Final Project Report
February 2, 2015

Using the New Rome Formation as a geologic weighing lysimeter for water management in Wisconsin's sand plain

(WDNR Project Number 14-HDG-03)

Principal Investigators

David J. Hart, Hydrogeologist, Wisconsin Geological and Natural History Survey, University of Wisconson-Extension
Kenneth R. Bradbury, Hydrogeologist, Wisconsin Geological and Natural History Survey, University of Wisconson-ExtensionMichael J. Parsen, Hydrogeologist, Wisconsin Geological and Natural History Survey, University of Wisconson-Extension

Table of Contents

List of Figures and Tables

Figures

Tables

Project Summary

Title: *Using the New Rome Formation as a geologic weighing lysimeter for water management in Wisconsin's sand plain*

Project I.D.: WDNR Project Number 14-HDG-03

Investigators: Principal Investigators: *David J. Hart[1], Hydrogeologist; Kenneth R. Bradbury[1], Hydrogeologist; and Michael J. Parsen[1], Hydrogeologist.*

1. Wisconsin Geological and Natural History Survey, University of Wisconsin–Extension, 3817 Mineral Point Road, Madison, WI 53705

Period of Contract: July 1, 2013- June 30, 2014; No Cost Extension to August 31, 2014 provided.

Background/Need: This project tested the concept of using geologic weighing lysimeters (GWLs) to estimate components of the water balance in parts of Wisconsin's central sand plain where the New Rome Formation (NRF), a regional aquitard, occurs. As described in the proposal body, additions or subtractions of water at the land surface are transmitted as pressure changes beneath the aquitard, and relatively simple measurements of these pressure changes can be translated into estimates of recharge and evapotranspiration at the field scale or larger. Such a method is attractive because it is completely independent of crop, cover, and soil types and is based on hydraulic response rather than on plot measurements or energy-balance theory. It therefore provides an independent check on these more common methods. In addition to testing the method, we also tested and documented physical properties of the NRF, a potentially significant regional aquitard.

The "sand plain" of central Wisconsin is an economically important agricultural region that depends heavily on irrigation from high-capacity wells for crop production. There is evidence that groundwater drawdown and increased evapotranspiration associated with this water use is reducing lake levels and streamflows in local surface water resources, and that climate change might be amplifying these impacts. As a result, there have been conflicts between farmers who use groundwater for irrigation, local property owners and environmental groups concerned about environmental degradation, and regulatory officials charged with approving new high-capacity wells. Results of this work will help inform these issues.

Objectives: 1) To test the concept that geologic weighing lysimeters (GWLs) can be used to estimate groundwater recharge and evapotranspiration over large areas of Wisconsin's central sand plain. 2) To refine our understanding of the hydrogeologic properties and function of the NRF, a widespread aquitard underlying parts of the central sand plain.

Methods: We applied traditional hydrogeologic testing, ground penetrating radar, laboratory testing, and geoprobe coring to determine physical properties of the NRF and its suitability as a GWL. We chose a site in west central Adams County were the NRF was known to be present from well construction reports. This site had both irrigated field (Field) and prairie grassland (Grassland) areas. We installed piezometers above, in, and below the NRF in the Field. We installed piezometers above, in, and below the (NRF) in the grassland. We also installed pumping wells below and above the NRF in the grassland to stress the piezometers. We conducted pumping tests in the deep and shallow pumping wells and recorded the response in the other wells and piezometers. A weather station and soil moisture probe were installed in the grassland. Finally, we installed a stilling well in Klein Creek, located several hundred meters from the piezometers and pumping wells. Together, these measurement systems will enhance our understanding of the role of the NRF in the local groundwater flow system.

To help us understand the stratigraphy and deposition of the NRF, we collected ground penetrating radar (GPR) data and four geoprobe cores. We collected GPR data in a fine-scale grid that connected the Field and grassland piezometer installations. We also collected GPR profiles away from the Field site that suggest that deposition that we saw at the Field site is present elsewhere. The NRF was present in three of the cores. It was not present in the fourth core, located farther to the east. A sample from the core collected at the Field site was sent to the UW-Madison soils lab for permeability measurements using the falling head laboratory test.

Results and Discussion: The NRF acts as an aquitard at both the Field and Grassland installations but has too large and variable hydraulic conductivities to be used as a GWL. We observed that the heads in the shallow aquifer above the NRF are greater than the heads in the deep aquifer below the NRF. Also, during pumping tests in the grassland, the water table well did not responds to pumping from below the aquifer and the deep piezometer did not respond to pumping from the shallow aquifer from just above the NRF. We also observed reverse well fluctuations that indicate that the NRF is acting as an aquitard. The reduction of effective stress from pumping water levels in the deep aquifer, "squeezed" the aquitard and caused water levels to rise; which is the opposite direction that water levels would be expected to change from pumping alone.

The NRF is not homogeneous but varies with depth and distance. This is indicated by the different values of head decrease across the NRF of 0.2 feet in the Field versus 2.0 feet in the Grassland installation. This difference in head change occurs over a horizontal distance of several hundred meters. The thickness of the NRF and stratigraphy also change over that distance. The geoprobe core and GPR data showed this variation. The geoprobe cores show that the NRF grades, top to bottom, from clay drapes in sand to interbedded sands and clays to massive clays. The GPR records support this and show dipping beds merging onto the more clay-rich layered NRF. In addition to the visual and geophysical evidence of variation with depth, the pumping tests also showed variation in hydrogeologic response with depth. When pumping from the deep aquifer, there was no drawdown observed in the piezometer in the NRF. However, when pumping from the shallow aquifer, the drawdown in the piezometer finished in the NRF was 0.3 feet. The NRF piezometer was placed in the middle of the aquitard and not towards the top so this amount of drawdown was unexpected but can be explained if the upper part of the NRF is more conductive than the lower part. This project has resulted in the first measurements of the hydraulic conductivity of a regional aquitard in an area of the state that is experiencing increased groundwater use and provides a better understanding of the depositional environment of the NRF.

Conclusions/Implications/Recommendations: The NRF is present over much of the southern central sand plain and influences groundwater flows throughout this area. When present, the NRF separates the sand into shallow and deep aquifers. If most of the irrigation water wells withdraw water from the lower aquifer and if the NRF is present, then the impacts of the pumping will be distributed over greater distances. This will make it less likely that an individual well is linked to the reduction of flow in a specific reach of stream. The presence of the NRF creates a different groundwater flow regime in the southern central sand plains than that observed in the north, where there has been more study and concern over groundwater.

Related Publications:

Hart, D., Streiff, C., and Stewart, E., 2014. Hydrogeologic characterization of an aquitard using poroelastic responses and near surface geophysics. American Geophysical Union, Abstracts with Programs, Fall Meeting, San Francisco.

Key Words: *aquitard, glacial hydrostratigraphy, pumping tests, poroelastic response, loading test, Noordbergum effect*

Funding: Wisconsin Department of Natural Resources

INTRODUCTION

In central Wisconsin, irrigation use has dramatically increased over the last several decades. This increase has given rise to concerns over impacts to surface waters from groundwater pumping (Kraft and others, 2012). We instrumented an irrigated field and a nearby grassland prairie to assess the potential of the New Rome Formation (NRF) for use as a geologic weighing lysimeter (van der Kamp and Schmidt, 1997). This instrumentation also served to assess the hydrogeologic properties of the NRF so that its role in the regional flow system can be understood. Prior to this investigation, there were no estimates of the vertical conductivity of this regionally extensive aquitard in a region that is experiencing growth in groundwater use. We used near-surface geophysics and poroelastic responses, in addition to traditional hydrogeologic tools such as pumping tests and sediment characterization, to assess the hydrogeologic parameters of the New Rome and the upper and lower sands.

