Investigating Intra-annual Variability of Well Water Quality in Lincoln Township

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Final Report

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Acknowledgements

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EXECUTIVE SUMMARY

The purpose of this research study is to investigate the intra-annual variability of well water quality in Lincoln Township. Residents solely rely on private wells and groundwater as their primary water supply from the Silurian dolomite bedrock aquifer and have been experiencing higher contamination rates of nitrates and bacteria.

Ten wells were selected and tested monthly for one year to investigate seasonal variability, with a specific interest in bacteria and nitrate contamination of wells.

The goals of this research were:

1. Establish baseline data of the intra-annual variation of well water quality for ten wells.
2. Investigate groundwater and land-use interactions in the region.
3. Recommend a long-term strategy for monitoring Lincoln Township's well water.

Coliform bacteria were detected at least once in six different wells; four wells did not detect bacteria in any of the 12 sampling events. Levels of coliform bacteria measured were generally low, with the maximum number reported as 60.2 MPN cfu/100mL. The greatest number of sample periods that any one individual well tested positive was seven. Wells that were positive one period often came back negative the following sample period, even though no chlorination or corrective measures took place. None of the wells tested positive for *E.coli* bacteria. Coliform and *E.coli* bacteria testing methods are not capable of determining contamination source and have little utility for assessing changes in groundwater quality over time.

Nitrate concentrations were stable in one-half of the wells (standard deviation < 1.0 mg/L) while one-half were determined to have significant intra-annual variability (standard deviation >1.0 mg/L). The largest difference between the minimum and maximum concentration of nitrate-nitrogen in one well was 13.6 mg/L. Nitrate and chloride concentrations, which were correlated in six of ten wells, have potential for tracking trends or changes to groundwater over time.

Nitrate, chloride, alkalinity, total hardness and conductivity measurements suggest aquifer conditions were most stable during the winter period when the soil near the surface was below 0 degrees Celsius. Because this time period is likely to be uninfluenced by rapid recharge events, it represents an opportune time to sample for the purposes of long-term monitoring. Changes in well water quality of individual wells and increased variability measured between wells seemed to coincide with the snow-melt and spring recharge periods. Sampling following spring would help to identify those wells that are most susceptible to intra-annual variation.

Recommendations:

1. Sample 25 wells bi-annually
    a. We recommend: January when wells are under relatively stable aquifer conditions; and mid-June to assess groundwater conditions following the spring groundwater recharge period.
2. Test wells for nitrate and chloride because they have the most utility for understanding land-use trends or human changes, as well as alkalinity for its potential ability to inform interpretation of water quality results.
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ABSTRACT

The purpose of this research study is to investigate the intra-annual variability of well water quality in Lincoln Township whose residents solely rely on private wells and groundwater as their primary water supply from the Silurian dolomite bedrock aquifer. Ten wells were selected and tested monthly for one year to investigate seasonal variability, with a specific interest in bacteria and nitrate contamination of wells.

Coliform bacteria were detected at least once in six different wells; four wells did not have detections of bacteria in any of the 12 sampling events. Levels of coliform bacteria measured were generally low, with the maximum number reported as 60.2 MPN cfu/100mL. The greatest number of sample periods that any one individual well tested positive was seven. Wells that were positive one period often came back negative the following sample period, even though no chlorination or corrective measures took place. None of the wells tested positive for *E.coli* bacteria.

Nitrate concentrations were stable in one-half of the wells (standard deviation < 1.0 mg/L) and showed in the other half greater monthly variability (standard deviation >1.0 mg/L). The largest difference between the minimum and maximum concentration of nitrate-nitrogen in one well was 13.6 mg/L. Nitrate and chloride concentrations, which were correlated in six of ten wells, have the most utility for monitoring changes in groundwater quality that result from land-use practices.

Nitrate, chloride, alkalinity, total hardness and conductivity measurements suggest groundwater chemistry was most stable during the winter period when the soil temperature near the surface was below 0 degrees Celsius. A change in groundwater chemistry indicated by increased variability seemed to coincide with the snow-melt and spring recharge periods.

Results suggest that, in this geologic setting, an annual coliform bacteria test is largely inadequate to assess the bacteriological safety of a water system year round and has limited ability to track changes in water quality over time. Even though significant intra-annual variability existed in nitrate concentrations, it seems that a cost-effective monitoring strategy could be implemented in Lincoln Township that would test private wells for nitrate and chloride to examine whether these chemical constituents are changing over time as a result of land-use practices.

Introduction

Groundwater is the primary water source for residents of Lincoln Township and its quality is a concern for all those that rely on private wells. Unlike public water systems, private water supplies have no requirements to routinely test and many homeowners have not done extensive testing to understand the quality of their household water supply. Knowing when and what to test for is critical to understanding the suitability of a private well. If drinking water does not meet the health-based water quality standards established by the U.S. Environmental Protection Agency (EPA) it is not recommended it be used for drinking and cooking, and in some extreme cases may not be suitable for bathing.

The Wisconsin well code is based on the premise that a properly constructed well should provide bacteriologically safe water continuously without the need for treatment. A summary of 159 private well water samples submitted to University of Wisconsin-Stevens Point by Lincoln Township residents between 2004 and 2014 show a greater percentage of coliform bacteria than is normally found statewide, 32% in the Township of Lincoln compared to the statewide average of approximately 15% (CWSE, 2014). While coliform bacteria do not generally cause people to become sick, the presence of coliform bacteria indicate a potential pathway for pathogens (i.e. *Eschericheria coli* (*E. coli*), giardia, cryptosporidium, norovirus, etc.) to enter the water supply. All coliform bacteria positive samples are also tested for *E. coli*; a specific type of bacteria that, if present, provides confirmation that a well is being contaminated by animal or human fecal waste. Fecal bacteria are an obvious water quality concern in areas where land-spreading of animal waste occurs or residences rely on private on-site wastewater treatment systems (POWTS).

The samples collected over the past decade also display a high percentage of wells with nitrate at concentrations in excess of what is considered suitable for drinking water purposes; 20% in the Township of Lincoln compared to the statewide average of 9% (DATCP, 2008). Nitrate is the most widespread groundwater contaminant in Wisconsin and concentrations greater than 2 mg/L of nitrate-nitrogen provide evidence of impacts from the following sources: nitrogen fertilizers, manure and/or bio-solid application of waste to agricultural fields, leaking manure storage lagoons, and/or septic system effluent. Fifty percent of wells tested in Lincoln Township provide conclusive evidence of nitrate concentrations above background or natural concentrations found in groundwater.

Anecdotal and documented evidence suggest "brown water" incidents (i.e. sudden changes in water quality that occur during snowmelt or spring rains) have occurred for many years throughout Northeast Wisconsin. Since 2006, sixty-four wells have been replaced throughout Wisconsin due to confirmed contamination by livestock manure (L. Chern, personal communication, April 8, 2014); three-quarters of these wells were located in areas of geologic concern in susceptibility criteria outlined in the Northeast Wisconsin Karst Task Force Report that occurs in portions of Door, Kewaunee, Brown, Calumet, Manitowoc, Fond du Lac and Dodge Counties.

The Karst Task Force Report assigns areas with shallow soils (<50 feet to carbonate bedrock) a significant vulnerability to contaminants such as bacteria and nitrate. These shallow soils, found throughout Lincoln Township, have little ability to attenuate or filter contaminants, and have a greater likelihood of containing landscape features (i.e. sinkholes, fracture traces, surface rock outcrops and disappearing streams) that provide direct conduits to groundwater (Erb & Stieglitz, 2007). Research has shown karst aquifers respond quickly to precipitation and

snowmelt events and the largest recharge events occur in early spring and additional recharge often occurs after the first killing frost. Once contaminants are in a karst aquifer, they are able to travel long distances in a short time, making it difficult to pinpoint the original contamination source (Sherrill, 1978; Bradbury and Muldoon, 1992).

The percentage of wells detecting bacteria and elevated nitrate concentrations in Lincoln Township lends credence to groundwater vulnerability assessments. One limitation to the existing private well water data set is the ability to determine whether groundwater quality is changing or has changed over time, a key question. The annual and intra-annual variability of groundwater quality and infrequent testing behavior of well owners makes it difficult to infer water quality patterns or trends from voluntary private well water testing events. Given variability of groundwater quality in karst regions, a well sampled once per year for bacteria and nitrate may give homeowners a false sense of safety regarding their water supply. More detailed data are needed to establish better guidelines for homeowners to reliably assess the safety of their well water system and provide a foundation for monitoring potential changes to groundwater quality.

In an effort to understand the variability of well water quality during the year and potentially develop a long-term monitoring strategy to assess whether groundwater quality is changing, the Township agreed to investigate intra-annual variability of well water by sampling ten wells monthly for one year. The objective of the sampling project was threefold: 1) establish baseline data regarding the intra-annual variation of well water quality for ten wells, 2) investigate groundwater and land-use interactions in the region, and 3) recommend a long-term strategy for monitoring Lincoln Township's well water.

Methods and Materials

Study Area

The area of focus is Lincoln Township, a 35.7 square mile area located in northern Kewaunee County, Wisconsin. Lincoln Township has approximately 334 households that rely solely on private wells and groundwater as their primary water supply. The soils are predominantly medium to fine-textured. Thicknesses of Pleistocene glacial deposits vary from nearly absent in some areas to as much as 100 feet thick. The underlying geology consists of dolomite bedrock from the Silurian Period which is the principal aquifer for household private wells.

The dominant land cover is agricultural (70%) followed by wetland (21%) and forest (6%) (WI DNR, 1998). Kewaunee County is a leader in percentage of cropland acres under nutrient management at 76% (GCC, 2013). According to the 2013 Nutrient Management plans, Lincoln Township contains approximately 13,500 cows (calves, heifers, beef, and dairy) of which approximately 82% are located on three permitted Concentrated Animal Feeding Operations (CAFO) within the Township. All households in the town presumably rely on private wells and private on-site waste systems.

Weather & Soil Data

Daily climate and soil data was accessed using the Michigan State University Extension weather station located at the Roethle Orchards in Casco Township, located just south of Lincoln Township, at http://www.agweather.geo.msu.edu/mawn/station.asp?id=lux&rt=24. Parameters evaluated were soil moisture (in^3/in^3), minimum and maximum soil temperature at a 2 inch depth, precipitation, and maximum and minimum air temperature.

Well Sampling and Analysis

Ten wells were selected from participants of previous Kewaunee County voluntary testing programs. Attempts were made to ensure wells were spatially distributed and represented a variety of well and casing depths (Figure 1, Figure 2).

Figure 1: Schematic of Lincoln Township. Shaded regions represent location of sample well(s). Numbers correspond to well ID.

