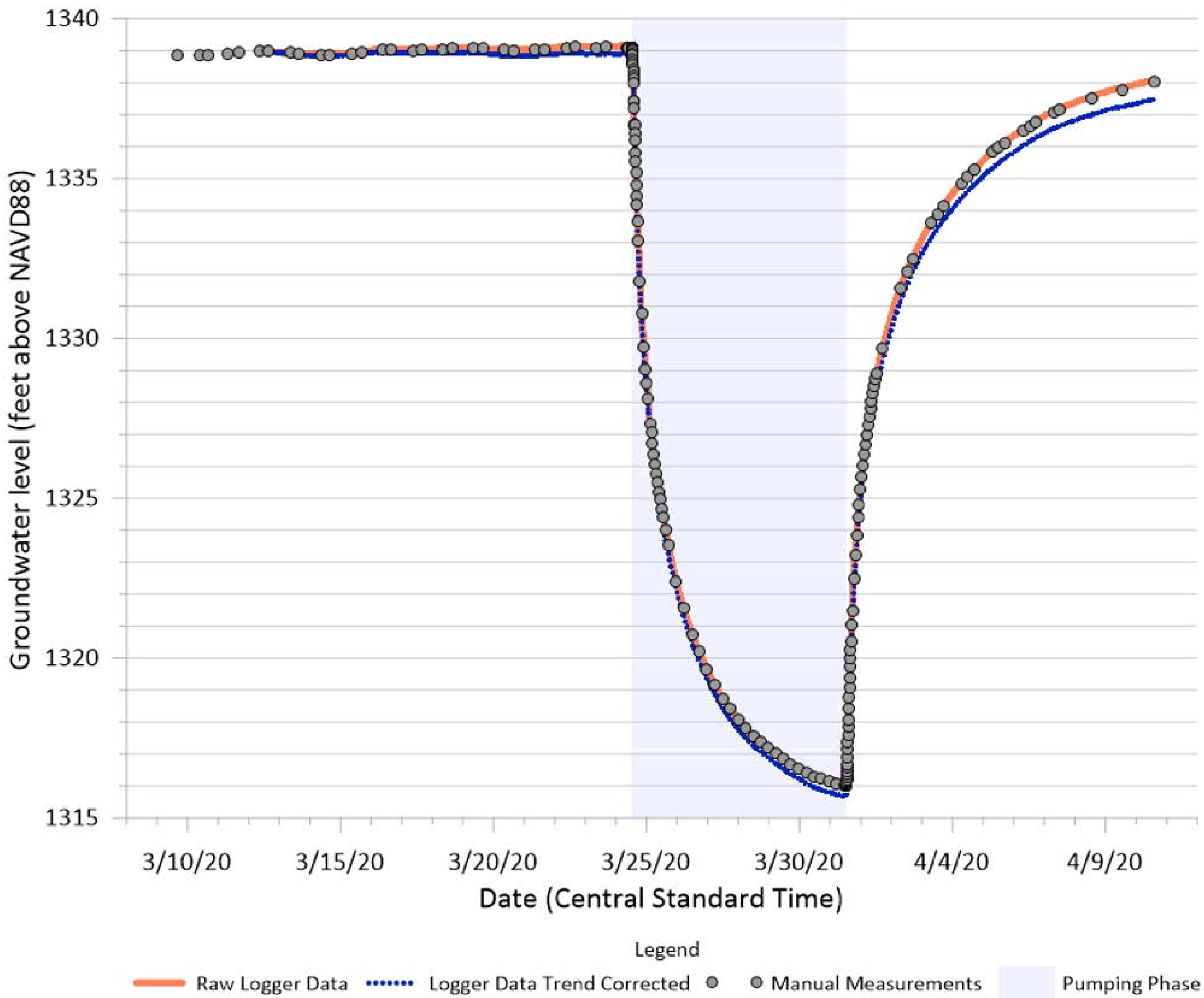

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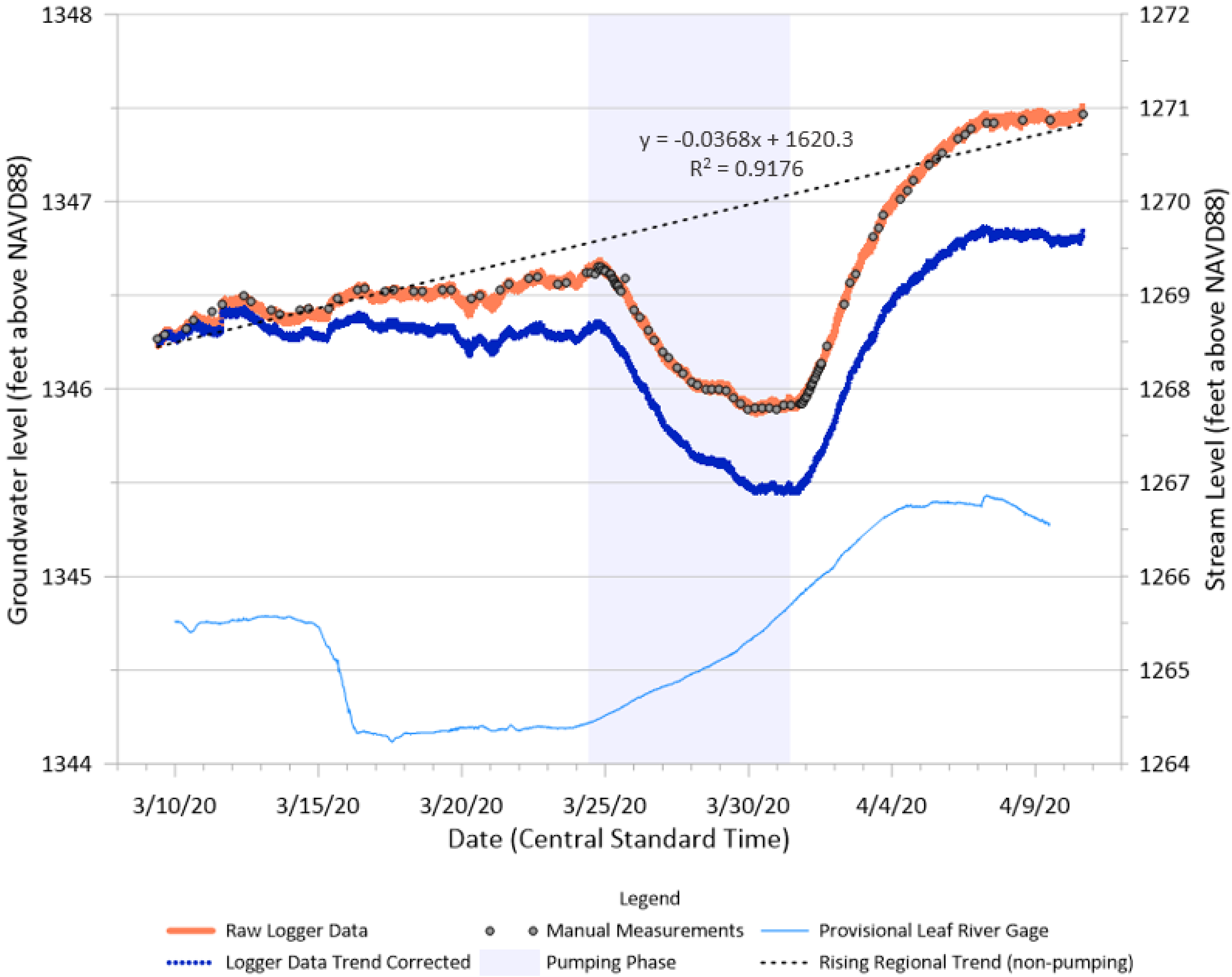


Figure 10. Shallow Obwell & Eckenrude Domestic Well Hydrograph with Precipitation & Leaf River Data

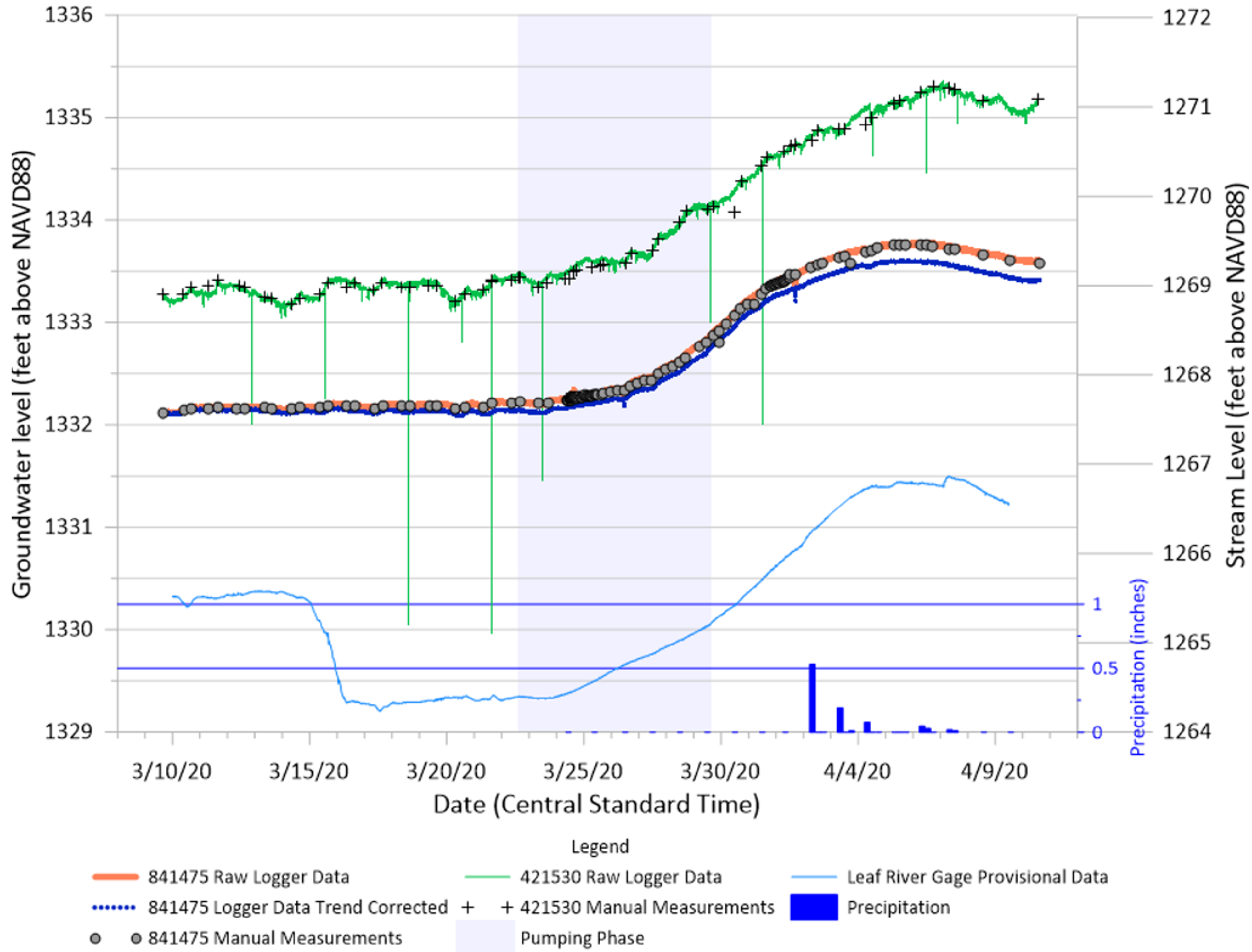


Figure 11. Proposed Irrigation wells and Deep Obwell Hydrographs with Precipitation

