Lower WI River Floodplain Lake Recharge and Delineation

Groundwater modeling to delineate recharge areas contributing to Jones Slough, Norton Slough, Bakkens Pond, and Long Lake

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Summary

Sloughs along the Lower Wisconsin River act as a refuge and nursery habitat for riverine fish species, including the endangered Starhead topminnow. These sloughs are an important local economic resource for tourism and personal recreation such as fishing and boating. Since 2008, there has been a marked decrease in the water quality of the Lower Wisconsin River floodplain lakes. In particular, high phosphorus and nitrogen concentrations, low dissolved oxygen levels, and dense metaphyton cover have been observed in these groundwater-fed lakes located within Sauk County, WI. Although the exact causes for the deterioration in water quality are unclear, nutrients applied via fertilizer and manure to sandy soils in the agricultural areas of the adjacent Pleistocene terrace are likely contributors to the problem.

The objectives of this study are to identify key recharge zones contributing to the lakes and to evaluate the effectiveness of nutrient mitigation strategies for the sloughs. The primary tool for this work is a three-dimensional groundwater flow model developed as part of a Wisconsin Department of Natural Resources River Planning grant. Calibration targets include water level data collected over several years of continuous monitoring at over 20 well sites within the floodplain and along the river. Samples for nitrate, orthophosphate and dissolved oxygen concentrations, as well as stable isotopes of oxygen and hydrogen, were collected to provide additional constraints on groundwater flow paths and on potential recharge area nutrient sources.

Results showed that groundwater recharge sites for wells with the highest nitrate concentrations were located near the base of the bluffs. Recharge areas on the western portion of the floodplain were more variable. Groundwater travel times ranged from 1-15 years for most groundwater wells and 4-10 months for the water table wells. This implies that nutrient influxes to the sloughs are likely to continue for the next decade, even if all inputs were to cease today. Specific remediation efforts and nutrient sources should be evaluated on a site by site basis.

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1. Introduction

Throughout the Midwest, agricultural contaminants, such as nutrients, are a threat to both surface and groundwater quality resulting in environmental and public health issues. The Driftless Area, a region spreading across the Midwest untouched by the last glacial expansion, is particularly susceptible to groundwater contamination because of its sandy soils and karst topography. However, the relationship between variations in groundwater nutrient concentrations and fluxes in such a pervious system is not well understood (Holman et al., 2010; Fitzgerald et al., 2015). Since 2008, there has been a marked decrease in the water quality of the Lower Wisconsin River floodplain lakes. In particular, high phosphorus (P) and nitrogen (N) concentrations, low dissolved oxygen levels, and dense metaphyton cover have been observed in Jones Slough, Norton Slough, Long Lake, and Bakkens Pond - all located within Sauk County, WI (Figure 1). These predominantly groundwater-fed floodplain lakes, also known as sloughs, act as a refuge and nursery habitat for riverine fish species - including the endangered Starhead topminnow. They are also an important local economic resource for tourism and personal recreation such as fishing and boating in the Town of Spring Green. Although the exact causes for the deterioration in water quality are unclear, it is hypothesized that nutrients applied via fertilizer and manure to sandy soils in the agricultural areas of the adjacent Pleistocene terrace are likely contributors to the problem. Given the importance of both agriculture and tourism/recreation to the local economy, there is a need to identify strategies to protect water quality in the sloughs while still providing adequate land for agricultural activities.

Figure 1. Heavy metaphyton growth in Jones Slough 9/9/15. Image taken by Dave Marshall.

1.1 Previous Work

Through the support of the Wisconsin Department of Natural Resources (WDNR) Lakes Planning grant and the River Alliance of Wisconsin, a preliminary study investigating water pollution in floodplain lakes and sloughs along the lower Wisconsin River was conducted (Marshall, 2013). Results showed that nitrogen levels far exceeded the USEPA recommended criterion of 1.88 mg/L (total N) for controlling eutrophication in this ecoregion (U.S. Environmental Protection Agency, 2000). Concentrations of up to 9.43 mg/L were measured for samples collected during May 2013. This preliminary study suggested that excessive surface application of nutrients over coarse sandy soils and subsequent rapid leaching into the groundwater are the main causes of nutrient contamination as seen in Figure 2. Following the initial surface water sampling, a network of monitoring wells (including 9 sets of nested piezometers) was installed adjacent to Norton Slough, Bakkens Pond, and Jones Slough from 2014-2015. Samples collected from these wells between July 2014 and April 2015 ranged from 1.3 to 44.5 mg/l as nitrate-N.

Concentrations in water table wells were consistently much lower than concentrations found in the deeper piezometers at the same location. Maximum nitrate-N concentrations were most often found in piezometers screened between 40 and 50 feet below the land surface indicating that groundwater, rather than surface runoff, was the primary source of nitrate contamination. Samples for total P were only collected from a few wells in the summer of 2014, but these yielded concentrations of up to 30 µg/L in piezometers screened approximately 20 feet below the water table adjacent to the sloughs and one measurement of over 100 µg/L in a well screened approximately 10 feet below the water table in the floodplain between Norton Slough and the Wisconsin River. A more recent sampling round conducted in the fall of 2015, included P analyses of additional wells. In that sampling round, there were moderate concentrations of less than 50 µg/L in most wells, with exceptions of wells within the floodplain between Norton Slough and the Wisconsin River, where concentrations exceeded 100 µg/L (Marshall, personal communication). A 2016 update to Marshall's report supported the conclusion that water quality changes were not due to internal loading, but rather caused by recent nutrient loadings sourced from contaminated groundwater (Marshall, personal communication). The updated report included additional field data and found that nitrogen, as inorganic NO_x, was the primary driver of eutrophication in the studied water bodies. The occasional high phosphorus concentrations present (mostly in Jones Slough) were determined to be linked to internal responses to the nitrogen loading and *not* considered the cause of eutrophication.   It was recommended that reducing groundwater nitrate concentrations should be a main priority as the deep groundwater elevations at which they were found suggests that these flow paths may ultimately discharge as springs along the Lower

Wisconsin River. Extensive vegetated buffer zones (>300 meters/ 985 ft.) were proposed to increase biotic uptake of nutrients and clean recharge.

Figure 2. Comparison in metaphyton growth in Norton Slough from 2008 to 2011

Two previous models have been constructed incorporating the study area. The larger regional model is the 2001 Sauk County model, a 2-dimensional analytic element model constructed by the Wisconsin Geologic and Natural History Survey (WGNHS) using the stepwise groundwater flow modeling system, GFLOW, to delineate zones of contribution for municipal wells in Sauk County, WI (Gotkowitz et al., 2002). GFLOW does not have the capability to model more than one aquifer and the constructed model does not include the sloughs or other small lakes in the area and only accounts for horizontal flow at a large regional scale. The second model is a 3-dimensional, finite-difference MODFLOW model of groundwater flow near Spring Green, WI. This model was developed as an inset to the Sauk County regional model and covers a similar area to the model constructed for this study. The Spring Green inset model is steady state and uses the Strongly Implicit (SIP) Solver Package in MODFLOW. It has two layers that are portrayed as continuous units. While graphically these layers appear to have variable thickness in Groundwater Vistas (the graphic user interface for MODLFOW), the MODLFOW code actually simulates layers of uniform thickness but with varying transmissivity (Transmissivity [T] = hydraulic conductivity [k] *unit thickness[b]). This numerical implementation can have a significant impact on the modeled flow paths – particularly at the local scale of interest to this study. Neither of the previous models was designed to tackle the issue of contamination sources to the sloughs, nor did they provide a sufficient level of detail to distinguish slight variations in vertical gradients between the sloughs and Wisconsin River, which is important for identifying the primary groundwater recharge zones that ultimately discharge to the sloughs. As such, there was a need to develop a new model with a more detailed scale than that of the regional model and with a more realistic portrayal of the study area's geologic units than that of the inset model.

1.3 Objectives

This report was commissioned by Sauk County's Conservation Planning & Zoning Department through the WDNR River Planning Grant. It is focused on addressing the issue of poor water quality in the sloughs along the Lower Wisconsin River, with wider implications for resource management in sandy agricultural floodplains. In doing so, the following research questions are addressed:

1. What are the sources of groundwater nutrient contamination to sloughs?

2. What are some potential remediation approaches for managing the nutrient contamination?

Research question 1 was addressed using a combination of isotopic, physical, and chemical data to iteratively calibrate a 3-D steady-state groundwater flow model developed using the USGS code, MODFLOW. Piezometer nests and staff gauges constructed for this project, as well as existing private wells, were the primary source of data for this multi-year project spanning from 2014-2016. Research question 2 was answered by using the groundwater flow model (hereafter referred to as the "UW model") to test remediation strategies, specifically the feasibility and effectiveness of groundwater buffer zones and induced discharge sites.

1.4 Report Outline

Chapter 2 describes the study area and field methods used in this study. Chapter 3 covers the results from field investigations including isotopic, physical, and chemical data. Chapter 4 describes the construction process for the 3-D steady-state numerical groundwater flow model (UW model) as well as results and limitations. Suggestions for mitigation strategies to treat contaminated groundwater based on the results of the UW model and multi-year water quality data are discussed in Chapter 5, along with recommendations for future work. Well and staff gage construction details, slug test analyses, and data collected for water conductivity, temperature, nutrient concentrations, and isotopic signatures can be found in the appendices.

2. Site Description and Methodology

2.1 Site Description

The Lower Wisconsin River (LWR) is a stretch of the Wisconsin River that begins below the Prairie du Sac dam and extends to where it flows into the Mississippi River, making it the longest free-flowing section of river in the Midwest at 92.3 miles. In 1989, the Lower Wisconsin State Riverway (LWSR) and the LWSR Board were created, establishing land management and acquisition standards for the Riverway in recognition of the biological importance of this unique ecosystem ("Lower Wisconsin State Riverway," 2016). The dynamic connectivity of water bodies within fluvial hydrosystems provides critical habit for aquatic species vulnerable to a river's fast currents. These water bodies also function as a nursery for many riverine fish species (Amoros and Bornette, 2002). In the LWSR, the oxbow lakes provide habitat for rare fish species including those ranked as "State Special Concern": such as the mud darter (*Etheostoma asprigene*), pirate perch (*Aphredoderus sayanus*), pugnose minnow (*Opsopoeodus emiliae*), and one ranked as "State Endangered": the starhead topminnow (*Fundulus dispar*).

This study focused on the water quality of Jones Slough, Norton Slough, Long Lake, and Bakkens Pond. Located near the town of Spring Green, all four are categorized as spring-fed lakes by the Wisconsin DNR (Table 1). Bakkens Pond lies within a State Natural Area and was originally an open floodplain with an oxbow channel until two impoundments were constructed to create waterfowl habitat. Long Lake is located downstream of Bakkens Pond and is dammed near the Hwy 130 bridge on the Wisconsin River. The northern side of Long Lake is residential while the southern side is a protected area - the Sauk County School Forest. Jones Slough and Norton Slough are located adjacent to each other and contain no impoundments. In 2014, a 12-acre permanent conservation easement was established upgradient of Norton Slough on what was previously agricultural land.

Table 1. Maximum depth and area of the lakes included in the study

Name	Max. Depth (ft.)	Area (acres)
Bakkens Pond	6	19
Jones Slough	8	7
Long Lake	10	5
Norton Slough	8	14

2.2 Land Use

Landuse in southern Sauk County is predominantly agriculture, occurring on the broad Pleistocene terrace and adjacent to upland streams. In the late 1990s, center pivot irrigation began to dominate the landscape and led to an increase in well installation and construction (Figure 3). The top five crops harvested in Sauk County during 2015 were corn, alfalfa hay, and soybean (

Table **2**). Dairy and cattle farming is also present in the area. Spring Green has two municipal wells with average pumping rates of 46 and 179 gpm (Gotkowitz et al., 2002).

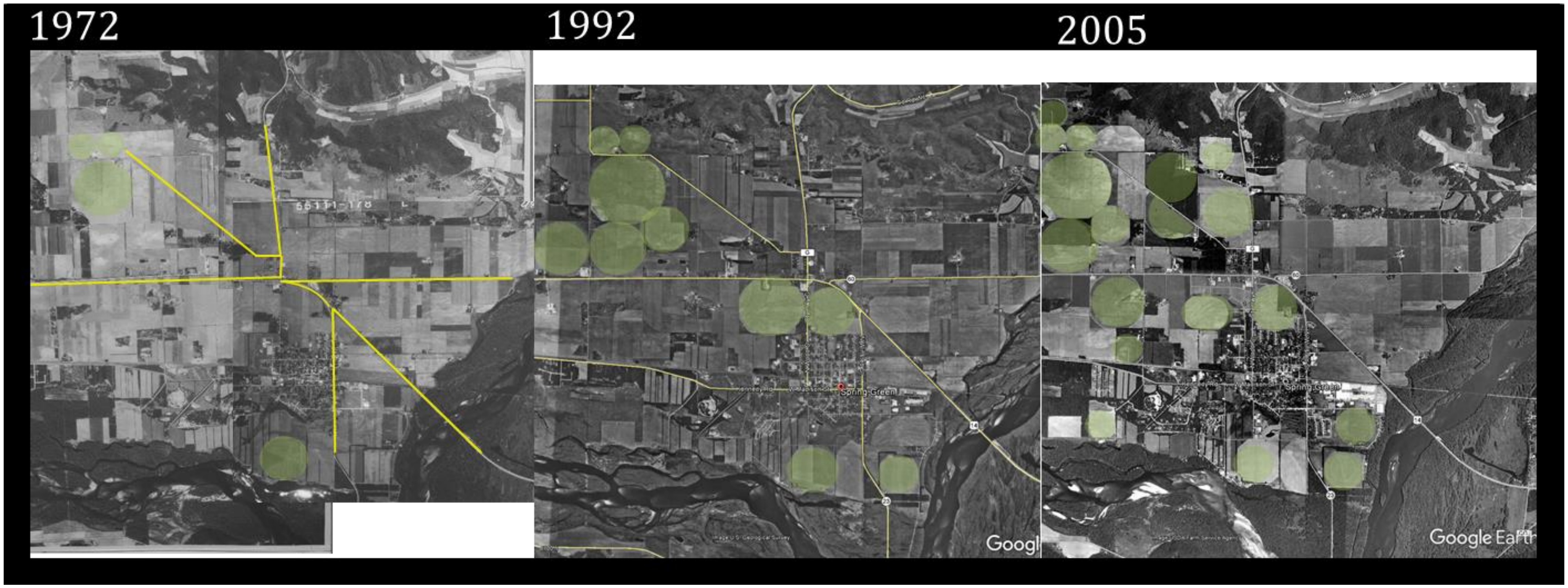


Figure 3. Aerial photographs showing increase in pivot irrigation (green circles) between 1972 to 2005 near Spring Green, WI.

Table 2. Top five crops harvested in Sauk County in 2015

Crop	Acres
Corn - grain	70,700
Hay - Alfalfa	36,300
Soybean	33,400
Corn-silage	15,600
Winter wheat	5,150

2.3 Climate

Sauk County is located in south central Wisconsin and has a continental climate. Based on continuous weather records at the Lone Rock Tri County Airport, WI, the average winter temperature (December through February) is 20.8°F for 1981 to 2010 (NOAA, 2016). The average summer temperature (June through August) for the same period is 69.5 °F. This area receives most of its rainfall during the summer, with the winter months normally being the dry period; average winter precipitation from 1981 to 2010 is 3.50 inches while the average summer precipitation is 14.27 inches. The average total annual precipitation is 35 inches (NOAA, 2016).

2.4 Geology

The study area is located within the Driftless Area, a region that extends across Iowa, Wisconsin, Minnesota, and Illinois and that was left untouched by the last glacial expansion. Most of the bedrock is Paleozoic in age, underlain by Precambrian igneous and metamorphic basement. The subsequent descriptions of geologic units and formations are based on Clayton and Attig (1990), which provides a thorough account of Sauk County's geology (Figure 4).

Paleozoic Geology

Narrow uplands composed of Cambrian sandstone (Tunnel City, St. Lawrence, and Jordan formations) and dolomite-capped bluffs define the northern edge of the study area and are characterized by their steep slopes and shallow depths to bedrock (Figure 4). These bluffs border the Pleistocene terrace, a broad ancient floodplain consisting of hundreds of feet of thick sediment deposited by glacial meltwater streams. Underlying this unit are sandstones of the Elk Mound Group, which include the undifferentiated Wonewoc, Eau Claire, and Mount Simon formations. These formations are described as glauconitic and fine-grained with average thicknesses of 100 to 150 ft. A thin layer of the Tunnel City Formation, composed of glauconitic and dolomitic sand and sandstone, overlies the Elk Mound Group near the base of the bluffs.

Quaternary Geology

The southern portion of the study area is defined by the Lower Wisconsin River, which has its modern floodplain within the Pleistocene terrace. This material is predominantly sand to slightly gravelly sand. In some places, thin layers of peat and silty overbank sediment overlie it. A significant unit of peat material that was deposited during the late Holocene is present beneath Bakkens Pond. Elongated windblown sand dunes that formed during the mid-Holocene trend east-west across the Pleistocene terrace, varying in thicknesses from about 5 to 10 feet. Non-glacial stream sediment and eroded hillslope sediment of composition similar to that of the terrace sands fill the steep valleys in the upland region with thicknesses typically less than 15 feet.

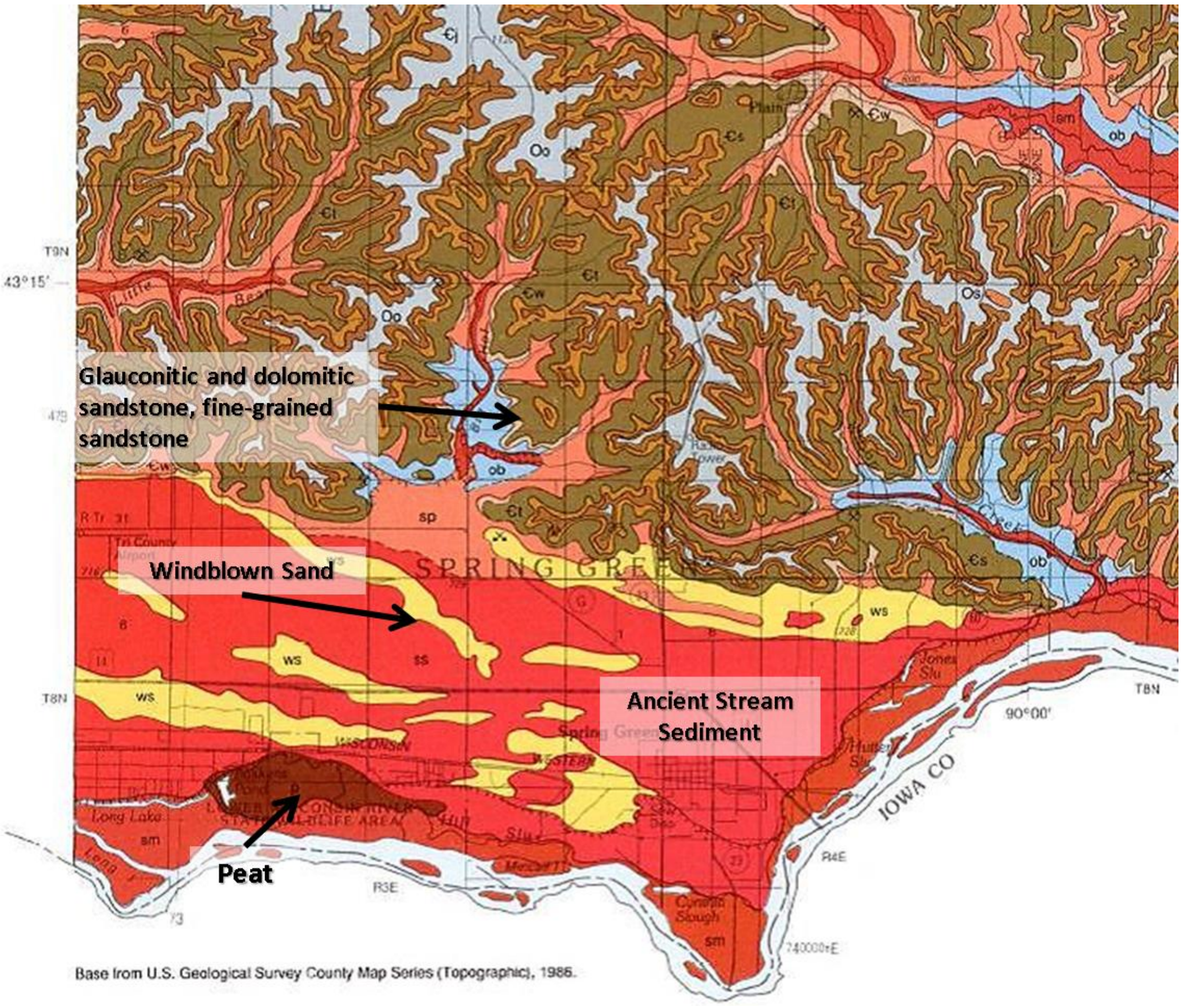


Figure 4. Select portion of a map of Sauk County geology published by the Wisconsin Geological and Natural History Survey. A small portion of the study area, including Lone Rock to the west, is not shown.

2.5 Hydrogeology

Hydrostratigraphy

There are three main hydrostratigraphic units within the study area: the unlithified aquifer, the sandstone aquifer, and the Eau Claire aquitard (Gotkowitz et al., 2005).The unlithified aquifer is the topmost unit for almost the entire study area and is the predominant aquifer (Figure 5). The glacial outwash material here varies from sand and gravel to silty and clayey sediment (Gotkowitz et al., 2005). The sandstone aquifer consists of all the saturated Paleozoic bedrock described above, and is thickest in the upland bluffs (800 – 900 ft.) and along the edge of the LWR (500-600 ft.). For most of the study area, the unlithified and sandstone aquifers function as a single unit with heterogeneous hydraulic properties (Gotkowitz et al., 2005). The Eau Claire aquitard, which includes a mixture of shale, siltstone, and dolomite, is present in the western and southwestern portions of Sauk County (Hart and Thomas, 2005). Within the study area, the Eau Claire aquitard is only found at the southernmost edge, directly south of Spring Green at Pecks Landing, and is around 10 feet thick in this area.

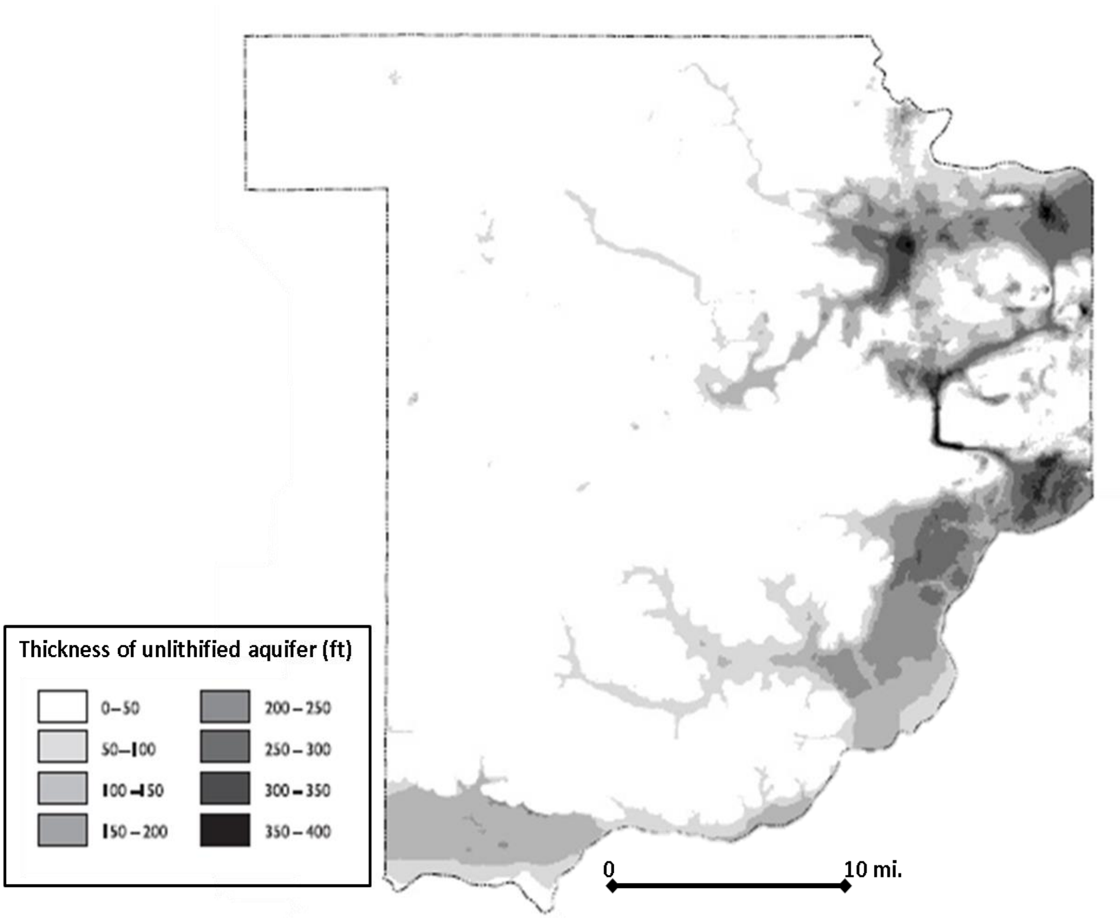


Figure 5. Extent and thickness of unlithified aquifer in Sauk County. Figure from Gotkowitz et al. (2015)

Groundwater Flow System

The LWR is the focus of regional groundwater discharge from flow paths that travel through both the bedrock and the valley sediments (Figure 6). However, other surface water features in the area, such as the riparian sloughs, also receive groundwater discharge. Because of the relatively flat landscape between the bluffs and the river, and the high conductivity of the meltwater sediments, most surface water features in the area are groundwater fed. Groundwater recharge in the area is likely to occur readily through the glacial outwash and alluvial sediments in the valley as well as on the hillslopes of the dolomite bluffs (Juckem, 2003; Gotkowitz et al., 2005)

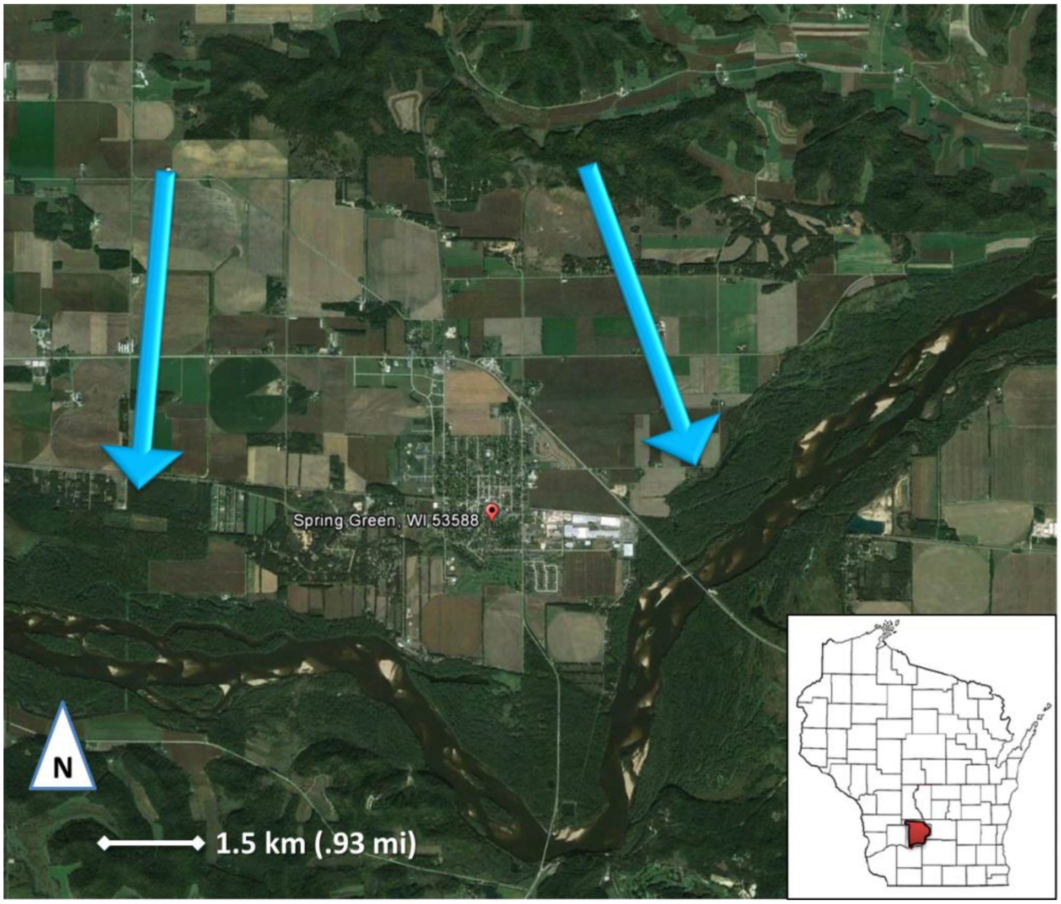


Figure 6. Google Earth aerial image of study area. Blue arrows show the generalized regional flow direction.

3. Field Methods

3.1 Instrumentation

Thirty-four 1- or 2-inch diameter water table wells and piezometers were installed for this study at depths ranging from 7.5 to over 80 feet below ground surface (Figure 7). Most of the wells were constructed in nests of three to six, with screens lengths varying from 10 feet for water table wells to 2 feet for deeper piezometers. Ken Wade and Dave Marshall installed all but four of the wells; BP5, BP6, FP3, and WRFP were constructed by the University of Wisconsin-Madison's hydrogeology field course in June 2015 (Figure 8). See Appendix A for all construction information. In addition, two Town of Spring Green monitoring wells (JRT and BPT) and six private water supply wells were monitored for water level and/or quality. Surface water levels were also monitored at four staff gages in the sloughs and river (Norton Slough, Bakkens Pond, Long Lake, WR, and Lone Rock river stations).

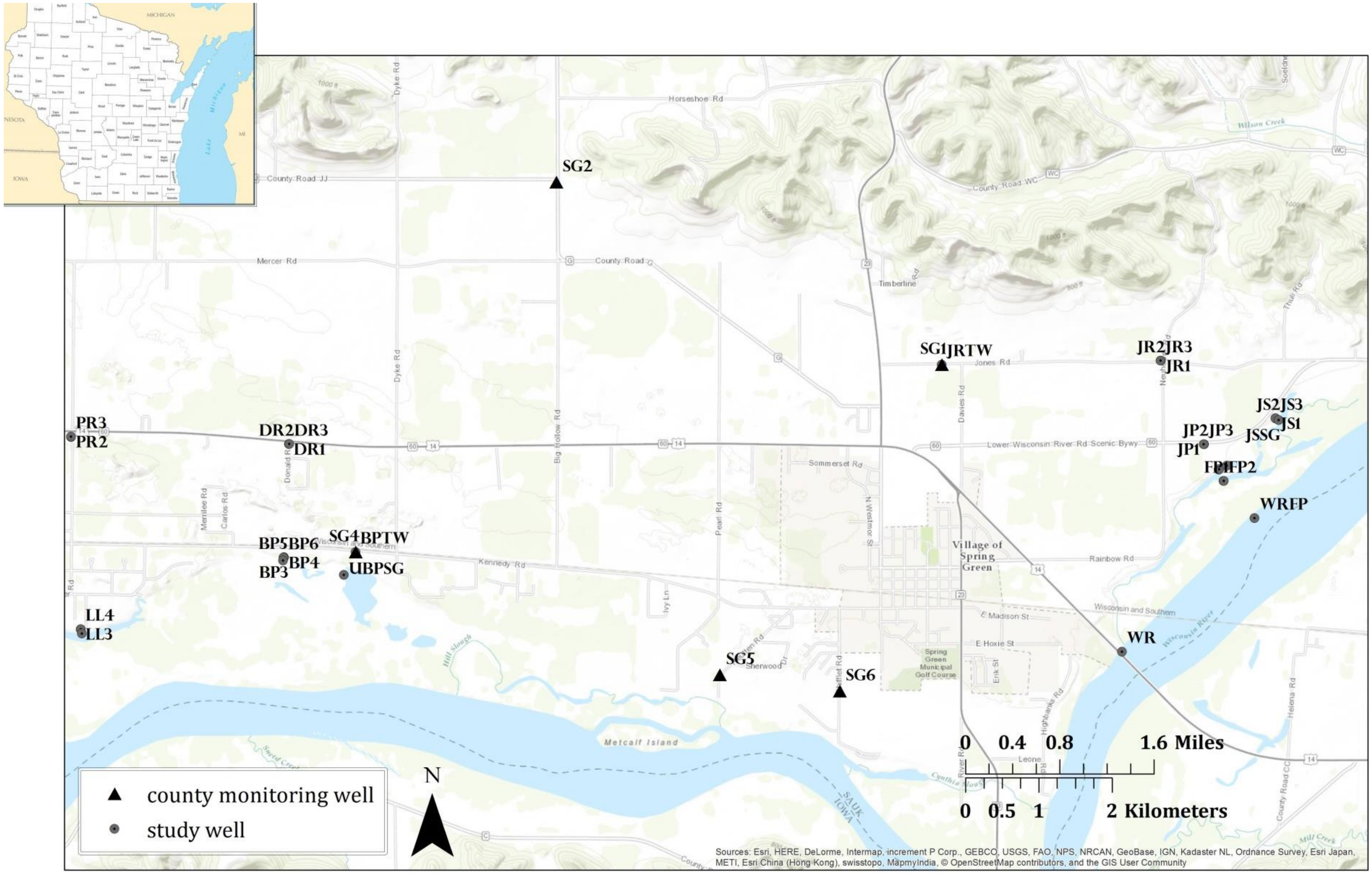


Figure 7 Location of monitored well sites. Both well nests and singular wells are represented by a red dot. See well construction log in Appendix A for well IDs key.

Figure 8. Bakkens Pond well nest showing BP1-BP4. BP5 and BP6 (not pictured) were constructed by the UW-Madison Hydrogeology Field Course.

3.2 Water level

Water level monitoring in wells and in the sloughs occurred between May 2014 and October 2016 with measurements taken every 6 hours by HOBOware pressure transducers. Transducers were left in the wells during the winter months. Records during this time period may not be reliable, especially in the staff gages and water table wells, due to ice heaves and cold temperatures. The staff gage at Long Lake had to be reinstalled on two occasions after being knocked over by ice. It was later discovered that water levels recorded for Bakkens Pond in late May 2015 were not representative of natural conditions, as the WDNR was draining the pond to put in a new outlet structure at that time.

Manual depth-to-water measurements were periodically recorded using a “popper” (measuring tape with steel pipe cap affixed to the end) or an electric meter. Data recorded by the HOBOware pressure transducers were corrected for barometric pressure using a HOBOware transducer located above ground in Blue Mounds, WI. Short gaps in data (<24 hrs.) due to datalogger or operator error were interpolated using a MATLAB code developed by Kim Scherber, Elisabeth Schlaudt, and Josh Olson in which trends in previous and subsequent data points were analyzed to estimate the true value of the missing data. The purpose of interpolating was to make analysis of long-term changes in vertical gradients within well nests more efficient.

3.3 Slug Testing

Slug tests to estimate hydraulic conductivities within the study area were conducted on October 22, 2016 for groundwater wells at sites Donald Road, Jones Road, and Norton Slough. Tests were conducted by releasing a solid PVC rod in freefall down the well. Rates of water displacement and recovery were measured using INW’s AquiStar Smart Sensor, which recorded changes in pressure at half-second intervals (Figure 9). Each site was tested at least four times: two slug-in and two slug-out tests. Results were analyzed in AquiferWin 32 Version 5.01 using the Hvorslev “T0” Method (Hvorslev, 1951). The recovery time for all the sites was on the order of seconds; these extremely fast rates are likely due to the permeable nature of the glacial outwash material in the floodplain (Table 3). As a result, not all slug tests were fit for analysis and some response data appeared to be oscillatory (underdamped): a characteristic feature of slug tests in highly conductive materials (Butler, 1997). See Appendix B for tables of calculations and slug dimensions. Groundwater wells BP2, BP3, and BP4 at Bakkens Pond were tested by the University of Wisconsin-Madison hydrogeology field course on June 11th, 2015 using identical field methods to those described above. Results were manually analyzed in Excel using the Hvorslev "Slope" Method.

Figure 9. Performing slug test at Norton Slough well nest site.

Table 3. Average hydraulic conductivity by well

Well ID	K (m/s)	K (m/day)	Screen Elevation
BP2	9.14E-04	79	679.8
BP3	5.79E-04	50	667.5
BP4	4.88E-04	42.1	654.6
DR2	6.25E-04	54	688.3
DR3	2.08E-03	180	676.1
JR2	5.48E-04	47.4	698.1
JR3	1.68E-03	145.5	686.2
NS2	1.75E-03	151.2	694.6
NS3	8.91E-04	77	682.2
NS4	6.90E-04	59.6	669.9

3.4 Chemistry

Field Measurements

Temperature and conductivity were measured for all well sites using an Extech ExStik EC40. Starting in spring 2015, samples for nitrate-N were collected for well sites on a near-monthly basis from spring to fall and were analyzed using the in-house capabilities of Dave Marshall who used a YSI/ Xylem Pro Plus. An YSI Pro 20 Dissolved Oxygen meter was used to measure concentrations during summer 2016. Chemetrics® test kits based on colorimetric methods were used to periodically measure in situ concentrations (mg/L) of orthophosphate, nitrate-N, and dissolved oxygen during summer 2016 and acted as a quality check against the YSI probes.

Isotopes

Samples for isotope analyses were collected on May 24, 2016 and July 12th, 2016, in glass scintillation vials after pre-rinsing the vials three times with the water to be sampled. See Appendix F for the full list of sites at which isotopic samples were collected. The samples were analyzed by the Iowa State University Stable Isotope Lab for oxygen ($\delta^{18}O$) and deuterium (δD) isotopes via a Picarro L2130-i Isotopic Liquid Water Analyzer, with Autosampler and ChemCorrect software. Each sample was analyzed a total of six times. To account for memory effects, only the last three injections were used to calculate mean isotopic values. Oxygen and deuterium isotope values are reported in δ relative to the standard Vienna Standard Mean Ocean Water (VSMOW). Reference standards (VSMOW, USGS 48, USGS 47) were used for regression-based isotopic corrections, and to assign the data to the appropriate isotopic scale. At least one reference standard was used for every five samples. The combined uncertainty (analytical uncertainty and average correction factor) for $\delta^{18}O$ is ± 0.07‰ (VSMOW) and δD is ± 0.36‰ (VSMOW), respectively.