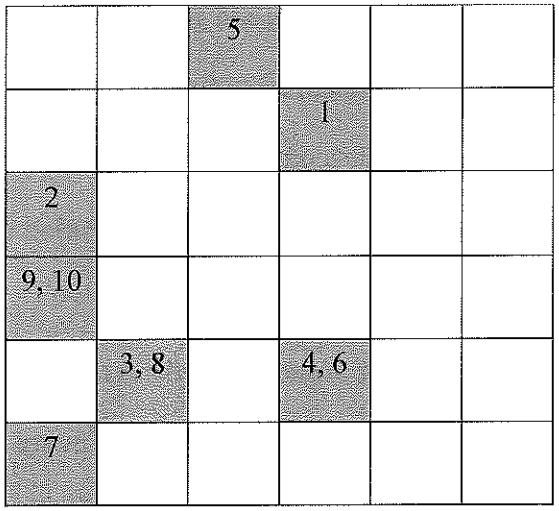
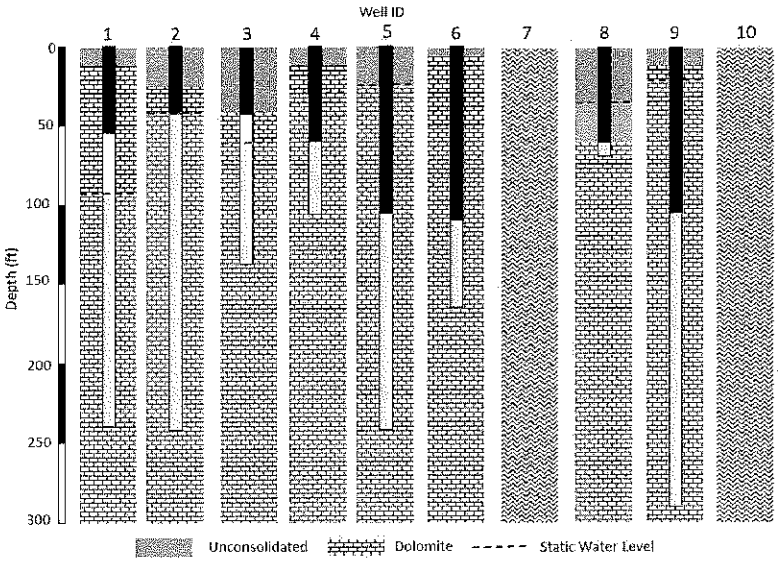


Figure 2: Diagram of well depth, casing depth (blackened portion of well), static water level and geologic record for wells with a known well construction. Well construction information could not be found for wells 7 and 10.



Preference was given to wells with a known well construction report and a previously measured nitrate-nitrogen concentration greater than 10 mg/L and/or a positive coliform/*E-coli* bacteria test. Data from private wells tested multiple times often shows that when an initial test

measures nitrate concentrations less than 1 mg/L, over time there is often little to no change in future nitrate measurements. A low nitrate concentration in groundwater could be because: 1) there is no source of nitrate into the aquifer where a particular well receives its water from, 2) the groundwater accessed by the well is less susceptible to contamination by nitrate because of soils, geology or well construction, or 3) nitrate has yet to penetrate deep enough into the aquifer where a particular well is accessing groundwater. Since variability was the major focus of investigation, selecting wells that had elevated nitrate concentrations or a history of bacterial contamination was a more targeted use of resources for studying how intra-annual fluctuations would inform long-term monitoring efforts.

The wells were sampled over a twelve month period. All of the well testing dates were identified before the first sample was collected. During winter months, indoor faucets were used. Unfortunately, this meant that some water samples were collected from softened sources for a few of the periods and affected total hardness measurements and subsequent analysis. Measurements of other constituents were determined to not have been affected. Prior to sampling, each faucet was sterilized with a flame and cold water was allowed to run for 10 minutes before sample collection. All wells were sampled by Davina Bonness, Kewaunee County Land & Water Quality Specialist. Samples were placed in a cooler, kept cold using ice packs, and shipped to the Water Environmental Analysis Lab located in Stevens Point, WI where they arrived within 30 hours of sample collection.

The laboratory has a formal quality control program in place and holds certification from the Wisconsin (DNR State Certification Lab No. 750040280) and United States Geologic Survey for a wide-array of elements and matrices. Among the practices that the laboratory employs are

periodic analyses of laboratory reagent blanks, fortified blanks, duplicate samples, and calibration solutions as continuing checks on performance.

All wells were sampled monthly and the water analyzed for: Total coliform/*E.coli*, nitrate-nitrogen, chloride, total hardness, alkalinity, conductivity, and pH. Total coliform and *E.coli* bacteria MPN (most probable number) counts were measured using the IDEXX Quanti-Tray/2000®. Nitrate-nitrogen and chloride were determined colorimetrically by flow injected analysis on a Lachat QuikChem 8000®. Hardness and alkalinity were measured by titration using Standard Methods. Probes were used to measure conductivity and pH in the laboratory.

Source Assessment

A geographic information system was used to map land-use and measure total non-cropland, total cropland acres, and cropland acres under nutrient management plans within a half mile radius of each well (Table 1). The average amount of cropland surrounding selected wells was 68%, while the percent of cropland acres under nutrient management averaged 89%.

Table 1: Land-use within half-mile radius of selected wells

Well ID	Non-cropland (acres)	Non-cropland (%)	Total Cropland (acres)	Cropland (%)	Cropland with a Nutrient Management Plan (acres)	Cropland with a Nutrient Management Plan (%)	Fertilizer nitrogen (lbs/acre of cropland/yr)	Manure Nitrogen (lbs/acre of cropland/yr)	Total agricultural nitrogen (lbs/acre of cropland/yr)	Total nitrogen from agricultural sources (lbs)	# of septic systems	Nitrogen from septic systems (lbs)
1	134	27	368	73	295	80	31	27	58	21,432	6	150
2	314	63	188	37	178	95	31	28	59	11,073	7	175
3	181	36	321	64	321	100	26	39	65	20,881	11	275
4	117	23	385	77	385	100	16	63	78	30,130	7	175
5	132	26	370	74	370	100	13	70	83	30,684	1	25
6	107	21	395	79	395	100	29	51	79	31,383	6	150
7	127	25	375	75	185	49	26	44	69	25,916	9	225
8	293	58	209	42	191	91	13	33	47	9,762	14	350
9	45	9	457	91	337	74	38	54	92	41,943	11	275
10	134	27	368	73	368	100	33	51	83	30,706	14	350
Average	**158**	**32**	**344**	**68**	**303**	**89**	**25**	**46**	**71**	**25,391**	**8.6**	**215**

Table 2: Lincoln Township manure nutrient sources and method/timing of applications

Types of Manure Applications	Spring Surface	Spring Incorp.	Summer Surface	Summer Incorp.	Fall Incorp.	Fall Surface	Winter Surface
Liquid Pit/Lagoon Manure	X	X	X	X	X		
Solid Heifer/Yard Manure	X	X	X		X	X	X
Calf Manure			X		X		
Sand Manure				X		X	

Table 3: Lincoln Township fertilizer nutrient sources and method/timing of applications

Fertilizer & N-P-K Analysis	Spring Surface	Spring Incorp.	Summer Surface	Summer Incorp.	Fall Incorp.
Ammonium Sulfate (21-0-0)	X	X	X		
28% Liquid UAN (28-0-0)	X	X			
Boron (0-0-0)	X				
Diammonium Phosphate, DAP (18-46-0)	X	X	X		
ESN (44-0-0)		X			
Liquid 6 (6-24-6)	X	X			
Liquid 7 (7-21-7)		X			
Liquid 9 (9-18-9)		X			
Potash (0-0-60)	X	X	X		
Potassium Chloride (0-0-61)	X	X	X		X
Seasons Pass Liquid (6-18-6)		X			
Starter 5 (5-14-42)	X	X			
Starter 9 (9-23-30)		X			
Starter Blend (13-15-20)		X			
Starter ESN19 (19-19-19)	X	X			
Super U (46-0-0)	X				
Urea (46-0-0)	X	X	X		
Yieldmaxx Corn Starter (17-17-17)	X	X			
Yieldmaxx Hayland (3-8-45)			X	X	
Yieldmaxx Soybeans (7-18-31)	X	X			
Yieldmaxx Wheat (21-12-15)	X				

To determine what general land-use practices exist, nutrient management plans from 2013 were used to summarize typical manure and/or fertilizer applications, and tillage practices around wells (Table 2, Table 3). The summary does not suggest that all of these practices occurred around each well, but rather outlines the common practices in those areas around the

wells selected for investigation. While the intent of this summary is not to assign rankings or assert that any of these are better or worse than others, it speaks to the complexity of not only managing nutrients as a method to increase productivity but also as a groundwater contaminant.

Current nutrient management principles allow farmers to apply nutrients based on maximum economic return and implications to groundwater quality are not a criteria for setting nitrogen application rates (Laboski & Peters, 2012). When applied at recommended rates the amount of nitrate that ends up leaching past the root zone of plants is largely a function of how much is applied, which can be highly variable from year to year (Andraski et. al., 1999; Jaynes et al., 2001; Masarik et al. 2014). The risk of groundwater contamination by pathogens increases during certain times of the year or under certain climatic conditions (Pasquarell and Boyer, 1995; Zheng et al., 2013). Geologic and soil conditions also influence groundwater susceptibility, and data exists to show that the impact of agricultural practices on well water quality is greater and more obvious (i.e. greater occurrence of bacteria detects and elevated nitrate) in areas with shallow soils and carbonate rock, even though management practices may be similar or even more stringent (Erb & Stieglitz, 2007).

In order to account for all sources of groundwater nitrate and pathogens in Lincoln Township, septic systems were also quantified. In 2013, Kewaunee County Zoning identified 384 Lincoln Sanitary Permits (of which 63 are holding tanks). These data were used to quantify the number of septic systems and holding tanks within the half mile radius of each well, which contained an average of 8.6 septic systems, with a minimum of 1 and a maximum of 14. A typical septic system can leach approximately 20-25 pounds of nitrogen per year (U.S. EPA, 2002).

Results and Discussion

Weather

Weather data was summarized through the twelve month sampling period (Figure 3). Weather data six months prior to initial sampling was also included to provide insight into the conditions preceding the sample collection period. Maximum soil temperature data equal to or less than 0°C indicated frozen conditions for 120 days in the winter of 2014; 41 days longer than for the winter of 2013. Precipitation and soil moisture data for April 2013 indicated a slightly wetter period immediately following the start of unfrozen soil surface conditions. This suggests a more rapid infiltration of snow melt and/or rain than that which occurred in April 2014, where conditions indicate a slower and less intense infiltration period.