This new understanding of the hydrogeologic characteristics of a regional aquitard in an area of increased water use is essential for estimating and communicating the impacts of increased water use. We can better estimate the impacts to surface waters from groundwater pumping for irrigation if we know the role that the New Rome aquitard plays in the regional flow system.

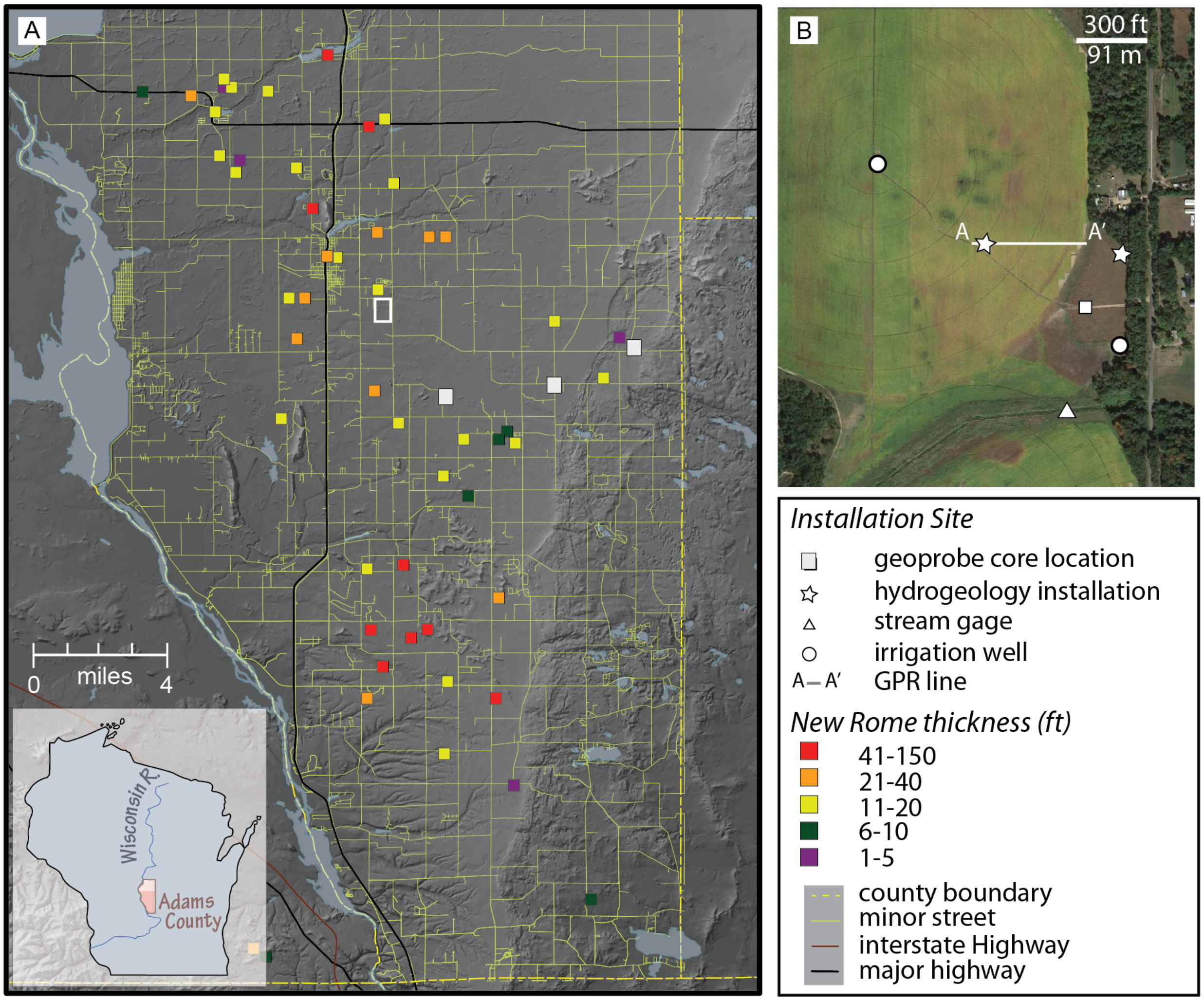

Figure 1. Location map. A. Digital elevation model (DEM) of the study area. The location of the study area is shown by pink shading within Adams County on the inset map of Wisconsin. Colored squares indicate thickness of the New Rome aquitard as shown from well cuttings. The white square locates the installation site. B. Installation site and location of the GPR, core, and hydrologic instrumentation.

METHODS AND RESULTS

Geoprobe

We collected one geoprobe core in the Field and Grassland site shown in Figure 1B. Three additional Geoprobe cores were also collected in Adams County along a line east of the first core as shown in Figure 1A. The NRF was present in the three western cores. These three cores were all located in the Glacial Lake Wisconsin basin. The eastern most core is located in the outwash plain just to the east of the lake shore (Clayton, 1987). Figure 2 shows is a geologic log with photos of sediment core from selected depths. This core reveals a slightly more complicated structure to the NRF than previously thought. Previously, workers (Brownell, 1986) described the New Rome as a lacustrine silt and clay, sometimes with rhythmites or interbedded silts and clays without mention of variation in the sedimentary structure and grain size with depth. In this core we do see variation with depth. There is a sharp transition from sands to clay at the bottom of the NRF. The NRF then transitions gradually from clay to clay with some sand stringers, to sand and clay interbedded and finally to sand with a few clay drapes. Using standard drilling techniques such as mud rotary or even hollow stem augers, it would be very difficult to see these transitions. In addition to describing the core, a falling head permeability laboratory test was conducted on this core from 38 feet depth in the massive clay portion of the aquitard. The vertical hydraulic conductivity of the core from that test was 2.6×10^{-4} feet/day.