4. Results of Field Investigations

4.1 Nutrients

There was a general trend of increasing nitrate-N concentrations with depth across most well sites (Figure 10). The highest levels appeared to occur in wells with screen midpoints between 640-675 feet above msl. Concentrations in water table wells tended to stay below 10 mg/L. Water table wells on the eastern side of the study area had higher median nitrate concentrations as compared to the western side. Between July 2014 and October 2016, the monthly median nitrate concentration for all well sites trended upward slightly, although this trend was not statistically significantly (Figure 11). The magnitude of seasonal fluctuations in nitrate varied by well nest, but fall tended to be the season with highest concentrations.

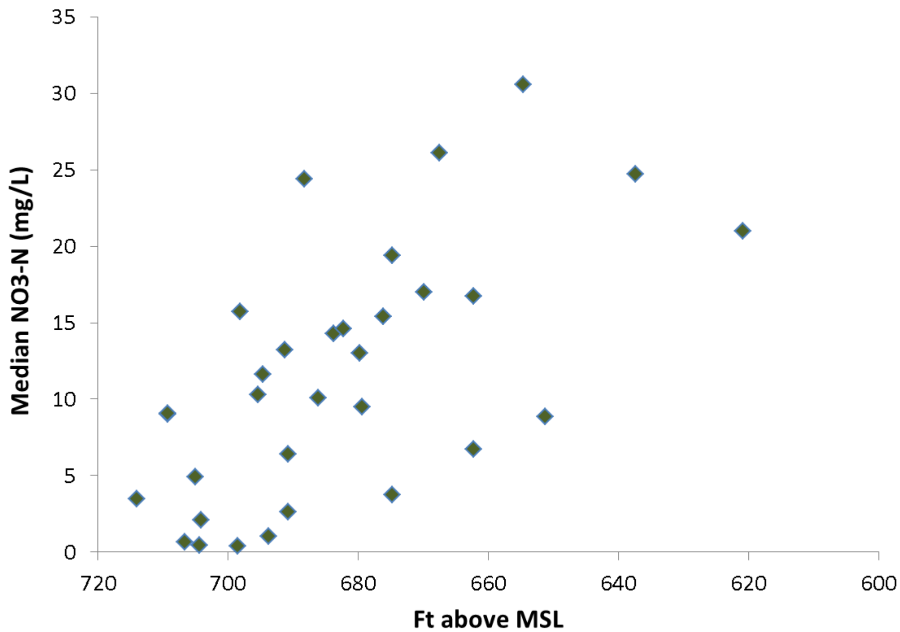


Figure 10. Median nitrate concentrations where each point represents a single well. Plotted in terms of screen midpoint elevation (feet about msl).

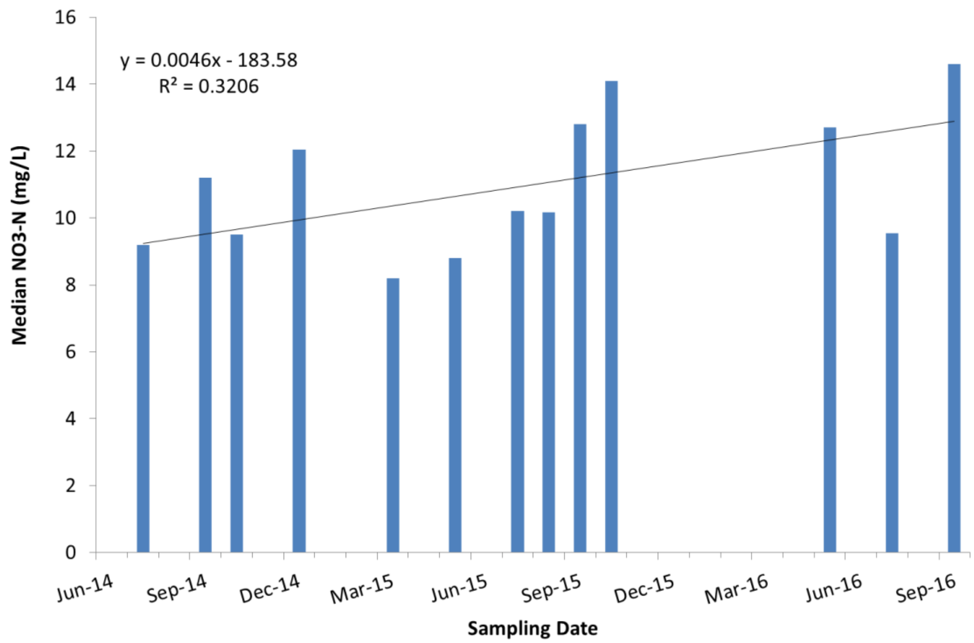


Figure 11. Change in nitrate concentrations with time where each point represents the median concentration of all monitored wells for that sampling round.

The Bakkens pond well nest, a collection of six wells ranging in screen depth from 10.75 to 83.75 feet below ground surface (BGS), had the highest average nitrate concentrations among the monitored well sites (Figure 12). BP4, screened between 45.2 - 47.2 ft. below ground surface (BGS), had the highest median concentration at 30.6 mg/L and a maximum of 44.5 mg/L measured on July 10th, 2014. DR2, JS2, and NS4 also had notably high median concentrations at 24.4, 19.4, 17.0 mg/L respectively.

Changes in nitrate concentrations with time for all monitored wells can be found in the Appendix E.

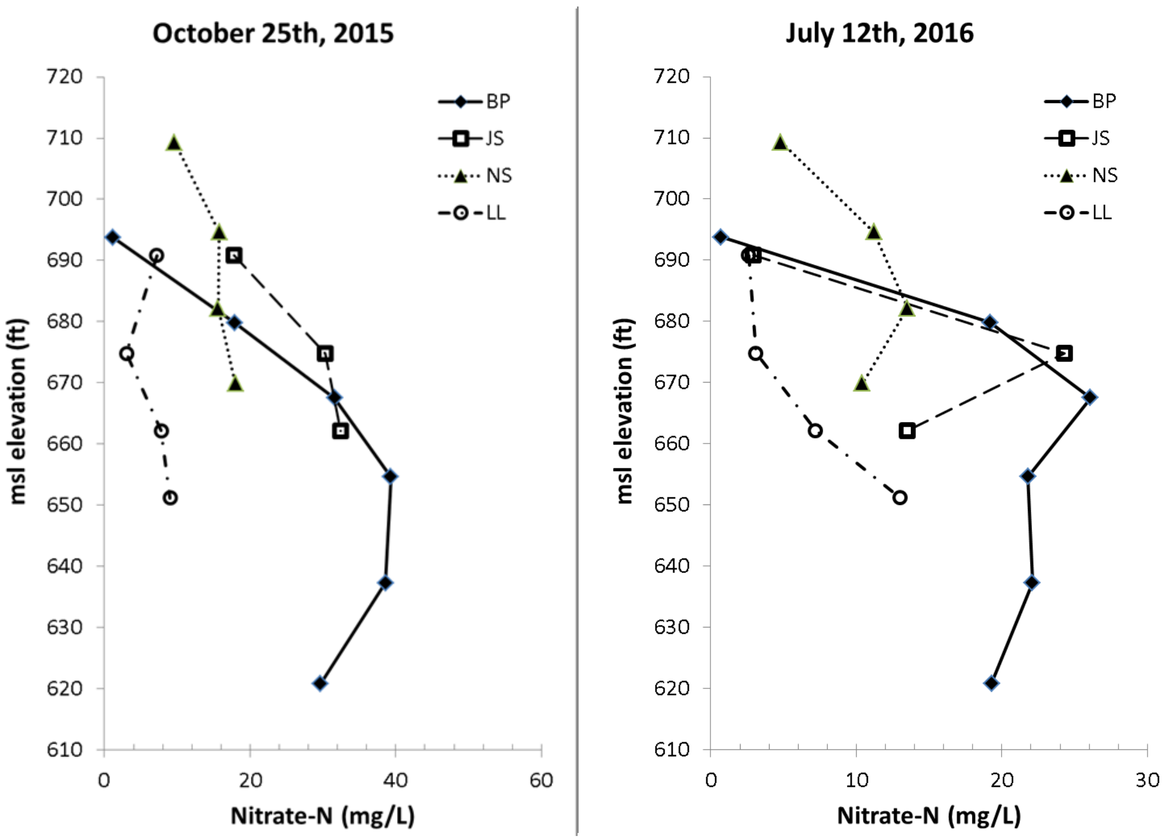


Figure 12. Changes in nitrate concentrations with depth for well nests BP, JS, NS, and LL. Each point represents a well within the respective well nest.

Samples for measurement of phosphorus concentrations were collected much less frequently than those for nitrogen/nitrate and were not collected at all sites. In September 2015, total phosphorus (mg/L) was measured in samples at the Bakkens Pond, Jones Slough, Long Lake, and Norton Slough well nests (Figure 13). Only PR3, the deepest well, was sampled at the Porter Road site. Total phosphorus concentrations were below 0.06 mg/L for all wells, except for LL1, which had a reading of 0.454 mg/L, an order of magnitude higher than any other readings. The Long Lake site is located on a residential property and the reading may have been related to lawn fertilizer application or another similar source. For the Bakkens Pond and Norton Slough wells, total phosphorus increased with depth, while for Jones Slough and Long Lake wells, concentrations decreased with depth. Orthophosphate concentrations were measured at almost all well sites on July 13, 2016 using the Chemetrics® test kits. Most results were between 0 – 0.1 mg/L. The LWR modern floodplain wells (FP1, FP2, FP3, WRLR) had very high orthophosphate concentrations ranging from 0.6 for WRLR (located on the banks of the river) to 5.0-6.0 mg/L for FP3 (located inland from WRLR). The water table well at Jones Slough (JS1) had the highest orthophosphate reading among the inland well nests at 2.0-3.0 m/L.

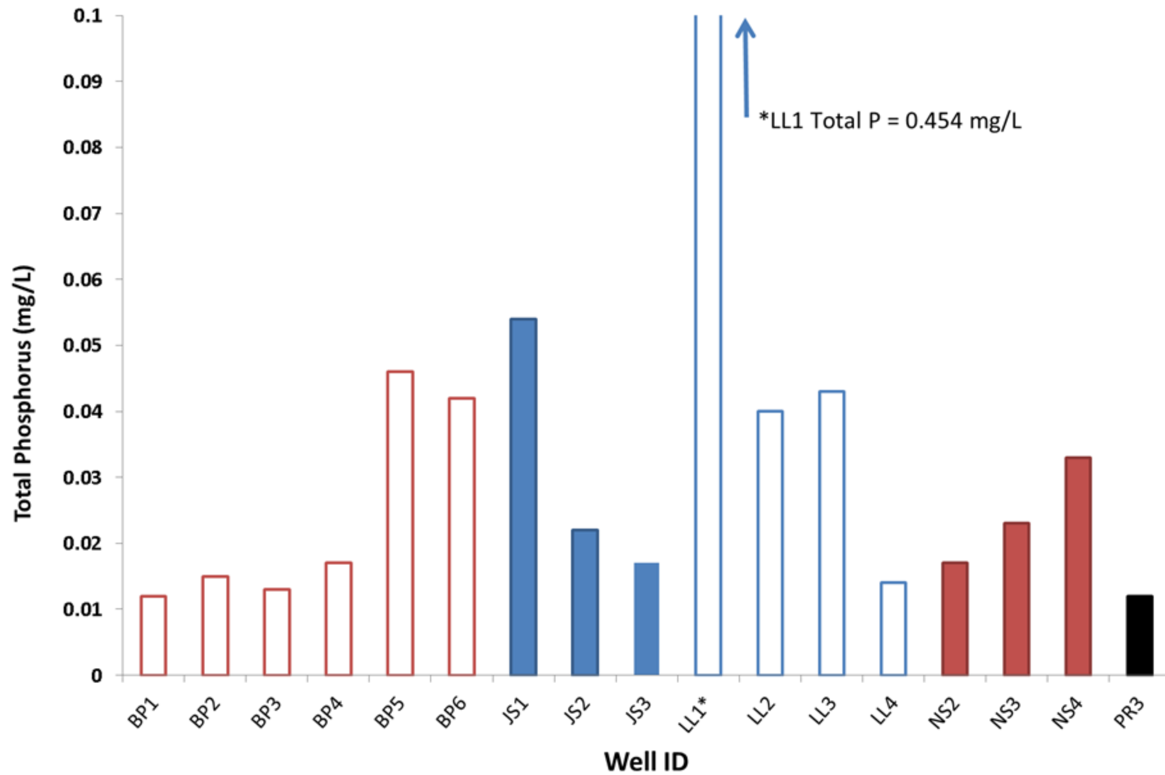


Figure 13. Phosphorus concentrations measured in well water on September 20th, 2015

4.2 Isotopes

Stable isotope analyses of water, $\delta^{18}O$ and δD, can be used to indicate flow paths within the groundwater system and mixing of groundwater and surface water in the slough. Previous work has shown that groundwater flow paths in the floodplain of the Lower Wisconsin River can be identified by differences in isotopic signatures that reflect seasonal variations in the isotopic composition of recharge (Pfeiffer et al., 2006). By plotting $\delta^{18}O$ and δD of samples and comparing their relative position along the local meteoric water line (the average linear relationship between oxygen and hydrogen isotope ratios in precipitation), samples can be broadly categorized as having a winter or summer recharge source. Winter precipitation in Wisconsin tends to be isotopically depleted with respect to the heavier isotopes, while summer precipitation tends to be enriched with respect to ^{18}O and D (Figure 14). For this project, samples were plotted along the local meteoric water line (LMWL) created as part of a larger study of the Nine Spring watershed in Fitchburg and Madison, WI (Swanson et al., 2006). Evaporation results in the enrichment of heavy isotopes, which would manifest itself on an isotope plot as a departure from the meteoric waterline. All samples plotted relatively linearly along the LMWL indicating little effect of evaporation.

Samples for isotopes were collected on two occasions, approximately 1.5 months apart, during the summer in 2016. Results of the isotope analysis showed three groupings of samples along the LMWL (Figure 14). Water table well signatures tended to plot on the extreme ends, suggesting more recent water sources. Deeper wells, intercepting older water from flow paths originating much farther away, tended to plot in the middle. Between May 24th and July 12th, 2016, the number of data points that shifted up versus down along the LMWL was equal (11 v. 11) (See Appendix F for individual well isotope plots). The general trend appeared to be that the data points associated with water table wells shifted upward and the deepest wells in each nest shifted downward. However, this was not true for all cases; the water table wells for Porter Rd, Jones Prairie, and Bakkens Pond shifted downward and the deepest well at Jones Road (JR3) shifted upward. The most notable change in positions occurred for PR1 (water table at Porter Rd) and FP2 (the second deepest well on the floodplain between Norton Slough and the river). PR1 completely flipped its position from the end representing a summer precipitation source to spring snowmelt. FP2 moved towards the "summer end" of the mixed source cluster.

The movement of the water table wells towards isotopically heavier values indicates the addition of spring and summer recharge. Some of the mid-depth wells may have just begun to receive the addition of spring snowmelt, thereby “lightening” their isotopic signatures. The floodplain wells (FP1, FP2, and FP3) may have water that re-infiltrated from the slough or river, resulting in “mixed” source signatures.

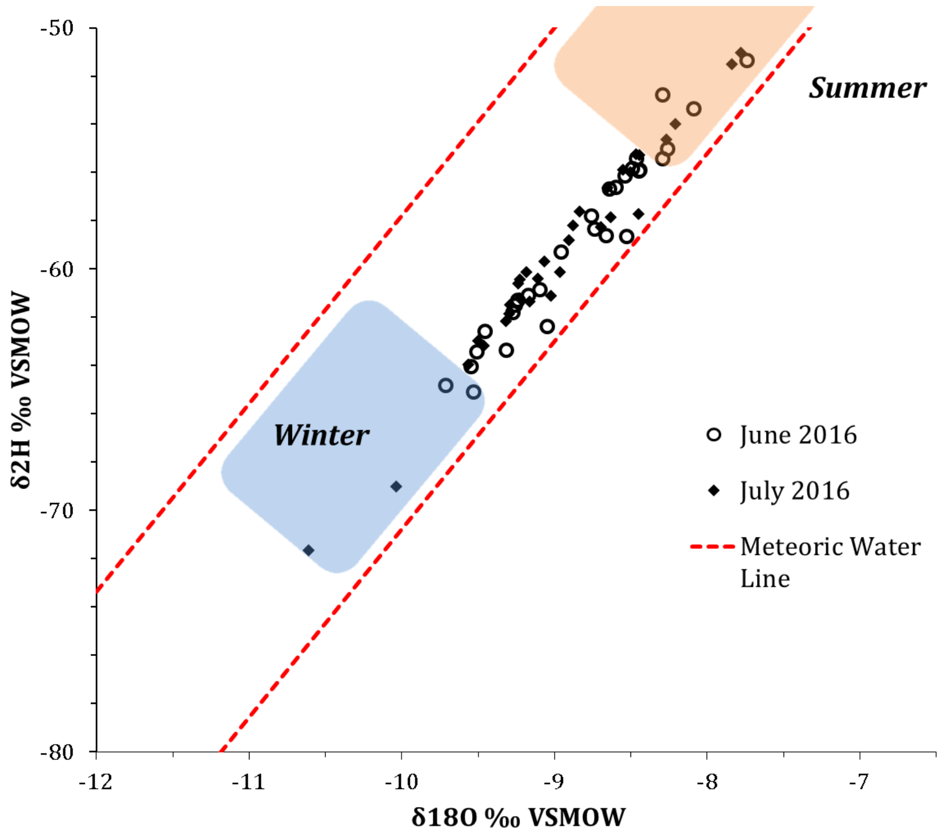


Figure 14. Plot of LMWL (zone between dashed red lines) and well isotopic signatures. The colored boxes represent the generalized precipitation/ recharge sources based on the isotopic signature.

4.3 Groundwater Flow System

The resulting water table maps developed from the continuous water level records confirmed the initial hypothesis of a shallow but consistent gradient across the floodplain from the upland bluffs to the river (Figure 15). Vertical gradients calculated within well nests instrumented with pressure transducers across the study area were very small and, in some cases, below the precision limit for the pressure transducers.

Within the Bakkens Pond (BP) well nest, there was a constant upward gradient between BP2 and BP1, the water table well. The magnitude and direction of the vertical gradients between the subsequently deeper wells (BP3-BP6) fluctuated seasonally on the order of .008 - .07 ft. /ft.

For Long Lake, the vertical gradient between LL2 and the water table well (LL1) and between LL3 and LL2 was downward overall. Vertical water movement from LL4 to LL 3 was upward, although the absolute magnitude (+/-) among all wells appeared to stay within the same range, fluctuating between 0 to 0.015 ft. /ft.

The gradient between the water table well (NS1) and the next deepest well (NS2) at the Norton Slough site was the smallest for the monitored wells nests – essentially negligible, with all values being 10^{-3}. The gradient between NS3 and NS4 was the largest for this well nest with an absolute magnitude of about 0.02.

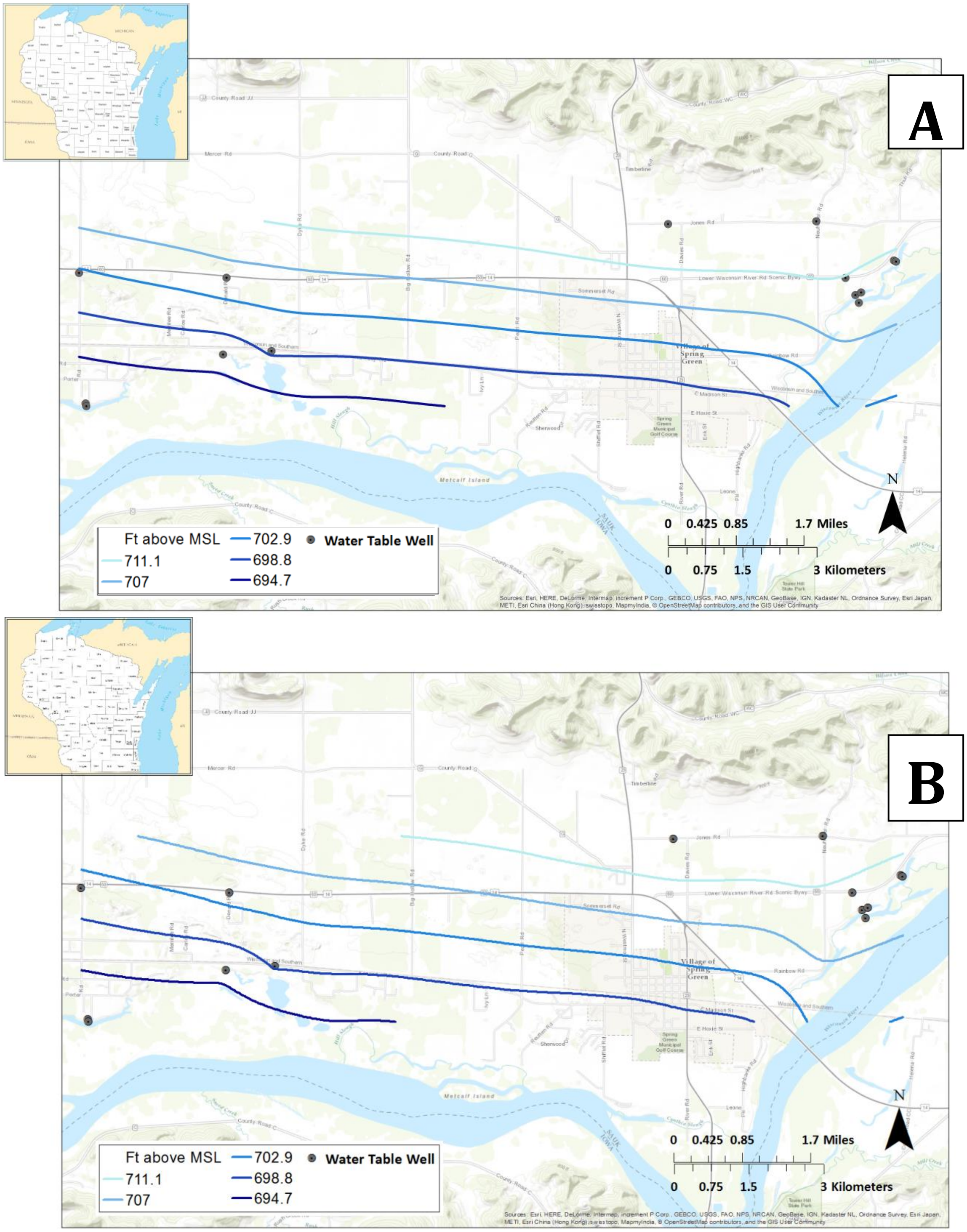


Figure 15. Water table maps based on manual depth to water readings and pressure transducer records. Figure 15A depicts the baseflow conditions on which the flow model was based, while Figure 15B is the water table based on manual measurements taken on July 12th, 2016.

5. Groundwater Flow Model

5.1 Conceptual Model

Models are not meant to be used for perfectly replicating reality, but rather as tools for exploring an aspect of it. In this case, the focus of the UW model was to determine the source of the groundwater that eventually discharges into the eutrophic sloughs. As such, certain assumptions and simplifications were required to produce an effective and efficient model. Much of the basis of the conceptual model comes from the hydrostratigraphy previously described: the unconfined sand/gravel aquifer and the lower sandstone aquifer (Figure 16). However, through the iterative model construction process, the conceptual model had to be adjusted to incorporate a more nuanced representation of the study area. In order for the model output to successfully match observed water levels in the wells, properties for the unconfined aquifer had to be subdivided between the areas around the upland streams and just below the bluffs. This was achieved primarily by altering the hydraulic conductivities and is discussed further in subsequent sections.

Part of developing a conceptual model requires defining a water budget. For the UW model, inflows came primarily from precipitation, along with some reaches of the LWR and upland streams. Outflows were also from the LWR and streams. Bear Creek, Little Bear Creek, and Wilson Creek were the main sources of inflow/outflow to the UW model, outside of the LWR. Upland springs and ephemeral streams were included within the model because of previous research indicating enhanced recharge occurring on and at the base of the bluffs (Juckem, 2003). These bluffs may serve as "recharge hotspots" for groundwater feeding into the sloughs. The effects of evapotranspiration were incorporated by using recharge values that reflected net recharge (precipitation minus evapotranspiration).

The UW model was constructed to simulate steady-state baseflow conditions, meaning that hydraulic heads did not change with time. A transient flow model would have significantly complicated the modeling process and was considered not appropriate at this stage. Baseflow refers to the water in a stream/river that comes from groundwater. By simulating baseflow conditions, the resulting flow paths represent conditions under which groundwater, rather than surface water, is the primary source of slough water. Depending on the stage of the river, local gradients can reverse such that river water becomes the dominant water source to the sloughs.

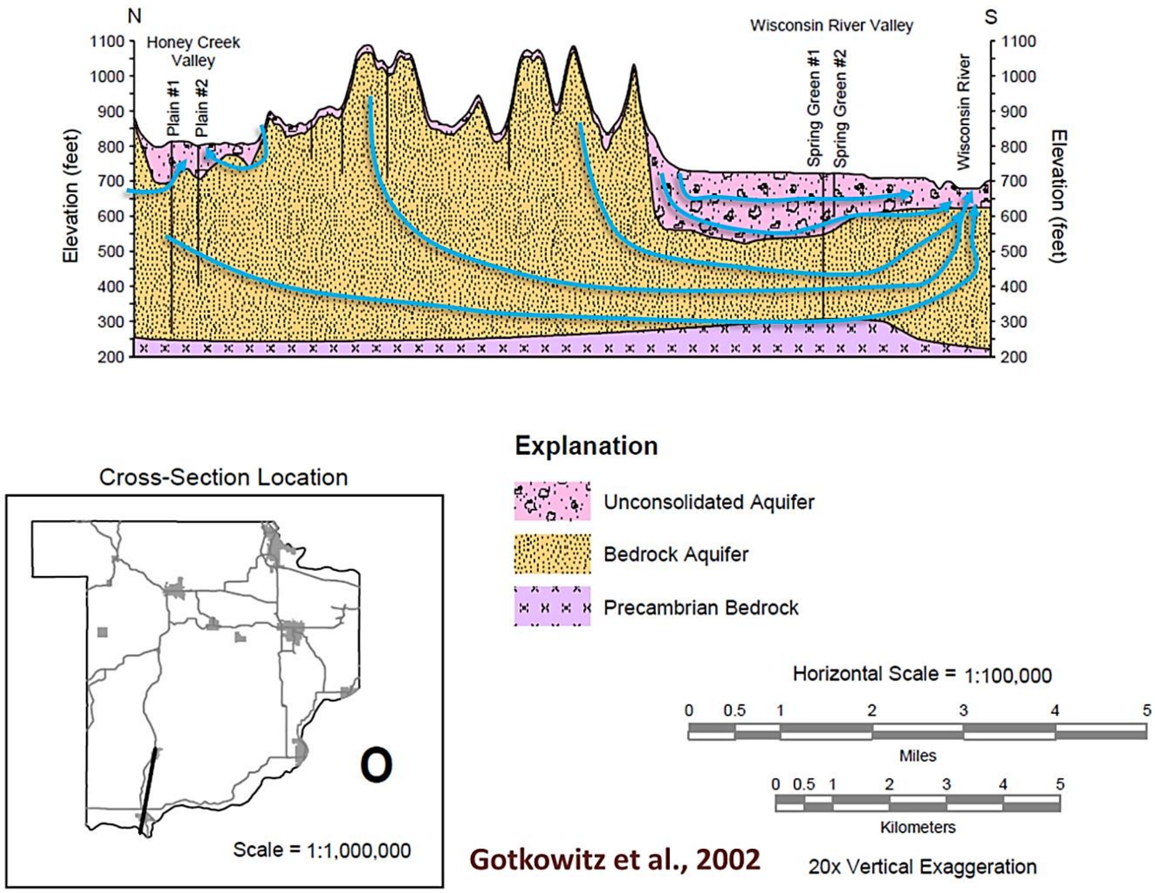


Figure 16. Conceptual model showing hypothesized groundwater flowpaths originating with the bluffs and the LWR valley. Figure adapted from Gotkowitz et al. (2002).

5.2 Model Code

The program used for this project, MODFLOW 2000 (MODFLOW), is a United States Geological Survey (USGS) modular ground-water modeling program that uses the finite – difference method to numerically solve the 3-dimensional groundwater flow equation for a porous medium, yielding the distributions of hydraulic head (Harbaugh et al., 2000). The Preconditioned Conjugate Gradient 2 Solver (PCG2) was chosen as the solver package. This iterative solver has two convergence criteria: a residual criterion and a hydraulic head criterion (Hill, 1990). Including the residual as a convergence criterion is important because it effectively forces the model solution to have an acceptable water balance error. MODFLOW was chosen for this project because of its modular structure that allows for greater flexibility and compatibility with add-on programs. The optimal areal extent of the UW model was unknown at the outset of this project and MODFLOW offers many opportunities for expansion including a variety of solvers and interfaced programs such as the particle-tracking code MODPATH. Most importantly, GFLOW, the modeling system used by the Sauk County model, has an export feature that extracts a local MODFLOW model from the regional Analytic Element Model allowing for the incorporation of boundary fluxes. MODFLOW's widespread use in peer-reviewed groundwater flow modeling research further supports its credentials as a reliable code that successfully solves governing and boundary condition equations within computer rounding error.

5.3 Construction and Boundary Conditions

Groundwater Vistas 6.79 (Rumbaugh and Rumbaugh 2011) was used as the pre- and post-processing graphic user interface. This interface also accommodates particle tracking with the USGS code MODPATH. The real-world areal extent of the UW model is approximately 163.98 mi^2 (424.7 km^2), centered on the town of Spring Green, WI. The numerical steady state model consists of 172 rows, 388 columns, and 9 layers with 80 m grid spacing. Each of the nine layers is of uniform thickness, apart from the bottom of layer 9 where the variable elevations represent the contact of sandstone bedrock with Precambrian rock. Layer thicknesses were determined based on the location of the features of focus, the sloughs and the river (Table 4). More layers with smaller thicknesses were created near the elevation of these surface water bodies to allow for greater detail in particle tracking and flow path analysis.

Table 4. Model layer bottom elevations

Model Layer	***meters above msl***	***feet above msl***
1	216	708.7
2	212	695.5
3	208	682.4
4	200	656.2
5	189	620.1
6	170	557.7
7	130	426.5
8	95	311.7
9	variable	variable

The bluffs, which act as a local water table divide, define the northeastern boundary of the UW model and the Wisconsin River defines the southern boundary. They are represented by a no-flow boundary in layer 1 and by multi-node wells in layers 2-9 to accommodate the regional flux from the north in the deeper portion of the bedrock. Bear Creek and Little Bear Creek make up the west and northwestern boundaries respectively. The Lower Wisconsin River and perennial rivers/streams were treated as constant head boundaries (CHBs). Springs and ephemeral streams (determined by USGS topographic maps of the region) were treated as drains. Water will flow out of the model at drain nodes if the water table is above the base of the drain. If the water table is below the base of the drain, the drain node will be dry. This distinction between perennial and ephemeral streams was made to check model validity by observing at what locations the drains became active during model calibration. Exact placement of the stream CHB conditions within the layers was determined by joining the model grid with a stream shapefile containing elevation data in ArcMap GIS and then importing the resulting grid-centered points into GW Vistas (See section 5.5 for greater detail of this process).

All water levels in the UW model represent baseflow conditions which were determined to occur, on average, between the months of July and October on the basis of plots of long-term river stage flow records from the staff gages at the Highway 14 Bridge and Lone Rock. Water elevations for the constant head and multi-node well boundary conditions were extracted from the results of the Sauk County GLFOW model and calibrated with monitoring well water level data.

5.4 Parameters

As previously mentioned, the values for hydraulic conductivity were based on the results from Gotkowitz et al. (2005) and slug tests conducted between 2015-2016. Five different hydraulic conductivity zones were used in the UW model to represent the following units: the Wisconsin River valley, the modern floodplain silt-sand, uplands alluvium, sandstone bedrock aquifer, and the dolomite-capped bluffs (Table 5, Figure 17). Recharge was applied to the top-most active layer of the UW model in two zones, representing one recharge rate for the bluffs and another for recharge in the floodplain (2.92E-03 and 1.94E-03 ft./day) respectively. These were based on the results of a study conducted by Juckem (2003) and the modeling results of Gotkowitz et al. (2005) (Table 6).

Table 5. Model hydraulic conductivities (K)

Kx, Ky, Kz		Layer ID	
(m/d)	(ft./d)		
90, 90, 9.0	297, 297, 29.7	Wisconsin River Valley	3
45, 45, 4.5	148, 148, 14.8	Modern Floodplain - Silt	4
25, 25, 2.5	82, 82, 8.2	Uplands Alluvium	2
5, 5, 0.5	16.4, 16.4, 1;64	Weathered Sandstone	6
1, 1, 0.1	3.3, 3.3, .33	Sandstone Bedrock Aquifer	1
0.25, 0.25, 0.0025	0.82, 0.82, 0.0082	Dolomite Capped Bluffs	5

Table 6. Model recharge rates

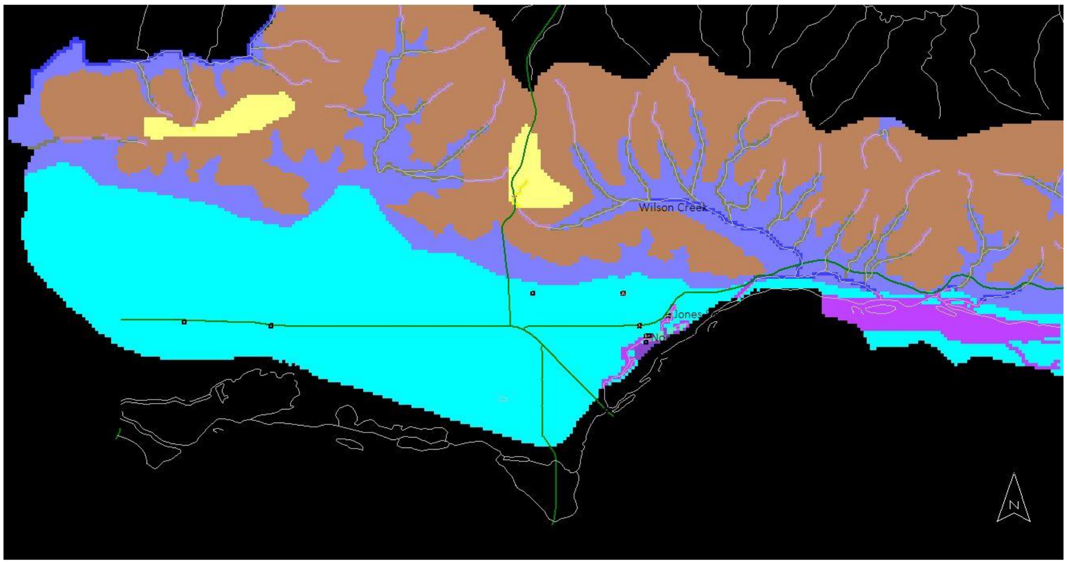
Recharge Rate		
Zone	(m/day)	(ft./day)
1 - sandstone & dolomite bluffs	8.90E-04	2.92E-03
2 - floodplain	5.90E-04	1.94E-03

Color key for Figure 17 (below) showing model hydraulic conductivity (K) zones.

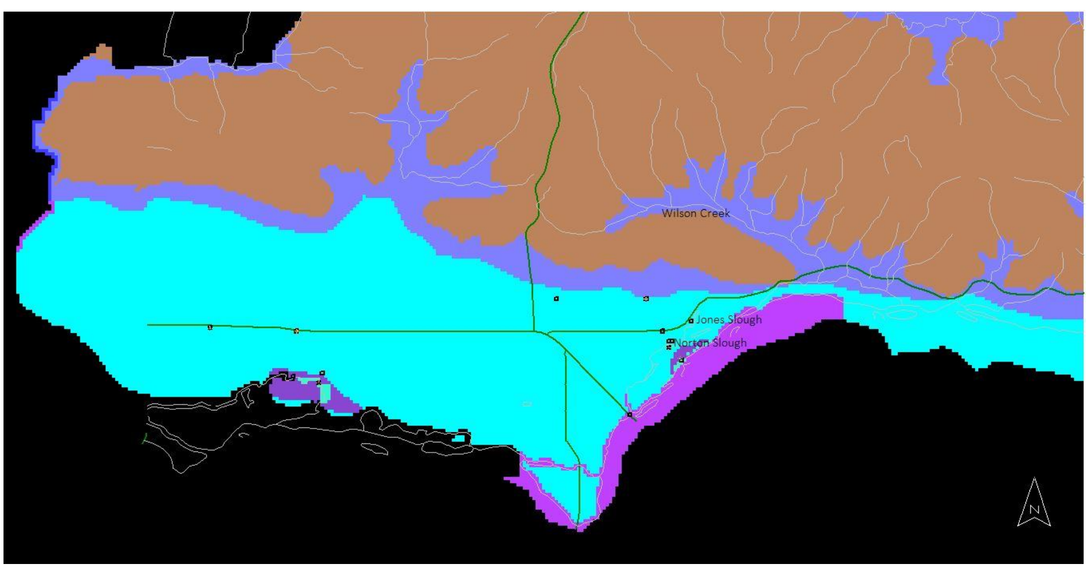
	Kx	Ky	Kz		Color
1	1	1	0.1	0	
2	25	25	2.5	0	
3	90	90	9	0	
4	45	45	4.5	0	
5	0.25	0.25	0.0025	0	
6	5	5	0.5	0	

Figure 17. Plan view of hydraulic conductivity (K) zones for groundwater flow model. The bright purple-/violet-colored region corresponding to the location of the LWR in layer 1-3 is not a unique K zone, but rather a constant head boundary feature. The green lines represent major roads and the small black squares represent well sites.

