# DEVELOPING A GROUNDWATER FLOW MODEL FOR SLOUGH MANAGEMENT IN SAUK COUNTY, WI

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

(Geoscience)

At the

UNVERSITY OF WISCONSIN-MADISON

2017

## Abstract

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.

# Acknowledgements

Special thanks to my advisor, Dr. Jean Bahr, for her mentorship and keen eye for detail and Ken Wade for his field assistance and resourceful 'Macgyvering'. Thank you to my committee members, Eric Roden and Mike Cardiff, for their time and effort in reviewing my thesis. This research could not have been possible without all the people behind the field work - Dave Marshall, Timm Zumm & boat, Doug and Sheryl Jones, Ben Heinle, the 2015 Hydrogeology Field Course, and many more. Mike Cardiff and Jim Rumbaugh were indispensable resources in my battles with MODFLOW and GW Vistas and their help was greatly appreciated. Thank you to the hydro group for keeping me sane and willingness to listen to me vent about computers and models in general. The "Stitch n' Bitch" group, Sarah Bremmer, Lesley Parker, and Stephanie Napieralski, suffered through multiple practice presentations and provided valuable feedback on figures (remember a scale!).

Finally, I would like to thank my parents, Paula Schmietendorf and Roy Schlaudt, for their continuous support and belief in my potential. My mother is the best editor I know, and she continues to be my greatest source of inspiration. This thesis is dedicated to them.

*Generous support for this research was provided by:*

The Geological Society of America Research Grant

Wisconsin's Department of Natural Resources River Planning Grant for Lower WI River Floodplain Lake Recharge Delineation

Sauk County Conservation Planning and Zoning Department

UW-Madison Department of Geoscience Weeks Research Assistantship

Minnesota Groundwater Association Scholarship Foundation

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# 1. Introduction

## 1.1 Motivation

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 the permeable nature of its characteristic sandy soils. 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.


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

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 (Figure 3). 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 insufficient to explain the density of free floating plant cover and anoxia in the sloughs.  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 conservation buffers (>1,000 ft. wide, depending on the slough) were proposed to increase biotic uptake of nutrients and clean recharge.

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.

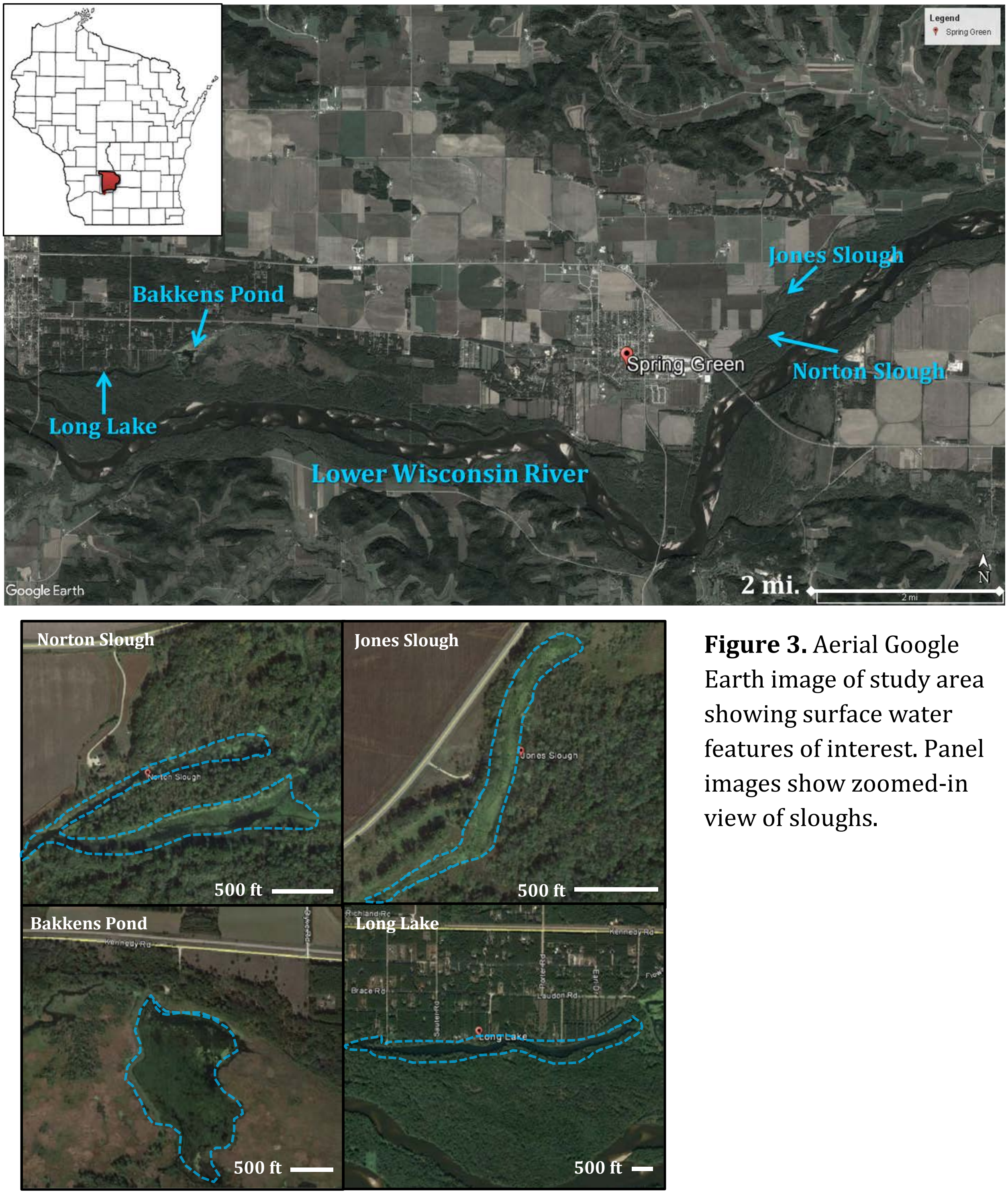



**Figure 3.** Aerial Google Earth image of study area showing surface water features of interest. Panel images show zoomed-in view of sloughs.

### 1.3 Objectives

This thesis includes the results of a project entitled "Lower WI River Floodplain Lake Recharge Delineation" that was commissioned by Sauk County's Conservation Planning and 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 Thesis 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 sloughs provide habitat for rare fish species including those ranked as "State Special Concern", such as the mud darter (*Etheostoma asprigene*), pirate perch (*Aphredoderus sayanus*), and 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

Land-use 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 4). 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).

Unfortunately, definitive records of fertilizer application practices in Sauk County are not available. Surveys of agricultural chemicals in Wisconsin's private drinking water wells conducted in 1994, 2001, and 2007 indicated no statistically significant change in the proportion of wells containing nitrate-N during this time period (VandenBrook et al., 2002; Brandt et al., 2008). In 2007, an estimated 56% of wells in Wisconsin contained nitrate-N and 9% contained concentrations exceeding the US EPA drinking water standard of 10 mg/L (Brandt et al., 2008). It should be noted that these studies were limited by the number of sampled wells; 336 water samples were part of the 2001 survey and 398 were part of the 2007 survey. According to the Center for Watershed Science and Education at the University of Wisconsin- Stevens Point, nearly 900,000 household rely on private wells as their primary water supply ("WI Well Water Viewer," 2017). Figure 5 shows average concentrations by township of nitrate-N as voluntarily reported by private well owners.

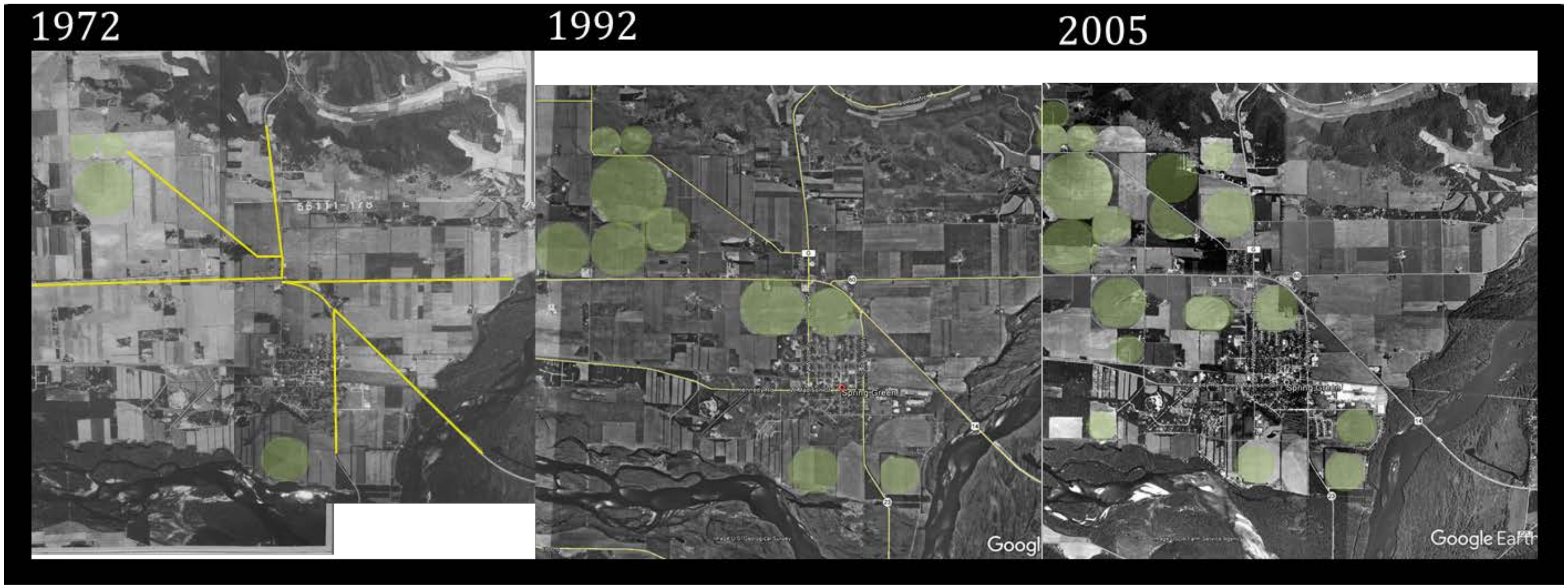



**Figure 4**. Aerial photographs showing increase in pivot irrigation (green circles) between 1972 to 2005 near Spring Green, WI.

**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 |

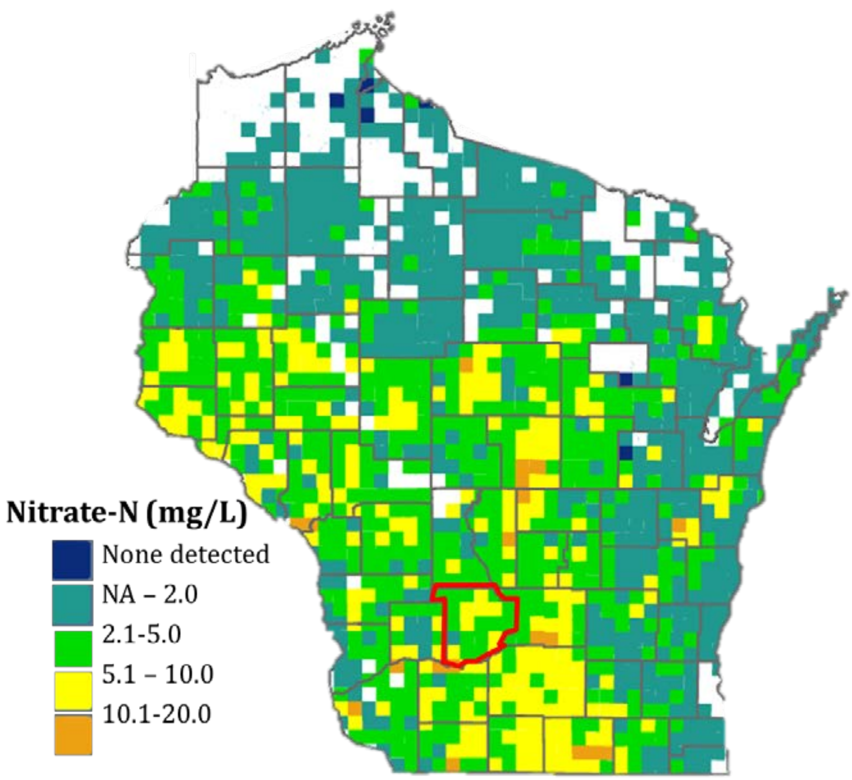



**Figure 5.** Average nitrate concentrations by township. Created using the University of Wisconsin-Stevens Point Well Water Quality Viewer (2017).

## 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 6).

### 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 6). 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.

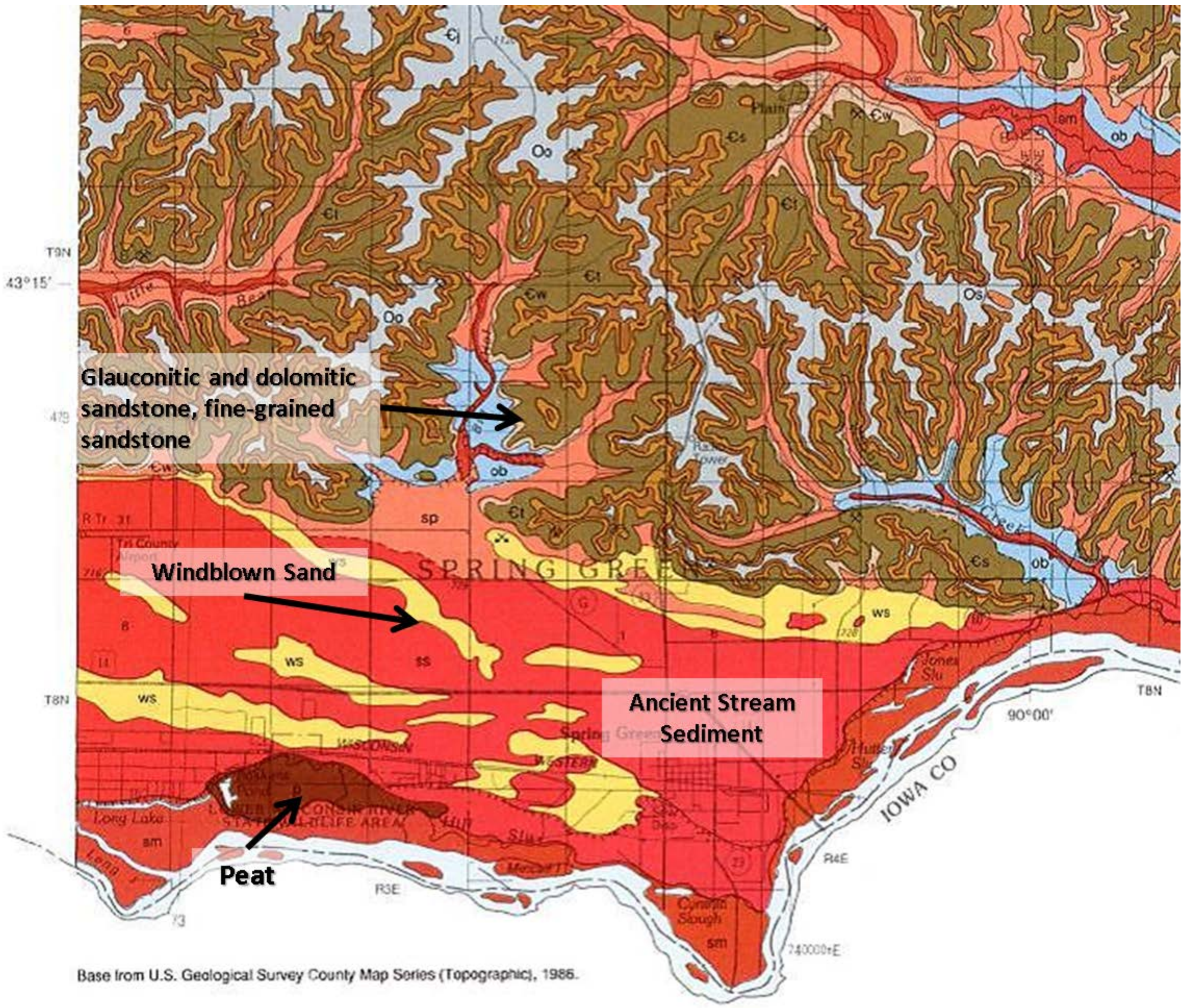



**Figure 6.** Select portion of a map of Sauk County geology published by the Wisconsin Geological and Natural History Survey. A small portion of the study area, including Lone Rock to the west, is not shown.

## 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 7). The glacial outwash material here varies from sand and gravel to silty and clayey sediment (Gotkowitz et al., 2005). The sandstone aquifer consists of 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.

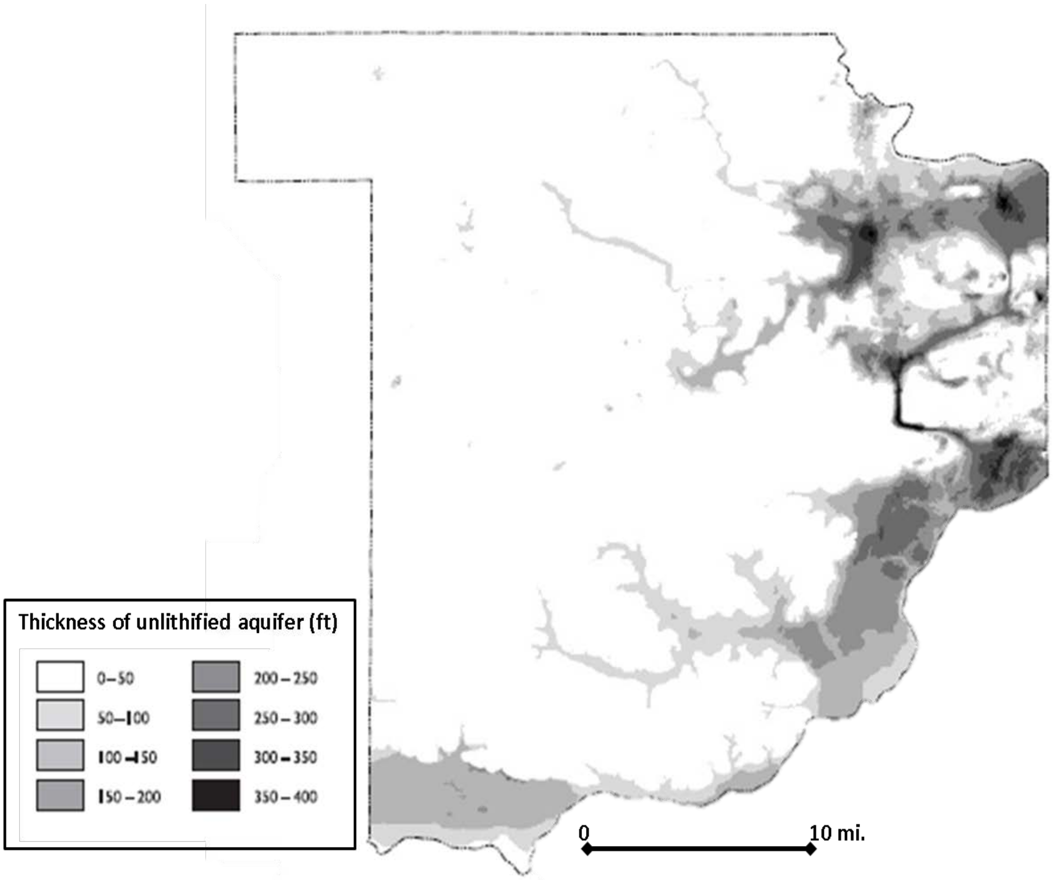



**Figure 7.** Extent and thickness of unlithified aquifer in Sauk County. Figure from Gotkowitz et al. (2015)

**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. 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)

# 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 8). 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 9). 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).

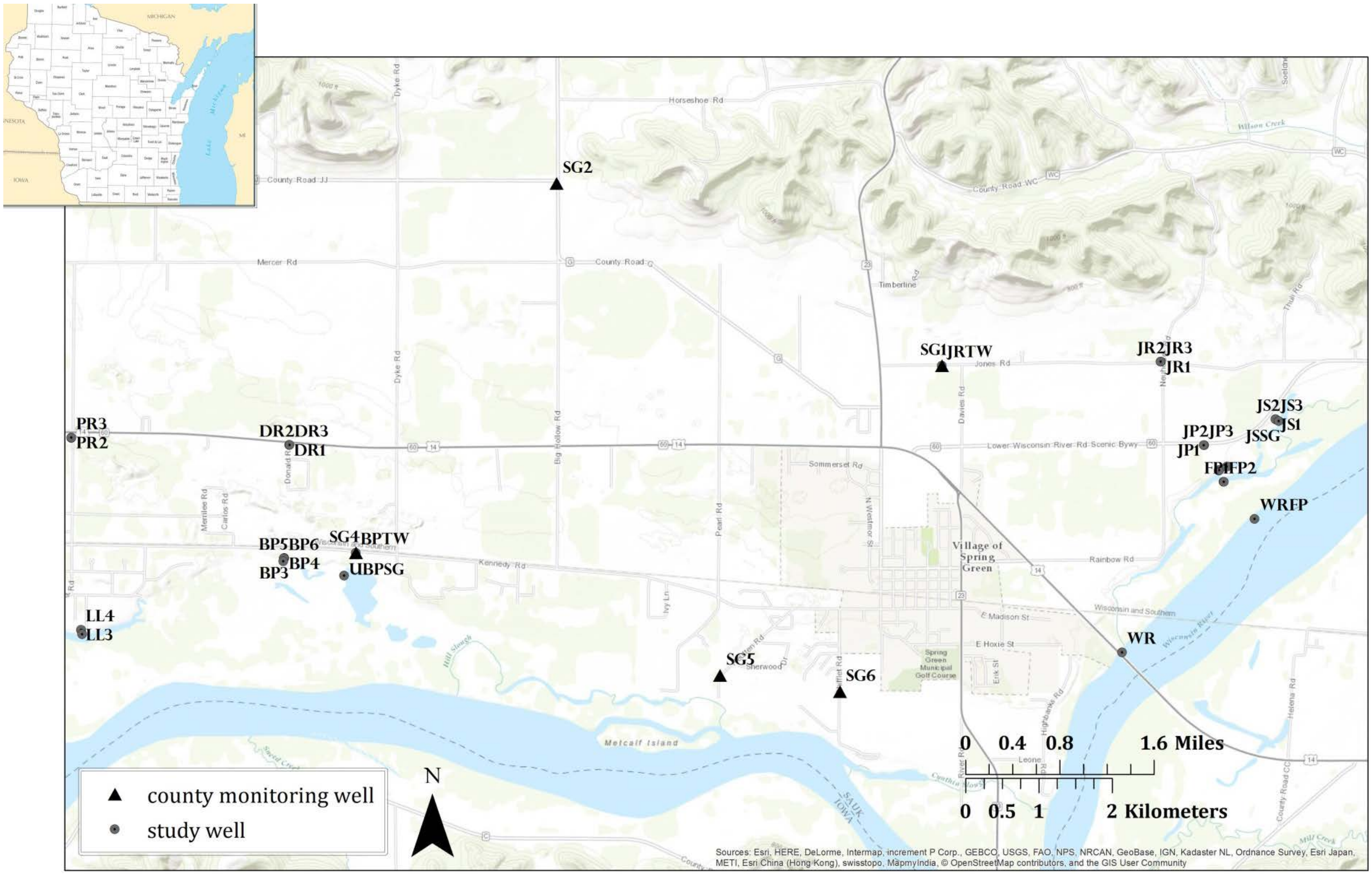



**Figure 8** Location of monitored well sites. Both well nests and singular wells are represented by a red dot. See well construction log in Appendix A for well IDs key.

**Figure 9.** 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 tape. 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 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 10). 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.

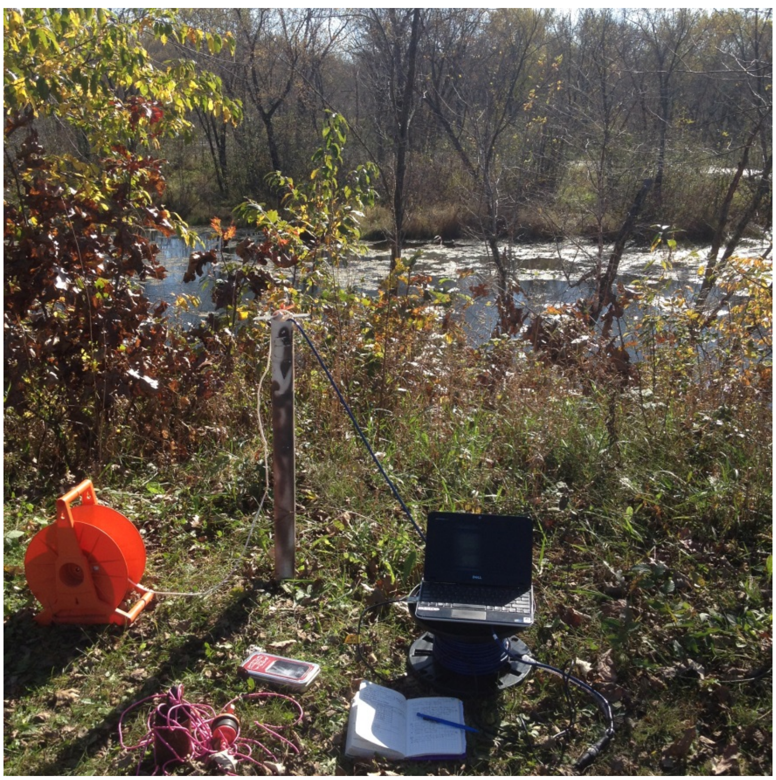


**Figure 10.** Performing slug test at Norton Slough well nest site.

**Table 3.** Average hydraulic conductivity by well

| Well ID | K (m/s) | ft/day | Screen Elevation (Ft above msl) |
|---|---|---|---|
| **BP2** | 9.14E-04 | 259 | 680 |
| **BP3** | 5.79E-04 | 164 | 668 |
| **BP4** | 4.88E-04 | 138 | 655 |
| **DR2** | 6.25E-04 | 177 | 688 |
| **DR3** | 2.08E-03 | 591 | 676 |
| **JR2** | 5.48E-04 | 156 | 698 |
| **JR3** | 1.68E-03 | 477 | 686 |
| **NS2** | 1.75E-03 | 496 | 695 |
| **NS3** | 8.91E-04 | 253 | 682 |
| **NS4** | 6.90E-04 | 196 | 670 |

## 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 (Appendix E. Dissolved Oxygen. 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 ($\delta D$) 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 $\delta D$ 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 11). 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 12). The magnitude of seasonal fluctuations in nitrate varied by well nest, but fall tended to be the season with highest concentrations.

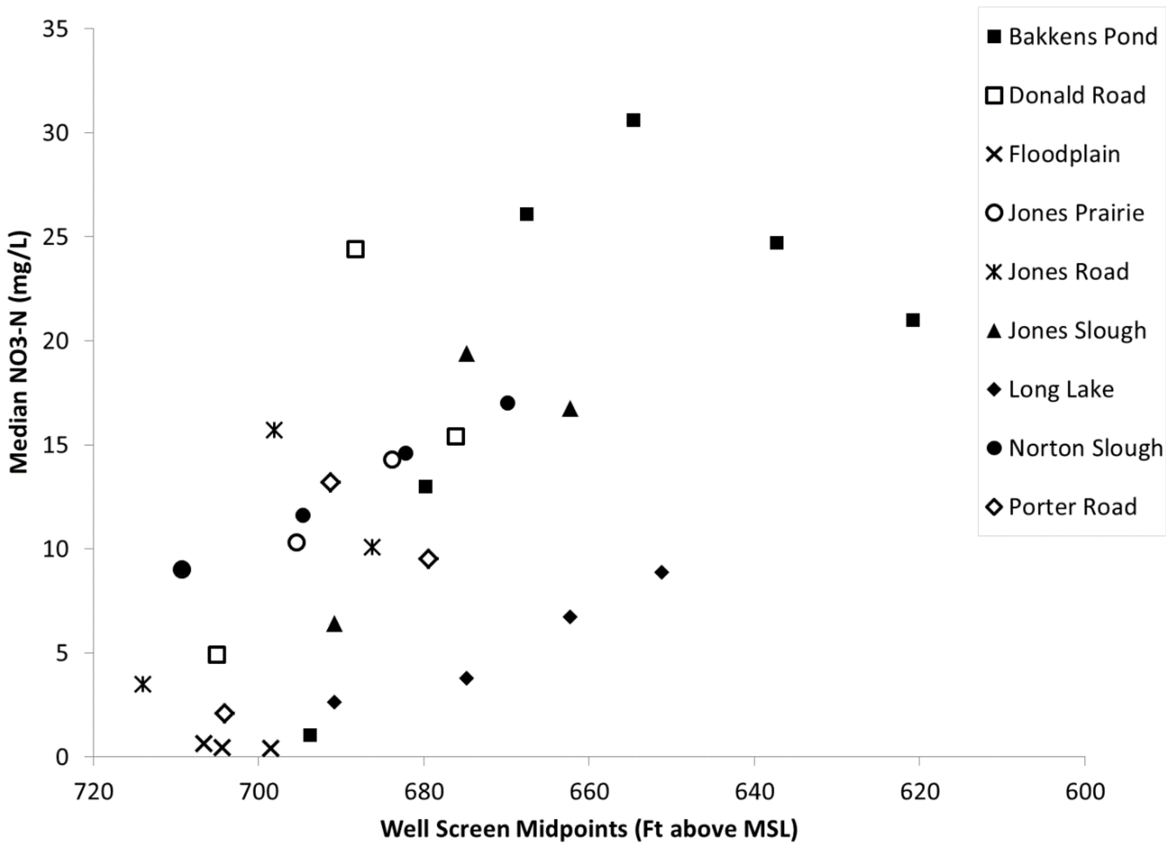



**Figure 11.** Median nitrate concentrations where each point represents a single well. Plotted in terms of screen midpoint elevation (feet above mean sea level). Symbols correspond to well nest location.

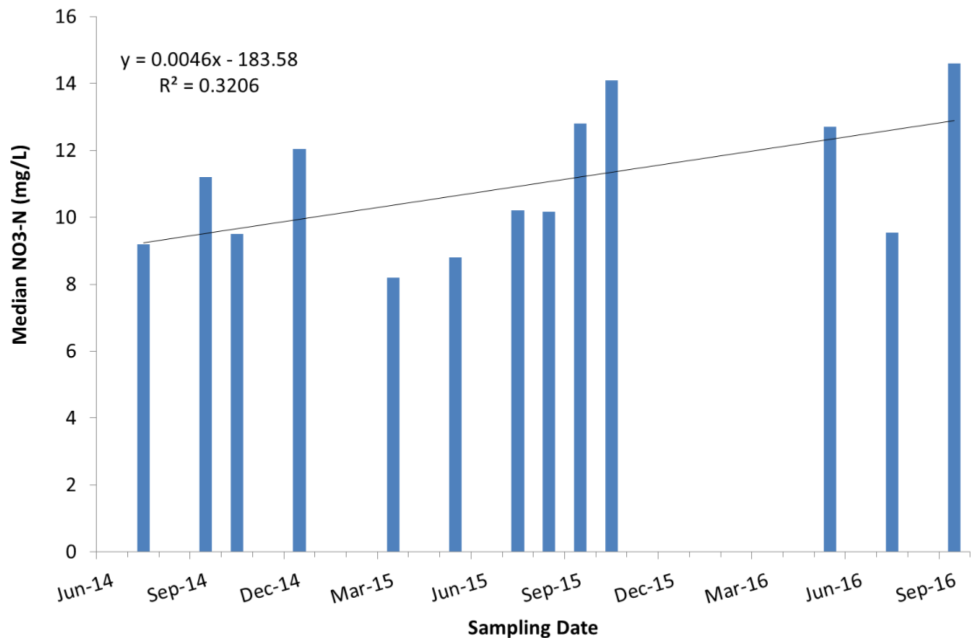



**Figure 12**. Median nitrate concentrations over time where each point represents the median concentration of all monitored wells for that sampling round.

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 13). 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 10$^{th}$, 2014. DR2, JS2, and NS4 also had notably high median concentrations at 24.4, 19.4, 17.0 mg/L respectively.

Nitrate concentrations for all monitored wells and sampling rounds can be found in Appendix F.

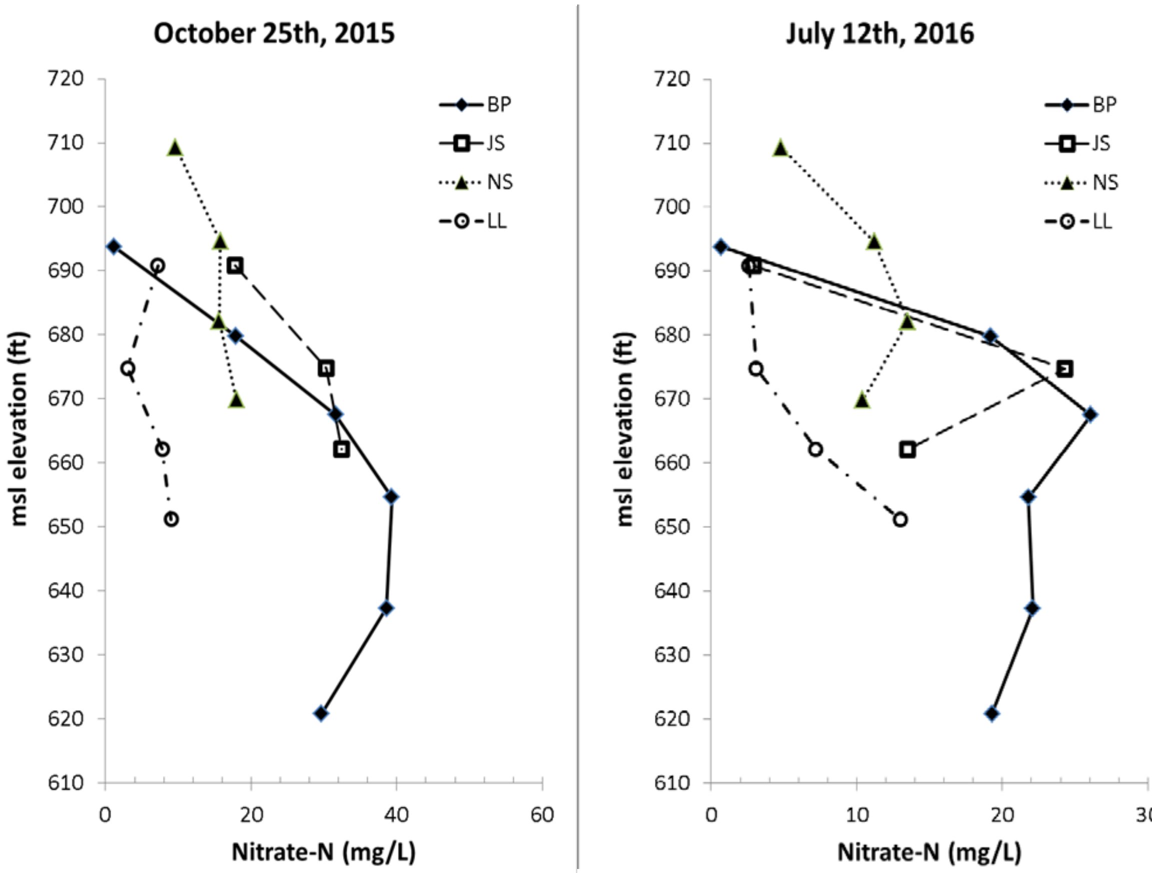



**Figure 13**. Nitrate concentrations versus depth for well nests BP, JS, NS, and LL. Each point represents a well within the respective well nest. Water table elevations (ft. above msl) for Bakkens Pond, Jones Slough, Long Lake, and Norton Slough were 695.2, 709.9, 691.3, 709.1 on October 25$^{th}$ and 695.4, 710.5, 691.0, 709.8 on July 12$^{th}$, respectively.

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 14). 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.