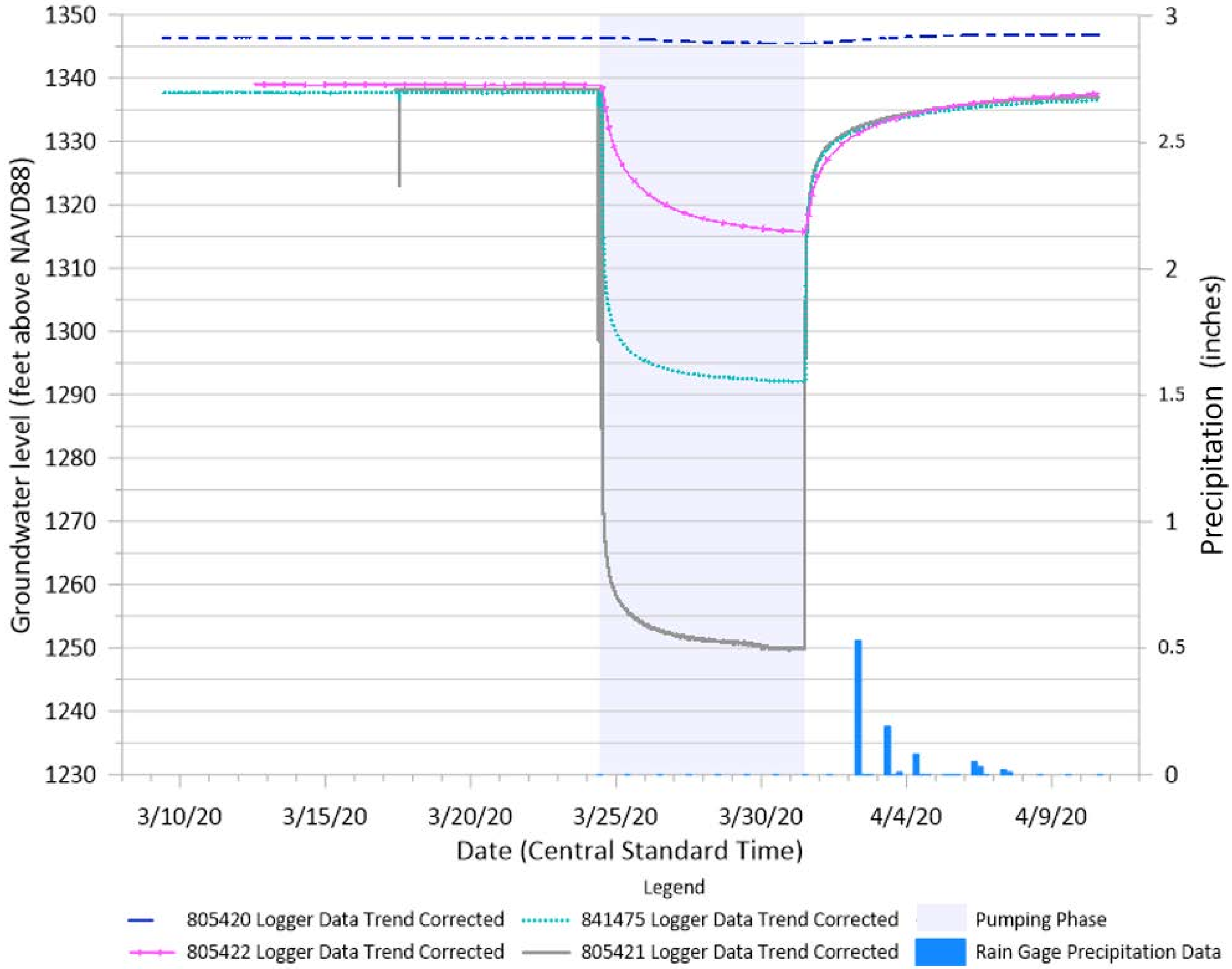


Figure 12. Caponera Domestic Well 728573 Hydrograph

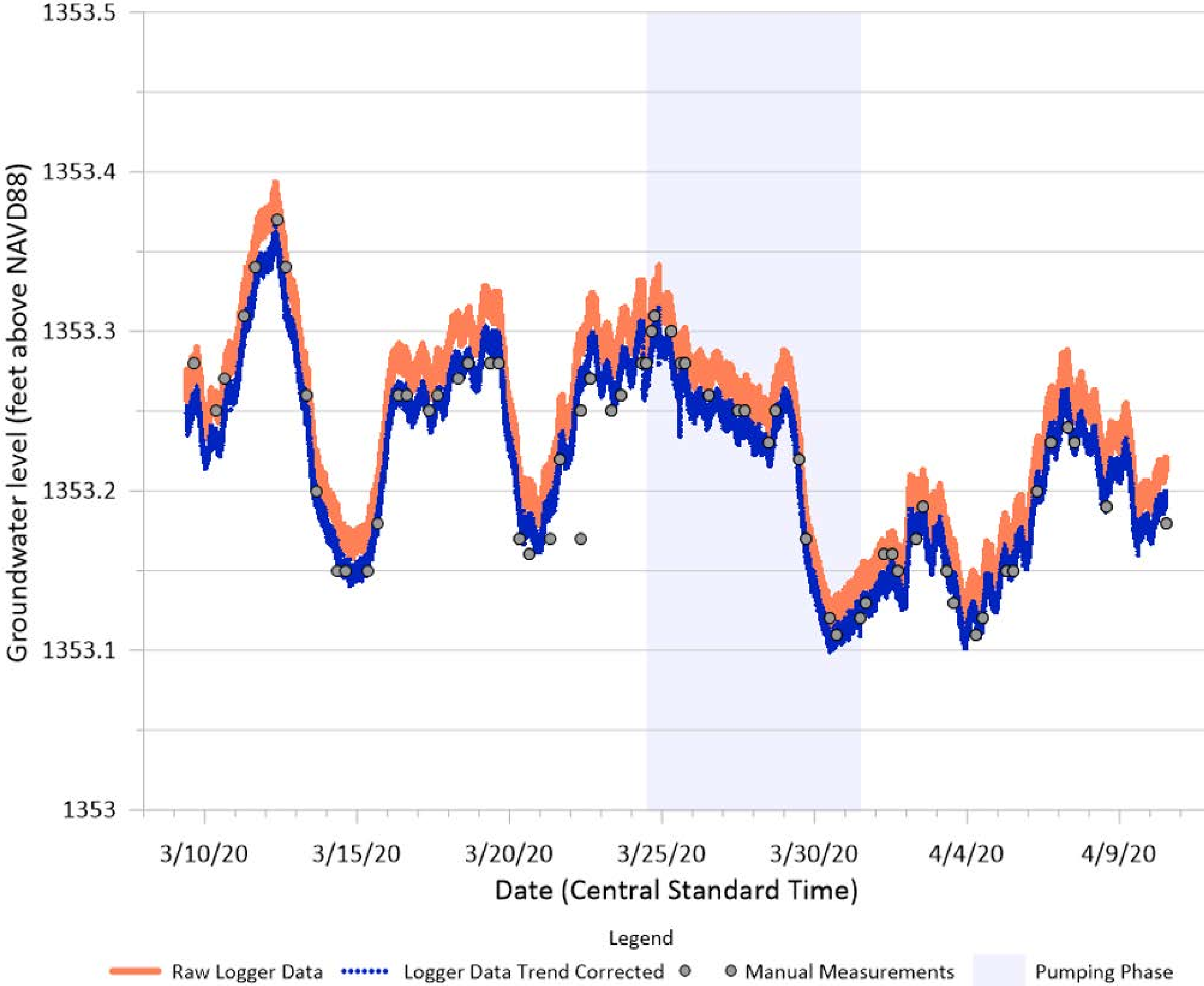
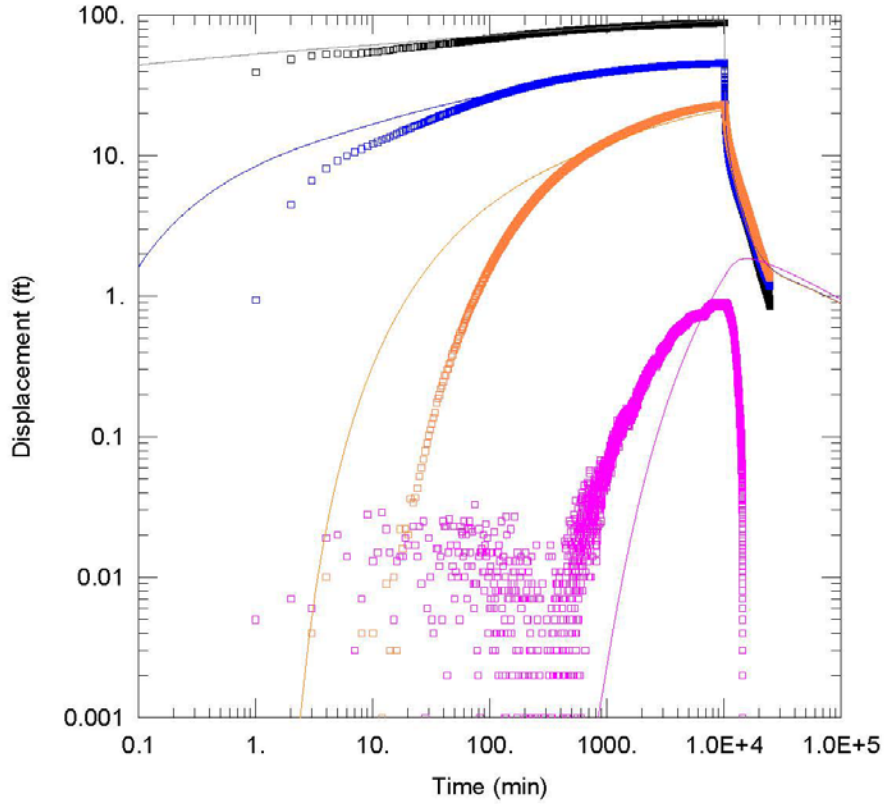


Figure 13. AQTESOLV Neuman-Witherspoon Solution



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteAT2020filteredNWSp.aqt
Date: 05/07/20 Time: 15:08:25

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

AQUIFER DATA

Saturated Thickness: 20. ft
Aquitard Thickness (b'): 37. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 10. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
▫ 805421	1146969.321	16939144.14
▫ Deep Obwell 841474	1146768.908	16939132.83
▫ East Irrig 805422	1149817.921	16939361.15
▫ NWIrrig805420	1143225.12	16945005.37

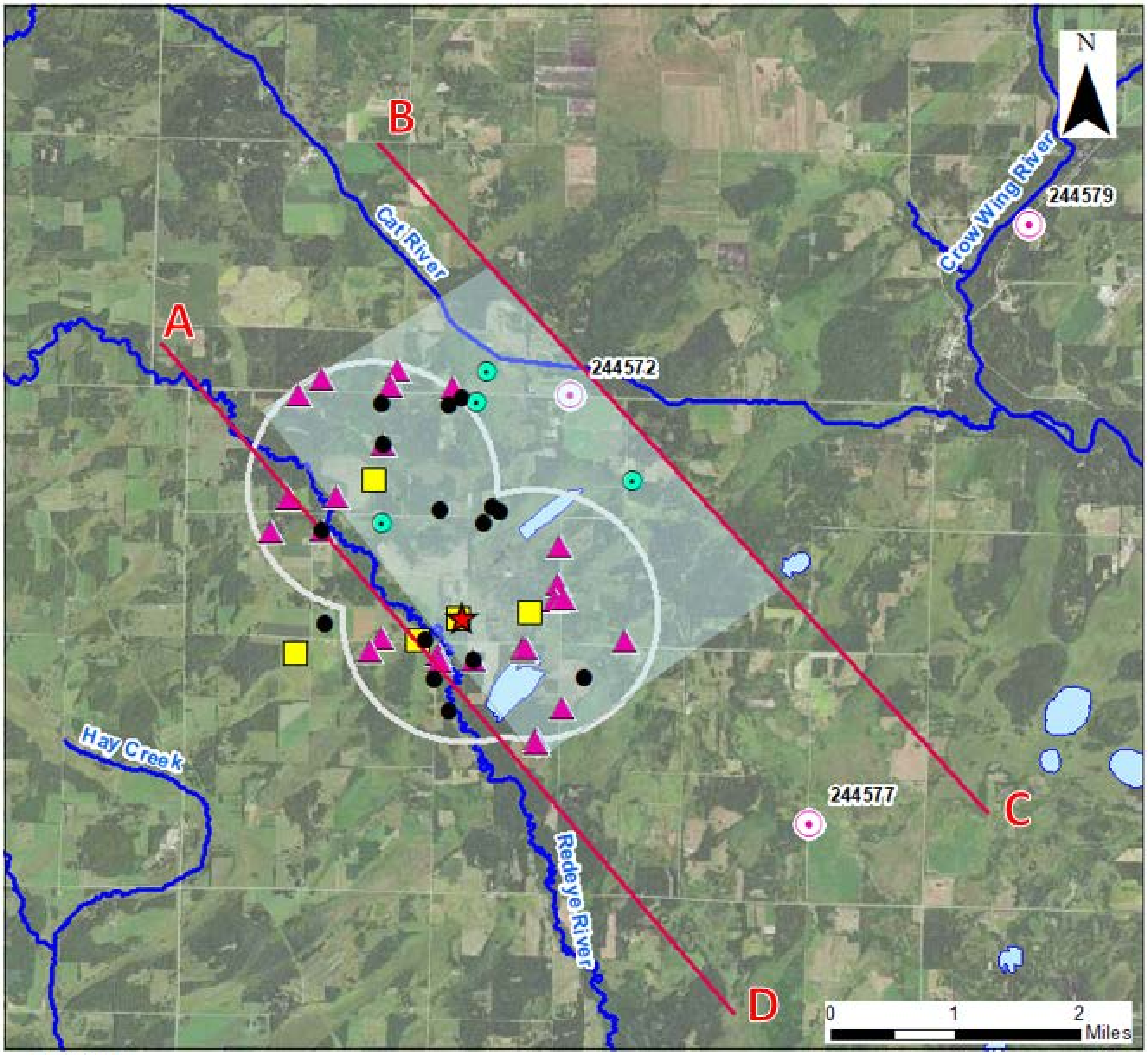
SOLUTION

Aquifer Model: Leaky
Solution Method: Neuman-Witherspoon

T = 3067. ft^2/day
1/B = 9.86E-5 ft^{-1}
T2 = 5000. ft^2/day

S = 1.34E-5
ß/r = 9.447E-5 ft^{-1}
S2 = 0.001

Figure 14. Domestic Well Risk Evaluation Area



Legend

- CWI - Unverified Wells
- CWI - Verified Wells
- BarrierBoundaries
- Production Well
- Monitored Wells
- DNR Domestic Well Survey
- DNR Observation Well
- Domestic Well Risk Evalution Area
- 1 Mile Buffer Around Permit Applications
- Public Water Watercourse
- Public Waters Basins