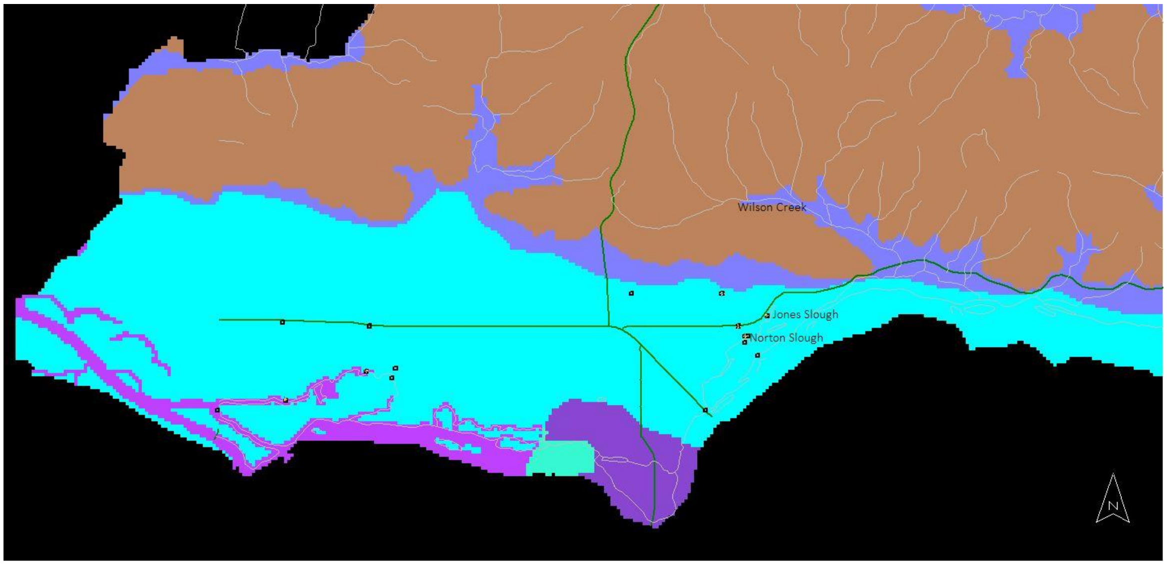
Layer 1



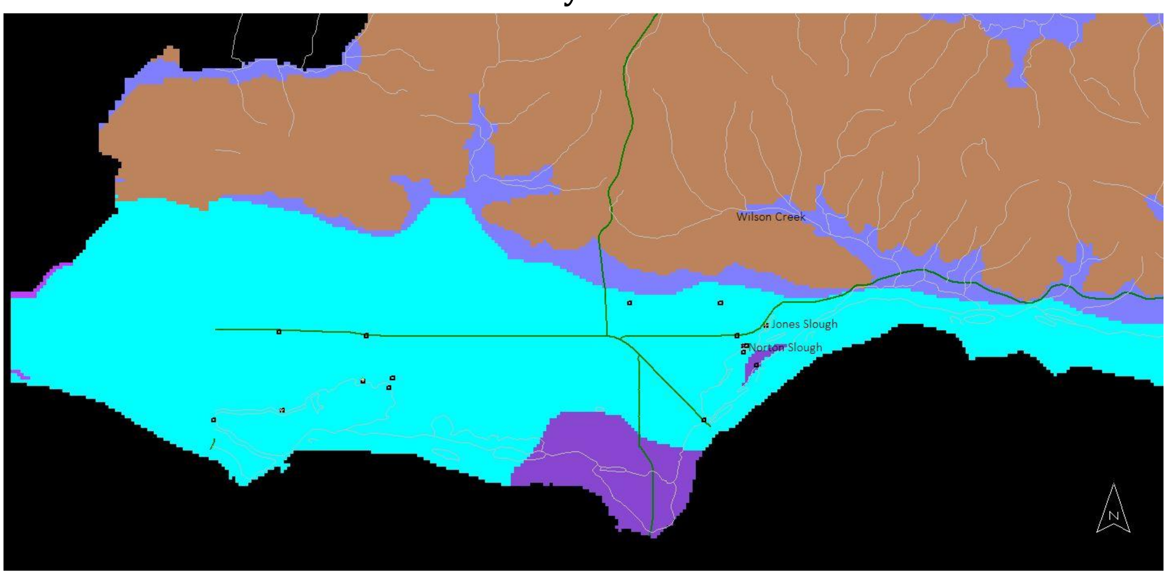
Layer 2



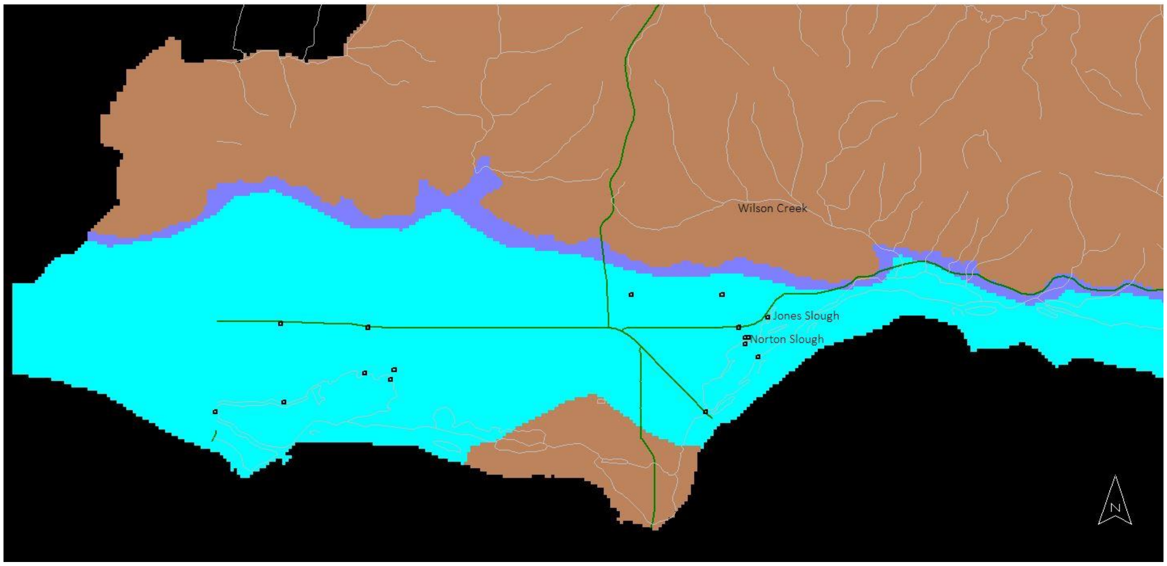
Layer 3



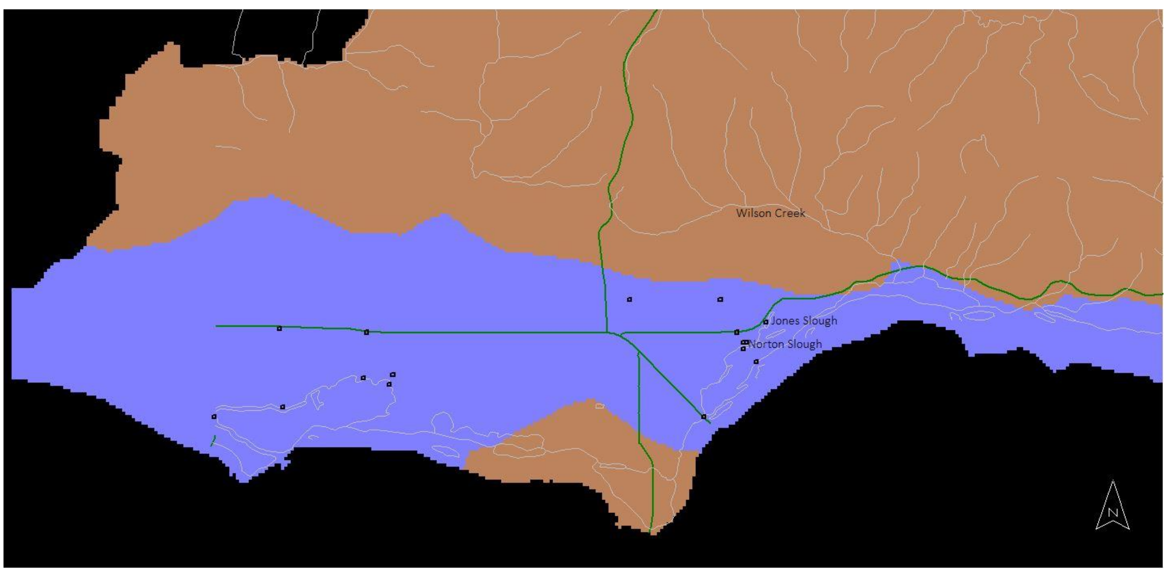
Layer 4



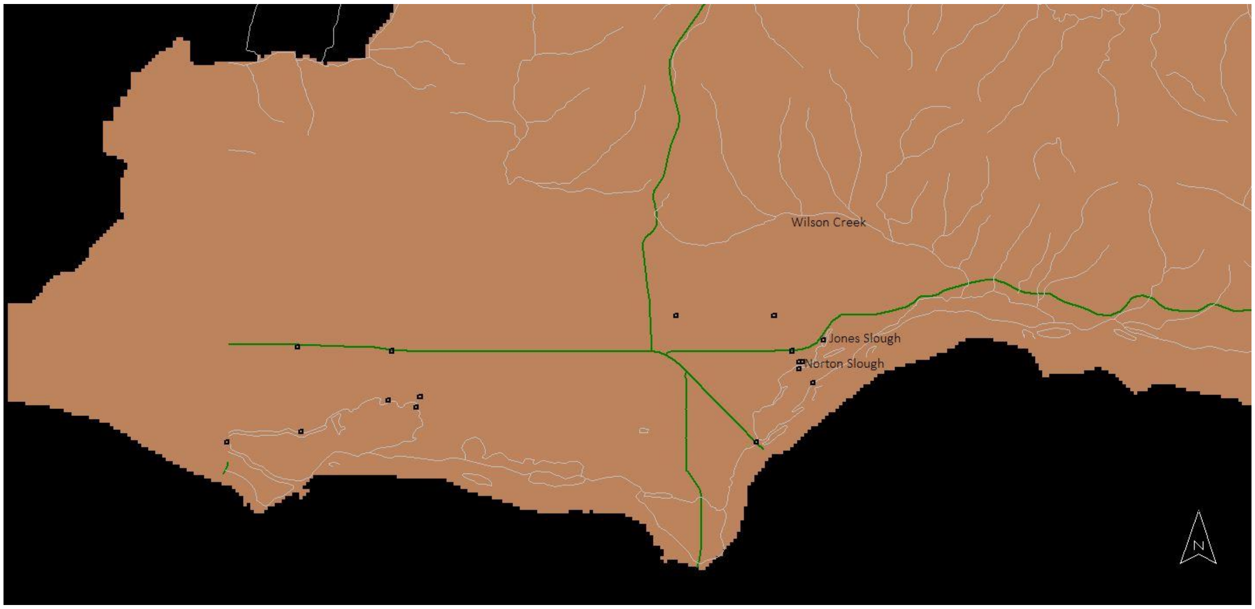
Layer 5



Layer 6



Layers 7-9



5.5 Refinement

The GFLOW model (discussed under Chapter 1.1) played an important role in structuring the UW model setup. For example, the solution from the GFLOW model was used as the starting heads for the UW model. Determining the optimal starting heads for a model is an important process because of the approach used by the model to solve the groundwater flow equation. With a numerical model, starting "guesses" (water elevations) for each grid cell are provided by the modeler and then the model iteratively solves the groundwater flow equation using the given parameters (hydraulic conductivity, recharge, etc.) until the difference between the current and previous solution is considered negligible (falls within a set tolerance or percent error range). Using starting heads that are too far off from the final solution may result in the model failing to converge to an acceptable mass balance error (calculated as the difference between total inflows and total outflows).

Another important contribution from the GFLOW model came during the development of appropriate boundary conditions for the northern edge of the UW model. Initially, the approach was to extract a MODFLOW model from the GFLOW model with an equivalent grid extent and specify that the perimeter of the extracted MODFLOW model be a CHB equal to the final steady-state water elevations in the solved GFLOW model. Then, the constant heads (CHDs) from this extracted MODFLOW model were used to create the border of constant heads in all layers that formed the northernmost boundary. Where streams crossed the boundary, the heads in the subsequently deeper layers were manually modified to create a subtle upward gradient so as to simulate the effects of a flowing stream at the surface. The motivating belief was that the areal extent of the UW model was great enough that these elevations would not significantly affect flow regimes between the sloughs and river within the floodplains and therefore it would be reasonable to use CHDs from a previously calibrated and validated model. This assumption proved to be adequate for the flowpaths but problematic for model stability; the head difference between the constant CHBs and the heads in nearby upland streams (such as the tributaries to Little Bear Creek) were, in some cases, a few meters. Even after manually smoothing the CHD gradients, the UW model remained unstable (i.e. it would not converge upon a solution). A more realistic and stable approach was devised for the subsurface layers that involved re-extracting a MODFLOW model from GFLOW, but this time setting the northern perimeter as a specified flux boundary. This flux boundary was implemented in the UW model using the Multi-Node Well package as a border of wells with screens extending through layers 2-9 with specified flow rates (flow in and out of the UW model) based on the solution from the GLFOW model. The geometry of layer 1 was then modified using Little Bear Creek as a

CHB for the northwest portion and an equipotential (contour line of hydraulic head) from a previous iteration of the UW model that reflected a local surface water divide between upland streams (Figure 18).

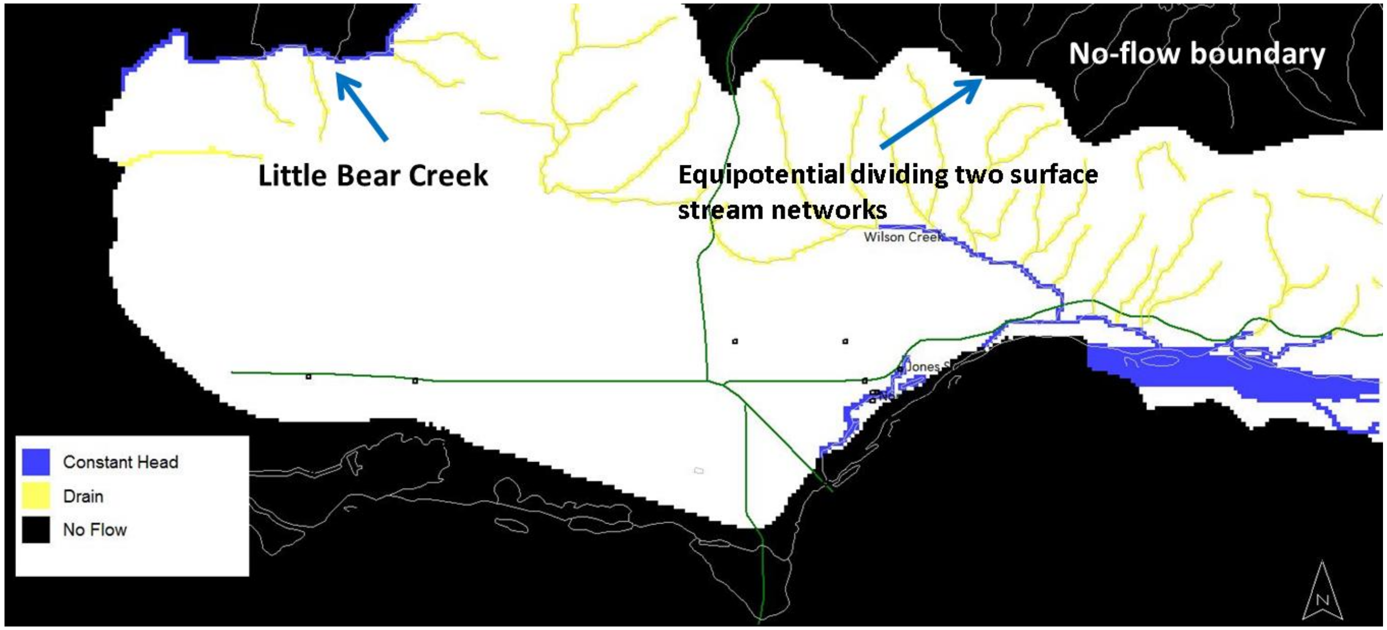


Figure 18. Boundary conditions in layer 1. The equipotential used to define the northeast boundary follows a local surface water divide.

One of the more significant challenges of the model building process was representing surface water features with their real-world water elevations. The major stream networks in the UW model were created using an ArcGIS stream shape (line) file and surface digital elevation model (DEM) file. First, the model grid was exported as a shapefile from GWVistas to ArcGIS. Next the stream shape file was converted from a line to a series of points. A surface elevation was then assigned to each grid cell by using the "extract multi-values to points" tool with stream network points and surface elevation DEM. A spatial join tool was used to select and then export the grid cells that intersected with the stream shapefile as a new layer using the "closest match" option. The result was a slightly coarsened representation of the stream network within the model grid. Because of the resolution of the DEM (5 m) and the fact that "closest match" was used (an additional spatial error), there were many instances where the extracted elevation was not realistic for the stream and each cell had to be manually checked. Issues with stream elevations within the UW model included the following:

- Discontinuous stream reaches (isolated "islands")
- Unreasonably large changes in head elevation between adjacent cells (unrealistic gradients)
- Streams in layers 2-4 with active cells in the overlying layers (subterranean rivers)
- Streams not automatically relocating into the proper layer based on their elevation when resizing layer elevations. Example: streams with elevations ~215 m would be in layer 5 (at the time, an elevation range of 170-208 m) when they should have been reassigned to layer 4

Continued issues with streams not reflecting realistic flow scenarios (e.g. creating bizarre "mounds" in the water table, no model convergence on a solution, etc.) led to the approach of converting the upland streams to "drain" features in the UW model. This meant that the streams would not become active (i.e. have flow) until the water table elevation was equal to, or greater than the set elevation of the stream. This was to reflect the ephemeral nature of the upland springs and was determined by using a USGS topographic map which marked streams with intermittent flow with dashes. It also served as a built-in conceptual check during model development; most of the upland streams should not be flowing under baseflow conditions, and therefore too many activated drains would indicate an unrealistic model scenario.

The extent of the active zones in each layer was determined also using the surface DEM file. In Arc GIS, the surface DEM file was converted to a contour of elevation (line shape file). The geometry of the active area in a layer was determined by selecting all contours that were greater than, or equal to, the bottom elevation of that respective layer. A similar approach was employed to determine zones of hydraulic conductivity using the bedrock DEM file provided by the WGNHS. For example, the shape for the bedrock K-zone layer was determined by selecting all contour lines with values >310 m (the bottom elevation of layer 1). These lines were then imported as a shapefile into GWvistas under hydraulic conductivity properties and used as a guide to draw a polygon to fill in the contours.

5.6 Model Calibration and Sensitivity

In addition to field-collected data, the head elevations and contours from the water-table elevation map of Sauk County (Gotkowitz and Zeiler 2003) and results of the county

GFLOW model (Gotkowitz, Zeiler, and Dunning 2002) were used as calibration targets for the flow model. Twenty-two hydraulic head targets based on base-flow conditions of monitored wells sites and points of interest within the water table map were also used as calibration targets. It should be noted that there was considerable discrepancy between the map and modeled water table heads around the radio tower, located between WI-23 and Wilson Creek, where the map by Gotkowitz and Zeiler (2003) showed a water table mound. Simulated heads in this area were about 20 feet lower in the GFLOW model. Inspection of DNR well construction logs, made available through the WGNHS, did not provide any additional insight as some results supported the water table map's mound and others supported the relatively smooth water table gradient in the GFLOW model. Through the iterative model building process, it was observed that forcing the heads in this area to match those of the water table did not significantly affect the heads within the floodplain. However, simulations that generated a mound had significant model mass balance errors (>20%). Final parameter values were chosen through a combination of trial-and-error methods to match observed hydraulic heads and PEST, an optimization program used to iteratively solve the model while manipulating selected parameters to minimize the sum of squared errors. The final model parameters closely matched with the observed values, except for the one hydraulic head target at the radio tower corresponding to the water table mound (Figure 19).

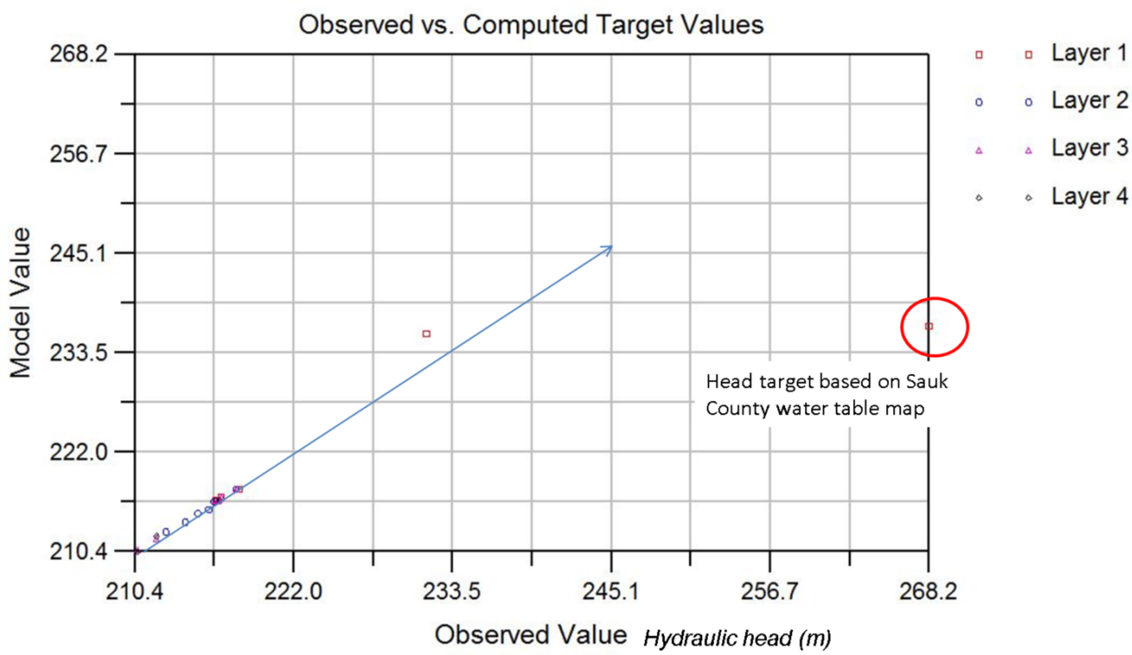


Figure 19. Plot of observed v. modeled values of hydraulic head.

A sensitivity analysis of the key parameters, hydraulic conductivity and recharge, was conducted using the tool in Groundwater Vistas that allows selected parameters to be multiplied by a given factor and then applied to the model. Calibration statistics are calculated for each model run (equivalent to the number of multiplication factors). Below are the results of the sensitivity analysis for horizontal (Kx) and vertical (Kz) hydraulic conductivities and recharge rates for the sandstone bedrock (Zone 1) and Wisconsin River Valley (Zone 3) (Figure 20). Each parameter was analyzed separately for each zone; hence the notation in the figure legend (e.g. where Kx zone1 is the sensitivity analysis of the horizontal hydraulic conductivity assigned to the sandstone bedrock). The results below are interpreted by examining the change in the sum of squared residuals for a given change in parameter value. The parameters for the Wisconsin River Valley, where the sloughs and recharge sites are located, appear to be insensitive to changes in value of hydraulic conductivity. This suggests that the predicted groundwater recharge sites within the Wisconsin River Valley can be viewed with greater confidence than recharge sites located within the uplands.

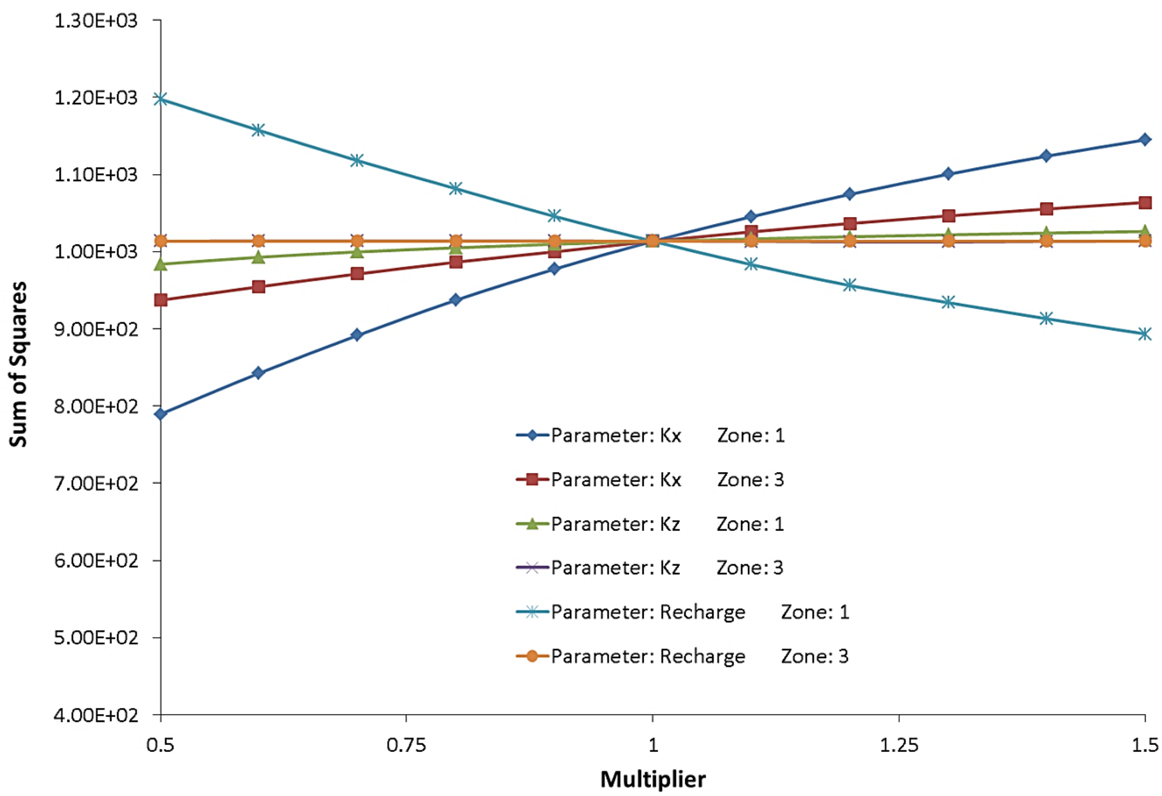


Figure 20. Results of sensitivity analysis for hydraulic conductivity and recharge values assigned to the sandstone bedrock and Wisconsin River valley. Plotting changes in parameter (multiplier) against the sum of squared residuals.

To further quantify model uncertainty, Stochastic MODFLOW was used to apply the Monte Carlo method, a first order uncertainty analysis based on repeated random sampling (Rumbaugh et al., 1998). With Stochastic MODFLOW, model input parameters are varied according to probability distributions pre-selected by the user. The model is then run for a set number of iterations, or "realizations". With each new realization, the range of possible input variables are sampled and randomly applied according to the probability distribution previously selected. The variability in the resulting solutions for the solved 3-dimensional groundwater flow equation can then be analyzed. For the UW model, the six hydraulic conductivity zones were varied using a triangular distribution, where the original model value is set as the most probable value for the realizations and likelihood of other values between the set minimum and maximum decreases linearly (Figure 21). The minimum and maximum credible parameter values were set as -/+ 50% the model value to encompass all the previous literatures' estimates for the hydraulic conductivities. Stochastic MODFLOW only supports steady-state models running MODFLOW Original 88/96 and MODPATH V2 or earlier. As a result, the UW model (running MODFLOW 2000) was modified to run the Original 88/96 version and the solver package was changed from SIP to SOR (Successive Over-Relaxation), one of the original MODFLOW solvers that is compatible with the 88/96 version. Layer 9 also had to be changed from a confined to an unconfined layer due to the program requirement that no parameters being analyzed exist in a confined layer. This did not overly affect model results given that no modeled particle flowpaths went below layer 5 when using MODPATH. These modifications resulted in a slightly higher mass balance error (1.5%), but near identical solutions for hydraulic head. Issues with the UW model size and backwards compatibility between MODPATH and Stochastic MODFLOW prevented successful execution in analyzing model uncertainty in particle flowpaths.

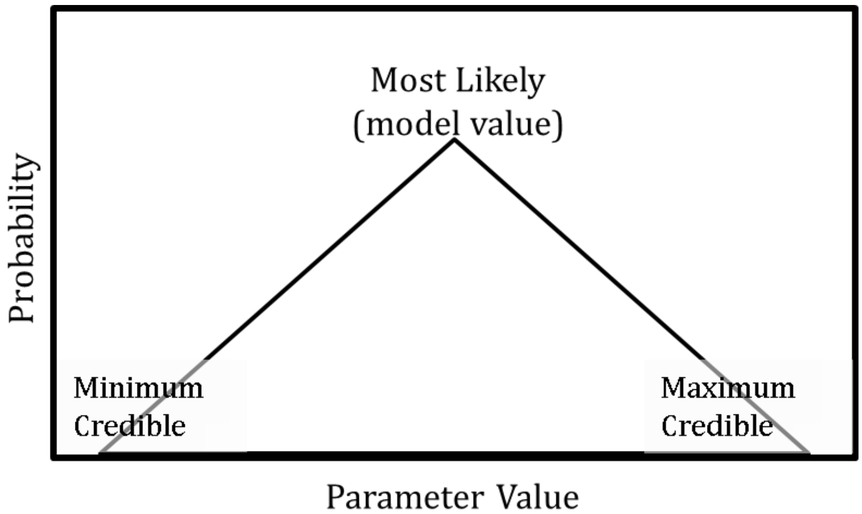


Figure 21. Output from triangular distribution sampling. Figure adapted from Rumbaugh et al. (1998).

The standard deviation in hydraulic heads was calculated after 50 iterations and is shown below in Figure 22. The top panel shows the results for layer 1 while the second panel shows the results for layer 4, which closely resembled the results for layers 3 and 5-9. Unsurprisingly, standard deviations increased with distance away from the area with calibration targets: the floodplain. The areas with the highest uncertainty in the yellow to orange zone (north of Wilson Creek and Little Bear Creek) do not include any of the recharge zones calculated for the sloughs. Based on this figure, it appears that changing the estimates +/- 50% for bedrock and weathered bedrock hydraulic conductivities has a significant impact on model results.

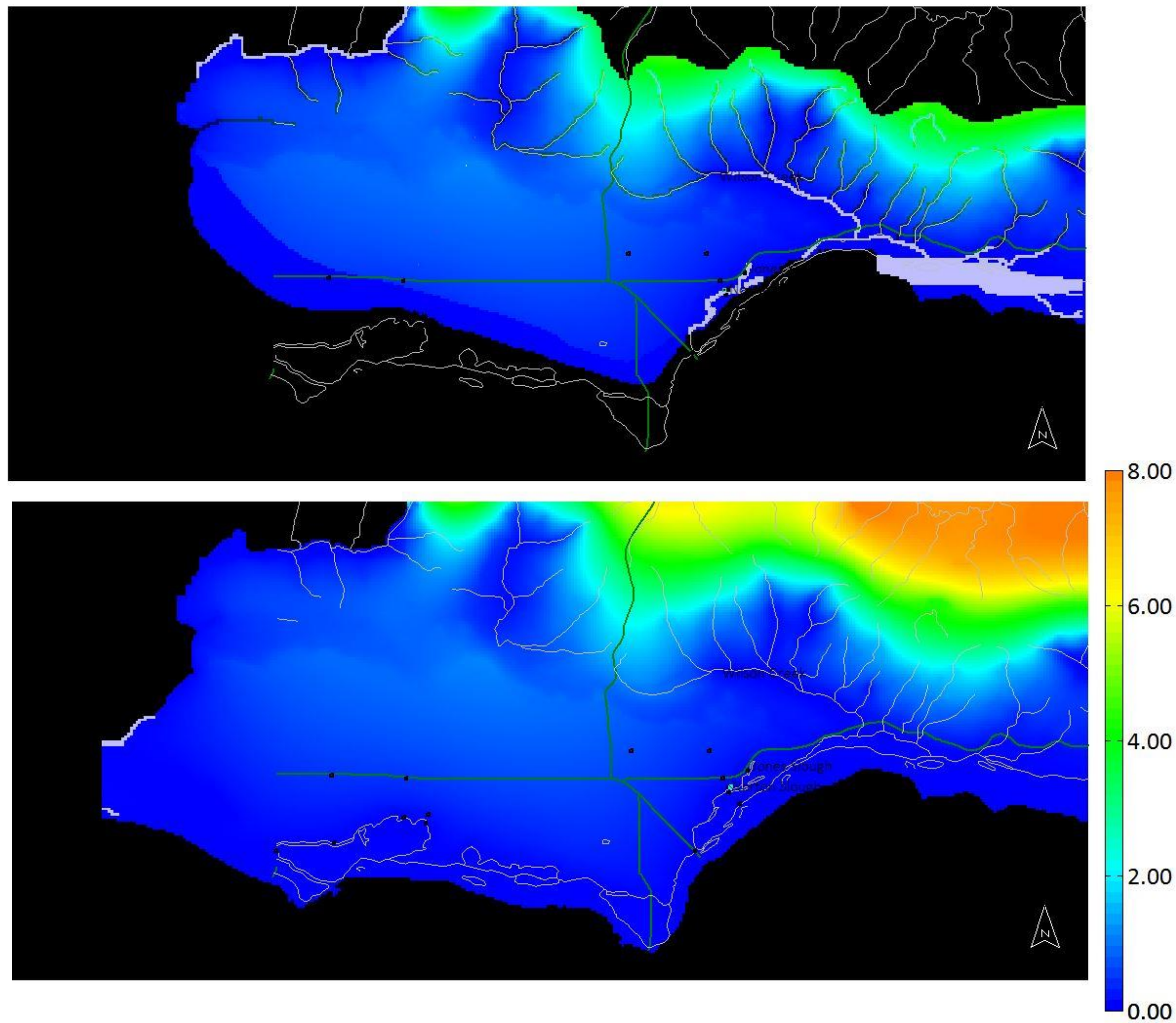


Figure 22. Standard deviations in estimates of hydraulic head calculated by Stochastic MODFLOW.

5.7 Model Results

The final calibrated model had an acceptable mass balance error of less than 1% (-0.429). Comparing Figure 15 with Figure 23 below, it can be seen that the hydraulic heads and resulting water table map for the UW model consistently agreed with the water table maps constructed from field data.

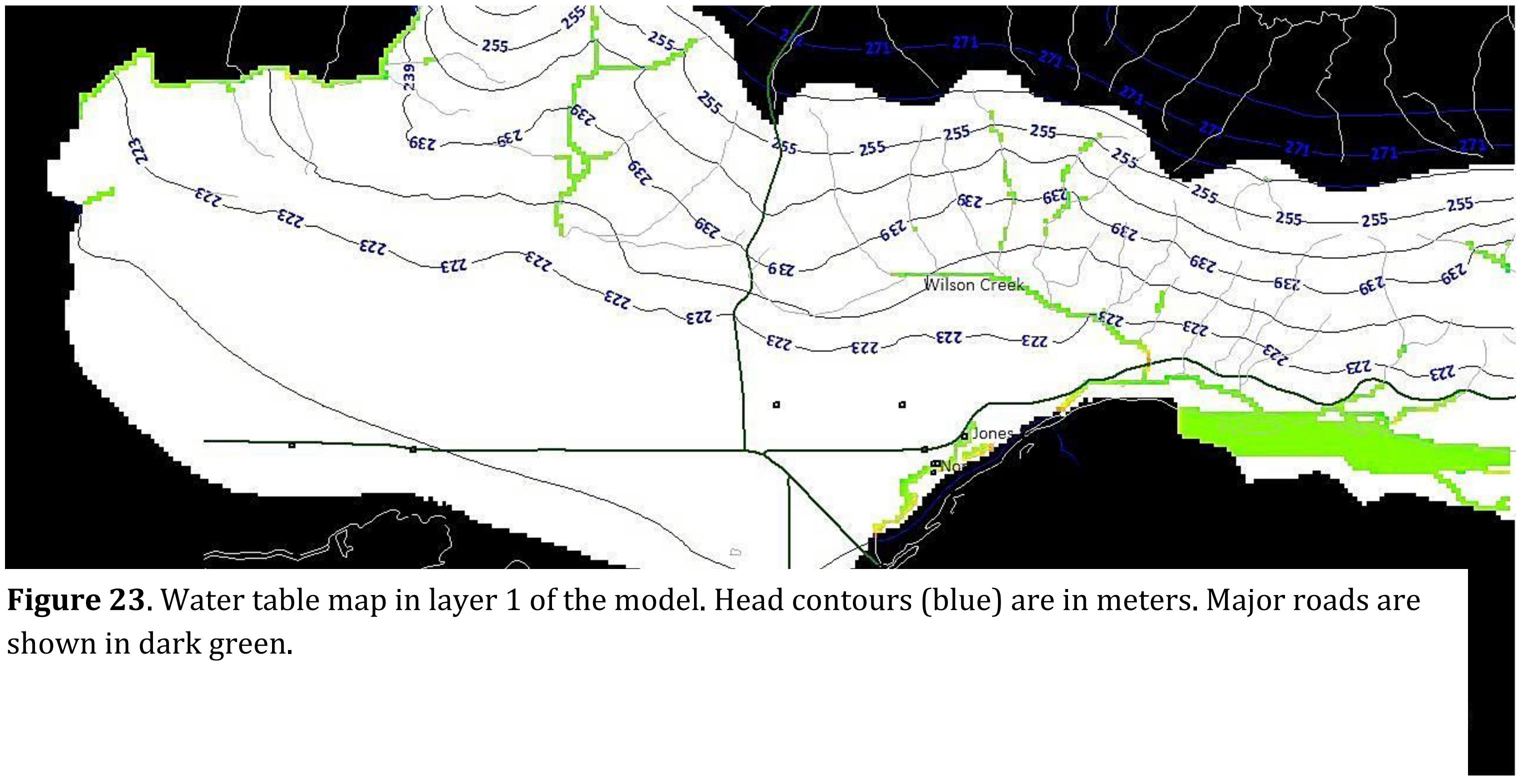


Figure 23. Water table map in layer 1 of the model. Head contours (blue) are in meters. Major roads are shown in dark green.