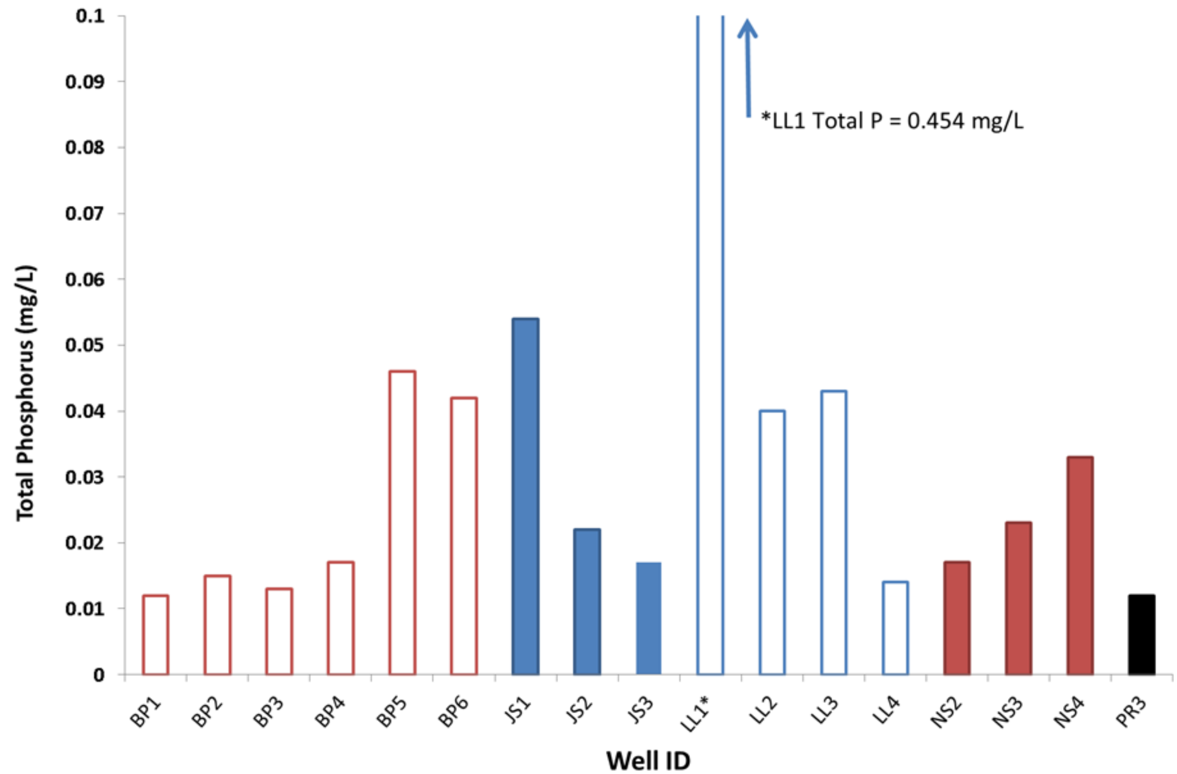



**Figure 14.** Phosphorus concentrations measured in well water on September 20th, 2015

## 4.2 Isotopes

Stable isotope analyses of water, $\delta^{18}O$ and $\delta D$, 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 $\delta D$ 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 15). 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 15). 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 significant changes in isotopic signatures for the water table wells from the May 24$^{th}$ to June 12$^{th}$ samplings match expectations for “young” groundwater directly connected with the land surface. 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. The deepest wells within their respective well nests also had “mixed-source” signatures indicating, in this case, that the groundwater flowpaths through these wells are not directly connected to the surface (e.g. through fracture flow) and that the flowpaths are old enough to have received contributions from water over a range of seasons.

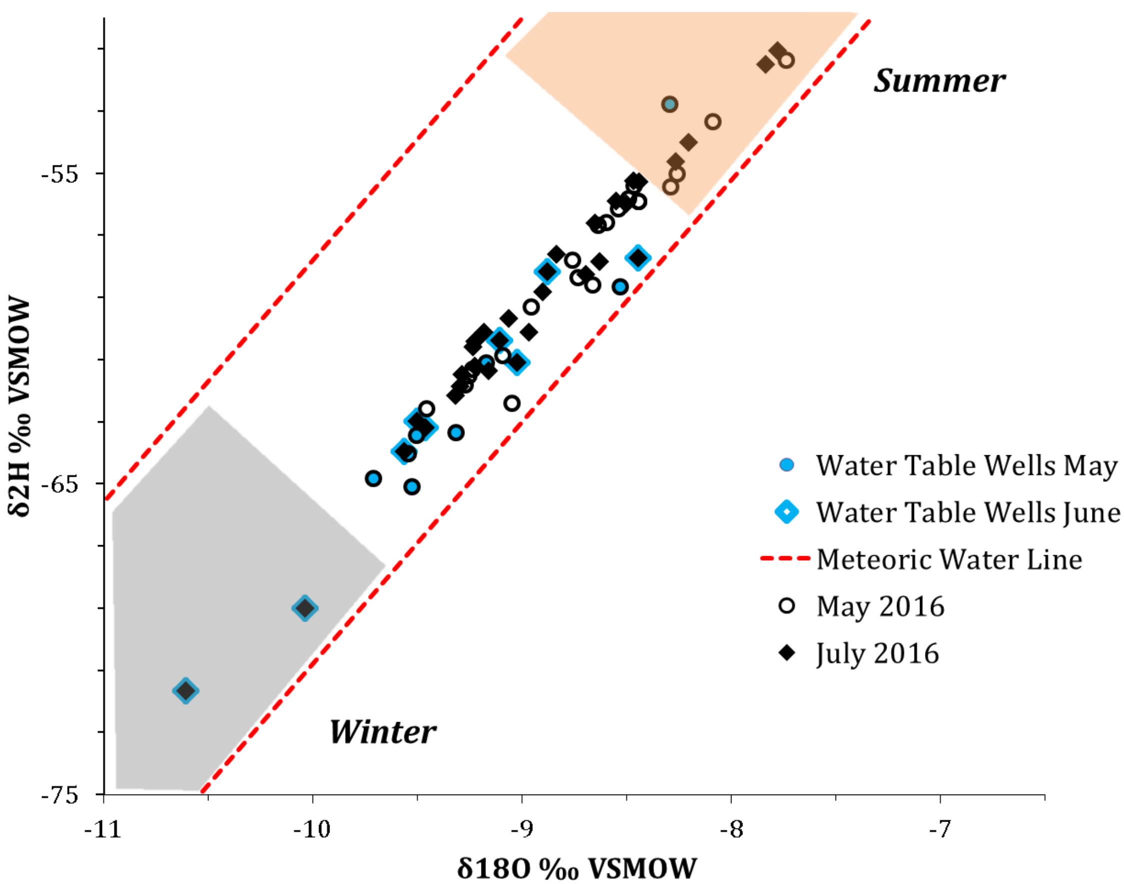



**Figure 15.** Plot of LMWL (zone between dashed red lines) and well isotopic signatures. The colored boxes represent the generalized precipitation/ recharge sources based on the isotopic signature. Water table well points are highlighted blue.

### 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 16). 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.

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.

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.

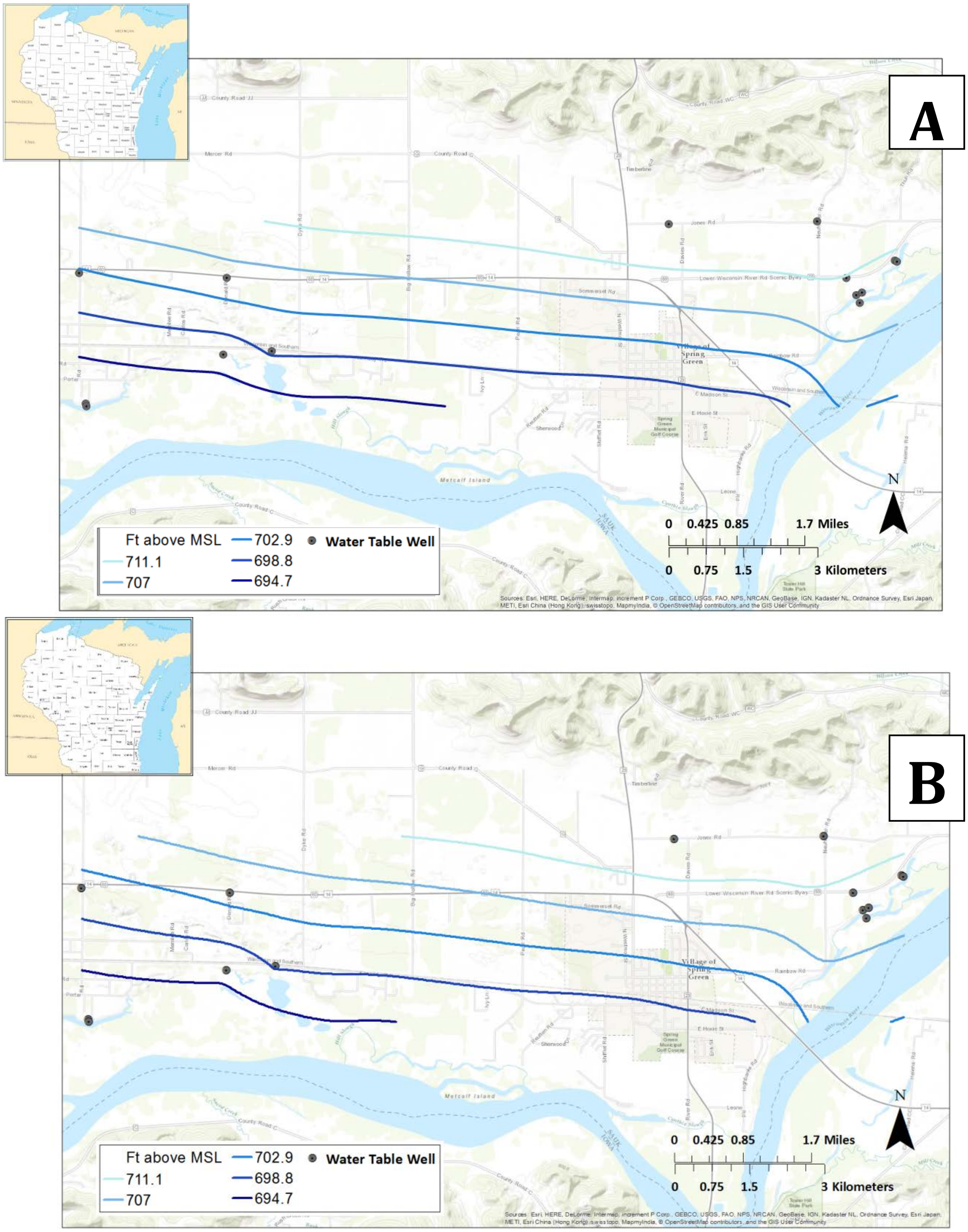



**Figure 16.** Water table maps based on manual depth to water readings and pressure transducer records. Figure 15A depicts the baseflow conditions on which the flow model was based, while Figure 15B is the water table based on manual measurements taken on July 12th, 2016.

# 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 17). 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 (located between the bluff peaks in the Figure 17 cross section) 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 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 (Figure 18). 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.

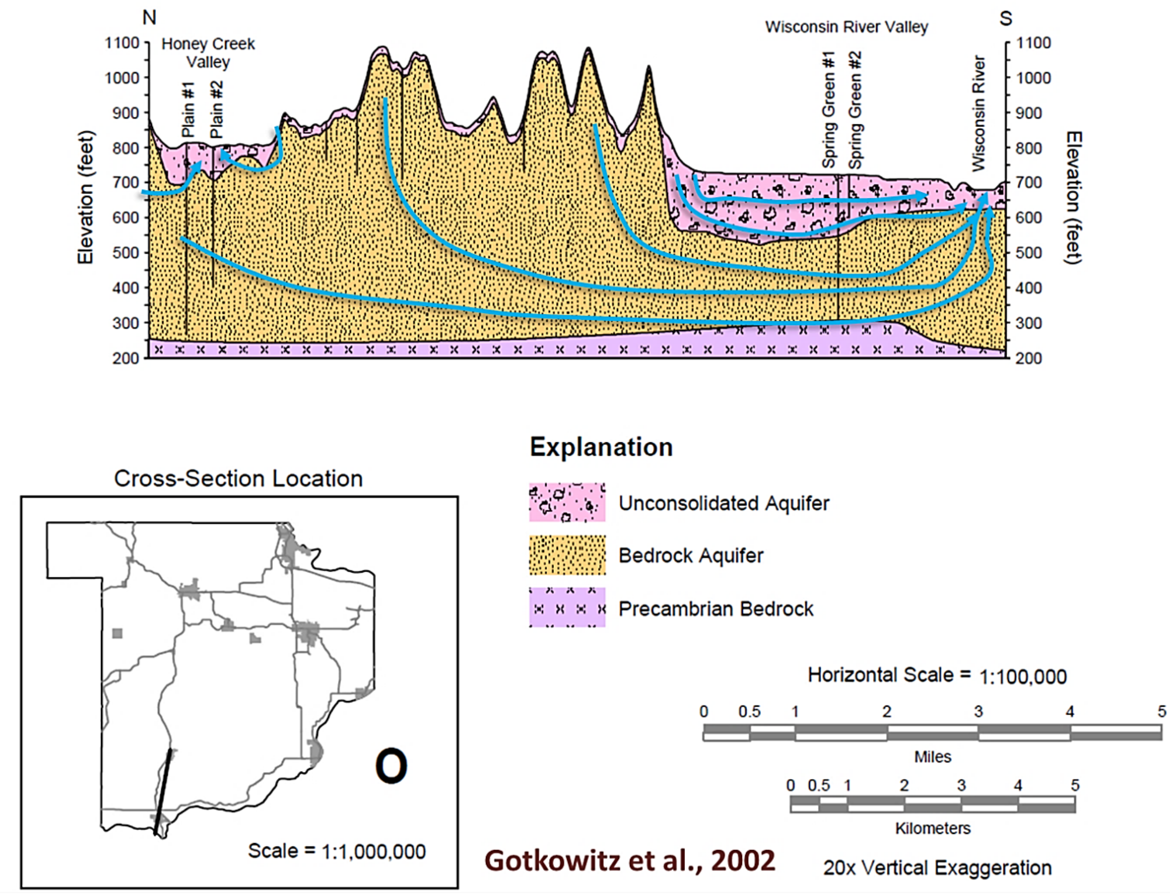



**Figure 17.** Conceptual model showing hypothesized groundwater flowpaths originating with the bluffs and the LWR valley. Figure adapted from Gotkowitz et al. (2002).

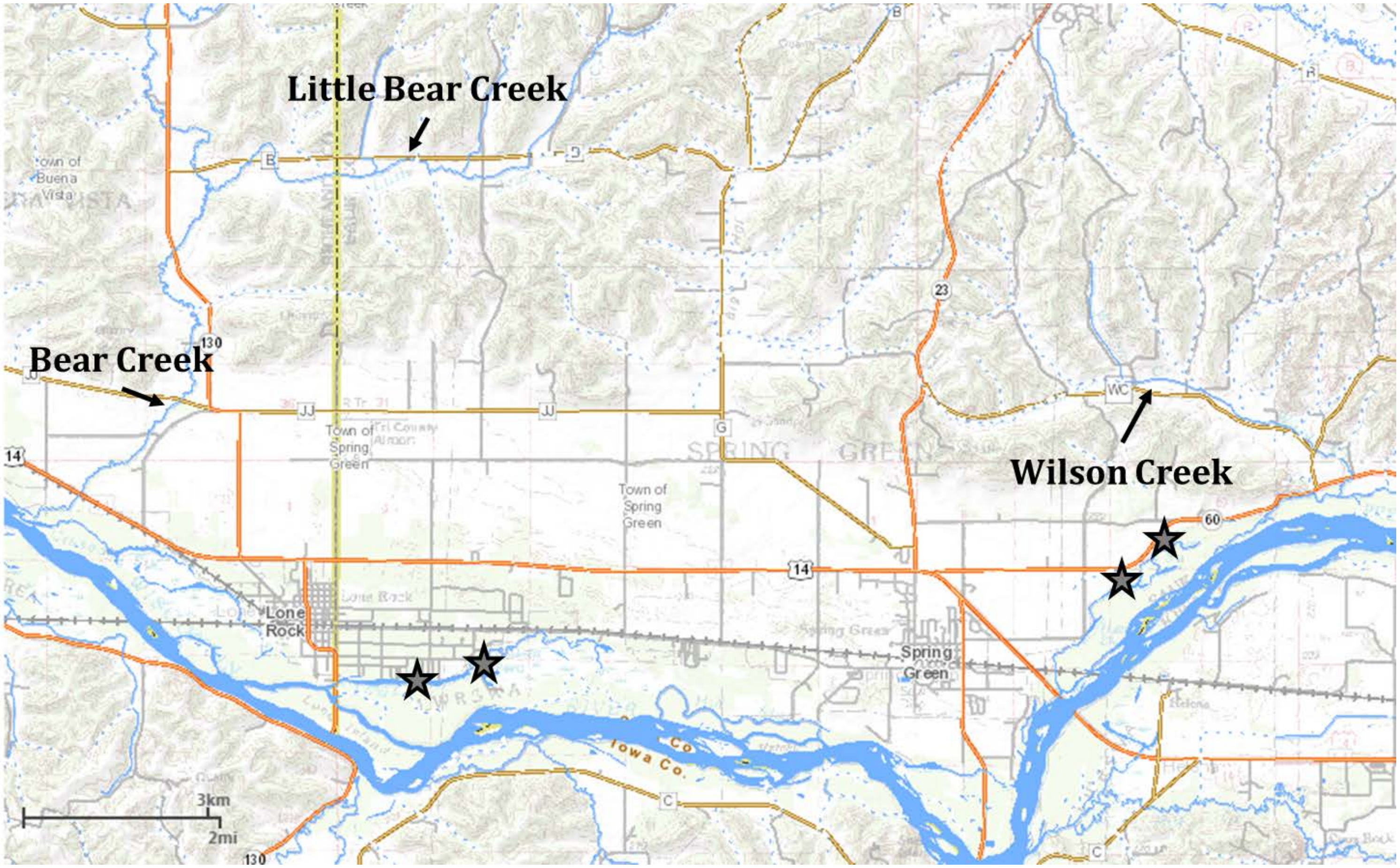



**Figure 18.** Map showing location of modeled surface water features. Sloughs are represented with a grey star. Map was generated using the WDNR surface water viewer tool.

## 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 | 709 |
| **2** | 212 | 696 |
| **3** | 208 | 682 |
| **4** | 200 | 656 |
| **5** | 189 | 620 |
| **6** | 170 | 558 |
| **7** | 130 | 427 |
| **8** | 95 | 312 |
| **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. These locations 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 (location and type 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).

Water elevations for the multi-node well boundary conditions were extracted from the results of the Sauk County GLFOW model. Water elevations for the upland stream CHBs and drains were based on a combination of the Spring Green USGS topographic map and the WGNHS Sauk County water-table map (Gotkowitz and Zeiler, 2003; US Geological Survey, 2016). Elevations for the section of the Lower Wisconsin River present in the model were linearly interpolated based on the two staff gages near the

Highway 14 Bridge and Lone Rock, WI. 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 river staff gages.

### 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. Six 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, the weathered sandstone bluffs, and the dolomite-capped bluffs (Table 5, Figure 19). These values were based on the modeling results of Gotkowitz et al. (2005) and the results of model calibration using PEST (discussed further in section 5.6). 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). Field experiments and numerical modeling of the upper Coon Creek Watershed (also located in the Driftless region of southwest Wisconsin) showed hillslope recharge to be about 2.3 times higher than ridge-top recharge rates (Juckem, 2003). Porosity and specific yield values used for the MODPATH particle tracking were based on ranges for sediments and sedimentary rocks in Fetter's *Applied Hydrogeology* (2000). The two zones were split between the sandstone bedrock and the floodplain and assigned specific yields/ porosities of 0.1/ 0.1 and 0.25/ 0.2 respectively.

**Table 5.** UW 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

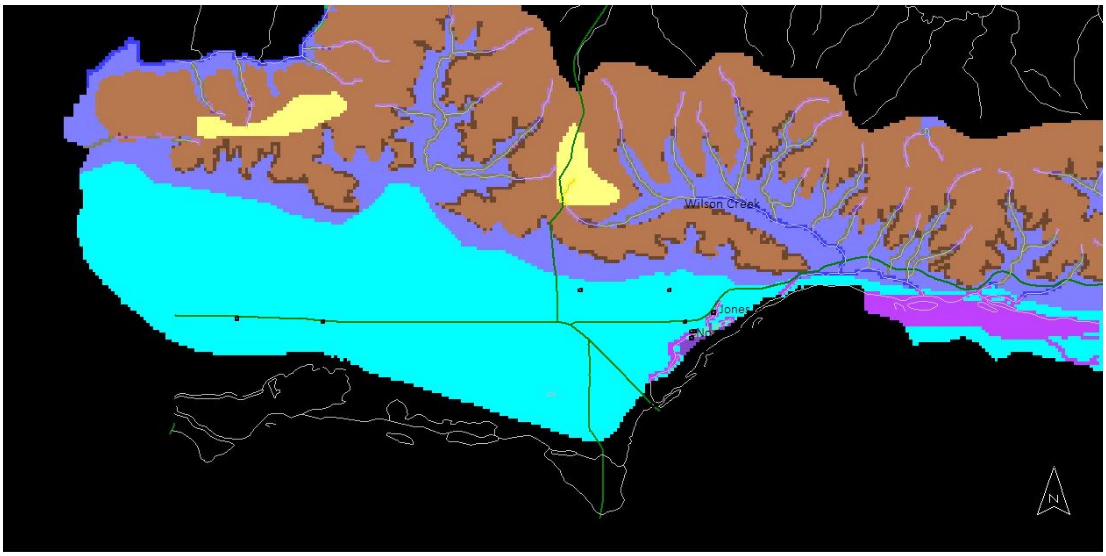
| Zone | Recharge Rate (m/day) | (ft./day) |
|---|---|---|
| 1 - sandstone & dolomite bluffs | 8.90E-04 | 2.92E-03 |
| 2 - floodplain | 5.90E-04 | 1.94E-03 |

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

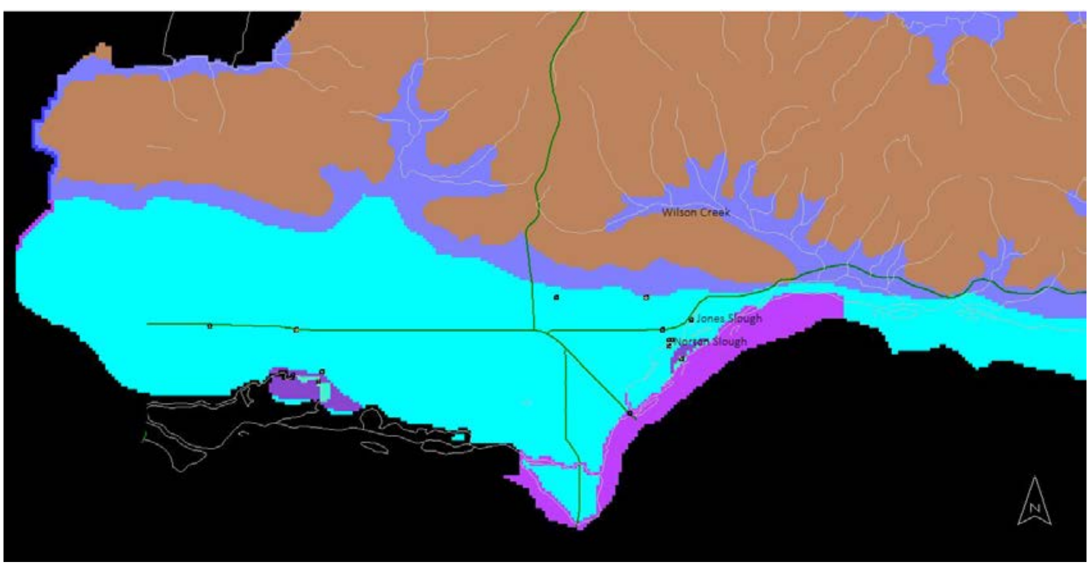
| | Kx | Ky | Kz | | Color |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0.1 | 0 | |
| 2 | 25 | 25 | 2.5 | 0 | |
| 3 | 90 | 90 | 9 | 0 | |
| 4 | 45 | 45 | 4.5 | 0 | |
| 5 | 0.25 | 0.25 | 0.0025 | 0 | |
| 6 | 5 | 5 | 0.5 | 0 | |

**Figure 19.** 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.

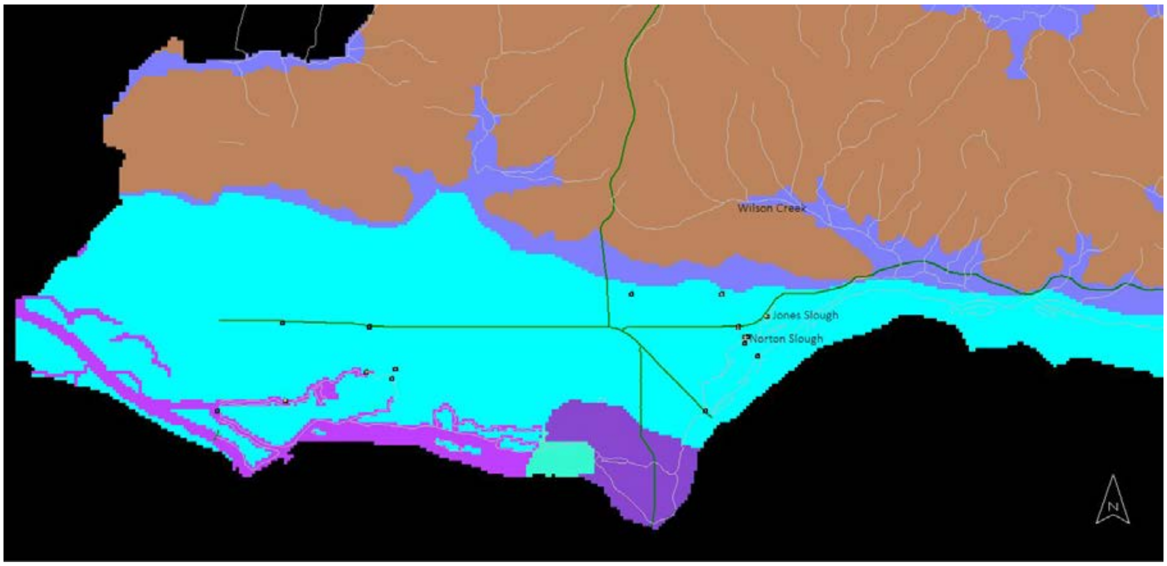
**Layer 1**



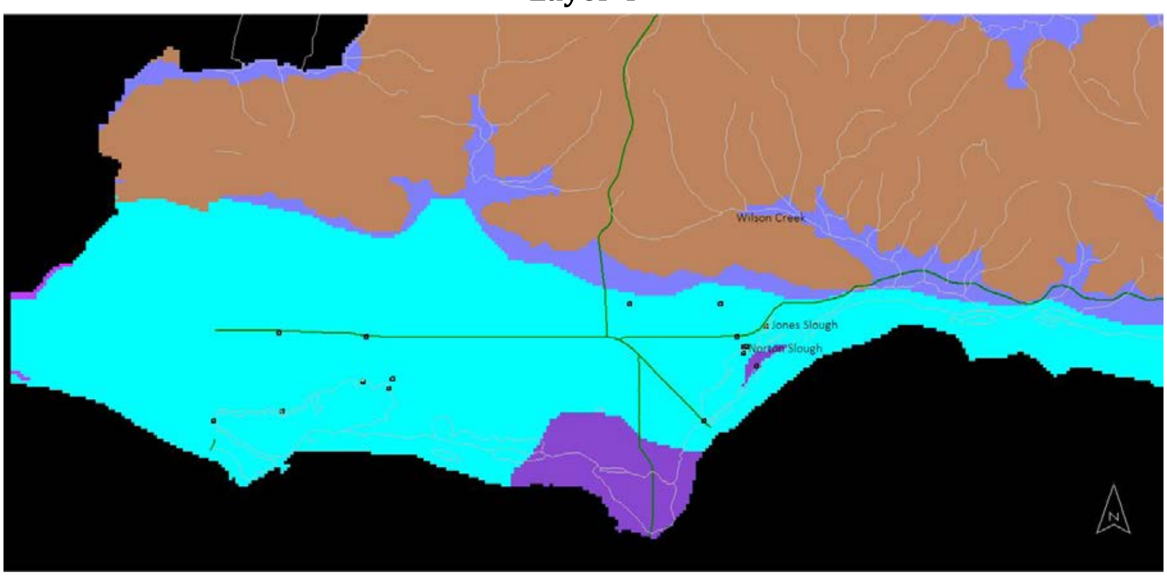

**Layer 2**



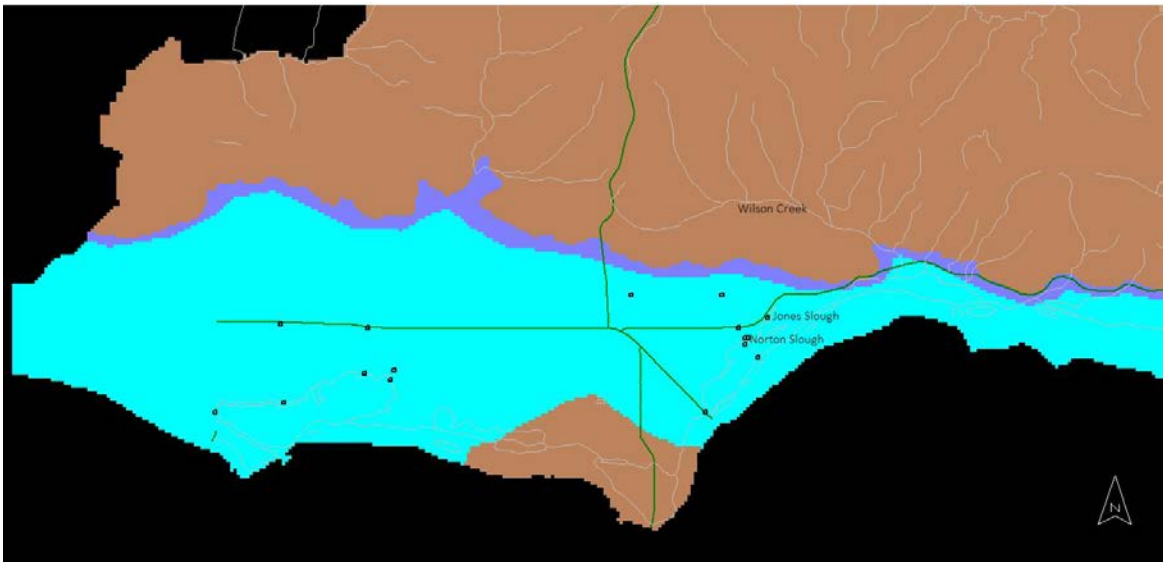
**Layer 3**



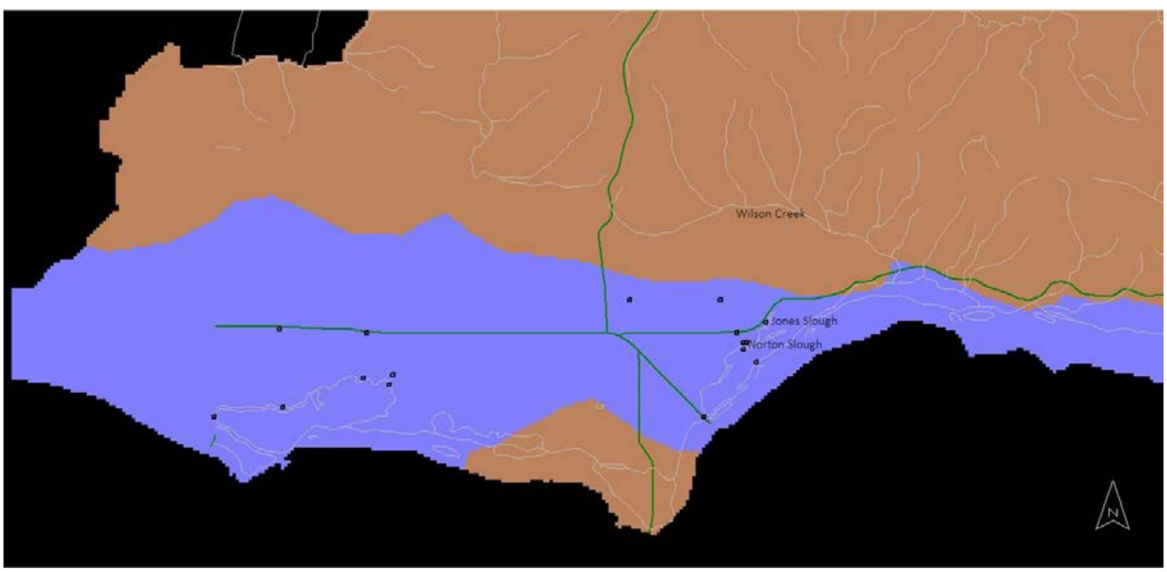

**Layer 4**



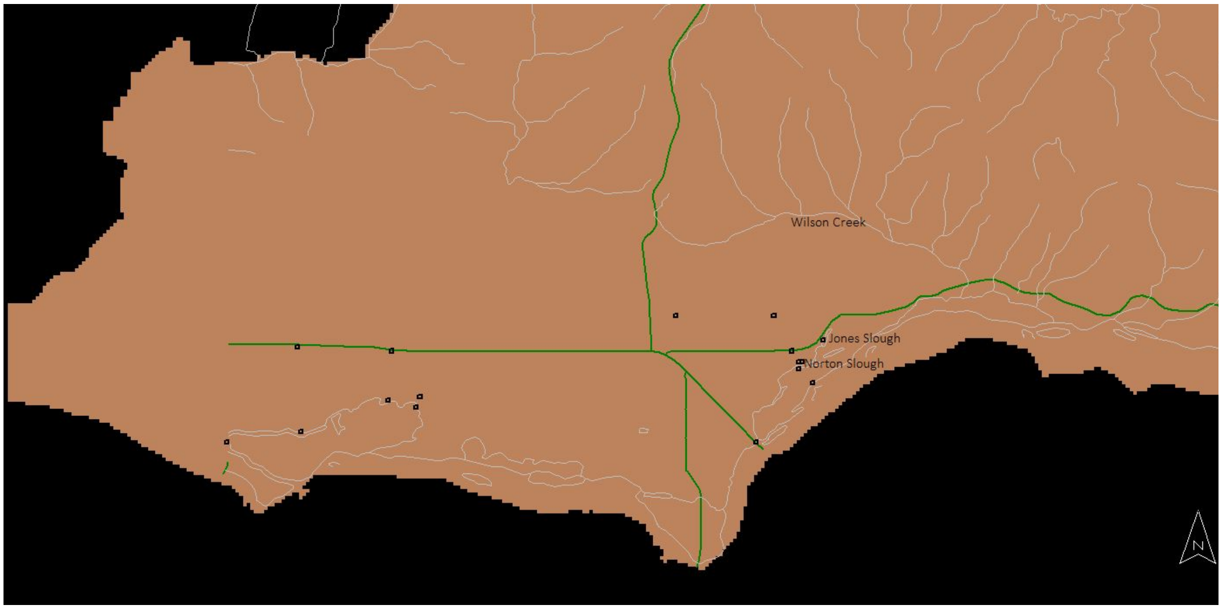
**Layer 5**




**Layer 6**



**Layers 7-9**




### 5.5 Refinement Process

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. Instead of using constant heads, 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. A visual explanation of this process can be seen in Figure 20. 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 21).