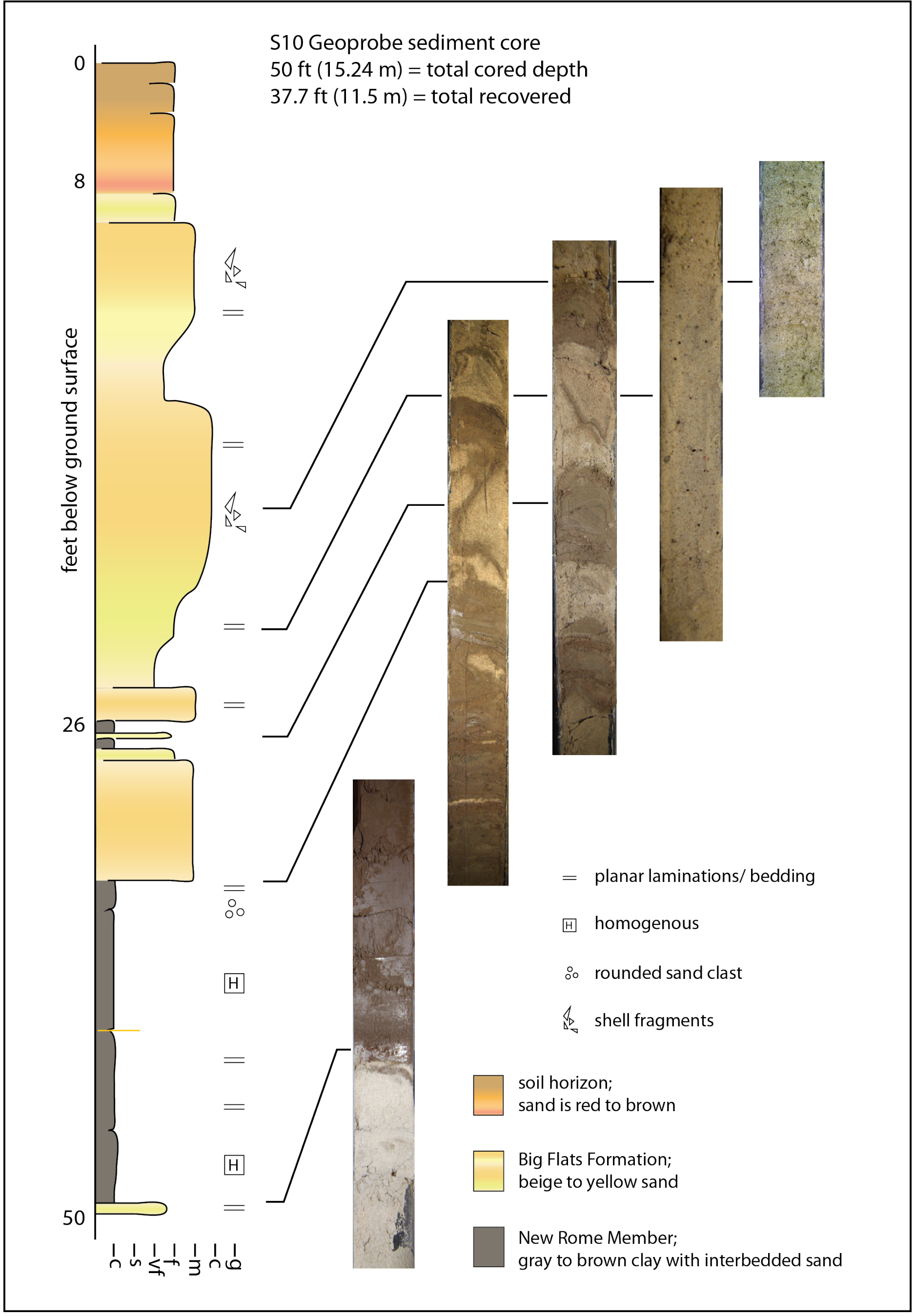

Figure 2. Sediment core from the Field and Grassland site with photos showing different lithologies from the massive clay at the bottom of the aquitard to the the clay drapes in the transition from aquitard to shallow aquifer and sands in the aquifer. The depth scale varies with depth due to different recovery rates from the core

Ground Penetrating Radar

We used ground-penetrating radar (GPR) to help understand the sediment and transition from aquitard to shallow aquifer. We used a GSSI SIR-3000 control unit with an 80 MHz antenna to image the sediment of the upper aquifer and the top of the NRF. GPR sends radio pulses into the ground and receives reflections. Changes in sediment and water content create the reflectors.

Figure 3 shows the GPR data (top) and a line drawing (bottom) delineating clinoform geometry in shallow Pleistocene sediments. See Figure 1B for the line location. The image shows dipping beds or clinoforms. These clinoforms are stacking into aggradational-progradational, degradational, and retrogradational packages, which define high stand, falling stage, and retrogradational systems tracts respectively (refer to Neal and Abreu 2009 for a review of sequence stratigraphic terms). It appears that a sequence boundary separates the falling stage and transgressive systems tract. A composite sequence boundary separates clinoforms (below) from a channel belt (above). The GPR record coupled with the geoprobe core indicate the transitional nature of the upper NRF. The dipping beds of the clinoforms toe onto the lake sediments of the NRF, creating the transition seen in the core. In addition to providing insight into the site, this geological interpretation is a powerful tool to understand the hydrostratigraphy of the site and the basin.

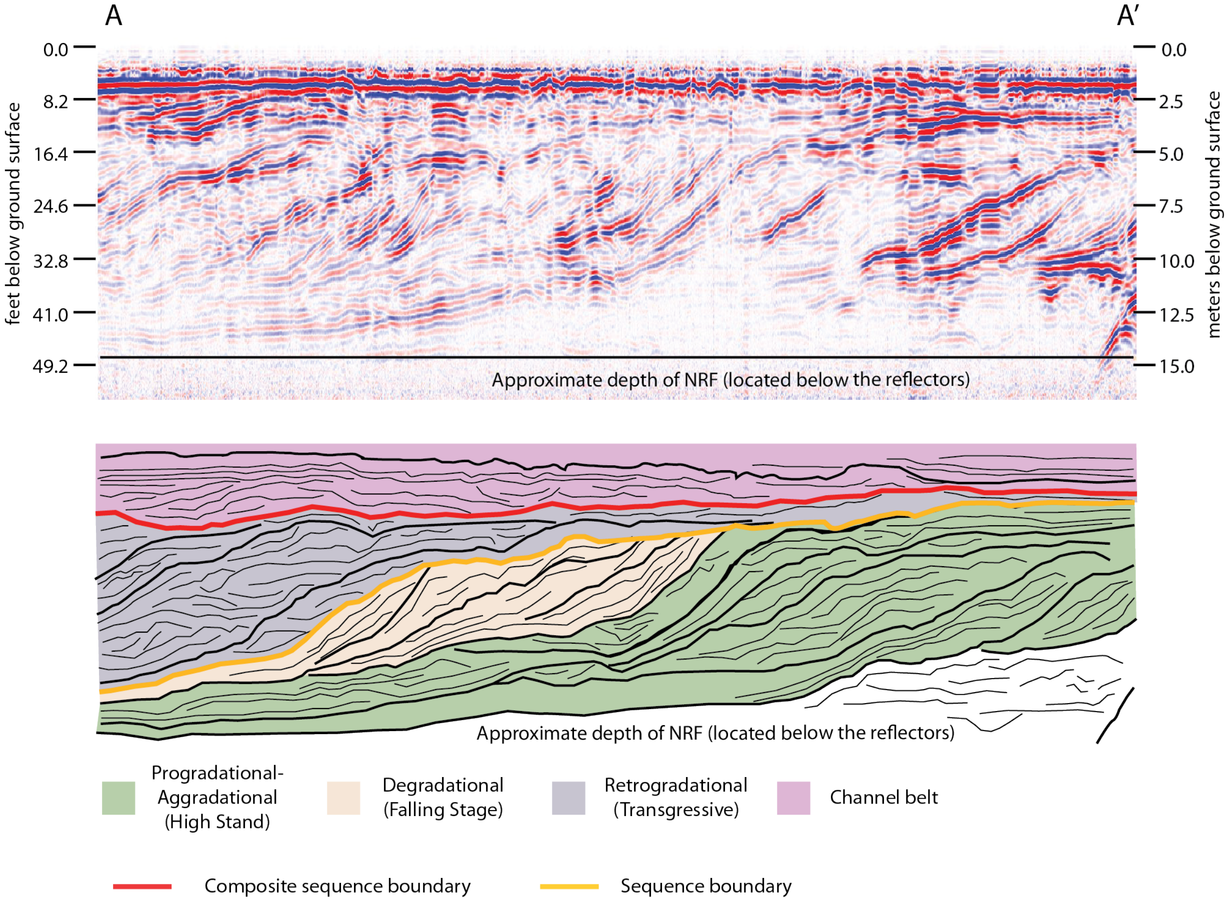

Figure 3. GPR record at the installation site.