Groundwater Recharge Zones

MODPATH, an advective transport model supported by MODFLOW, was used to reverse track imaginary particles from the monitoring wells back to their recharge site. These particle paths delineate groundwater flowpaths from a recharge area to the well. Particles were placed within model layers at approximately the same elevation as the respective well screen's midpoint. Dispersion or chemical reactions are not simulated; the only output is the particle flow path and travel time.

Figure 25 and Figure 26 show cross sections of transects A-A' and B-B' (Figure 24) with the resulting nitrate concentrations and isotopic signatures from water samples collected at the Bakkens Pond, Donald Road, Norton Slough, Jones Prairie, Jones Road, and floodplain FP1, FP2, and FP3 well nests in July 2016. Each dot represents the screen midpoint of a single well. For the nitrate samples, the color of the dot corresponds to its relative nitrate concentration (low, medium, or high). The "high" nitrate concentrations are seen in the deeper wells, which had their recharge zones set the farthest back in the floodplain near the bluffs. Although intense agriculture is present within the floodplain, nutrient concentrations in mid-level wells with recharge zones in this region tended to have low to medium nitrate concentrations. For the isotopic samples, the dot's color and shape correspond to its relative position on the MWL and the associated recharge source (summer, winter, or 'mixed' precipitation/infiltration). The "mixed source" isotopic signatures for the shallow groundwater wells are likely due to mixing of water from deep groundwater flowpaths and re-infiltration of river and/or slough water. This is supported by the MODPATH results, which showed extremely short flowpaths within the floodplain for the reverse particle tracking of these wells. Given that the horizontal gradients observed around the sloughs and modern floodplain were so small (Figure 15), seasonal changes in the river stage could easily reverse local horizontal gradients between the LWR and the sloughs. Fluctuations in the hydraulic gradient caused by changes in the river stage may also explain the “summer” signature for the mid-level wells reflecting recharge (e.g. NS3) from approximately a year ago. The deeper wells with “mixed source” signatures indicate groundwater old enough to have received contributions from infiltration during both the winter and summer months.

The recharge areas for Jones Prairie and Norton and Jones Slough wells appeared to occur at base of the bluffs, just south of Wilson Creek (Figure 27). The shorter distance between the sloughs and the bluffs seemed to narrow the recharge zone. Recharge sites for the western portion of the study area were spread over a larger range of distance from the river (Figure 27). BP6, with a screen depth considerably deeper than any of the other wells, had the longest flowpath, originating from a field between the bluffs. In almost all cases, flowpath length was positively correlated with well screen depth. Interestingly, although the elevation of LL4’s well screen midpoint was similar to that of BP4 (651.2 versus 654.6 feet above msl), LL4 had a noticeably shorter flowpath. The same held true for wells BP3 (667.5 ft. msl) and LL3 (662.2 ft. msl).

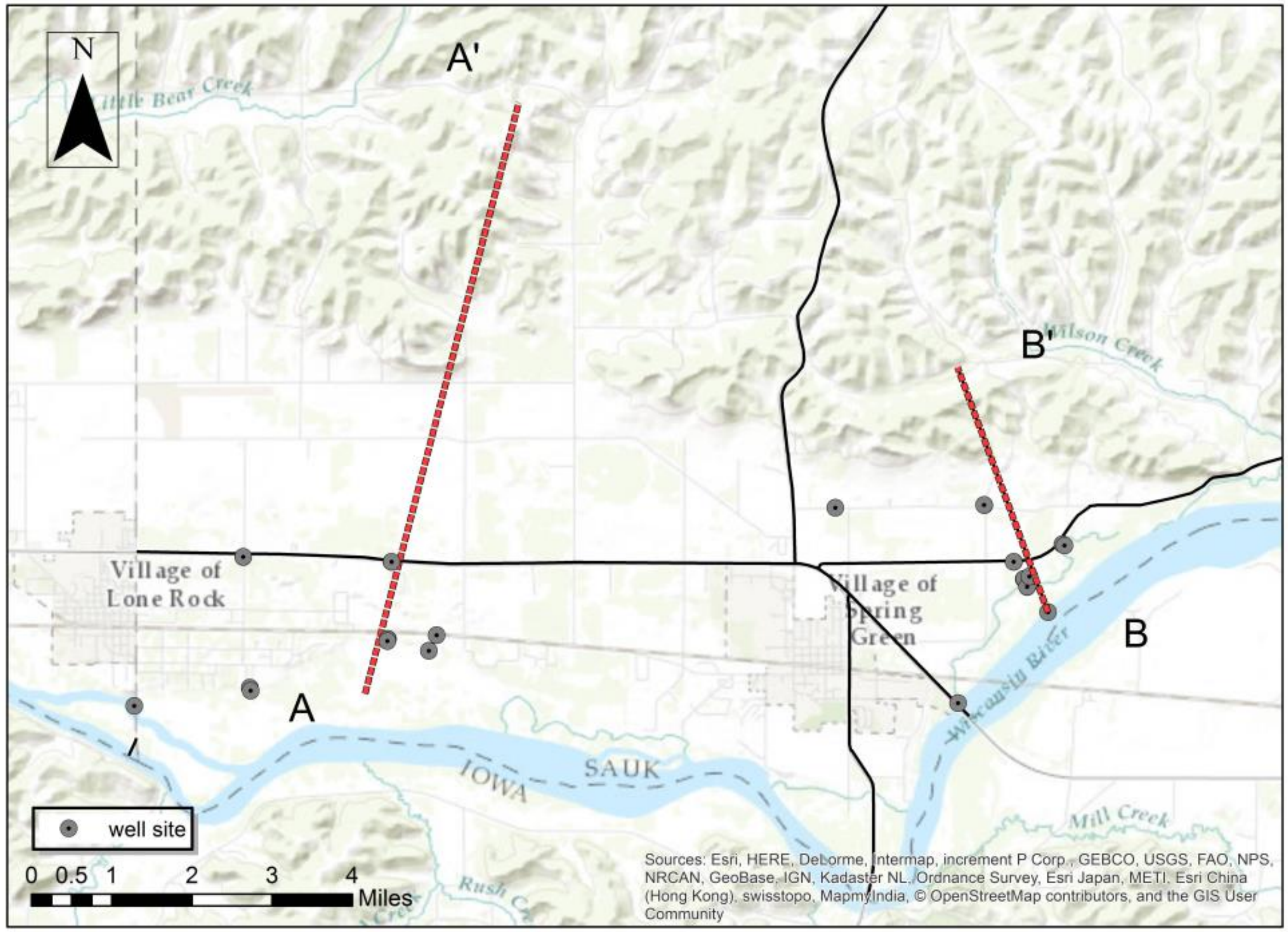


Figure 24. Map of study area showing location of cross sections in profile below. Locations of individual wells and well nests are represented by solid grey circles. Transects are delineated with dotted red lines and labeled A-A' and B-B'. Major roads are shown with a solid black line.

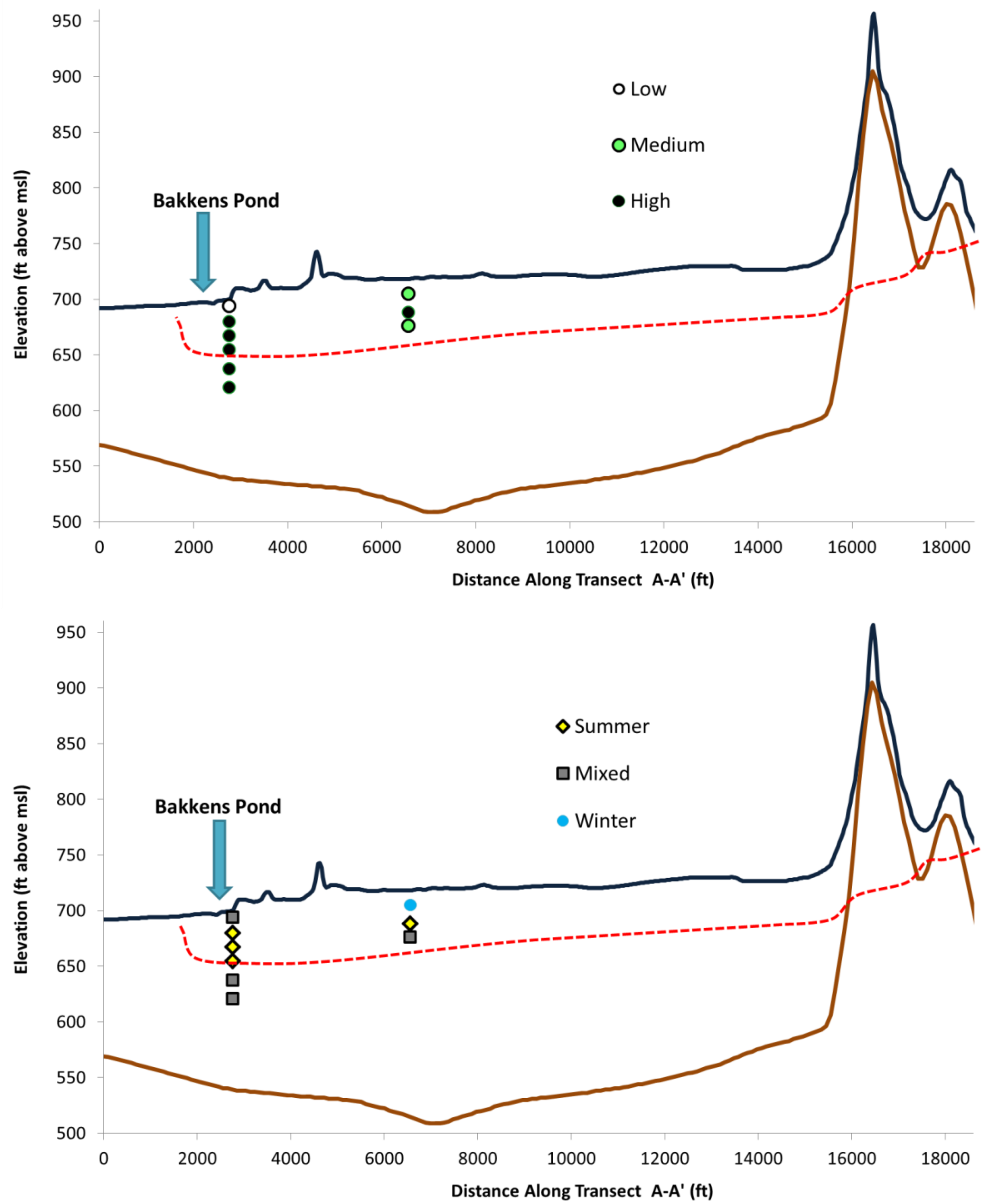


Figure 25. Results of nitrate (top) and isotopic (bottom) analysis for samples collected at Bakkens Pond and Donald Rd well nests on July 12th, 2016. The solid dark blue line represents land surface elevation while the brown line represents the top of the bedrock. The dashed red line represents a potential flowpath based on MODPATH results. Each dot corresponds to a single well. Low nitrate = 0.4-7.0, medium = 7.1 – 15, and high = 15.1 – 26.1 (mg/L).

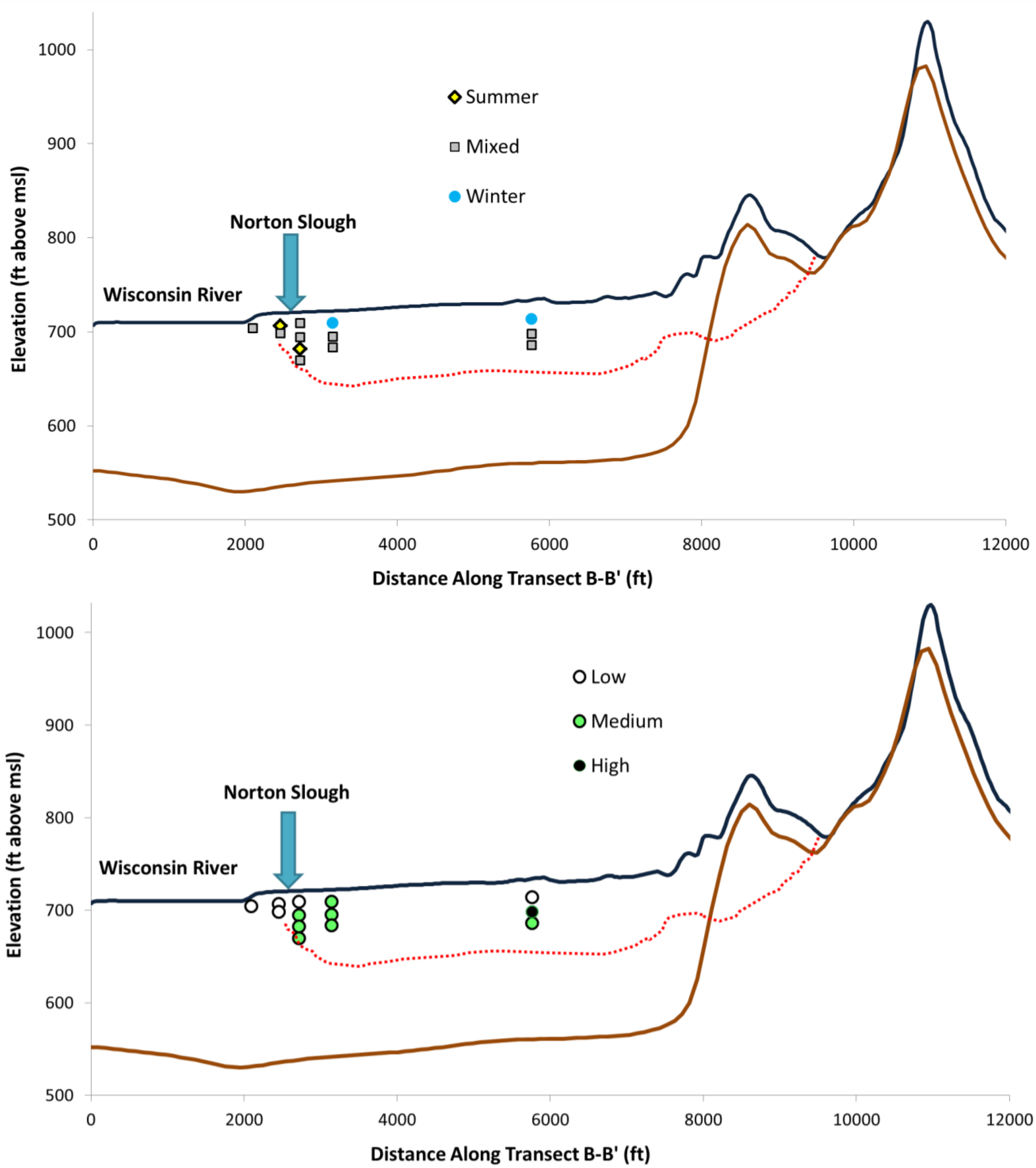


Figure 26. Results of nitrate (top) and isotopic (bottom) analysis for samples collected at Norton Slough, Jones Prairie, Jones Rd, and floodplain sites FP1, 2, and 3. Well nests on July 12th, 2016. The solid dark blue line represents land surface elevation while the brown line represents the top of the bedrock. The dashed red line represents a potential flowpath based on MODPATH results. Each dot corresponds to a single well. Low nitrate = 0.4-7.0, medium = 7.1 – 15, and high = 15.1 – 26.1 (mg/L).

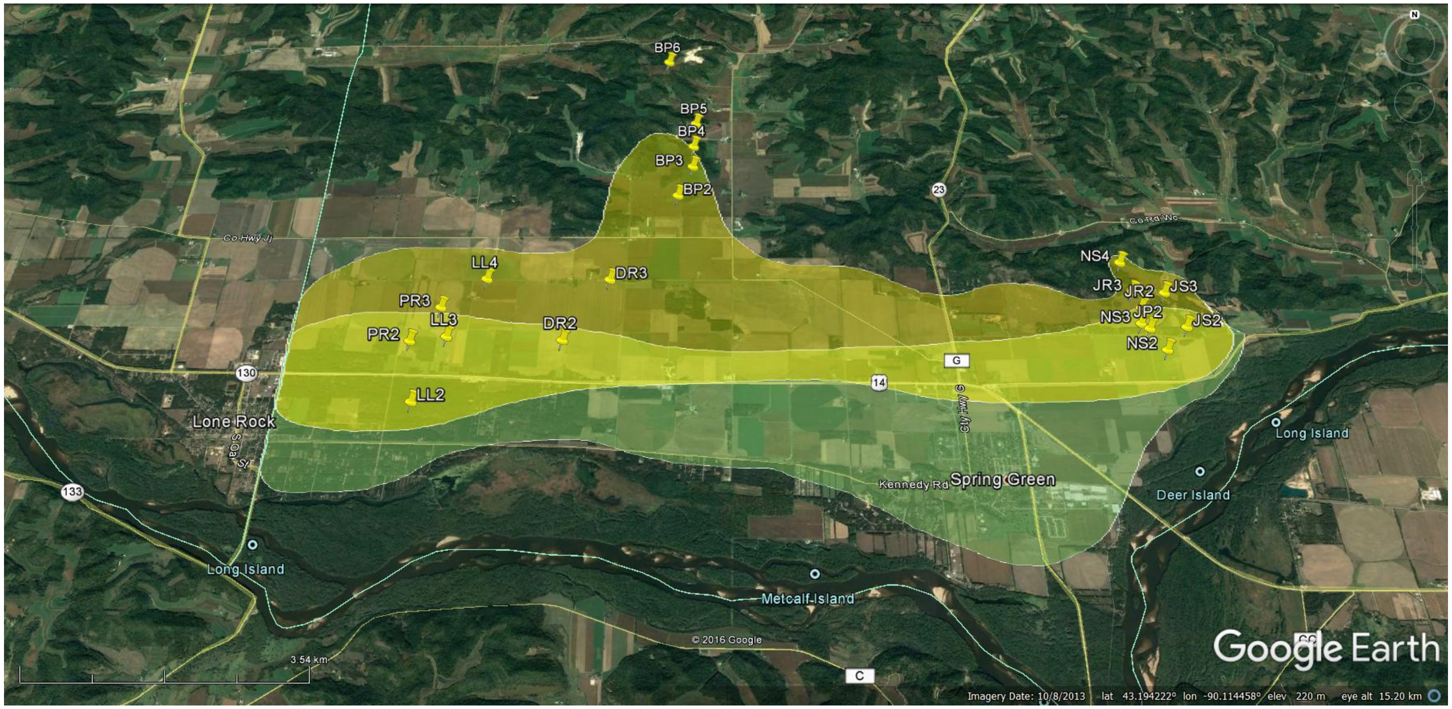


Figure 27. Google map image showing approximate recharge zones for all water table wells (green polygon) and groundwater wells (yellow polygon), with some overlap. Pinpoints are the ***approximate*** groundwater infiltration site for the respective well based on MODPATH results.

Travel Times

Groundwater travel times, determined by backward particle tracking for most well sites (excluding water table wells), are shown in Figure 28 and were between 5 and 15 years. The longest travel time was for the deepest well, BP6, at 42.4 years. Water table wells tended to have travel times ranging from 4 to 10 months.

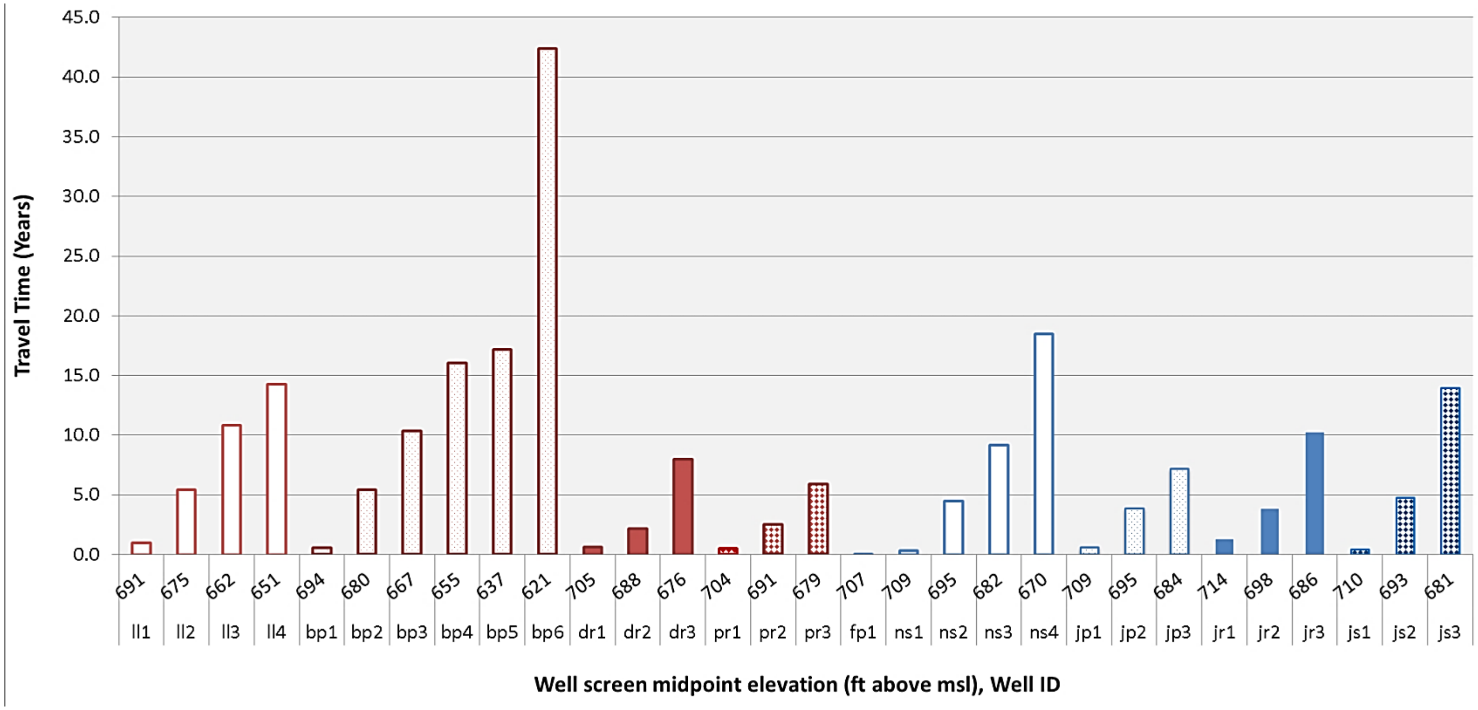


Figure 28. Groundwater travel time by well. X-axis label shows well screen midpoint elevation (ft msl) and well ID.

6. Discussion and Conclusion

The wells with the highest median nutrient concentrations during the study period tended to have recharge sites located at the base of the sandstone bluffs. This may be due to the steeper hydraulic gradient and resulting deeper flowpaths. By the time groundwater reaches the floodplain, its flow is primarily horizontal until it reaches its discharge point – whether a surface water feature or pumping well. The shorter, shallower flowpaths originating within the floodplain have more interaction time with the nutrient rich top-layers. This, combined with lower depths to water table with increasing proximity to the modern floodplain, create conditions more favorable for denitrification (high organic carbon content and low oxygen levels). However, travel times within the Pleistocene terrace are relatively fast, in some cases, 440 ft. /month (about a mile/year). Further exploration would be needed to determine whether or not this would be slow enough for significant denitrification to occur. Additionally, in conversations with the Sauk County Conservation Planning and Zoning Department (CPZ), it was suggested that farmers on the Pleistocene terrace are more conscientious of their nutrient use than their counterparts farming in the uplands and around the bluffs. CPZ employees also noted that they know at least some floodplain farmers who apply nitrogen inhibitors to their fields.

As previously noted, the deterioration in slough water quality appeared approximately between 2008 and 2011 (Marshall, personal communication). Aerial images provided by the CPZ show a sharp increase in the number of "crop circles" between 1992 and 2005, indicative of pivot irrigation. The elapsed time between the introduction of pivot irrigation and the appearance of eutrophic conditions in the sloughs roughly coincides with the 15-year travel times required for groundwater (originating around the base of the bluffs in the northwest-extent) to reach the sloughs and LWR. A more thorough investigation into the evolution of farming practices within the study area would provide some helpful insight into future trends.

6.1 Strategies for Remediation

Buffer Zones

The use of numerical groundwater models to identify and track pollutant sources has become more common in both industry and academia (Bear and Cheng, 2010; Anderson et al., 2015; Chaminé, 2015). In particular, these types of models have become an important tool for resource managers in identifying and testing various remediation strategies for non-point source (NPS) pollution in agricultural watersheds (Bernardo et al., 1993; Almasri and Kaluarachchi, 2007; Bailey et al., 2015). One of the more well-studied management approaches for riparian and floodplain systems is the vegetated buffer. The placement, width, and vegetation composition of buffers has been shown to greatly influence their effectiveness at reducing nitrogen loading to surface water bodies (Dosskey, 2001; Hickey and Doran, 2004; Correll, 2005; Tiwari et al., 2016). However, the majority of studies examine buffers designed for treating overland runoff or very shallow groundwater (Anbumozhi et al., 2005; Sahu and Gu, 2009). The results of this study could be used to test the feasibility of using upland buffers to reduce nitrate loading via groundwater that discharges to surface water features miles away.

The study by Bailey et al. (2015) looked to address a similar problem along the Arkansas River in Colorado by building a groundwater flow model (supported by extensive field data) to test various remediation strategies for reducing nutrient pollution to an alluvial aquifer. Similar to this study, Bailey et al. worked on a regional scale – albeit a much larger area (>420 mi^2). Over twenty-seven best management practice (BMP) scenarios were analyzed. Bailey et al. determined that regional groundwater nitrate concentrations could be reduced by about 40% over approximately 40 years by focusing on reducing the application of N fertilizers and enhancing riparian buffer zones. Ongoing work by that research group is focused on evaluating the socioeconomic feasibility of the BMPs and on targeting sites that would yield the highest impact per unit of investment. Although discussed in the context of California's arid climate, Mayzelle et al. (2014) looks at the economic feasibility of groundwater buffers and provides a helpful framework for considering costs. They take into account population growth and the additional cost of drinking water treatment for nitrate contamination compared to the establishment costs of land-use changes. The economic value of agriculture to the residents and local economy is considered in the analysis and balanced with various less nutrient-intense/N-fixing crop alternatives. A similar approach could be taken to calculating the financial trade-offs of altering agricultural practices within the Pleistocene terrace and near the bluffs.

Assuming the objective is to improve water quality to the sloughs, vegetated buffers should be situated around the recharge sites identified by the model for the wells with the highest median nitrate concentrations. Determining the exact placement of the buffers would require further analysis beyond the present scope of this study. The coarseness of the model makes it difficult to delineate exact boundaries (each cell is 262x262 ft. /80 x 80 m).

For the Norton Slough well nest, expansion of the Spring Green Nature Preserve (Appendix H) shows potential. Specifically, expanding the area east of WI-23 and south of Co Rd WC would encompass the recharge areas for the wells with the greatest nutrient loads. For the Bakkens Pond well nest, the area between the base of the bluffs, north of Co Rd JJ, and west of Co Rd G seems to be most critical. The main take-away from the model results is that buffers adjacent to the sloughs would prove ineffective for reducing nutrient transport to the sloughs, based on land use patterns for the past 20 years.

Induced Discharge

Groundwater collection trenches or seepage trenches are an effective approach to treating non-point source pollution of surface waters (Schipper et al., 2004). Varying widely in construction methods and complexity, the basic premise is that a cavity is excavated perpendicular to flow to intercept groundwater flowpaths and induce groundwater discharge. The hydraulic conductivity of the fill material must be of a higher hydraulic conductivity than the surrounding in-situ material in order for groundwater to be collected. The fill material may be organic matter, gravel, sand, or simply open air, depending on the contaminant being treated. For example, research has shown that media with a higher percentage of organic content (wood) and higher groundwater temperatures had significantly higher denitrification rates (Schmidt and Clark, 2013). Schipper et al. (2004) examined the functioning of a denitrification wall constructed in a coarse sandy aquifer in New Zealand. Construction proved to be difficult as the walls of the trench below the water table kept collapsing. An excavator was used to create a 40x3x3 m (length x width x depth) trench filled with a mix of sawdust and original material. It was found that the addition of saw dust decreased the bulk density of wall material, increased the total porosity, and decreased the hydraulic conductivity relative to the aquifer. The result was that the contaminated groundwater simply bypassed the wall by flowing around and under it. To explain the apparent contradiction in decreased hydraulic conductivity and higher porosity of the wall, the authors posited that the sawdust increased the proportion of *disconnected* pore space. Additionally, the act of homogenizing the aquifer material in the trench may have served to create a block of poorly sorted (well-graded) material with lower permeability. This paper provides useful insight on considerations for constructing groundwater collection trenches in aquifers with high hydraulic conductivities.

For the purpose of this study, an "induced discharge" site (IDS) would only be effective on a very local scale to protect a specific resource. If it were determined that water quality in a particular slough was of high priority, this approach would be the most effective at getting relatively immediate results. A schematic of a hypothesized IDS for Norton Slough is shown below (Figure 29). The IDS covers four cells within MODFLOW (appx. 275,583ft^2); this was the smallest size possible to intercept the flowpaths to Norton Slough. MODPATH was used to forward and reverse track imaginary particles from Norton Slough's monitoring wells and the IDS back to their respective discharge and recharge sites (Figure 29). The optimal depth for the IDS, assuming baseflow conditions in the slough, proved to be 707.1 ft. (215.5 m) - or approximately 18 ft. below the land surface. An IDS elevation of 215.9 ft. intercepted flowpaths for wells NS1-NS3, but did not successfully capture the deepest well, NS-4. Simulations with the IDS's elevation *below* 215.5 drew in water from the sloughs and, eventually, the river. The results showed that the five particles placed within the IDS at its optimal elevation did originate from within the same area determined to be the recharge zone for the high-nutrient well particles, confirming the placement of the IDS (Figure 29.C.). Overall, the impact of the IDS was to shift Norton Slough's contributing groundwater recharge zones to south of the IDS (Figure 29. B.) and to slow travel times for groundwater between the IDS and the slough. The discharged groundwater could be collected and treated or, alternatively, could be constructed as a "denitrification wall". Natural vegetation could be planted within the site to fix the nitrogen but would have to be harvested in order to permanently remove the nutrients from the system. Re-infiltration would be another concern for a "collect and treat" method. A transient model with a finer grid mesh would be required to determine the optimal width and length of the IDS.

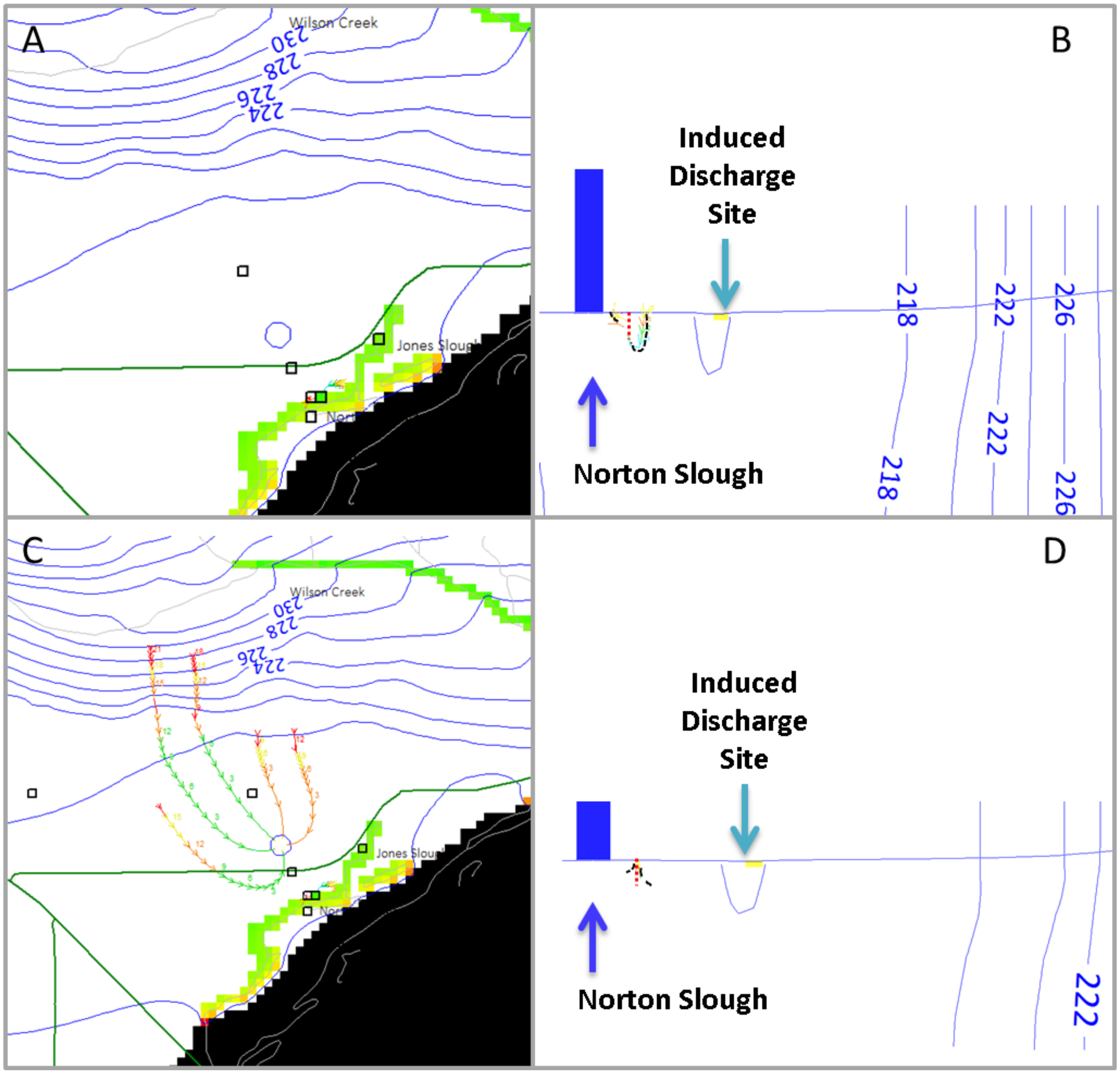


Figure 29. Plan and cross section view in GW Vistas of an IDS for treating groundwater to Norton Slough. A and B show the result of reverse particle testing (where the wells are the endpoint). C and D show the result of forward particle testing for the well (D) and the IDS (C). The vertical red dots in C and D represent the well nest. The black dashed line in C and D represents flowpaths.

6.2 Implications for Management

The travel times associated with the high nutrient flow paths indicate water quality issues for the sloughs are not a problem that can be solved quickly. If remediation efforts were enacted today, it is likely that the effects would not be seen for at least 5-10 years. Based on current land use, it appears that agriculture is the dominant source of nutrients to the sloughs. Comparing recharge sites with historical land-use records would be helpful for identifying particular land use activities that may have significantly affected the nutrient loads. Unless nutrient application practices have drastically changed within the last 10 years, present nutrient loadings to the sloughs will most likely continue for the immediate future. Given the apparent effect of the bluffs on localized groundwater recharge, the most efficient remediation efforts should be focused on recharge sites along the base of the bluffs.

Using a combination of hydraulic head and nutrient and isotopic sampling to constrain groundwater flowpaths proved to be a very useful approach. Independently, each parameter does not indicate much about the sourcing of the high-nutrient groundwater flowpaths. Although hydraulic head data were used as direct calibration targets for the UW model, the isotopic signatures served as an independent conceptual check against the modeled results through providing relative age dating by indicating whether the water sample originated from winter or summer recharge, or was the result of mixed flowpaths. Sampling for nitrate within the well nests was critical for establishing the comparative distances of the nitrate sources. Although eutrophication has not been documented as a critical issue within the LWR around Spring Green, it would be interesting to see at what depth nitrate concentrations drop off and whether these deeper flowpaths discharge to the river.

6.3 Future Work

Although the MODPATH program does not consider chemical reactions (such as denitrification), the thickness and porous nature of the glacial outwash material that fills the Pleistocene terrace suggests that such reactions may not drastically affect estimates of nutrient fluxes to the sloughs. Favorable conditions for high denitrification rates require low oxygen and high organic carbon content. However, further study would be required to confirm that there is limited denitrification. Additionally, this model was for steady state conditions and did not consider seasonal fluctuations in water levels or how those may affect the groundwater flow paths. The possible effects of interactions with the LWR water should be explored in future models.

Model results for the groundwater flowpaths were presented to the CPZ in March, 2017, along with recommendations for best practices within the floodplain, comparing approaches such as groundwater buffer zones and induced discharge sites. This study provides an important tool for developing targeted management strategies by identifying key areas of concern. By using a range of calibration targets, the project also provided insight into what kind of data are most useful when constructing a groundwater flow model. This may improve the efficiency and effectiveness of similar model development projects and potentially increase the use of models for resource management in the area.