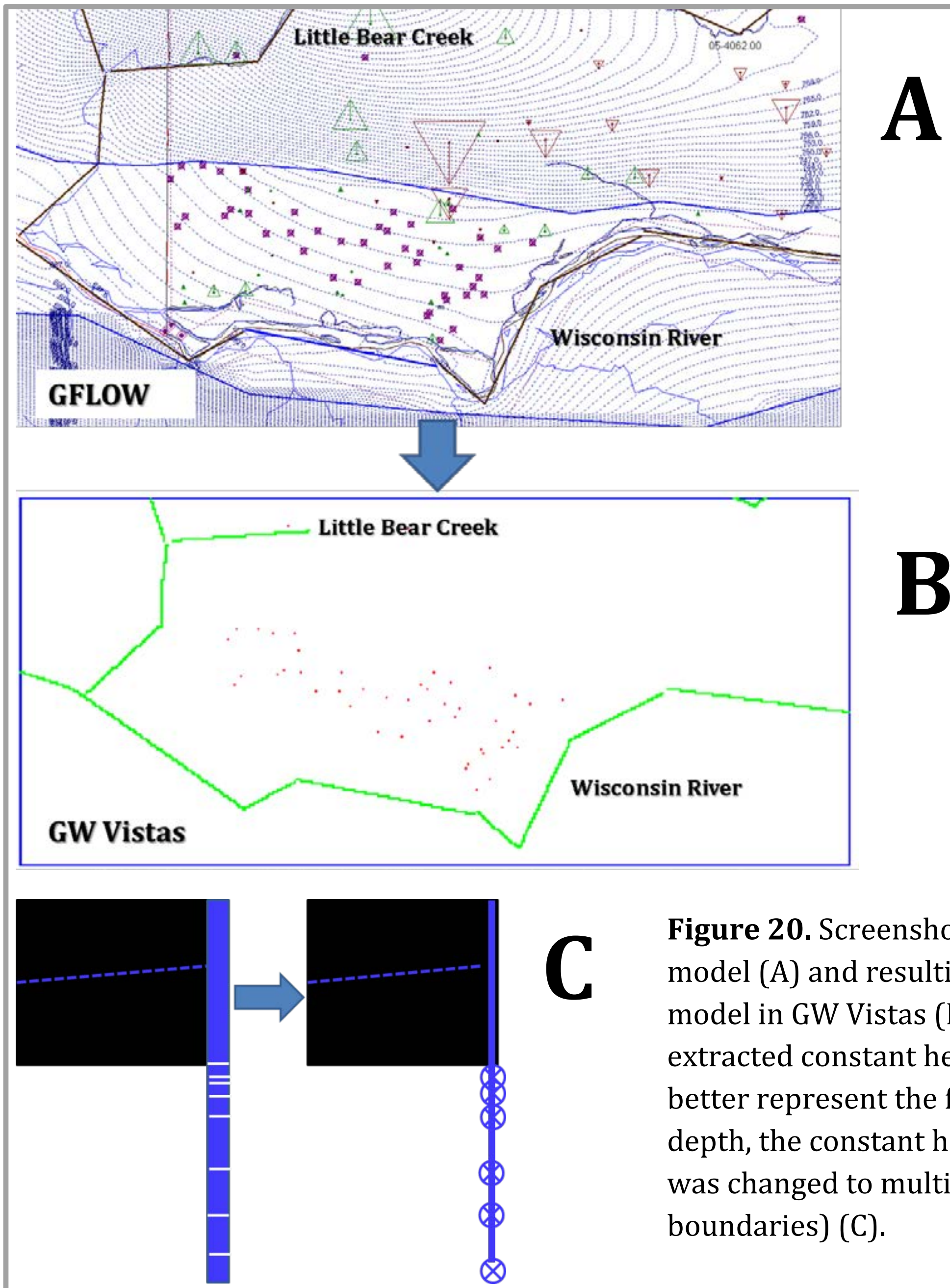



**Figure 20.** Screenshot of the GLFOW model (A) and resulting MODFLOW model in GW Vistas (B) showing the extracted constant heads (blue). To better represent the flow dynamics at depth, the constant head boundary was changed to multi-node wells (flux boundaries) (C).

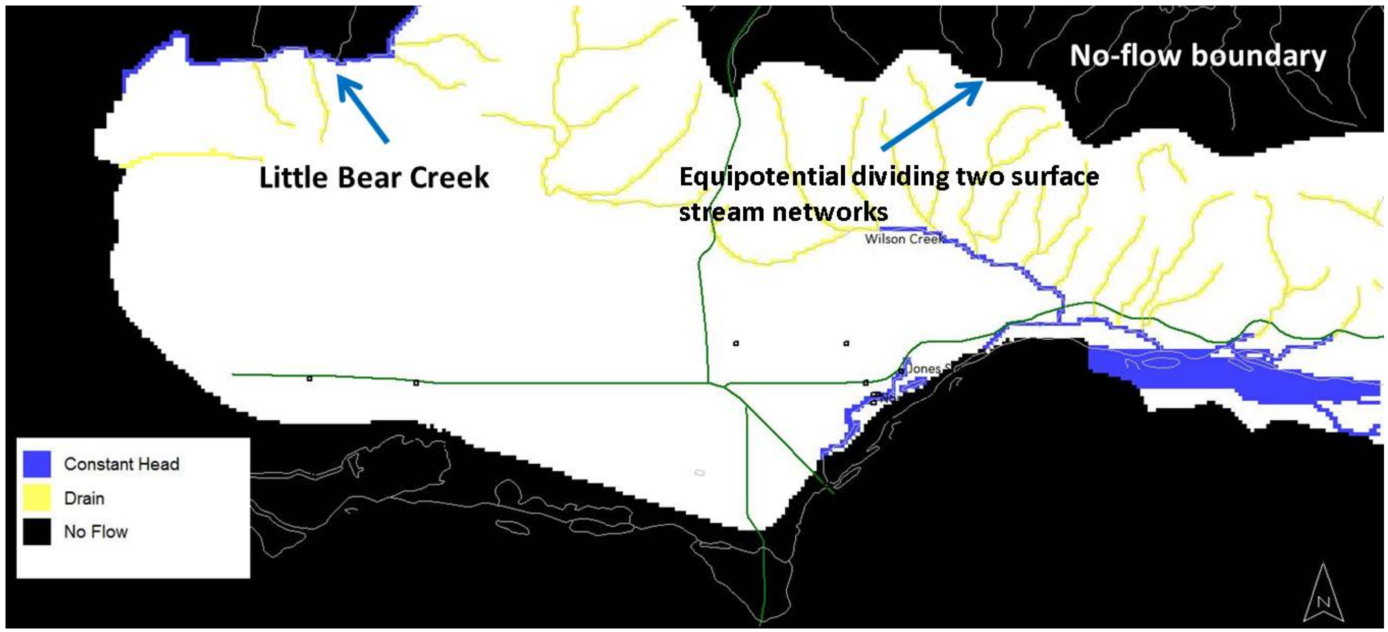



**Figure 21**. Boundary conditions in layer 1. The equipotential used to define the northeast boundary follows a local surface water divide.

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.

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 22). This target, based on the county water table map, was removed from the model during analyses of model sensitivity to variation in zones of hydraulic conductivity and recharge because of the inability for other data sources to corroborate the value and the target's undue influence on the sensitivity results.

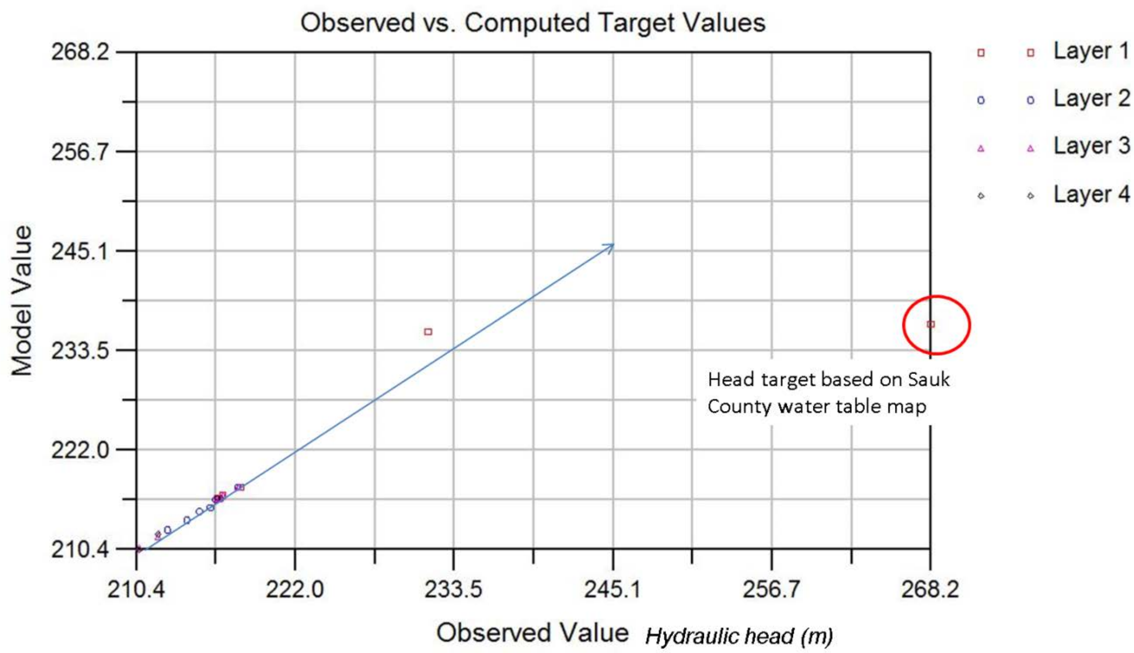



**Figure 22**. Plot of observed v. modeled values of hydraulic head.

A sensitivity analysis of the key parameters, hydraulic conductivity (K) and recharge, was conducted using a tool in Groundwater Vistas that allows selected parameters to be multiplied by a given factor (a "multiplier") and then applied to the model. Calibration statistics were calculated for each model run based on twenty-one hydraulic head targets. The total number of runs was equivalent to the number of multiplication factors.

Figure **23** shows the results of the sensitivity analysis for recharge and horizontal hydraulic conductivity (Kx) estimates by plotting the root mean square error (RMSE) against the parameter's multiplier.

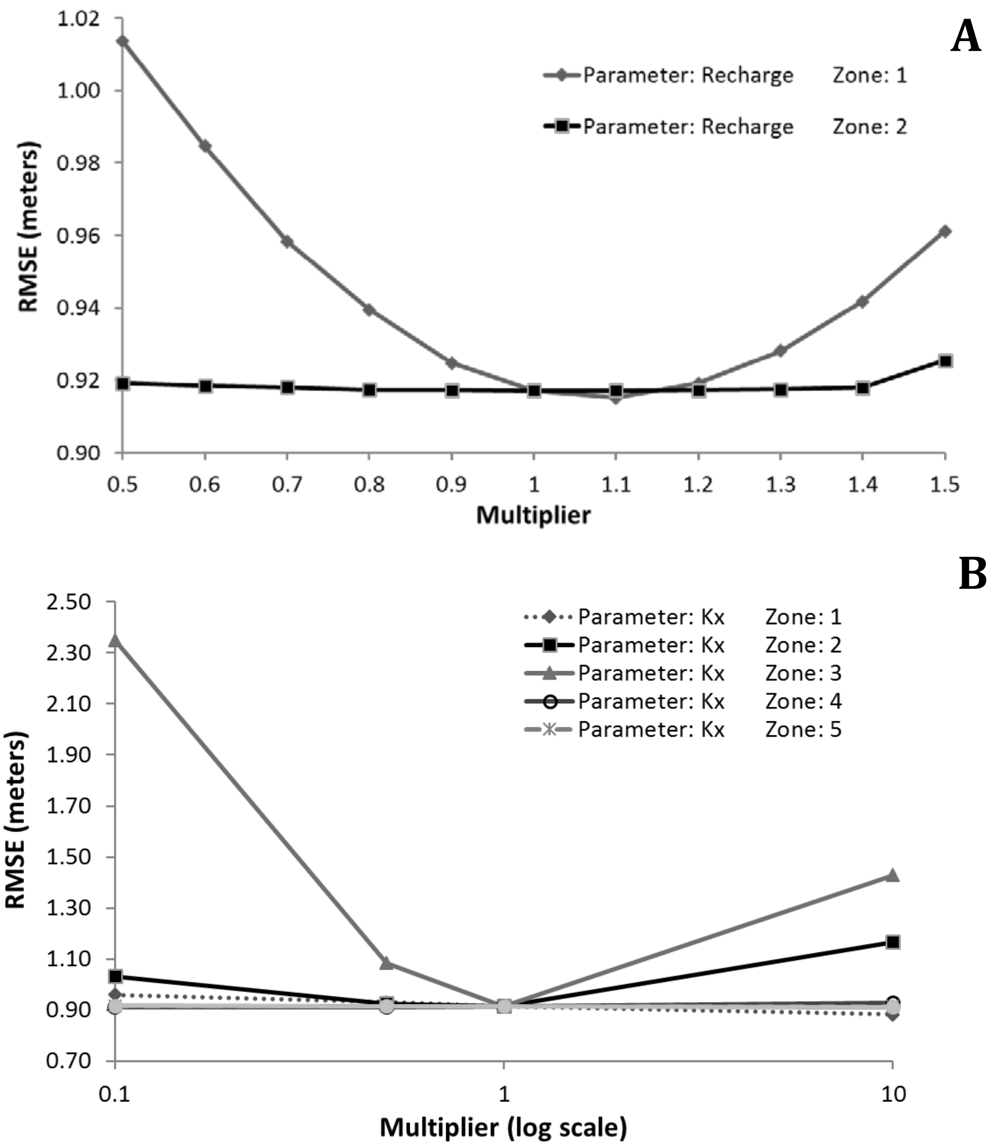



**Figure 23.** Results of sensitivity analysis for recharge (A) and hydraulic conductivity values (B). Plotting changes in parameter (multiplier) against the root-mean-square error.

For recharge, model estimates of hydraulic head were relatively sensitive to changes in zone 1 - which represented the bluffs (Figure 23 A). A slightly higher (1.1x) recharge rate yielded an RMSE that was 0.002 meters less than the base case, a value that would be below the detection limit of the dataloggers used to monitor water levels in the study area indicating that, statistically, the base-case recharge value was an optimal choice for the model. The UW model was insensitive to changes in recharge for zone 2, showing essentially no change in the RMSE until the 1.5 multiplier, at which point the RMSE increased by only 0.007 meters. In Figure 23 B, the "zones" correspond to the hydrogeologic units in Table 5. For the base-case scenario (multiplier = 1), the model estimate of hydraulic head differed from the targets by less than 1 meter, on average, for all Kx zones. The UW model was most sensitive to changes in Kx for zones 2 and 3 (essentially, the Pleistocene terrace), areas that contained all but one of the targets and therefore had relatively well-constrained values. Plots of RMSE for variations in Kx of these two zones show a rough "U" shape with the base-case scenario having the smallest error. Changes in Kx for zones 1, 4, and 5 appeared to have little to no effect on the RMSE. Even after changing Kx estimates by an order of magnitude, the RMSE for these zones varied by less than a hundredth of a meter (Figure 23. B). The insensitivity of the model to these parameters is likely linked to the fact that almost all of the major constant head boundaries (the Lower Wisconsin River and sloughs) and head targets were located in zones 2 and 3. Such insensitivity to changes in K indicates that there could considerable uncertainty in groundwater travel times to the areas of interest.

## 5.7 Model Results

The final calibrated model had an acceptable mass balance error of less than 1% (-0.429) with the outflows being slightly greater than the inflows. Comparing Figure 16 with Figure 24 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. Hydraulic head values ranged from about 207 meters (679 feet) to 289 meters (948 feet). The hydraulic gradient flattened sharply between the bluffs and the Pleistocene terrace, delineating the sharp change in topography and geology (sandstone bluffs to glacial outwash material).

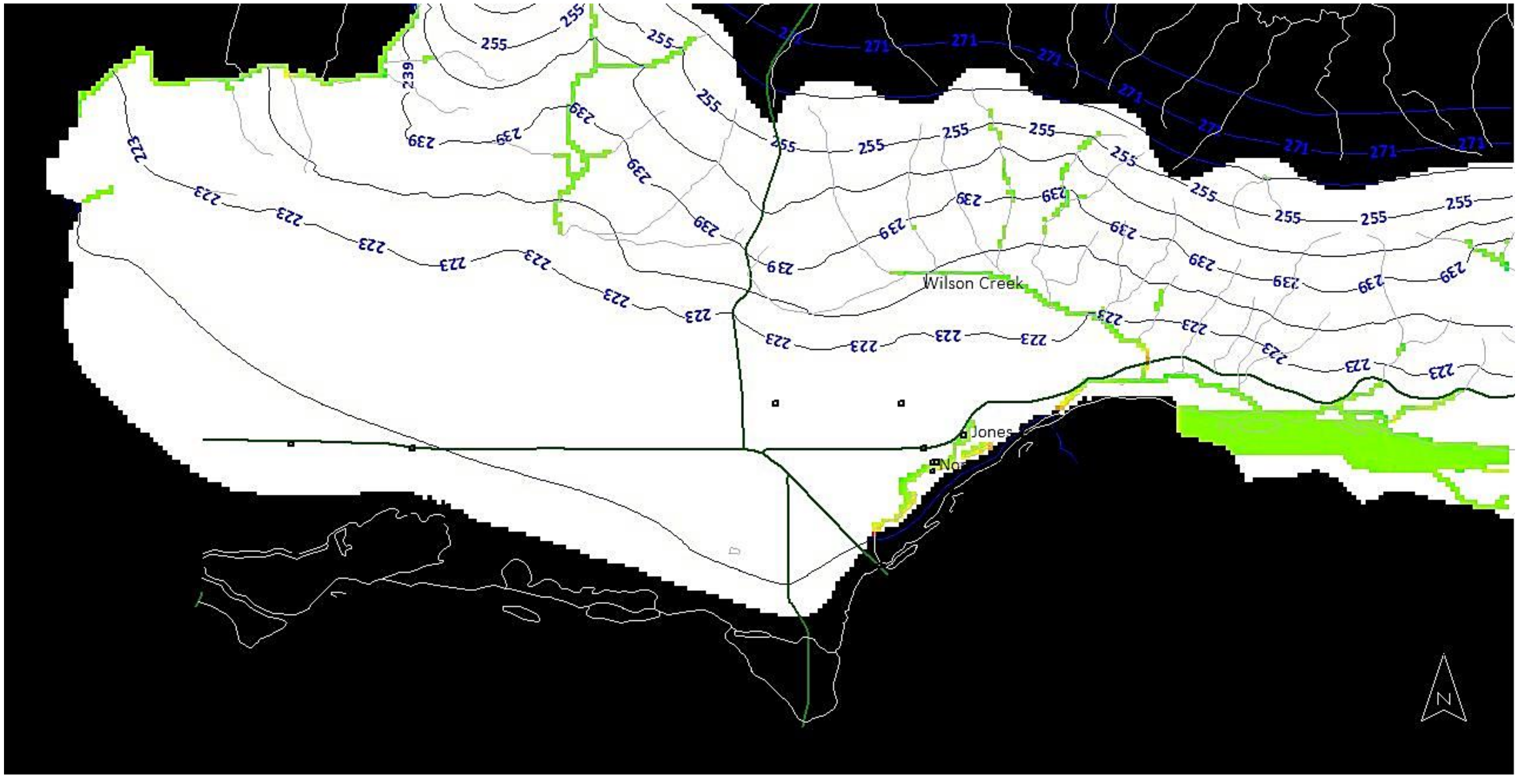



**Figure 24**. Water table map in layer 1 of the model. Head contours (blue) are in meters. Major roads are shown in dark green.

**Recharge Zones Contributing to Sloughs and Monitoring Wells**

MODPATH, an advective transport model supported by MODFLOW, was used to reverse track imaginary particles from the monitoring wells and sloughs back to their recharge sites. Neither dispersion nor chemical reactions are simulated; the only output is the particle flow path and travel time. The particle paths delineate groundwater flowpaths from a recharge area to the well or slough. For the wells, single particles were placed within model layers at approximately the same elevation as the respective well screen's midpoint (elevations are recorded in Appendix A). Slough particles were placed at approximately the sediment-water interface at a density of 1 particle/ grid cell that covered the approximated areal extent of the slough (Figure 25). The number of particles used to track the slough water depended on the surface area of the slough. Twelve particles were used for Jones Slough, ten for Norton Slough, twelve for Bakkens Pond, and twenty for Long Lake.

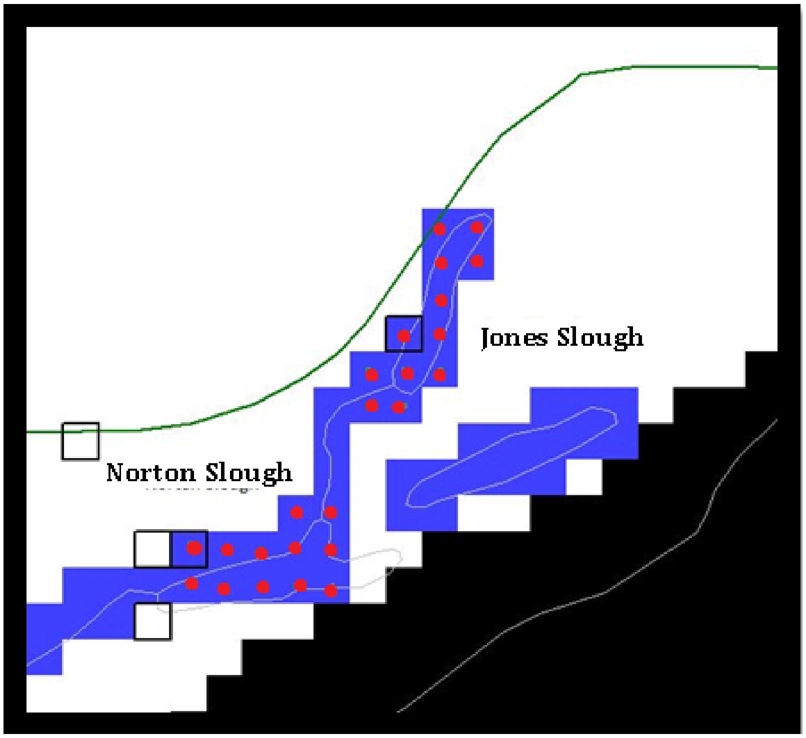



**Figure 25**. Particle placement (red dots) for Jones and Norton Sloughs in Layer 1 of the model. Blue grid cells represent CHBs.

**Sloughs**

The areal extents of the recharge zones for the sloughs were correlated to the distance between the water bodies and the bluffs (Figure 26). Norton and Jones Sloughs, which were located closest to the sandstone bluffs, had the smallest recharge zones in terms of the distance from the discharge point (the slough). However, the range in recharge sites among particles within a single slough was quite variable. The majority of particles in Norton Slough backtracked to only a few hundred meters north of the slough, with a few originating at the base of the bluffs near Wilson Creek. Less than half a mile away, particles for Jones Slough seemed to originate almost entirely from the base of the

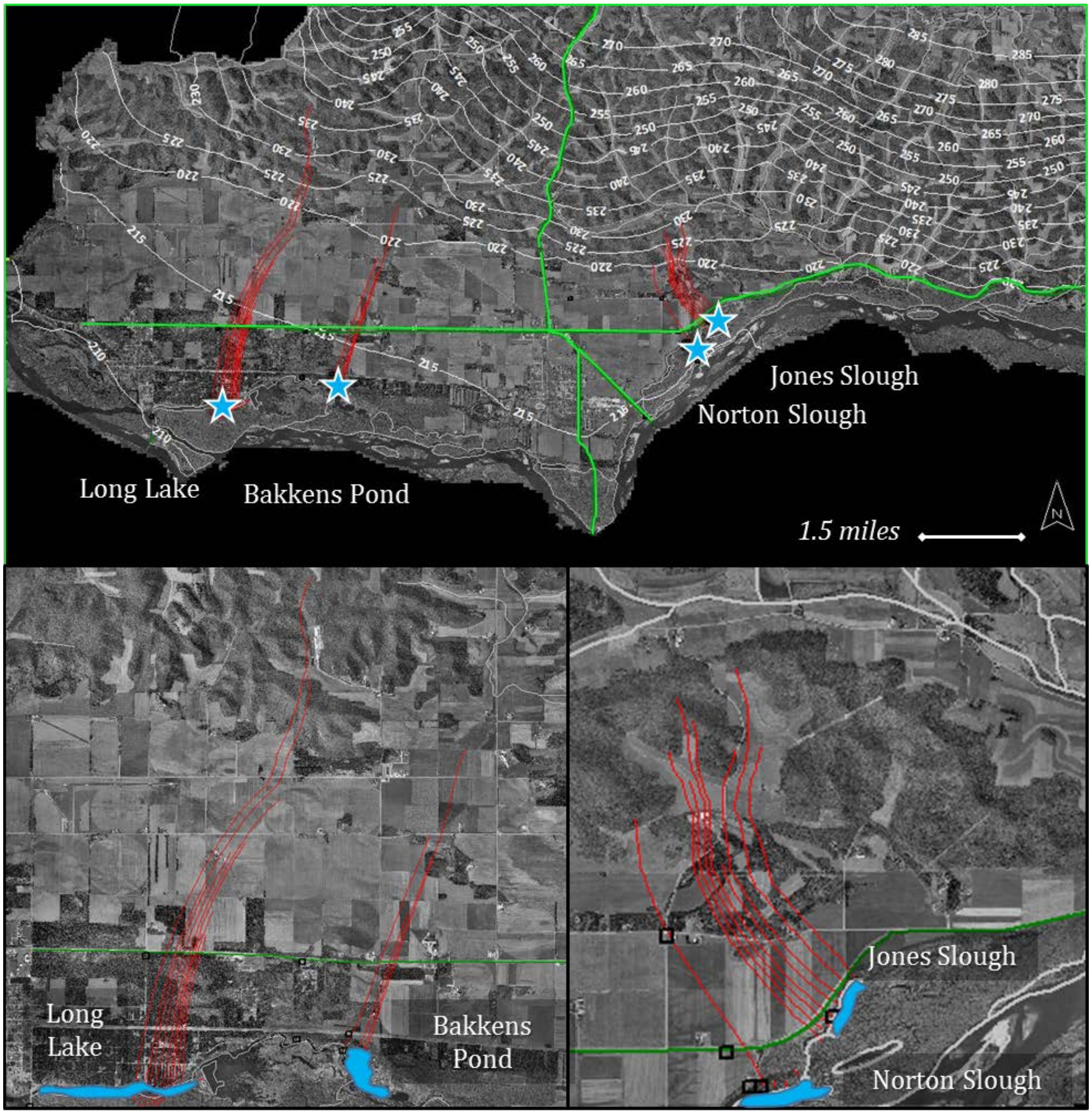



**Figure 26.** Model layer 4 showing MODPATH results for slough reverse particle tracking. Particle paths are shown in red. Sloughs are highlighted in top panel with blue stars. Blue lines in top panel represent head contours of the water table. Green lines represent major roads.

bluffs. The width of the Pleistocene terrace narrows from Norton Slough to Jones Slough so that the relatively sharp change in elevation from floodplain to bluff occurs over a shorter distance for Jones slough. This appears to be a sharp enough contrast to overwhelm any local trends in the hydraulic gradient and cause recharge to occur farther back in the terrace for Jones Slough. Long Lake displayed the greatest range in flowpath lengths, with about half of the particle recharge sites ranging across the Pleistocene terrace, all the way back to the bluffs south of Little Bear Creek. The recharge zone for the other half of the particles originated in the Sauk County School Forest, a protected area in the floodplain between Long Lake and the river. This was in contrast to all the other sloughs, which had their recharge zones primarily north of the discharge points. Bakkens Pond's recharge zone spanned the width of the Pleistocene terrace with almost all of the recharge sites occurring over a mile away.

**Groundwater Wells**

Similar to the sloughs themselves, the deeper wells in the nests adjacent to Jones Slough and Norton Slough appeared to have their recharge areas located at the base of the bluffs, just south of Wilson Creek. Recharge sites for wells in the western portion of the study area were spread over a larger range of distances from the river (Figure 27). All of the water table wells had their recharge sites within a few meters of the well. Additionally, all of the recharge sites were located north of their respective wells. In most 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. LL4's particle travel time was 14 years compared to BP4's 16 years. The same held true for wells BP3 (667.5 ft. msl) and LL3 (662.2 ft. msl), despite having very similar particle travel times of 10.3 and 10.8 years respectively. BP6, with a screen depth considerably deeper than any of the other wells, had the longest flowpath, originating from a field between the bluffs near County Road G. BP6 and BP5 were the only slough wells that did *not* have flowpaths terminating into their respective sloughs.

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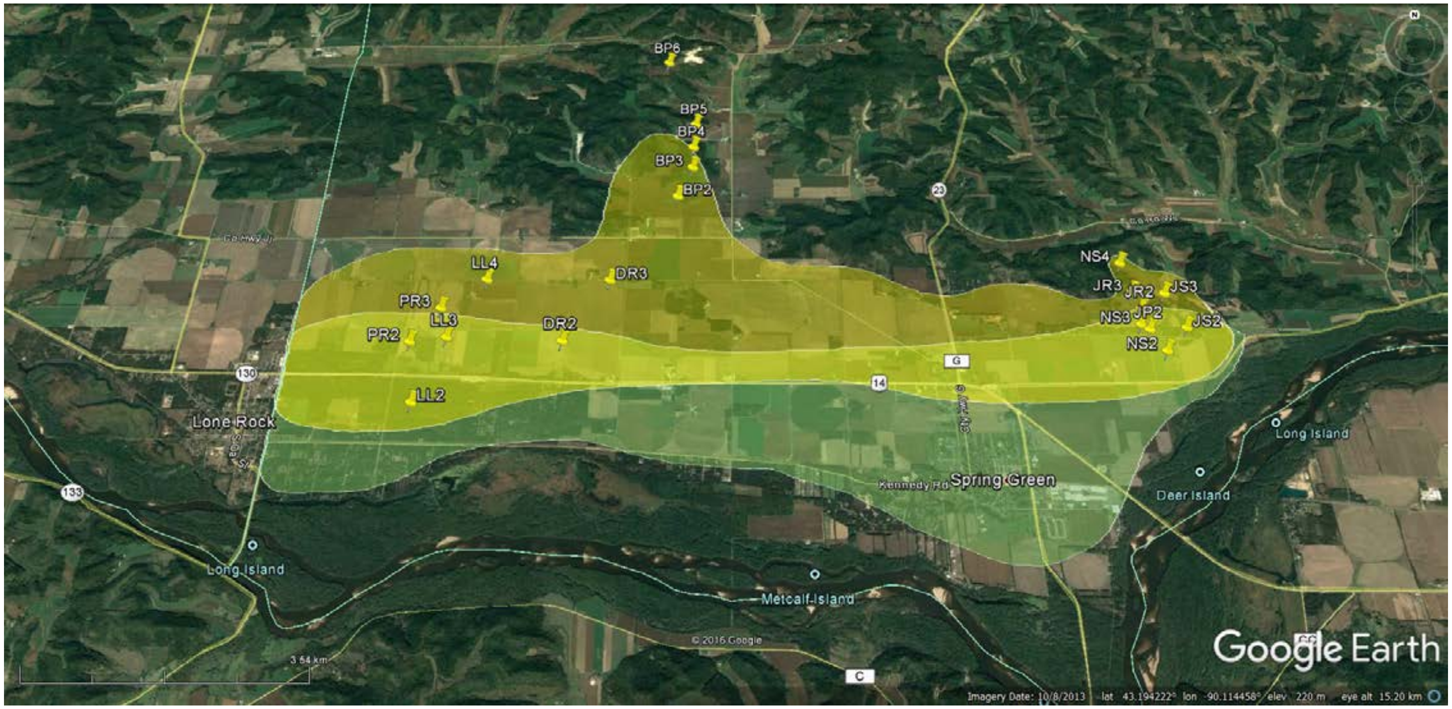


**Figure 27.** Google map image showing approximate recharge zones for all water table wells (green polygon) and groundwater wells (yellow polygon), with some overlap. Pinpoints are the ***approximate*** groundwater infiltration site for the respective well based on MODPATH results.

**Cross Sections**

Cross sections showing monitoring well locations were constructed along transects A-A' and B-B' that are shown in Figure 28. Figures 29 and 30 show nitrate concentrations and isotopic signatures from water samples collected in well nests associated with Bakkens Pond, Donald Road, Norton Slough, Jones Prairie, Jones Road, and the floodplain (FP1, FP2, and FP3) in July 2016. Each dot represents the screen midpoint of a single well and vertical clusters represent a single well nest. Also shown on each cross-section is a dashed red line that corresponds to the deepest flow path that discharges to the slough that occurs along the section. Dots above the dashed red line represent monitoring wells for which the groundwater will eventually discharge to the slough. Dots below the dashed red line represent monitoring wells for which groundwater will eventually discharge to the Wisconsin River.

For the nitrate samples, the color of the dot corresponds to its relative nitrate concentration in July (low = 0.4-7.0, medium = 7.1-15, or high = 15.1-26.1 mg/L). The "high" nitrate concentrations are seen in the deeper wells, which have their recharge zones set the farthest back in the Pleistocene terrace near the bluffs. BP4 had the highest median nitrate concentration of 30.6 mg/L out of all the wells in this study and represented the lower boundary of groundwater that eventually discharged into Bakkens Pond. Although intense agriculture is present within the Pleistocene terrace, nutrient concentrations in mid-level wells with recharge zones in this region tended to have low to medium nitrate concentrations. The Long Lake well nest had the lowest median nitrate concentrations out of the four sloughs and its recharge sites were located within the Pleistocene terrace (Appendix H).

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 in Appendix H, 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 16), 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.

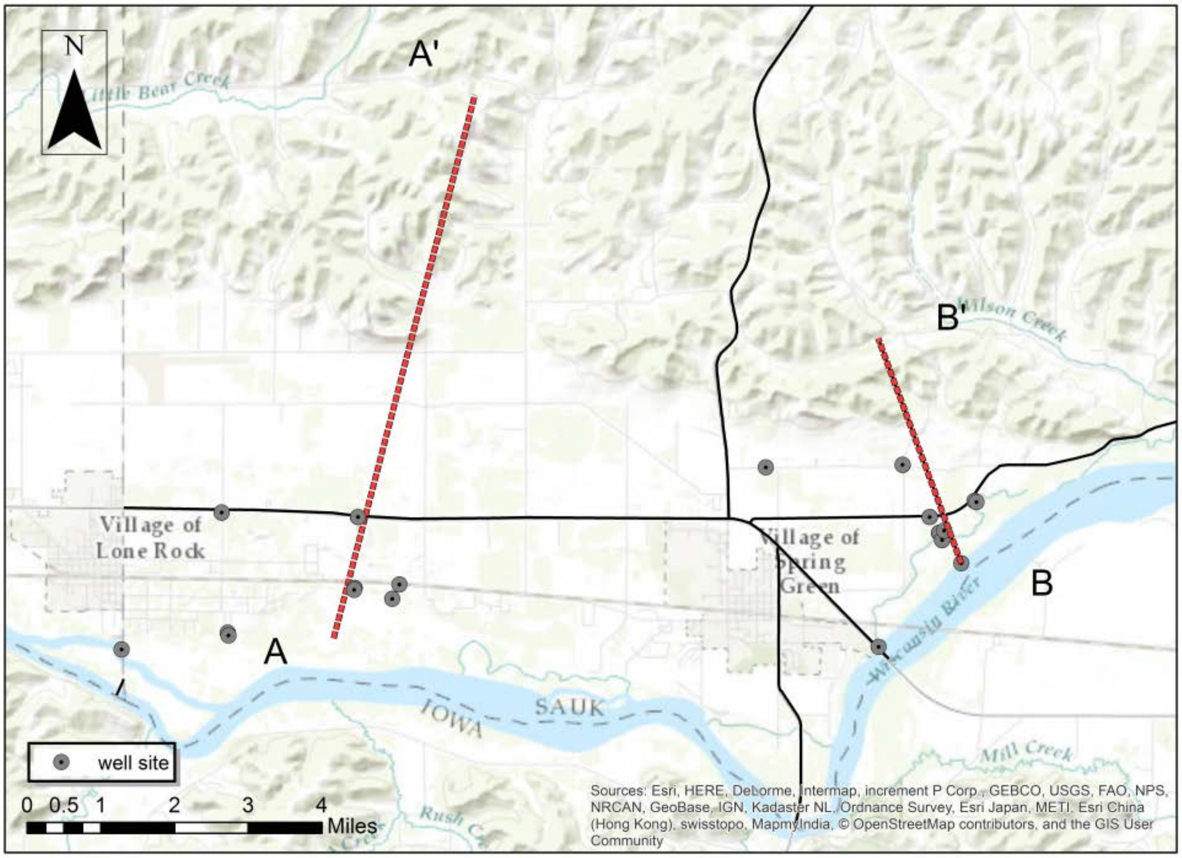


**Figure 28.** Map of study area showing location of cross sections in profile below. Locations of individual wells and well nests are represented by solid grey circles. Transects are delineated with dotted red lines and labeled A-A' and B-B'. Major roads are shown with a solid black line.