Well Sampling

The 159 wells previously sampled in Lincoln Township between 2006 and 2014 indicate an average pH of 7.74, average alkalinity of 312 mg/L as $CaCO_3$, and average total hardness of 354 mg/L as $CaCO_3$. Summary water quality statistics for the 10 individual wells sampled in this investigation indicate that these wells have average water quality (Table 4). This suggests that wells selected are typical for this area and water quality is comparable with previous samples. Individual wells were in some cases two to four times the Township's average concentration of 5.0 and 33.3 mg/L for nitrate-nitrogen and chloride respectively. However, a main objective of this investigation was to quantify variability; therefore the elevated nitrate and chloride concentrations are a result of the decision to study variability of impacted wells.

Bacteria

Coliform bacteria were detected at least once in six wells; four wells did not have detectable bacteria in any of the 12 sampling events (Table 4). The highest Most Probable

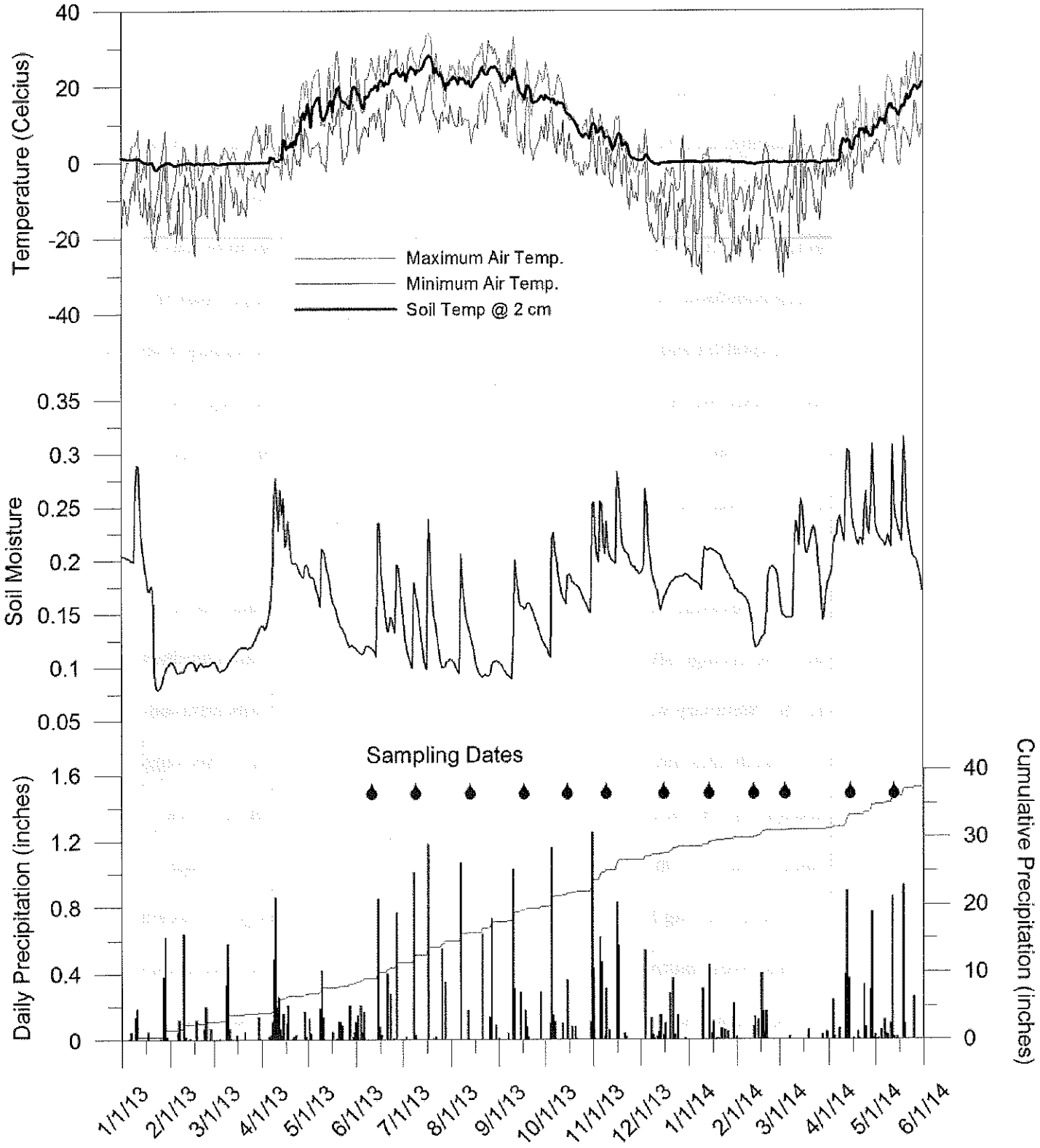


Figure 3. Weather and soil data representing period from Jan. 1 2013 to May 31 2014. Date of well water sample collection indicated by water droplets. Shaded region represents periods when the maximum soil temperature at 2 cm was less than or equal to 0 degrees Celcius (32 degrees Fahrenheit) indicating frozen or near frozen soils.

Table 4. Summary of monthly well testing data for the twelve month period from June 2013 to May 2014. Values represent the annual mean with standard deviation provided in parentheses.

Well	pH	Conductivity	Alkalinity	Total Hardness	Nitrate	Chloride	Total Coliform	Total Coliform	E-Coli
		$\mu s\ cm^{-1}$	$mg\ L^{-1}$ $CaCO_3$	$mg\ L^{-1}$ $CaCO_3$	$mg\ L^{-1}$	$mg\ L^{-1}$	Sample Periods Positive	MPN Cfu $100\ mL^{-1}$	Sample Periods Positive
1	7.84(0.3)	713(7)†	287(7)	389(11)	14.9(0.4)	17.9(1.0)	1	0.9(0.3)	0
2	7.85(0.3)	766(33)	324(4)	NR	16.0(0.5)	13.4(1.0)	0	ND	0
3	7.75(0.3)	909(42)	347(6)	478(13)	18.5(2.2)	41.1(3.7)	0	ND	0
4	7.79(0.3)	712(48)	336(11)	385(20)	7.4(2.2)	14.9(13.5)	6	6.2(17.1)	0
5	7.80(0.2)	783(31)	304(12)	413(32)	13.8(3.8)	30.9(3.2)	6	1.7(2.4)	0
6	7.80(0.2)	743(34)	309(7)	NR	9.0(2.7)	25.6(1.9)	0	ND	0
7	7.94(0.3)	836(33)	319(8)	NR	12.8(1.4)	33.2(1.6)	2	2.5(8.1)	0
8	7.74(0.2)	994(29)	377(6)	507(23)	10.2(0.7)	44.9(0.7)	7	3.4(5.1)	0
9	7.93(0.3)	628(14)	322(3)	349(8)	1.4(0.3)	11.1(1.1)	0	ND	0
10	7.87(0.2)	1032(112)	358(12)	509(36)	0.2(0.2)	95.1(36.0)	4	6.3 (13.1)	0

† Conductivity not measured in month of July, mean and standard deviation for 11 sampling dates.
ND None detected; indicates a Most Probable Number of <1 for total coliform bacteria.
NR Not reported; one or more samples from softened source.

Number (MPN) measured was 60.2 MPN cfu/100 mL in Well #4 on the 4/15/2014 sample date (Figure 4). The greatest number of sample periods that any one individual well tested positive was seven. Wells 4, 5, and 8 showed the most frequent occurrence of contamination by coliform bacteria, having detections in more than half of sampling events. The 11/9/2013 and 12/16/2013 sample dates had the greatest number of wells with a bacteria detect, both with four positive wells. Wells that were positive one period often came back negative the following sample period, even though no chlorination or corrective measures took place. None of the wells tested positive for *E.coli* bacteria, a specific type of fecal bacteria, on any of the sample dates.

When it comes to maintaining bacteriological safety of well water, wells cased below the water table are generally preferred. When the water table is at or below the casing of a well drilled into fractured carbonate rock, as in wells 1, 2, and 3, the concern is that fractures which receive throughfall from sinkholes and other rapid infiltration features which intersect the open borehole can directly inject leachate or surface water into the well causing sudden changes in water quality and increased risk of contamination from bacteria and potentially pathogens. With casing extended past the water table the idea is that groundwater deeper in the aquifer may be better buffered from contaminants delivered by rapid throughfall events, and is therefore less likely to be influenced by these types of contamination. Examination of eight out of ten wells for which well construction reports could be located, well construction alone cannot explain coliform bacteria results. Wells 1, 2, and 3, where well construction would perhaps be considered most susceptible based on water table and casing depth had only one bacteria detection over the course of the twelve sampling events.

The number and length of fractures along with the intersection of these fractures with bacteria sources is a more important factor for determining contamination susceptibility than