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A. Well and Staff Gages

Wells installed by Ken Wade & Dave Marshall (2" diameter slotted screen PVC) 2014

Location	Well Name	Approximate Water Table Depth (ft. BGS)	Screen Length (ft.)	Well Screen Depth (ft. BGS)	Well Collar Elevation (ft. MSL)
Porter Road (PR)	PR1	14.0	10	9.6 - 19.6	721.228
	PR2		2	26.7 - 28.7	721.452
	PR3		2	38.5 - 40.5	721.406
Donald Road (DR)	DR1	9.5	10	6.8 -16.8	719.266
	DR2		2	27.7 - 29.7	719.448
	DR3		2	39.8 - 41.8	719.419
Long Lake (LL)	LL1	11.5	10	7.5 - 17.5	705.805
	LL2		2	27.5 - 29.5	705.784
	LL3		2	40.0 - 42.0	705.655
	LL4		2	51.3 - 53.3	705.993
Bakken Pond (BP)	BP1	5.5	8	2.75 - 10.75	704.052
	BP2		2	20.4 - 22.4	703.682
	BP3		2	32.4 - 34.4	703.389
	BP4		2	45.2 - 47.2	703.315
Jones Road (JR)	JR1	12.5	10	8.9 - 18.9	730.425
	JR2		2	28.75 - 30.75	730.348
	JR3		2	40.85 - 42.85	730.585
Jones Prairie (JP)	JP1	16	10	13 - 23	729.813
	JP2		2	30.9 - 32.9	729.796
	JP3		2	42.5 - 44.5	729.765

Norton Slough (NS)	NS1	16.5	10	12-22	728.842
	NS2		2	31-33	728.801
	NS3		2	43-45	728.657
	NS4		2	55-57	728.37
Jones Slough (JS)	JS1	16.0	10	13-23	725.574
	JS2		2	31-33	725.466
	JS3		2	43-45	725.545

Wells installed by Ken Wade & Dave Marshall (2.0" diameter Steel Drive Point) 2014

Location	Well Name	Approximate Water Table Depth (ft. BGS)	Screen Length (ft.)	Well Screen Depth (ft. BGS)	Well Collar Elevation (ft. MSL)
Wisconsin River Floodplain (WR)	FP1	1.5	2.6	1.5 - 4.0	714.465
	FP2	1.5	2.6	10. - 13.1	712.413
Wisconsin River Stage @ HW 14	WR	2.5	2.6	4.0 -6.6	708.912
Wisconsin River Stage @ Lone Rock	WRLR	3.4	2.6	4.0 -6.6	696.295

Wells Installed by University of Wisconsin-Madison hydrogeology field course June 2015

Location	Well Name	Approximate Water Table	Screen Length	Well Screen Depth (ft.	Well Collar Elevation (ft.

		Depth (ft. BGS)	(ft.)	BGS)	MSL)
Bakken Pond (BP)*	BP5	5.5	1.98	81.77-83.75	703.273
	BP6		1.98	65.26-67.24	703.283
Wisconsin River Floodplain (WR)**	FP3	1.4	2.2	4.5-6.7	711.968
	WRFP	2.5	2.2	4.5-6.7	711.636

*Geoprobe installed 1.25” diameter PVC

**2” diameter steel drive points

Town of Spring Green Wells Monitored (1.5" diameter Steel Drive Points) (Water Elevations Only)

2014-2015

Location	Well Name	Approximate Water Table Depth (ft. BGS)	Screen Length (ft.)	Well Screen Depth (ft. BGS)	Well Collar Elevation (ft. MSL)
Jones Rd. Town Well (JRT)	JRT	4.0	?	Above 13.0	723.177
Bakken Pond Town Well (BPT)	BPT	5.0	?	Above 13.0	705.823

Slough Staff Gages

Location	Well Name	Gage Collar Height (ft.)	Gage Collar Elevation (Ft. MSL)
Jones Slough Staff Gage	JSSG	4.84	713.497
Norton Slough Staff Gage	NSSG	4.43	712.900
Bakken Pond Staff Gage	BPSG	4.49	698.448
Lower Bakken Pond Staff Gage	LBPSG	3.30	696.149
Upper Bakken Pond Staff Gage	UBPSG	3.5	699.336
Long Lake Staff Gage	LLSG	4.80	695.017

<u>Other Groundwater Monitoring Points (Water Quality Only)</u>

Doug Jones Water Supply Well (JW)

Blair Anderson Water Supply Well (AW)

Neuheisel Water Supply Well (NW)

Reddemann Water Supply Well (RW)

Paukner Water Supply Well (PW)

Larson Water Supply Well (LW)

B. Slug Test Analysis

Values for slug and monitoring well dimensions used to calculate hydraulic conductivity for DR2, DR3, JR2, JR3, NS2, NS3, and NS4.

Slug dimensions		**Well dimensions**	
Diameter (m)	0.025	diameter (m)	0.051
length (m)	1.53	screen length (m)	0.610
volume (m^3)	7.51 e-4	well head area (m^2)	2e-3
h0 = slug vol/ well head area (m)	0.371		

AquiferWin32 Results for DR2, DR3, JR2, JR3, NS2, NS3, and NS4

Red text indicates oscillations that make results questionable. UN = unusable, 'good' indicates that line of best fit already went through 0, 0.

Slug Test ID	Hvorslev Solution (m/s)		Hvorslev – manually fitted through 0,0 (m/s)
DR2.1 slug in	5.68E-04		6.08E-04
DR2.1 slug out	6.45E-04		good
DR2.2 slug in	UN		UN
DR2.2 slug out	6.21E-04		good
DR3.1 slug in	UN		UN
DR3.1 slug out	5.59E-03		6.21E-04
DR3.2 slug in	UN		UN
DR3.2 slug out	3.55E-03		
DR3.3 slug out	UN		UN
JR2.1 slug in	5.55E-04		8.51E-04
JR2.1 slug out	5.42E-04		good
JR2.2 slug in	1.93E-03		7.15E-04
JR2.2 slug out	2.09E-03		5.87E-04
JR3.1 slug in	1.30E-03		1.47E-03
JR3.1.1 slug in	1.36E-03		1.82E-03
JR3.1 slug out	1.81E-03		good
JR3.2 slug in	UN		UN
JR3.2 slug out	1.32E-03		1.62E-03
NS2.1 slug in	4.66E-03	manually fitted line	1.54E-03

NS2.1 slug out	2.83E-03		1.60E-03
NS2.2 slug in	1.10E-03	deleted "2nd spike" in AquiferWin 32 analysis	1.87E-03
NS2.2 slug out	1.99E-03	few usable data points	good
NS3.1 slug in	UN		UN
NS3.1 slug out	9.72E-04		7.65E-04
NS3.2 slug in	1.47E-03		1.17E-03
NS3.2 slug out	1.04E-03		7.42E-04
NS4.1 slug in	UN		UN
NS4.1 slug out	4.30E-04	*fitting early drawdown	5.01E-04
NS4.2 slug in	7.27E-04	manually fitted line/ ignored spikes	good
NS4.3 slug in	7.94E-04	manually fitted line/ ignored spikes	good
NS4.3 slug out	5.92E-04		7.36E-04

Slug test analysis for BP2, BP3 and BP4 using 6/11/2015 data

The "slope" method to evaluate the Hvorslev solution is more robust than the To method that is described in many text books. This solution is based on the equation,

$$K = \frac{2.303 r^2 \ln(L/r)}{2L(t_2 - t_1)} \log \frac{H_1}{H_2}$$

which is appropriate for a semi-log plot of normalized head change (H) on the log scale and time on the arithmetic scale. If you choose H_1 and H_2 so that they are one log cycle apart and determine t = t_2-t_1, the time change for one log cycle of normalized head change, the above equation becomes

$$K = \frac{2.303 r^2 \ln(L/r)}{2L\Delta t}$$

The plots of the slug tests we did on 6/11/2015 yielded the following ts:

BP2 4 sec

BP3 6.5 sec

BP4 8.1 sec

The r for the wells was 1/12 ft (1 inch) and L was 2 ft

Solving for K yields:

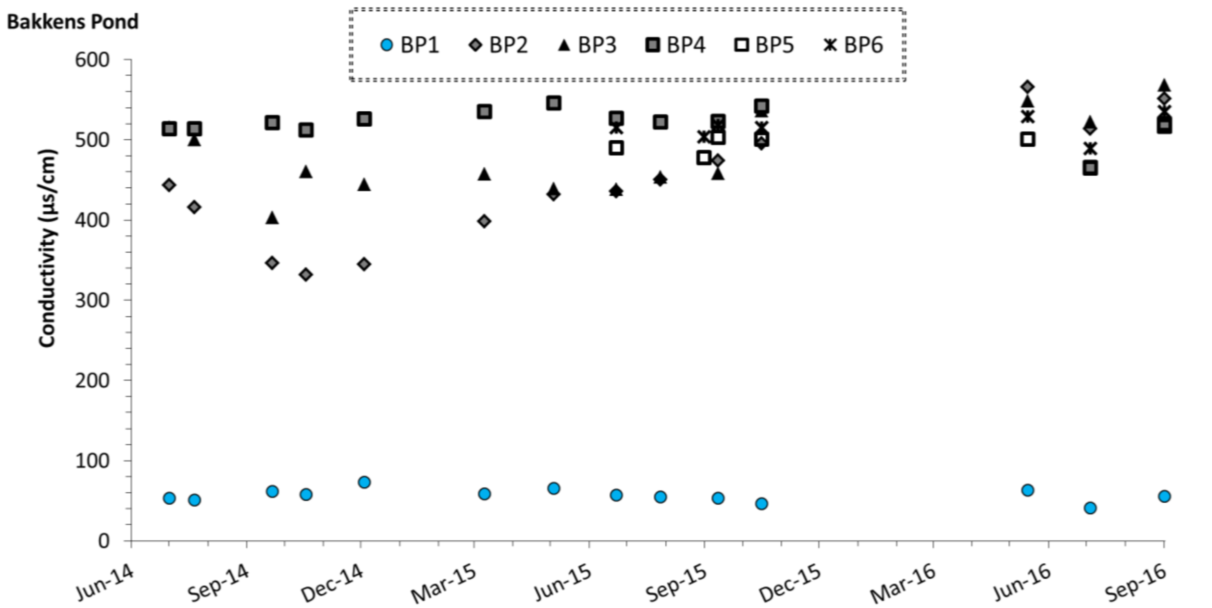
BP2 3×10^{-3} ft/s (1×10^{-3} m/s)

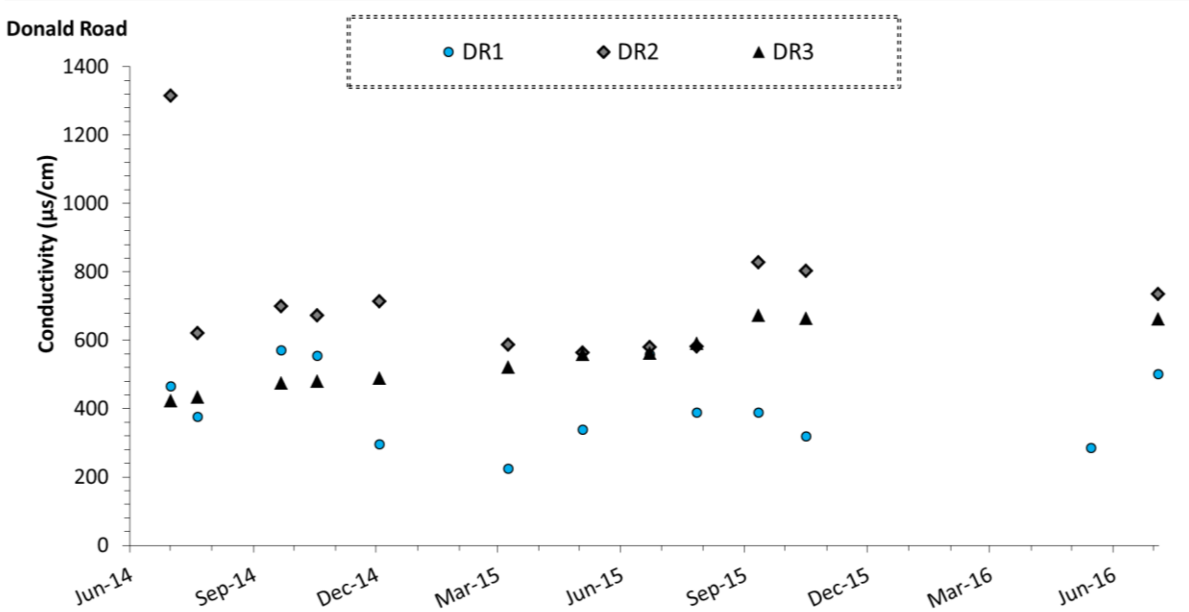
BP3 1.9×10^{-3} ft/s (6×10^{-4} m/s)

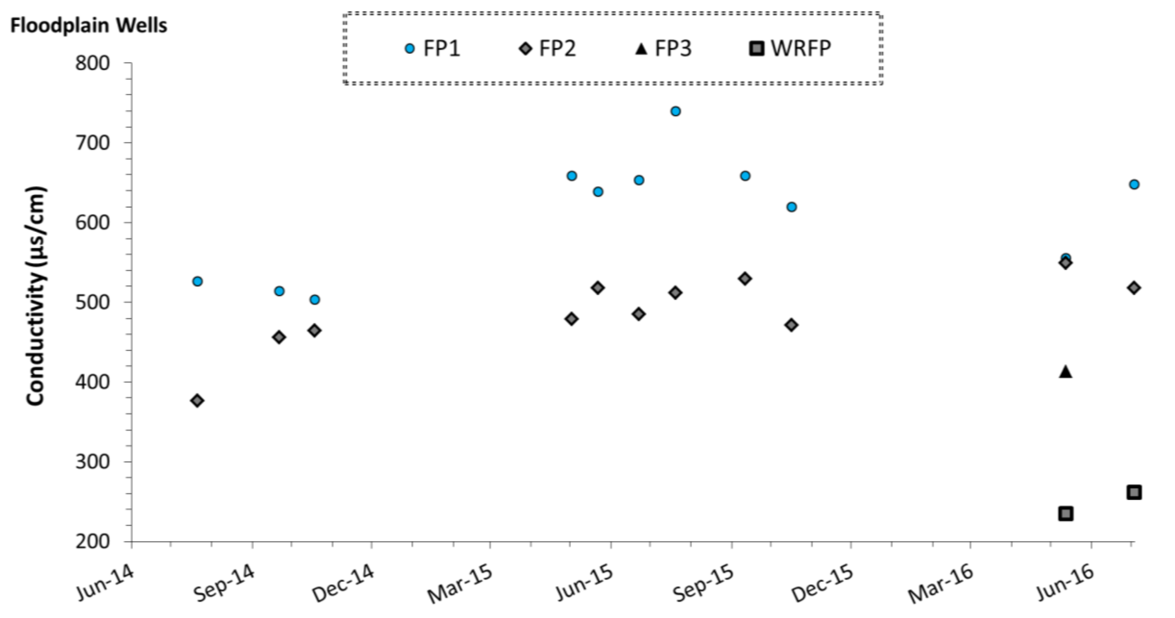
BP4 1.6×10^{-3} ft/s (5×10^{-4} m/s)

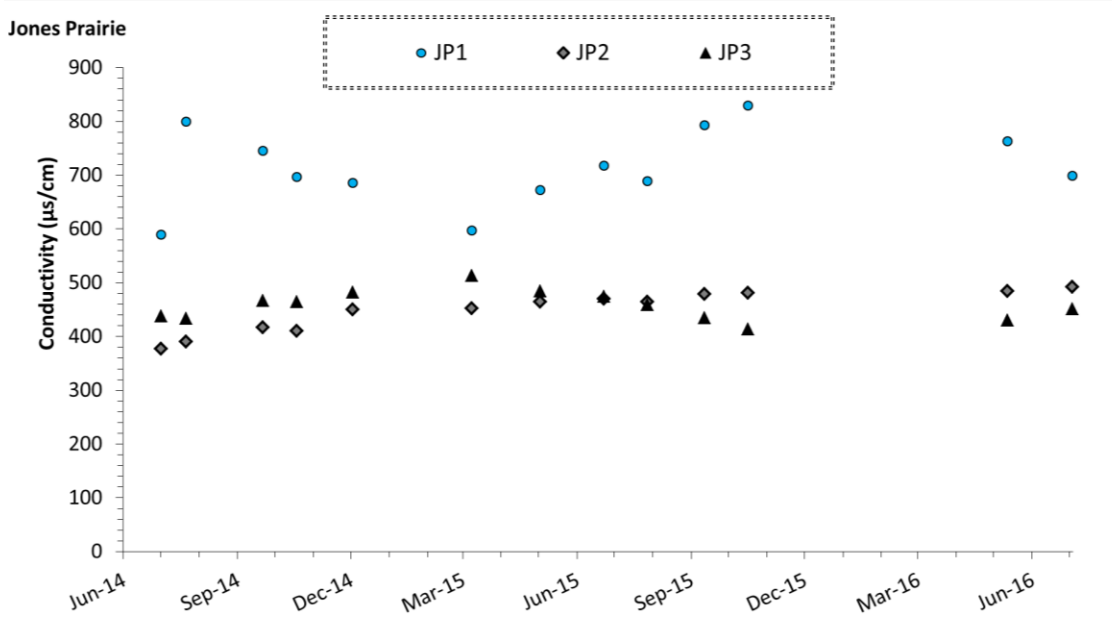
C. Conductivity

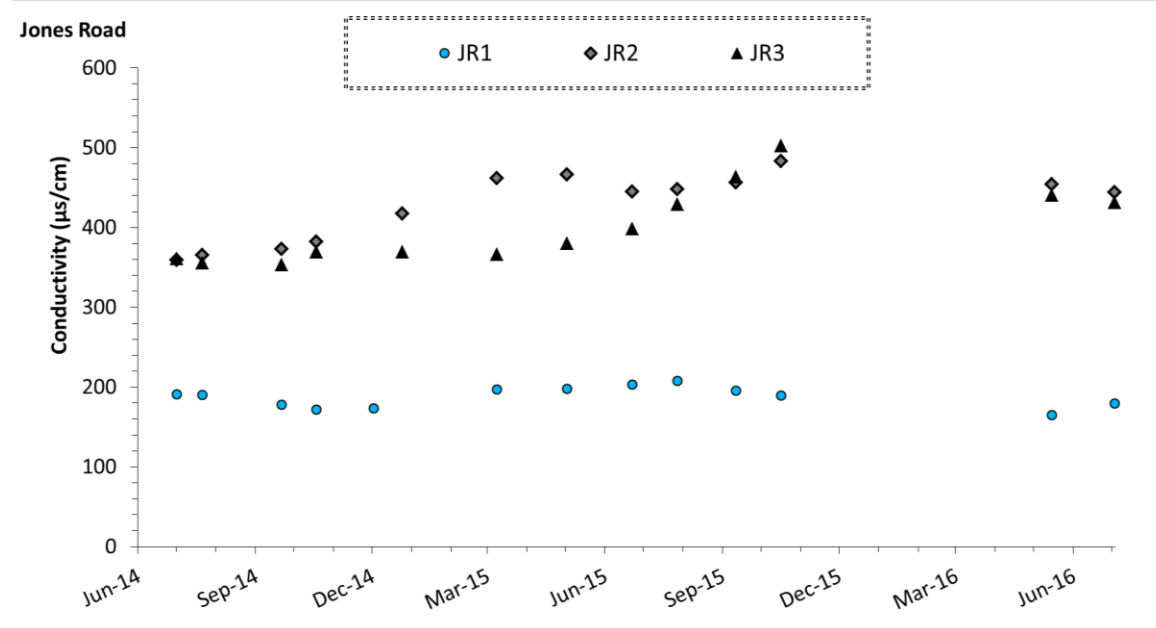
Change in conductivity with time by well nest site. Points correspond to results for wells within the respective well nest

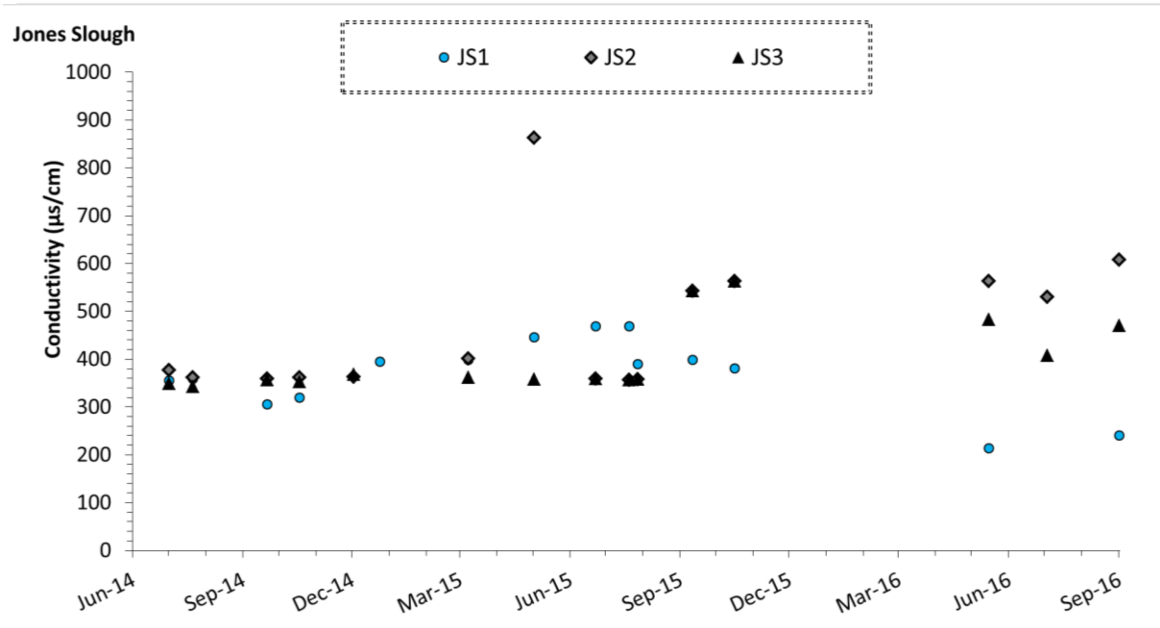

Bakkens Pond
BP1
BP2
BP3
BP4
BP5
BP6
Conductivity (µs/cm)
0
100
200
300
400
500
600
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

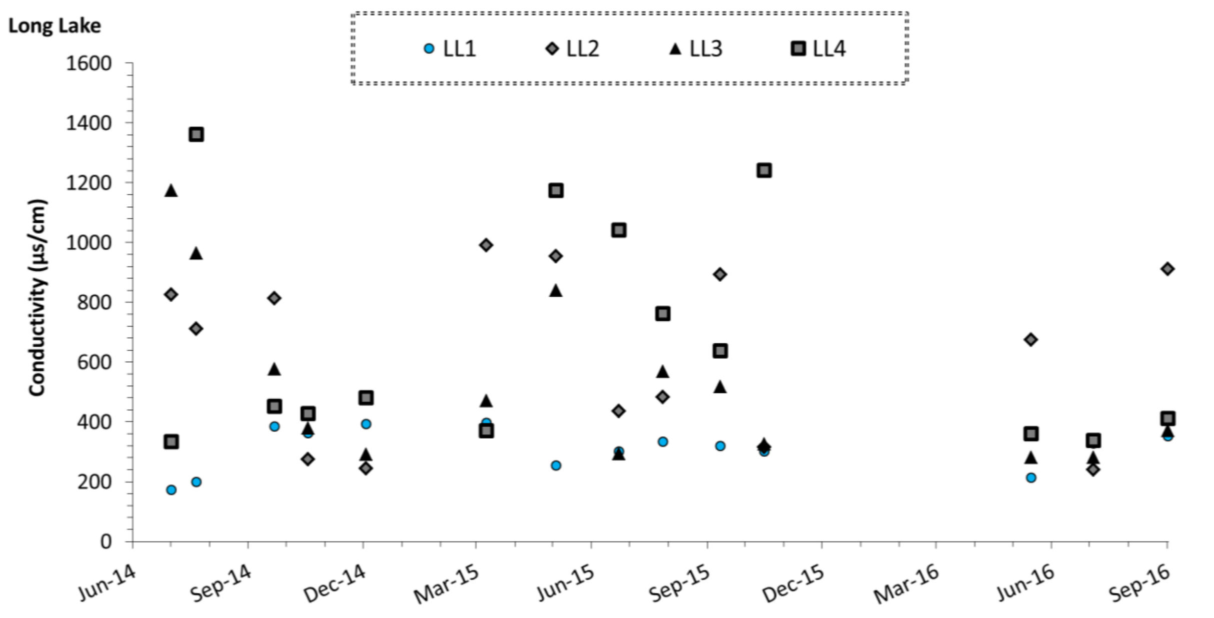

Donald Road
DR1
DR2
DR3
Conductivity (µs/cm)
0
200
400
600
800
1000
1200
1400
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

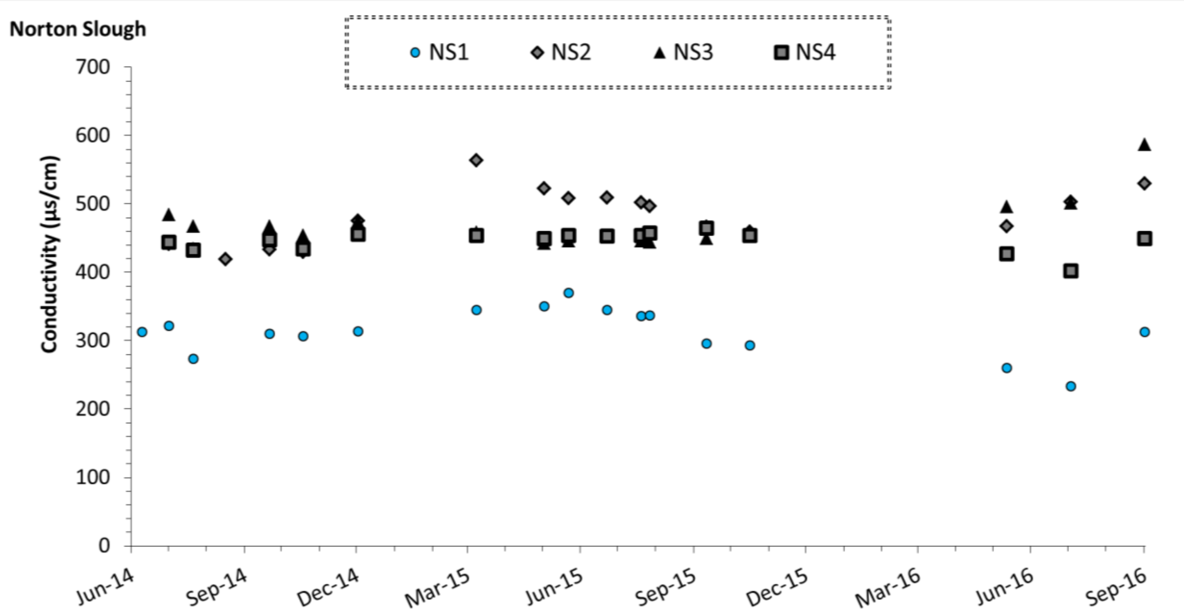

Floodplain Wells
FP1
FP2
FP3
WRFP
Conductivity (µs/cm)
800
700
600
500
400
300
200
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

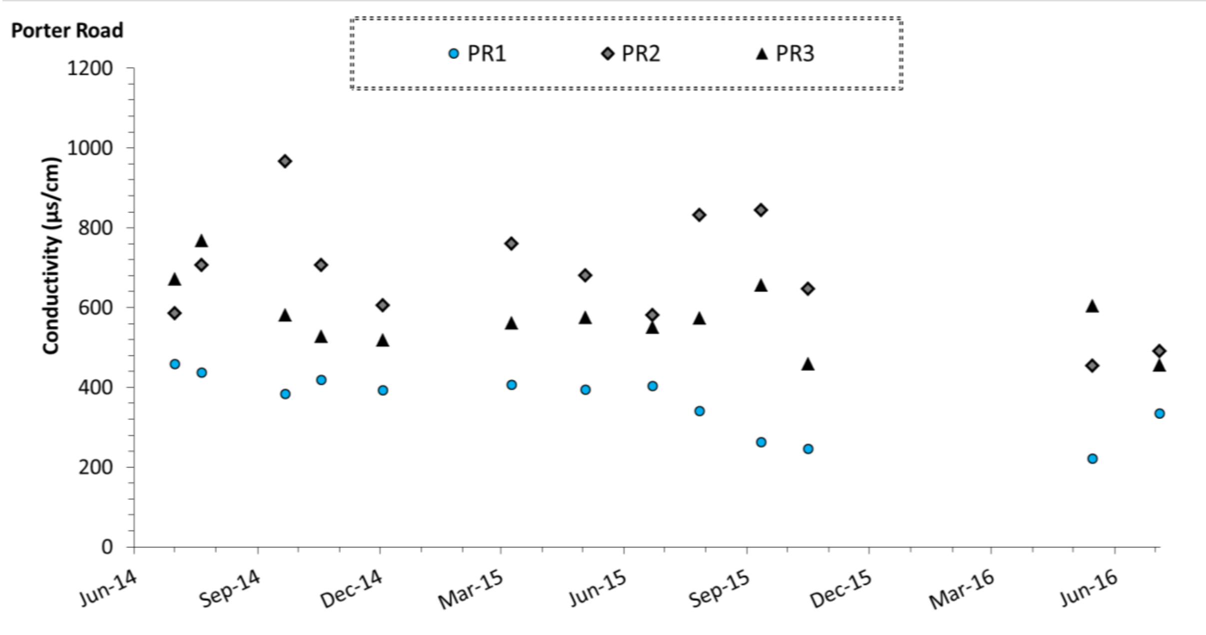

Jones Prairie
JP1
JP2
JP3
Conductivity (µs/cm)
900
800
700
600
500
400
300
200
100
0
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


Jones Road
JR1
JR2
JR3
Conductivity (µs/cm)
0
100
200
300
400
500
600
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


Jones Slough
JS1
JS2
JS3
Conductivity (µs/cm)
0
100
200
300
400
500
600
700
800
900
1000
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

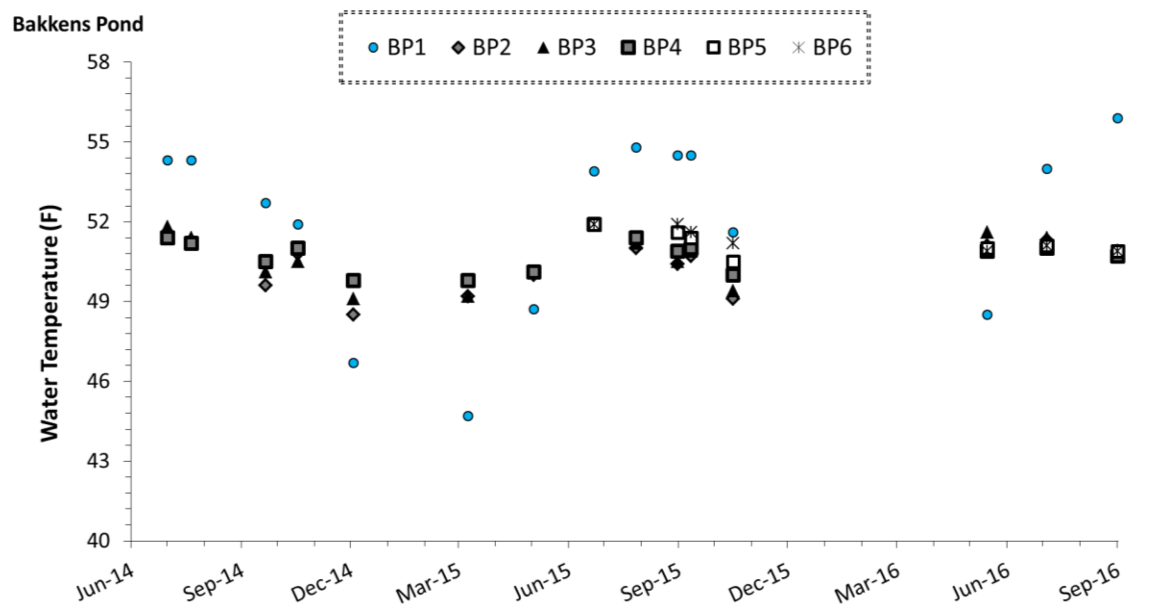

Long Lake
LL1
LL2
LL3
LL4
Conductivity (µs/cm)
0
200
400
600
800
1000
1200
1400
1600
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

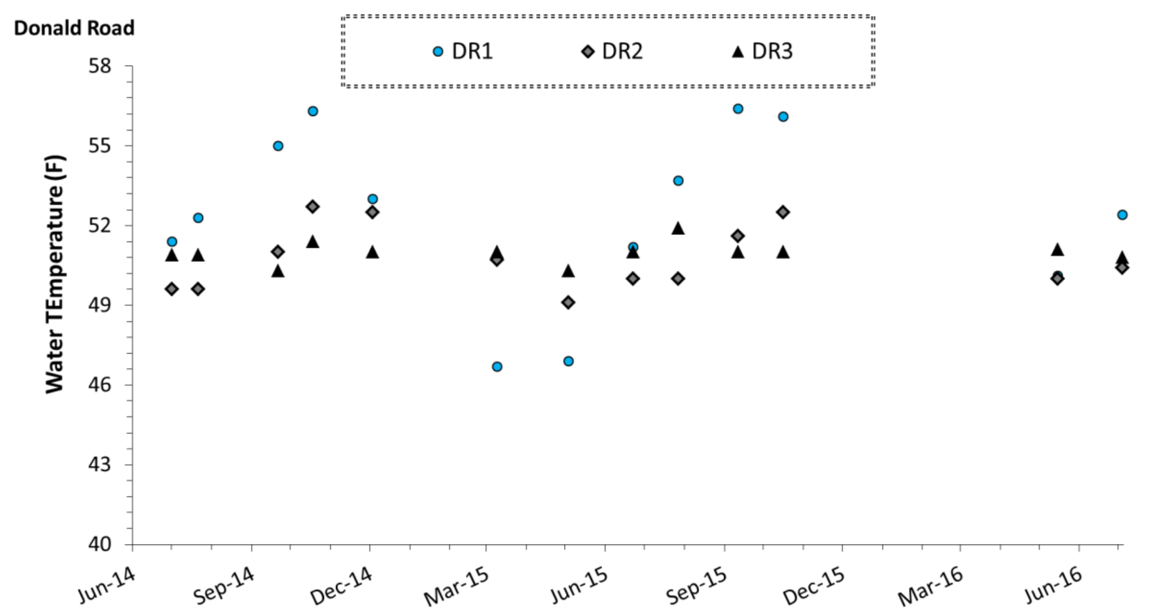

Norton Slough
NS1
NS2
NS3
NS4
Conductivity (µs/cm)
0
100
200
300
400
500
600
700
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

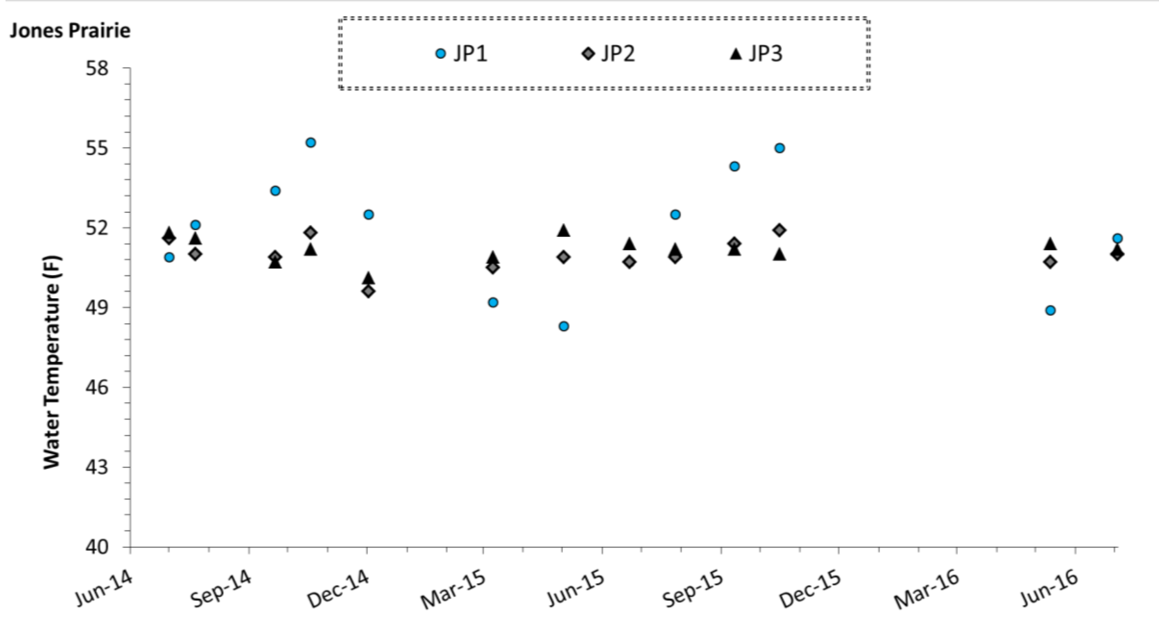

Porter Road
PR1
PR2
PR3
Conductivity (µs/cm)
1200
1000
800
600
400
200
0
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

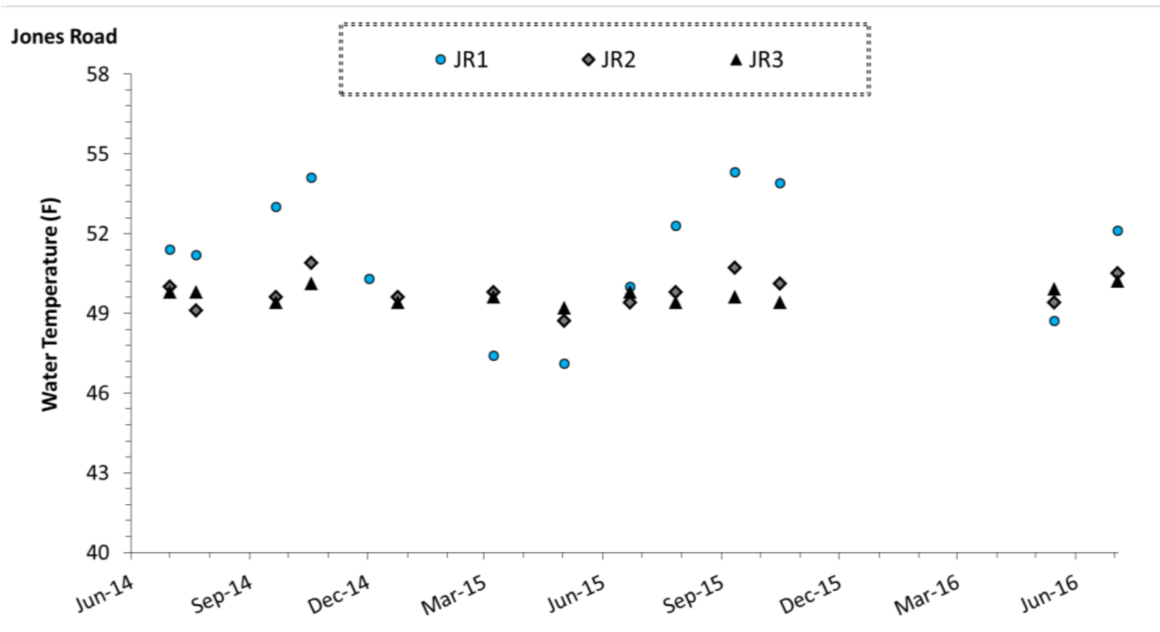
D. Temperature

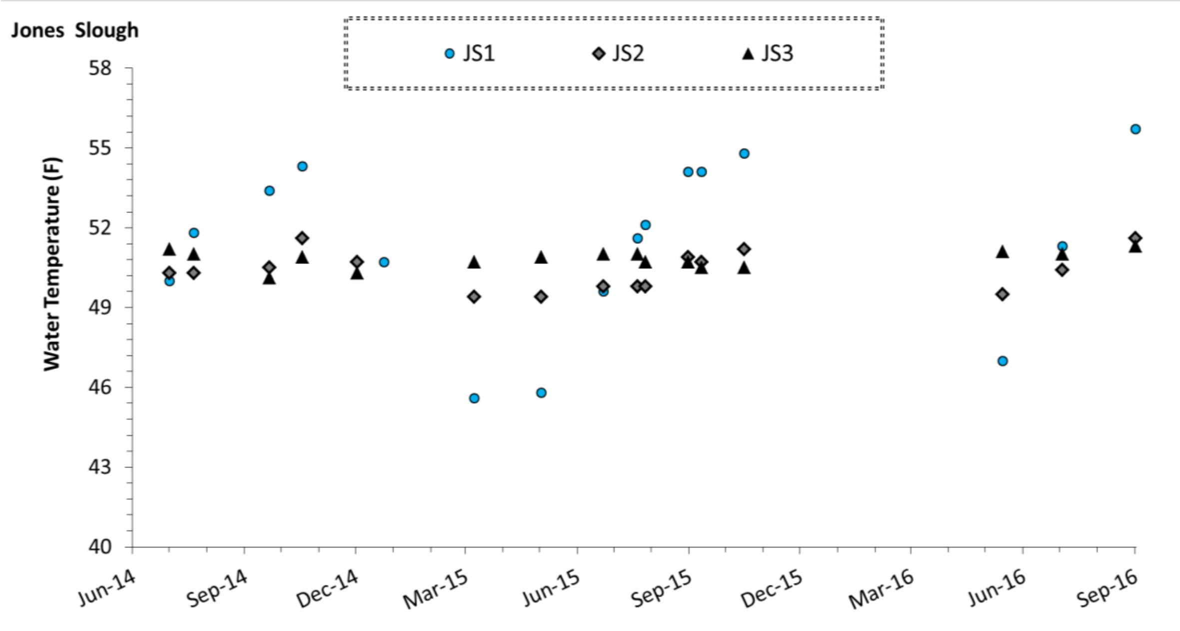
Change in conductivity with time by well nest site. Points correspond to results for wells within the respective well nest.