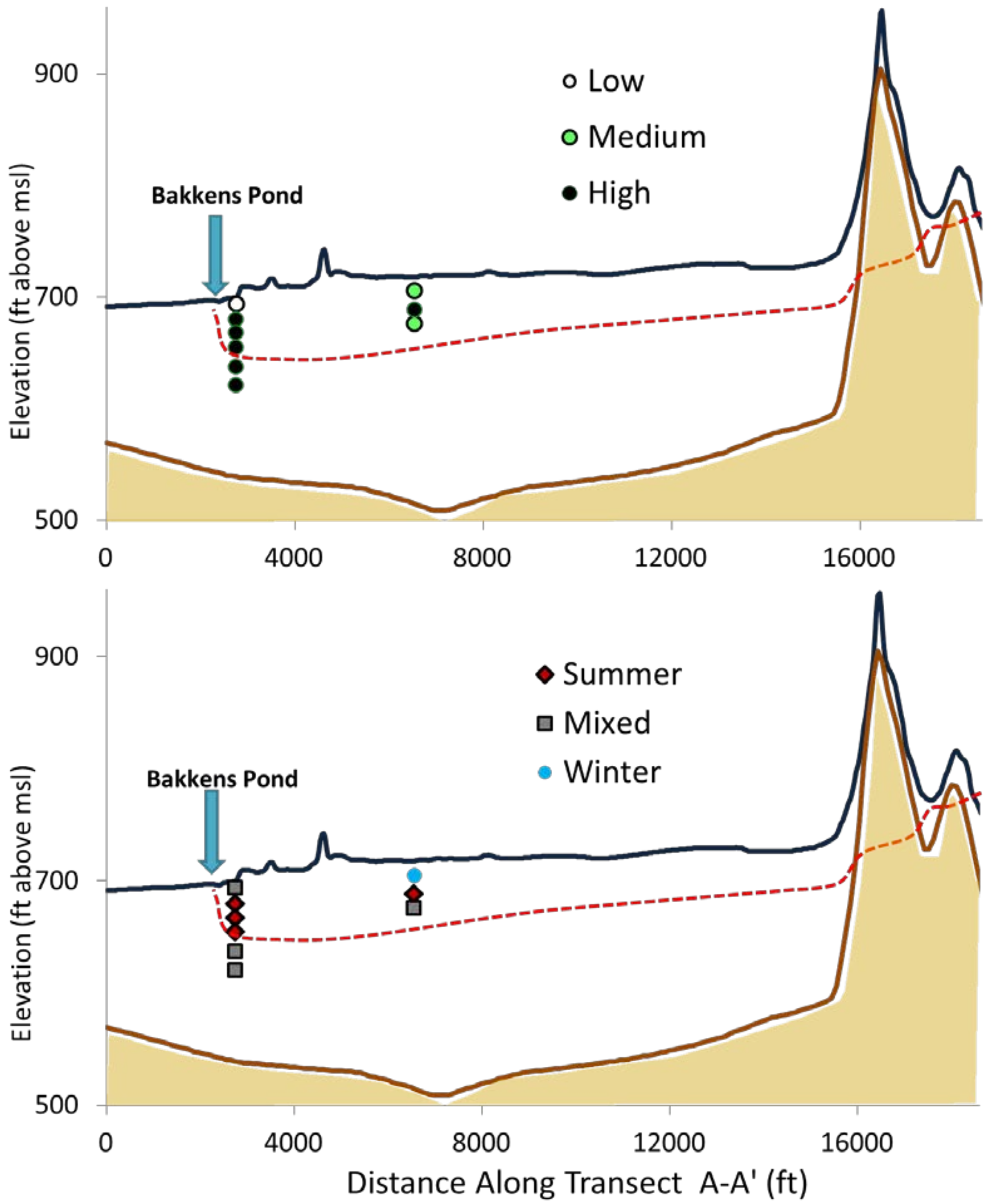


**Figure 29.** Cross sections A-A s show the resulting nitrate concentrations and isotopic signatures from well water in late July. Each dot represents a single well sample. The vertical clusters represent well nests located along the transect (identified from left to right as Bakkens Pond and Donald Road).The dashed red line is the modeled particle path for BP5 from MODPATH. The solid black line is the land surface elevation and the brown shading represents bedrock.

Low nitrate = 0.4-7.0, medium = 7.1 – 15, and high = 15.1 – 26.1 (mg/L).

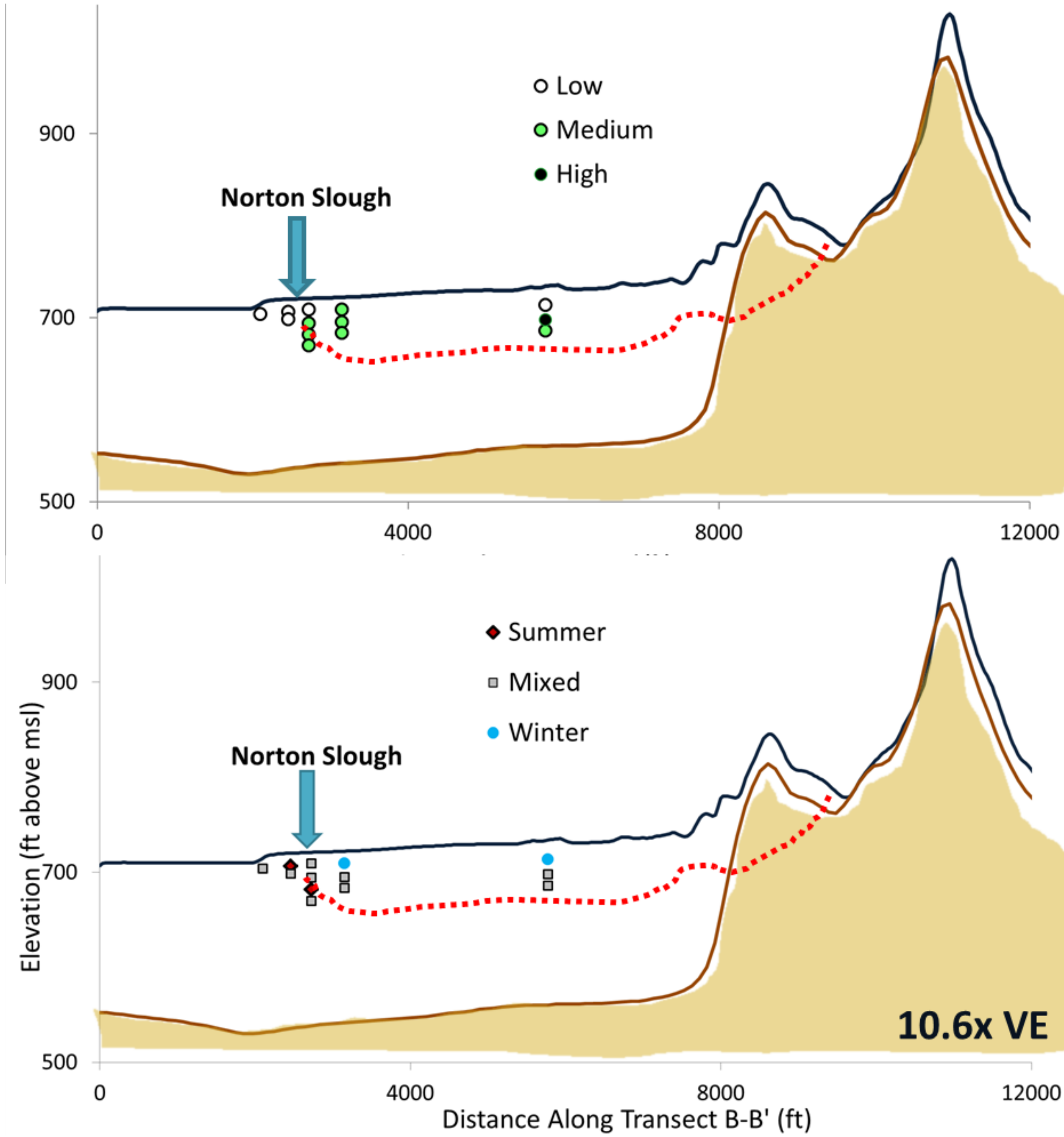


**Figure 30.** Cross sections B-B show the resulting nitrate concentrations and isotopic signatures from well water in late July. Each dot represents a single well sample. The vertical clusters represent well nests located along the transect (identified from left to right as the floodplain, Norton Slough, Jones Prairie and Jones road). The dashed red line is the modeled particle path for NS4 from MODPATH. The solid black line is the land surface elevation and the brown shading represents bedrock.

Low nitrate = 0.4-7.0, medium = 7.1 – 15, and high = 15.1 – 26.1 (mg/L).

**Travel Times**

Groundwater travel times, determined by backward particle tracking for most well sites (excluding water table wells), are shown in Figure 31 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. Travel times from recharge areas to the sloughs, shown in Appendix I as part of the sensitivity analysis, had an average travel time of 7.8 years. Long Lake had the overall largest and most variable travel times for its particles, which ranged from a few months to 123 years, depending on the particle's placement within the slough.

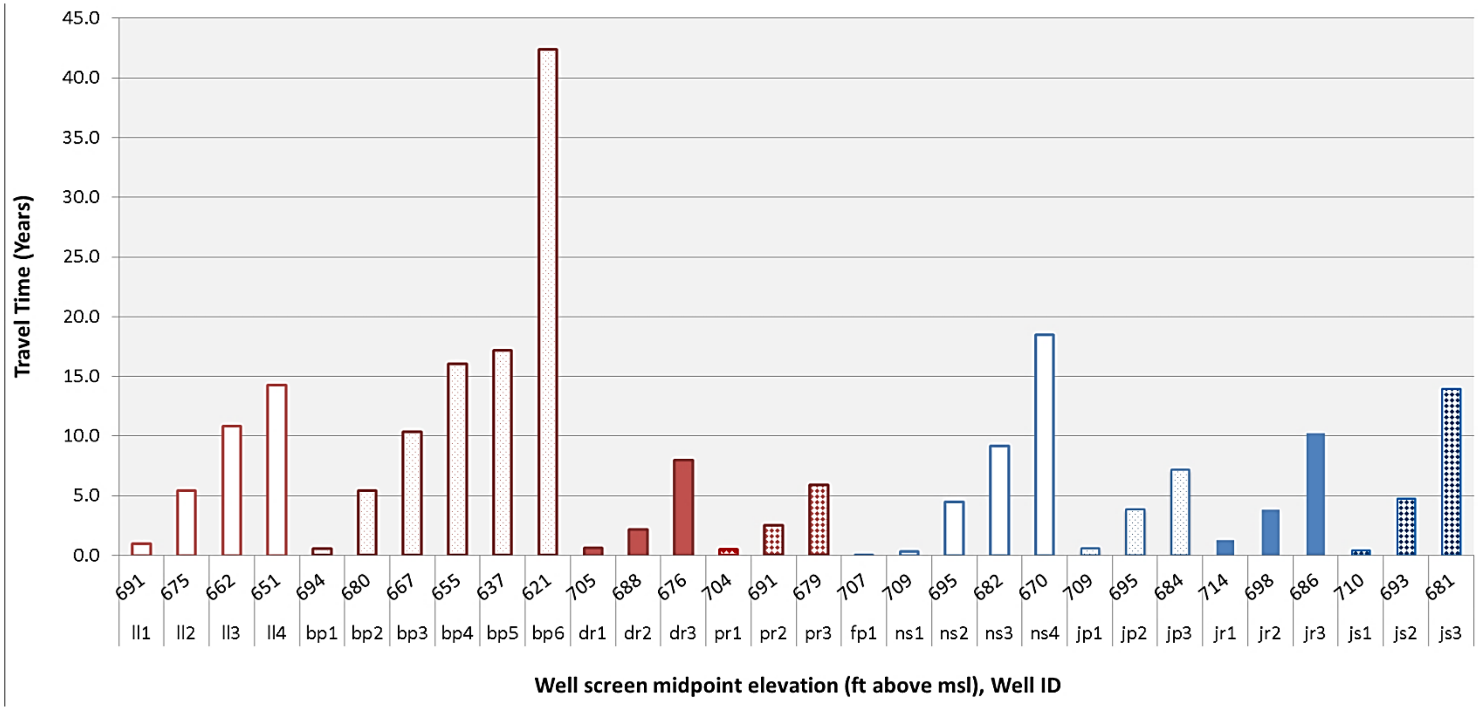


**Figure 31.** Groundwater travel time by well. X-axis label shows well screen midpoint elevation (ft msl) and well ID.

## 5.8 Evaluation of recharge area and travel time uncertainty

MODPATH simulations for reverse particle tracking from the sloughs were conducted to explore the uncertainty in flow paths and travel times for groundwater discharging to the sloughs that could result from model insensitivity to changes in the hydraulic conductivities (K) of zones 1, 4, 5, and 6. Two simulations were conducted in which both the horizontal and vertical Ks of zones 1, 4, 5, and 6 were varied by factors of 0.5 and then 2 times the original values (See Appendix I for table of K values modeled and particle travel times). K values for zones 2 and 3 were left the same as in the calibrated model since calibration had been shown to be sensitive to variations in those parameters in the sensitivity analysis discussed in section 5.6. Figure 32 below shows the results of the two simulations in layer 3, compared to the base-case (center). The blue contours represent the water table in meters and the solid blue polygon in the southwest corner shows the location of the river constant head boundary. A change in the color of the particles' flowpaths represents the particle's movement from one layer to another. The red star in each panel represents the northernmost recharge site and it used to highlight the changes in flowpath length among simulations. The red brackets in each panel encompass five contour lines and emphasize the change in gradient among the simulations. While these simulations demonstrate that simulated heads in the upland areas are actually quite sensitive to changes in Ks of zones 1, 4, 5 and 6, this sensitivity was not revealed in the RMSE values calculated during the sensitivity analysis because of the lack of calibration targets in the uplands.

Because zones 2 and 3 remained unchanged, and because Ks of the remaining zones in the calibrated model were mostly lower than those in zones 2 and 3, doubling the Ks of the remaining zones served to homogenize the flow system. The result was an overall flattening of the model's hydraulic gradient and an increase in travel distance between the groundwater recharge areas and discharge zones at the sloughs. However, the relative direction and path taken by the particles did not change drastically. The longest particle pathway, originating in Long Lake, more than quadrupled and some of Long Lake's recharge sites flipped from south to north of the lake. Interestingly, the more homogenous system that ensued from doubling K resulted in greater variability in travel times. The average travel time from doubling K was 36.1 years, but 91% of the particles had travel times less than the average. Although the overall range in hydraulic head values did not change drastically, the subdued gradient in the northeast region of the model produced in this simulation is unrealistic based on known topography and comparisons with the Sauk County water table (an inset of which can be seen in Appendix J).

Halving the Ks of zones 1, 4, 5, and 6 increased the range between the highest K (90 m/d) and the lowest K (0.125 m/d). This resulted in an overall steepening of the hydraulic gradient in the upland areas outside of the Wisconsin River floodplain. The spread of the recharge zones for the sloughs was more compact and less variable than the base-case. It appeared that greater contrast in K zones surrounding the floodplain concentrated the recharge zones for the sloughs. Unlike when Ks were doubled, the particle travel distance between the groundwater recharge areas and discharge zones at the sloughs did not change drastically. The northernmost Long Lake particle in this simulation had a travel time of 78.9 years, about 45 years less than the base-case. Of the particles that moved beyond the slough's boundaries, about 60% had longer travels times than they did in the base-case. Overall, halving K reduced the average travel time from 7.8 years (base-case) to 6.3 years, although the percent of particles that had travel times less than the average remained the same (63%).

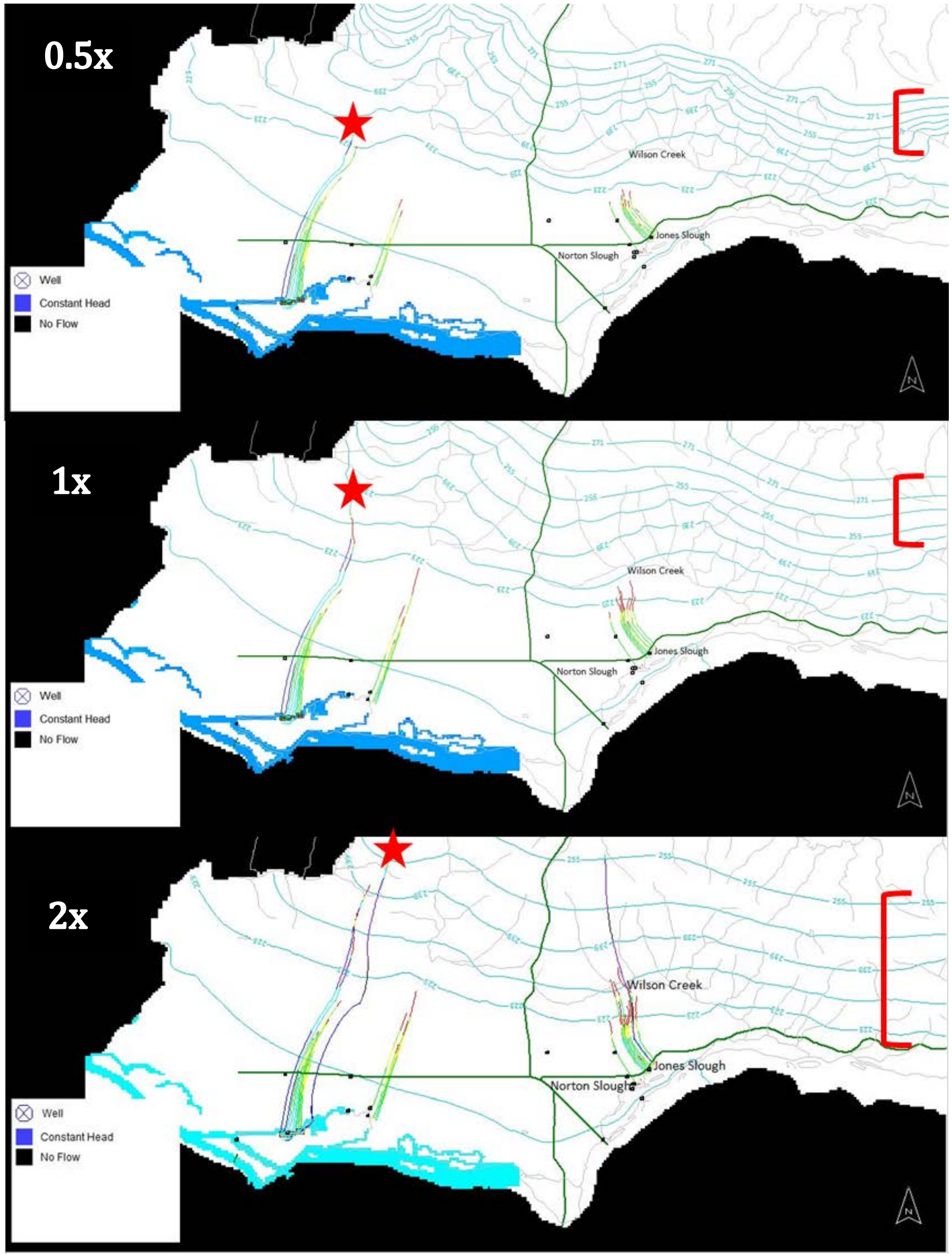


**Figure 32.** Model plan view showing MODPATH particle flowpaths and hydraulic head contours (meters) that resulted from halving (0.5x) and doubling (2x) hydraulic conductivities in zones 1, 4, 5, and 6. Change in length of flowpath for Long Lake is highlighted by a red star. Changes in the hydraulic gradient are highlighted with a red bracket.

# 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 through the lower portion of the unconsolidated aquifer. Groundwater flow within the Pleistocene terrace is primarily horizontal until it reaches its discharge point – whether a surface water feature or pumping well – because of the high hydraulic conductivity of the glacial outwash material that makes up the unconsolidated aquifer. Therefore, the shorter, shallower flowpaths originating within the Pleistocene terrace have more interaction time with the more carbon-rich top layers than the flowpaths that originate on or at the base of the sandstone bluffs. 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 262 x 262 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 ditch 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 in Figure 33. 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 33). 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 33.C.). Overall, the impact of the IDS was to shift Norton Slough's contributing groundwater recharge zones to south of the IDS (Figure 33. 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.

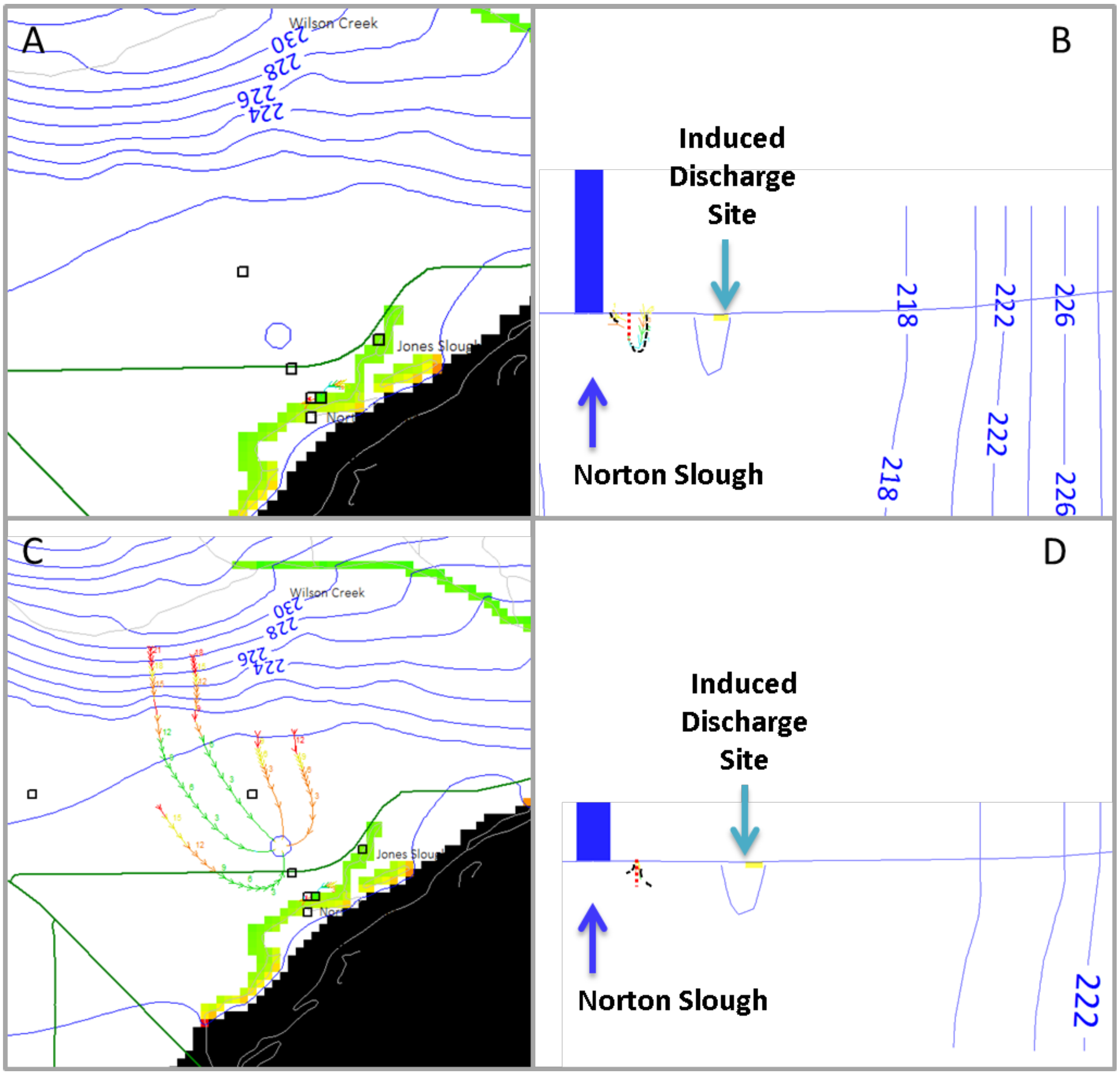


**Figure 33.** Plan and cross section view in GW Vistas of an IDS for treating groundwater to Norton Slough. A and B show the result of reverse particle testing (where the wells are the endpoint). C and D show the result of forward particle testing for the well (D) and the IDS (C). The vertical red dots 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 significantly changed within the last 10 years, present nutrient loadings to the sloughs will most likely continue for the immediate future. Nutrient application within the Pleistocene terrace and along the bluffs is negatively affecting groundwater quality. The lower nitrate concentrations seen in the shallower wells is likely due to a combination of greater denitrification near the land surface and different nutrient management practices within the floodplain. Given the apparent effect of the bluffs on localized groundwater recharge and resulting deeper flowpaths, recharge sites along the base of the bluff should be a priority for remediation efforts.

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 significantly affect estimates of nutrient fluxes to the sloughs. Favorable conditions for high denitrification rates require low oxygen and high organic carbon content. Measurements of dissolved oxygen within the wells taken on May 24$^{th}$ and July 12$^{th}$, 2017, showed that concentrations generally exceeded the range typically favorable for denitrification to occur, with the exception of the floodplain sites (Korom, 1992). 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 Sauk County Conservation Planning and Zoning Department 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. Finally, this project lays the groundwork for a potential study focus for the Nelson Institute for Environmental Studies' Water Resources Management (WRM) practicum. The WRM practicum is an interdisciplinary workshop where a student-faculty team creates a project around a contemporary problem in water resources. The socioeconomic dimensions of developing any lasting solutions to the environmental issues, combined with the requisite land use policy changes, would provide a rich learning opportunity. It is hoped that any future practicum would be able to expand upon the results of this study and test the political practicality and efficacy of the recommended mitigation strategies.

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# Appendices

## 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. above 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 | JP1 | 16 | 10 | 13 - 23 | 729.813 |

| | | | | | |
|---|---|---|---|---|---|
| Prairie (JP) | 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 |

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

| Location | Well Name | Approximate Water Table Depth (ft. BGS) | Screen Length (ft.) | Well Screen Depth (ft. BGS) | Well Collar Elevation (ft. MSL) |
|---|---|---|---|---|---|
| Wisconsin River<br><br>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<br><br>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 |

<u>Wells Installed by University of Wisconsin-Madison hydrogeology field course June 2015</u>

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

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

<u>2014-2015</u>

| 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 |

<u>Slough Staff Gages</u>

| 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:

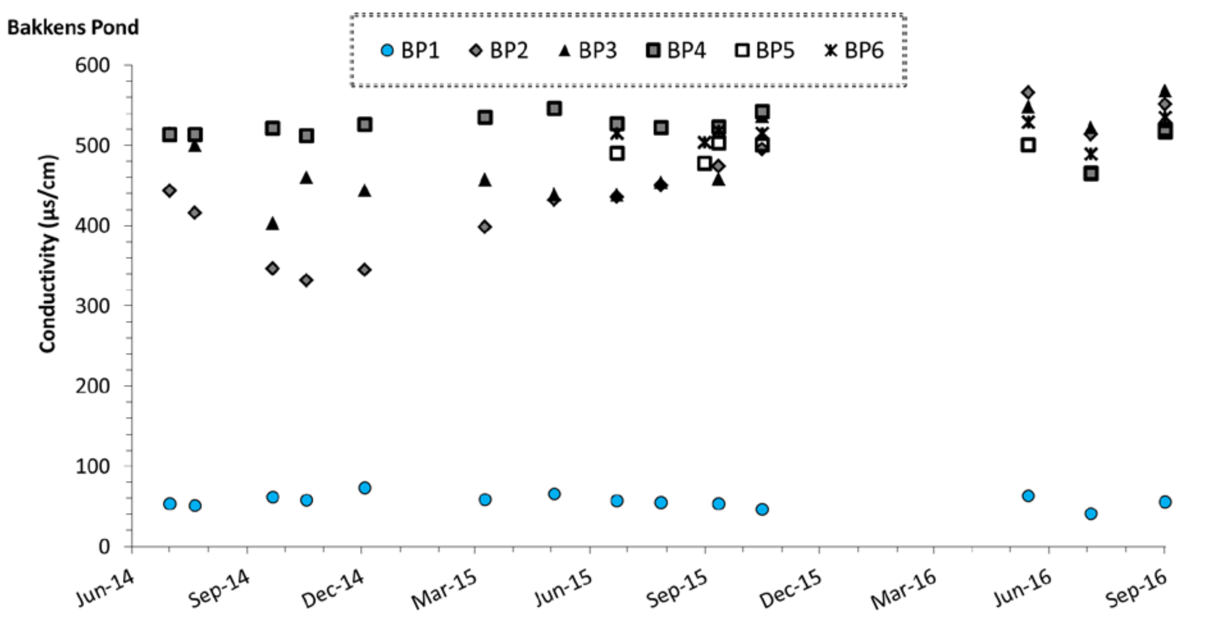
**BP2** $3 \times 10^{-3}$ ft/s ($1 \times 10^{-3}$ m/s)

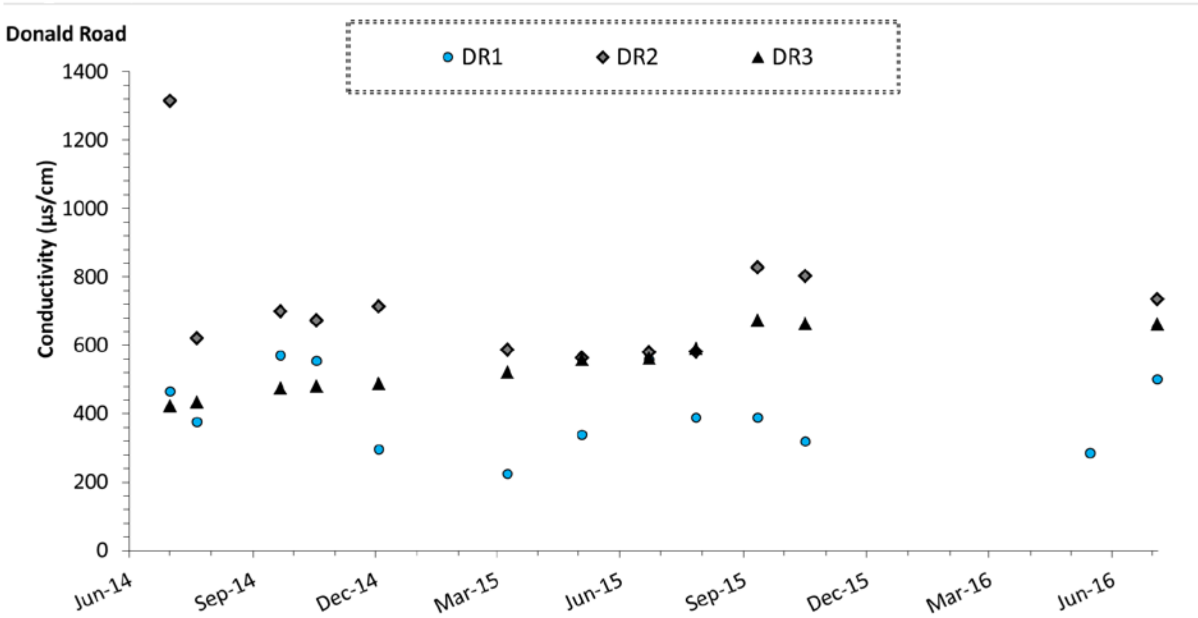
**BP3** $1.9 \times 10^{-3}$ ft/s ($6 \times 10^{-4}$ m/s)

**BP4** $1.6 \times 10^{-3}$ ft/s ($5 \times 10^{-4}$ m/s)

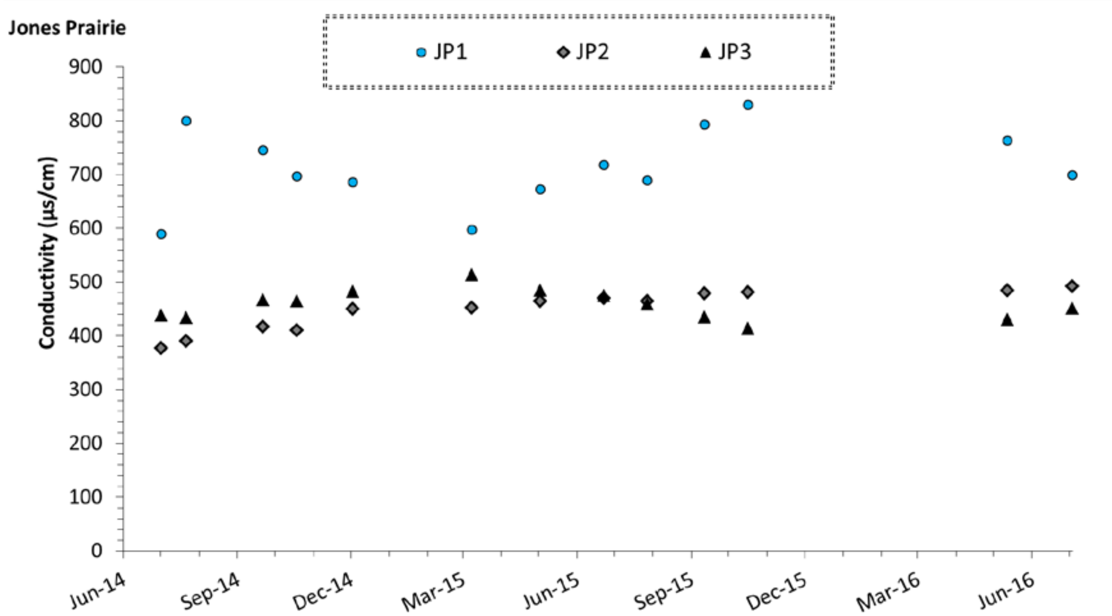
### C. Conductivity

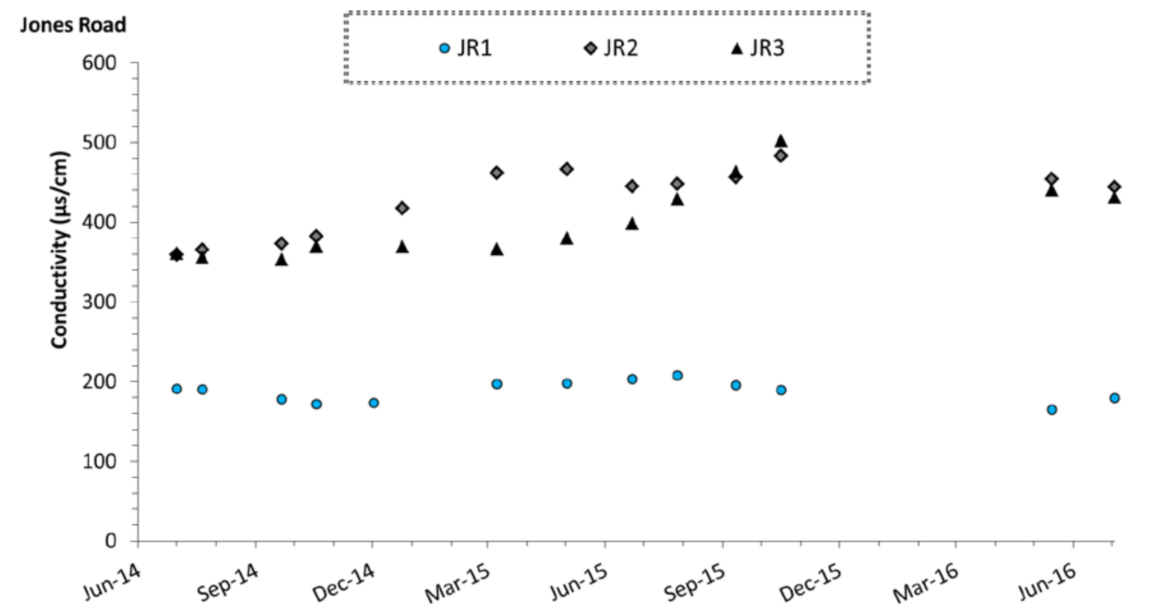
Change in conductivity with time by well nest site. Points correspond to results for wells within the respective well nest