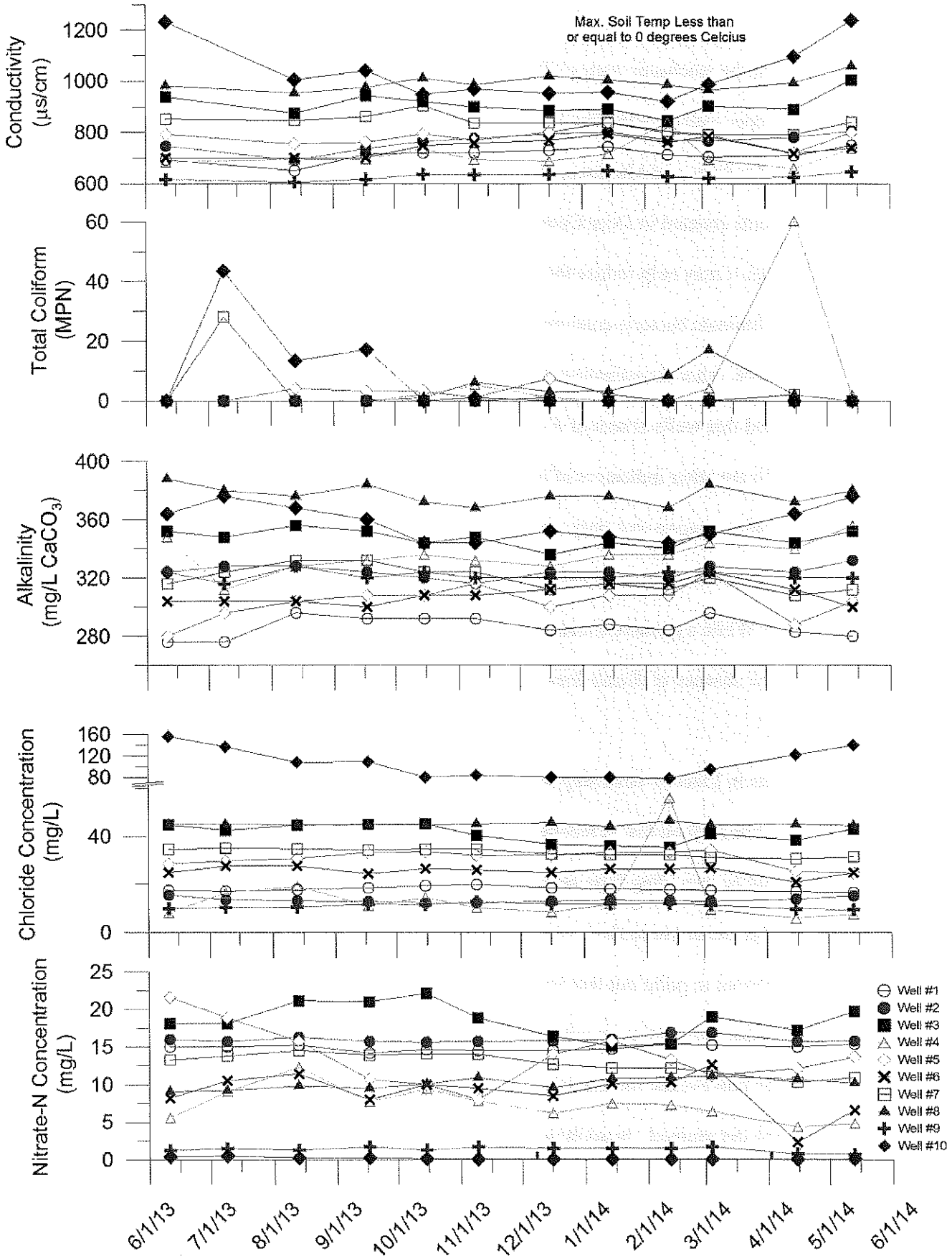


Figure 4. Monthly sample result for each of the 10 wells sampled. Shaded region represents period when maximum soil temperature at 2 cm was less than or equal to 0 degrees Celcius.

well construction; the stochastic nature of these features makes it difficult to say with certainty that drilling a deeper well or extending the casing deeper into the aquifer would lessen the risk of contamination (Bradbury and Muldoon, 1992). A study by Braatz (2004) showed that stricter casing requirements enacted in Door County because of similar geology and water quality concerns, although it may help reduce the severity of contamination or number of incidents, did not completely eliminate bacteria contamination of new wells.

Furthermore, other investigations that performed side-by-side testing of multiple fecal indicators revealed that wells absent of *E.coli* were sometimes positive for enterococci and coliphages, which are other indicators of fecal waste sources (Atherholt et al. 2003; Braatz, 2004). These studies suggest that only using *E.coli* as an indication of human or animal waste likely underestimates the number of wells that are contaminated with fecal types of bacteria or other pathogens. While a positive *E.coli* test confirms human or animal waste source contamination, the absence of *E.coli* does not necessarily mean that a well is free of pathogenic microorganisms.

Residents in Lincoln Township who perform a once yearly presence-absence coliform bacteria test (the test method that is recommended and most accessible to the average homeowner) could be providing false sense of bacteriological safety when the test comes back absent. The data presented here show variable coliform bacteria detections from month to month. It is important to point out that sample dates were pre-selected and because this investigation was not designed to specifically study well water conditions associated with snowmelt or large rain events, the maximum degree to which wells may have been affected by bacteria cannot be determined. In addition, this study did not determine the minimum length of time bacteria occupied the wells after they were contaminated. Certainly the data shows that the

contamination period may be as little as one month; however, more frequent sampling may have shown contamination periods to be less than that length of time.

Because the timing of sample collection appears critical to the detection of bacteria, using annual coliform bacteria data collected by grab samples to interpret trends related to land-use is of little utility. Without the ability to quantify, detect and distinguish between specific bacteria or pathogens associated with known sources or carriers, the detection of coliform bacteria alone is simply an indication of a well's susceptibility to bacterial contamination and indicates the potential for other pathogenic contamination. Spatial analysis of coliform bacteria data has sometimes been useful for indicating regions, like Lincoln Township, that are more geologically sensitive to this type of contamination. Coliform and *E.coli* bacteria presence are considered inconclusive as to whether the particular source is of animal or human origin (Zheng et al., 2013). If coliform and *E.coli* bacteria counts were to be performed on the same wells consistently, it is a potentially useful metric for understanding annual climatic conditions that contribute to increased rates of bacterial contamination; however, the variability of this dataset and the time dependency of sampling for bacteria indicates that this could be difficult to show with any certainty.

In-line sampling methods that are capable of continuously sampling a portion of water coming into the home from a well would be a better method for assessing the variability and severity of bacteriological contamination of wells in these settings. Investigating the use of alternative methods of quantifying, detecting and identifying bacteria and viruses such as those described by Millen et al. (2012) would be beneficial to understanding the magnitude of contamination as well as determining the time of year with greater risk or likelihood of contamination. These methods have been successfully employed to detect and identify human

enteric viruses found in municipal water systems and could also be applied to bovine viruses (Borchardt et al., 2012; Bradbury et al, 2013).

Nitrate-Nitrogen

Nitrate-nitrogen is the most widespread groundwater contaminant in Wisconsin. Background or natural levels of nitrate-nitrogen in groundwater are generally less than 1 mg/L. Concentrations above 1 mg/L indicate influence by one or more of the following sources: nitrogen fertilizers, manure or other bio-solids (both application to land-surface or leakage from storage), or septic system drainfields. Nitrate-nitrogen concentrations above the drinking water standard of 10 mg/L should not be consumed by infants or women who are pregnant or expecting to become pregnant, all other persons are encourage to avoid long-term consumption of water greater than 10 mg/L (WI DNR, 2014).

Six of the study wells had a mean nitrate-nitrogen concentration above the drinking water standard of 10 mg/L (Table 4). Four of those wells (4, 5, 6, and 8) had a maximum nitrate-N concentration greater than the drinking water standard of 10 mg/L while also including one or more sample periods with a nitrate-N concentration less than the standard. Five of these wells 3, 4, 5, 6, and 7 had a standard deviation greater than 1.0 mg/L indicating a greater degree of intra-annual variability. The largest difference between the minimum and maximum in one well was 13.6 mg/L in well number 5 (Figure 4). Wells 1, 2, 8, 9, and 10 had a standard deviation less than 1.0 mg/L and appear relatively stable during the course of the sample period. Given the greater variability of nitrate concentrations measured in some wells, anyone with a nitrate concentration above 2 mg/L and less than 10 mg/L who is concerned about drinking water above the 10 mg/L nitrate-nitrogen standard should consider testing more frequently than once per year.

Nitrate, because of its mobility through soils and groundwater, is generally considered to be a good indicator of groundwater susceptibility and land-use impacts. The source assessment (Table 1) estimates that agricultural fertilizer and manure applications accounted for an average of 25,391 lbs N added to agricultural fields within the ½ mile radius around the wells in 2013, while the average amount of nitrogen from septic systems was estimated to be 215 lbs N. Research on Midwestern agricultural systems have previously shown that around 20% of agricultural nitrogen inputs were leached below the root zone into tile-drainage or groundwater (Masarik et al., 2014; Randall and Iravagarapu, 1995); we feel this is a reasonable estimate of loss below agricultural fields in Lincoln Township. Assuming that all of the septic system N and 5,078 lbs N (or 20% of total N inputs) from agricultural sources will end up in groundwater, we estimated that 96% of nitrate in groundwater around these wells is from agricultural sources while 4% is attributable to septic systems.

Average nitrate concentrations of wells were not correlated to soil thickness, well construction or any of the source assessment fields in Table 1. While the connection between land-use and groundwater quality is well understood, connecting land-use to water quality of a particular well in shallow carbonate rock aquifers is challenging because water quality for that well is likely controlled by a very discrete portion of the area around the well (Gotkowitz, 2006), and fracture flow in these types of aquifers is hard to predict. As a result, a half mile radius is probably not an accurate representation of the actual recharge area. However, without a more detailed investigation, understanding what discrete portion of the radius around each of the wells should be used for identifying the recharge area was not possible.

The degree to which nutrient management has been implemented around these wells (89% of cropland acres) is extensive, Kewaunee County is second (by percent of crop acres) in

the state for implementation of crop acres with a nutrient management plan (GCC, 2013). The extent to which nutrient management plans are being followed could not be verified; unless information exists to show otherwise, we assume here that they are an accurate representation of what is taking place on the landscape. As a result, we conclude that the elevated concentrations of nitrate in these ten wells are the result of what are considered to be acceptable agricultural management practices and not the result of gross mismanagement or negligence. The extent to which type of nutrient source and/or timing of nutrient applications correlate to the groundwater nitrate concentrations could not be quantified; understanding which practices may add to existing problems or alternatively result in less nitrate loss to groundwater is currently a major research priority for conservation professionals and policy makers.

While nitrate concentrations above 2 mg/L provide confirmation of being impacted by one or more human-related activity, the extent to which nitrate occurs in Lincoln wells is also largely a function of the soils and geology. Well sampling in areas with other soil or geologic conditions may reveal groundwater with little to no measurable nitrate, even if crops and management practices were similar or considered higher risk for nitrate leaching losses. If the goal is significant long-term reduction of nitrate concentrations in groundwater of Lincoln Township, it would likely require active efforts to reduce nitrogen inputs (e.g. less nutrient intensive cropping systems, strategic reduction in acreage, etc.) beyond the current source, rate and timing risk management strategies outlined in existing nutrient management plans.

Water quality correlations

An investigation of whether changes in one water quality constituent, such as nitrate, would also be expressed by changes in chloride, alkalinity, total hardness and/or bacteria was also performed. Correlation between constituents provides multiple lines of evidence to indicate

changes in water quality, and can strengthen our understanding of groundwater movement and monitoring. Changes in nitrate concentrations over the twelve sample events were compared to changes in other water quality parameters for each well.

Nitrate and chloride were positively correlated in six out of ten wells suggesting a linear relationship between these two constituents, meaning as nitrate concentrations increased so did chloride concentrations (Table 5). No correlation was found in wells 2 and 8 which showed relatively stable concentrations of nitrate and chloride throughout the twelve month period. Nitrate and chloride are considered mobile ions and given that both can have similar sources it is common for nitrate and chloride to increase or decrease in groundwater at the same time; areas with extensive road salt application may represent an exception to this relationship. Nitrate is part of a complicated cycle in which nitrogen occurs in ionic, gasous or organic forms as it is transferred between soils microorganisms, plants, organic matter and the atmosphere. By contrast, chloride in soils and groundwater exists in the ionic form and is not targeted for uptake by plants or microorganisms. Therefore it is often considered a more stable tracer than nitrate and is also useful for monitoring of groundwater quality (Freeze and Cherry, 1979), for example chloride is unaffected by the denitrification process which reduces nitrate concentrations.