Hydrogeologic Instrumentation

We instrumented an irrigated field (Field site) of sweet corn and a nearby native prairie (Grassland) to assess those impacts and compare hydrogeologic responses between these two different land uses. The hydrogeology of the two sites is similar, a layered system of 10 meters of sand over 2 to 3 meters of clay and silt over 30 meters of sand. The clay and silt is part of the recognized geologic unit, the New Rome Formation (NRF). Figure 1B shows the locations of the wells and installations.

The instrumentation consisted of piezometers in all three layers and pumping wells above and below the New Rome. The piezometers in and below the NRF at the both Field and Grassland consisted of buried vibrating wire transducers in a sand pack and sealed with bentonite, F2 and G3. The shallow wells at both the Field and Grassland used standard 2” PVC water table monitoring well design, F1 and G4. The pumping wells above and below the NRF at the Grassland site used 6” diameter PVC screens and casing, G1 and G2. The well construction, relationship to the NRF and observed water levels are shown in Figure 4. The screened intervals are shown as slotted, sand pack as stippled, and the bentonite seals as horizontal lines. The approximate lithologies as described during drilling by an experienced geologist are shown as well. Well logs and construction reports were submitted to the WDNR. A photograph of the Grassland installation is shown in Figure 5. A 2” PVC stilling well was installed in Klein Creek. The elevations of the wells, ground surface, and Klein Creek were collected using RTK-GPS.

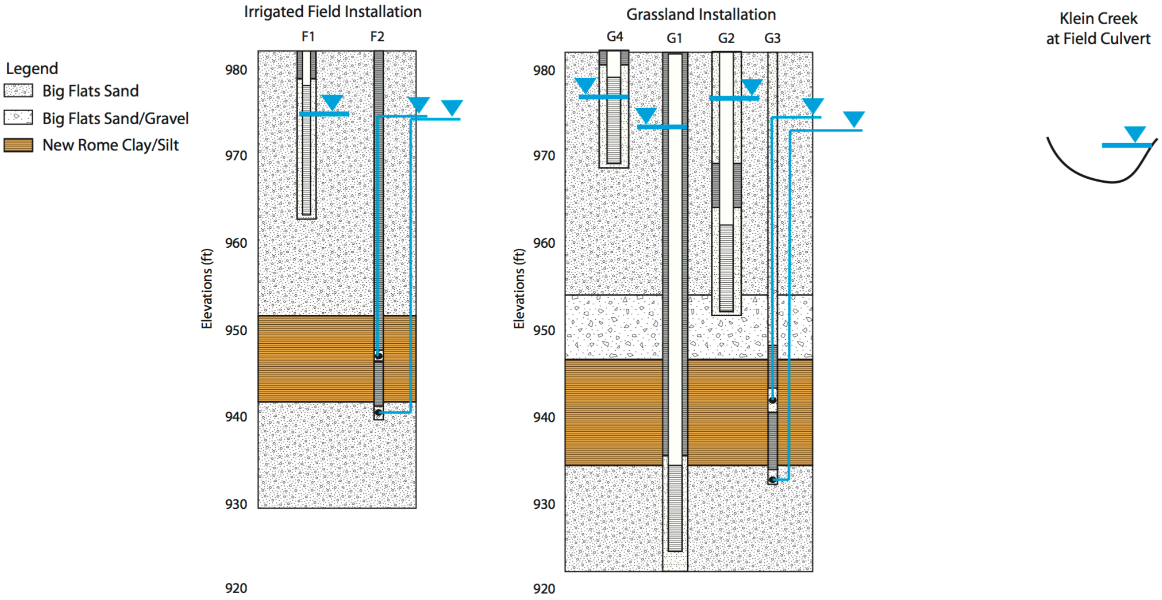

Figure 4. Field and Grassland site well construction and water levels. The stage of Klein Creek is also shown. The head values are from a non-irrigation pumping time period.

The measured head profiles provide some insights into the local flow system. The head gradients at both sites are downward although the change in heads at the Field installation is only about 0.8 feet across 10 feet of NRF aquitard (0.08 ft/ft gradient) while at the Grassland installation the change is 3.9 feet over 12.5 feet of NRF aquitard (0.31 ft/ft gradient). We also observe that the Field heads are intermediate to the Grassland heads. The stage of Klein Creek is the lowest head in at the installation site. This suggests that the shallow aquifer discharges to Klein Creek. The deeper aquifer might also provide some discharge to Klein Creek upward through the NRF though the amount is difficult to estimate without a groundwater flow model of the system.

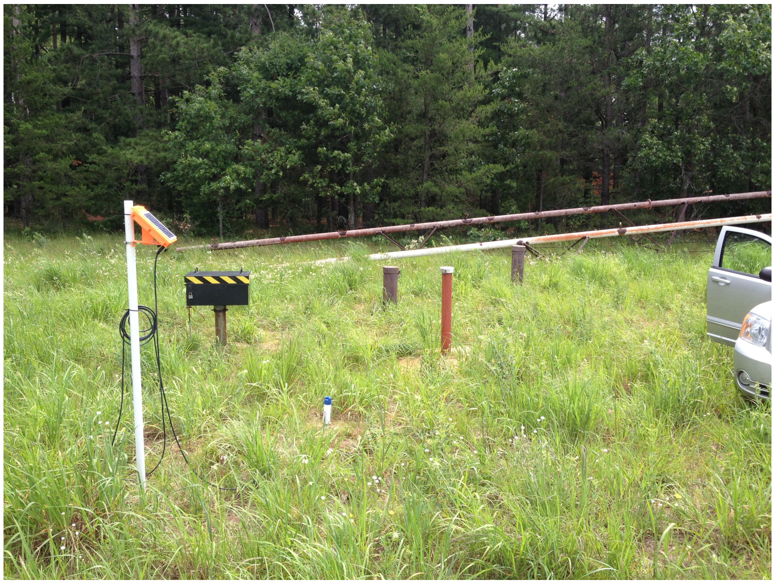

Figure 5. Installation in the Prairie. In addition to the four groundwater monitoring wells and piezometers, a soil moisture probe (shown in the foreground) and a weather station (not shown) have also been installed.

We collected water level data for these wells and piezometers from April to October, 2014. After installation of a weather station we also collected precipitation data from early August to October 2014. These data are all shown in Figure 6. The Field water levels are shown in green, the Grassland in tans and browns, Klein Creek in dark blue and cumulative precipitation in light blue. This plot shows the response of the water levels over time and the different inputs that were present. The first item to note is the longer-time response. The water levels rose in the Spring, possibly in response to precipitation and snow melt. June 20, 2014 is an example of that increase. The water level in Klein Creek also increased at the same time. The water levels in the wells and the creek then began a slow decline with occasional step increases, potentially from precipitation over the course of the summer. The water levels increased again in late summer after a series of larger rainfalls. Finally, water levels decreased until the end of the record in October. The rates of decline and step increases in the shallow and deep aquifers were nearly the same whether it was in the Field or the Grassland. Water levels in Klein Creek increase sharply in response to precipitation but decrease more gradually than the shallow aquifer levels.