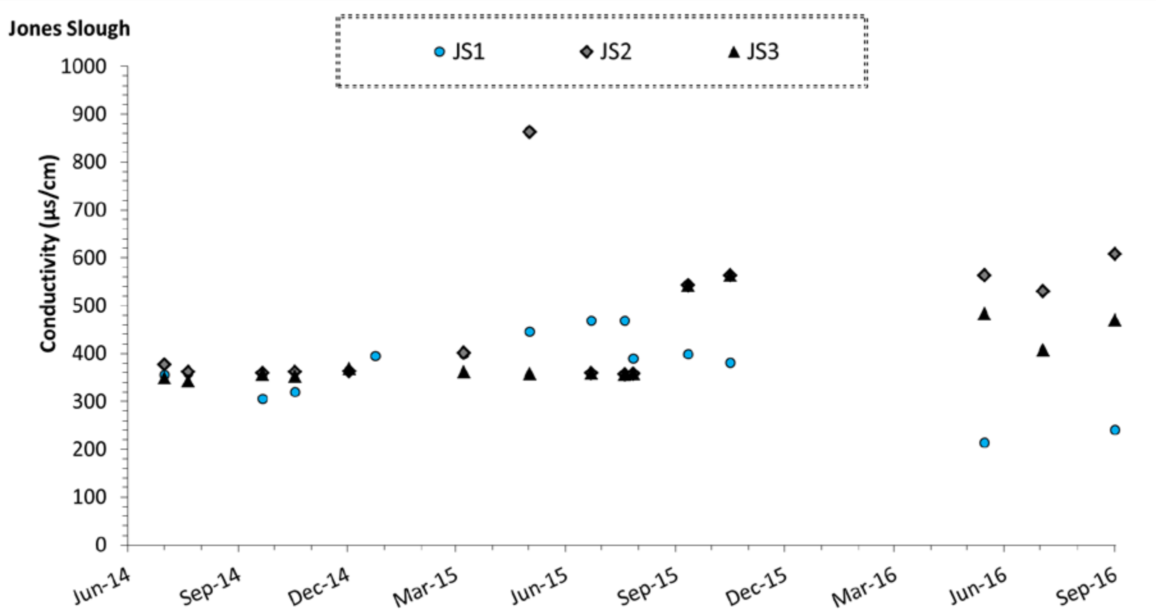


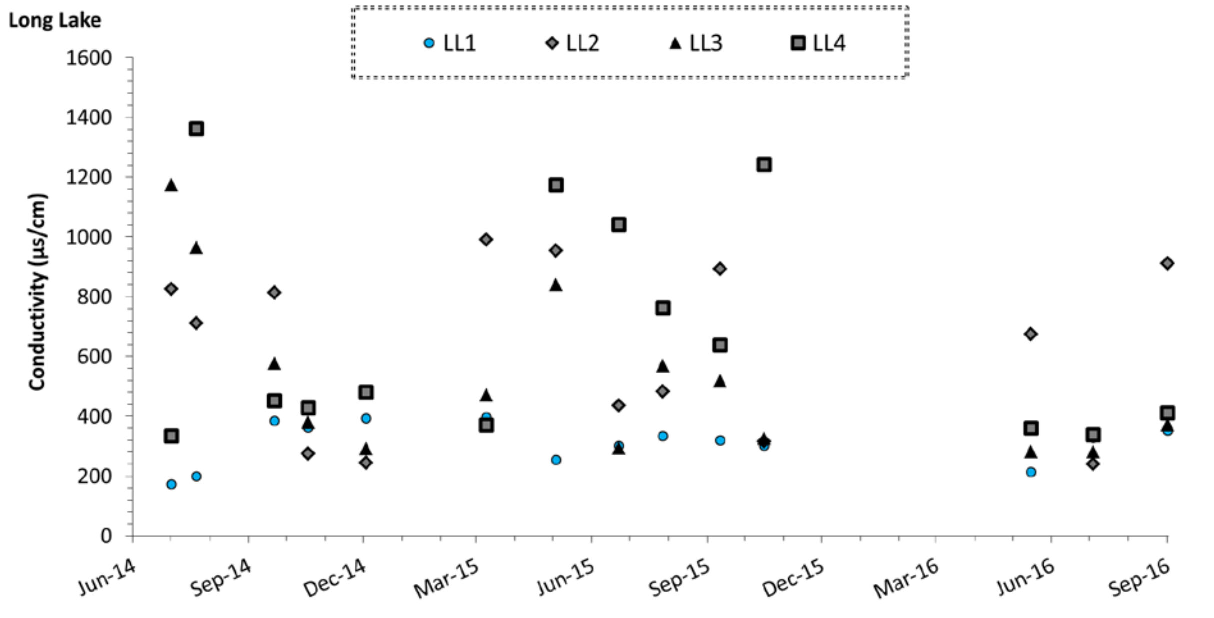



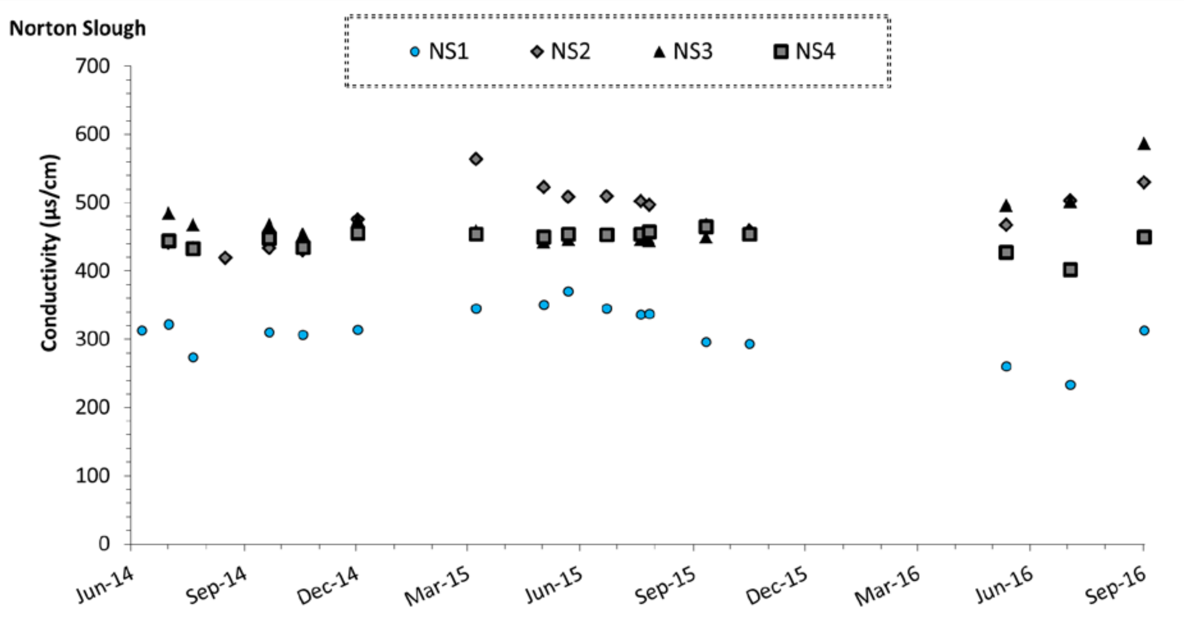

Floodplain Wells
FP1
FP2
FP3
WRFP
Conductivity (µs/cm)
800
700
600
500
400
300
200
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

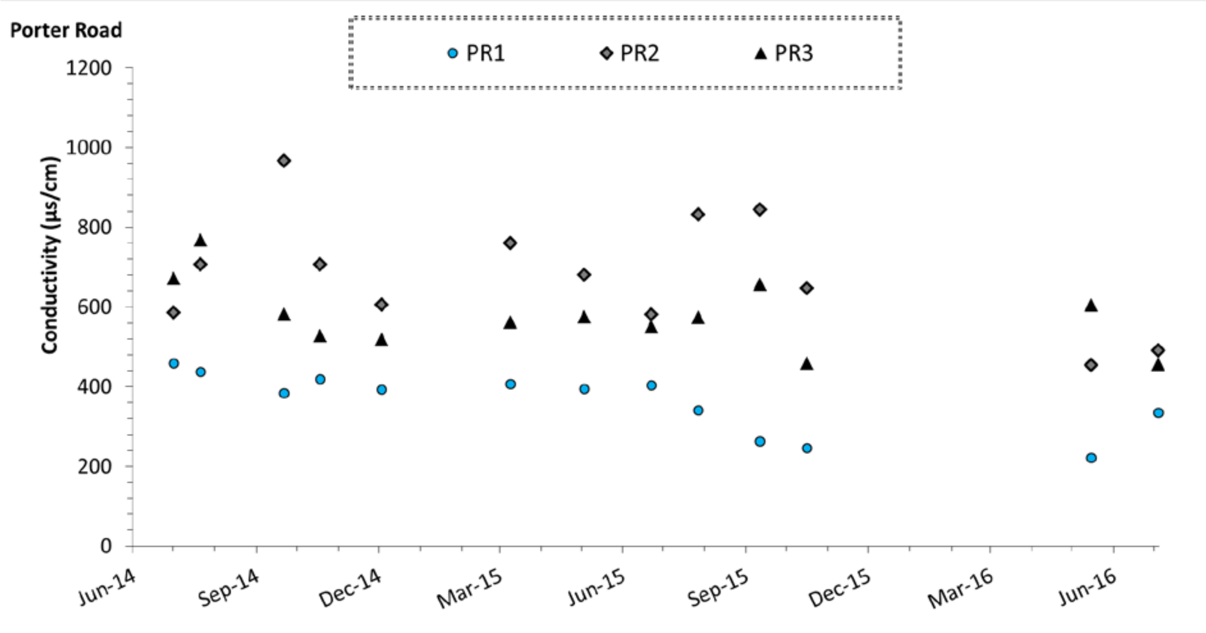

Jones Prairie
JP1
JP2
JP3
Conductivity (µs/cm)
900
800
700
600
500
400
300
200
100
0
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


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

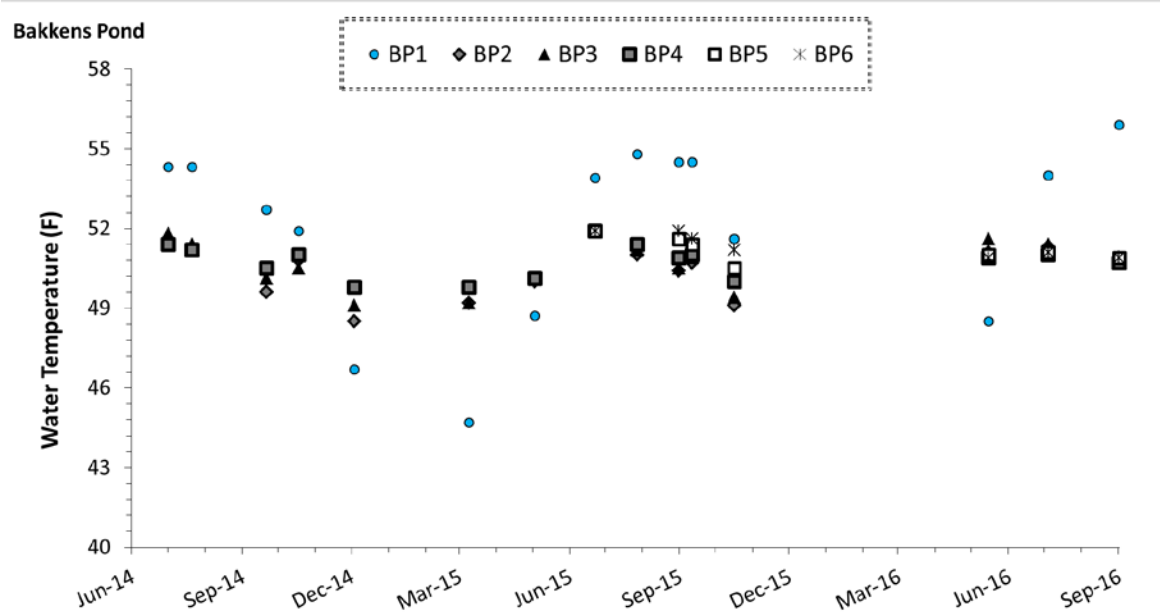

Long Lake
LL1
LL2
LL3
LL4
Conductivity (µs/cm)
1600
1400
1200
1000
800
600
400
200
0
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

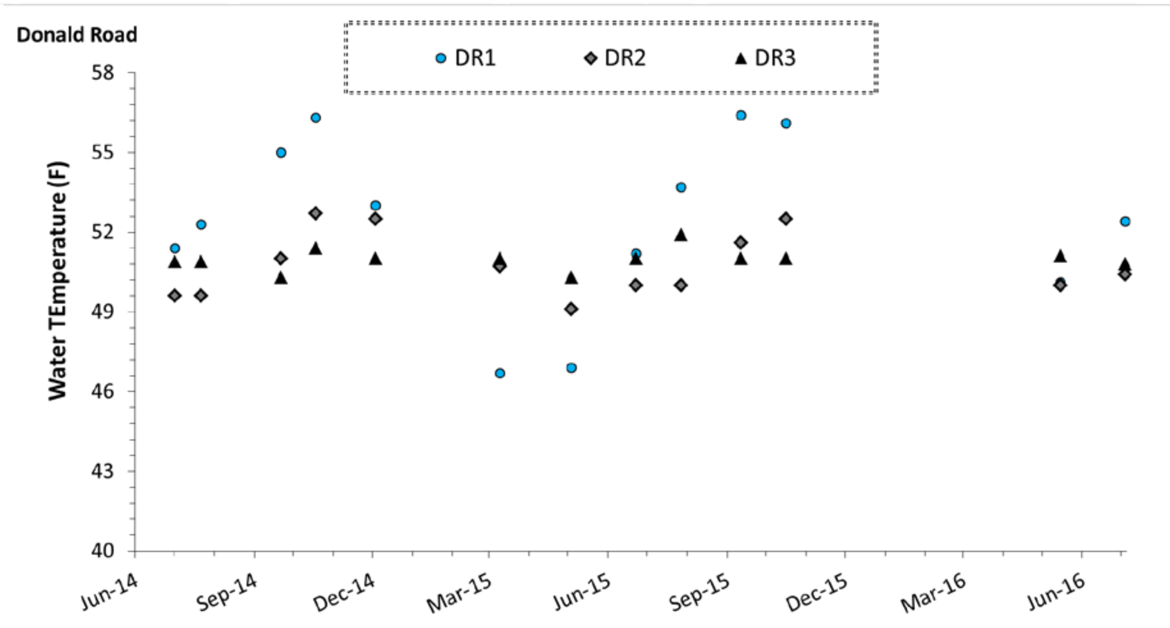

Norton Slough
NS1
NS2
NS3
NS4
Conductivity (µs/cm)
700
600
500
400
300
200
100
0
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

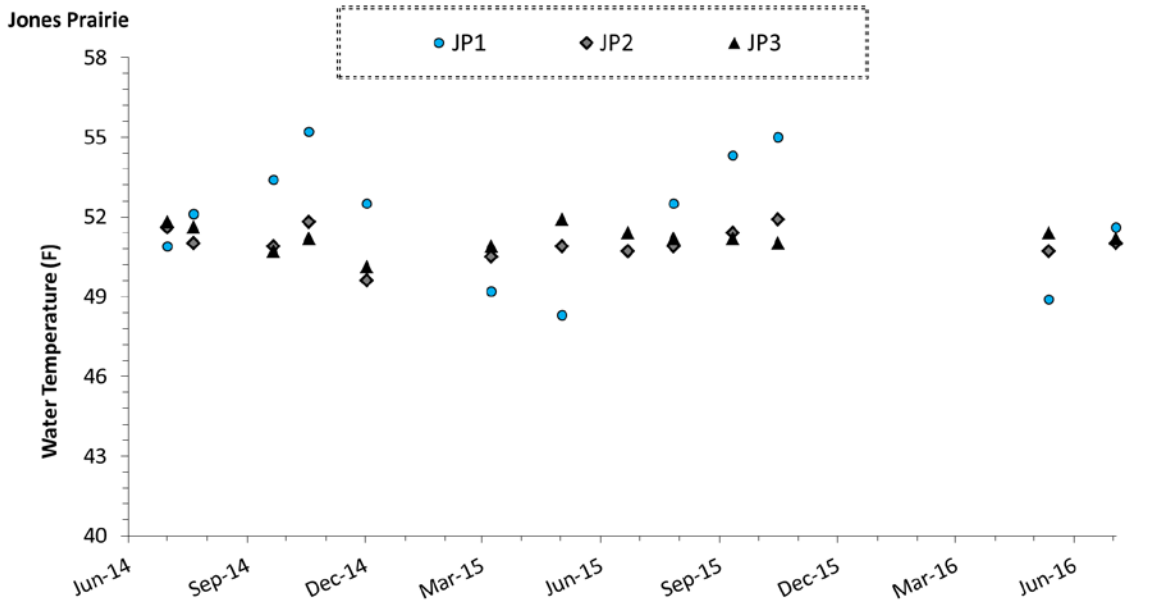

Porter Road
PR1
PR2
PR3
Conductivity (µs/cm)
0
200
400
600
800
1000
1200
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16

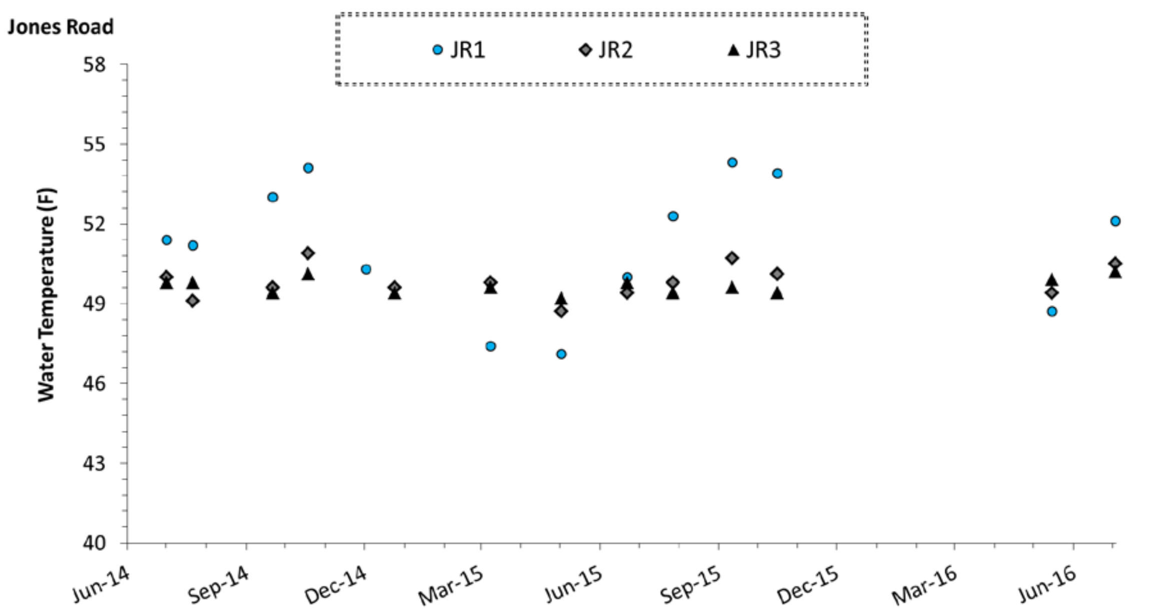
**D. Temperature**

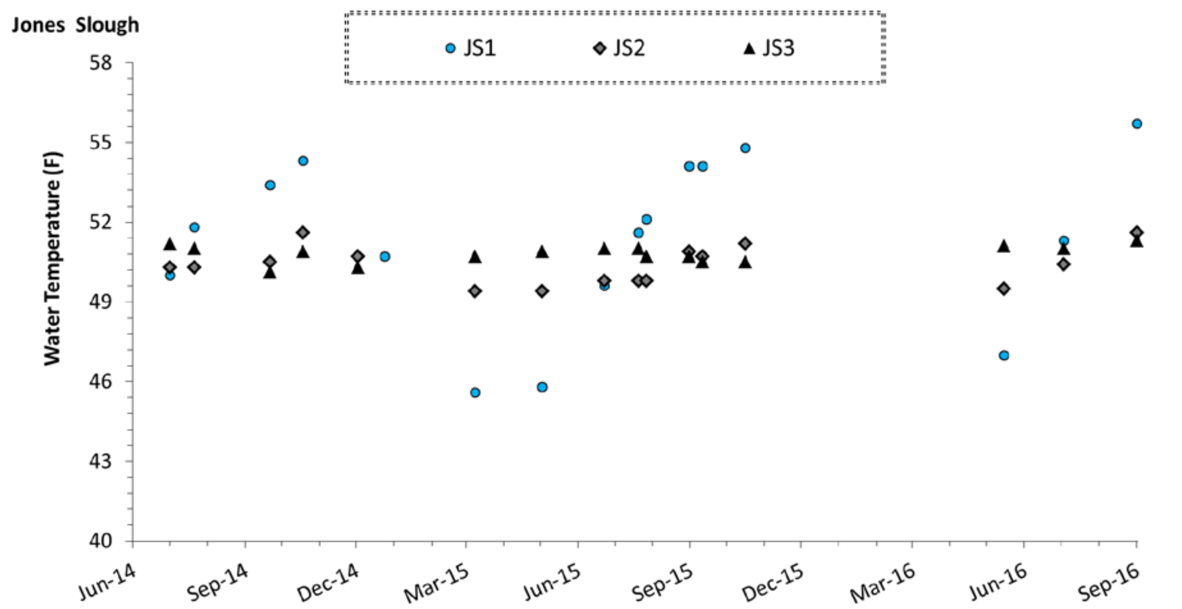
Change in temperature with time by well nest site. Points correspond to results for wells within the respective well nest.

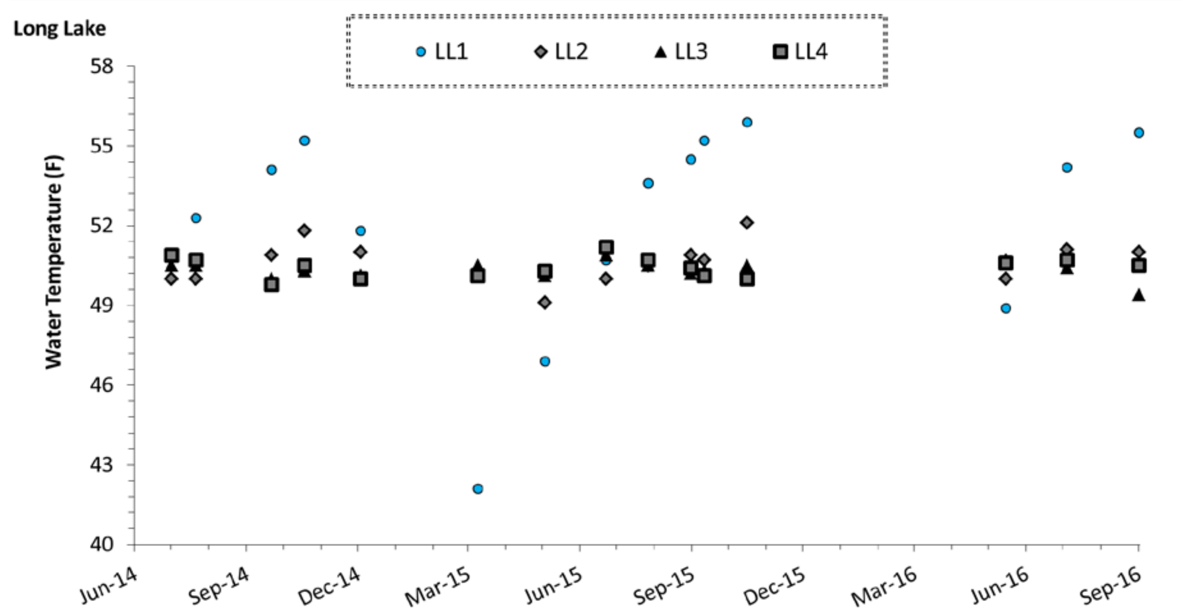


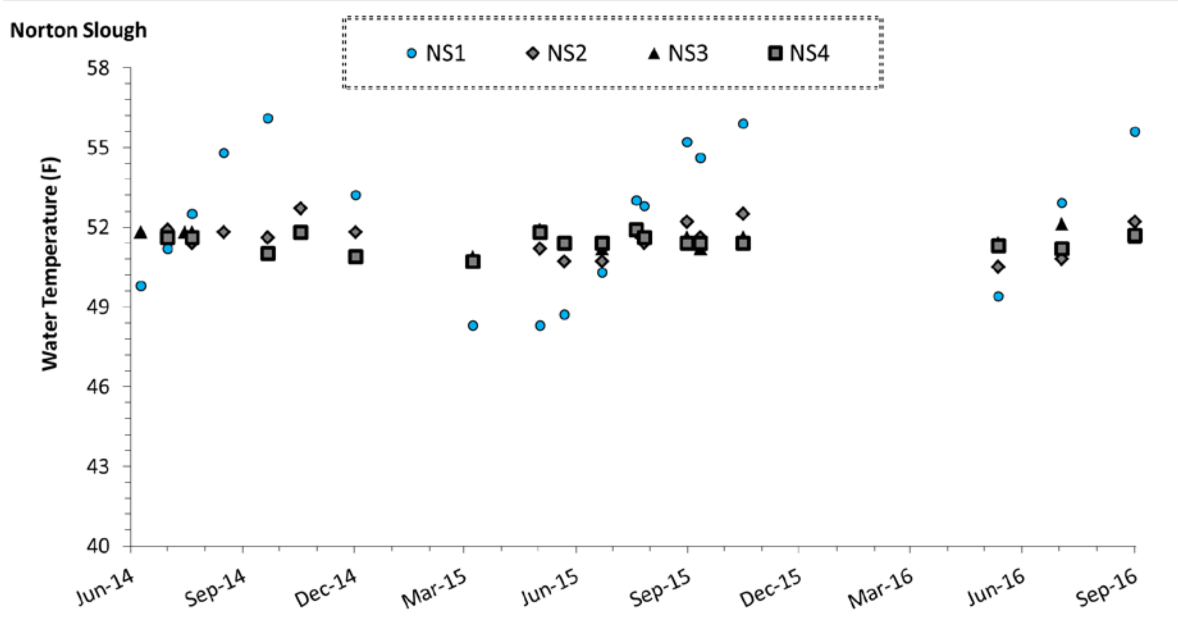



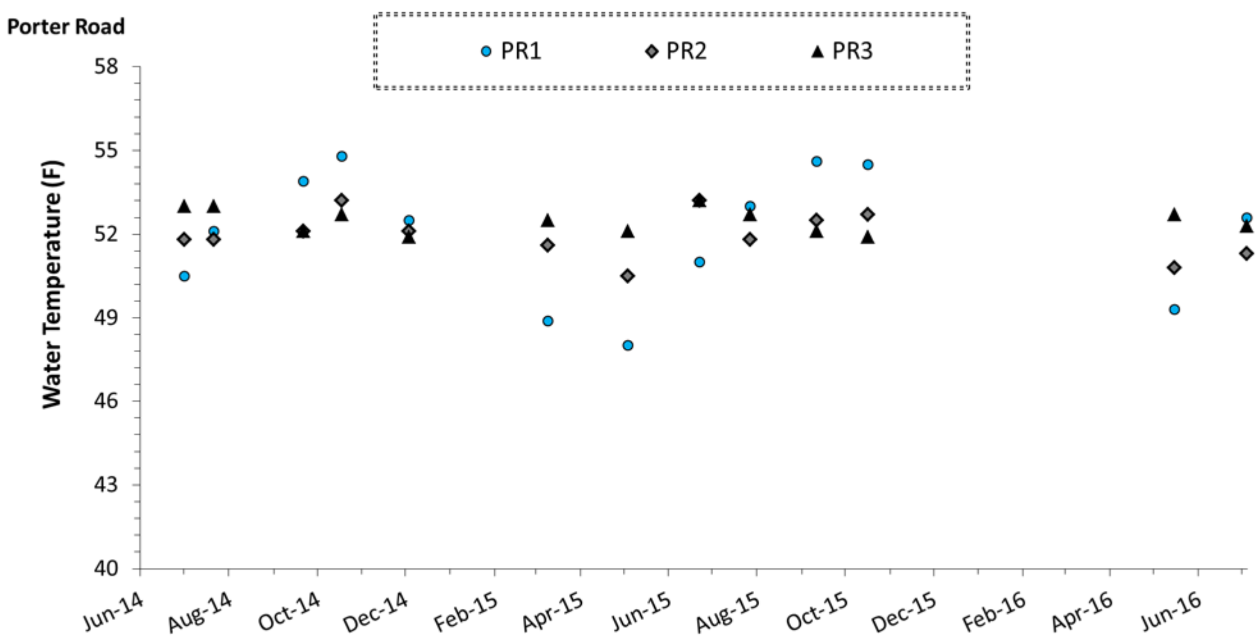

Jones Prairie
JP1
JP2
JP3
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16


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
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

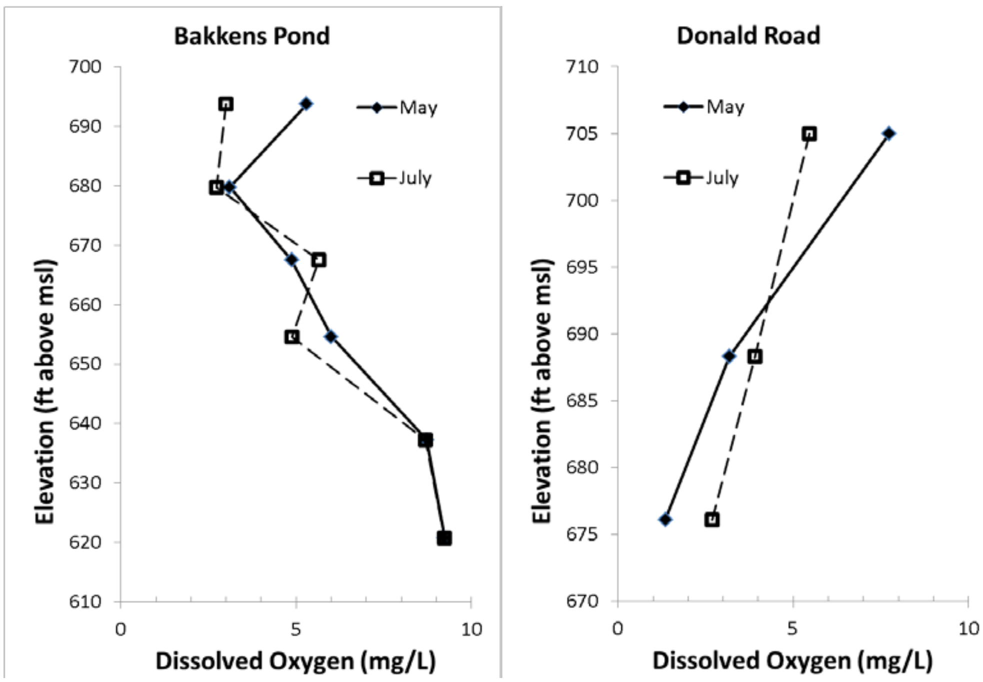

Long Lake
LL1
LL2
LL3
LL4
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16

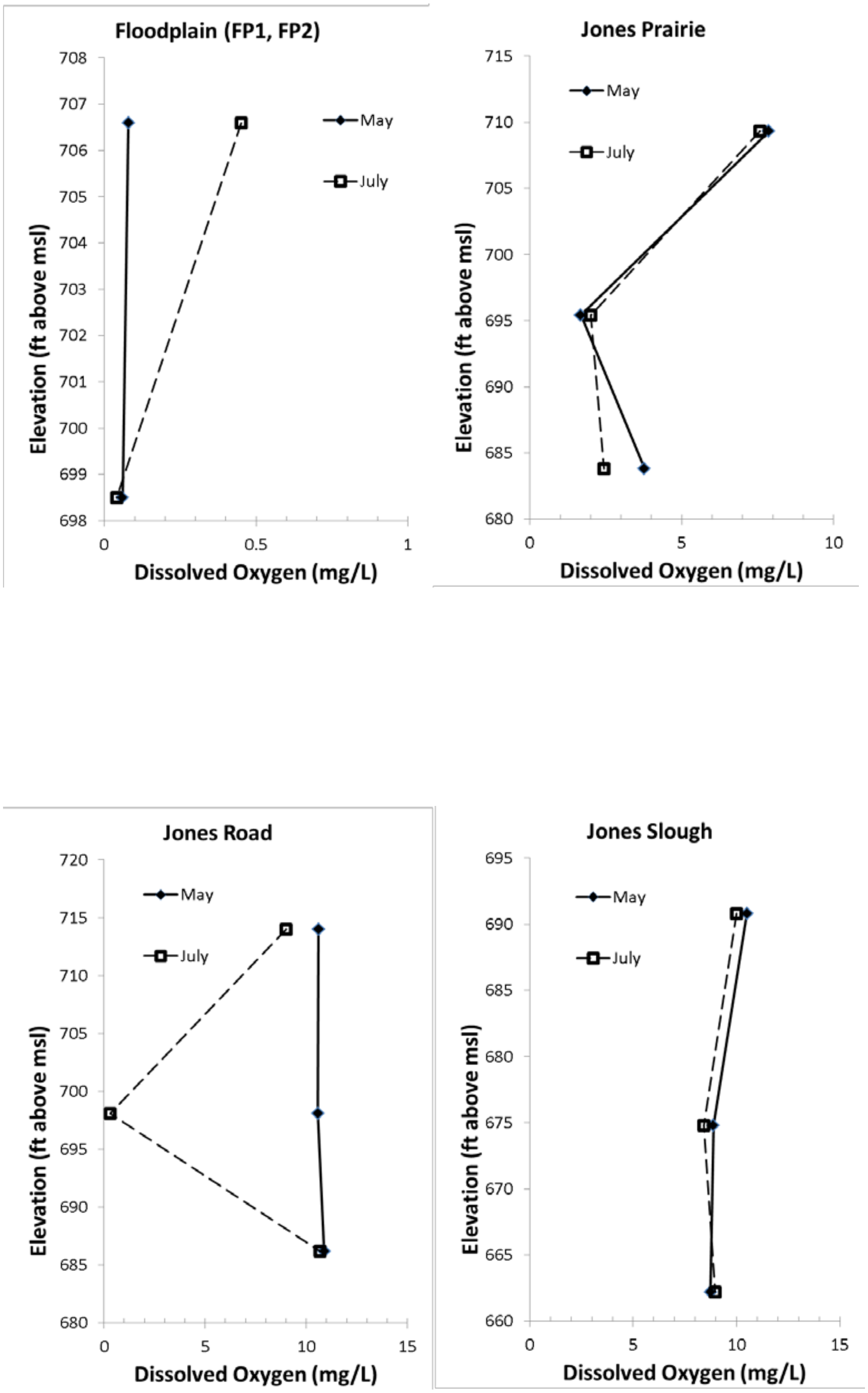

Norton Slough
NS1
NS2
NS3
NS4
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Sep-14
Dec-14
Mar-15
Jun-15
Sep-15
Dec-15
Mar-16
Jun-16
Sep-16


Porter Road
PR1
PR2
PR3
Water Temperature (F)
58
55
52
49
46
43
40
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
Aug-15
Oct-15
Dec-15
Feb-16
Apr-16
Jun-16

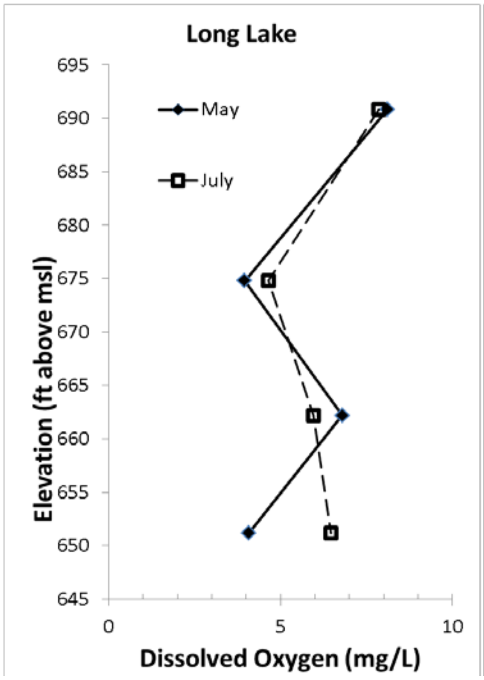
## E. Dissolved Oxygen

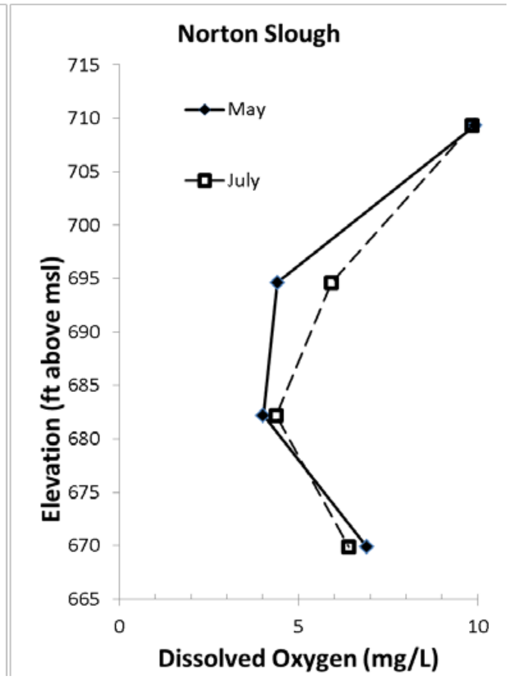
Changes in dissolved oxygen (DO) concentrations with depth recorded on May 24th and July 12th, 2016 where each point/ node corresponds to a well within its respective well nest (e.g. Donald Rd: DR1, DR2, and DR3). Note the differences in the x-axis among the well nests, particularly for the floodplain site. The majority of wells had DO concentrations above the levels expected for denitrification to occur.

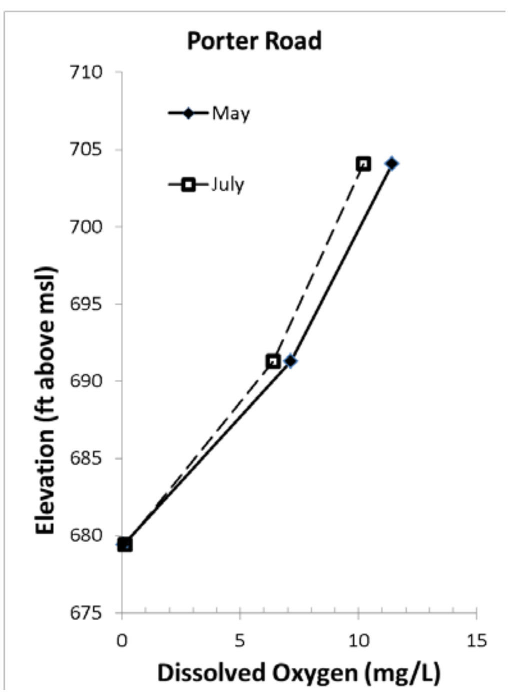



Floodplain (FP1, FP2)
708
707
706
705
704
703
702
701
700
699
698
0
0.5
1
May
July
Elevation (ft above msl)
Dissolved Oxygen (mg/L)
Jones Prairie
715
710
705
700
695
690
685
680
0
5
10
May
July
Elevation (ft above msl)
Dissolved Oxygen (mg/L)
Jones Road
720
715
710
705
700
695
690
685
680
0
5
10
15
May
July
Elevation (ft above msl)
Dissolved Oxygen (mg/L)
Jones Slough
695
690
685
680
675
670
665
660
0
5
10
15
May
July
Elevation (ft above msl)
Dissolved Oxygen (mg/L)

*Note:* the DO concentration recorded for JR2 on July 12th is unusually low and may be due to technical error.