Base Data: MN DNR Quicklayers: Minnesota Public Water Delineations, Minnesota County Well Index
Coordinate System: NAD 1983 UTM Zone 15N
Prepared By: amyourd **Date Saved:** 5/18/2020

DEPARTMENT OF NATURAL RESOURCES

Figure 15. Proposed Irrigation Wells and Nearby Surface Water Features

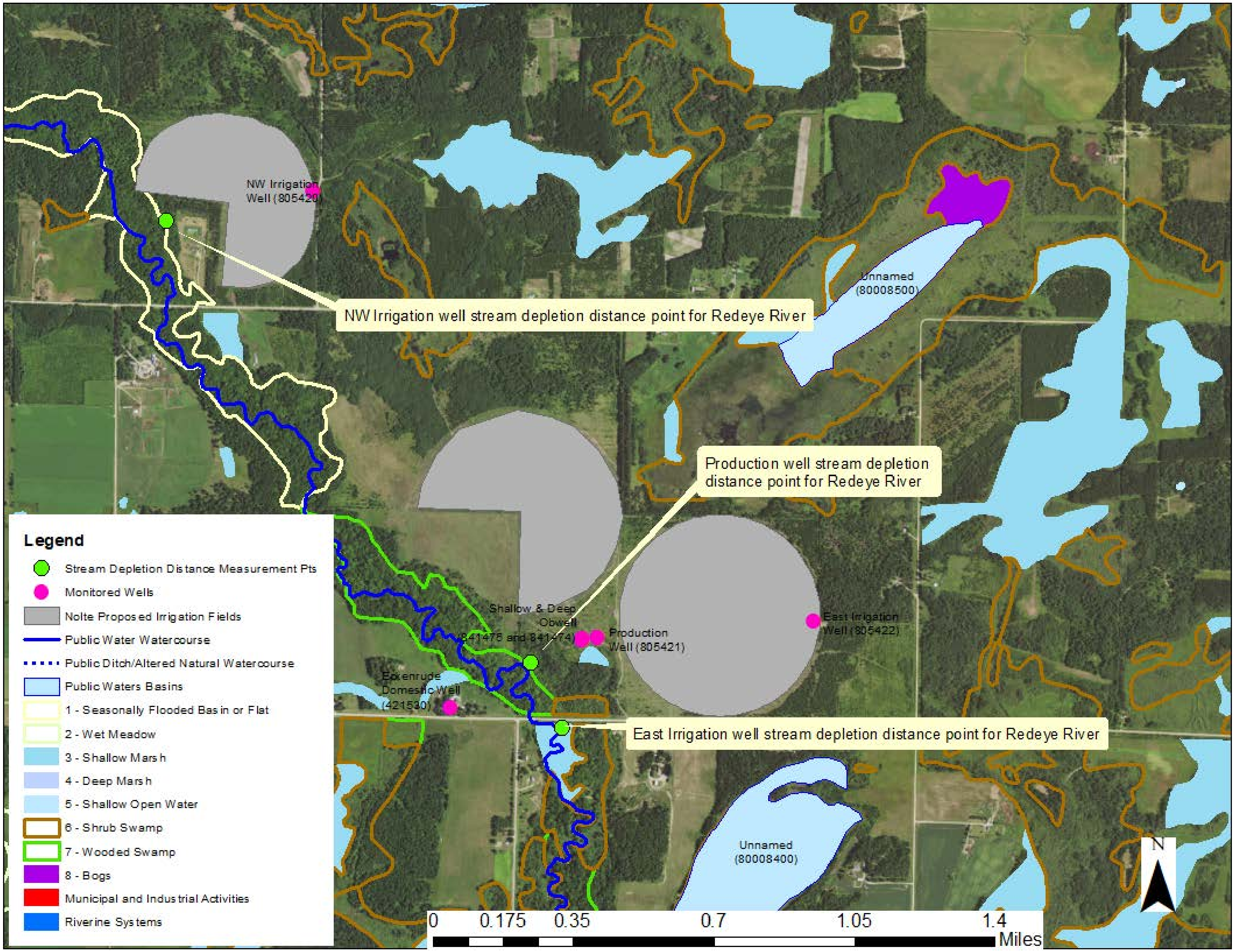
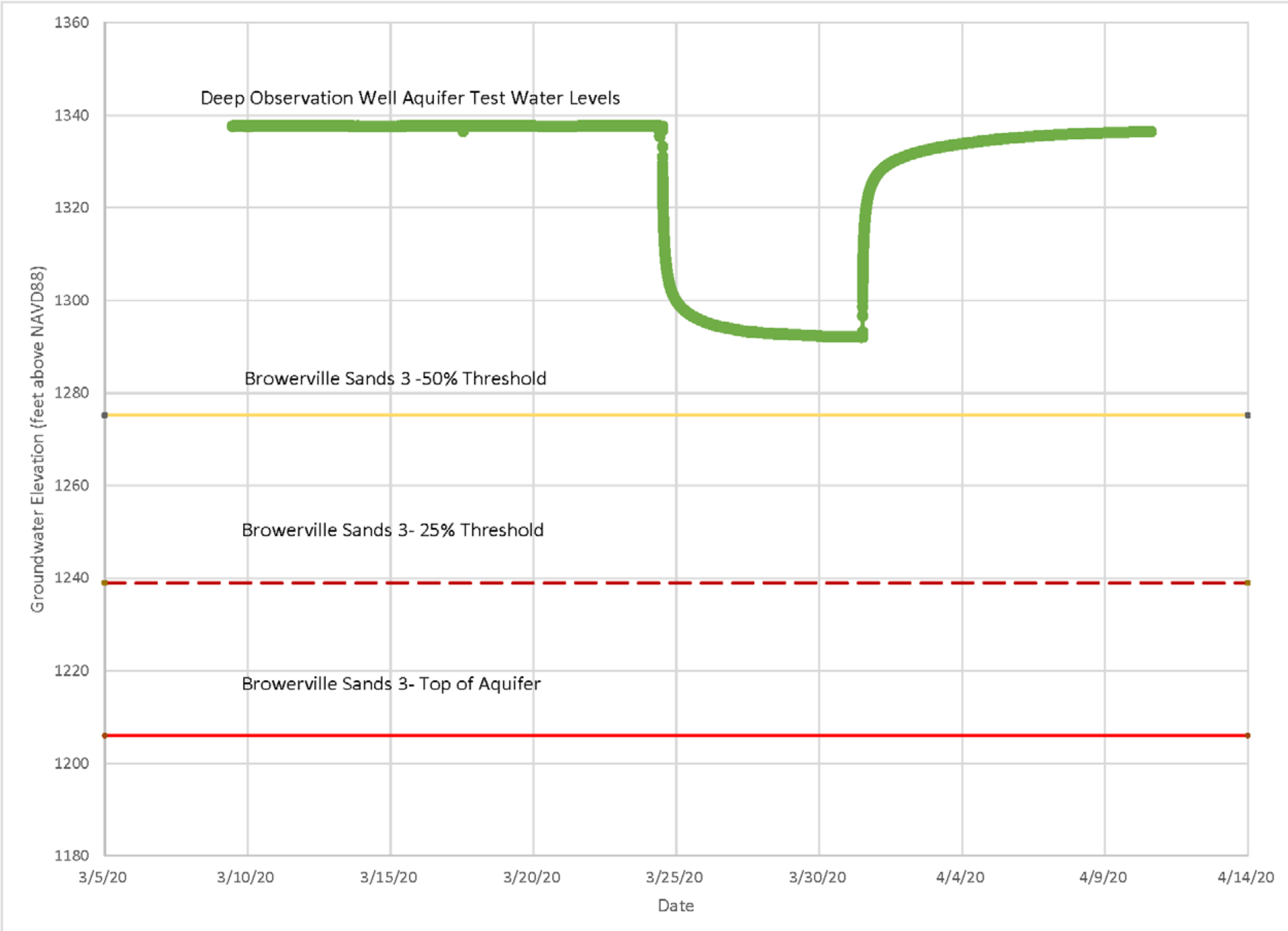


Figure 16: Production and East Irrigation well Thresholds*

*using the Deep Observation well



Appendix A. Flow meter measurements

Figure A-1. Production well flow meter set-up

Table A-1. Flow meter measurements

Date/time (CST)	Pumping Rate (gpm)	Flow Meter Reading (gallons x 100)	Initials of Person Measuring	Interval Elapsed Time (minutes) from Pump Start 3/24/20 13:30	Pumping gallons between readings	Pumping interval rate (gallons/minute)	Difference between flow meter pumping rate vs calculated interval rate
3/24/20 8:00		506559.5	KA				
3/24/20 12:25		506565.5	DW				
3/24/20 12:30		506565.5	DW	0.0			
3/24/20 12:30	760	506569.3	DW	0.5	3.8	760	0
3/24/20 12:31	800	506573.3	DW	0.5	4	800	0
3/24/20 12:31	800	506577.3	DW	0.5	4	800	0
3/24/20 12:32	840	506581.5	DW	0.5	4.2	840	0
3/24/20 12:32	760	506585.3	DW	0.5	3.8	760	0
3/24/20 12:33	800	506589.3	DW	0.5	4	800	0
3/24/20 12:33	840	506593.5	DW	0.5	4.2	840	0
3/24/20 12:34	800	506597.5	DW	0.5	4	800	0
3/24/20 12:34	800	506601.5	DW	0.5	4	800	0
3/24/20 12:35	800	506605.5	DW	0.5	4	800	0
3/24/20 12:36	820	506613.7	DW	1.0	8.2	820	0
3/24/20 12:37	780	506621.5	DW	1.0	7.8	780	0
3/24/20 12:38	820	506629.7	DW	1.0	8.2	820	0
3/24/20 12:39	800	506637.7	DW	1.0	8	800	0
3/24/20 12:40	830	506646	DW	1.0	8.3	830	0
3/24/20 12:42	825	506662.5	DW	2.0	16.5	825	0
3/24/20 12:44	825	506679	DW	2.0	16.5	825	0
3/24/20 12:45	800	506687	DW	1.0	8	800	0
3/24/20 12:50	790	506726.5	DW	5.0	39.5	790	0
3/24/20 12:55	800	506767.5	DW	5.0	41	820	-20
3/24/20 13:00	790	506807	DW	5.0	39.5	790	0
3/24/20 13:05	800	506847	DW	5.0	40	800	0
3/24/20 13:10	800	506887	DW	5.0	40	800	0
3/24/20 13:15	800	506927	DW	5.0	40	800	0
3/24/20 13:20	790	506966.5	DW	5.0	39.5	790	0
3/24/20 13:25	790	507006	DW	5.0	39.5	790	0
3/24/20 13:30	800	507046	DW	5.0	40	800	0
3/24/20 13:35	800	507086	DW	5.0	40	800	0
3/24/20 13:40	790	507125.5	DW	5.0	39.5	790	0
3/24/20 13:50	810	507206.5	DW	10.0	81	810	0
3/24/20 13:52	850	507223.5	DW	2.0	17	850	0