Irrigation also decreases water levels but seems to only affect the deep aquifer. The irrigation well locations are shown in Figure 1B. Starting in mid-June, sharp drops and slightly longer recovery cycles from irrigation pumping are seen in the wells and piezometers in the deep aquifer and to a lesser degree in wells in the New Rome. The grower confirmed that irrigation was occurring during this time. We plan to incorporate the grower's pumping records in future. They are not available at the time of this report. The head in the deep aquifer seems to decrease slightly more than the shallow aquifer over the growing season. This is apparent in the Field heads. In Spring, the deep aquifer has a slightly higher head than the shallow aquifer while at the end of the growing season, by Fall the deep aquifer has a slightly lower head than the shallow aquifer. The Field wells respond less than the Grassland wells to pumping. We do not have the pumping records for the irrigation wells and so do not know which irrigation well was creating the drawdowns, making a more quantitative approach difficult. The shallow aquifer and Klein Creek do not show a response to irrigation pumping. It may be that the unconfined response of the shallow aquifer buffers it from the rapid drawdowns from the irrigation wells. Also of interest is that we don't see any water level increases in the shallow aquifer Field well during irrigation. The amount of water applied during an irrigation cycle is designed so that the water should stay in the root zone and not move nutrients or extra water downward away from the root zone (Wallendals, 2014).

Similar to the shallow aquifer wells, Klein Creek doesn't show any measurable response to irrigation pumping.

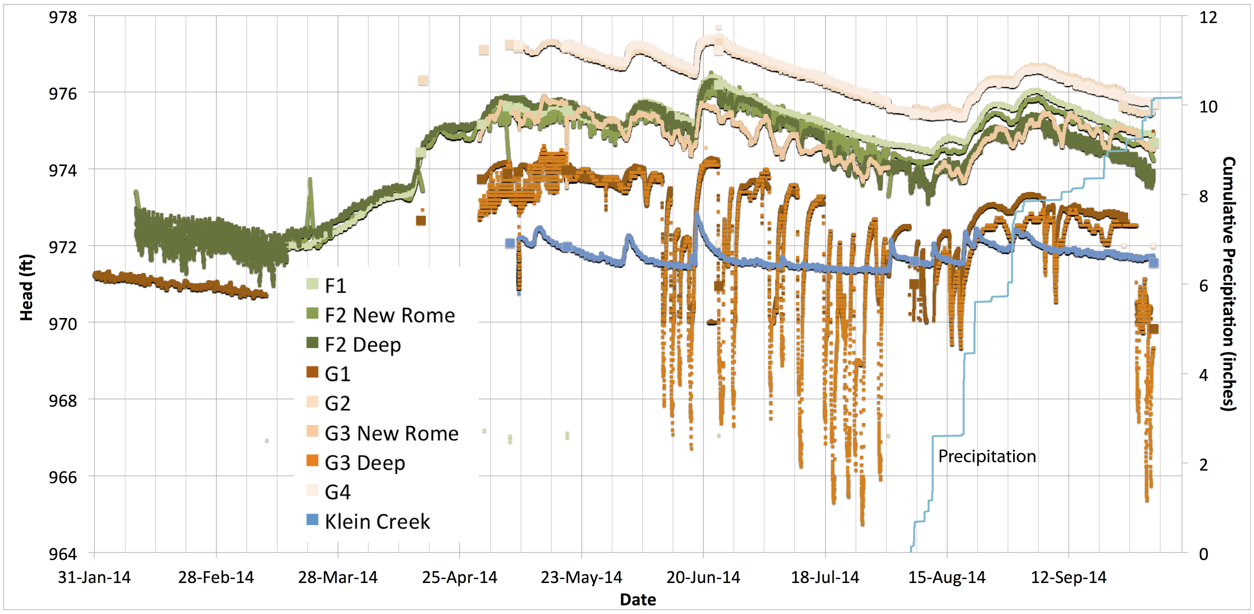

Figure 6. Water levels over time in the Field and Grassland sites. Klein Creek and the cumulative record of precipitation beginning in August are also shown.

Pumping tests

We performed two aquifer pumping tests at the field site – one focused above and one below the New Rome Formation. The main purpose of these tests was to assess the vertical hydraulic conductivity of the aquitard by measuring the vertical transmission of hydraulic stress across it. A secondary purpose was to measure the hydraulic properties (hydraulic conductivity and storage) of the sandy aquifer above and below the aquitard. The tests were conducted by pumping from wells G1 (deep test) and G2 (shallow test) while monitoring responses in neighboring wells and piezometers. The wells were pumped using a submersible electric pump, and the water was discharged to the 10 Ave ditch. The tests were run for about 4 hours .

Shallow Pumping Test

We pumped from well G2 above the New Rome aquitard at a rate of 30 gallons/minute for more than 4 hours. Figure 7 shows the water levels measured during this test. The pumping rate was initially too high and was reduced to 110 liters/minute to prevent total dewatering of the well. There was little drawdown in the unconfined observation well G4 (green line on figure 7). In contrast, there was greater drawdown in the NRF aquitard piezometer, G3 New Rome (purple line). Drawdown in G3 New Rome was unexpected because wells G4 and G3 New Rome were equidistant from the pumping well, G2, and we expected little or no response from the piezometer inside the aquitard (G3 New Rome). Instead we saw that largest response there. There was no significant response in the deep aquifer well, G1, or piezometer, G3 deep. We analyzed data from G2 and G4 using a Neuman unconfined pumping test analysis. The results were a horizontal hydraulic conductivity of 300 feet/day and a specific yield of 0.14. We did not conduct a longer term test needed to show a response in the deep aquifer because the drawdown in the NRF in G3 New Rome indicated that our conceptual model and the aquitard homogeneity required for that analysis would not be met.

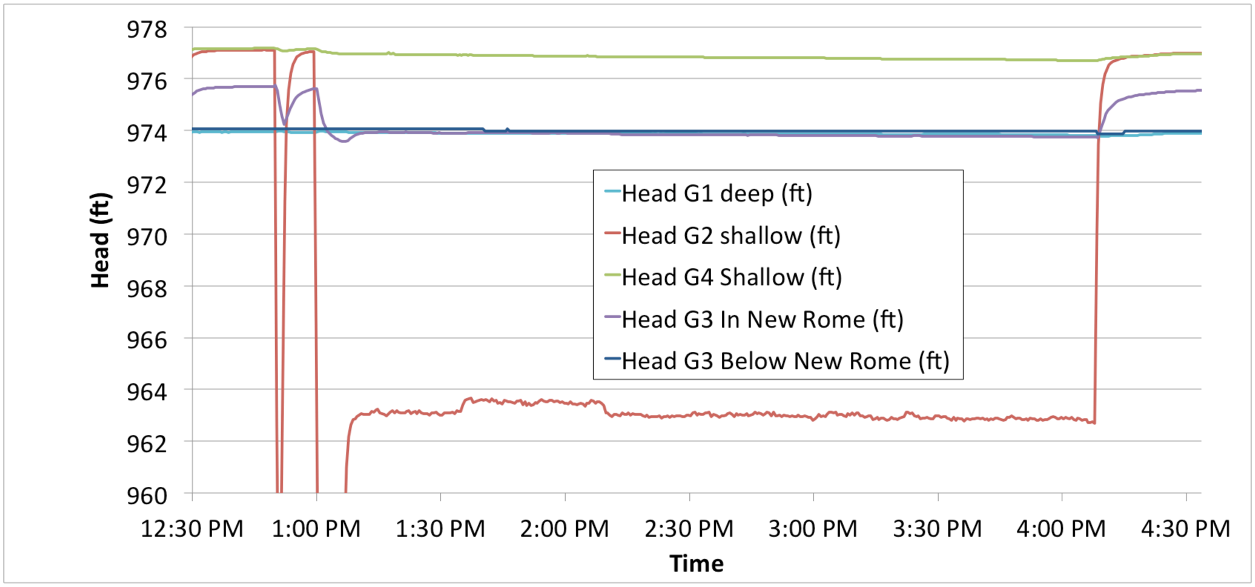

Figure 7. A shallow aquifer pumping test.