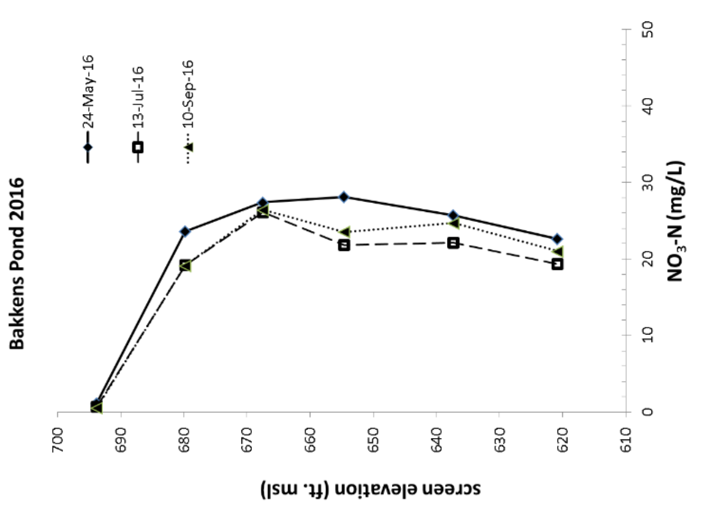


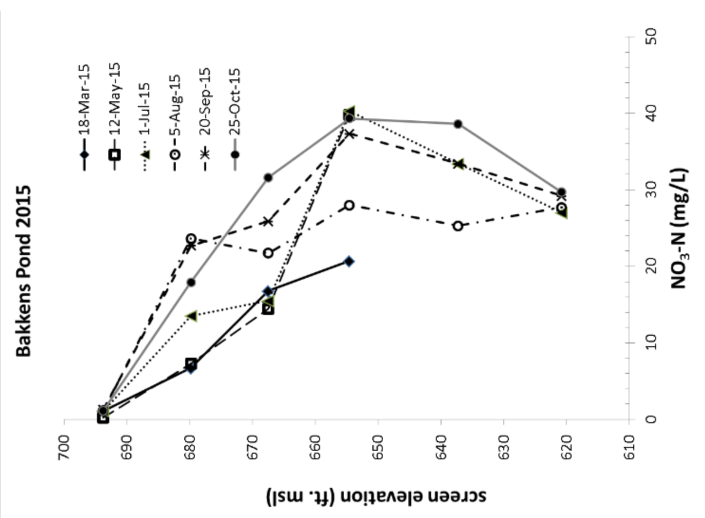



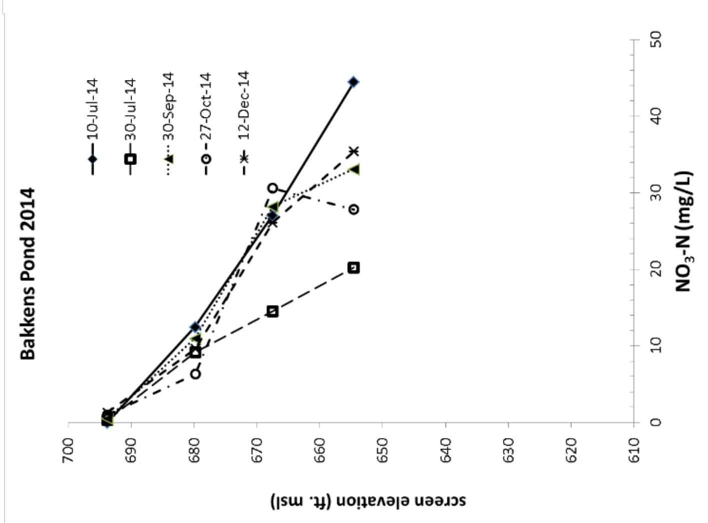



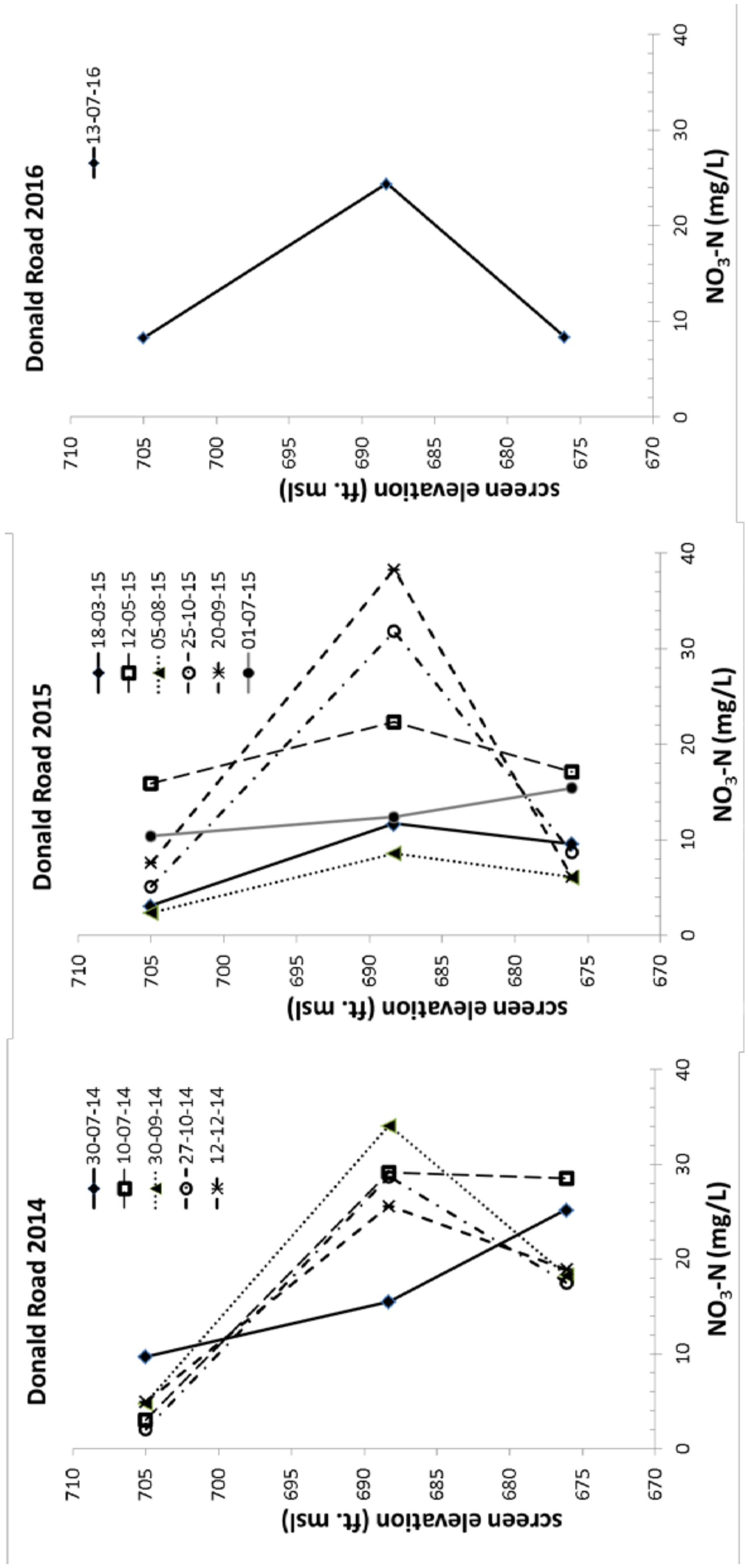
## F. Nutrients

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

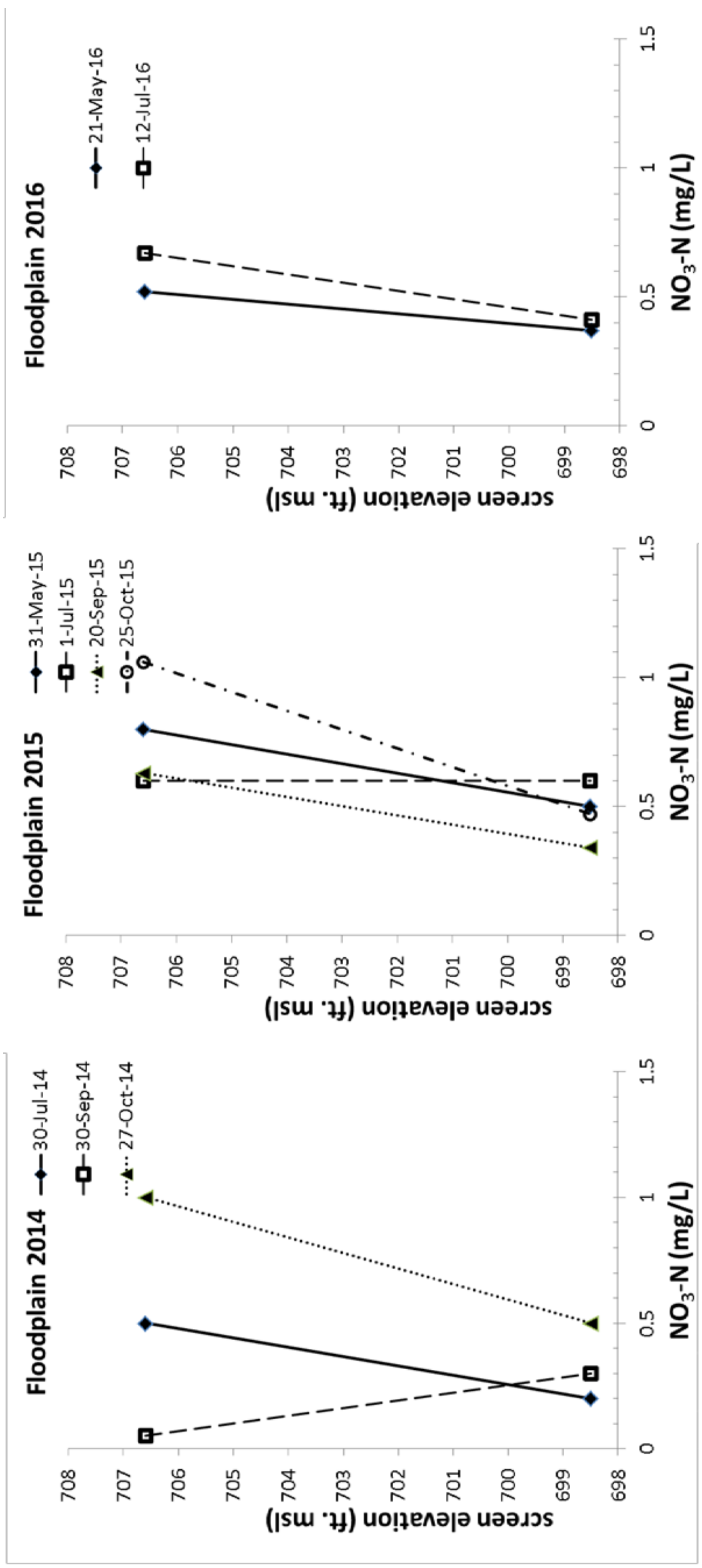


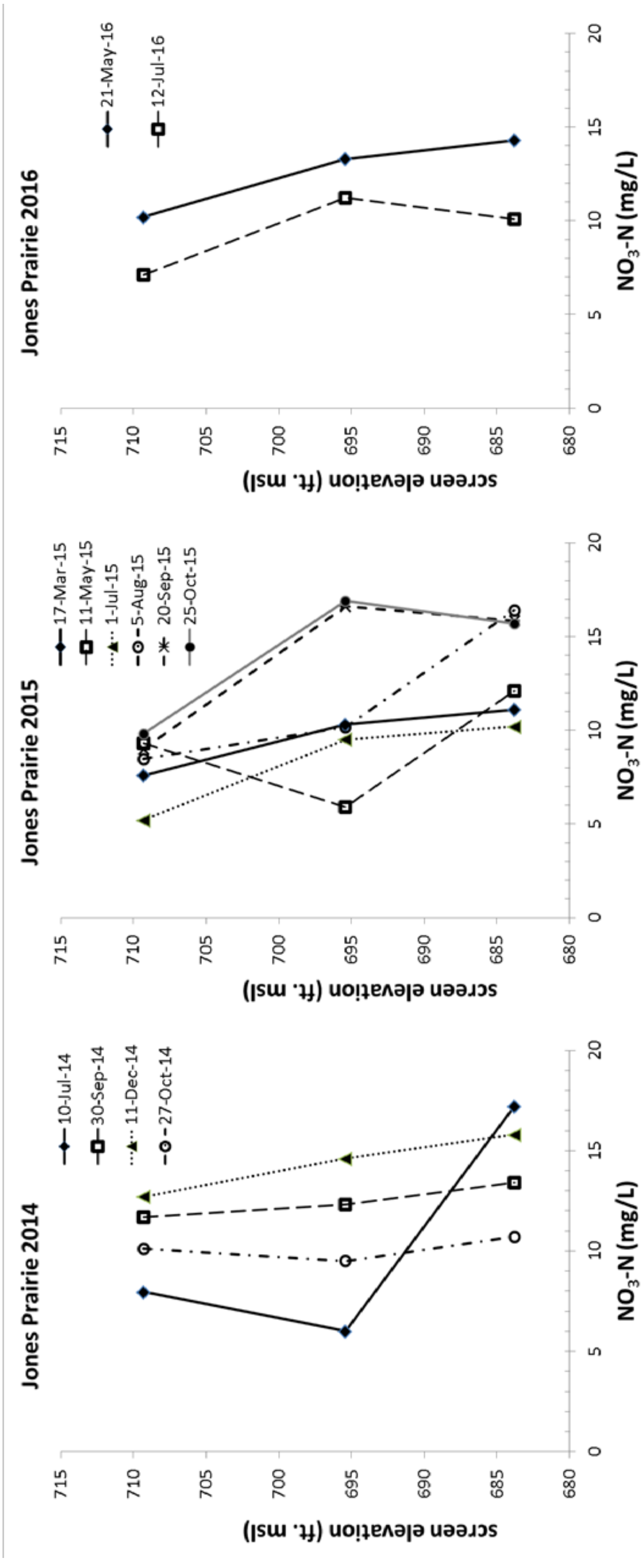



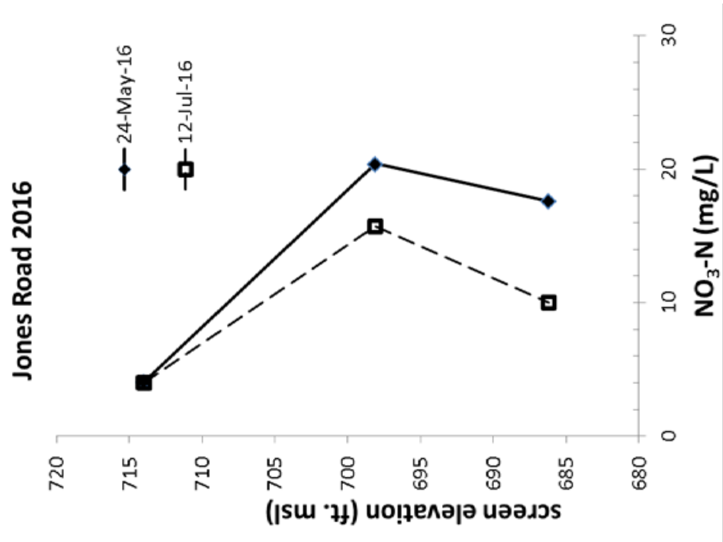


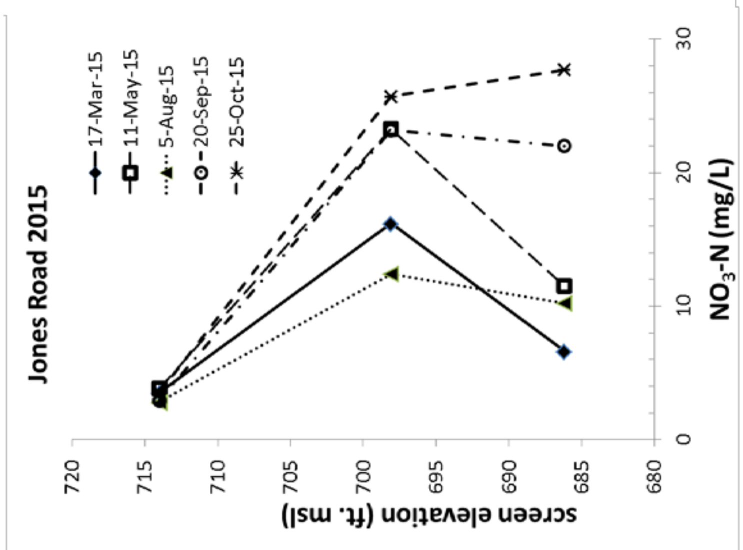
Donald Road 2016
13-07-16
Donald Road 2015
18-03-15
12-05-15
05-08-15
25-10-15
20-09-15
01-07-15
Donald Road 2014
30-07-14
10-07-14
30-09-14
27-10-14
12-12-14
NO$_3$-N (mg/L)
screen elevation (ft. msl)
0
10
20
30
40
670
675
680
685
690
695
700
705
710

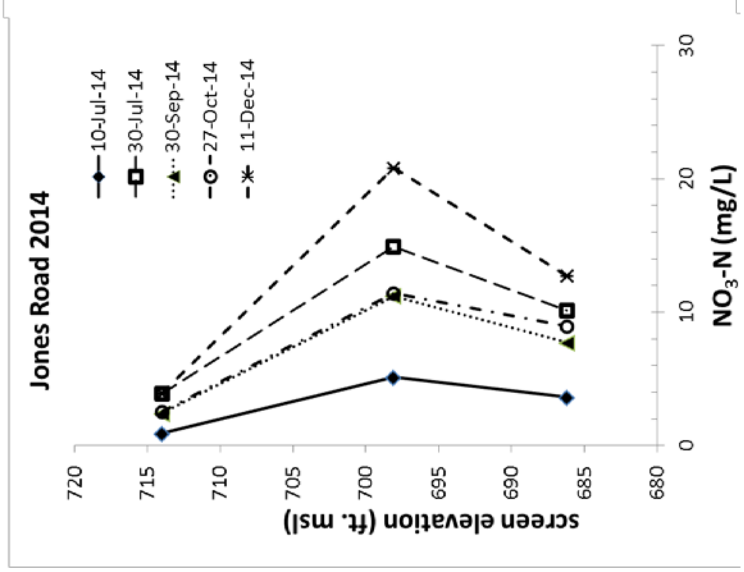


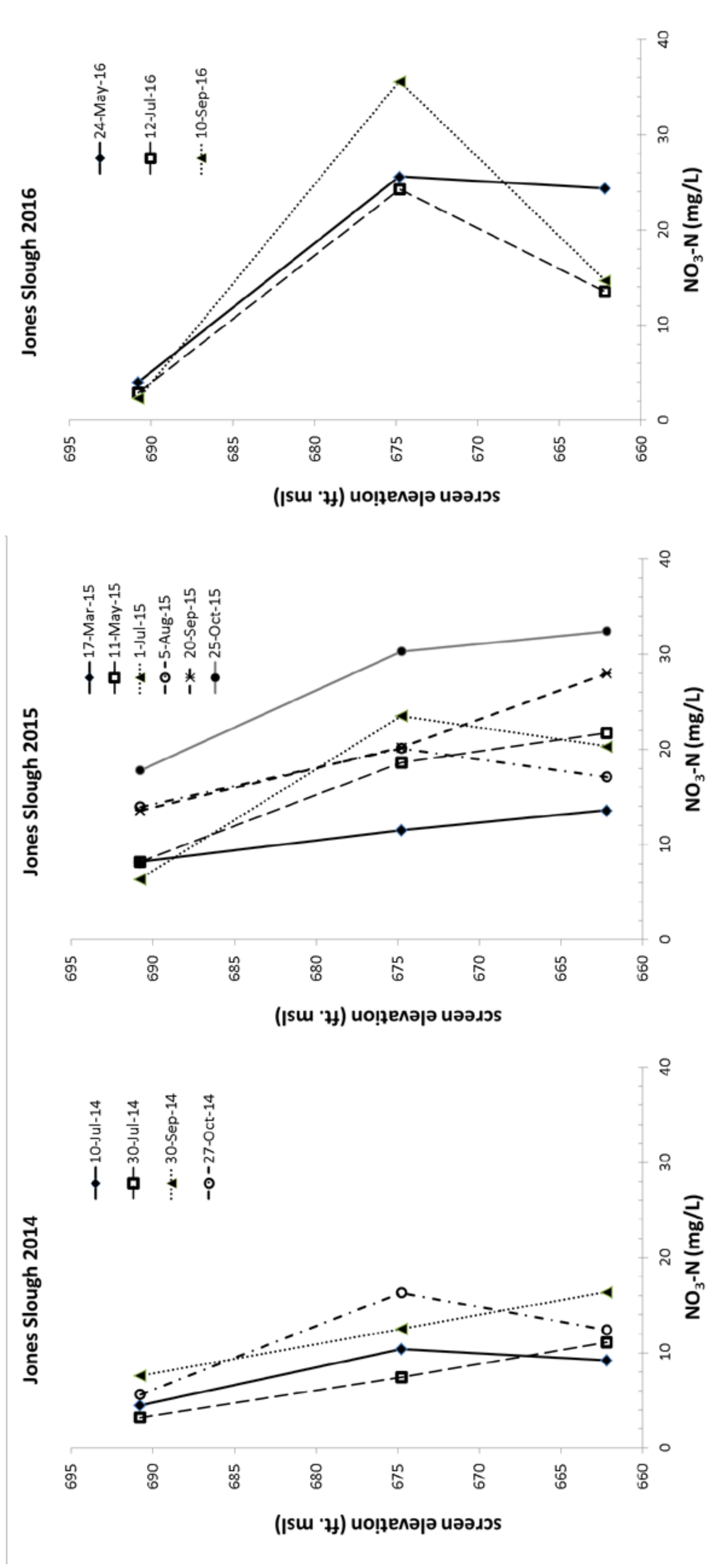
Floodplain 2014
30-Jul-14
30-Sep-14
27-Oct-14
Floodplain 2015
31-May-15
1-Jul-15
20-Sep-15
25-Oct-15
Floodplain 2016
21-May-16
12-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)
708
707
706
705
704
703
702
701
700
699
698
0
0.5
1
1.5

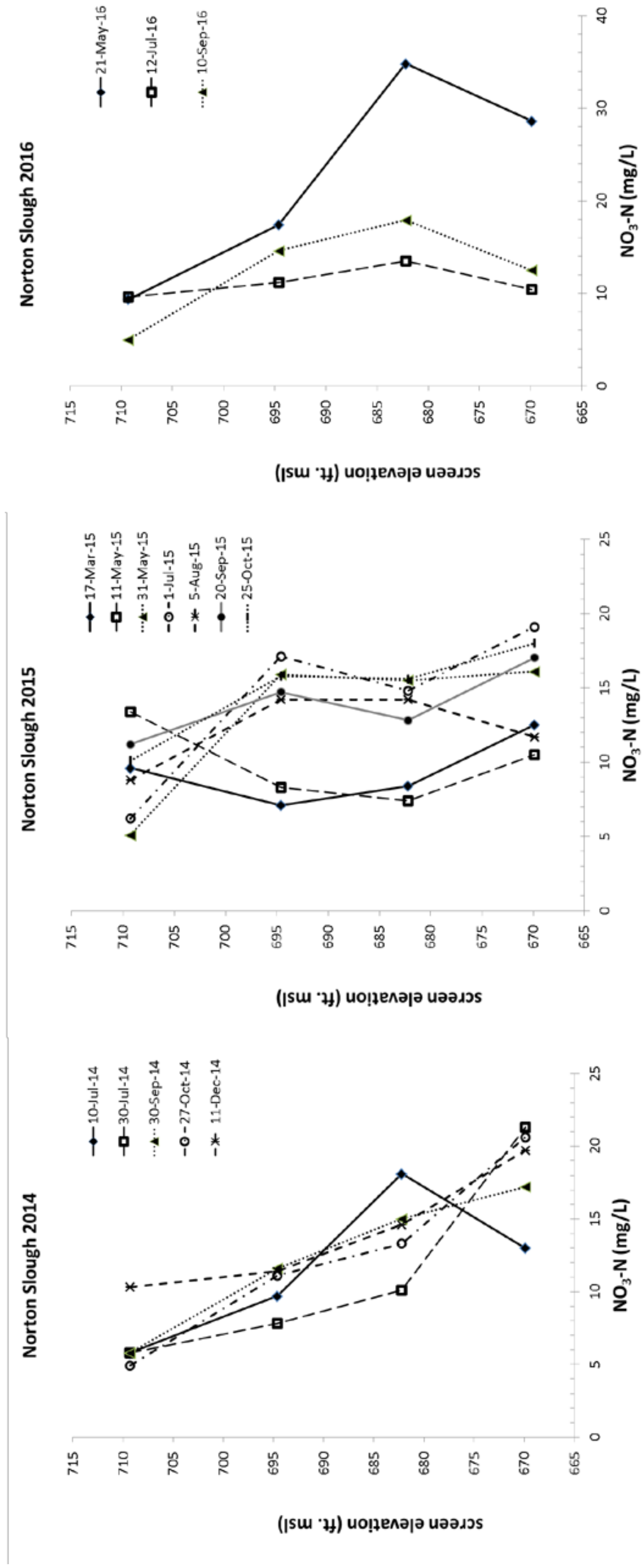

Jones Prairie 2014
10-Jul-14
30-Sep-14
11-Dec-14
27-Oct-14
screen elevation (ft. msl)
NO3-N (mg/L)
Jones Prairie 2015
17-Mar-15
11-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
NO3-N (mg/L)
Jones Prairie 2016
21-May-16
12-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)

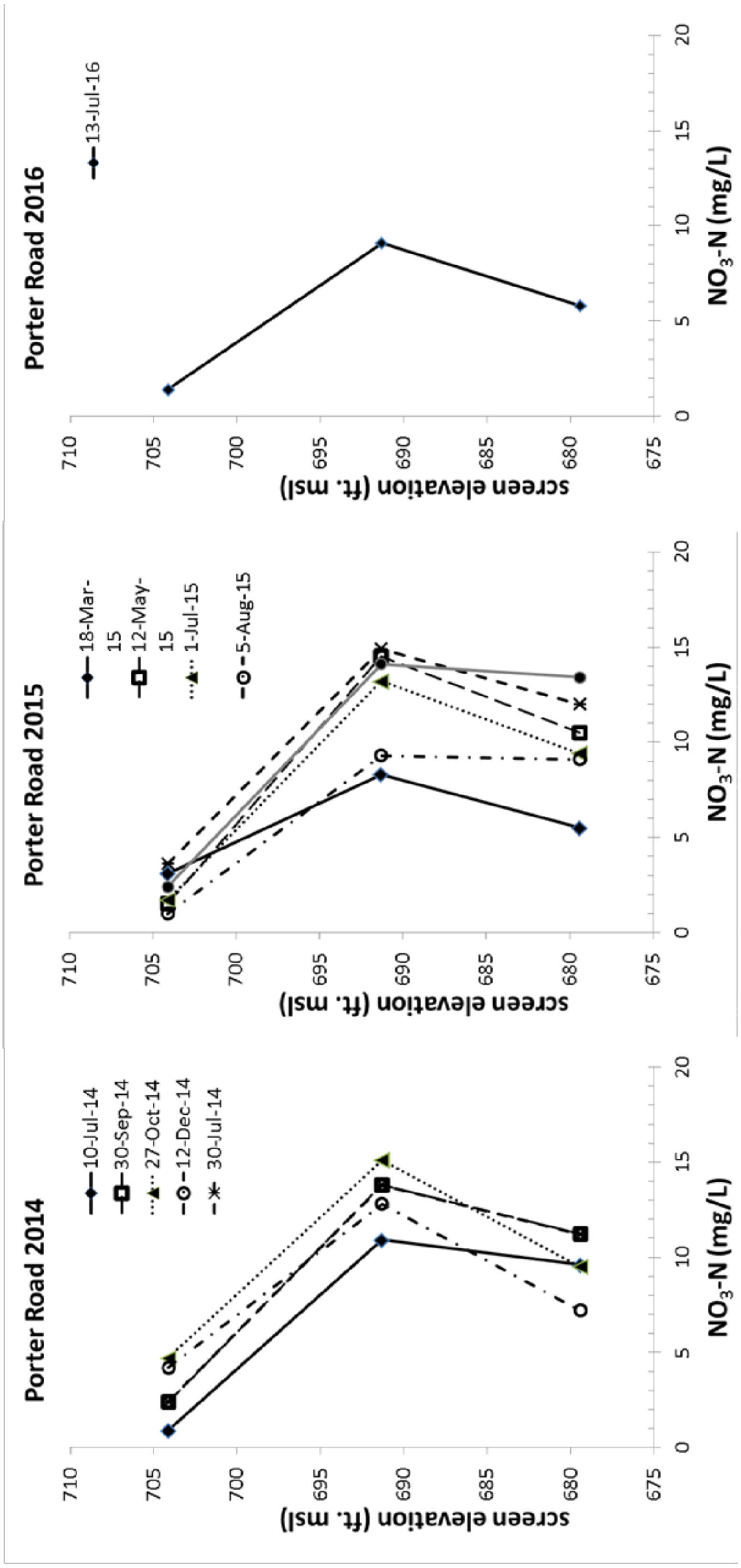

Jones Road 2016
24-May-16
12-Jul-16
screen elevation (ft. msl)
720
715
710
705
700
695
690
685
680
0
10
20
30
NO3-N (mg/L)

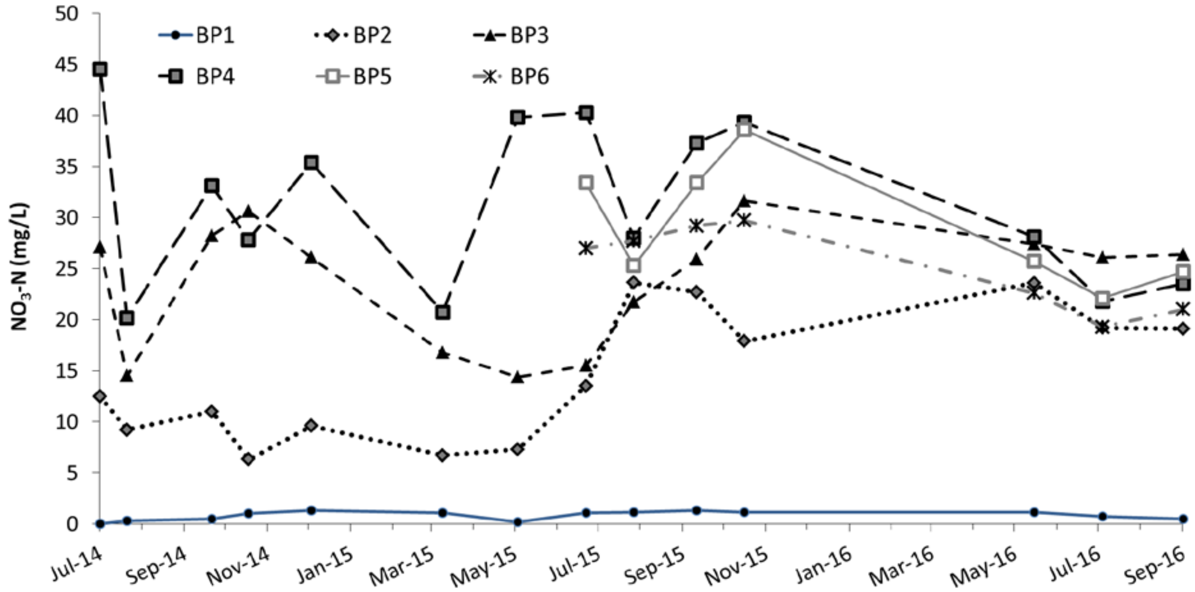

Jones Road 2015
17-Mar-15
11-May-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
720
715
710
705
700
695
690
685
680
0
10
20
30
NO3-N (mg/L)


Jones Road 2014
10-Jul-14
30-Jul-14
30-Sep-14
27-Oct-14
11-Dec-14
screen elevation (ft. msl)
720
715
710
705
700
695
690
685
680
0
10
20
30
NO3-N (mg/L)

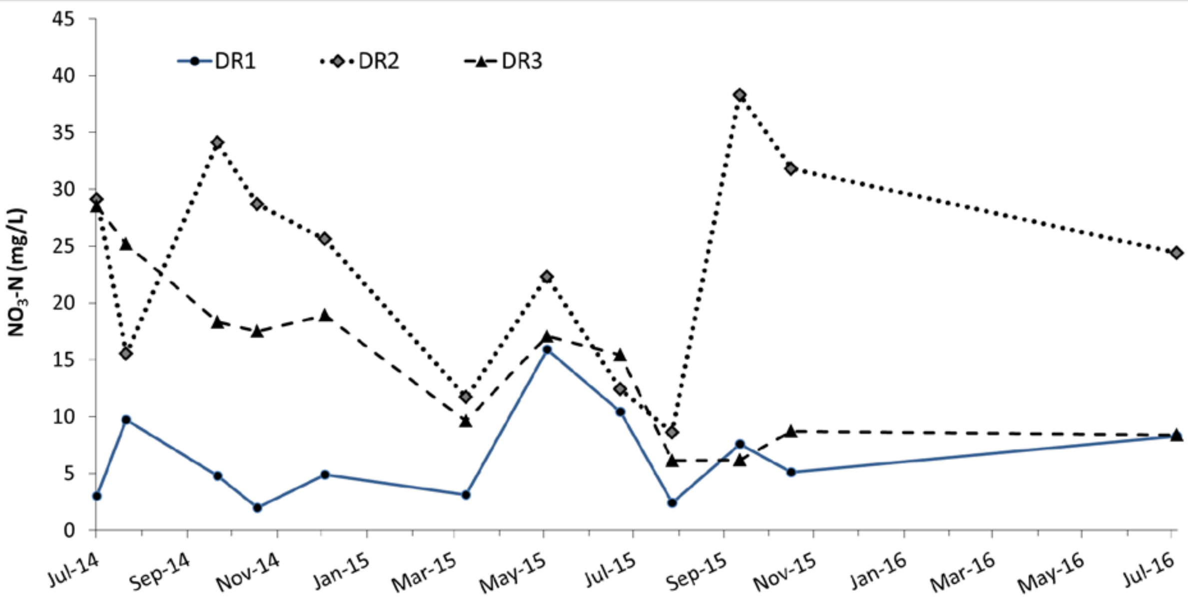

Jones Slough 2016
24-May-16
12-Jul-16
10-Sep-16
screen elevation (ft. msl)
NO3-N (mg/L)
Jones Slough 2015
17-Mar-15
11-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
screen elevation (ft. msl)
NO3-N (mg/L)
Jones Slough 2014
10-Jul-14
30-Jul-14
30-Sep-14
27-Oct-14
screen elevation (ft. msl)
NO3-N (mg/L)


Norton Slough 2016
21-May-16
12-Jul-16
10-Sep-16
Norton Slough 2015
17-Mar-15
11-May-15
31-May-15
1-Jul-15
5-Aug-15
20-Sep-15
25-Oct-15
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)