Date/time (CST)	Pumping Rate (gpm)	Flow Meter Reading (gallons x 100)	Initials of Person Measuring	Interval Elapsed Time (minutes) from Pump Start 3/24/20 13:30	Pumping gallons between readings	Pumping interval rate (gallons/minute)	Difference between flow meter pumping rate vs calculated interval rate
3/24/20 14:00	869	507293	DW	8.0	69.5	869	0
3/24/20 14:12	783	507387	DW	12.0	94	783	0
3/24/20 14:20	813	507452	DW	8.0	65	812	1
3/24/20 14:30	830	507535	DW	10.0	83	830	0
3/24/20 14:35	770	507573.5	DW	5.0	38.5	770	0
3/24/20 14:40	810	507614	DW	5.0	40.5	810	0
3/24/20 14:45	800	507654	DW	5.0	40	800	0
3/24/20 15:00	807	507775	DW	15.0	121	807	0
3/24/20 15:15	840	507901	DW	15.0	126	840	0
3/24/20 15:30	773	508017	DW	15.0	116	773	0
3/24/20 15:45	807	508138	DW	15.0	121	807	0
3/24/20 16:00	800	508258	DW	15.0	120	800	0
3/24/20 16:15	803	508378.5	DW	15.0	120.5	803	0
3/24/20 16:30	803	508499	DW	15.0	120.5	803	0
3/24/20 16:45	840	508625	DW	15.0	126	840	0
3/24/20 17:00	767	508740	DW	15.0	115	767	0
3/24/20 17:15	810	508861.5	DW	15.0	121.5	810	0
3/24/20 17:34	803	509014	DW	19.0	152.5	803	0
3/24/20 19:50	800	510102	DW	136.0	1088	800	0
3/24/20 20:03	807	510207	DW	13.0	105	808	-1
3/24/20 20:48	798	510566	KA	45.0	359	798	0
3/24/20 21:30	796	510901.5	DW	42.0	335.5	799	-3
3/24/20 22:37	797	511435	DW	67.0	533.5	796	1
3/24/20 23:45	798	511977.5	DW	68.0	542.5	798	0
3/25/20 0:37	798	512392.5	DW	52.0	415	798	0
3/25/20 1:35	797	512855.5	DW	58.0	463	798	-1
3/25/20 2:46	797	513421.5	DW	71.0	566	797	0
3/25/20 3:35	798	513813	KJ	49.0	391.5	799	-1
3/25/20 4:35	798	514292	KJ	60.0	479	798	0
3/25/20 5:35	798	514771	KJ	60.0	479	798	0
3/25/20 6:35	795	515248	KJ	60.0	477	795	0
3/25/20 7:35	796	515725.5	KJ	60.0	477.5	796	0
3/25/20 8:35	795	516202.5	KJ	60.0	477	795	0
3/25/20 10:20	798	517038	KA	105.0	835.5	796	2
3/25/20 10:35	793	517157	KA	15.0	119	793	0

Date/time (CST)	Pumping Rate (gpm)	Flow Meter Reading (gallons x 100)	Initials of Person Measuring	Interval Elapsed Time (minutes) from Pump Start 3/24/20 13:30	Pumping gallons between readings	Pumping interval rate (gallons/minute)	Difference between flow meter pumping rate vs calculated interval rate
3/25/20 11:35	798	517635.5	KA	60.0	478.5	798	0
3/25/20 12:43	797	518177.5	KA	68.0	542	797	0
3/25/20 15:36	793	519549.5	KJ	173.0	1372	793	0
3/25/20 17:04	792	520247	KJ	88.0	697.5	793	-1
3/25/20 19:02	796	521181		118.0	934	792	4
3/25/20 23:11	798	523165	KA	249.0	1984	797	1
3/26/20 5:00	800	525950	D	349.0	2785	798	2
3/26/20 11:33	798	529086.5	KJ	393.0	3136.5	798	0
3/26/20 17:03	800	531726.5	KJ	330.0	2640	800	0
3/26/20 23:09	800	534655	KA	366.0	2928.5	800	0
3/27/20 5:00	800	537463	D	351.0	2808	800	0
3/27/20 11:27	798	540550.5	KJ	387.0	3087.5	798	0
3/27/20 17:03	795	543221.5	KJ	336.0	2671	795	0
3/27/20 23:28	793	546273.5	DW	385.0	3052	793	0
3/27/20 23:29	750	546281	DW	1.0	7.5	750	0
3/28/20 5:00	797	548904	D	331.0	2623	792	5
3/28/20 11:24	805	551966.5	KJ	384.0	3062.5	798	7
3/28/20 17:03	797	554668.5	KJ	339.0	2702	797	0
3/28/20 23:00	796	557510	KA	357.0	2841.5	796	0
3/29/20 5:00	796	560377	D	360.0	2867	796	0
3/29/20 11:24	797	563437.5	KJ	384.0	3060.5	797	0
3/29/20 17:04	801	566162	KJ	340.0	2724.5	801	0
3/29/20 23:00	796	568995.5	KA	356.0	2833.5	796	0
3/30/20 5:10	798	571948.5	KJ	370.0	2953	798	0
3/30/20 11:28	798	574963.5	KJ	378.0	3015	798	0
3/30/20 17:01	796	577614	KJ	333.0	2650.5	796	0
3/30/20 22:54	794	580416	KA	353.0	2802	794	0
3/31/20 5:00	791	583310	D	366.0	2894	791	0
3/31/20 11:27	790	586369	KJ	387.0	3059	790	0
3/31/20 12:30	792	586868	KA	63.0	499	792	0

Appendix B. AQTESOLV Diagnostic Plots and Analysis

The data from the Production well, the Deep Observation well and the East Irrigation well were first analyzed using the diagnostic flow plots to determine the type of flow regime that may exist in the pumped aquifer per the recommended procedures for using AQTESOLV (Duffield, 2007).

The diagnostic plots of the Production well, Deep Observation well and East Irrigation well show:

- The pumped aquifer is receiving **recharge**, either through leakage or a constant head boundary, as evidenced by the following:
  - The composite plot (Figure B-1) shows that early on, the aquifer is behaving as a confined aquifer (the three wells have the same slope early on). Towards the end of the test, the wells deviate from that slope, indicating leakage or recharge to the system.
  - The radial flow plots of both the Deep Observation well (Figure B-2) and the East Irrigation well (Figure B-3) show a 1:1 unit slope during the test. This is also an indication that there is leakage or recharge to the system.
  - The derivative plots of the three wells (Figure B-4) show the derivative rapidly approaches zero as the test progresses, which is also an indication of leakage to the pumped aquifer.
- The Deep Observation well derivative plot shows a plateau in the first 10 minutes followed by a change in slope. This is an indication of a **no-flow boundary** (Figure B-4) that was quickly reached when pumping started. This means the boundary is close to the well.
- The bilinear flow diagnostic plots for both the Deep Observation well (Figure B-5) and the East Irrigation well (Figure B-6) show a 1:1 unit slope at mid to late time, respectively. This is an indication of a **channel type aquifer system** (2 no-flow boundaries).

Following the diagnostics, evaluation of the data began using the Theis (1935) confined solution (Figure B-7) on the wells completed within the pumped aquifer (Production well, Deep Observation well and East Irrigation wells). This was done to obtain the pumped aquifer transmissivity (T) and storativity (S). The diagnostics (Figure B-8) show that the T and S are a good fit for the pumped aquifer.

The next step is to incorporate the boundary conditions and leakage observed during the test.

The no-flow boundary locations were identified as follows:

- The first no-flow boundary was placed between the pumped well and the Caponera well as shown by Line A-D in Figure B-9 and Figure 14. Evidence for this location includes:
  - The Caponera well did not respond to pumping, even though this well is completed in the same aquifer as the Production well. This well is approximately twice as far from the pumped well as the East irrigation well. It should have exhibited about half the amount of drawdown as the East Irrigation well if no boundaries exist between it and the pumped well.

- According to the diagnostics, the no-flow boundary was observed within the first 10 min of the test in the Deep Observation well, indicating that the no-flow boundary must be close to the pumped well.
- The Wadena County Geologic Atlas (Lusardi, 2016) shows that channelized glacial meltwater flowed through the area from the NW to the SE following the approximate path of the Redeye River (Figure B-10). This deposited materials make up the Browerville and Hewitt Formations. The depositional environment of the glacial meltwater likely resulted in a channel deposit, with thicker sandier material towards the center of the channel and thinner finer material on the edges of the channel. The edges of the channel would coincide with the boundaries observed in the aquifer test data and the southern channel edges is close to the current Redeye River location. Therefore, the no-flow boundary was placed close to the Redeye river shown by line A-D in Figure B-9 and Figure 14. This is near where the Wadena-lobe till and drumlin area is located on the edge of the outwash deposit; just south and west of the wells and close to the Red Eye River.
- Placing a boundary location here allowed the AQTESOLV modeling to match the observed response during the aquifer test.

- The location of the second no-flow boundary was placed based on the glacial history noted in Figure B-10 and discussed above. It was assumed that this boundary would also be located where the Wadena-lobe till and drumlin area borders the glacial outwash area northeast of the monitored well. The location was moved iteratively closer to the monitored wells until a best fit to the observed data was seen in Aqtesolv. The final boundary location is shown in Line B-C of Figure B-9.
- Note that AQTESOLV is not able to use complex boundary conditions and boundaries need to be parallel or at right angles to each other. Therefore, the geologic boundaries were simplified into straight parallel lines as shown in Figure B-9 and Figure 14. In addition, in glacial deposits, no-flow boundaries generally are caused by changes in geologic material rather than physical boundaries. This means that drawdown may propagate through the boundaries but it is much less than inside the boundaries.

Leakage into the system was modeled by the Neuman-Witherspoon (1969) leaky confined two aquifer solution. This solution was deemed the best fit to the geology of the area and the response seen in the aquifer test. The geology of the area as indicated by the Wadena County Geologic Atlas (Lusardi, 2016) shows at least two confined aquifers near the monitored wells. In addition, the shallower confined aquifer, in which the NW irrigation well is completed, showed a response to pumping indicating that it provides water to the pumped aquifer either through direct connection, leakage, or both.

Generally, the Neuman Witherspoon (1969) solution relies on an observation well completed in the shallow confined aquifer above the pumped aquifer to calculate the aquifer and leakage parameters. Unfortunately, the only well completed in the shallower confined system is the NW Irrigation well and this well is too far away from the Production well to obtain reliable aquifer and leakage parameters for the shallow system. The response of the NW Irrigation well to the rising Redeye river during the test indicates that this shallow confined aquifer is also a leaky or in direct connection to the River. Therefore, the shallow confined aquifer S was estimated as 0.001 using literature values (Driscoll, 1968). The shallow confined aquifer T was estimated from the limited specific capacity data collected when the NW Irrigation well was installed in 2014. Both the Hantush (1960; Figure B-11) and the Cooley Case (1973; Figure B-12) solution were used to evaluate this data to give a range of values for T of approximately 2700 to 5500 ft^2/day. Note that because this was a single well test, S and leakage values cannot be calculated reliably. These two solutions fit the geologic data from the site the best and resulted in conductivity values ranging from 75 to 150 ft/day. These conductivity values fit within literature values (Duffield, 2007) for sands; the source aquifer material for the wells. A T value of 5000 ft^2/day was chosen to represent this system as it fit the aquifer test data the best in AQTESOLV.

To get more precise shallow confined aquifer parameters, an aquifer test using the NW Irrigation well as the pumping well would need to be conducted.

The shallow confined aquifer parameters, the two parallel straight barrier (no-flow) boundaries shown in Figure B-9 and the pumped aquifer T and S values obtained with the Theis Solution were used in the Neuman Witherspoon (1969) solution method in AQTESOLV.

The assumptions for this solution are shown in Table B-1 along with the sites ability to meet each assumption.

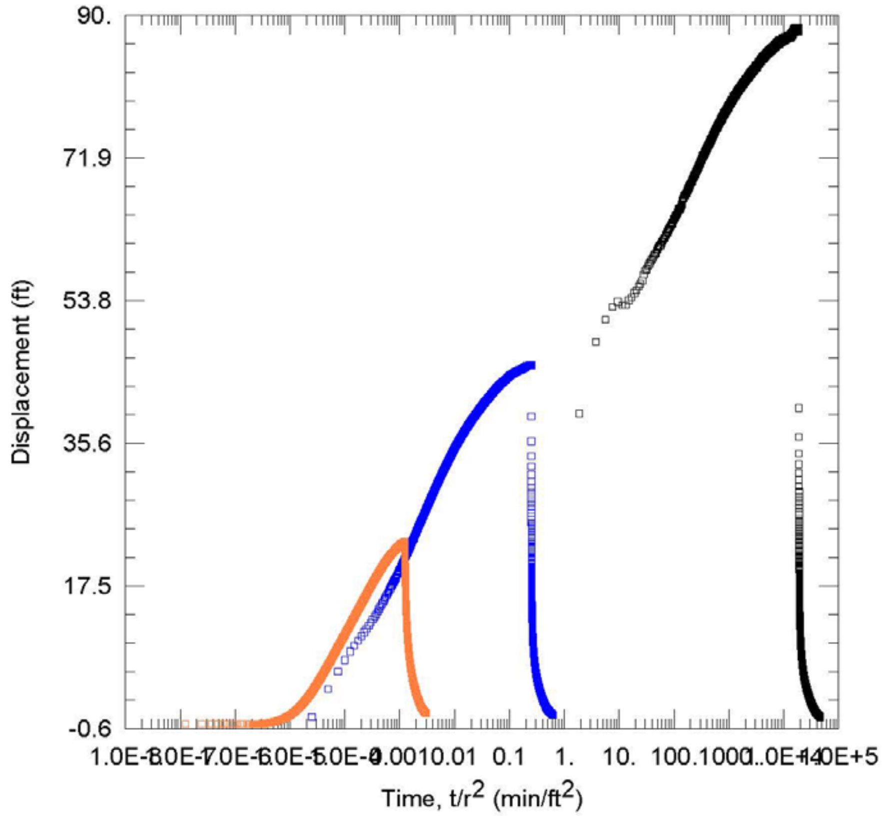
The final pumped aquifer storativity (S) was adjusted in AQTESOLV to better match observed values. Figure 13 and Table 8 of the main report contain the final AQTESOLV report and calculated aquifer parameters.