Fewer correlations existed between other constituents. Whereas the source of elevated nitrate and chloride is associated with various human related activities, alkalinity and total hardness are associated with the dissolution of carbonate minerals from the soil or bedrock that groundwater flows through. Alkalinity and total hardness are often related to 1) the length of time groundwater has been in the aquifer and 2) the carbonate content of the rock or soils that the water has contacted along the flow path. In aquifers where the flow path and amount of time it takes groundwater recharge to reach a well is consistent, alkalinity and total hardness values are

Table 5. Value of Pearson correlation analysis (r) and p-values calculated between water quality measurements for all periods for each individual well.

Correlation	Well ID									
	1	2	3	4	5	6	7	8	9	10
	----------r----------									
	----------p-value----------									
Nitrate/Chloride	**-0.699**	-0.070	**0.890**	**0.969†**	-0.308	**0.943**	**0.957**	0.026	**0.833**	**0.716**
	0.011	0.828	0.000	0.000	0.330	0.000	0.000	0.935	0.001	0.009
Nitrate/Alkalinity	-0.271	0.108	**0.624**	**-0.624**	**-0.695**	0.296	**0.825**	-0.554	-0.012	**0.792**
	0.394	0.738	0.030	0.030	0.012	0.350	0.001	0.062	0.972	0.004
Chloride/Alkalinity	0.560	0.554	**0.756**	-0.178	**0.640**	0.086	**0.735**	-0.368	0.026	**0.866**
	0.058	0.062	0.004	0.581	0.025	0.791	0.007	0.239	0.937	0.000
Chloride/Cond.	0.026	0.150	**0.604**	**0.891**	0.385	0.346	**0.754**	-0.157	0.179	**0.971**
	0.939	0.660	0.049	0.000	0.242	0.297	0.007	0.644	0.599	0.000
Cond./Alkalinity	-0.342	-0.050	0.477	0.064	0.246	**0.755**	0.516	-0.107	**-0.648**	**0.824**
	0.304	0.884	0.138	0.852	0.466	0.007	0.104	0.755	0.031	0.002
T. Hardness/Nitrate	-0.296	ND	**0.704**	0.010	0.097	ND	ND	0.542	**0.585**	**0.673**
	0.351		0.011	0.974	0.765			0.069	0.046	0.016
T. Hardness/Cond.	**0.606**	ND	**0.683**	-0.536	0.468	ND	ND	0.202	-0.005	**0.966**
	0.048		0.020	0.089	0.147			0.551	0.989	0.000

Bold values indicate significance ($p<0.05$).
ND, Not determined; one or more samples from softened source.
† Excludes chloride outlier from 2/12/14 sample date.

often relatively stable. Changes in these two constituents may be related to biogeochemical reactions or may be reflective of changes in groundwater flow paths. For instance, a sudden drop in alkalinity and hardness may reflect a sudden influx of surface water that has not had time for significant carbonate dissolution to occur or some seasonal variation in water within a well. Conductivity is a measure of total ions dissolved in water and since calcium and magnesium are responsible for a large portion of water's overall conductance, conductivity usually responds similarly to total hardness and alkalinity. A study by Muldoon & Bradbury (2010) successfully used a continuous monitoring probe to measure sudden declines in conductivity that were related to rapid groundwater recharge events. Chloride can also impact conductivity measurements which helps explain the strong correlation between these two constituents in Well 10 (Table 5).

In the Lincoln Township wells the standard deviation of conductivity, alkalinity and total hardness averaged less than 5, 5 and 2% of the mean concentration, respectively. The relative stability of these three measurements seems to indicate that these parameters were not overly influenced by rapid throughflow of precipitation or snow-melt into the aquifer. Overall, nitrate and chloride had greater variability; standard deviation averaged 24 and 18% respectively. Greater variability of nitrate and chloride when other constituents had relatively stable concentrations suggest that variability is not solely from rapid influxes of low conductivity surface water. Rather the greater variability in nitrate and chloride may reflect seasonal variability related to the source of these contaminants.

Relationship of variability to long-term monitoring

Characterizing the intra-annual variability of water quality is important in developing a useful long-term monitoring strategy. The absence of variability in groundwater quality occurs when the following two conditions are met: 1) the groundwater traveling to the well takes a

consistent path through the aquifer and 2) the groundwater system is in equilibrium with land-use in the recharge area of a well. Equilibrium may be representative of natural conditions (unaffected by human impact) or in the case of elevated contaminants such as nitrate, reflect some repeatable land-use pattern that has been in place long enough for groundwater quality to have stabilized with the current practice(s). The lag time between what happens on the land surface and the point in which concentrations at some monitoring location below the ground stops changing will depend on the geologic properties of the soils and aquifer materials and depth below the water table.

When variability does occur, it becomes important to study why those changes are occurring and what implications they have for long-term groundwater monitoring. With a constituent such as nitrate, changes in water quality may be indicative of land-use change or, in the absence of land-use change, may reflect some sort of annual climatic variability (Randall and Iragavarapu, 1995; Masarik et. al., 2014). Changes in water quality over some period of time that signify water quality is better or worse could be validated by a trend (either increasing or decreasing) such as a linear relationship between sample date and concentration over some period of time, or a sudden change where the average concentrations before and after are statistically different. Alternating increases or decreases in concentration where no linear relationship exists would indicate that groundwater is impacted but is not better or worse than at some previous point in time.

In order to answer the question of whether groundwater quality is better, worse, or stayed the same, it is necessary to understand the intra-annual variability of groundwater quality. Knowing how concentrations may fluctuate during the year helps to provide context to historical data. If little variation exists, then utilizing annual sampling data from past well testing to

interpret trends or changes over time may be useful and appropriate. If large amounts of intra-annual variability exist, sorting out the intra-annual variation from a long-term trend or change may require increasing the number of wells that are sampled on a regular basis and/or monitoring for a longer period of time.

Standard deviation is a measure of the average distance of values from the mean and is a standard way to measure and express variability. The standard deviation and average concentration of each parameter for the ten wells was plotted by sample period to understand variability during the year (Figure 5). Variability among nitrate, chloride, alkalinity and conductivity was lowest during the period when soil temperatures indicated frozen conditions and little to no groundwater recharge was likely occurring. Variability increased following the period indicating snow melt and non-frozen soil conditions when groundwater recharge commenced in the spring of 2014; variability was of similar magnitude at the beginning of the study period in June 2013 following the previous spring recharge period. While it is less obvious in the nitrate measurements, the chloride, alkalinity and conductivity all seem to indicate a gradual decline in variability following the spring recharge period in 2013.

Implications for long-term monitoring

These results suggest the composition of water from private wells was most stable during frozen soil conditions when little to no recharge was occurring, and most variable following the snow-melt and spring recharge season. The increased variability of June 2013 and April/May 2014 likely reflects the influx of groundwater recharge during the spring. The gradual decrease in variability that occurred in summer and fall may be the result of a prolonged period of little to no recharge, or perhaps smaller recharge events that did have as great an influence on groundwater quality. Because spring is a critical time for groundwater recharge in Wisconsin,

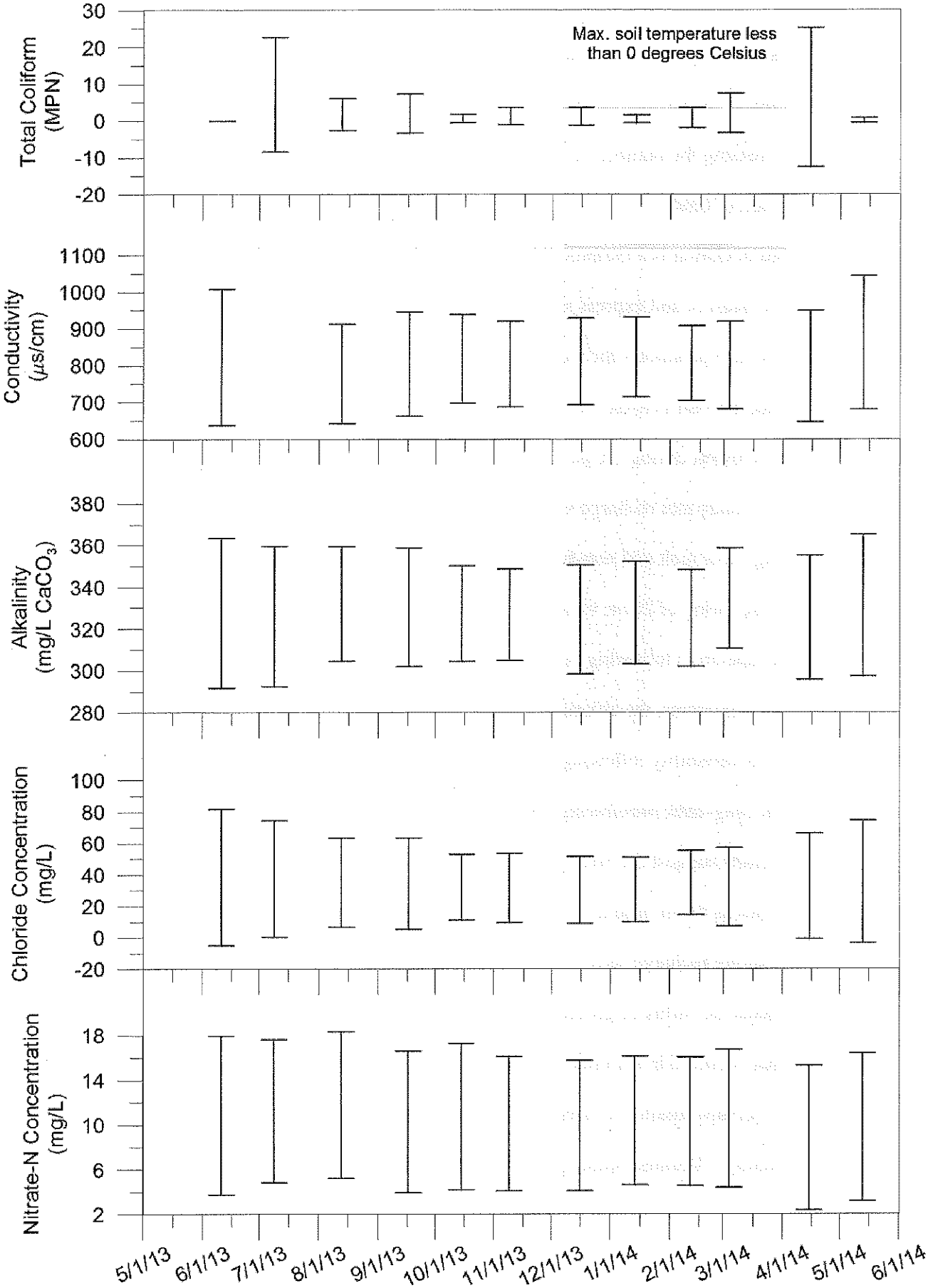


Figure 5. Standard deviation from the average of all ten wells for each sample period indicated by error bars.

monitoring nitrate and chloride concentrations after this period may prove insightful as to how the aquifer may or may not have been affected spring recharge each year.