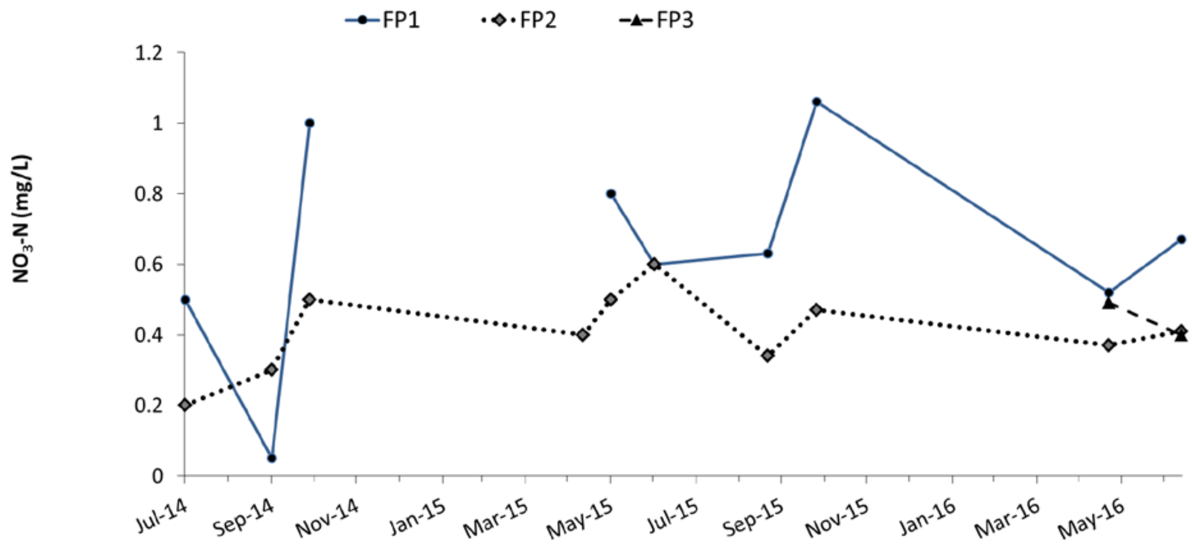

Porter Road 2016
13-Jul-16
screen elevation (ft. msl)
NO3-N (mg/L)
Porter Road 2015
18-Mar-15
12-May-15
1-Jul-15
5-Aug-15
screen elevation (ft. msl)
NO3-N (mg/L)
Porter Road 2014
10-Jul-14
30-Sep-14
27-Oct-14
12-Dec-14
30-Jul-14
screen elevation (ft. msl)
NO3-N (mg/L)

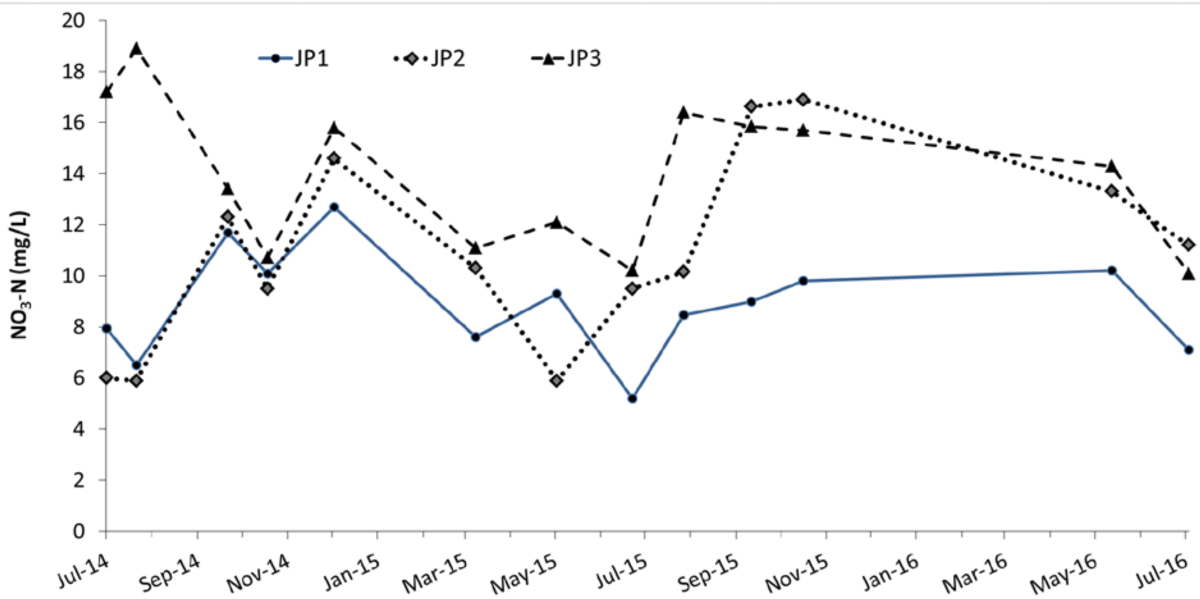


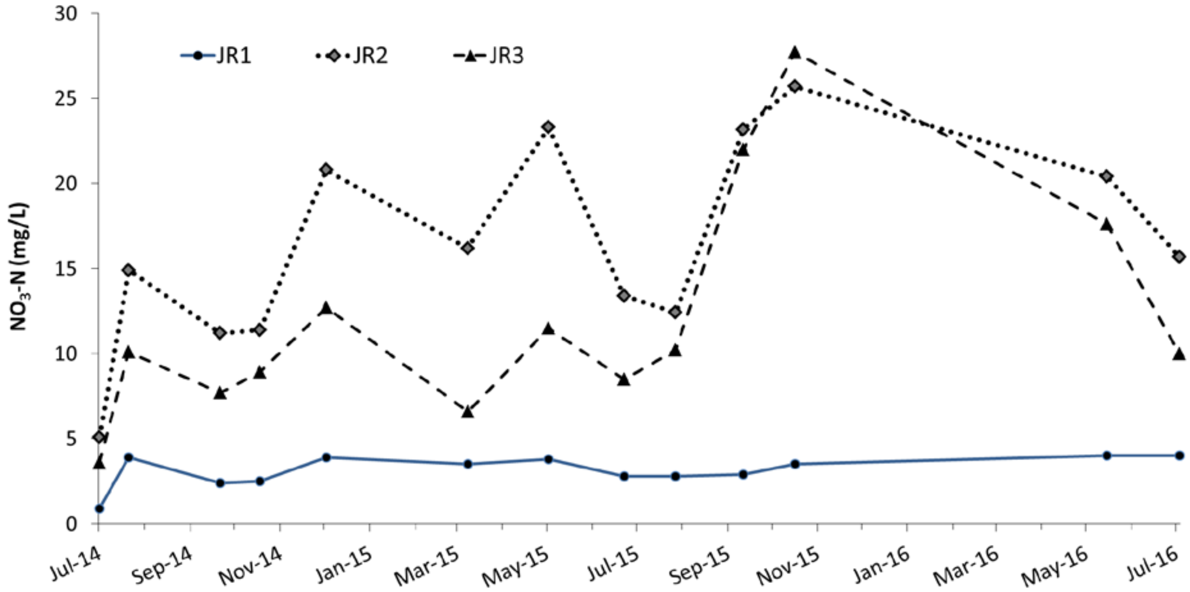
BP1
BP2
BP3
BP4
BP5
BP6
NO3-N (mg/L)
50
45
40
35
30
25
20
15
10
5
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16
Sep-16

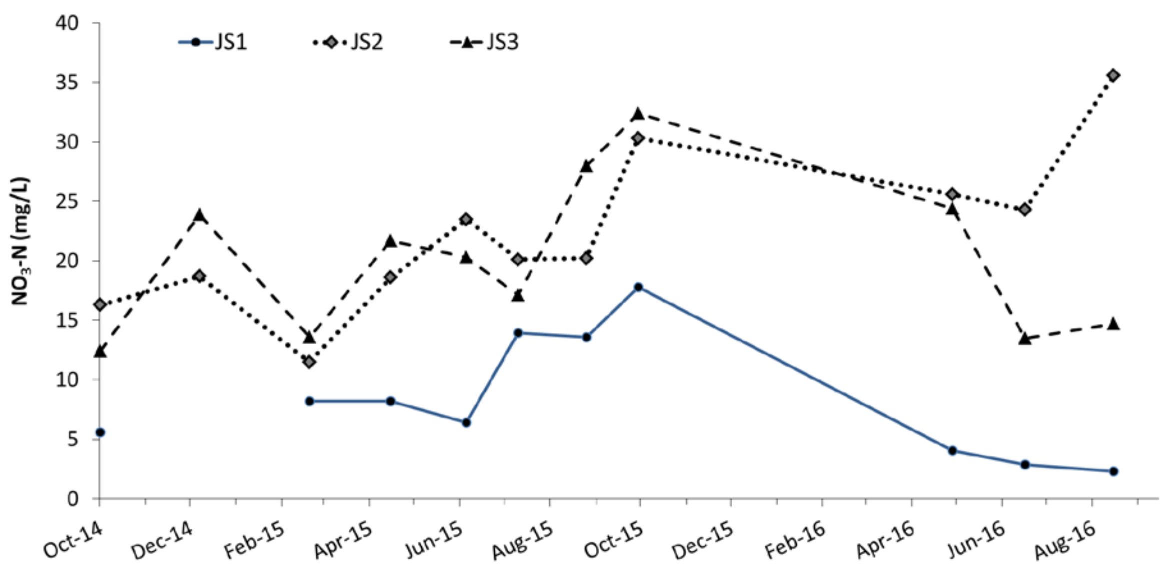



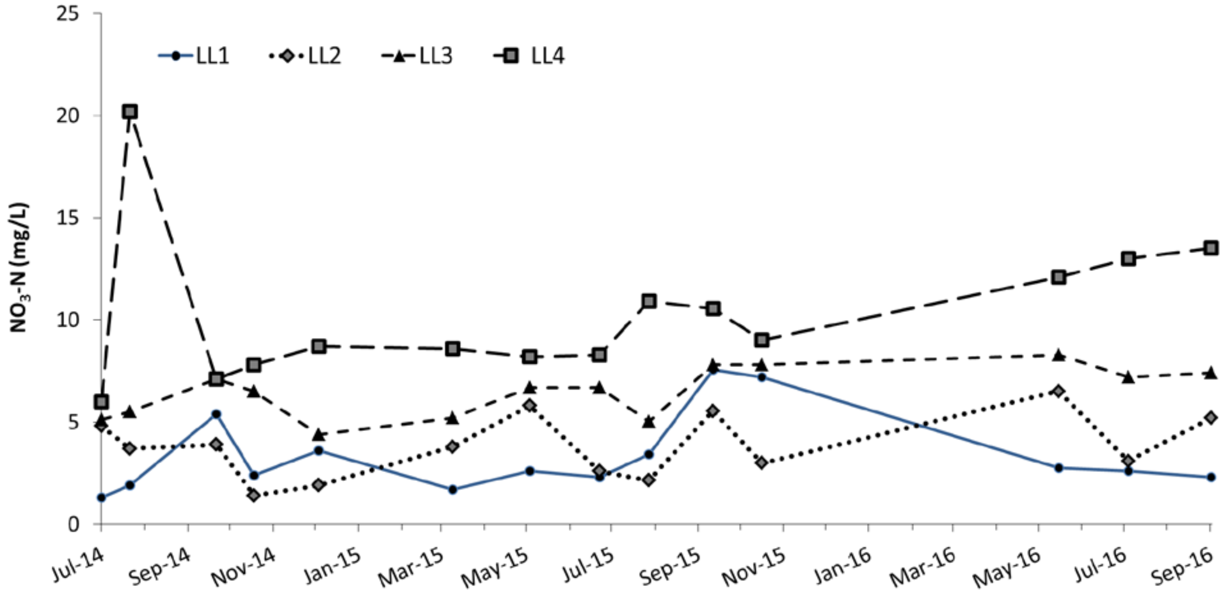
DR1
DR2
DR3
NO3-N (mg/L)
45
40
35
30
25
20
15
10
5
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16

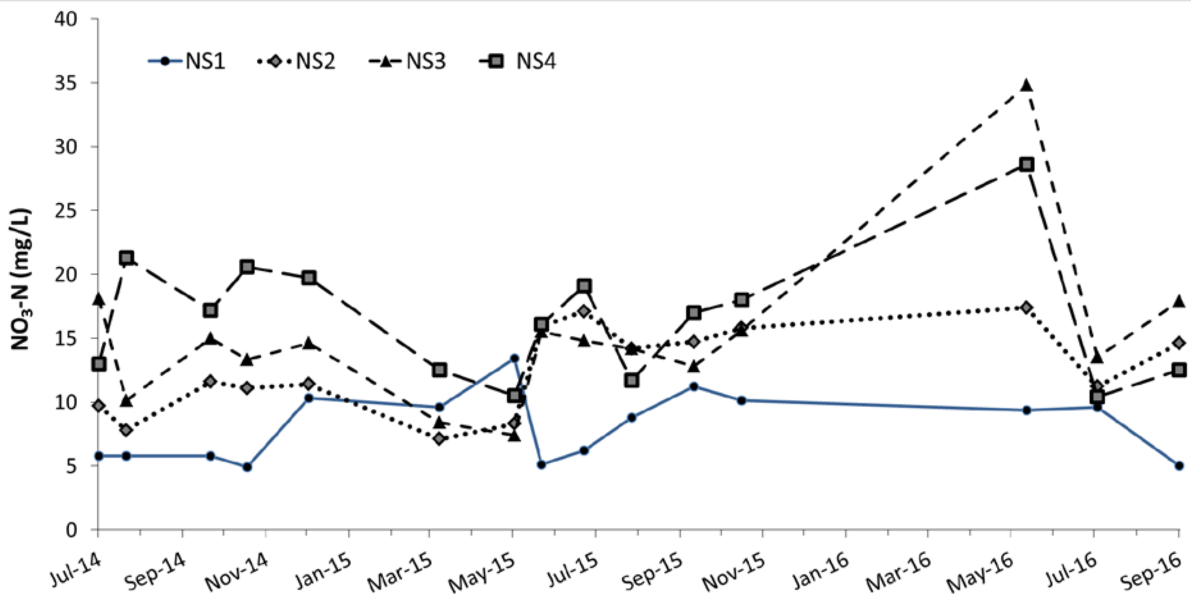

FP1
FP2
FP3
NO3-N (mg/L)
1.2
1
0.8
0.6
0.4
0.2
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16

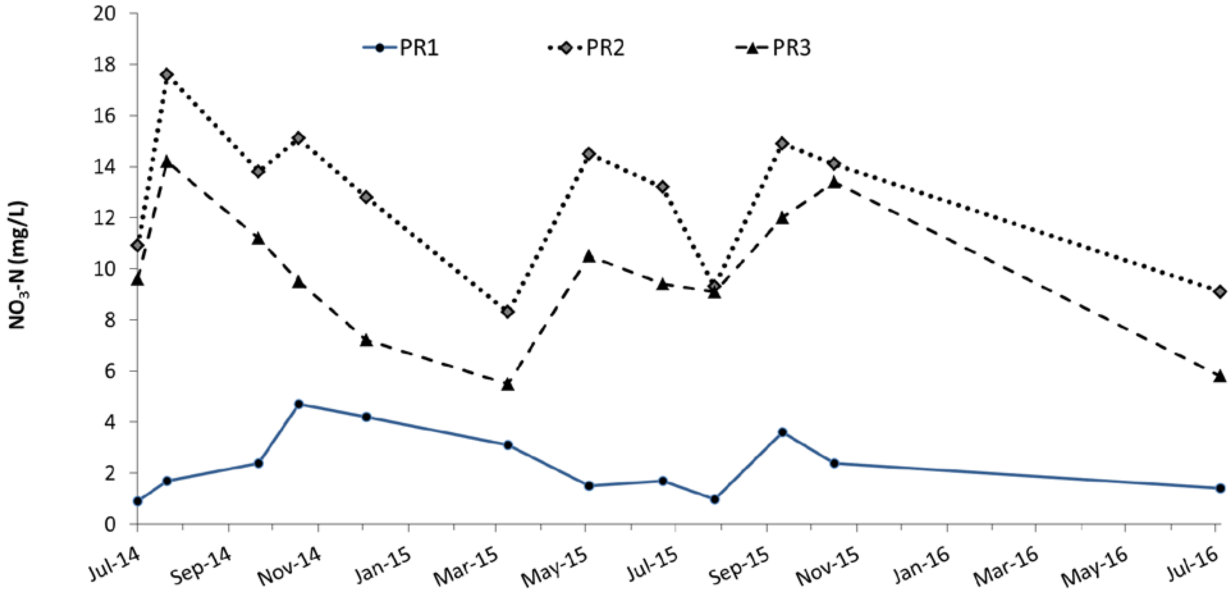

JP1
JP2
JP3
NO3-N (mg/L)
20
18
16
14
12
10
8
6
4
2
0
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Jul-15
Sep-15
Nov-15
Jan-16
Mar-16
May-16
Jul-16


JR1
JR2
JR3
$NO_3$-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
$NO_3$-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)
0
5
10
15
20
25
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)
0
5
10
15
20
25
30
35
40
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
$NO_3$-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 13th, 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 |

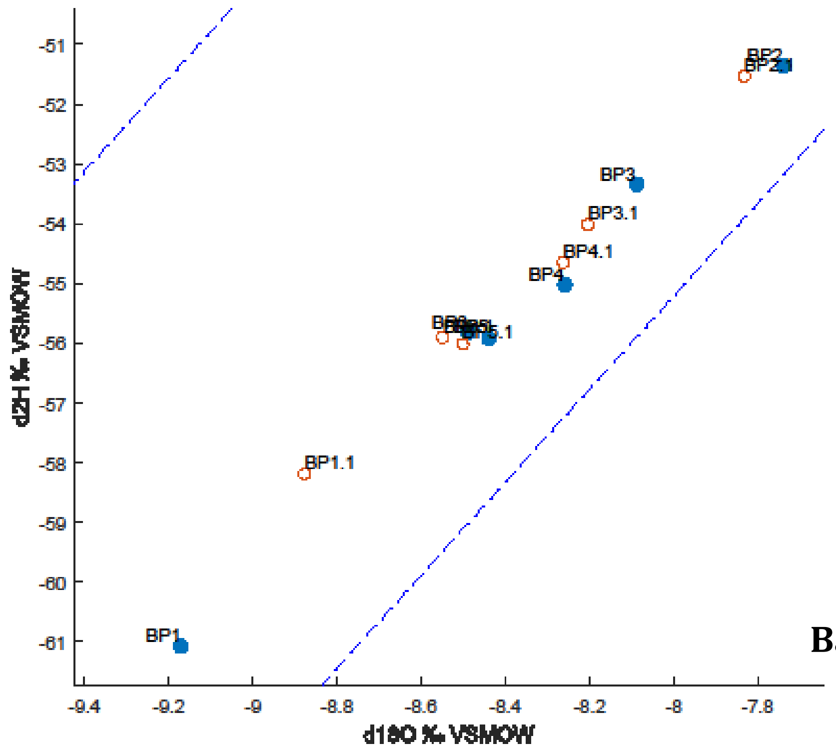
## G. Isotopes

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".

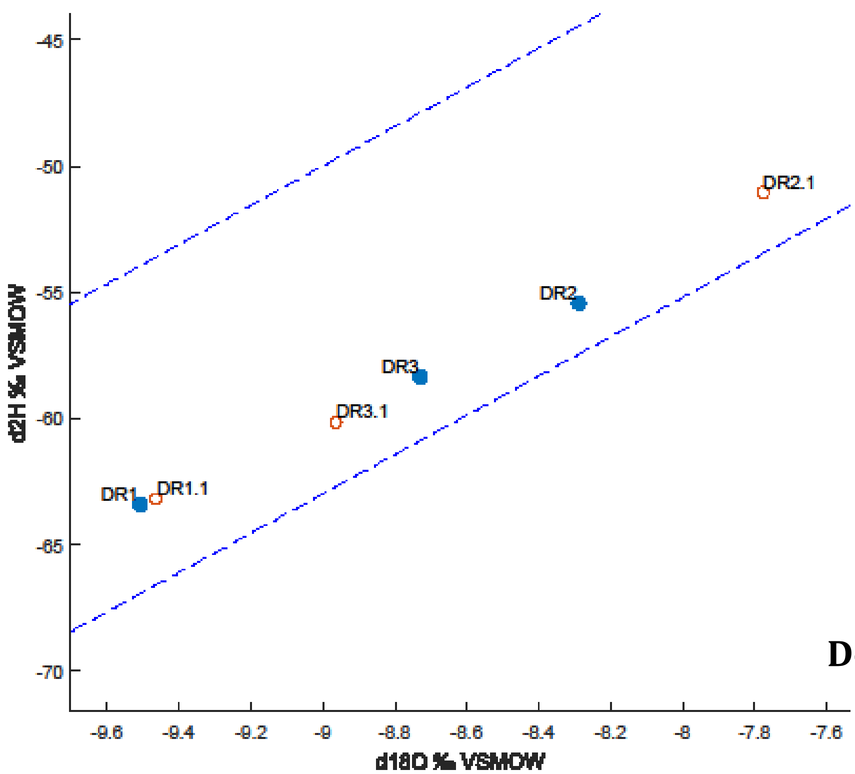
| Well ID | d18O (VSMOW) | dD (VSMOW) |
|---|---|---|
| **NS1** | **-9.31641** | **-63.35095** |
| **NS2** | -8.59964 | -56.59781 |
| **NS3** | -8.46440 | -55.42170 |
| **NS4** | -8.75903 | -57.78595 |
| **FP1** | -8.52984 | -58.65584 |
| **FP2** | -9.04829 | -62.39523 |
| **FP3** | -8.66306 | -58.60642 |
| **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 |
| | -9.71036 | -64.82326 |
| **LL1** | | |
| **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 |

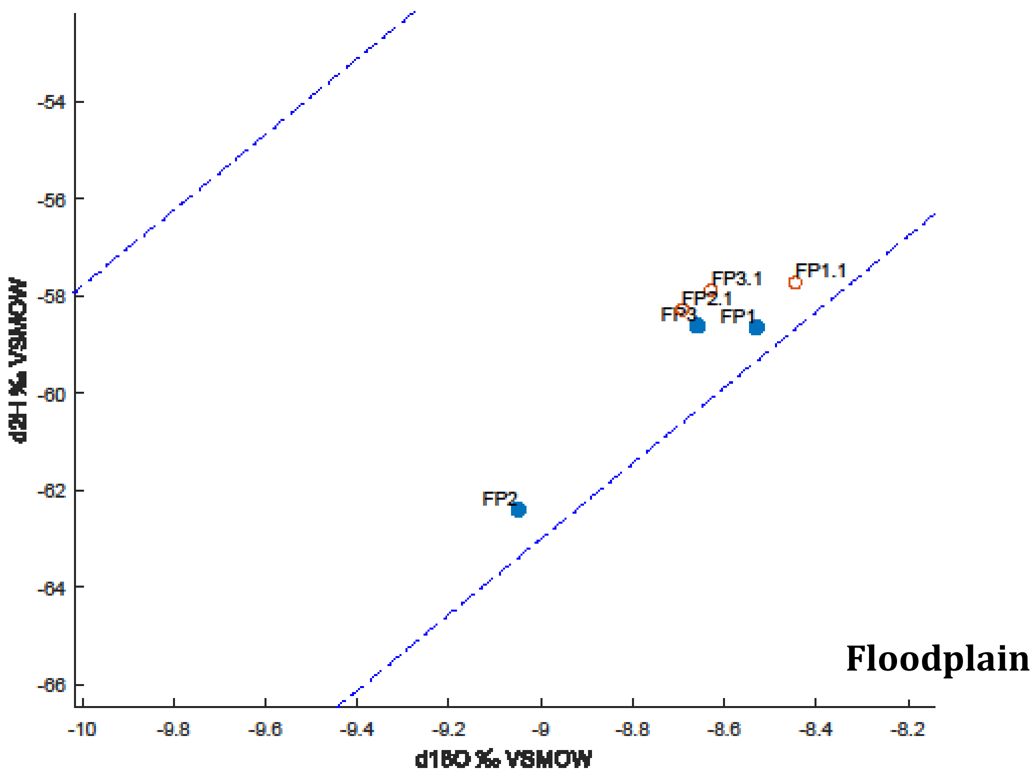
Plots of δ D versus δ¹⁸O by well nest for isotopic samples collected on May 24th (solid blue circles) and July 12th, 2016 (open orange circles). Boundaries for the LML are represented by blue dashed lines.



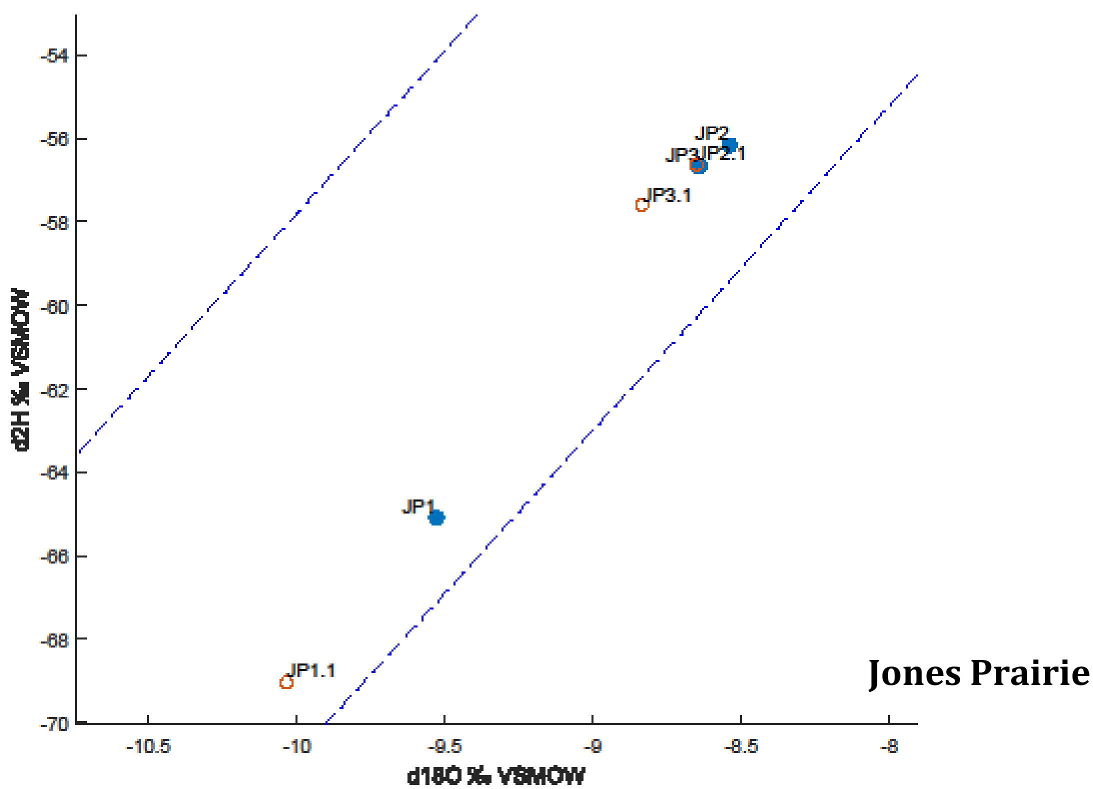

**Bakkens Pond**



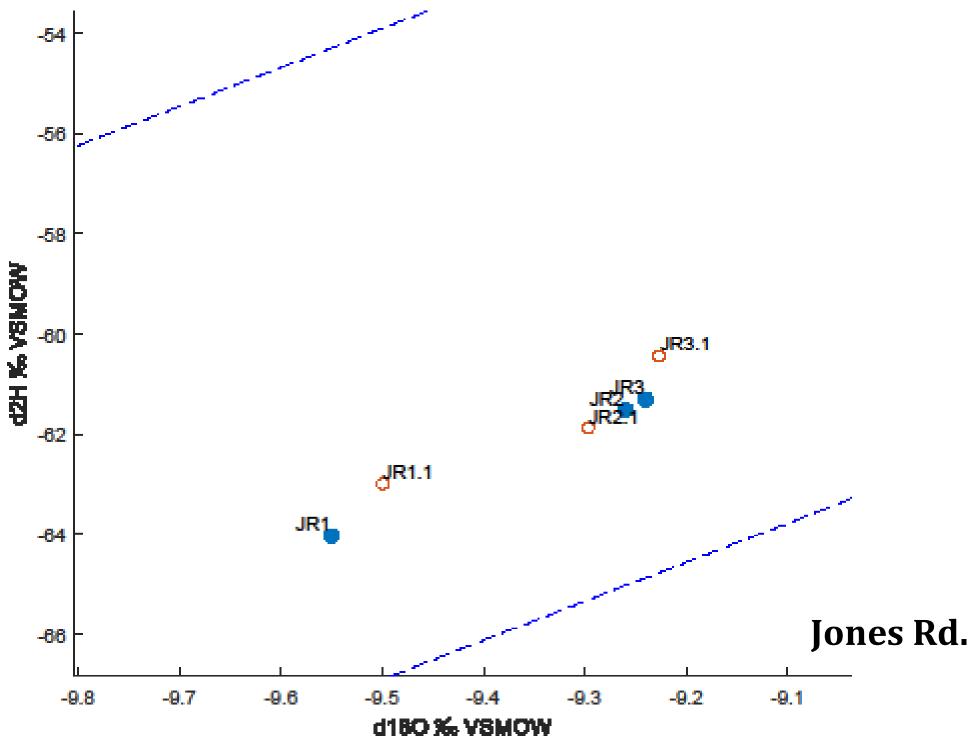

**Donald Rd.**



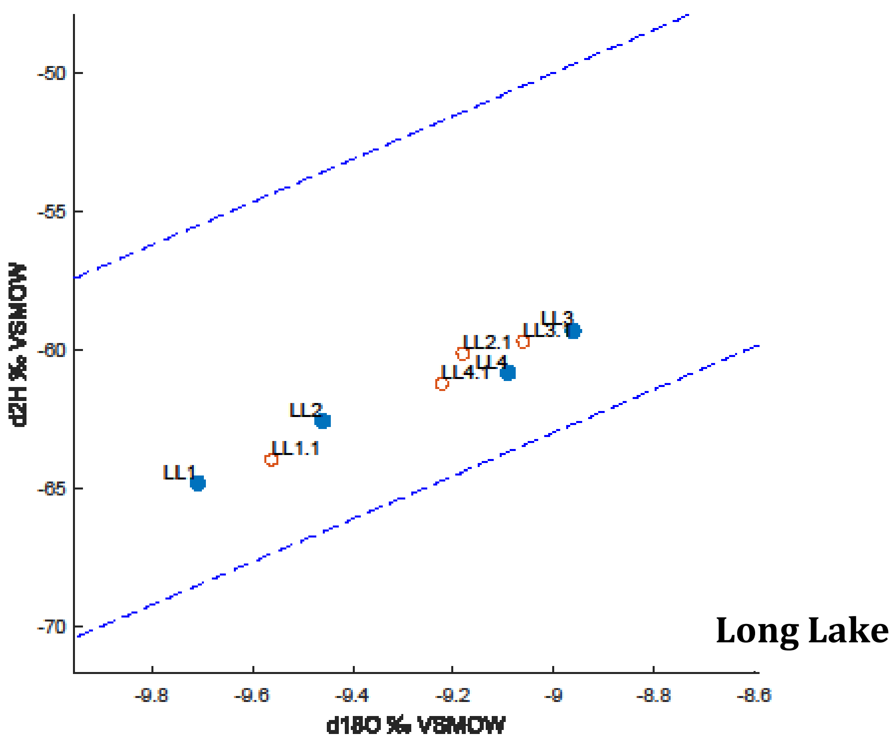
d2H ‰ VSMOW
d18O ‰ VSMOW
-54
-56
-58
-60
-62
-64
-66
-10
-9.8
-9.6
-9.4
-9.2
-9
-8.8
-8.6
-8.4
-8.2
FP3.1
FP1.1
FP2.1
FP3
FP1
FP2
Floodplain

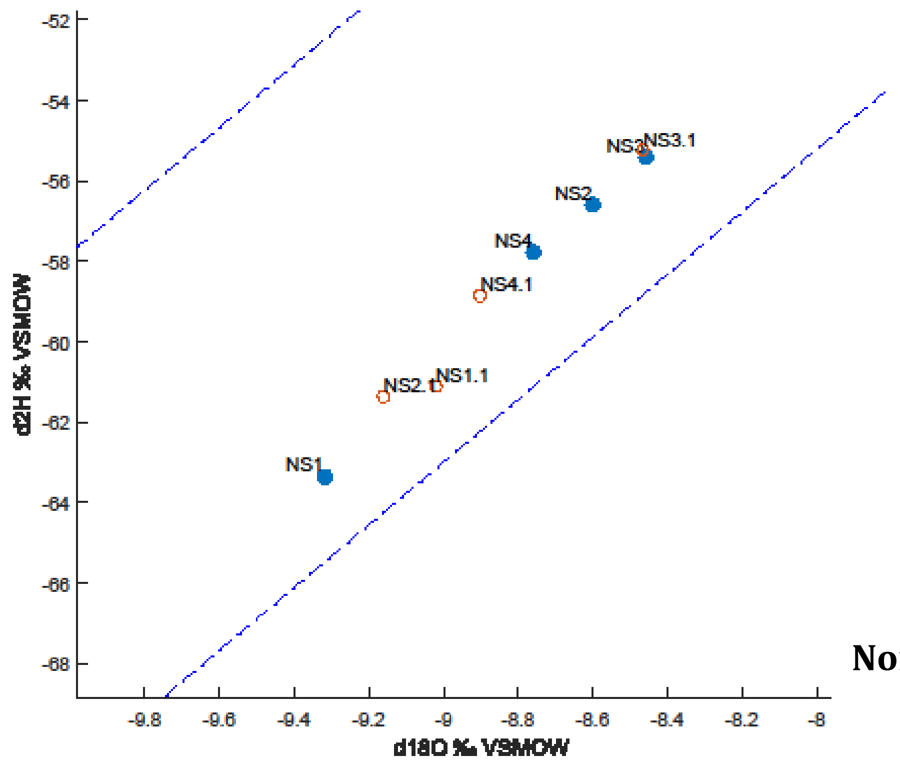
d2H ‰ VSMOW
d18O ‰ VSMOW
-54
-56
-58
-60
-62
-64
-66
-68
-70
-10.5
-10
-9.5
-9
-8.5
-8
JP2
JP3
JP2.1
JP3.1
JP1
JP1.1
Jones Prairie



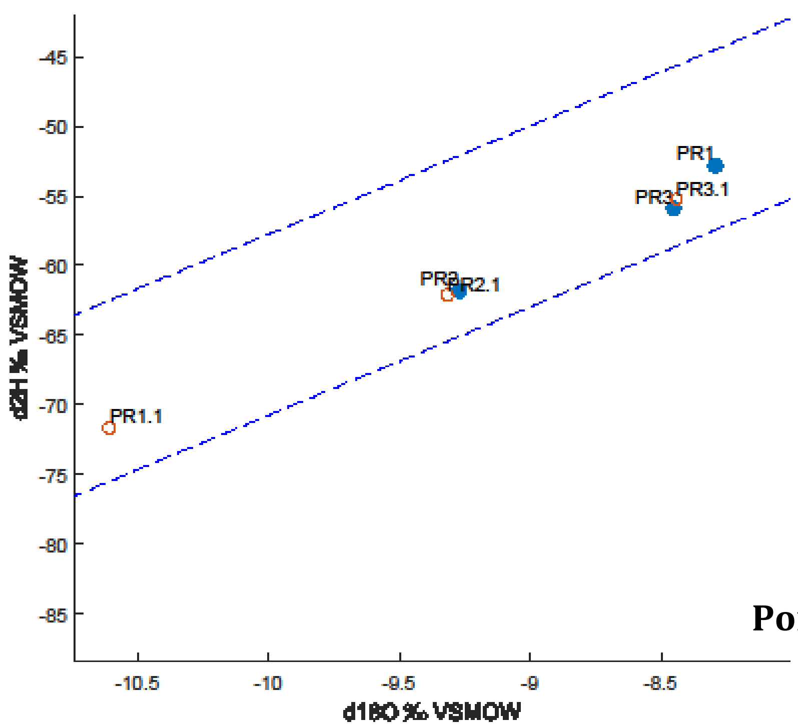
d2H ‰ VSMOW
d18O ‰ VSMOW
-54
-56
-58
-60
-62
-64
-66
-9.8
-9.7
-9.6
-9.5
-9.4
-9.3
-9.2
-9.1
JR3.1
JR3
JR2
JR2.1
JR1.1
JR1
Jones Rd.