Table B-1. Neuman-Witherspoon solution assumptions

Neuman-Witherspoon (1969) assumptions	Site ability to meet assumption
aquifer has infinite areal extent	this is Unknown but is a common assumption for most solution methods
aquifer is homogeneous, isotropic and of uniform thickness	this is probably not the case due to variabilities in glacial deposition but is a common assumption for most solution methods
pumping well is fully penetrating	Well log documents this
flow to pumping well is horizontal	this is Unknown but is a common assumption for most solution methods
aquifer is leaky confined	Site geology documents this
flow is unsteady	this is Unknown but is a common assumption for most solution methods
water is released instantaneously from storage with decline of hydraulic head	this is Unknown but based on the response to pumping is likely
diameter of pumping well is very small so that storage in the well can be neglected	Although the pumped well had well bore storage, the placement of the Deep observation well close to the Production well mitigated this

Neuman-Witherspoon (1969) assumptions	Site ability to meet assumption
confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, storage coefficient and thickness	This is Unknown and not likely. However it is a common assumption for most solution methods
flow is vertical in the aquitard(s)	this is Unknown but is a common assumption for most leaky confined solution methods

Figure B-1. Composite Plot of Production, Deep Observation, and East Irrigation Well



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteAT2020filtered.aqt
Date: 05/05/20 Time: 15:55:38

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

AQUIFER DATA

Saturated Thickness: 20. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b'): 37. ft
Aquitard Thickness (b"): 10. ft

WELL DATA

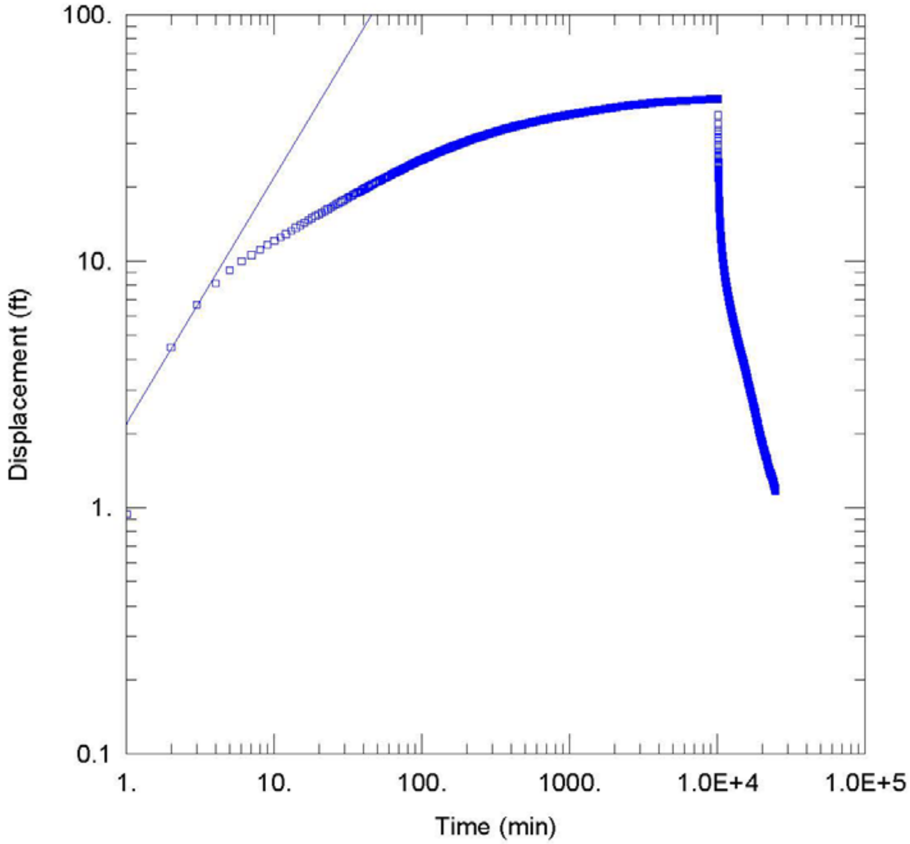
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
▫ 805421	1146969.321	16939144.14
▫ Deep Obwell 841474	1146768.908	16939132.83
▫ East Irrig 805422	1149817.921	16939361.15

Figure B-2. Radial Flow Plot of Deep Observation Well (841474)



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteRadialFlowplots.aqt
Date: 05/05/20 Time: 15:27:35

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

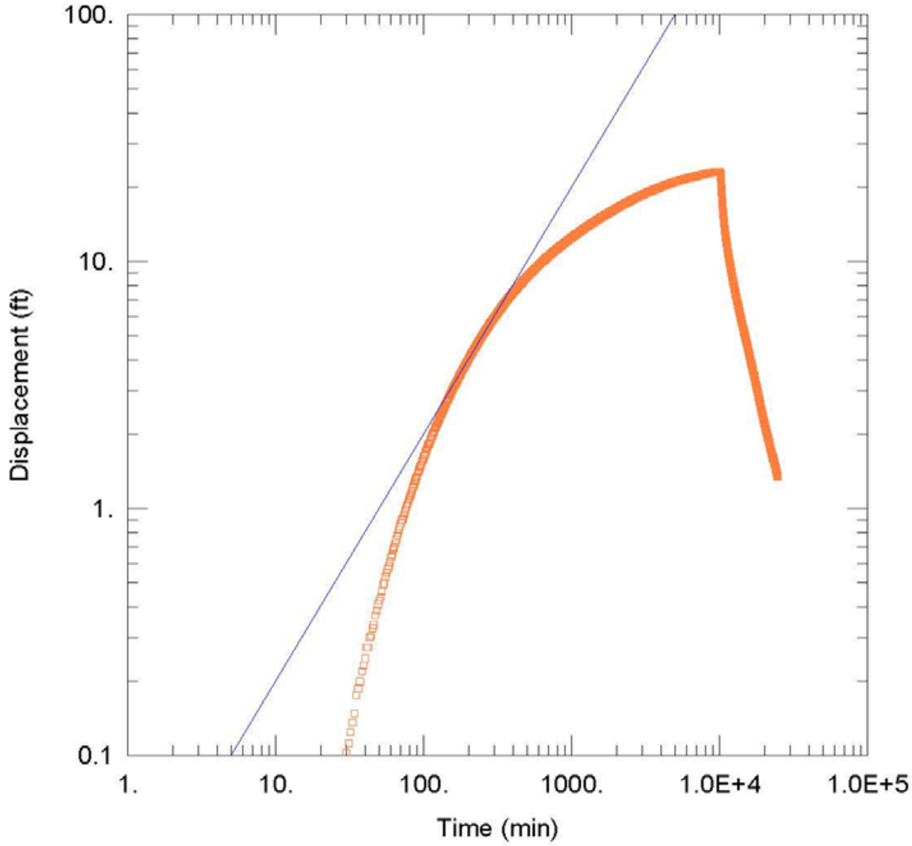
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
Deep Obwell 841474	1146768.908	16939132.83

Figure B-3. Radial Flow Plot of East Irrigation Well (805422)



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteRadialFlowplots.aqt
Date: 05/05/20 Time: 15:29:13

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

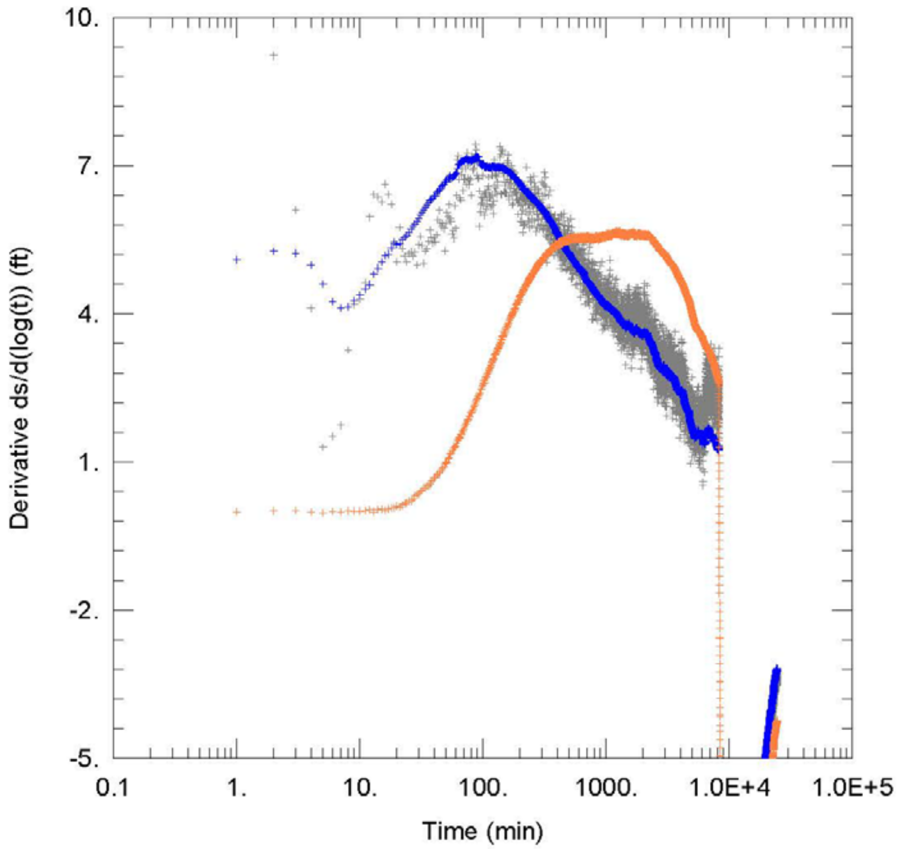
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
▫ East Irrig 805422	1149817.921	16939361.15

Figure B-4. Derivative Plot of Production, Deep Observation, and East Irrigation Well



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteATDerivplots.aqt
Date: 05/05/20 Time: 15:08:13

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

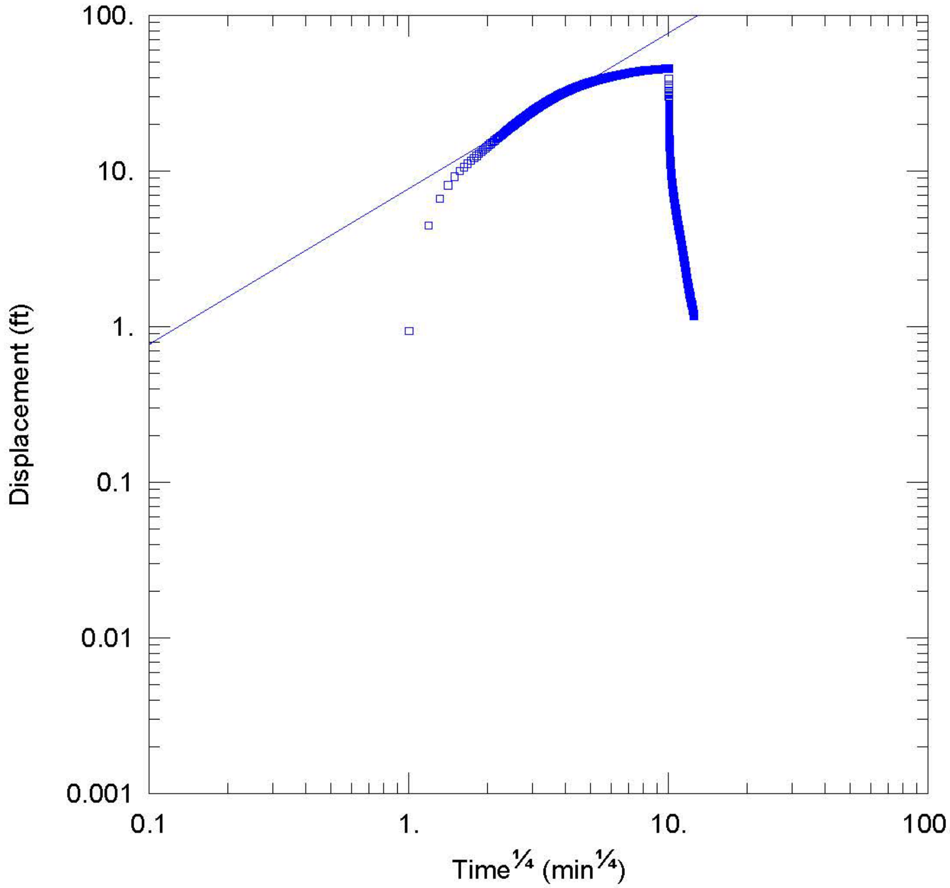
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14
Deep Obwell 841474	1146768.908	16939132.83
East Irrig 805422	1149817.921	16939361.15