For long-term monitoring purposes of private well water and groundwater quality, we feel that there are benefits to avoiding times of the year when variability is anticipated. Sampling wells when the groundwater aquifer is most stable appears to provide the best opportunity to detect trends or changes in groundwater over time. Measuring the magnitude of variability (difference between stable conditions and some minimum or maximum distance from the average) may also have benefits, in particular for understanding how annual climatic variability or particular land-uses may be influencing water quality from year to year.

Recommendations for future monitoring efforts

Even though there was significant intra-annual variability in private well water quality, it appears that these wells could be used in a cost-effective monitoring program in Lincoln Township to monitor groundwater quality. We feel that future monitoring efforts in Lincoln Township would benefit from an increasing the number of wells that are tested. In order to limit expenses related to sampling an increased number of wells, sampling frequency could be decreased from twelve down to twice per year. Because they are associated with human influences, nitrate and chloride have the most utility for understanding land-use trends or human influenced changes to groundwater; alkalinity is also potentially useful for characterizing aquifer properties. Sampling in January when soil conditions have the greatest potential to be frozen provides an opportunity to measure wells under relatively stable aquifer conditions. Sampling in mid-June provides some ability to assess groundwater conditions following the spring groundwater recharge period. Monitoring the magnitude of change between these two times of year could provide useful insight into land-use interactions with groundwater or climatic

variability from year to year. Well water quality information collected with this type of organized approach would assist in tracking long-term water quality, and ultimately examine whether well water quality is changing over time as a result of land-use practices.

Given the inherent limitations of grab sampling methods of quantifying bacteria/pathogens, we feel that coliform/*E.coli* testing is of little utility for long-term monitoring in this type of sampling approach. If bacterial or pathogenic contamination of wells is to be studied, alternative methods to grab samples that are capable of measuring or quantifying the impact of rapid recharge events in this type of groundwater aquifer should be investigated. Because this is an emerging area of research it would likely require the pursuit of outside grants or partnering with researchers to investigate this particular aspect of well water quality.

Trends and changes are difficult to detect and a solid commitment from well owners would be critical before starting such an effort. We believe that a minimum of 25 wells should be selected for bi-annual testing. We also feel that there is little value in only collecting this type of information for one or two years, selecting landowners with an understanding that testing might last 10 or more years would be important for developing a consistent dataset. A committed funding source is equally important to ensuring such data collection is meaningful and testing efforts are not terminated prematurely. Reasonable assurance that testing costs can be covered for a set period of time (we recommend 10 years) would be necessary before undertaking such an effort. It may be possible to pursue grants to expand testing to a larger number of wells in certain years or perform more detailed analysis for emerging compounds of interest. Technology is available to measure specific pathogens related to human wastewater and bovine manure; because the sampling method can be performed in-line this technology may also

be capable of determining a more complete picture of bacteria/pathogenic contamination of private wells (Borchardt et al., 2012).

Conclusions

The monthly sampling of ten wells in Lincoln Township measured significant variability in nitrate and chloride concentrations, both human-related contaminants. Nitrate variability was large enough that homeowners with an initial nitrate concentration above 2 mg/L should consider testing more than once per year to investigate the potential for the nitrate concentration to rise above the nitrate drinking water standard at some point during the year. Water quality results suggest aquifer conditions were most stable during the winter period when the soil near the surface was below 0 degrees Celsius. Changes in well water quality measured in individual wells and increased variability between wells seemed to coincide with the snow-melt and spring recharge periods.

Understanding whether a well is susceptible to bacterial contamination is important to anyone that relies on a private well, particularly when used as a source of water for drinking and cooking. The variability of coliform bacteria results and the inability to measure other pathogens of interest suggest that an annual present/absent type of coliform bacteria tests is likely insufficient to assess the bacteriological/pathogenic safety of a water supply over the course of the year. Until better test methods can be developed, homeowners that use private wells as their primary source of drinking and cooking water in Lincoln Township may also want to consider testing their well more frequently than once per year for coliform bacteria. While testing more frequently might help to identify wells that are more susceptible to local geologic conditions, testing methods are only a snapshot in time. Those relying on private wells as their primary

drinking and cooking source, especially households that have noticed frequent occurrences of gastrointestinal illness, may want to consider a treatment system like ultra-violet (UV) light or other types of treatment that kill pathogens which would provide some level of protection from pathogens should minor contamination incidents occur.

REFERENCES

Andraski, T.W., L.G. Bundy, and K.R. Brye. 1999. Crop Management and Corn Nitrogen Rate Effects on Nitrate Leaching. *J. Environ. Qual.* Vol. 29 No. 4, p. 1095-1103.

Atherholt, T., E. Feerst, B. Hovendon, J. Kwak, and D. Rosen. 2003. Evaluation of Indicators of Fecal Contamination in Groundwater. *Am. Water Works Assoc. J.* Vol. 95, Issue 10, p.119-131.

Borchardt, M.A., S.K. Spencer, B.A. Kieke Jr., E. Lambertini, F.J. Loge. 2012. Viruses in non-disinfected drinking water from municipal wells and community incidence of acute gastrointestinal illness. *Environ. Health Perspectives.* 120:1272-1279.

Braatz, L.A. (2004). A Study of Fecal Indicators and other Factors Impacting Water Quality in Private Wells in Door County, WI. MS Thesis. University of Wisconsin – Green Bay.

Bradbury, K. R., and M. A. Muldoon. 1992. Hydrogeology & Groundwater Monitoring of Fractured Dolomite In The Upper Door Priority Watershed Door County. Wisconsin Geological and Natural History Survey Open File Report, WOFR 92-2, 84 p.

Bradbury, K.R., Borchardt, M.A., Gotkowitz, M., Spencer, S.K., Zhu, J., Hunt, R.J. 2013. Source and transport of human enteric viruses in deep municipal water supply wells. *J. Environ. Sci. and Tech.* 47:4096-4103.

Center for Watershed Science and Education (2013) WI Well Water Viewer. http://www.uwsp.edu/cnr-ap/watershed/Pages/wellwaterviewer.aspx

DATCP. 2008. Wisconsin Groundwater Quality: Agricultural Chemicals in Wisconsin Groundwater. WI Department of Agriculture, Trade and Consumer Protection. Environmental Quality Section. ARM Pub 180.qxd 04/08.

Groundwater Coordinating Council (GCC). 2013. WI Groundwater Coordinating Council FY2013 Report to the Legislature. WI Dept. of Natural Resources. http://dnr.wi.gov/topic/Groundwater/GCC/report.html

EPA, 2002, "Onsite Wastewater Treatment Systems Manual," Office of Water, Office of Researchand Development, U.S. Environmental Protection Agency, Washington, DC, EPA/625/R-00/008.

Erb, Kevin and Ron Steiglitz (editors), (2007). Final Report of the Northeast Wisconsin Karst Task Force, 46 p. http://learningstore.uwex.edu/Final-Report-of-the-Northeast-Wisconsin-Karst-Task-Force-P1234C120.aspx

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Englewood Cliffs, New Jersey: Prentice Hall.

Gotkowitz, M.B. and S.J. Gaffield, 2006. Water-Table and Aquifer-Susceptibility Maps of Calumet County, Wiscoinsin. Wisconsin Geological and Natural History Survey Miscellaneous Map 56. Scale 1:100,000

Jaynes, D.B., T.S. Colvin, D.L. Karlen, C.A. Cambardella, and D.W. Meek. 2001. Nitrate Loss in Subsurface Drainage as Affected by Nitrogen Fertilizer Rate. *J. Environ. Qual.* 30:1305-1314.

Laboski, C. & J. B. Peters, J. 2012. Nutrient applications guidelines for field, vegetable, and fruit crops in Wisconsin. UW-Extension publication A2809.

Masarik, K. , Norman, J. and Brye, K. (2014) Long-Term Drainage and Nitrate Leaching below Well-Drained Continuous Corn Agroecosystems and a Prairie. *Journal of Environmental Protection*, **5**, 240-254. doi: 10.4236/jep.2014.54028.

Millen, H. T., Gonnering, J. C., Berg, R. K., Spencer, S. K., Jokela, W. E., Pearce, J. M., et al. Glass Wool Filters for Concentrating Waterborne Viruses and Agricultural Zoonotic Pathogens. *J. Vis. Exp.* (61), e3930, doi:10.3791/3930 (2012).

Muldoon, M.A & K.R. Bradbury. 2010. Assessing Seasonal Variations in Recharge and Water Quality in the Silurian Aquifer in Areas with Thicker Soil Cover. Report to WI Dept. of Natural Resources. DNR-198.

Pasquarell, G.C. and D.G. Boyer. 1995. Agricultural Impacts on Bacterial Water Quality in Karst Groundwater. *J. Environ. Qual.* 24:959-969.

Randall, G. W. and T. K. Iragavarapu. 1995. Impact of Long-Term Tillage Systems for Continuous Corn on Nitrate Leaching to Tile Drainage. *J. Environ. Qual.* 24:360–366. doi:10.2134/jeq1995.00472425002400020020x

Sherrill, M. G. 1978. Geology and Ground Water in Door County, Wisconsin, With Emphasis on Contamination Potential in the Silurian Dolomite. Wisconsin Geological Survey Water-Supply Paper 2047, 38 p.

WI DNR. 1998. WISCLAND Land Cover (WLCGW930). Madison, Wisconsin. Wisconsin Department of Natural Resources.

WI DNR. 2014. Nitrate in Drinking Water. WI Dept. of Natural Resources, Bureau of Drinking Water and Groundwater. PUB-DG-001 2014.

Zheng, Y., W.R. Kelly, S.V. Panno, W.T. Liu. 2013. Identification of Sources of Fecal Pollution of Karst Waters. Illinois State Water Survey. Champaign, Illinois. Contract Report 2013-02.

Appendix A. Water quality results of individual wells for each sample period.