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

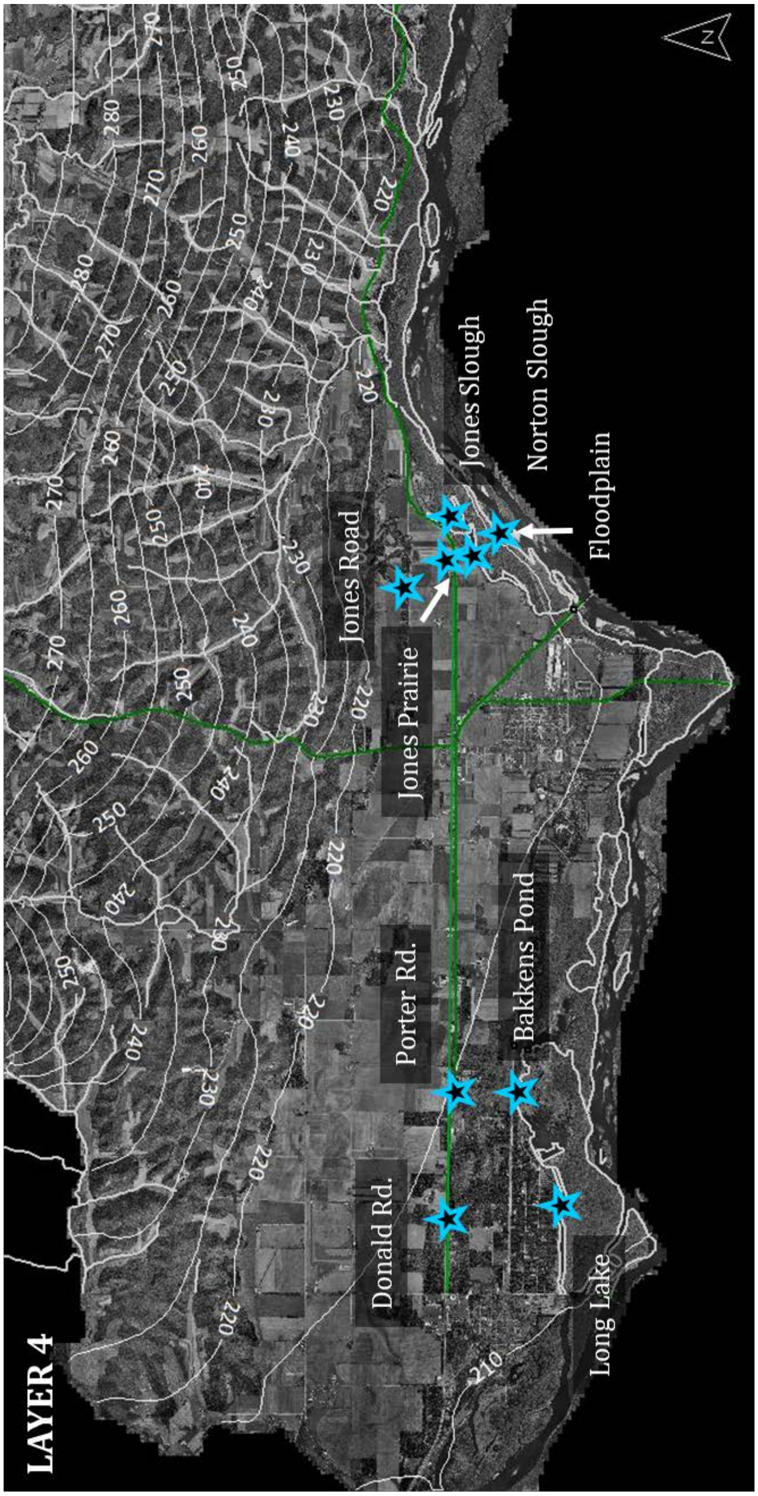



**Norton Slough**



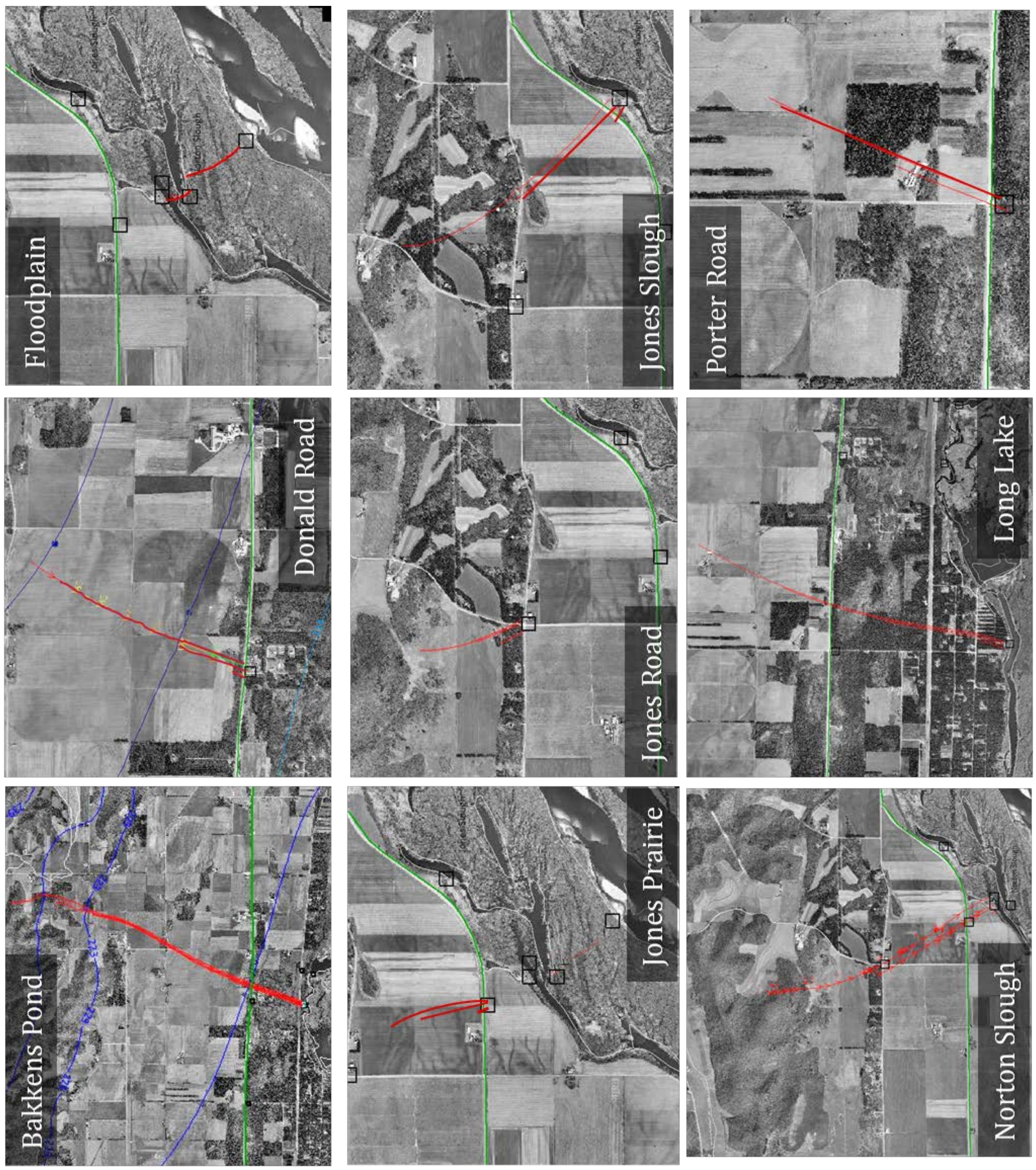

**Porter Rd.**

## H. Study Area Maps and Aerial Photographs of Recharge Sites



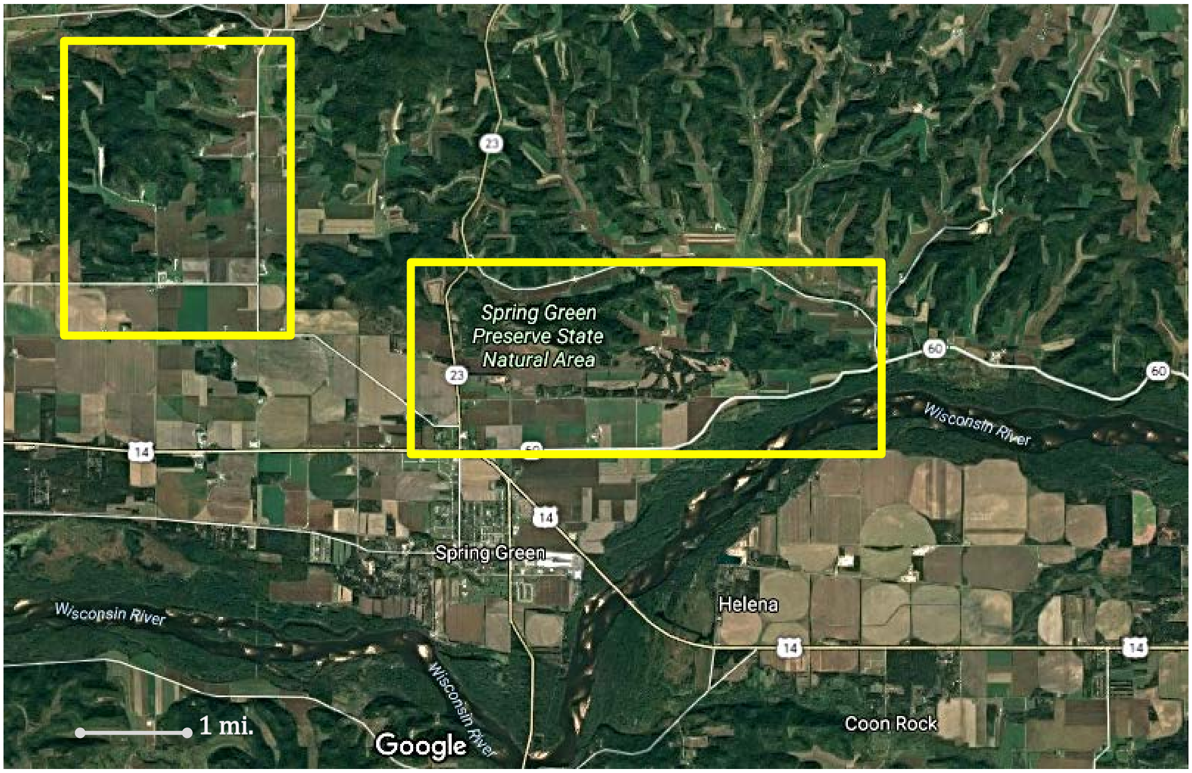

Model plan view showing head contours (meters) of the water table. Blue stars represent well nest site location. Zoomed-in panels below show results of reverse particle track for these well nests.

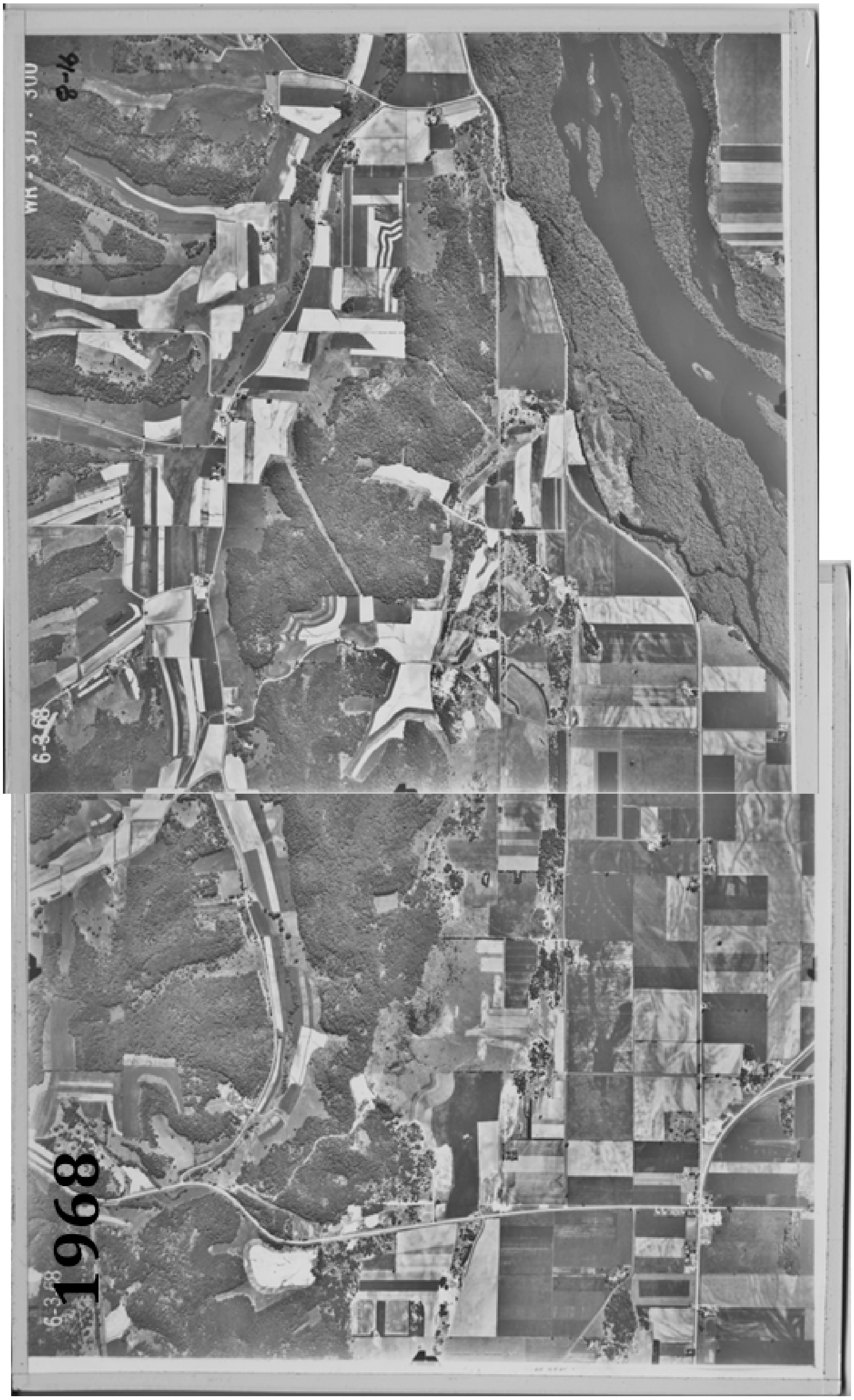
Zoomed-in panels of MODPATH reverse particle tracking results for all of the well nests. Particle paths are shown in red. Blue lines represent head contours. Green lines represent major roads. Black squares outline the location of the well nests in the model.



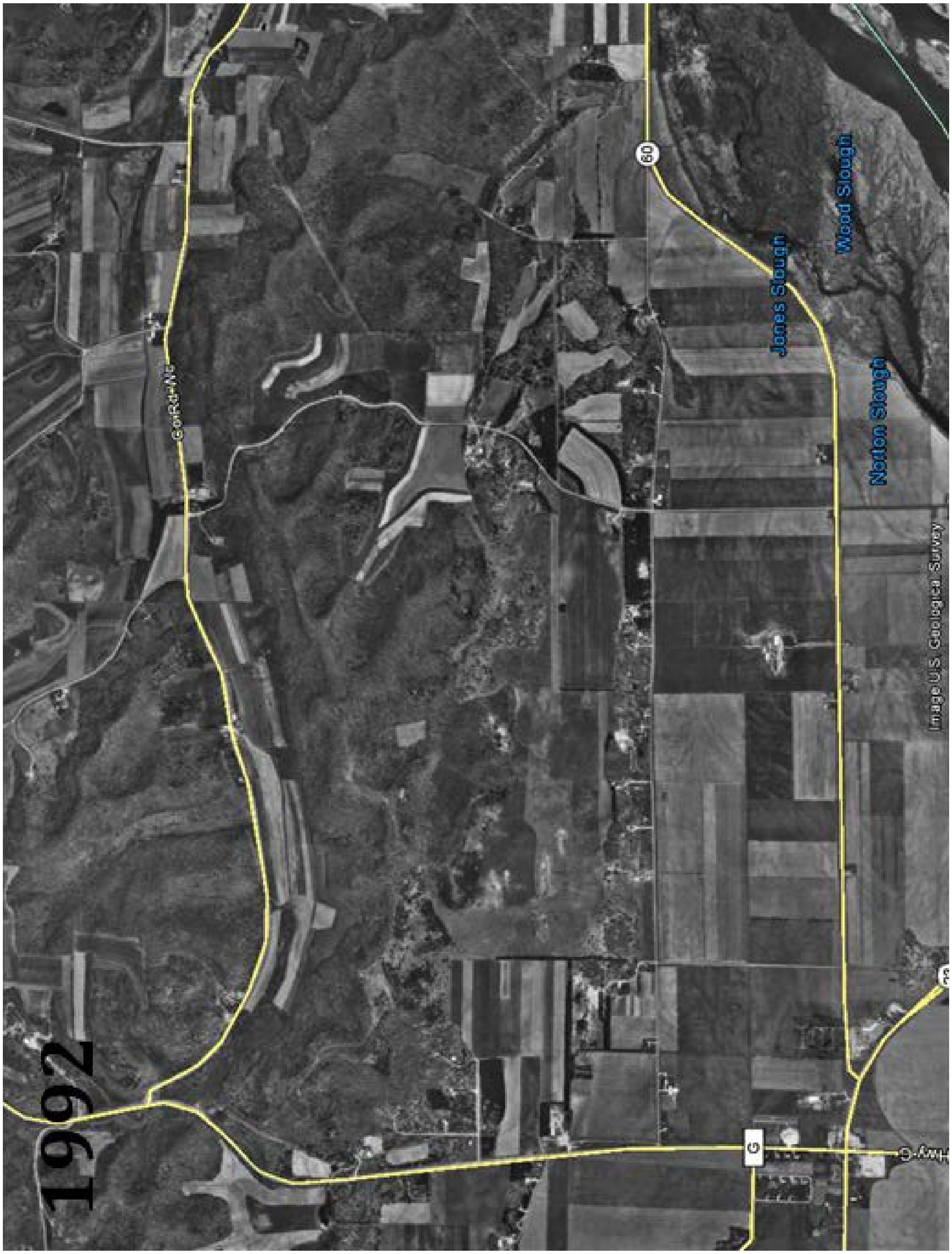
**Aerial Photography of Recharge Sites (1968-2013)**

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.

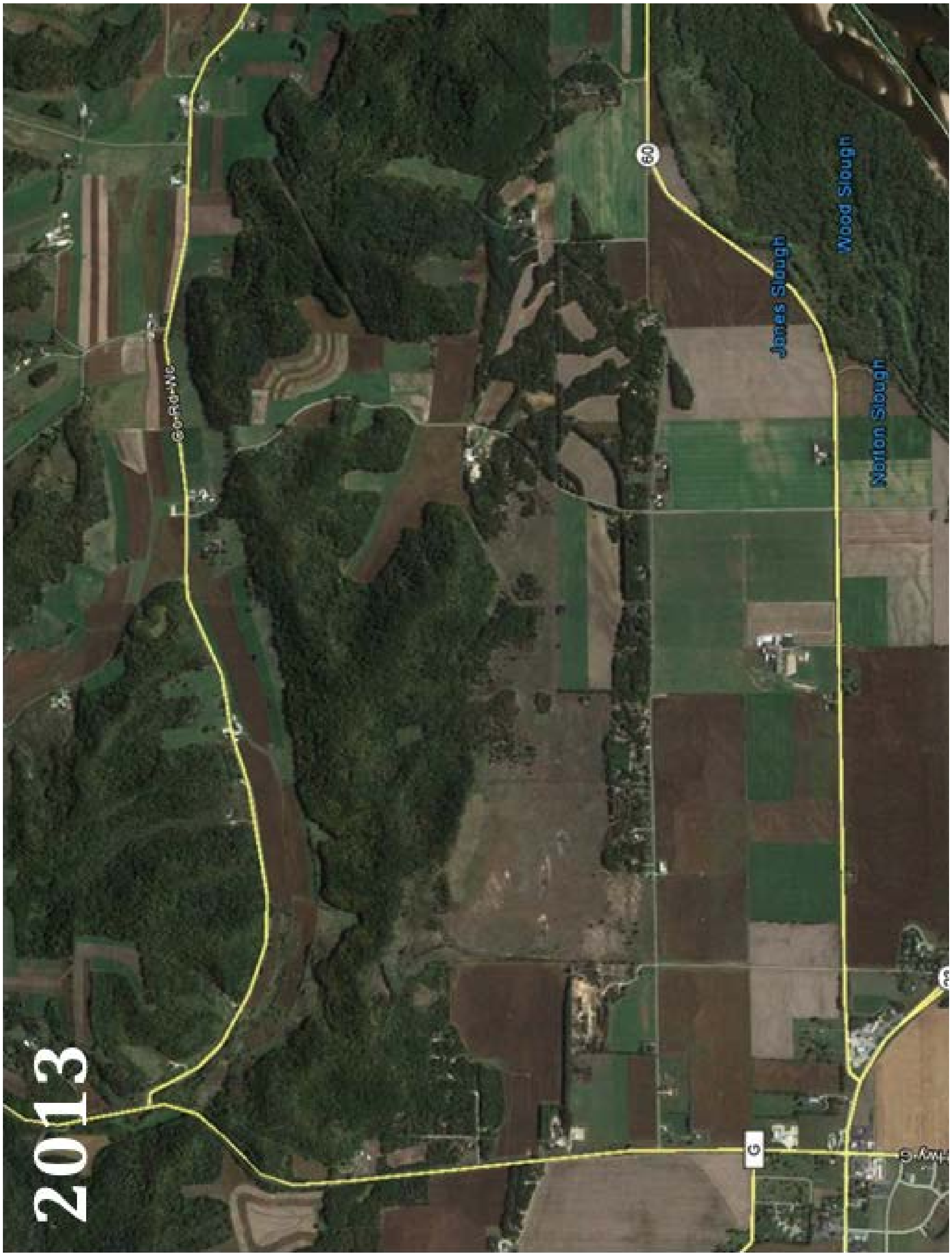


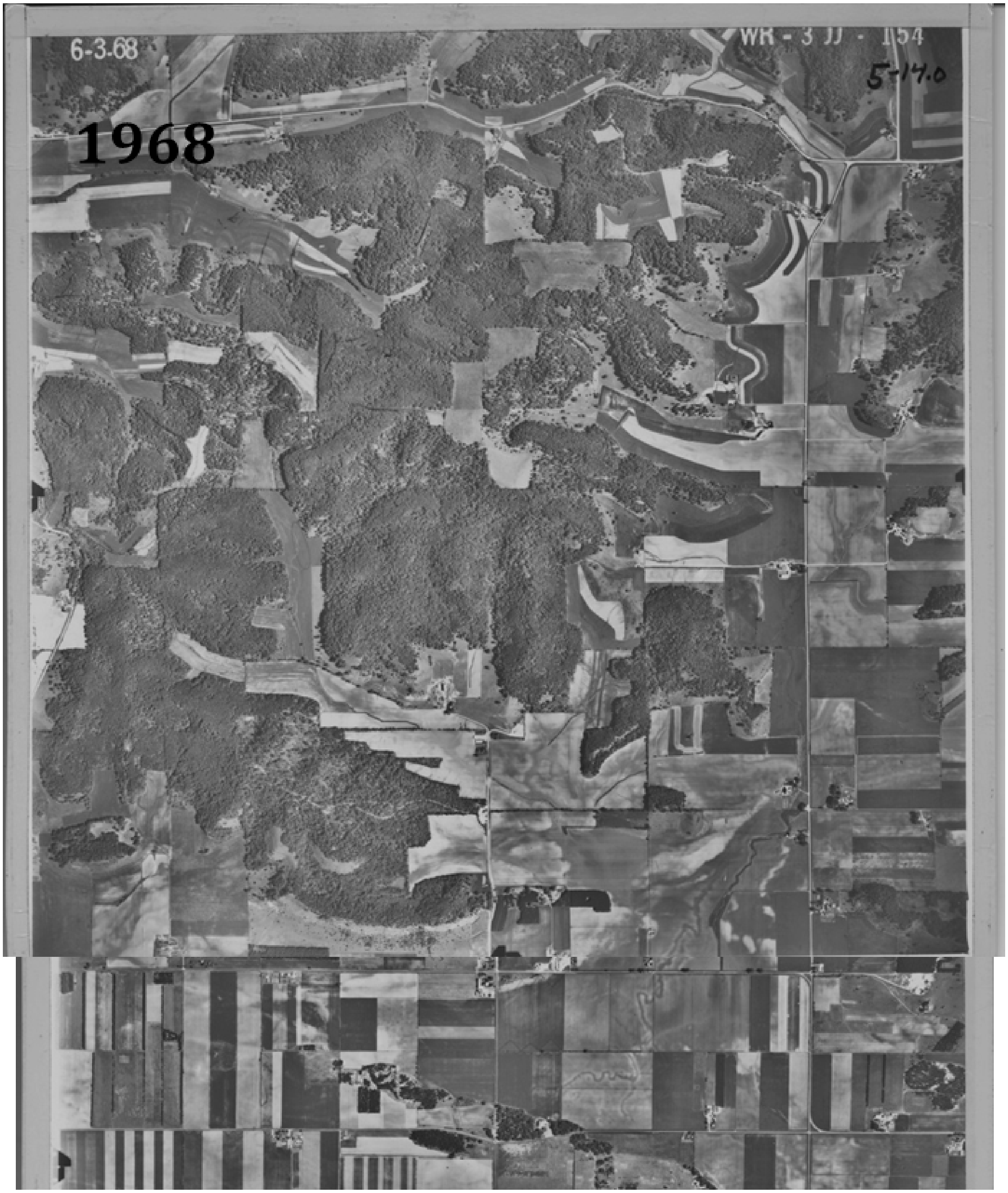

1968


1978
49
55111-178


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


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


2013
Jones Slough
Wood Slough
Norton Slough
60
G


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


55111 178
L
1978

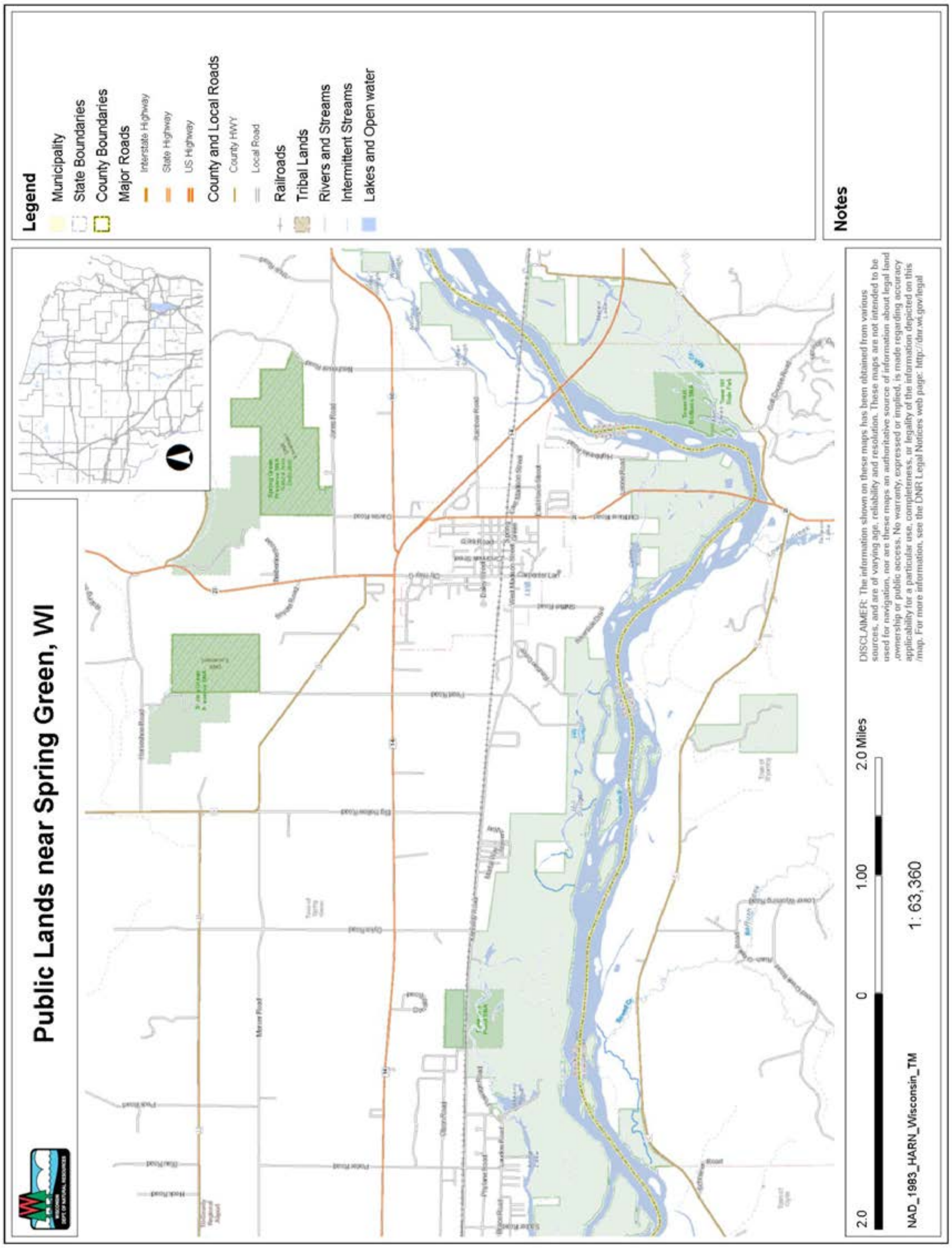

1992
B
G
Image U.S. Geological Survey
Co Rd Jj
1145 m
Googl


2005
B
G
Co Rd Jj
Image USDA Farm Service Agency
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.



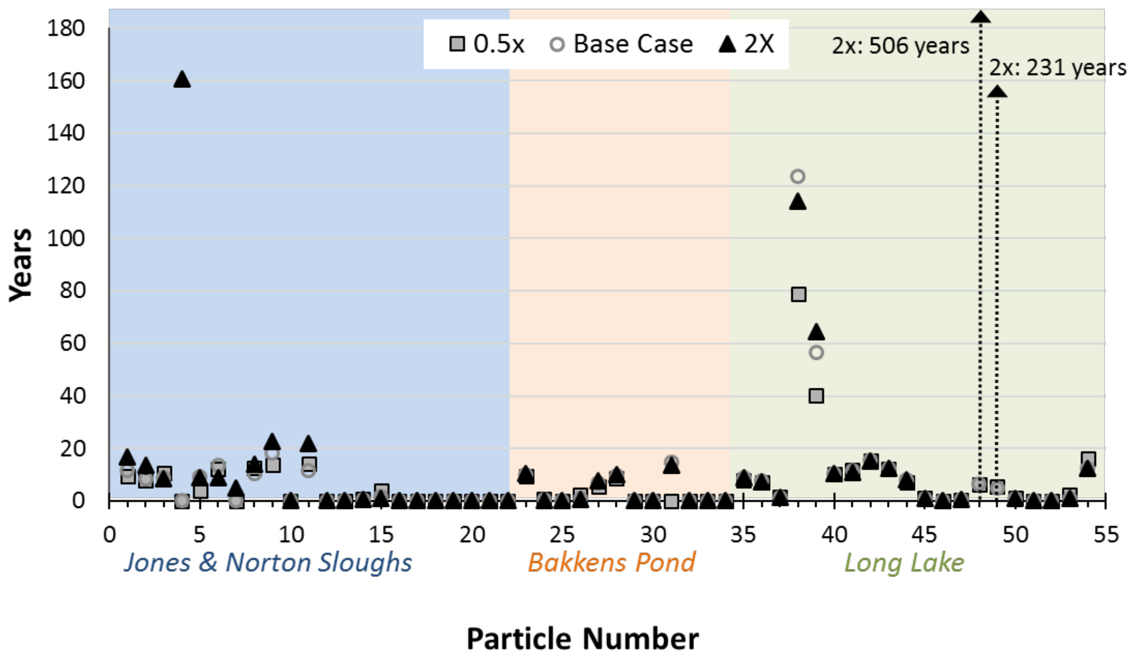
## I. Sensitivity Analysis

Hydraulic conductivities used in the two model runs exploring the effects of model insensitivity to changes in hydraulic conductivity zones 1, 4, 5, and 6. The table below shows the values used for the model runs.

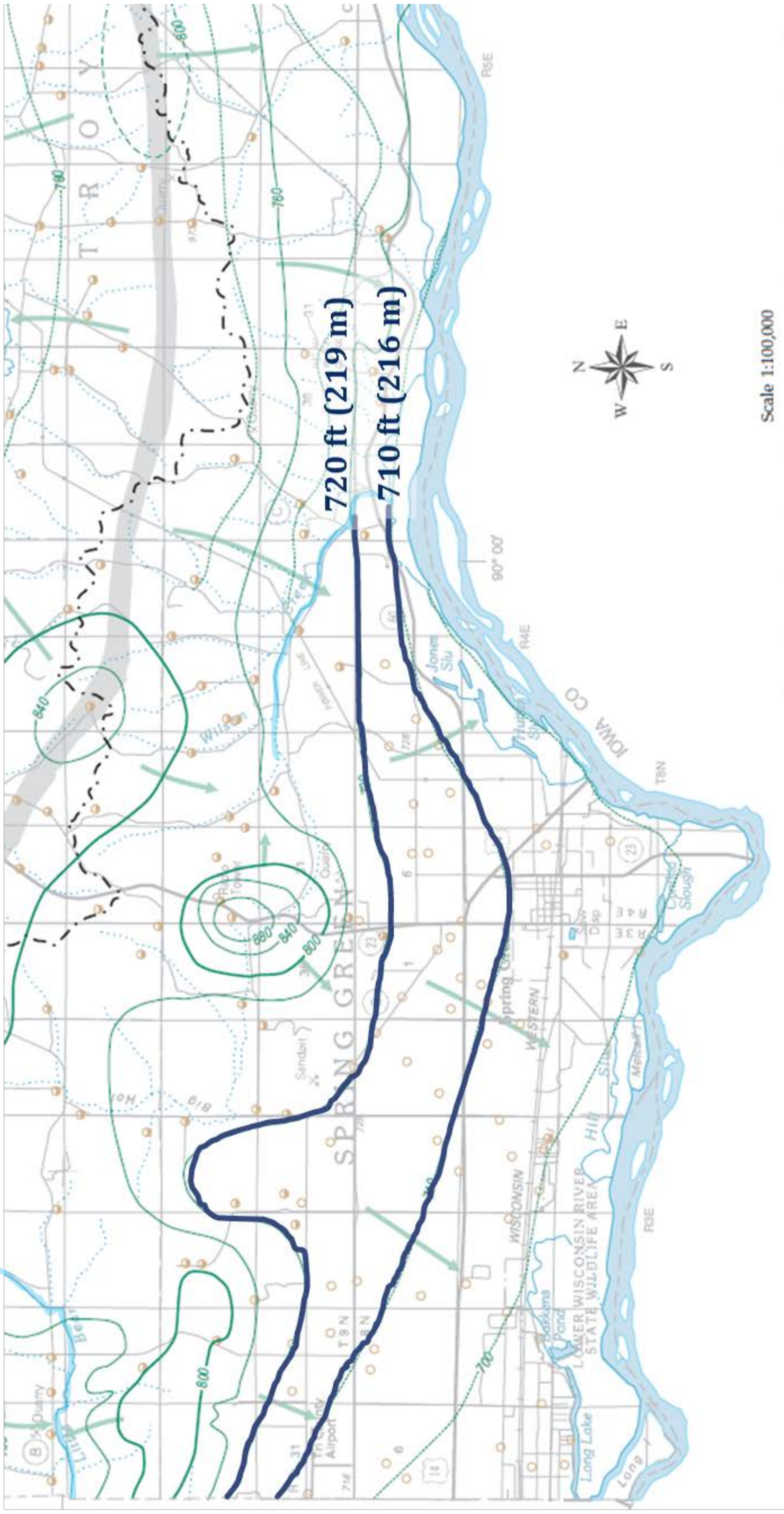
| Zone | Layer ID | Base Case (m/d) | 0.5*Kx (m/d) | 2*Kx (m/d) |
|---|---|---|---|---|
| **1** | **Sandstone Bedrock Aquifer** | **1** | **0.5** | **2** |
| ***2**** | ***Uplands Alluvium*** | ***25*** | ***25*** | ***25*** |
| ***3**** | ***Wisconsin River Valley*** | ***90*** | ***90*** | ***90*** |
| **4** | **Modern Floodplain – Silt** | **45** | **22.5** | **90** |
| **5** | **Dolomite-capped Bluffs** | **0.25** | **0.125** | **0.5** |
| **6** | **Weathered Sandstone** | **5** | **2.5** | **10** |

*Layers 2 and 3 remained unchanged for the model runs.

Comparison of particle travel times after halving (0.5x) and doubling (2x) hydraulic conductivities in zones 1, 4, 5, and 6. Particles are grouped by discharge site with the blue corresponding to particles in Jones and Norton Sloughs, orange to Bakkens Pond, and green to Long Lake.



## J. Inset of Sauk County Water Table Map




Scale 1:100,000

KILOMETERS

MILES

Gotkowitz, Madeline B, & Zeiler, K. K. (2003). *Water-Table Elevation Map of Sauk County, Wisconsin*. Madison.

## Accompanying material (CD)

**UW Model ("SG5_1") and supporting files**

**Slug Test Raw Data**

**MATLAB code for "Transducer Toolbox"**

**Pressure Transducer Water Level Records**

**Raw data for Measured Chemical and Physical Parameters**