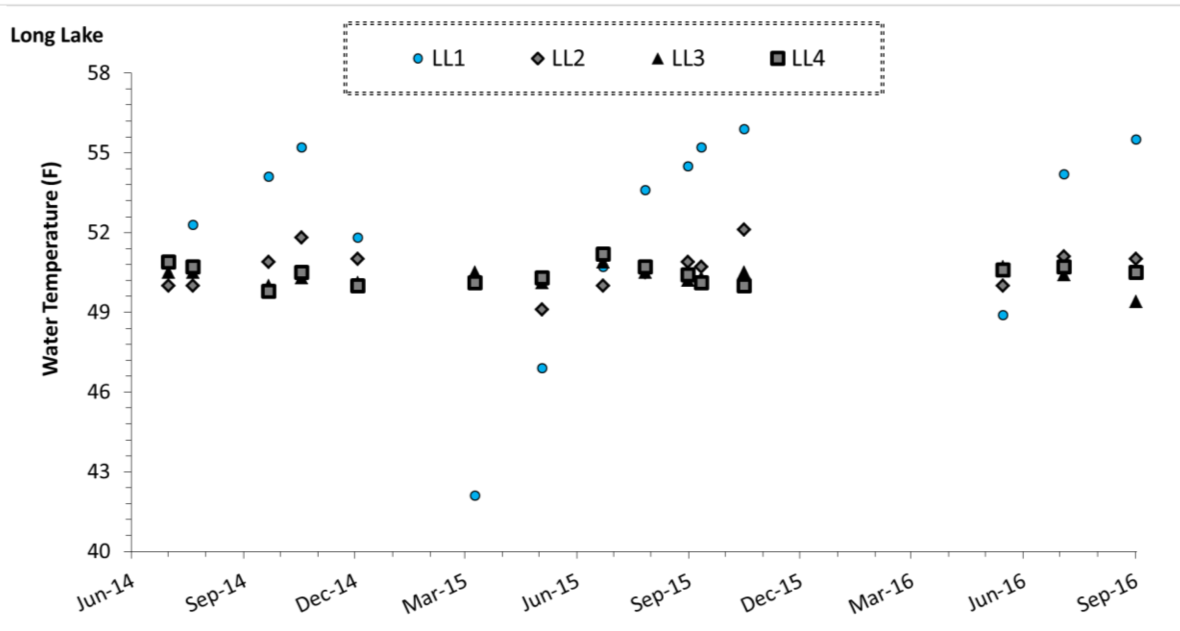


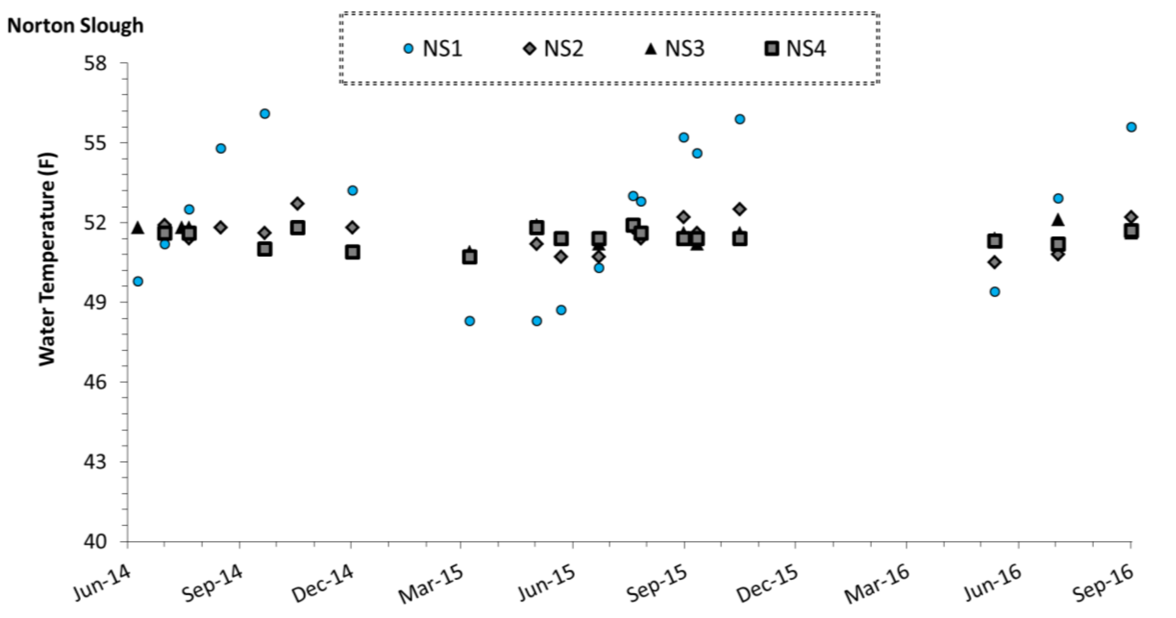


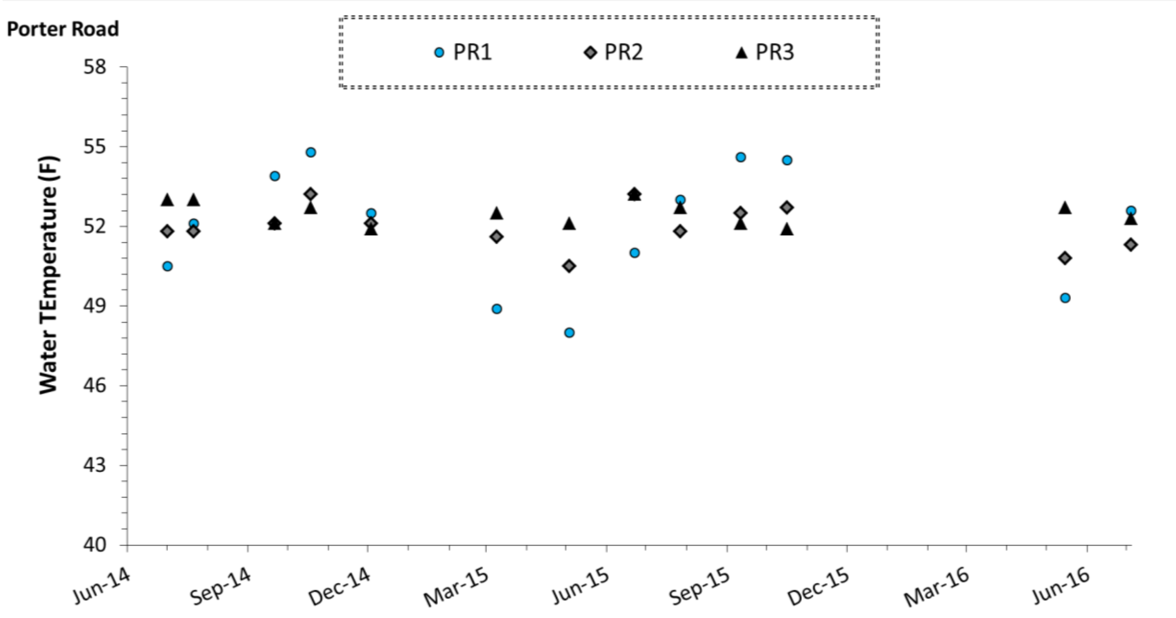

Jones Prairie
JP1
JP2
JP3
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


Jones Road
JR1
JR2
JR3
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


Jones Slough
JS1
JS2
JS3
58
55
52
49
46
43
40
Water Temperature (F)
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

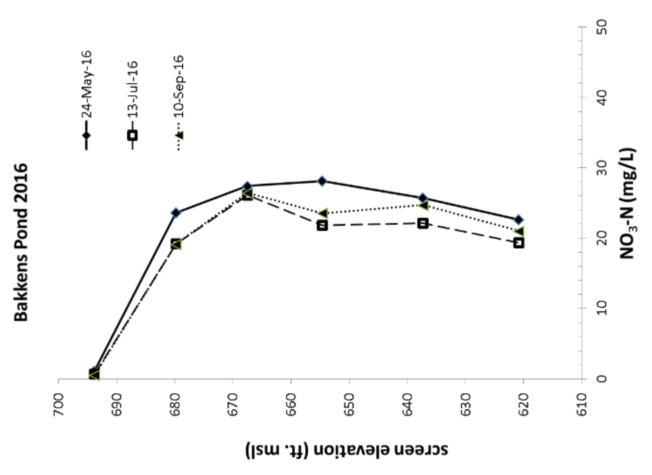

Long Lake
LL1
LL2
LL3
LL4
58
55
52
49
46
43
40
Water Temperature (F)
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

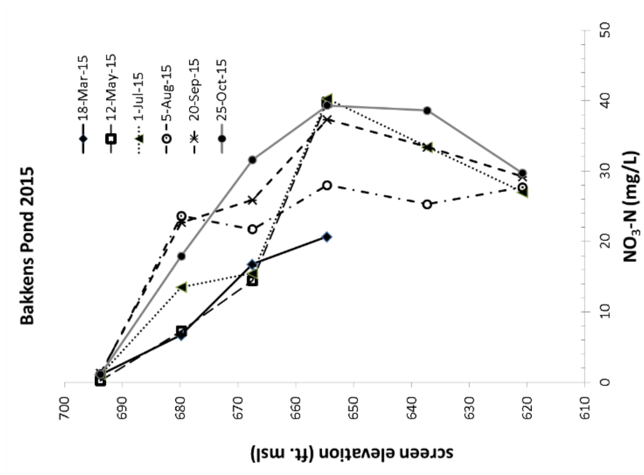

Norton Slough
NS1
NS2
NS3
NS4
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

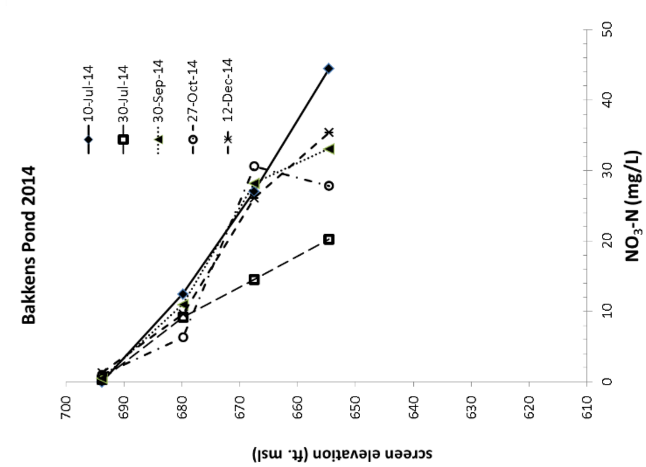

Porter Road
PR1
PR2
PR3
Water TEmperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

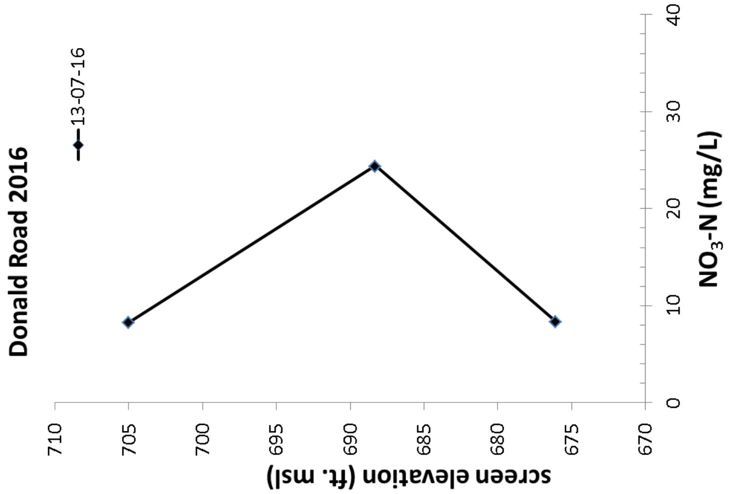
E. Nutrients

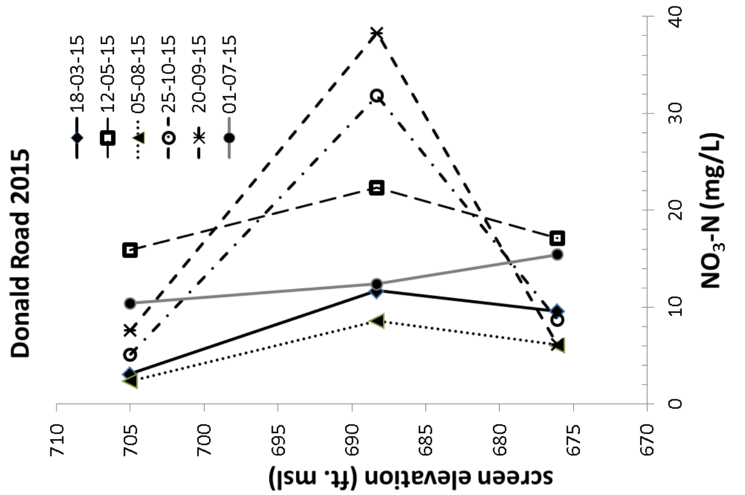
Change in nitrate concentrations with time by well nest site. Points correspond to results for wells within the respective well nest.

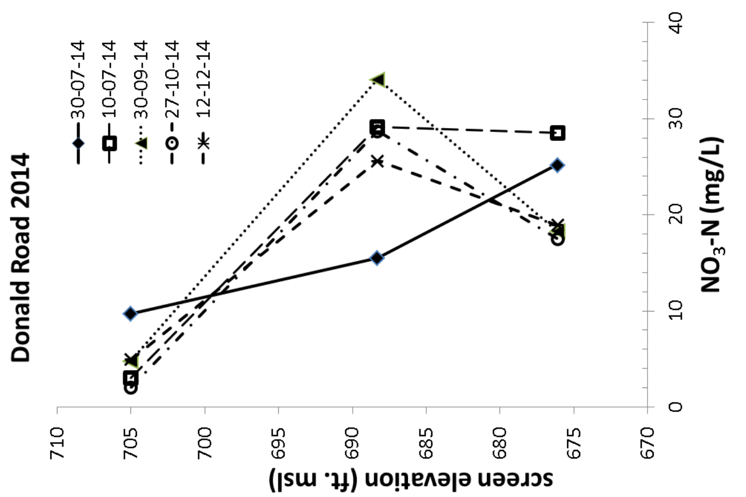


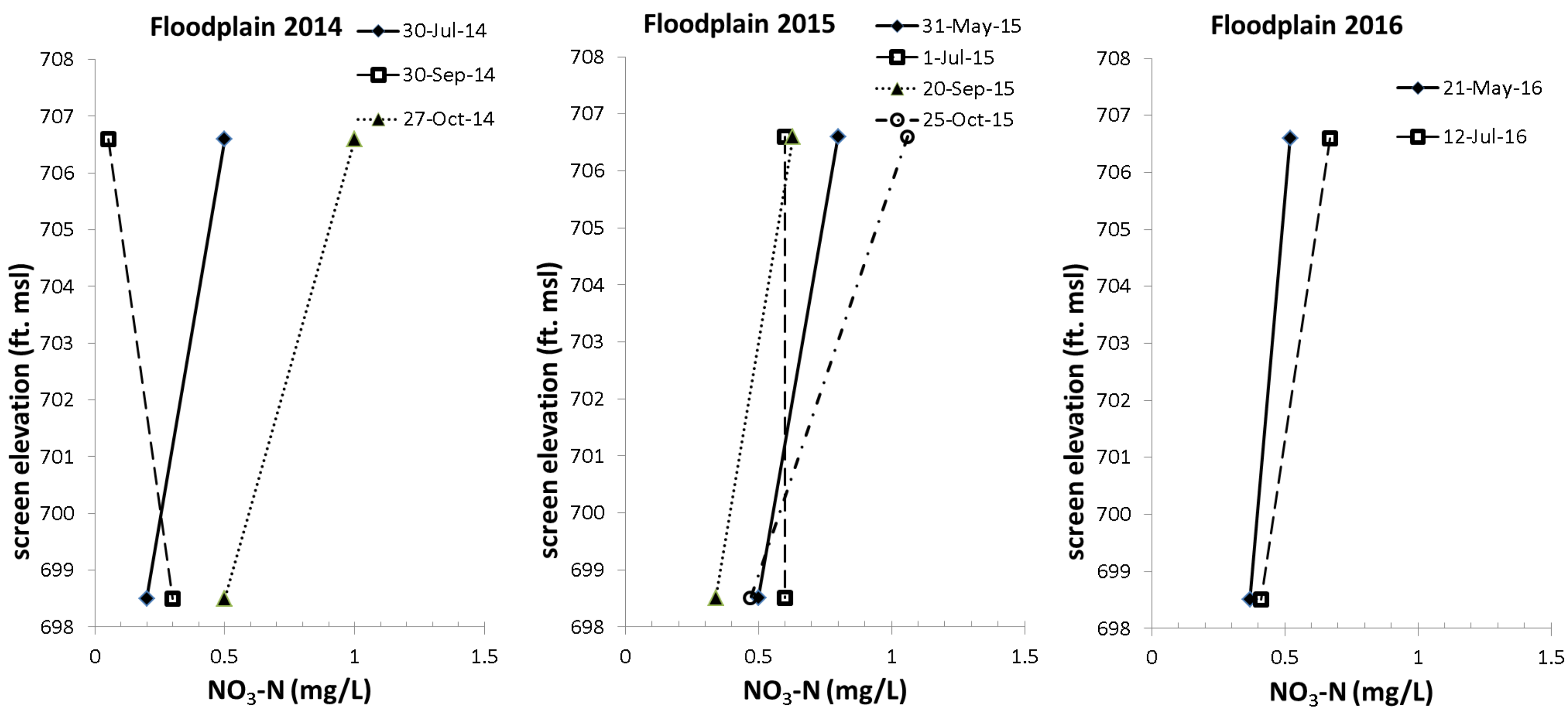




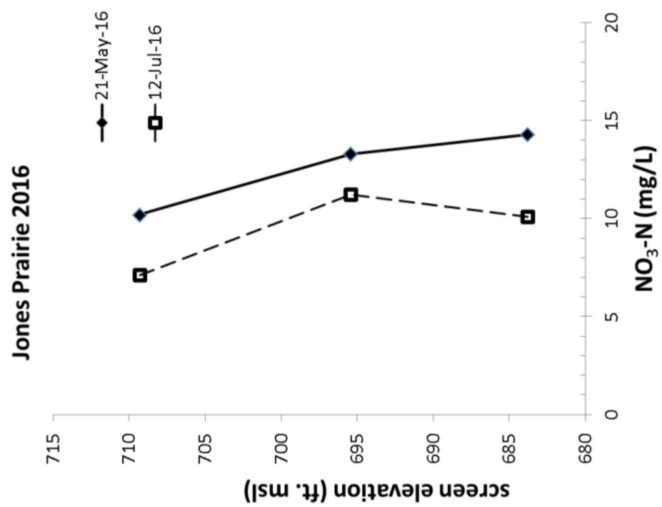

Donald Road 2016
13-07-16
NO$_3$-N (mg/L)
screen elevation (ft. msl)
0
10
20
30
40
710
705
700
695
690
685
680
675
670

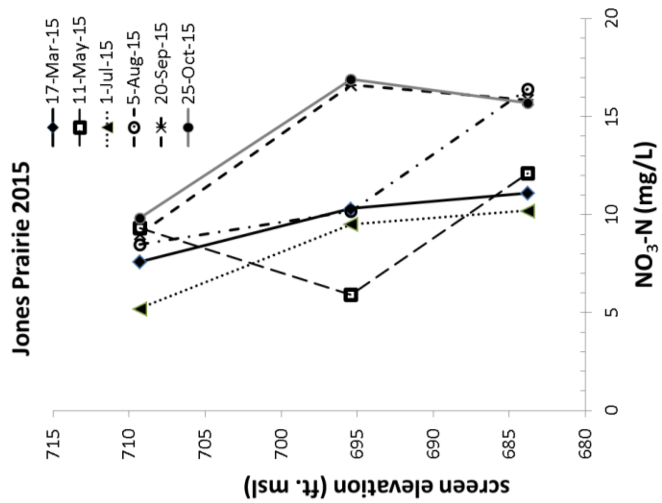

Donald Road 2015
18-03-15
12-05-15
05-08-15
25-10-15
20-09-15
01-07-15
NO$_3$-N (mg/L)
screen elevation (ft. msl)
0
10
20
30
40
710
705
700
695
690
685
680
675
670

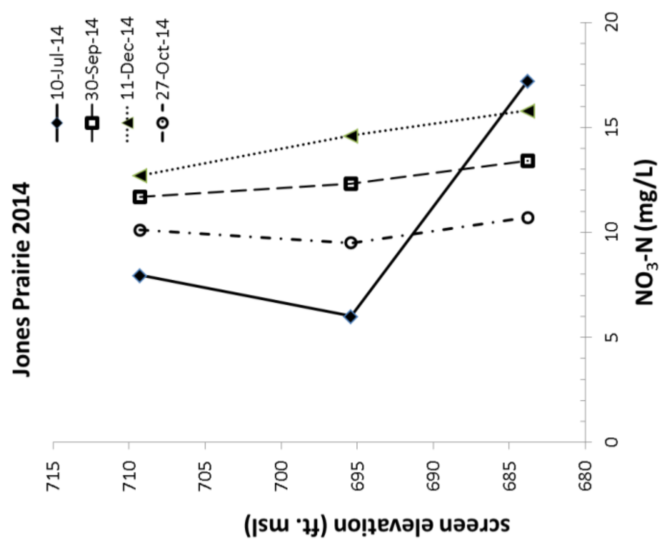

Donald Road 2014
30-07-14
10-07-14
30-09-14
27-10-14
12-12-14
NO$_3$-N (mg/L)
screen elevation (ft. msl)
0
10
20
30
40
710
705
700
695
690
685
680
675
670

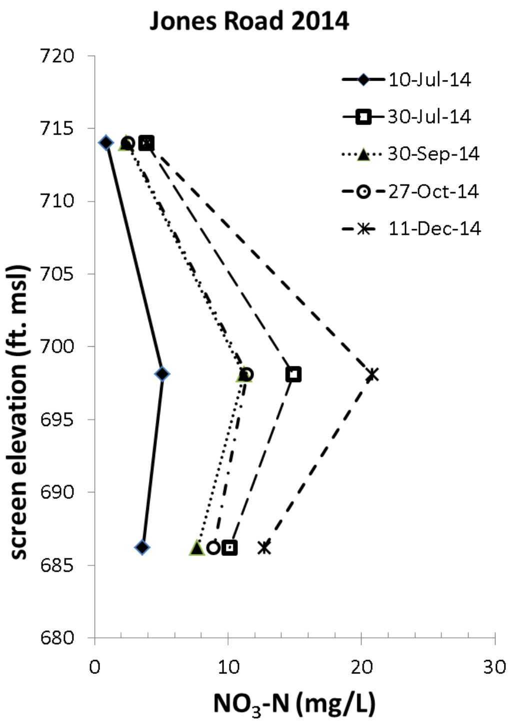


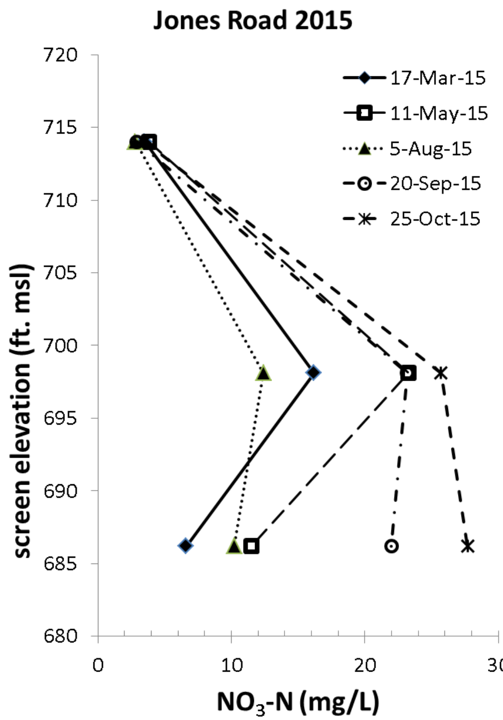
Floodplain 2014
30-Jul-14
30-Sep-14
27-Oct-14
Floodplain 2015
31-May-15
1-Jul-15
20-Sep-15
25-Oct-15
Floodplain 2016
21-May-16
12-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)

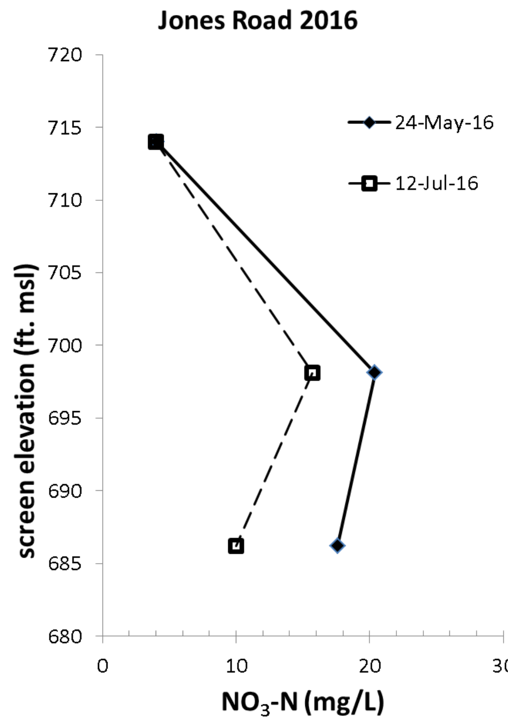

Jones Prairie 2016
21-May-16
12-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)

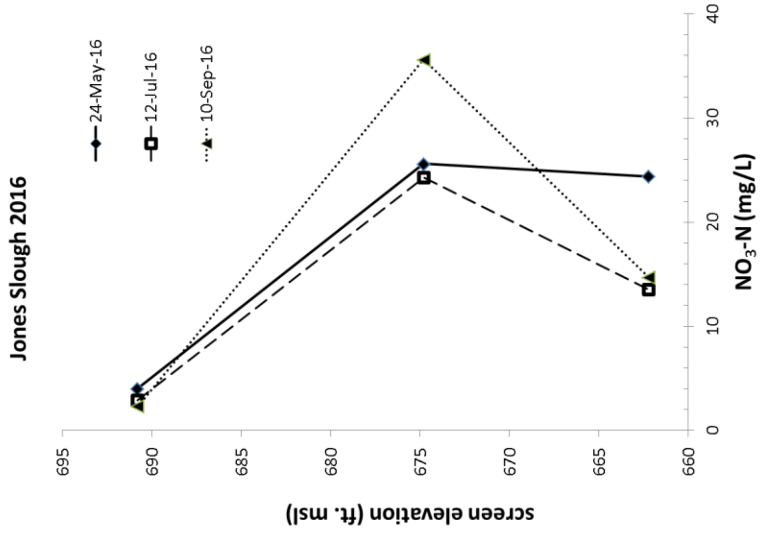

Jones Prairie 2015
17-Mar-15
11-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
NO3-N (mg/L)

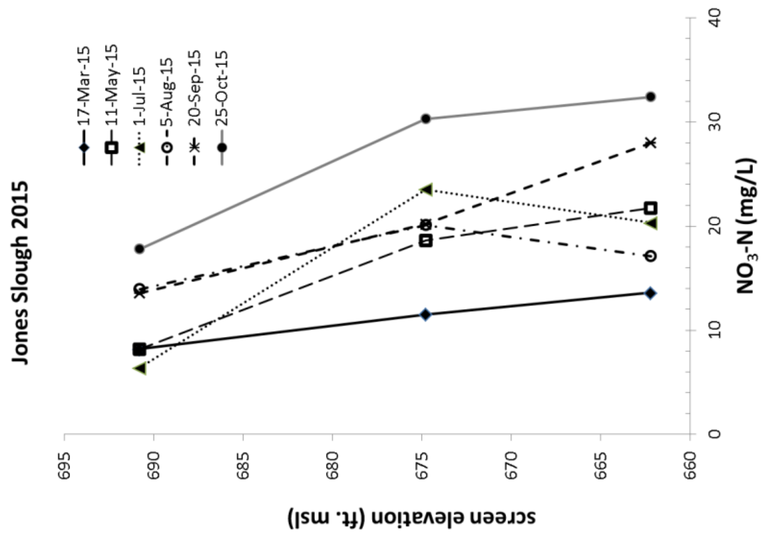

Jones Prairie 2014
10-Jul-14
30-Sep-14
11-Dec-14
27-Oct-14
screen elevation (ft. msl)
NO3-N (mg/L)

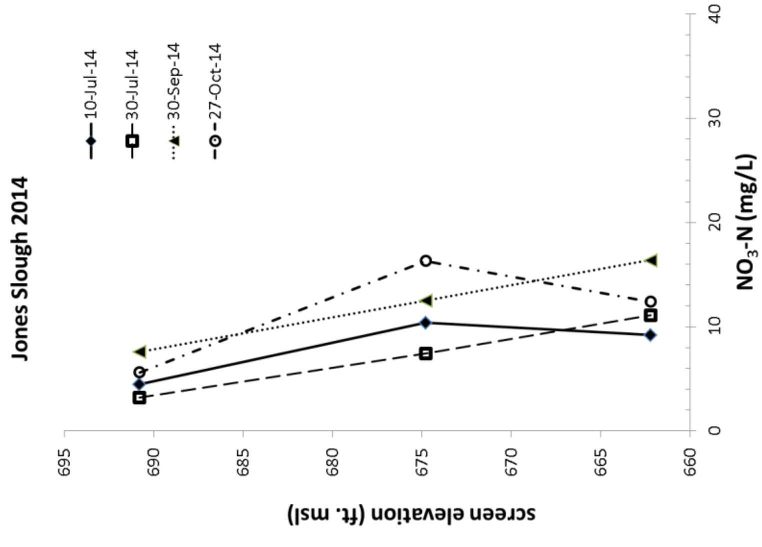

Jones Road 2014
10-Jul-14
30-Jul-14
30-Sep-14
27-Oct-14
11-Dec-14
screen elevation (ft. msl)
NO3-N (mg/L)

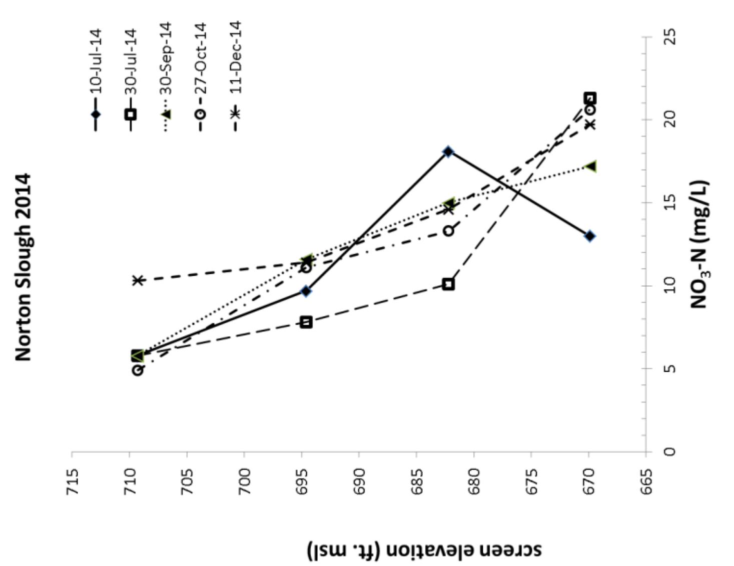

Jones Road 2015
17-Mar-15
11-May-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
NO3-N (mg/L)

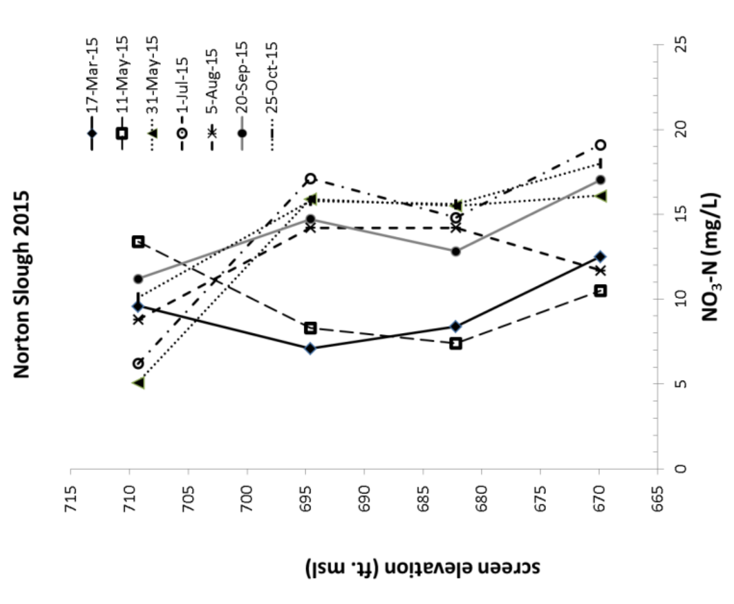

Jones Road 2016
24-May-16
12-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)

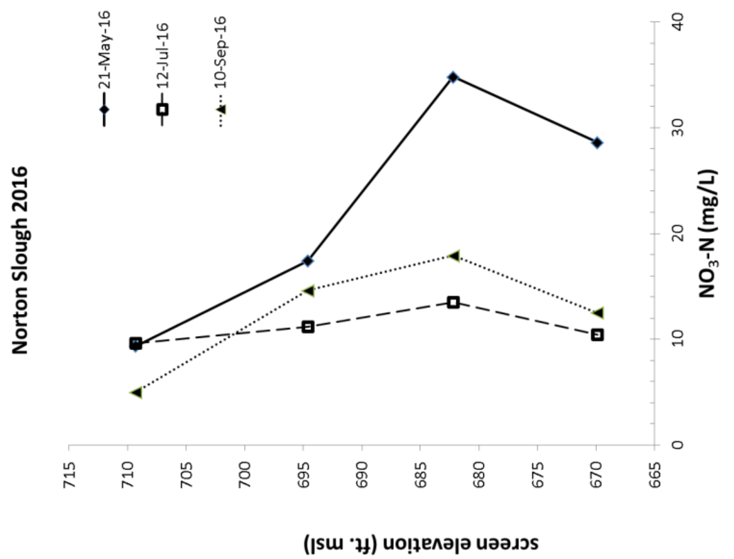

Jones Slough 2016
24-May-16
12-Jul-16
10-Sep-16
screen elevation (ft. msl)
695
690
685
680
675
670
665
660
0
10
20
30
40
NO3-N (mg/L)