Deep Pumping Test

We pumped from well G1, below the New Rome aquitard at a rate of 50 gallons/minute. Figure 8 shows water levels observed during this test. The piezometer below the New Rome, G3 Deep (purple line on figure 8), responded quickly as expected. There was no drawdown in the piezometer in the New Rome aquitard or in any of the wells or piezometers above the aquitard, G2, red, or G1, green. There is a reverse well fluctuation in the New Rome aquitard, G3 shallow, and in G2, located just above the New Rome aquitard. This poroelastic phenomenon is caused by a reduction in effective stress from pumping the aquifer, "squeezing" the aquitard (Hsieh, 1996) and is indicative of a confined aquifer or aquitard response. We analyzed data from G2 and G4 using a Theis confined pumping test analysis. The results were a horizontal hydraulic conductivity of 66 feet/day and a specific storage of $9\text{x}10^{-5}$ ft^{-1}.

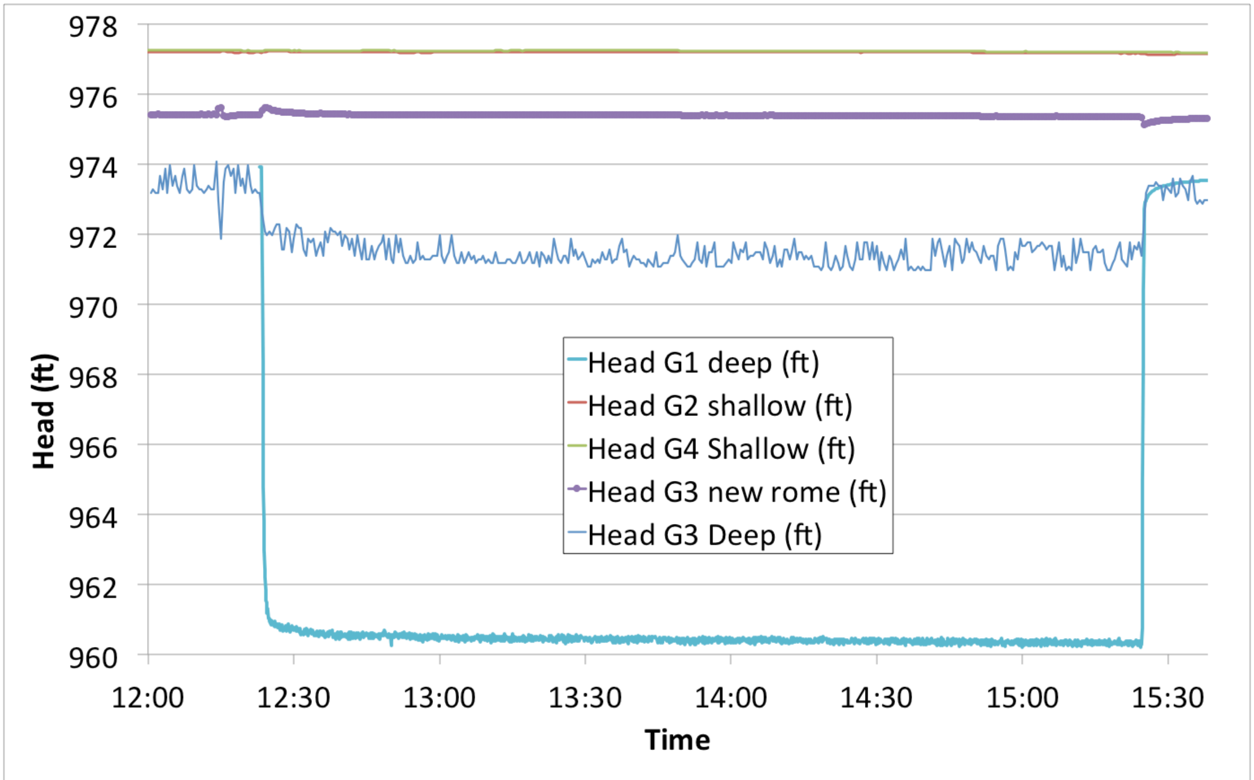

Figure 8. A deep aquifer pumping test.

The poroelastic response of 0.2 feet upward in the aquitard, G3 NR, during pumping from the deep aquifer was expected. The subsequent drawdown is negligible and not really enough to provide data for determing the vertical hydraulic conductivity in the aquitard. The dissipation of the reverse fluctuation could be due to horizontal or vertical flow. More interesting and informative is the presence of the reverse fluctuation in G2 of 0.06 feet upward. It suggests that G2 is partially confined and implies that the overlying aquifer does not start abruptly at the boundary we identified during drilling. It is more likely that the New Rome aquitard grades into the overlying shallow aquifer. An expanded view of the reverse fluctuations are shown in Figure 9.