Figure B-5. Bilinear Flow Diagnostic Plot of Deep Observation Well (841474)



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteAT2020filtered.aqt
Date: 05/05/20 Time: 14:53:53

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

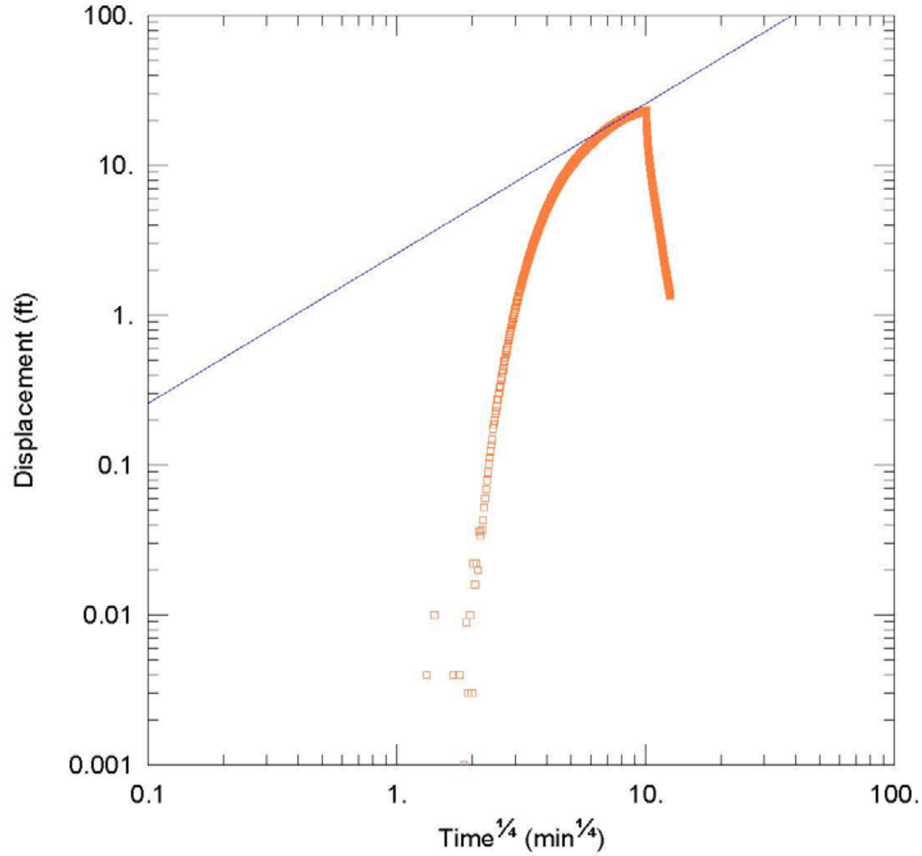
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
Deep Obwell 841474	1146768.908	16939132.83

Figure B-6. Bilinear Flow Diagnostic Plot of East Irrigation Well (805422)



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteAT2020filtered.aqt
Date: 05/05/20 Time: 14:55:24

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

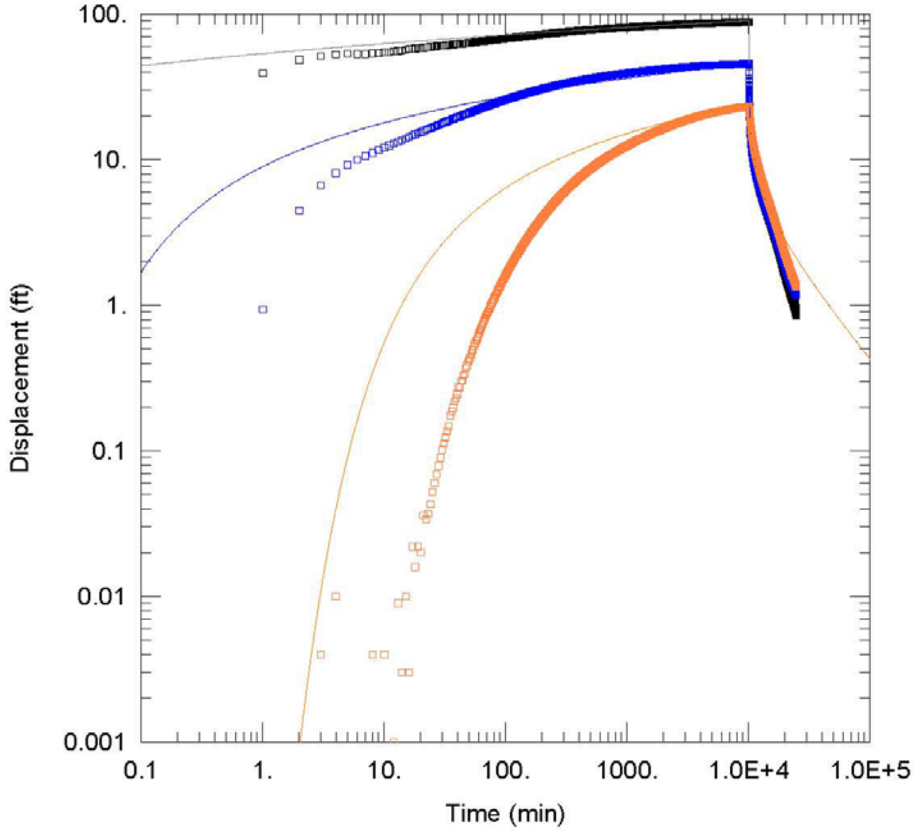
Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
East Irrig 805422	1149817.921	16939361.15

Figure B-7. Theis Confined Solution



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\NolteAT2020filteredTheis.aqt
Date: 05/07/20 Time: 14:58:43

PROJECT INFORMATION

Company: Nolte AT
Test Well: 805421

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
805421	1146969.321	16939144.14

Observation Wells

Well Name	X (ft)	Y (ft)
□ 805421	1146969.321	16939144.14
□ Deep Obwell 841474	1146768.908	16939132.83
□ East Irrig 805422	1149817.921	16939361.15
□ NWIrrig805420	1143225.12	16945005.37

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

T = 3066.7 ft^2/day

S = 1.34E-5

Kz/Kr = 1.

b = 20. ft

Figure B-8. Theis Confined Solution Diagnostics

AQTESOLV for Windows

Diagnostic Statistics

Estimation complete! RSS criterion (RTOL) reached.

Aquifer Model: Confined
Solution Method: Theis

Estimated Parameters

Parameter	Estimate	Std. Error	Approx. C.I.	t-Ratio	
T	3066.7	1.4	+/- 2.743	2191.1	ft^2/day
S	1.34E-5	8.001E-8	+/- 1.568E-7	167.4	
Kz/Kr	1.	not estimated			
b	20.	not estimated			ft

C.I. is approximate 95% confidence interval for parameter
t-ratio = estimate/std. error
Estimation window: 10 to 10080 min

K = T/b = 153.3 ft/day (0.05409 cm/sec)
Ss = S/b = 6.698E-7 1/ft

Parameter Correlations

	T	S
T	1.00	-0.85
S	-0.85	1.00

Residual Statistics

for weighted residuals

Sum of Squares . . . . . . 6.815E+4 ft^2
Variance . . . . 3.259 ft^2
Std. Deviation . . . . 1.805 ft
Mean . . . . -0.01045 ft
No. of Residuals 20910
No. of Estimates 2

05/07/20 1 15:00:15

Figure B-9. Aquifer Test No-Flow Boundaries for AQTESOLV

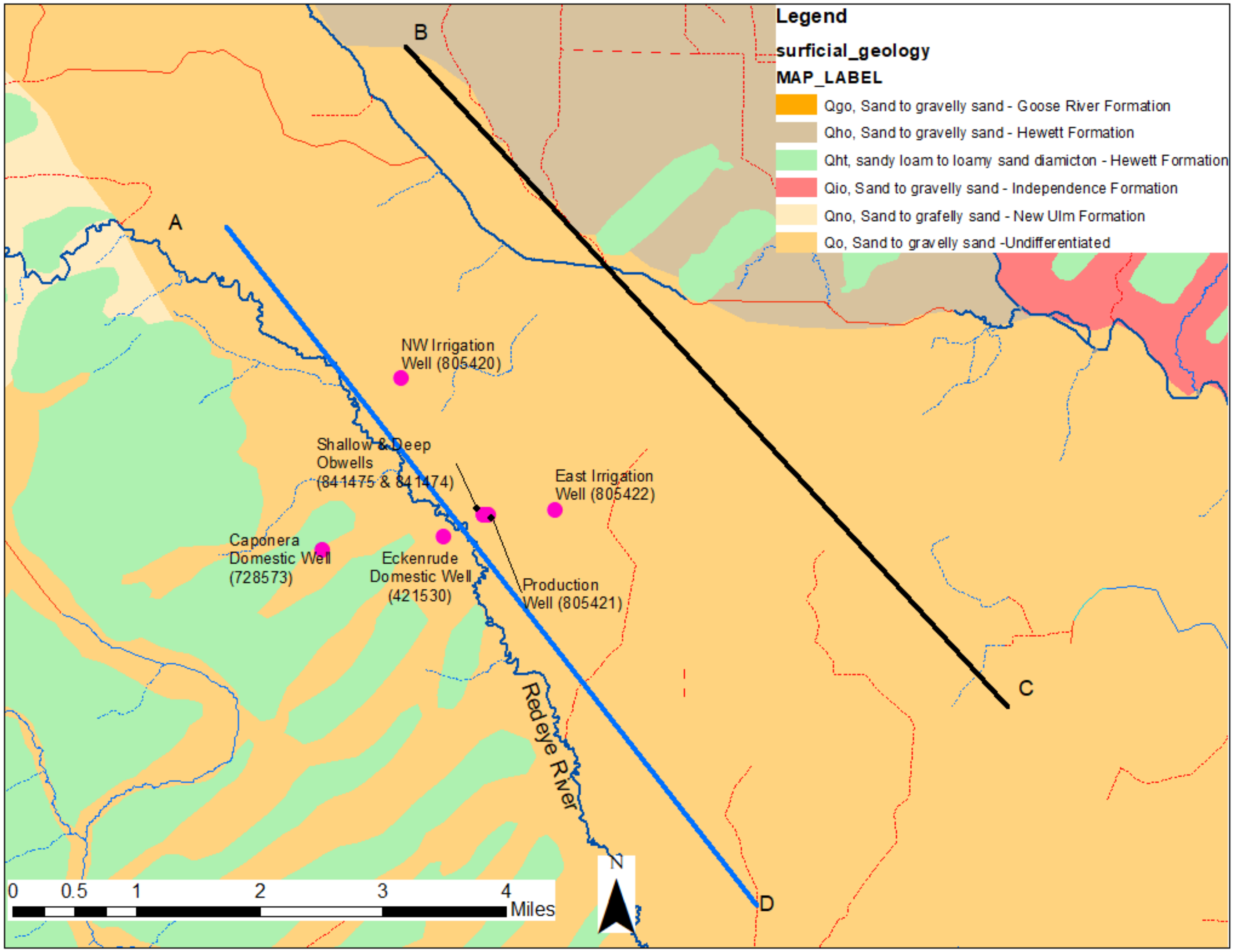


Figure B-10. Regional Glacial Meltwater Flow (Lusardi and Marshall, 2016)