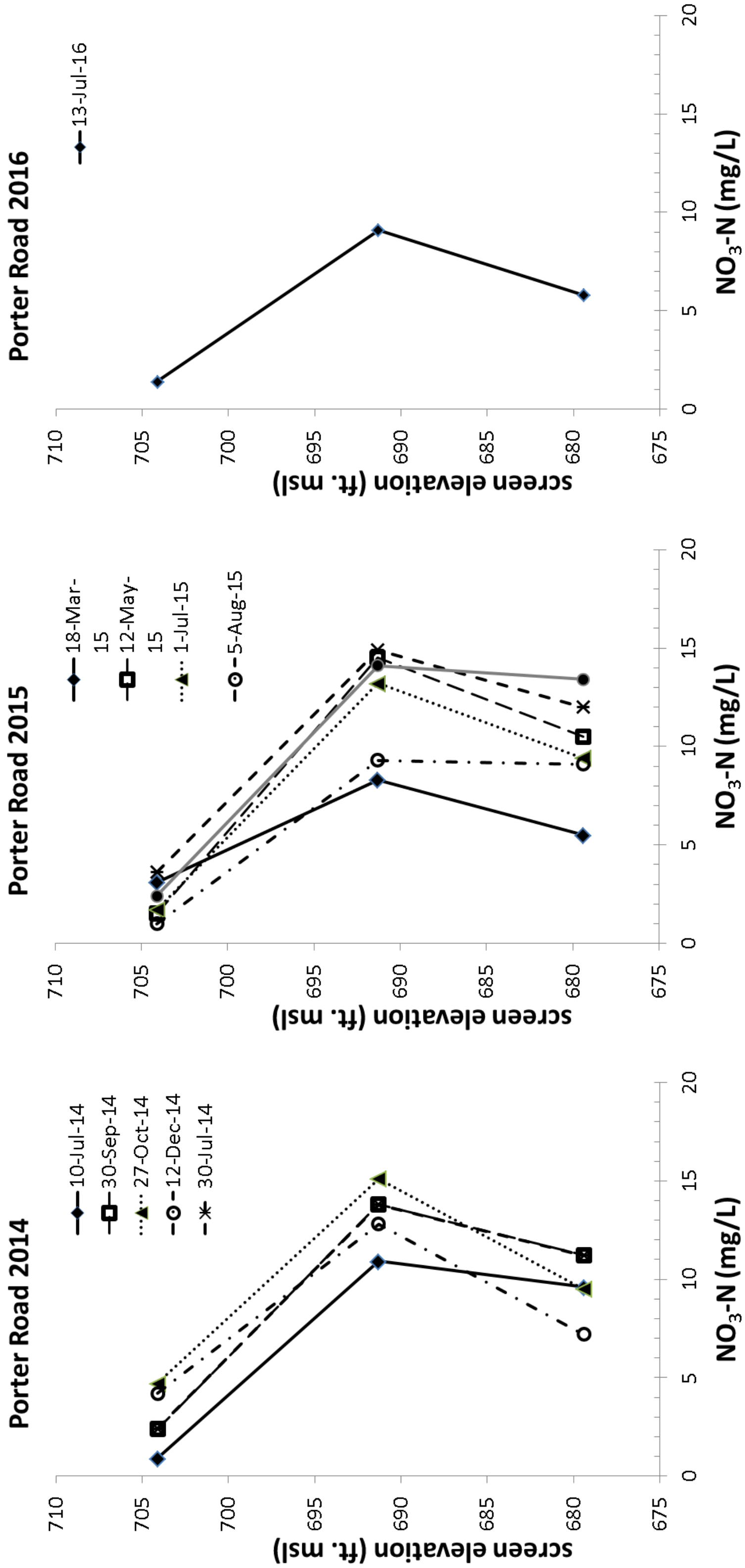

Jones Slough 2015
17-Mar-15
11-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
695
690
685
680
675
670
665
660
0
10
20
30
40
NO3-N (mg/L)

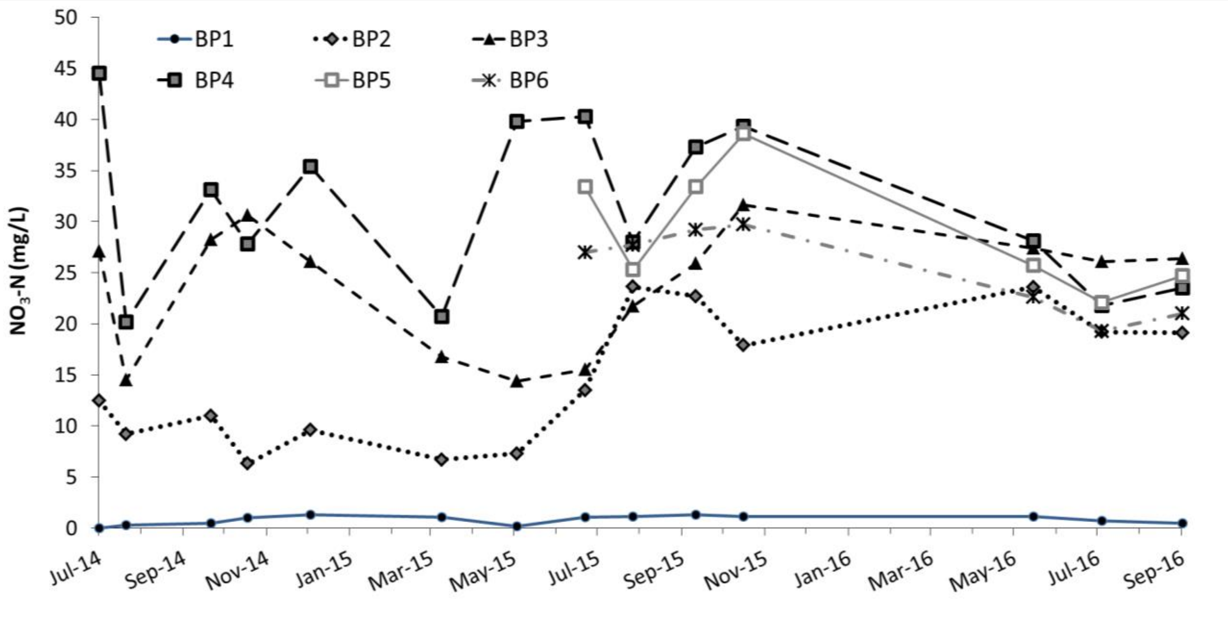

Jones Slough 2014
10-Jul-14
30-Jul-14
30-Sep-14
27-Oct-14
screen elevation (ft. msl)
695
690
685
680
675
670
665
660
0
10
20
30
40
NO3-N (mg/L)

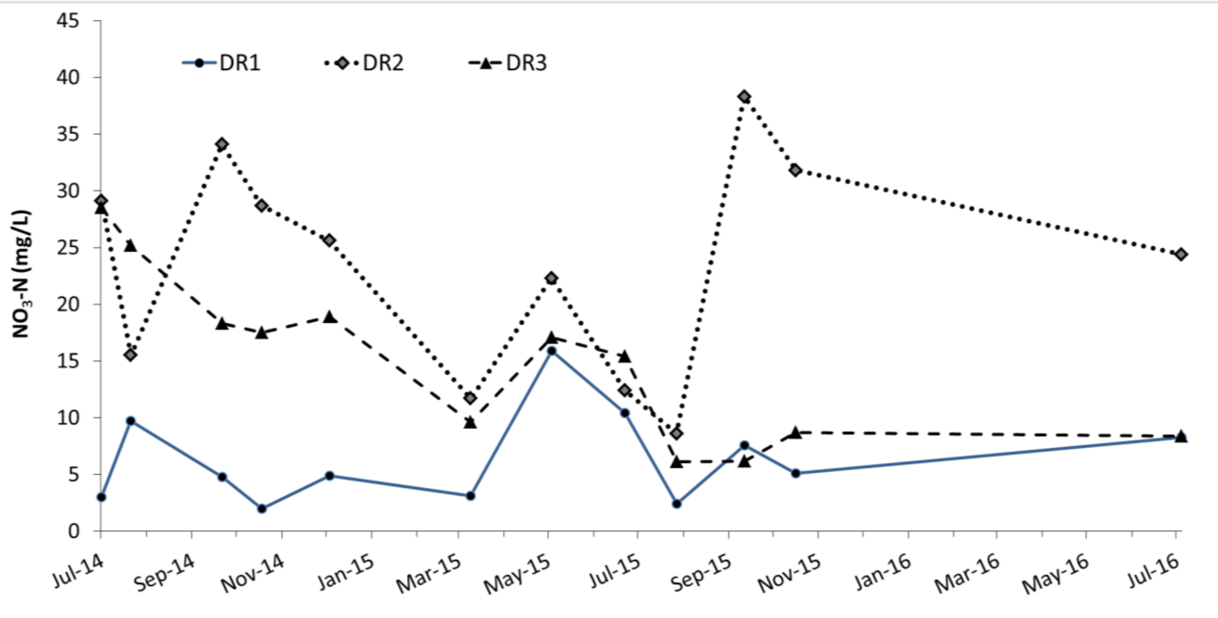

Norton Slough 2014
10-Jul-14
30-Jul-14
30-Sep-14
27-Oct-14
11-Dec-14
screen elevation (ft. msl)
NO3-N (mg/L)

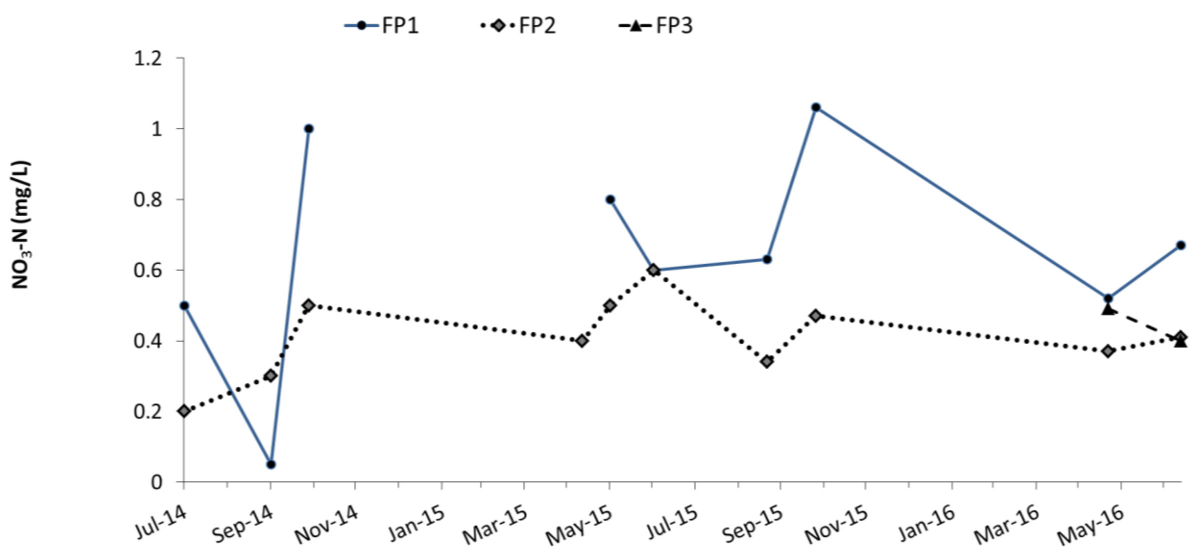

Norton Slough 2015
17-Mar-15
11-May-15
31-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
NO3-N (mg/L)

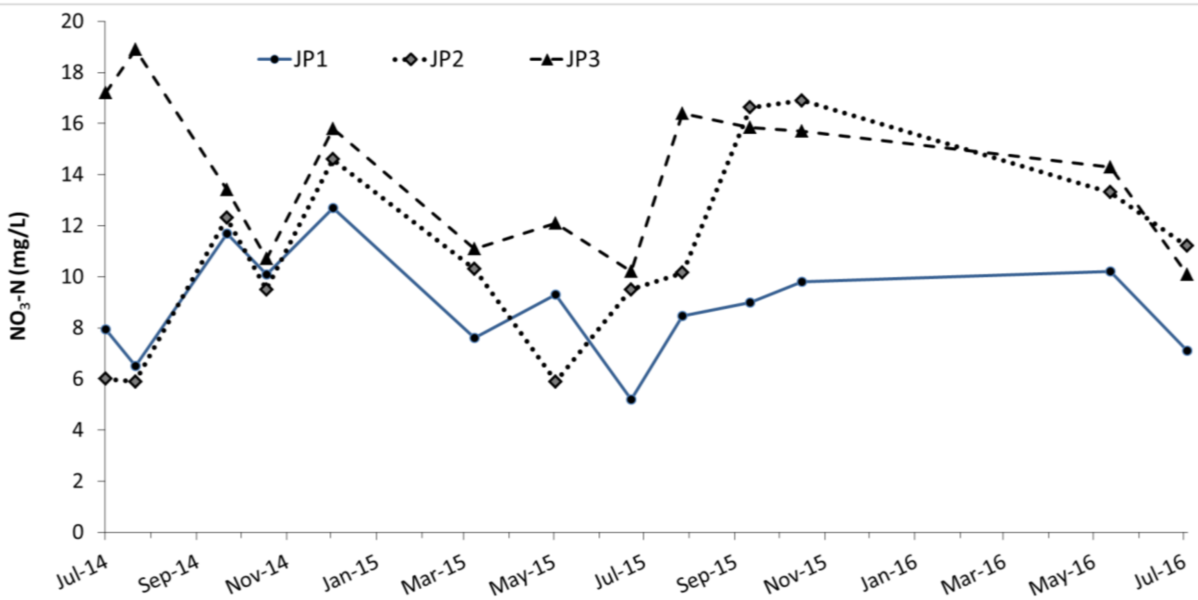

Norton Slough 2016
21-May-16
12-Jul-16
10-Sep-16
screen elevation (ft. msl)
NO3-N (mg/L)

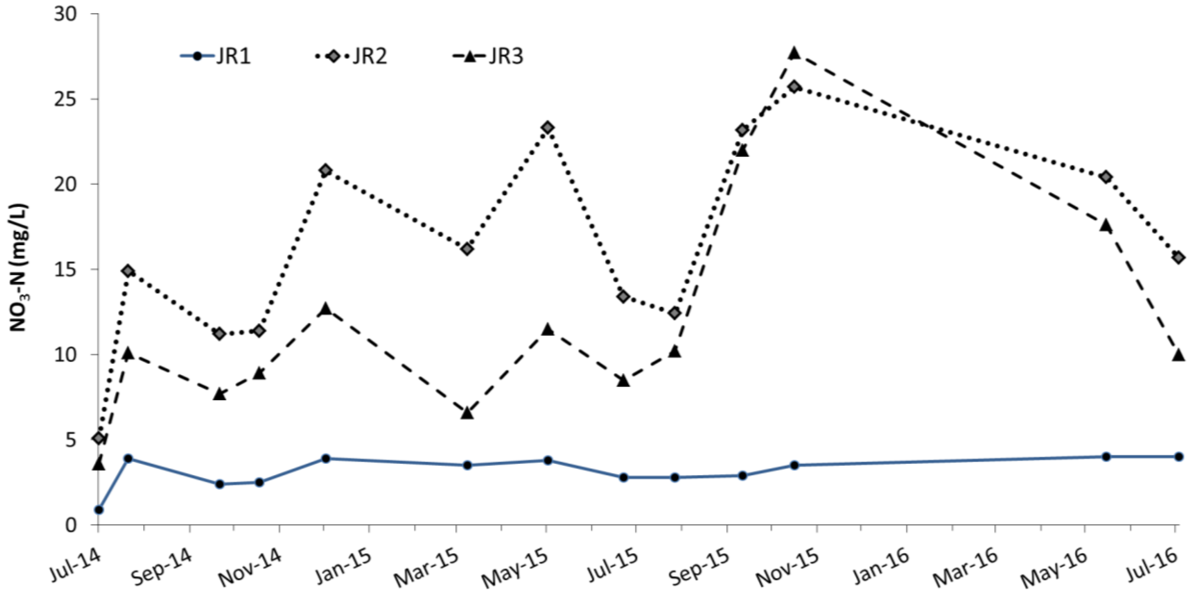

Porter Road 2014
10-Jul-14
30-Sep-14
27-Oct-14
12-Dec-14
30-Jul-14
screen elevation (ft. msl)
NO3-N (mg/L)
Porter Road 2015
18-Mar-15
12-May-15
1-Jul-15
5-Aug-15
screen elevation (ft. msl)
NO3-N (mg/L)
Porter Road 2016
13-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)

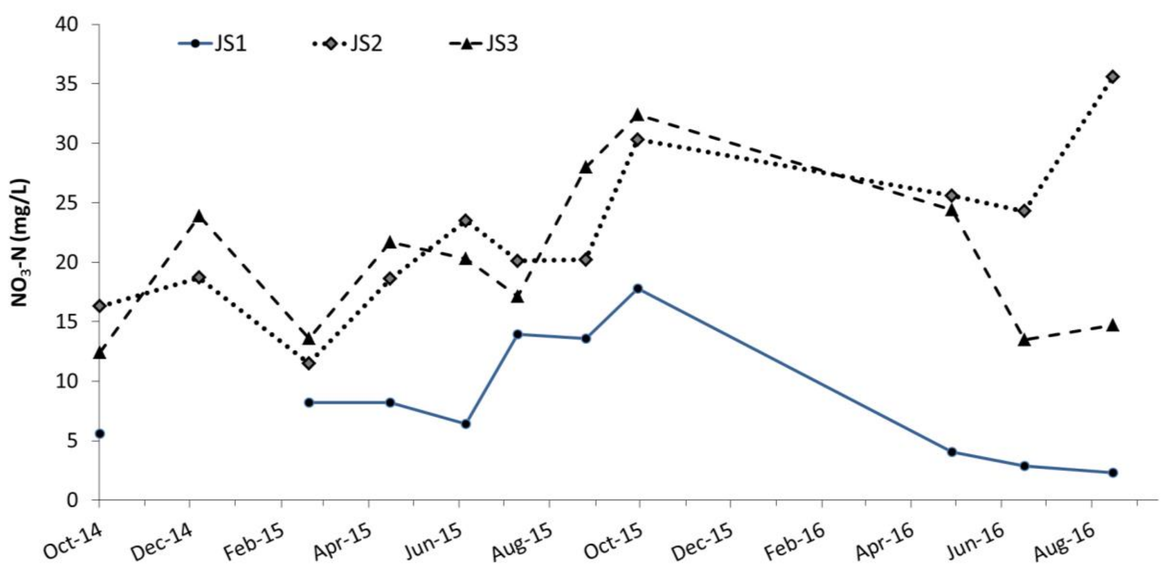

BP1
BP2
BP3
BP4
BP5
BP6
NO3-N (mg/L)
50
45
40
35
30
25
20
15
10
5
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16
Sep-16

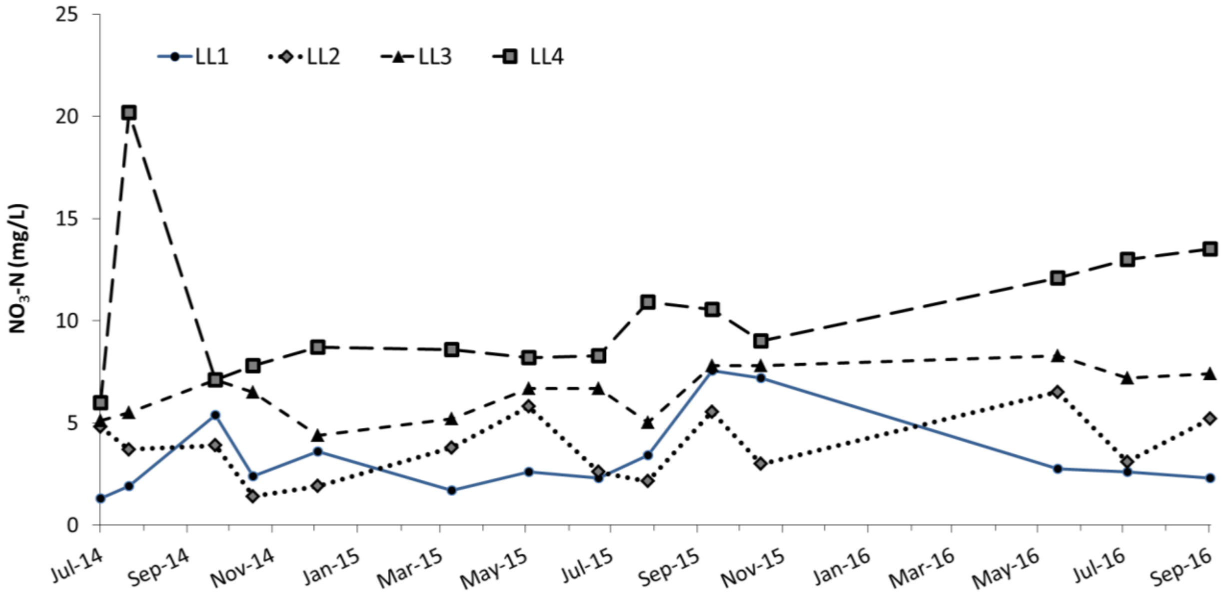

DR1
DR2
DR3
NO3-N (mg/L)
45
40
35
30
25
20
15
10
5
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16

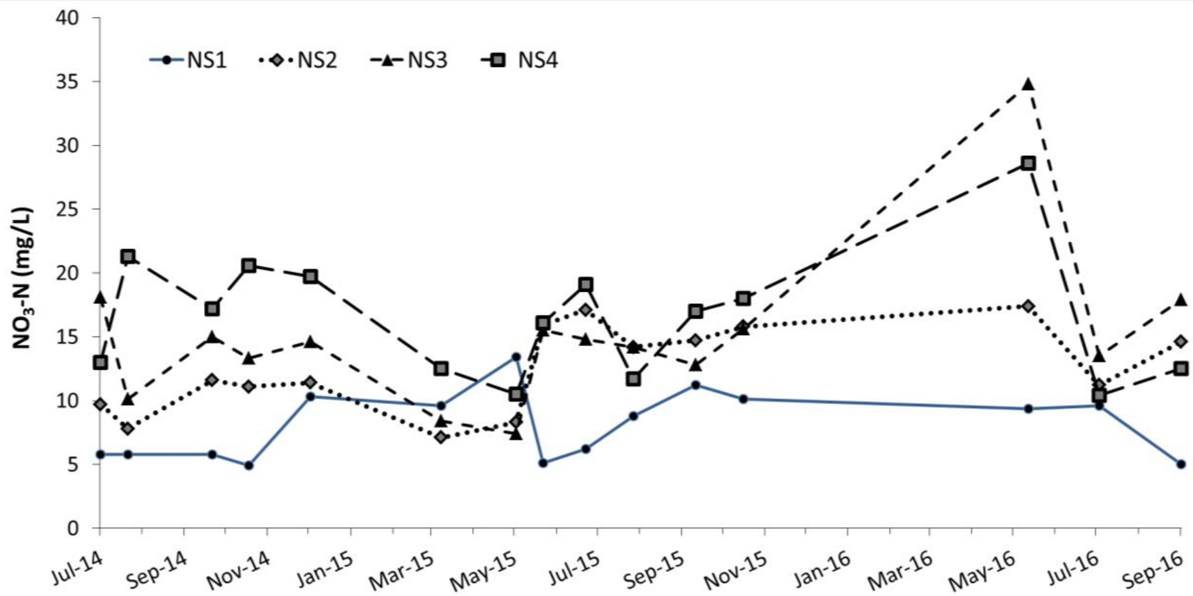

FP1
FP2
FP3
NO3-N (mg/L)
1.2
1
0.8
0.6
0.4
0.2
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16

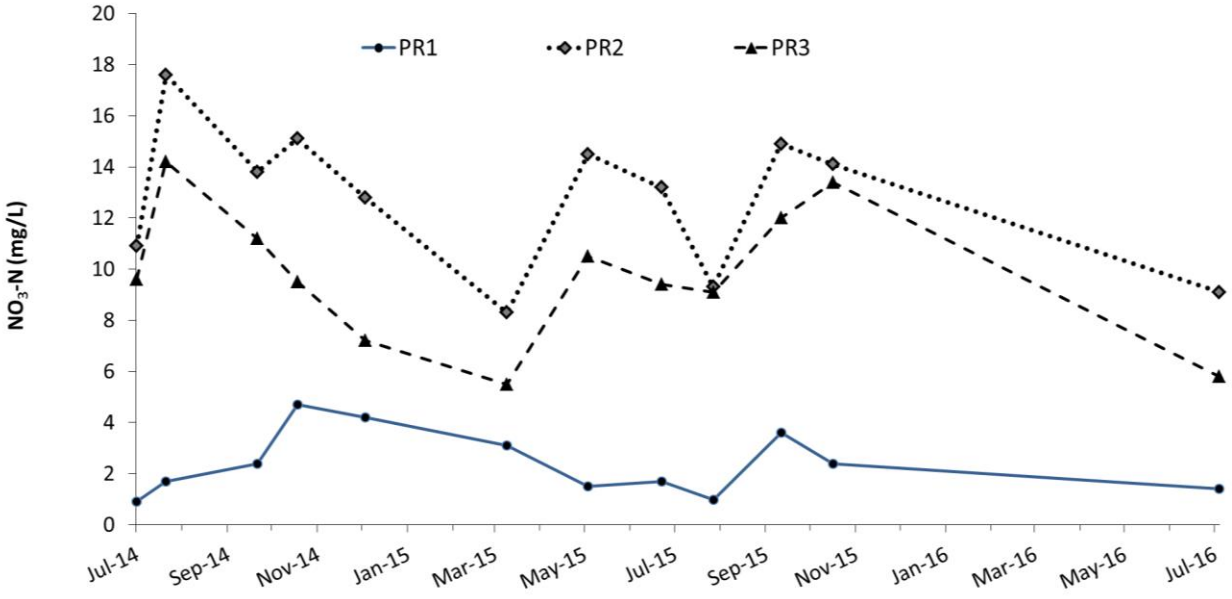

JP1
JP2
JP3
NO3-N (mg/L)
20
18
16
14
12
10
8
6
4
2
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16


JR1
JR2
JR3
NO3-N (mg/L)
30
25
20
15
10
5
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16


JS1
JS2
JS3
NO3-N (mg/L)
40
35
30
25
20
15
10
5
0
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
Aug-15
Oct-15
Dec-15
Feb-16
Apr-16
Jun-16
Aug-16


LL1
LL2
LL3
LL4
NO3-N (mg/L)
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16
Sep-16


NS1
NS2
NS3
NS4
NO3-N (mg/L)
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16
Sep-16


PR1
PR2
PR3
NO3-N (mg/L)
0
2
4
6
8
10
12
14
16
18
20
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16

Orthophosphate concentrations measured on July 13^{th}, 2016 using Chemetrics® test kits

Well ID	Colormetric Orthophosphate (mg/L)
	July 13th, 2016
BP1	0
BP2	0-0.1
BP3	0-0.1
BP4	0.1-0.2
BP5	0.2
BP6	0.2
DR1	0-0.1
DR2	0-0.1
DR3	0-0.1
FP1	4
FP2	0.8
FP3	5.0-6
JP1	0-0.1
JP2	0.6
JP3	0-0.1
JR1	0-0.1
JR2	0.6
JR3	0-0.1
JS1	2.0-3.0
JS2	0-0.1
JS3	0-0.1
LL1	0.1-0.2
LL2	0.3
LL3	0-0.1
LL4	0-0.1
NS1	0.1-0.2
NS2	0
NS3	0
NS4	0.1-0.2
PR1	0.1-0.2
PR2	0
PR3	0-0.1
WRFP	0.6

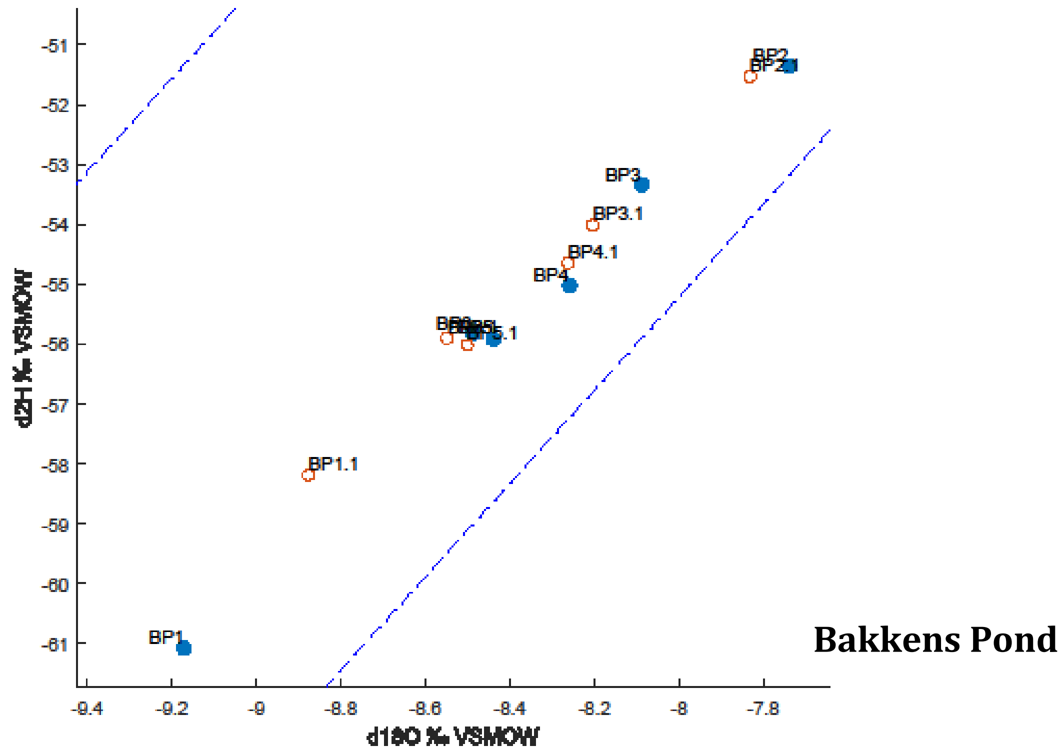
F. Isotopes

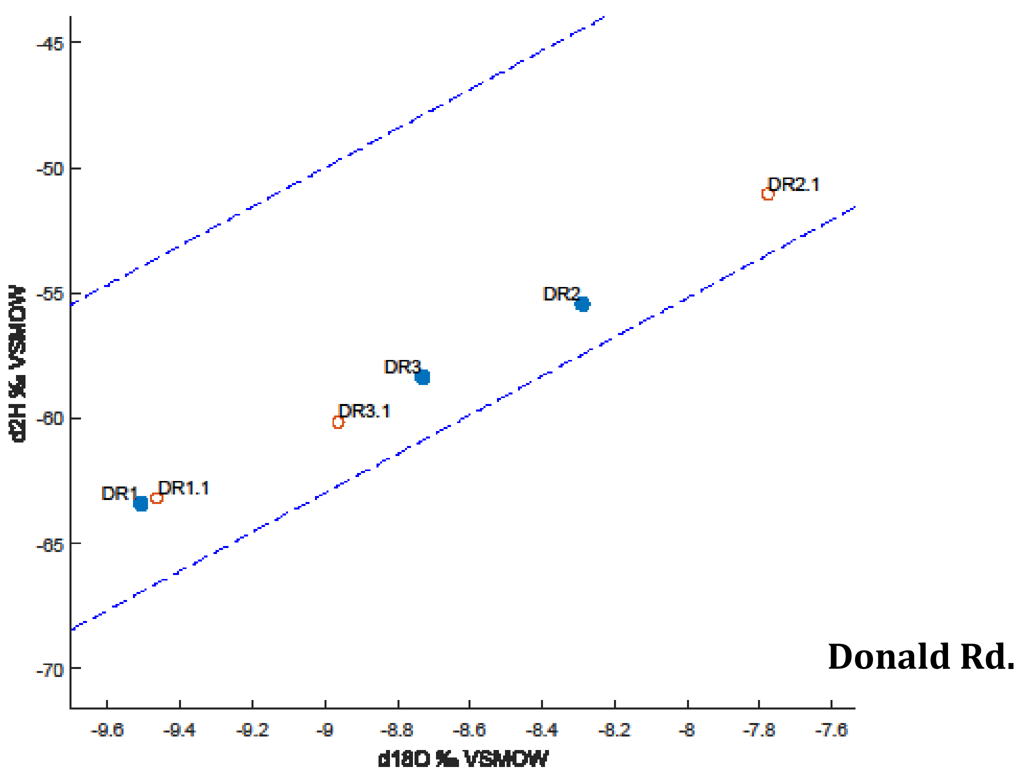
Table of isotopic analysis results for samples collected on May 24, 2016. Samples collected on the second round, July 12th, 2016, are labeled ".1", e.g. "NS1.1".

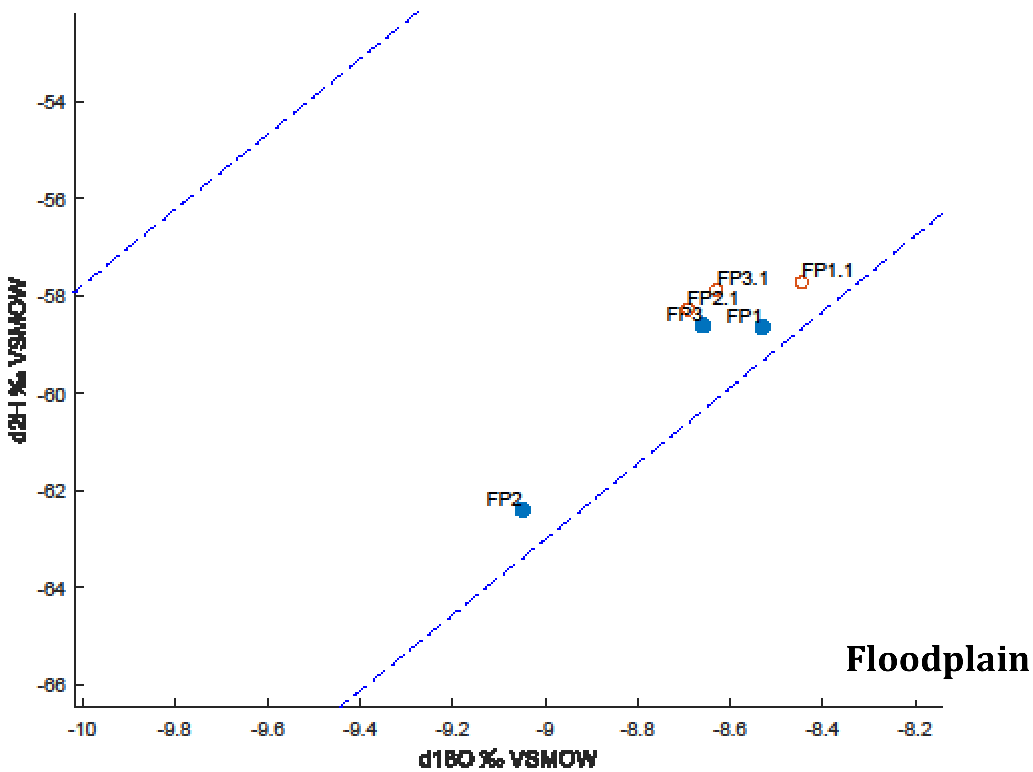
Well ID	d18O (VSMOW)	dD (VSMOW)
NS1	**-9.31641**	**-63.35095**
NS2	-8.59964	-56.59781
NS3	-8.46440	-55.42170
NS4	-8.75903	-57.78595
FP1	-8.52984	-58.65584
FP2	-9.04829	-62.39523
FP3	-8.66306	-58.60642
JP1	-9.52916	-65.10076
JP2	-8.53923	-56.15068
JP3	-8.63823	-56.66427
Well ID	d18O (VSMOW)	dD (VSMOW)
BP1	-9.17010	-61.09122
BP2	-7.73757	-51.35372
BP3	-8.08991	-53.34964
BP4	-8.26071	-55.01697
BP5	-8.44427	-55.91225
BP6	-8.49125	-55.82910
LL1	-9.71036	-64.82326
LL2	-9.45701	-62.59091
LL3	-8.95701	-59.29900
LL4	-9.09493	-60.85580
PR1	-8.29393	-52.79264
PR2	-9.27446	-61.80450
PR3	-8.44528	-55.92026
DR1	-9.50701	-63.42608
DR2	-8.29259	-55.44040
DR3	-8.73487	-58.35464
JR1	-9.54593	-64.03217
JR2	-9.25701	-61.51031
JR3	-9.23822	-61.30293
NS1.1	-9.021775	-61.1137581
NS2.1	-9.160465	-61.3692936
NS3.1	-8.46467	-55.25113907
Well ID	d18O (VSMOW)	dD (VSMOW)

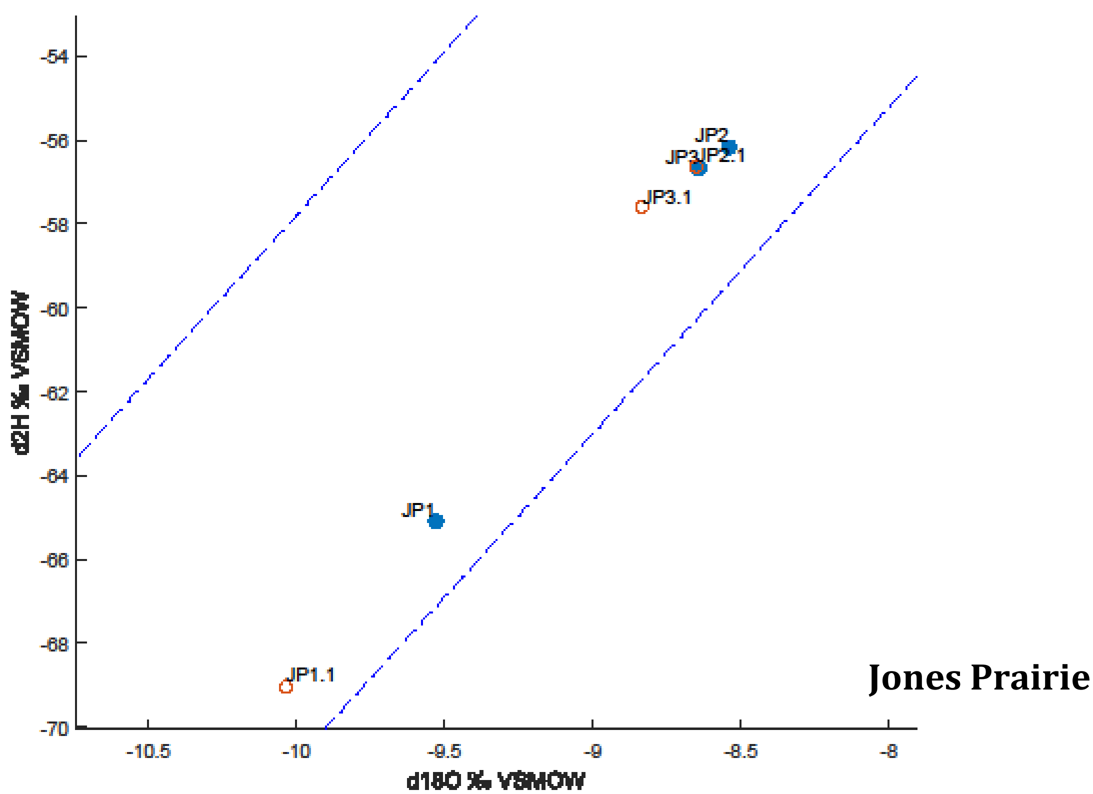
NS4.1	-8.90151	-58.83364657
FP1.1	-8.445575	-57.7286643
FP2.1	-8.69314	-58.2818235
FP3.1	-8.629155	-57.86561797
JP1.1	-10.036825	-69.0313502
JP2.1	-8.6516	-56.63203287
JP3.1	-8.83384	-57.6144249
BP1.1	-8.87806	-58.1916345
BP2.1	-7.833865	-51.52299303
BP3.1	-8.204375	-54.01421363
BP4.1	-8.263335	-54.6502131
BP5.1	-8.50219	-56.01173297
BP6.1	-8.54909	-55.90150197
LL1.1	-9.56146	-63.9797641
LL2.1	-9.1809	-60.14439337
LL3.1	-9.061305	-59.6977908
LL4.1	-9.223445	-61.212966
PR1.1	-10.60733	-71.6668732
PR2.1	-9.31624	-62.1829988
PR3.1	-8.44122	-55.28086803
DR1.1	-9.462635	-63.1981261
DR2.1	-7.77725	-51.0606909
DR3.1	-8.96449	-60.13938287
JR1.1	-9.500155	-62.98801913
JR2.1	-9.29681	-61.87000957
JR3.1	-9.22646	-60.44101497
JS1.1	-9.10486	-60.39525
JS2.1	-9.28777	-61.48186
JS3.1	-9.23484	-60.61237

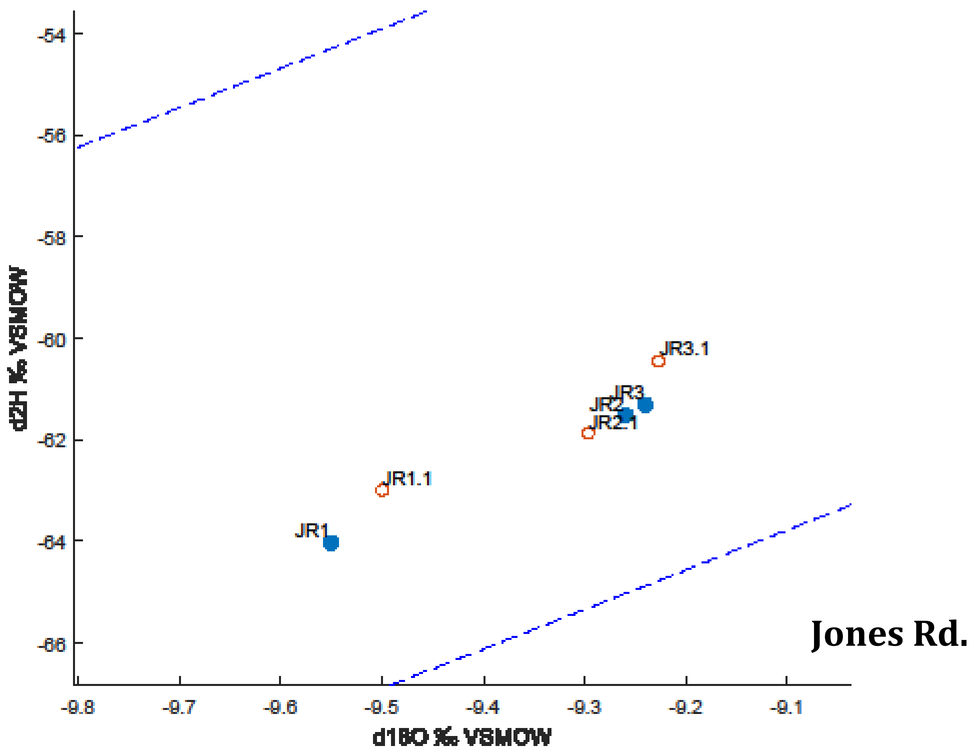
Plots of δ D versus $\delta^{18}O$ by well nest for isotopic samples collected on May 24th (solid blue circles) and July 12th, 2016 (open orange circles). Boundaries for the LML are represented by blue dashed lines.