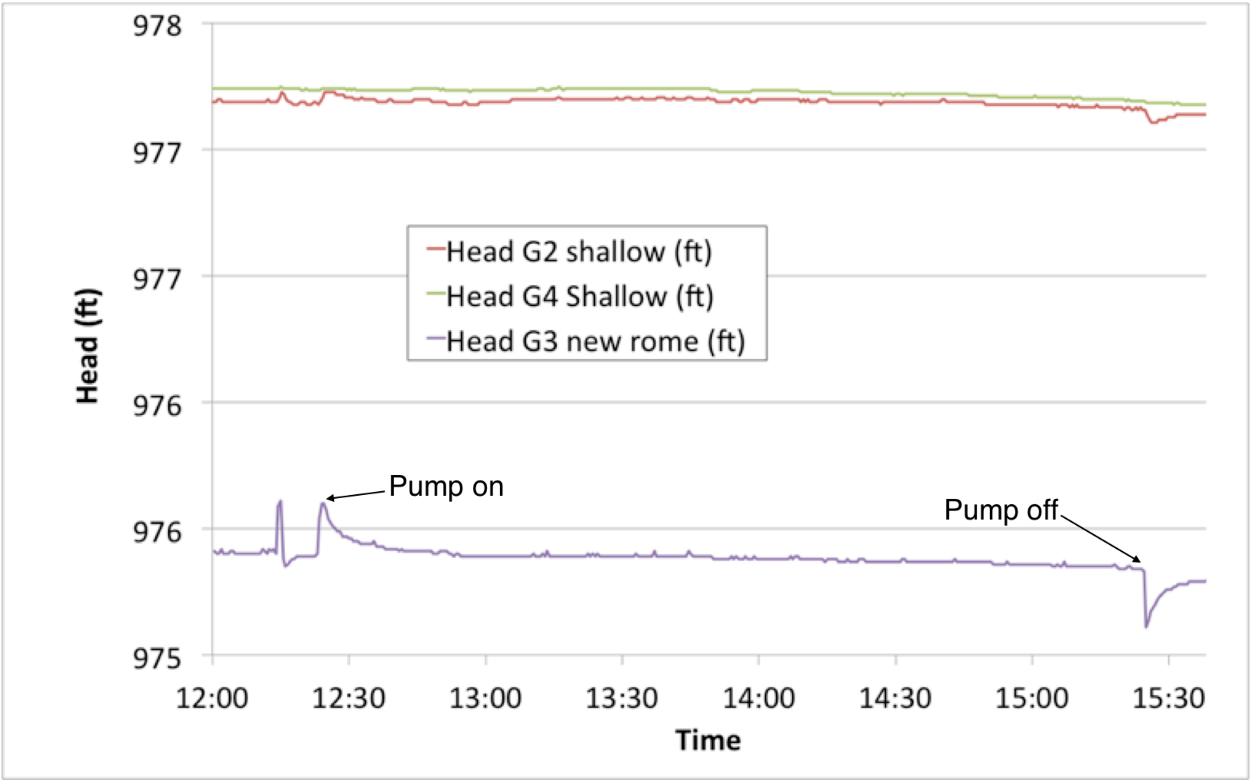

Figure 9. Close up of reverse well fluctuations in G3 New Rome and G2.

Loading Test

Following the pumping tests, we also conducted a loading test on the New Rome. A load applied at the surface should cause the water pressure or head in an underlying aquitard to increase. The aquitard is allowed to come to equilibrium and then the load is removed, causing the water pressure or head in the aquitard to decrease. We drove the WGNHS drill rig with a weight of 25,000 lbs over the piezometer in the New Rome aquitard, G3 New Rome. The head response is shown in Figure 10. The load compressed the aquitard, increasing the fluid pressure by 0.04 feet of head in the G3 New Rome. The pressure dissipation was crudely modeled using Terzaghi consolidation with 1-D vertical flow and an assumed specific storage of $3x10^{-5}$ $feet^{-1}$ (Wang, 2000). Using that analysis, the vertical hydraulic conductivity of the NRF was 0.6 feet/day. This value seems larger for an aquitard and we suspect that the model assumption of no horizontal flow was violated, especially since the assumption inherent in that analysis of an infinite extent of the load was not met. The high hydraulic conductivity is likely the result of horizontal flow. A more sophisticated approach using BIOT2 (Hsieh, 1994) to model point loads is planned that will allow us to include the suspected horizontal flow.

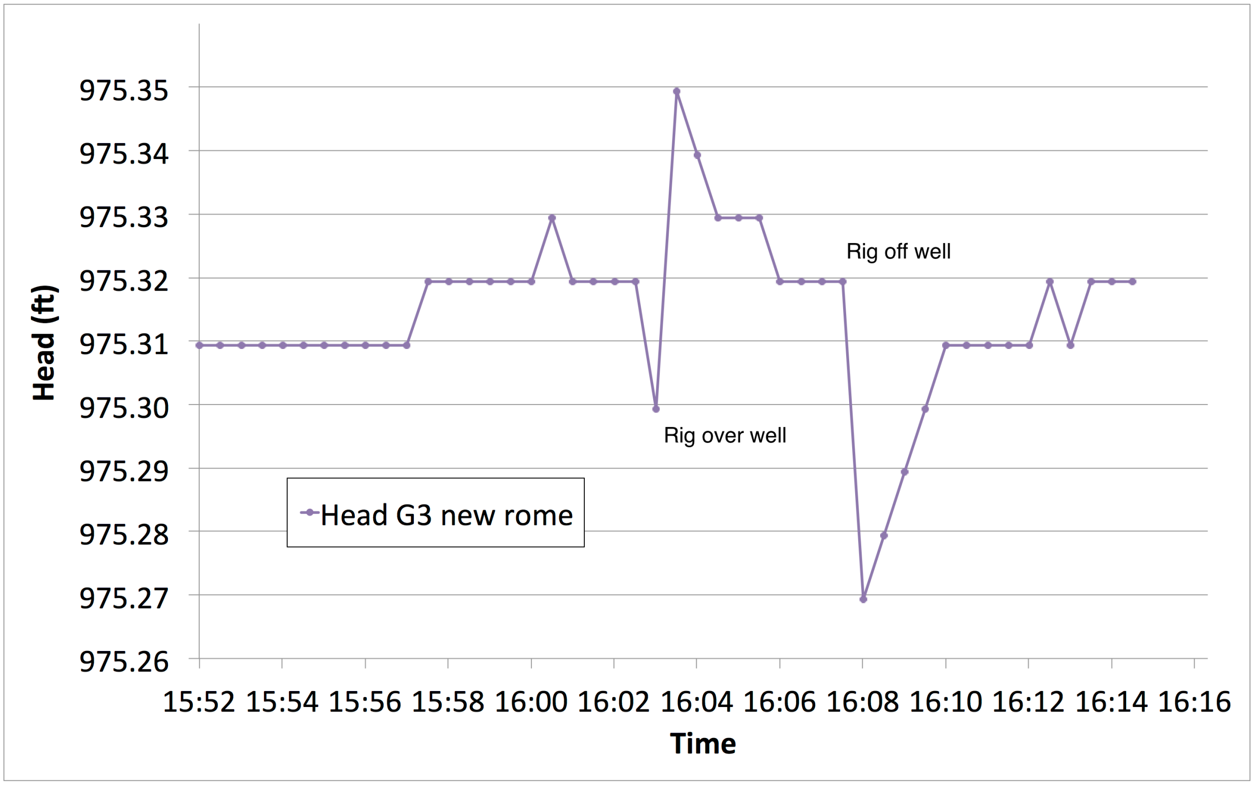

Figure 10. Record of head variation from loading and unloading test using the WGNHS drill rig.

DISCUSSION

One of the initial goals of this project was to determine whether the NRF could be used as a geologic weighing lysimeter. One of the criteria for an aquitard to be used as a geologic weighing lysimeter is that the variation of head from the overlying loads not dissipate for days or, better, months. This condition is possible in parts of Wisconsin. Piezometers have been installed in Glacial Lake Oshkosh clays that take months to years to equilibrate. However, the heads seem to dissipate quickly in the piezometers placed in the NRF. The heads dissipated in around 4 minutes during the loading test, a time that is much too short and not at all useful to determine evapotranspiration unloading by plants on a 24 hour cycle. It is possible that horizontal flow in the aquitard might affect that time constant. Water could move laterally, allowing the heads to quickly dissipate. That test is then inconclusive. It is interesting to note that during the deep pumping test, the reverse well fluctuation dissipated in a similar time frame as during the loading test. In the usual reverse well fluctuation test, drawdown occurs after the initial head rise. That was not present in our test.