Well #1

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/100mL	MPN cfu/ 100mL
6/11/2013	7.72	692	276	376	15.0	17.4	ND	ND
7/9/2013	7.74	NA	276	372	15.0	17.0	ND	ND
8/13/2013	8.23	650	296	372	15.2	17.8	ND	ND
9/17/2013	7.23	713	292	392	14.2	18.4	ND	ND
10/15/2013	8.11	720	292	396	14.6	19.4	ND	ND
11/9/2013	7.73	719	292	396	14.5	19.8	ND	ND
12/16/2013	8.00	729	284	388	14.5	18.4	1.0	ND
1/14/2014	8.09	743	288	405	14.7	18.0	ND	ND
2/12/2014	7.64	712	284	396	15.4	17.8	ND	ND
3/4/2014	7.68	704	296	400	15.2	17.5	ND	ND
4/15/2014	8.14	708	283	388	15.0	16.9	ND	ND
5/13/2014	7.72	750	280	384	15.4	16.5	ND	ND

Well #2

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/100mL	MPN cfu/ 100mL
6/11/2013	7.65	746	324	408	16.0	15.5	ND	ND
7/9/2013	7.74	NA	328	404	15.7	13.7	ND	ND
8/13/2013	8.44	690	328	400	16.3	13.1	ND	ND
9/17/2013	7.30	737	324	416	15.7	12.8	ND	ND
10/15/2013	8.08	763	320	408	15.6	12.2	ND	ND
11/9/2013	7.77	775	316	<4	15.7	12.3	ND	ND
12/16/2013	7.85	794	324	<4	15.8	12.9	ND	ND
1/14/2014	7.92	800	324	8†	16.0	13.5	ND	ND
2/12/2014	7.71	770	320	<4	16.9	13.0	ND	ND
3/4/2014	7.69	765	328	<4	16.9	12.9	ND	ND
4/15/2014	8.15	780	324	<4	15.7	13.8	ND	ND
5/13/2014	7.91	805	332	420	15.8	15.1	ND	ND

Well #3

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/100mL	MPN cfu/ 100mL
6/11/2013	7.59	938	352	484	18.1	44.8	ND	ND
7/9/2013	7.62	NA	348	472	18.1	42.6	ND	ND
8/13/2013	8.23	875	356	484	21.1	44.5	ND	ND
9/17/2013	7.14	943	352	492	21.0	44.9	ND	ND
10/15/2013	8.35	921	344	492	22.1	45.1	ND	ND
11/9/2013	7.73	899	348	464	18.8	40.2	ND	ND
12/16/2013	7.78	884	336	456	16.4	36.6	ND	ND
1/14/2014	7.80	891	344	480	15.1	36.0	ND	ND
2/12/2014	7.67	846	340	456	15.4	35.4	ND	ND
3/4/2014	7.63	903	352	488	19.0	41.1	ND	ND
4/15/2014	7.73	889	344	472	17.2	38.4	ND	ND
5/13/2014	7.69	1005	352	492	19.7	43.0	ND	ND

NA Not Analyzed; **ND** None Detected; **<4** Softened Water; **†** Partially Softened Water

Appendix A (cont.)

Well #4

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.52	683	348	388	5.6	8.3	ND	ND
7/9/2013	7.82	NA	312	376	9.1	16.4	ND	ND
8/13/2013	8.19	694	328	388	12.3	19.2	ND	ND
9/17/2013	7.37	694	332	388	7.7	11.1	ND	ND
10/15/2013	7.99	735	336	396	9.4	14.4	2.0	ND
11/9/2013	7.70	693	332	372	7.8	10.2	5.2	ND
12/16/2013	7.86	687	328	380	6.2	8.4	1.0	ND
1/14/2014	8.19	715	336	416	7.5	11.8	ND	ND
2/12/2014	7.57	839	336	336	7.3	55.8	ND	ND
3/4/2014	7.60	693	344	404	6.4	9.4	4.1	ND
4/15/2014	8.05	658	340	376	4.4	5.8	60.2	ND
5/13/2014	7.58	736	356	396	4.8	7.5	2.0	ND

Well #5

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.56	791	280	404	21.6	28.6	ND	ND
7/9/2013	7.84	NA	296	404	18.9	29.8	ND	ND
8/13/2013	8.19	755	304	400	15.7	30.7	4.1	ND
9/17/2013	7.57	760	308	408	10.7	33.2	3.1	ND
10/15/2013	8.03	793	308	412	10.0	33.5	3.1	ND
11/9/2013	7.91	768	316	396	8.0	31.9	1.0	ND
12/16/2013	7.79	800	300	404	14.0	32.1	7.5	ND
1/14/2014	7.95	838	308	440	15.8	33.3	2.0	ND
2/12/2014	7.53	797	308	424	13.3	33.3	ND	ND
3/4/2014	7.72	788	324	500	11.2	34.2	ND	ND
4/15/2014	7.71	718	288	372	12.1	25.4	ND	ND
5/13/2014	7.84	800	304	392	13.7	24.7	ND	ND

Well #6

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.62	700	304	372	8.2	24.9	ND	ND
7/9/2013	7.95	NA	304	368	10.5	27.7	ND	ND
8/13/2013	8.18	701	304	380	11.4	27.7	ND	ND
9/17/2013	7.51	701	300	376	8.0	24.4	ND	ND
10/15/2013	8.11	747	308	388	10.0	26.5	ND	ND
11/9/2013	7.85	758	308	<4	9.5	25.9	ND	ND
12/16/2013	7.71	768	312	<4	8.5	24.8	ND	ND
1/14/2014	7.85	794	316	<4	10.1	26.5	ND	ND
2/12/2014	7.72	761	316	8†	10.3	26.4	ND	ND
3/4/2014	7.61	784	324	104†	12.6	26.8	ND	ND
4/15/2014	7.80	717	312	80†	2.3	20.9	ND	ND
5/13/2014	7.79	740	300	368	6.6	24.8	ND	ND

NA Not Analyzed; **ND** None Detected; **<4** Softened Water; **†** Partially Softened Water

Appendix A (cont.)

Well #7

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.81	852	316	<4	13.3	34.6	ND	ND
7/9/2013	8.32	NA	324	<4	13.8	35.1	28.1	ND
8/13/2013	8.64	846	332	<4	14.5	34.7	ND	ND
9/17/2013	7.75	862	332	<4	13.9	34.3	ND	ND
10/15/2013	8.35	904	324	<4	14.1	34.5	ND	ND
11/9/2013	7.73	836	324	440	14.0	34.5	ND	ND
12/16/2013	7.75	838	312	440	12.7	32.7	ND	ND
1/14/2014	7.92	837	316	452	12.2	32.3	ND	ND
2/12/2014	7.80	803	312	436	12.2	32.3	ND	ND
3/4/2014	7.76	790	320	424	11.6	31.1	ND	ND
4/15/2014	7.75	790	308	424	10.3	30.5	2.0	ND
5/13/2014	7.73	840	312	412	10.9	31.4	ND	ND

Well #8

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.60	982	388	516	9.1	45.1	ND	ND
7/9/2013	7.90	NA	380	444	9.2	44.9	ND	ND
8/13/2013	8.13	953	376	500	9.8	44.8	ND	ND
9/17/2013	7.42	975	384	496	9.5	44.6	ND	ND
10/15/2013	8.07	1011	372	516	10.1	44.5	1.0	ND
11/9/2013	7.61	986	368	504	10.9	45.1	6.3	ND
12/16/2013	7.54	1019	376	516	9.6	45.7	3.0	ND
1/14/2014	7.80	1004	376	536	10.8	43.9	3.1	ND
2/12/2014	7.61	985	368	520	10.9	46.5	8.4	ND
3/4/2014	7.49	964	384	520	11.1	44.7	16.9	ND
4/15/2014	7.83	994	372	512	10.7	45.0	2.0	ND
5/13/2014	7.89	1059	380	380	10.2	44.4	ND	ND

Well #9

Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.74	615	324	344	1.2	9.9	ND	ND
7/9/2013	8.25	NA	316	344	1.5	10.4	ND	ND
8/13/2013	8.48	604	328	340	1.3	10.6	ND	ND
9/17/2013	7.74	616	320	344	1.7	11.7	ND	ND
10/15/2013	8.25	635	324	348	1.3	11.6	ND	ND
11/9/2013	7.77	634	320	344	1.7	12.7	ND	ND
12/16/2013	7.79	635	320	348	1.5	11.9	ND	ND
1/14/2014	7.92	650	320	364	1.5	11.9	ND	ND
2/12/2014	7.71	627	324	360	1.5	12.0	ND	ND
3/4/2014	7.68	621	324	360	1.7	11.4	ND	ND
4/15/2014	7.78	624	320	348	0.8	9.6	ND	ND
5/13/2014	8.04	647	320	320	0.7	9.4	ND	ND

NA Not Analyzed; **ND** None Detected; **<4** Softened Water; **†** Partially Softened Water

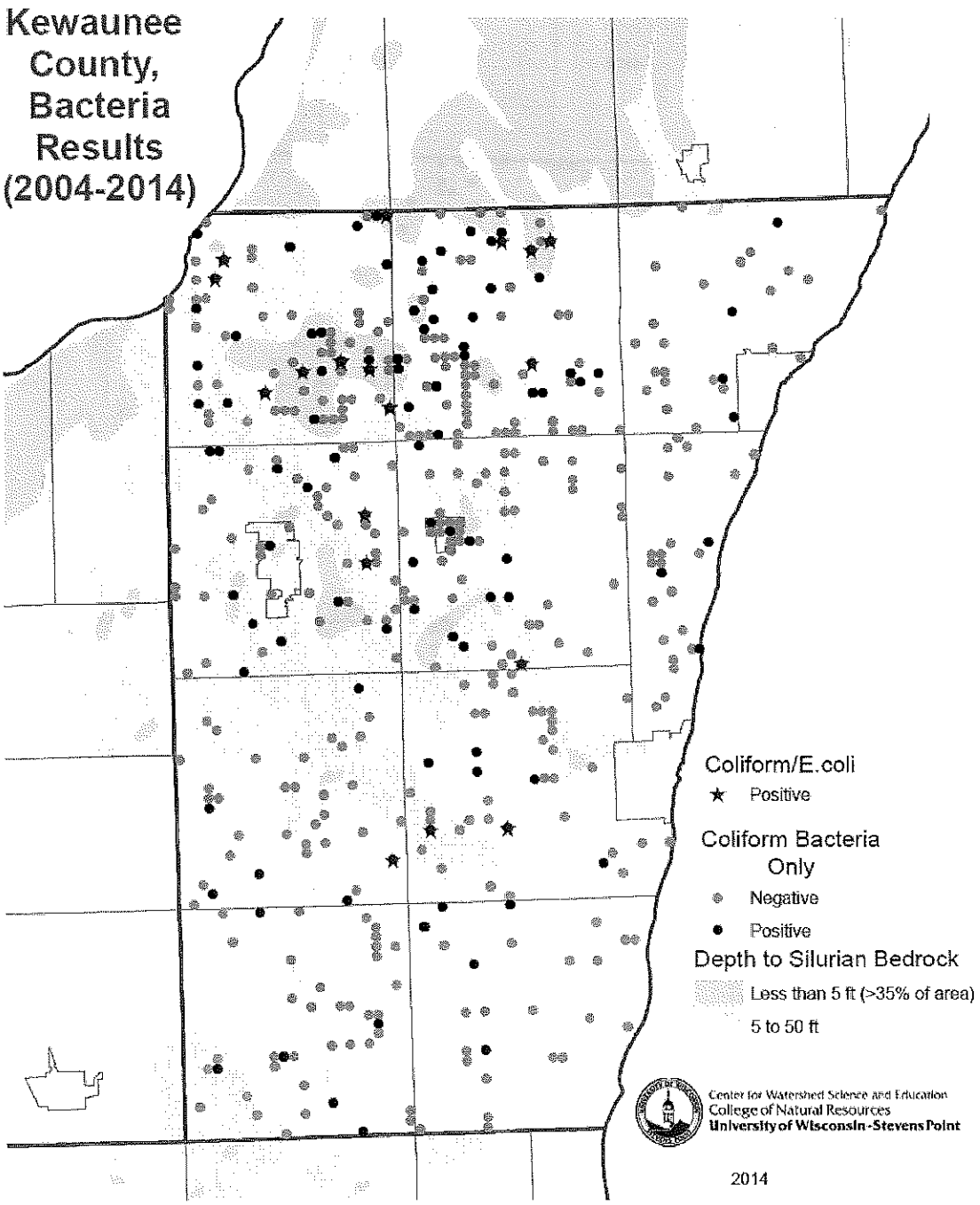
Appendix A (cont.)