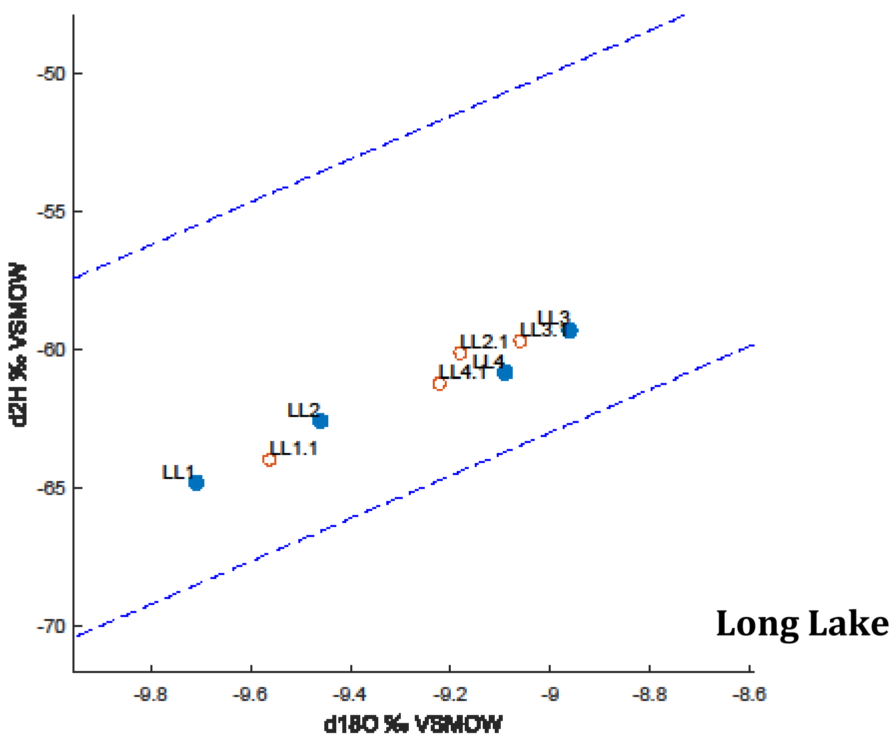


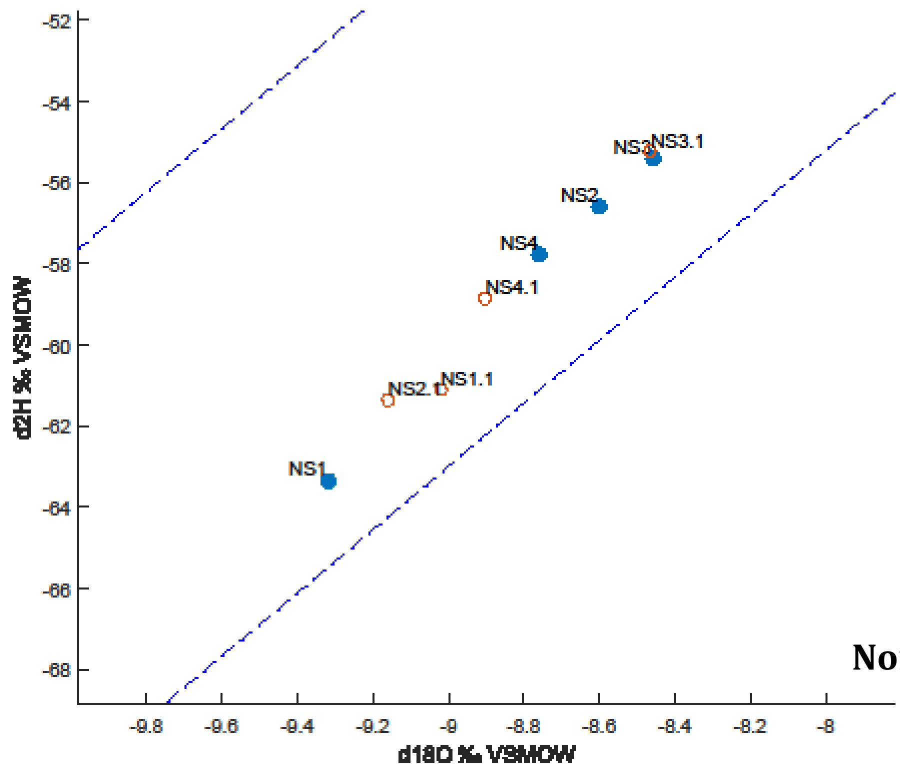



FP3.1
FP1.1
FP2.1
FP3
FP1
FP2
d2H ‰ VSMOW
d18O ‰ VSMOW
Floodplain

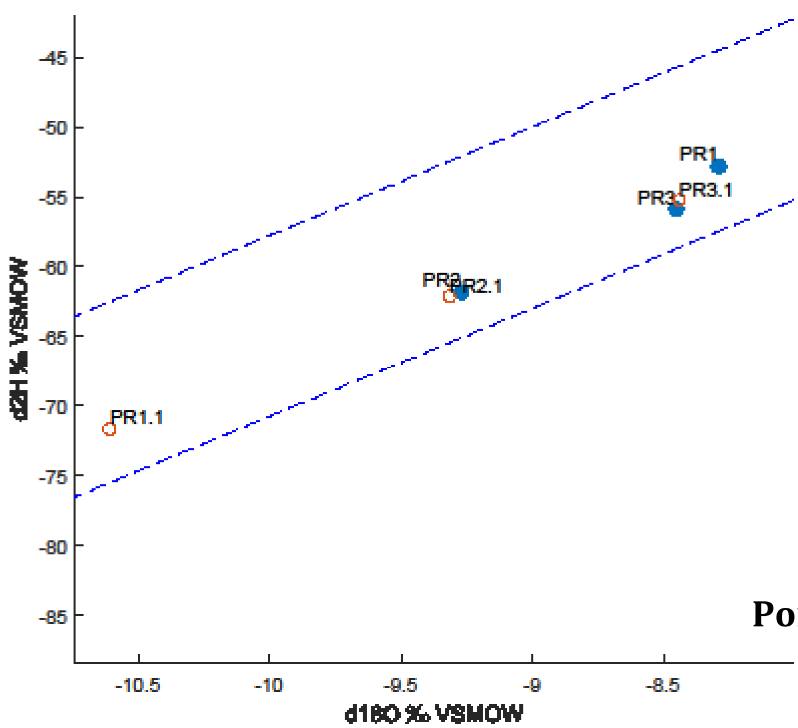

JP2
JP3JP2.1
JP3.1
JP1
JP1.1
d2H ‰ VSMOW
d18O ‰ VSMOW
Jones Prairie


Jones Rd.
d2H ‰ VSMOW
d18O ‰ VSMOW
-54
-56
-58
-60
-62
-64
-66
-9.8
-9.7
-9.6
-9.5
-9.4
-9.3
-9.2
-9.1
JR1
JR1.1
JR2
JR2.1
JR3
JR3.1


Long Lake
d2H ‰ VSMOW
d18O ‰ VSMOW
-50
-55
-60
-65
-70
-9.8
-9.6
-9.4
-9.2
-9
-8.8
-8.6
LL1
LL1.1
LL2
LL2.1
LL3
LL3.1
LL4
LL4.1

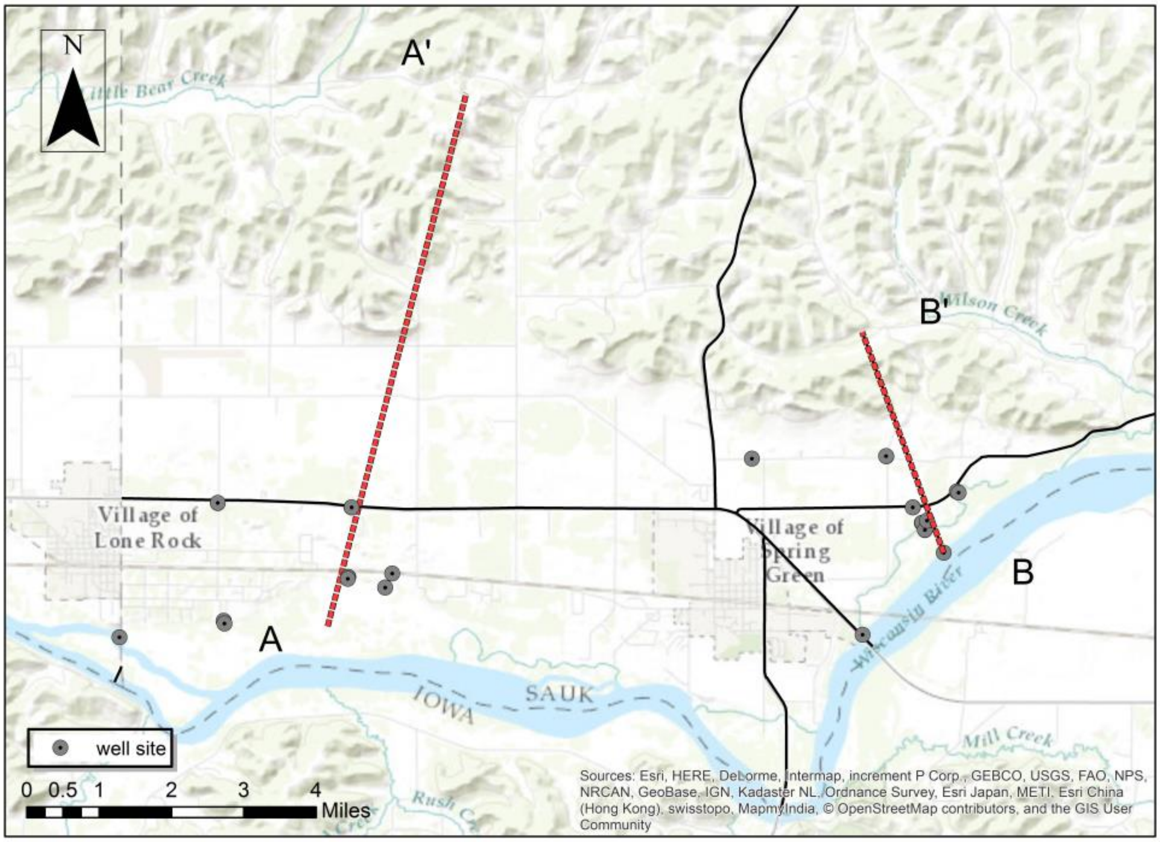


Norton Slough

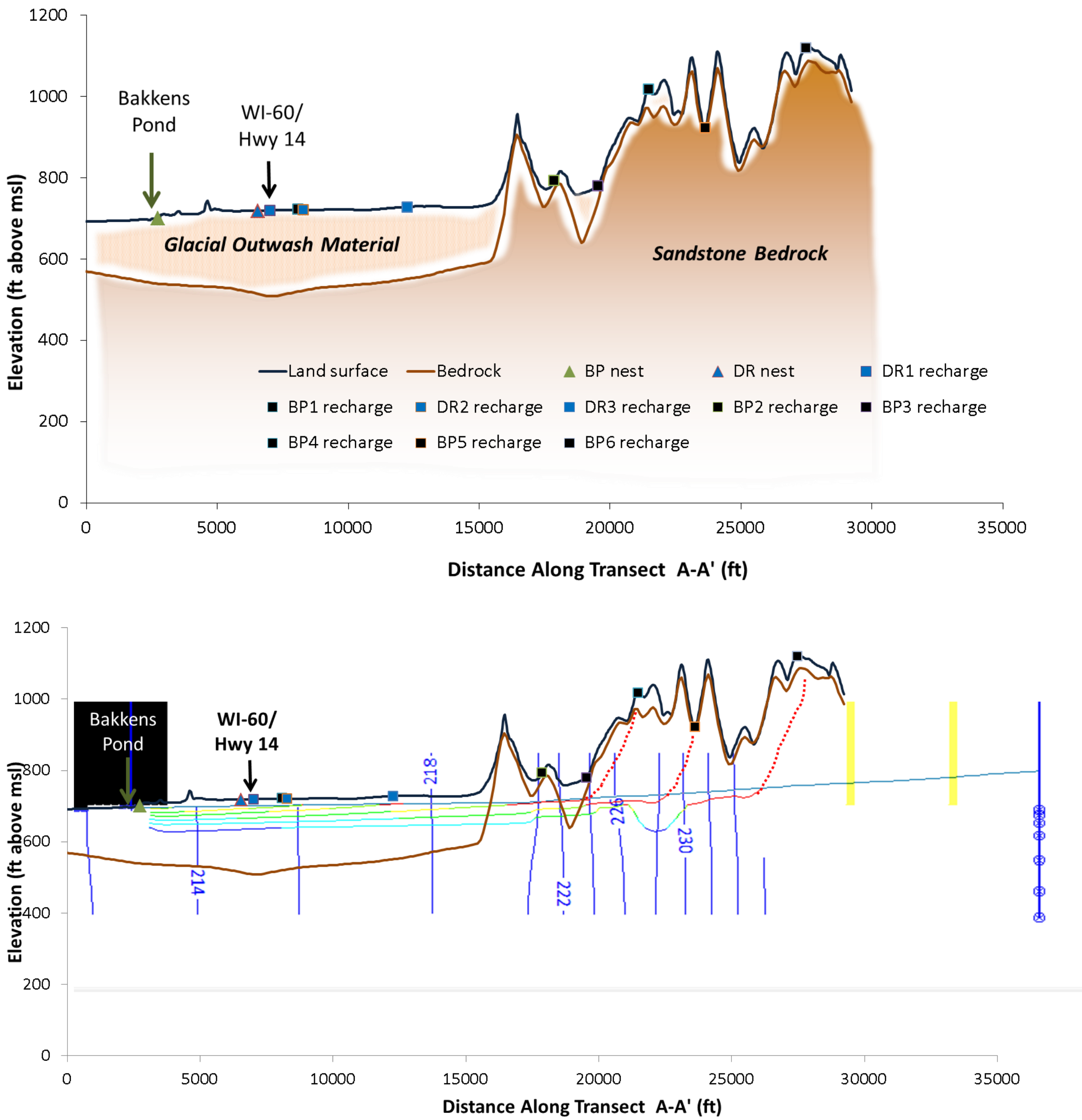


Porter Rd.

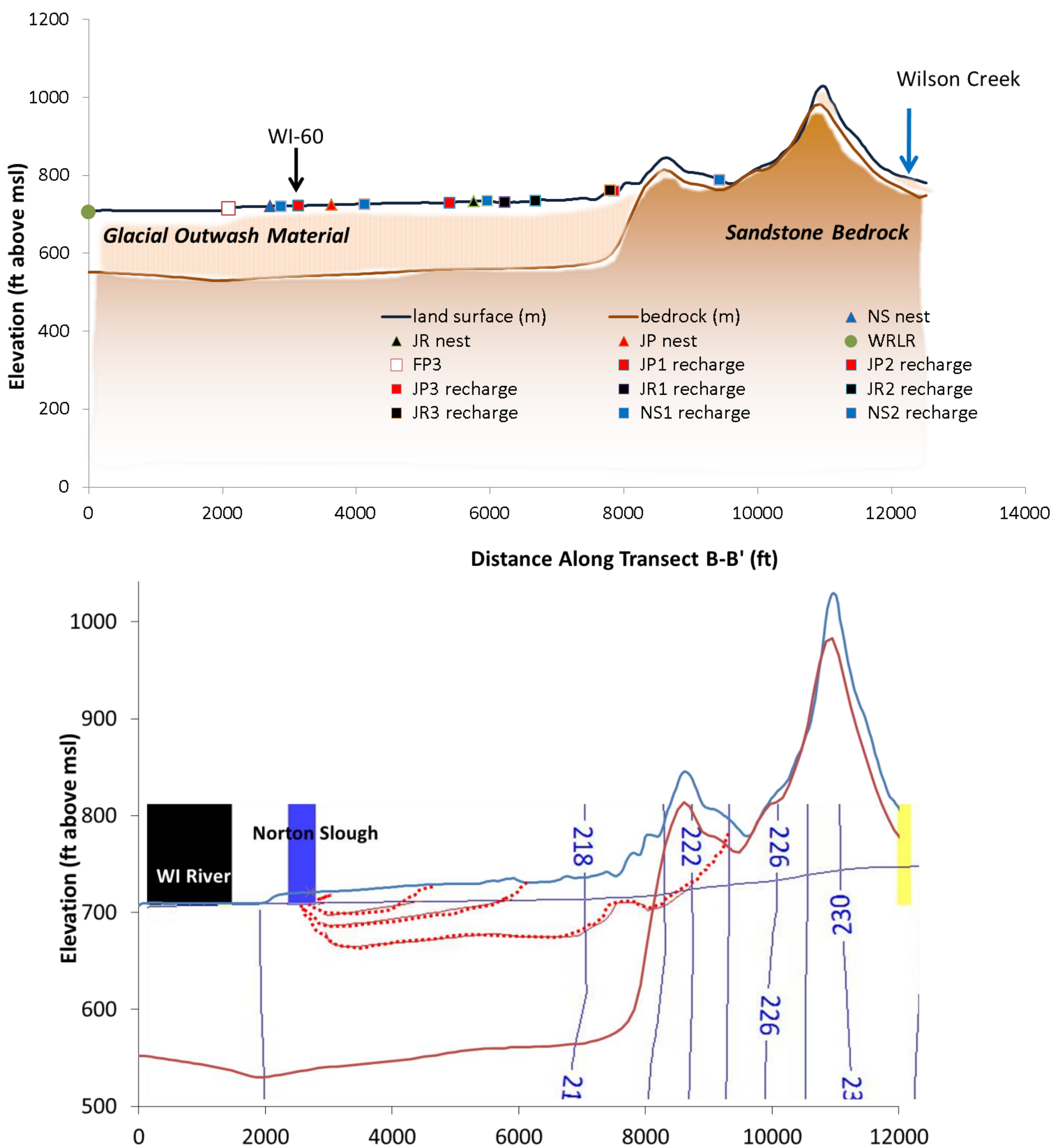
G. Cross Sections



Map of study area showing location of cross sections in profile below. Locations of individual wells and well nests are represented by solid grey circles. Transects are delineated with dotted red lines and labeled A-A’ and B-B’. Major roads are shown with a solid black line.



Cross sections A-A' including well nest sites BP and DR (triangles) and the model-predicted recharge sites for each of the wells (squares). The second panel displays a cross section from GWVistas of the MODPATH particle pathway results. The dotted redline represents the infiltration pathway through the unsaturated zone. The solid blue line is the land surface elevation and the solid orange line delineates the top of the bedrock.

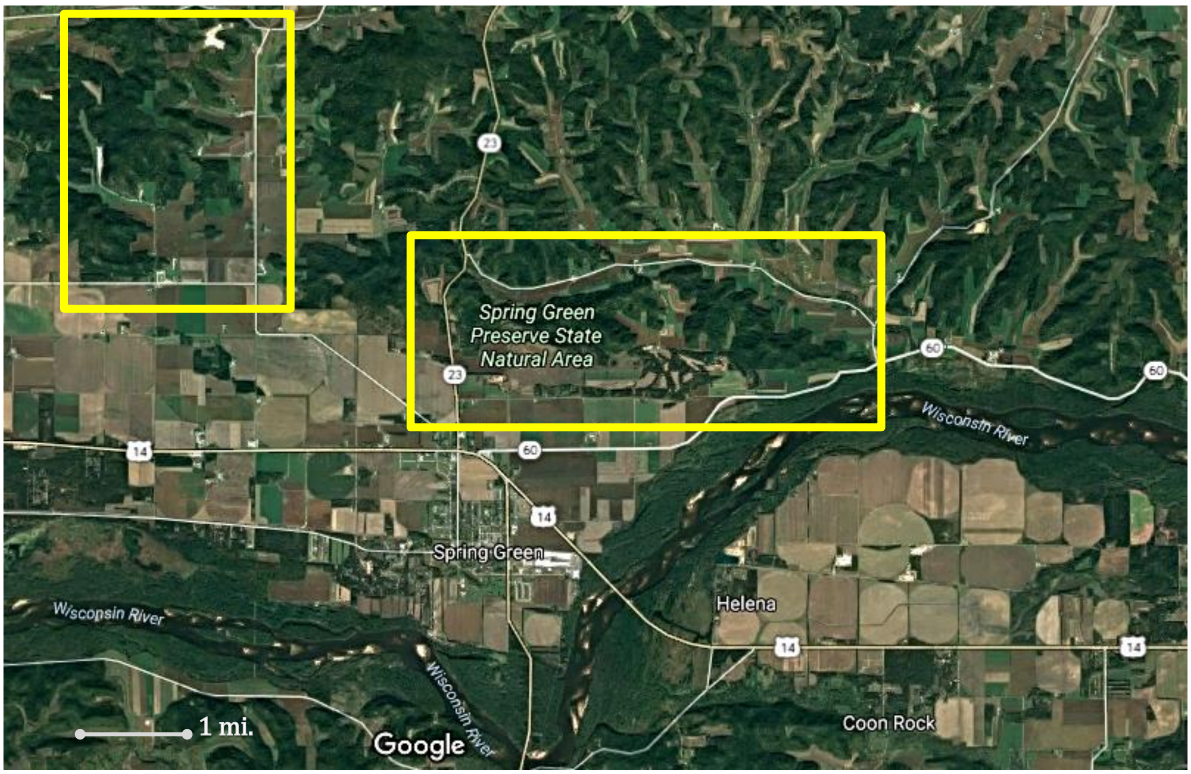


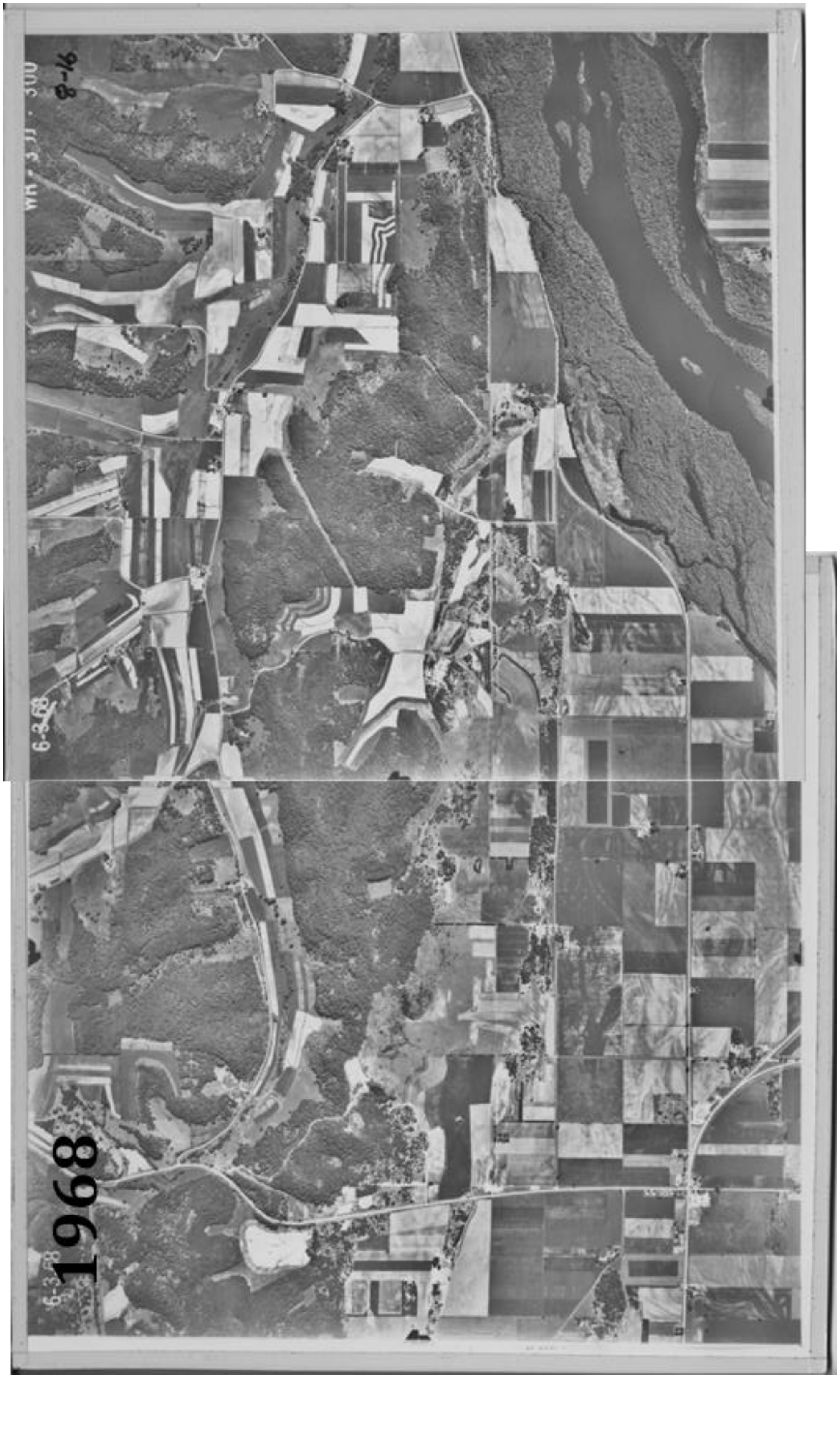
Cross section of B-B' including the location of well nest sites NS, JP, and JR (triangles) and the model-predicted recharge sites for each of the wells (squares). The location of the WRLR staff gage and floodplain wells (FP1-FP3) are also shown. The second panel displays a cross section from GWVistas of the MODPATH particle pathway results (dotted red lines). The solid blue line is the land surface elevation and the solid orange line delineates the top of the bedrock.

H. Study Area Maps and Aerial Photographs

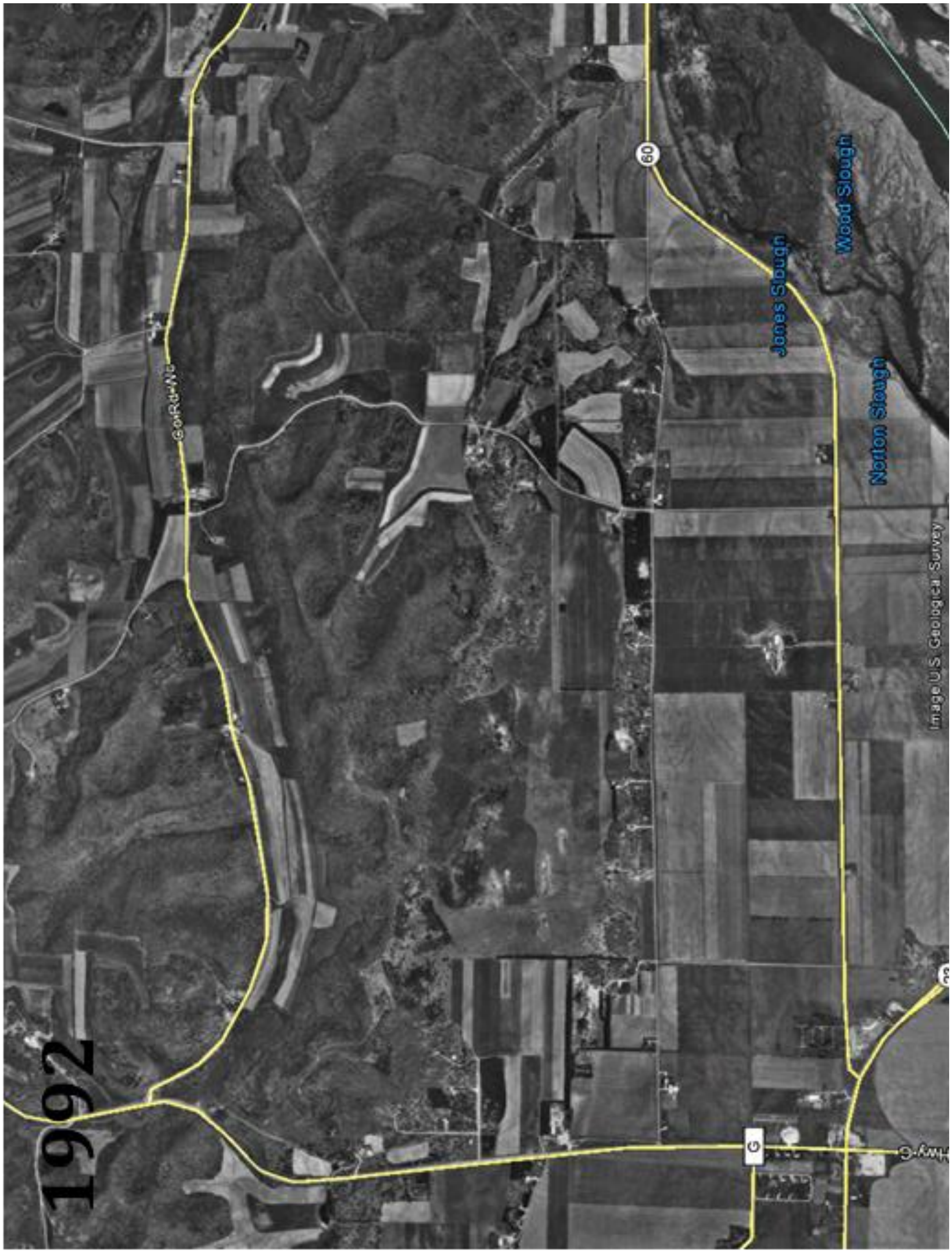
Aerial Photography of Recharge Sites (1968-2013)

Images provided by the CPZ showing changes in land use from 1968, 1978, 1992, 2005, and 2013 for the Norton Slough and Bakkens Pond well nests' recharge sites.



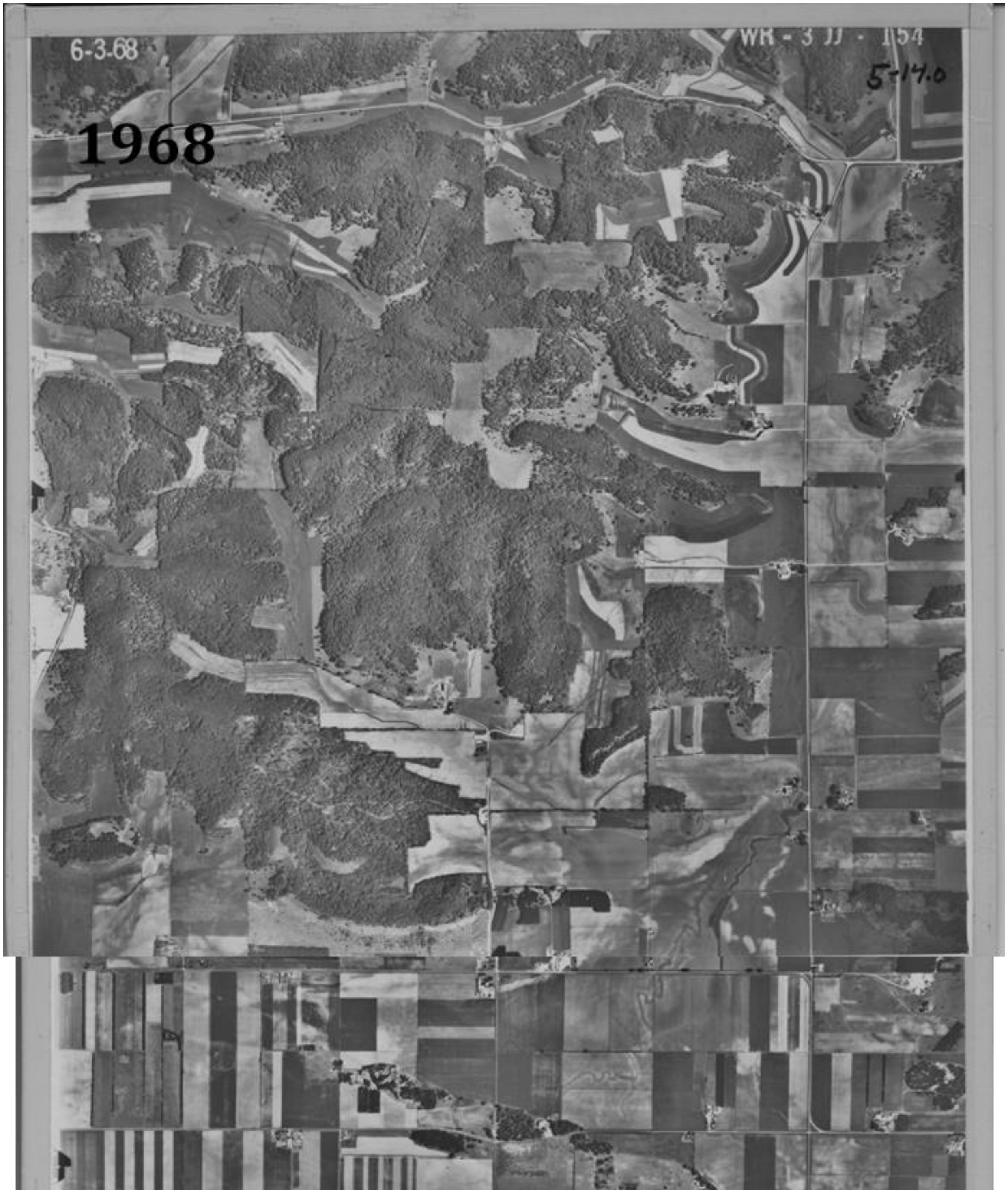

1968


1978


1992
Jones Slough
Wood Slough
Norton Slough
Image U.S. Geological Survey
60
G


2005
60
Jones Slough
Wood Slough
Norton Slough
Image USDA Farm Service Agency
G


2013
60
Jones Slough
Wood Slough
Norton Slough
G


6-3-68
WR - 3 JJ - 154
5-14.0
1968


55111-178
L
1978


1992
B
G
Image U.S. Geological Survey
Co Rd Jj
1145 m
Googl


2005
B
G
Co Rd Jj
Image USDA Farm Service Agency
1145 m
Google


2013
B
G
Co Rd Jj
1145 m
Google

Public Lands near Spring Green, WI.

Map generated by Wisconsin DNR Surface Water Viewer tool on 4/8/2017.