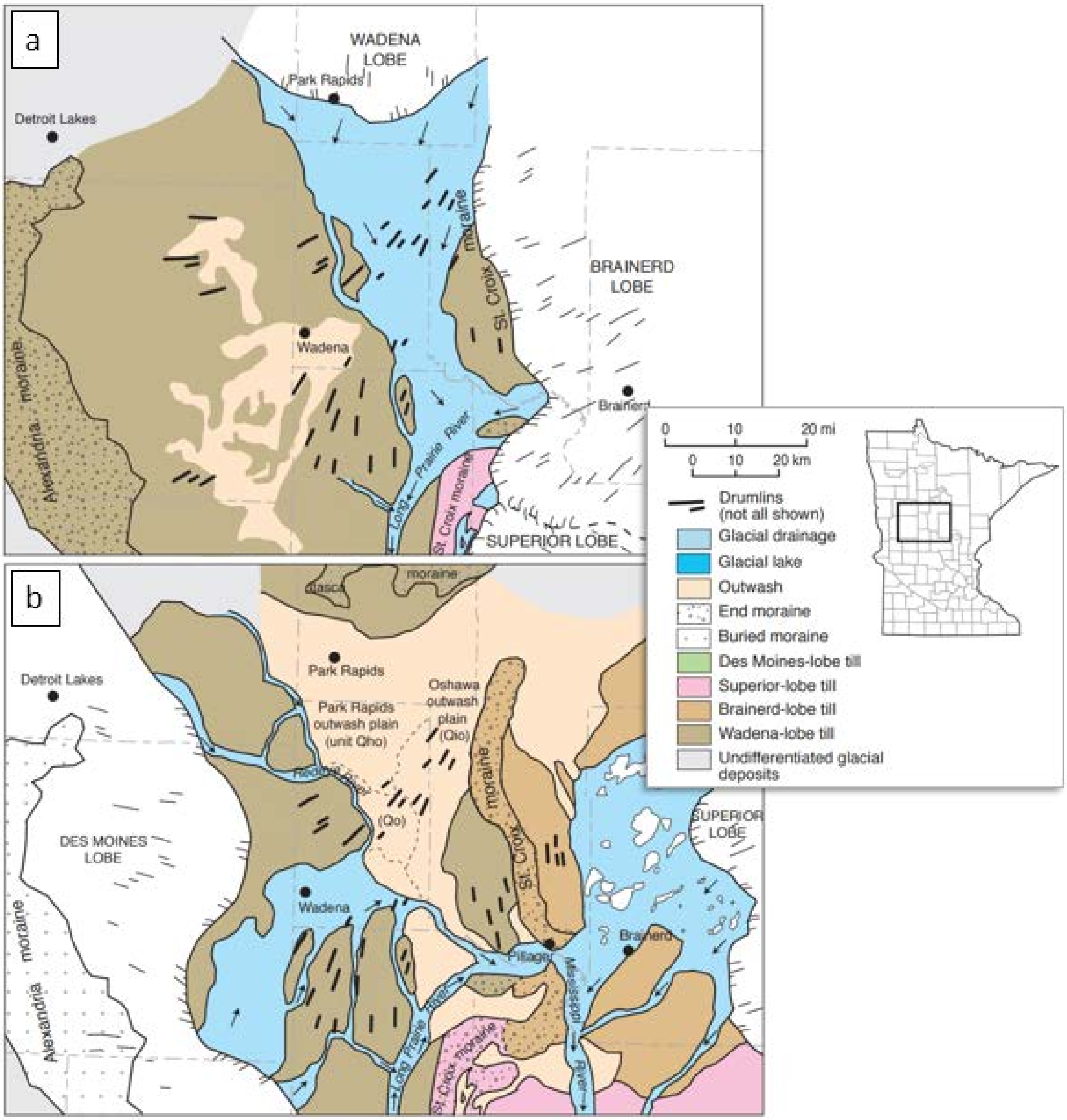
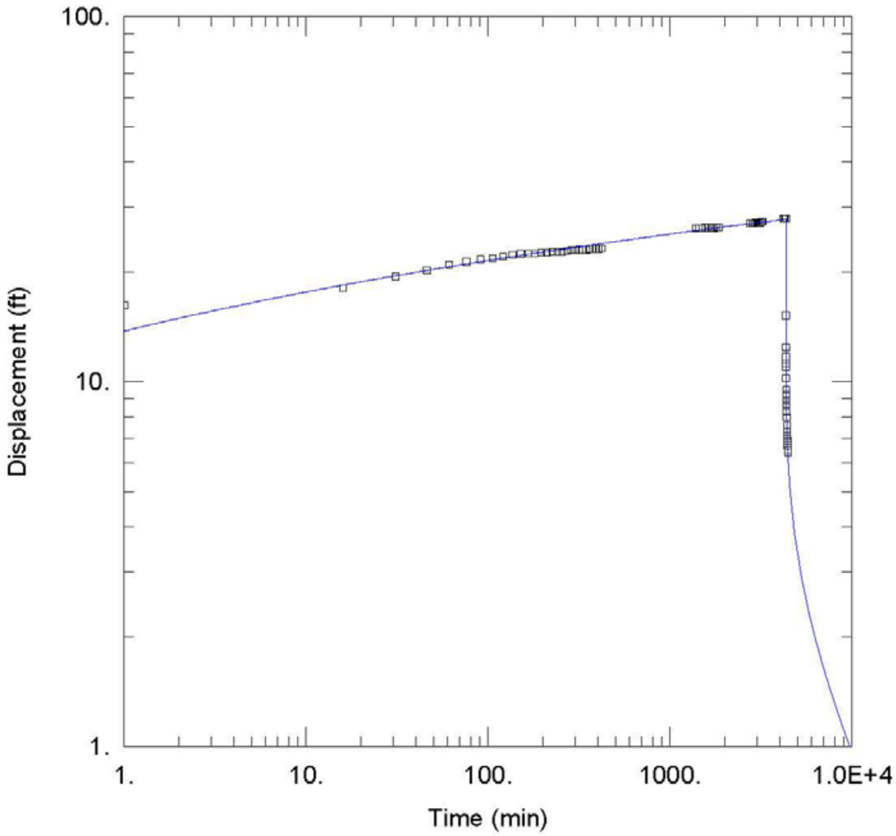


Figure B-10. Regional glacial history of Wadena County showing glacial meltwater (a) from the Brainerd and Wadena lobe flowing northwest to southeast, and (b) from the Des Moines lobe flowing northwest to east-southeast. Note the location of the Redeye River in (b) aligns with historical meltwater channel along with a geologic boundary between outwash and till.

Figure B-11. Hantush Solution Northwest Irrigation Well



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\805420SpecCapHantush.aqt
Date: 05/06/20 Time: 13:44:23

PROJECT INFORMATION

Company: Nolte Spec Cap 2017-4235
Test Well: 805420

AQUIFER DATA

Saturated Thickness: 36. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b'): 16. ft
Aquitard Thickness (b"): 10. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
805420	1143225.115	16945005.37

Observation Wells

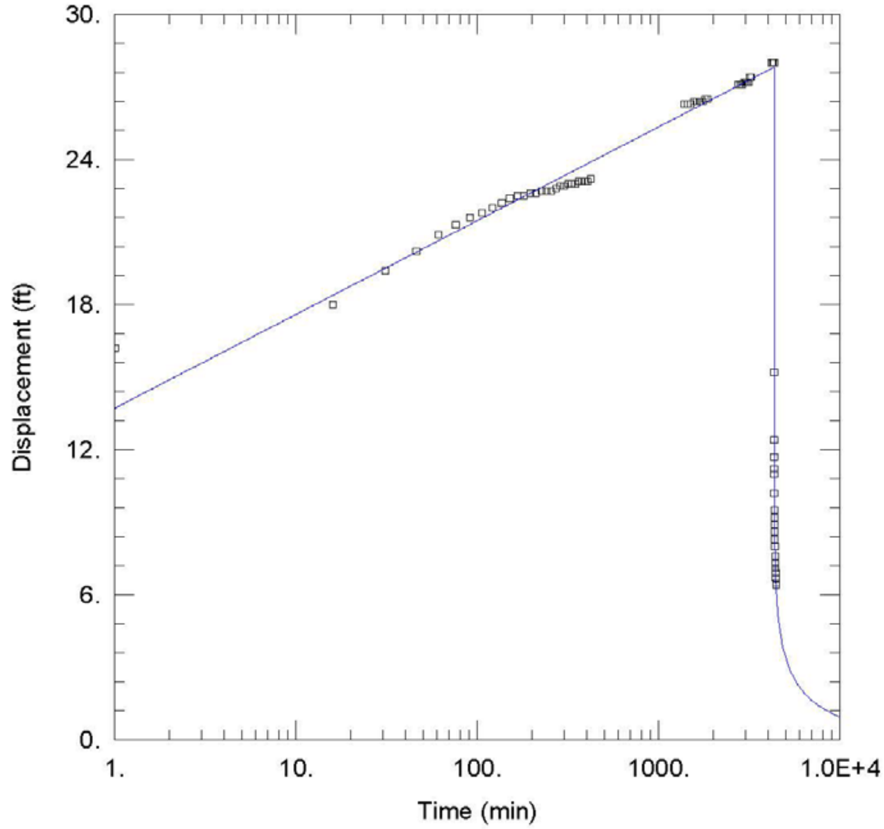
Well Name	X (ft)	Y (ft)
▫ 805420	1143225.115	16945005.37

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush

T = 2716.9 ft^2/day
S = 2.572E-5
r/B' = 1.0E-5
ß' = 1.002E-5
r/B" = 0.0006599
ß" = 2.751

Figure B-12. Cooley-Case Solution for Northwest Irrigation Well (805420)



WELL TEST ANALYSIS

Data Set: D:\groundwater review\Nolte\Aquifer Test Data\Analysis\805420SpecCap.aqt
Date: 05/06/20 Time: 13:19:34

PROJECT INFORMATION

Company: Nolte Spec Cap 2017-4235
Test Well: 805420

AQUIFER DATA

Saturated Thickness: 36. ft
Aquitard Thickness (b'): 16. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 10. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
805420	1143225.115	16945005.37

Observation Wells

Well Name	X (ft)	Y (ft)
▫ 805420	1143225.115	16945005.37

SOLUTION

Aquifer Model: Leaky
Solution Method: Cooley-Case

T = 5458. ft^2/day
r/B = NC.
S'/Sy = NC
S = Not Calculable (NC)
ß = NC
L/b' = NC

Appendix C. Stream Depletion Analysis

Production and East Irrigation wells

Aquifer parameters calculated from the aquifer test using the Neuman Witherspoon (1969) solution were applied to a stream analysis for the Production and East Irrigation wells. In addition, the permit application information shown in Table 1 of the report was used to simulate a single irrigation season. All methods for stream depletion require a measured distance between the pumped well and the river. The distances from each irrigation well to the Redeye River was estimated using 2019 land imagery data (MN DNR) and are shown in Figure 15 in the report figures.

The Production and East Irrigation wells are completed in the same deeper confined aquifer system overlain by a shallower leaky confined aquifer system. These two wells did not directly respond to the rising water levels in the Redeye River during the aquifer test indicating that this aquifer system is not in direct connection with the river. For the modeling exercise, it was assumed that the leaky confining unit at the river is the same thickness as at the Production well.

The Dudley Ward-Lough (2011) solution method for a semi-confined aquifer in a two-layer leaky aquifer system was used to calculate stream depletion. This solution method best matched the hydrogeology at the site of these two irrigation wells. This method assumes:

- Semi-infinite layers that are homogenous.
- No other connected streams/rivers.
- No horizontal flow or storage in the aquitard.
- Changes in transmissivity with drawdown are negligible.
- Changes in stream stages due to depletion are negligible.
- Stream is straight and infinitely long (or longer than reach along which depletion develops).
- Elastic storage of WT aquifer can be neglected (i.e. not "early" time).
- Well distance to stream is at least 5 stream widths and 4 times √(Kh/Kv).

These are common assumptions used in modeling.

In addition to the aquifer parameters detailed above, the following data were used to model stream depletion cause by pumping the Production and East Irrigation wells using the Dudley Ward-Lough solution method:

- Distance to the stream from the Production well: 950 ft
- Distance to the stream from the East Irrigation Well: 3630 ft
- Thickness of aquitard: This is the thickness of the aquitard above the confined aquifer between the river bottom and the top of the confined aquifer. This value is not known at the site. The Production well log shows an aquitard thickness of 37 feet. Since this well did not respond to the

rising water levels in the river, it was assumed that the aquitard thickness at the river was similar as at the well.

- Transmissivity of the unconfined aquifer: The average hydraulic conductivity found by Helgeson (1977) was 438 ft/day for the Pineland sands area. The thickness of the unconfined aquifer at the site is 58 feet according to the Production well log. This is equivalent to 25,400 ft^2/day.
- Specific yield of the unconfined aquifer: A value of 0.2 was selected based on the analysis completed by Helgeson (1977).
- Lambda (λ) : This term is related to the seepage flow rate per unit distance along the stream channel through the streambed and the difference between stream water surface elevation and groundwater elevation. Chen and Chen (2003) showed that this value can be obtained by multiplying the channel width (feet or meters) by 1 day^{-1} to determine λ in units of ft/day or m/day. For this site, the channel width was estimated from the 2019 land imagery data (MN DNR, 2019) at several locations near the Production well. Values ranged from 20-50 feet. An average value of 35 feet was used in the analysis.