Well #10

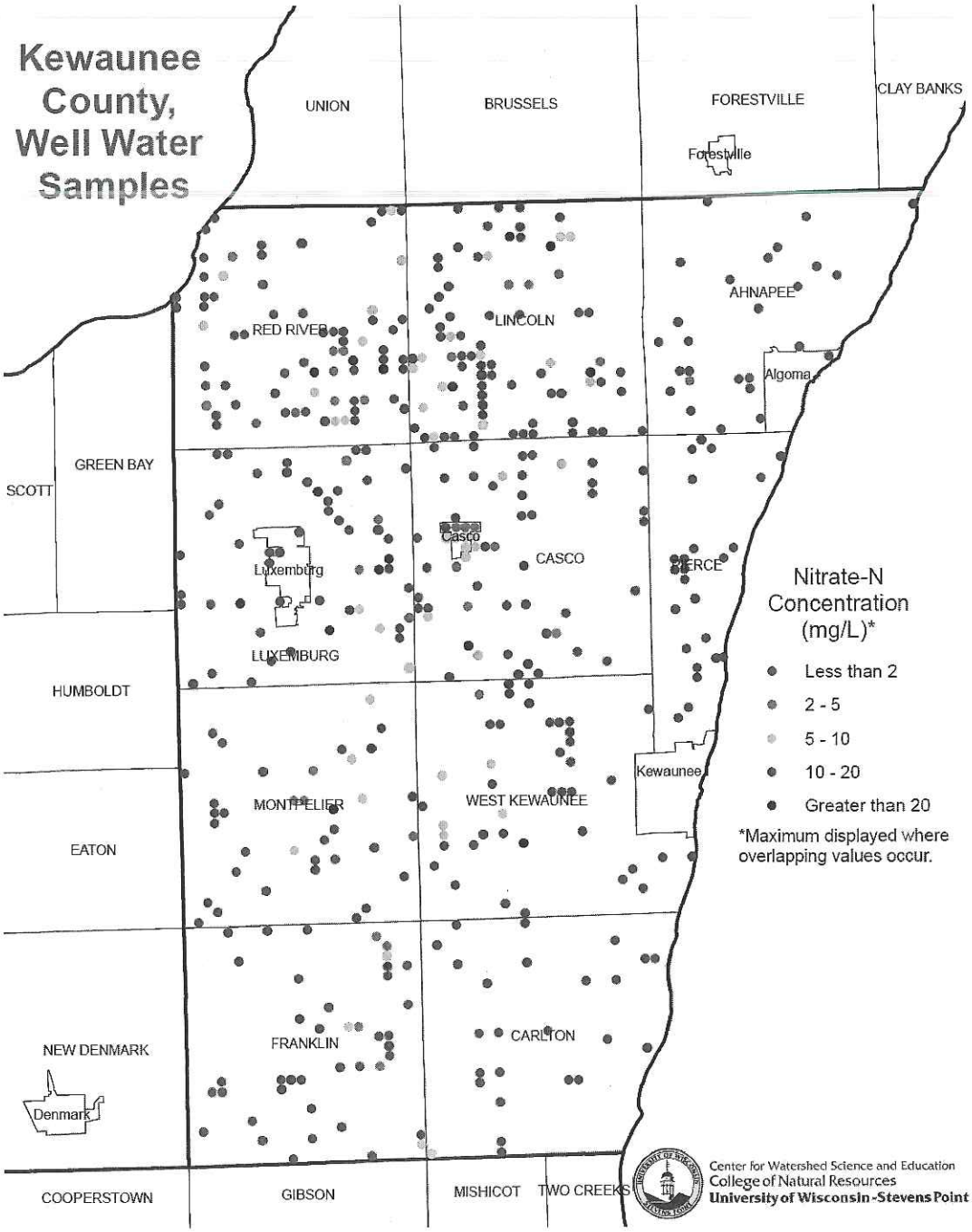
Sample Date	pH	Conductivity	Alkalinity	Total Hardness	Nitrate-Nitrogen	Chloride	Total Coliform	*E.Coli*
		µs/cm	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L	mg/L	MPN cfu/ 100mL	MPN cfu/ 100mL
6/11/2013	7.66	1231	364	584	0.4	156.0	ND	ND
7/9/2013	8.16	NA	376	540	0.5	137.0	43.5	ND
8/13/2013	8.01	1005	368	504	0.2	108.0	13.4	ND
9/17/2013	7.53	1040	360	508	0.2	109.0	17.1	ND
10/15/2013	8.28	949	344	476	0.1	79.8	ND	ND
11/9/2013	7.81	969	344	478	<0.1	83.9	1.0	ND
12/16/2013	7.76	952	352	484	<0.1	80.0	ND	ND
1/14/2014	7.95	956	348	488	<0.1	79.5	ND	ND
2/12/2014	7.76	921	344	480	<0.1	77.5	ND	ND
3/4/2014	7.73	988	350	480	<0.1	94.2	ND	ND
4/15/2014	7.89	1097	364	528	<0.1	122.0	ND	ND
5/13/2014	7.87	1238	376	556	0.1	140.0	ND	ND

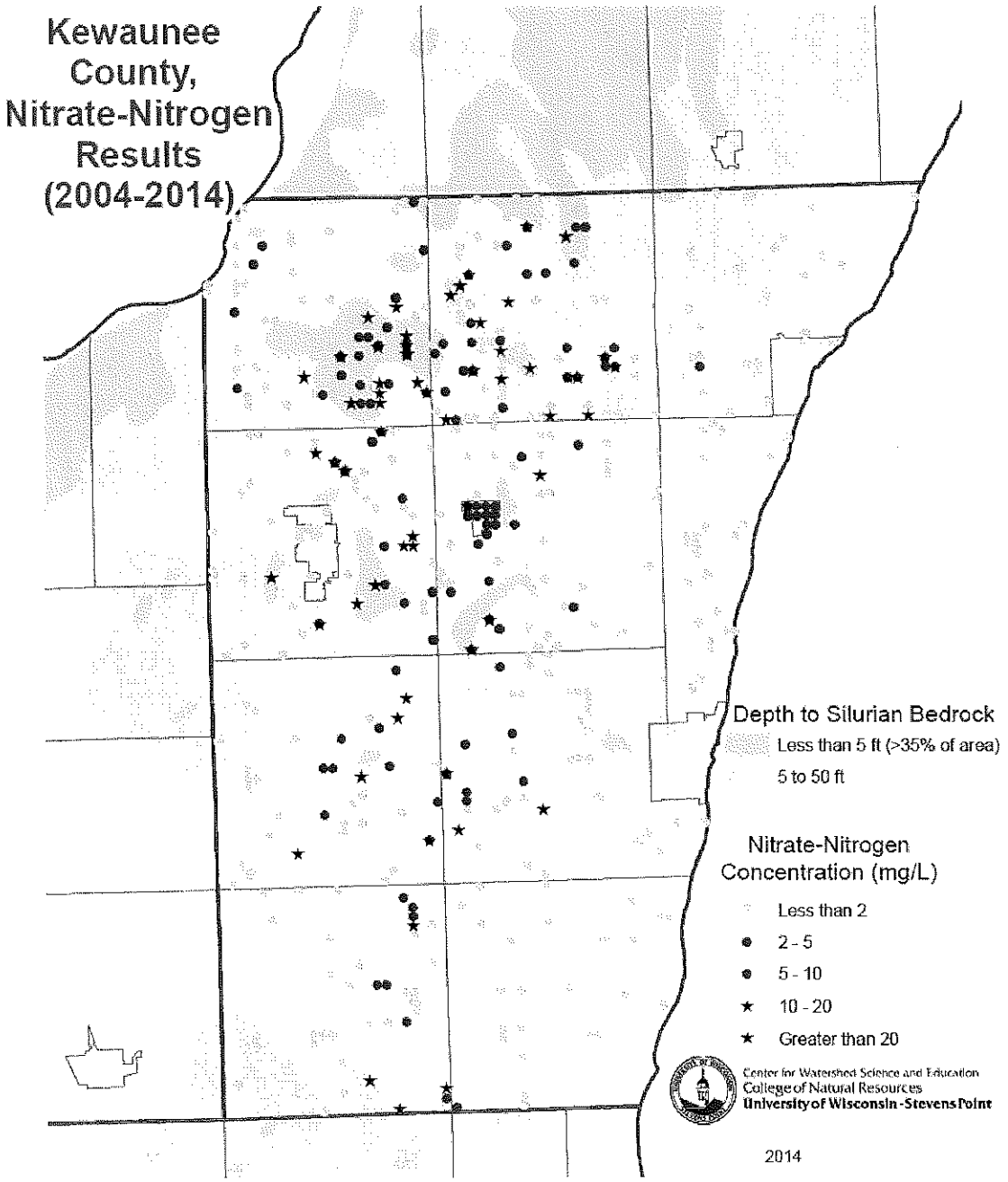
NA Not Analyzed; **ND** None Detected; **<4** Softened Water; † Partially Softened Water

Appendix B. Maps of Kewaunee County Well Water Testing Results (2004 – 2014)



Appendix B (cont.)



Disclaimer: This map represents data in the Center for Watershed Science and Education database for the period from 2004-2014. It does not represent all known private well tests and does not represent a scientifically conducted study.

Appendix B (cont.)