Using data from the shallow pumping test provides another line of evidence that our instrumentation in the NRF is not working as a geologic weighing lysimeter. The quick response of the G3 New Rome piezometer during the shallow pumping test suggests a good connection between the shallow aquifer and that piezometer. One hypothesis that we considered for that quick response was that the pumping test removed water from the shallow aquifer above the G3 New Rome piezometer, resulting in a reduced load on the aquitard. We rejected that hypothesis because the shallow aquifer water table well G4, located at a similar radius from the shallow pumping well G2, showed little decrease in head, far too small to indicate unloading by pumping in the G3 New Rome piezometer. The decreased head in G3 New Rome was due to fluid flow, not mechanical loading due to removal of overlying water.

The second stated goal of the proposal was to collect geologic and hydrogeologic data on the NRF so that its role in the groundwater flow system could be better understood. Some questions that this project addresses are the depositional history of the NRF, the variability of the NRF horizontally and vertically, measured parameters for the NRF, and the role of the NRF in a local flow system.

The depositional history of the NRF has long been understood as deep, quiet water lake sediment (Clayton, 1987). However, the transitions from sand and gravel aquifer to fine grained aquitard and then back to sand and gravel aquifer have not been studied. The depositional model can provide guidance on issues of variability. We found that at the installation site, there is a sharp contact at the base of the NRF from sand to clay and a gradual transition back to sand at the top. This depositional model has important implications for any future study or monitoring of this unit. A monitoring well placed in the upper transition zone might be wrongly assumed to be in the aquitard. This assumption might result in an overestimation of the hydraulic conductivity and connectivity of the NRF. Alternatively, if the same monitoring well is thought of as being in the aquifer, it would result in an underestimation of the hydraulic conductivity and transport potential of the overlying aquifer. We have also found that the total hydraulic head change across the NRF varies over a horizontal distance of several hundred feet from 0.8 feet in the Field site to 3.9 feet at the Grassland site. Since both sites are located nearly equidistant from Klein Creek, the local discharge point, we would expect the head drops to be the same for both sites. A potential cause of the difference would be a change in the vertical hydraulic conductivity of the NRF.

The results of the deep and shallow pumping tests, the loading test, and the falling head laboratory permeability test provided different hydrogeologic parameters for the NRF and the upper and lower aquifers. Table 1 is a summary of those results. The hydraulic conductivities of the upper and lower aquifers are similar to those found for the sands and gravels of the central sands. The storage coefficients are also reasonable values and give both an unconfined and confined values for the upper unconfined and lower confined aquifers.

The hydraulic conductivity of the core determined in the laboratory is around six orders of magnitude less than the aquifers. If this low permeability sediment is present in the lower part of the NRF across its entire extent it would limit the exchange of water between the upper and lower aquifers. However, the different head drops across the New Rome at the Field site versus the Grassland site suggest that the vertical hydraulic conductivity of the NRF varies spatially. Because the sediment sample was collected near the Grassland site, where the larger head drop was observed and from the depth with the most massive clays, we should expect this sediment to represent a lower bound of the vertical hydraulic conductivity of the NRF.

The loading test gave a higher than expected value for the conductivity of the NRF of 0.56 feet/day. We suspect that, given the horizontal layers of sands and clays observed in the core, the vertical flow assumption used to analyze the loading test data was violated. It seems more likely that the point load, which was distributed over each of the four wheels on the drill rig, stressed the NRF locally. That local stress then created a local head increase that subsequently dissipated due to horizontal flow. These data can probably provide a better estimate of the horizontal hydraulic conductivity in the NRF using the fully coupled poroelastic model, but such an analysis is beyond the scope of the current project.

Table 1. Hydrogeologic Parameters from Pumping, Loading, and Laboratory Testing.

Unit	Test Type	Hydraulic Conductivity (feet/day)	Specific Storage (S_s) and Yield (S_y)
Upper Aquifer	Pumping Test Neuman Analysis	$K_h = 300$	S_y=0.14
New Rome (transition)	Loading Terzaghi Analysis	K_z=0.56	Assumes S_s=3x10^{-5} ft^{-1}
New Rome	Laboratory Core Falling Head	K_z=2.6x10^{-4}	Not determined
Lower Aquifer	Pumping Test Theis Analysis	K_h=66	S_s=9x10^{-5} ft^{-1}

CONCLUSIONS AND RECOMMENDATIONS

- At the study site in Adams County, the New Rome aquitard varies from 10 to 12.5 feet thick, and is composed of clay, sandy clay, and silt. The aquitard divides the sand and gravel aquifer into upper and lower aquifers. The New Rome aquitard has a sharp contact with the sandy aquifer at its base and a gradual lithologic transition from clay to sand at its top. Accordingly, the top of the aquitard can be difficult to identify using standard drilling techniques.
    - We recommend that any groundwater monitoring above the NRF take this transitional boundary into account.
- At the study site, the hydraulic properties of the aquitard vary laterally.
    - Too little is known about the thickness, extent, and sediment composition of the NRF to treat it as one homogenous unit. Sediment cores should be collected before monitoring wells are installed with care paid to both lateral and vertical variation.
- Collecting sediment during standard well drilling is inadequate for identifying the top of the aquitard.
    - If a detailed geologic log is required, sampling methods that preserve sediment structure, e.g., split spoon or geoprobe sampling should be conducted. Identification of the clay drapes in the lower aquifer/upper NRF and the transition from sands to clays is not possible using hollow stem or mud rotary drilling.
- Ground-penetrating radar and core sampling are relatively inexpensive and helped identify a depositional model that resulted in a more realistic conceptual model than would have been indicated by drilling alone.
    - Hydrogeologic studies, such as groundwater monitoring schemes, in areas where the NRF is present should consider this more complicated depositional model and collect data to support the appropriate placement of monitoring devices. Additional lines of GPR data would help refine the depositional model and enhance our understanding of this regional aquitard.
- Loading tests are very easy to implement but analysis can be complex.
    - We need to create a fully couple poroelastic model to take advantage of this data.

REFERENCES

Brownell, J.R., 1986, Stratigraphy of Unlithified Deposits in the Central Sand Plain of Wisconsin, Masters Thesis, University of Wisconsin-Madison. p. 172.

Clayton, L., 1987, Pleistocene geology of Adams County, Wisconsin. Wisconsin Geological and Natural History Survey Information Circular, v. 59, p. 14.

Hsieh, P. A. (1996). "Deformation-induced changes in hydraulic head during ground-water withdrawal." Ground Water **34**(6): 1082-1089.

Kraft, G. J., K. Clancy, D. J. Mechenich and J. Haucke (2012). "Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited." Ground Water **50**(2): 308-318.

Neal, J. and V. Abreu, 2009, Sequence stratigraphy hierarchy and the accommodation succession method. Geology, v. 37, p. 779-782.

van der Kamp, G. and R. Schmidt (1997). "Monitoring of total soil moisture on a scale of hectares using groundwater piezometers." Geophysical Research Letters **24**(6): 719-722.

Wallendal, A., 2014, Personal Communication

Wang, H.F., 2000, Theory of Linear Poroelasticity with Applications to Geomechanics and Hydrogeology, Princeton, NJ, p. 287.

APPENDIX A: Awards, Presentations, Reports, Patents and Presentations

Hart, D., Streiff, C., and Stewart, E., 2014. Hydrogeologic characterization of an aquitard using poroelastic responses and near surface geophysics. American Geophysical Union, Abstracts with Programs, Fall Meeting, San Francisco.