The analysis showed that the Production well has minimal impact on the Redeye River after a single season of use (Figure C-2) with a single season depletion rate of 0.03 cubic feet per second (cfs). Although the August mean base flow (low flow value) for the Redeye River is unknown, this amount of depletion is unlikely to negatively impact this river.

The East irrigation well impact on the Redeye River was calculated similarly. The distance to the river was increased based on the 2019 land imagery data (MN DNR, 2019) and resulted in a depletion rate value of 0.04 cfs (Figure C-3). The depletion value is larger because this well is proposed to be pumped at a higher rate and will irrigate more acreage than at the Production well site. This amount of depletion is unlikely to negatively impact the Redeye river.

Figure C-2. Production Well Stream Depletion Calculations

Stream Depletion for Irrigation Wells (Two Aquifers)					
Permit application No.	2017-4236		**Stream Name**	Redeye River	
Well Unique No.	805421		**Reference flow**	NA	(cfs)
Parameters			**Results**		
T	3067	(ft^2/d)	**Max depletion, after 1st cycle**	0.00	(cfs)
S	0.0000134	(--)	**Days to max (1-cycle pumping)**	10.7	(d)
Atard. Thick.	37	(ft)			
Atard. Kv	0.00005	(ft/day)			
Twt	25400		**Max depletion, after 2-cycles**	0.01	(cfs)
Sy	0.2				
distance	950	ft	**Days to max (2-cycle pumping)**	12.6	(d)
$thick_{bed}/K_{bed}$	1	(d)	**Max depletion, after 14-day pumping**	0.02	(cfs)
Stream Width	35	(ft)	**Days to max (14-day pumping)**	18	(d)
λ_{Hunt}	35	(ft/day)			
Qmax	700	(gpm)	**Max depletion, 60-day season-averaged**	0.03	(cfs)
Q	1.56	(cfs)	**Days to 60-day season-averaged max**	61	(d)
Volume	32.6	(MGY)			
Qavg	0.84	(cfs, 60-day)			
Acres	100	(ac)			
Cycle*	3.17	(d)	**Max single season depletion rate**	**0.03**	(cfs)

* Assumes 85% efficiency and 1-inch net application rate per cycle (volume sprayed = 1/0.85 inches)

Reach length over which max single season depletion occurs	**TBD**	(mi)
Number of cycles in season	10.20	
Average on/off cycle length	5.88	
Inches pumped in 14 days	5.20	(in)

Model Assumptions

Semi-infinite layers that are homogenous

No other connected streams/rivers

No horizontal flow or storage in the aquitard

Changes in transmissivity with drawdown are negligible.

Changes in stream stages due to depletion are negligible.

Stream is straight and infinitely long (or longer than reach along which depletion develops).

Elastic storage of WT aquifer can be neglected (i.e. not "early" time).

Well distance to stream is at least 5 stream widths and 4 times $\sqrt{(K_h/K_v)}$.

References

Dudley Ward, N. and H. Lough, 2011, Stream depletion from pumping a semi-confined aquifer in a two-layer leaky aquifer system: *Journal of Hydrologic Engineering* , 16(11), 955-959.

Glover, R.E. and C.G. Balmer, 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Transactions, 35(3), 468-470.

Glover, R.E., 1974, Transient ground water hydraulics: Dept. Civil Eng., Colorado State Univ., Fort Collins, Colorado, 413 p.

Hunt, B., 2005, Visual basic programs for spreadsheet analysis: Ground Water, 43(1), 138-141.

Figure C-3. East Irrigation well stream depletion calculations

Stream Depletion for Irrigation Wells (Two Aquifers)					
Permit application No.	2017-4237		Stream Name	Redeye River	
Well Unique No.	805422		Reference flow	NA	(cfs)
Parameters			Results		
T	3067	(ft^2/d)	Max depletion, after 1st cycle	0.01	(cfs)
S	0.0000134	(--)	Days to max (1-cycle pumping)	11.8	(d)
Atard. Thick.	37	(ft)			
Atard. Kv	0.00005	(ft/day)			
Twt	25400		Max depletion, after 2-cycles	0.01	(cfs)
Sy	0.2				
distance	3630	ft	Days to max (2-cycle pumping)	14.2	(d)
$thick_{bed}/K_{bed}$	1	(d)	Max depletion, after 14-day pumping	0.02	(cfs)
Stream Width	35	(ft)	Days to max (14-day pumping)	19	(d)
λ_{Hunt}	35	(ft/day)			
Qmax	800	(gpm)	Max depletion, 60-day season-averaged	0.04	(cfs)
Q	1.78	(cfs)	Days to 60-day season-averaged max	61	(d)
Volume	45	(MGY)			
Qavg	1.16	(cfs, 60-day)			
Acres	138	(ac)			
Cycle*	3.83	(d)	Max single season depletion rate	0.04	(cfs)

* Assumes 85% efficiency and 1-inch net application rate per cycle (volume sprayed = 1/0.85 inches)

Reach length over which max single season depletion occurs	**TBD**	(mi)
Number of cycles in season	10.21	
Average on/off cycle length	5.88	
Inches pumped in 14 days	4.30	(in)

Model Assumptions

Semi-infinite layers that are homogenous

No other connected streams/rivers

No horizontal flow or storage in the aquitard

Changes in transmissivity with drawdown are negligible.

Changes in stream stages due to depletion are negligible.

Stream is straight and infinitely long (or longer than reach along which depletion develops).

Elastic storage of WT aquifer can be neglected (i.e. not "early" time).

Well distance to stream is at least 5 stream widths and 4 times $\sqrt{(K_h/K_v)}$.

References

Dudley Ward, N. and H. Lough, 2011, Stream depletion from pumping a semi-confined aquifer in a two-layer leaky aquifer system: *Journal of Hydrologic Engineering*, 16(11), 955-959.

Glover, R.E. and C.G. Balmer, 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Transactions, 35(3), 468-470.

Glover, R.E., 1974, Transient ground water hydraulics: Dept. Civil Eng., Colorado State Univ., Fort Collins, Colorado, 413 p.

Hunt, B., 2005, Visual basic programs for spreadsheet analysis: Ground Water, 43(1), 138-141.

NW Irrigation Well

The NW irrigation well responded immediately to rising water levels in the Redeye River. This indicates that this aquifer is in contact with the Redeye River. It is unknown if the connection is through direct contact or through leakage. For the stream flow depletion calculations, it was assumed the aquifer is connected directly to the river. This would give a conservative estimate of stream flow depletion based on the best available information.

Aquifer parameters for this well were estimated as discussed above in the report text. The specific capacity test data was used to calculate an aquifer T of 5458 ft^2/day (507 m^2/day) using the Cooley-Case (1973) method (Figure B-12). The assumed leaky confined aquifer storativity was 0.001. The permit application information listed in Table 1 of the report text was also used in this analysis (450 gpm pumping rate). The 2019 land imagery data shows the stream is located closer to this well than the public water course delineation (MNDNR, 2017) and therefore the land imagery distance calculation was used.

The Hunt (1999) method of analysis was used to calculate stream depletion using the spreadsheet developed by Hunt. This spreadsheet is available at: Hunt 1999 (https://sites.google.com/site/brucehuntsgroundwaterwebsite/). The Hunt (1999) method assumes the following:

- Streambed penetration of the aquifer and dimensions of the streambed cross section are relatively small.
- The streambed is clogged and that the clogging layer is semi-pervious.
- There is a linear relationship between the outflow seepage through the streambed and the change in piezometric head across the stream clogging layer.

It is unknown if these assumptions apply to the site. However, they are common assumptions used in modeling when information is not known.

The Hunt (1999) method requires the following parameters:

- Estimate of λ (lambda) as described above. Values ranged from 20-50 feet. An average value of 35 feet (11 meters) was used in the analysis. The streambed conductance and thickness were assigned values of 1.
- Distance of the well from the stream (L): This was estimated from the 2019 land imagery data (MN DNR, 2019) as 1960 feet (597 m).
- Irrigation efficiency: This was assumed to be 85%.
- Separation distance of the irrigated field from the stream (L2): This was estimated from the 2019 land imagery data (MN DNR, 2019) as 300 feet (91 m).

This solution method estimated a maximum stream depletion of approximately 1 cfs (27 L/s) over one year Figure C-4). An August mean base flow (low flow value) for the Redeye River is not available, therefore it is unknown if this amount of depletion will negatively impact this river. This depletion rate should be compared to the August mean baseflow for the Redeye River once it becomes available.

The accuracy of this calculation is limited due to the quality of the aquifer properties input to the model. Additional aquifer testing focused on the NW Irrigation well would refine the estimates of stream flow depletion.

Figure C-4. NW Irrigation well stream depletion calculations

Stream depletion analysis - Hunt (1999) solution

Pumped aquifer

Transmissivity (T)	507	(m^2/d)
Storage coefficient (S)	0.001	-

Streambed

Hydraulic conductivity (K")	1	(m/d)
Thickness (B")	1	(m)
Width (W)	11	(m)
Stream bed conductance (λ)	**11**	(m/d)

Well

Pumping rate (Q)	28	(L/s)
Separation distance (L)	597	(m)

Application efficiency

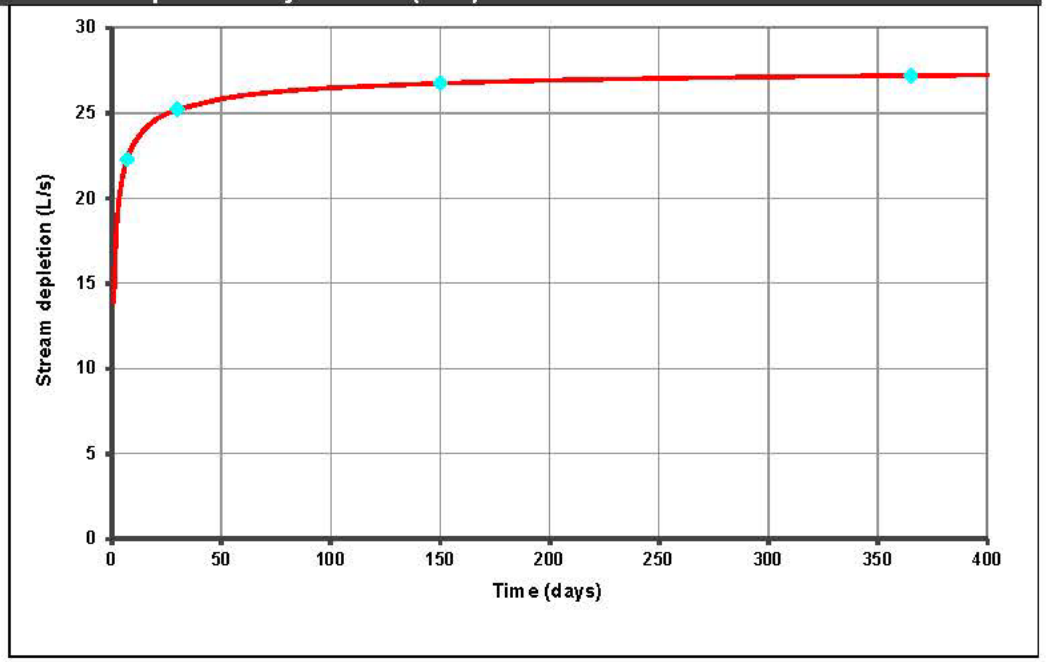
Irrigation efficiency	100%	
Separation distance (L2)	91	(m)

Stream depletion after

Time (days)	q (L/s)	%
7	22	**80%**
30	25	**90%**
150	27	**96%**
365	27	**97%**

Only the values in shaded cells can be updated - all other cells are dependent on those input values.

Setting lambda to a very high value will give Theis solution



Time	Depletion Rate	
	@100%	@100%
(days)	(L/s)	(L/s)
1.0	13.9	13.9
2.0	17.6	17.6
3.0	19.4	19.4
4.0	20.5	20.5
5.0	21.3	21.3
6.0	21.8	21.8
7.0	22.3	22.3
8.0	22.6	22.6
9.0	22.9	22.9
10.0	23.2	23.2
15.0	24.1	24.1
20.0	24.6	24.6
25.0	25.0	25.0
30.0	25.2	25.2
50.0	25.8	25.8
60.0	26.0	26.0
70.0	26.2	26.2
80.0	26.3	26.3
90.0	26.4	26.4
100.0	26.5	26.5
150.0	26.8	26.8
200.0	26.9	26.9
250.0	27.0	27.0
300.0	27.1	27.1
400.0	27.2	27.2