Long-Term Hydrologic Sustainability of Calcareous Fens along Glacial Lake Agassiz Beach Ridges, Northwestern MN

A THESIS

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Abstract

Calcareous fens are peat-accumulating wetlands fed by calcium-rich groundwater that support several threatened species of plants that evolved to thrive in these geochemical conditions. Fifty-three of Minnesota's nearly 300 identified calcareous fens are located in the Glacial Lake Agassiz beach ridge complex in northwestern Minnesota. Each of these fens is located immediately downslope of large sand/gravel beach ridges, where peat aprons have accumulated on the seepage face. This investigation characterizes the hydrology and landscape setting of two calcareous fens that are typical of the larger groups. Three potential sources of water to the fens are considered: groundwater from the surficial beach ridge aquifers, underlying confined aquifers, or a combination of the two influenced by seasonal hydrology. Water levels in wells in the confined aquifers, surficial beach ridge aquifers, and in and below the fens were compared with rainfall hydrographs to identify hydrologic connections. Hydrologic responses to rainfall events and associated hydraulic gradients suggest the calcareous fens are well-connected to the beach-ridge aquifer. Wells in the beach-ridge aquifers and wells in and below the fens respond synchronously to rainfall events. Water chemistry and stable isotopes are similar within the beach ridge aquifer and calcareous fens and differ significantly from water in confined aquifers. Beach ridge aquifer complexes are relatively thin (<8-10 m) and overly thick clay/clay loam till. These shallow aquifers exhibit high seasonal recharge and have permanent saturated zones, providing a continual source of water for the fens. Electrical resistivity profiles and 3D aquifer models characterized the glacial stratigraphy and highlight the well-developed physical connection between beach ridge aquifers and calcareous fens.

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Introduction

Calcareous fens (Figure 1) are found in a variety of geomorphic settings throughout the northern United States, Canada, and northern Europe. These fens generally range in area from less than an acre to a few tens of acres and are often associated with other wetland types (Aaseng et al., 2005). Calcareous fens are characterized as peat-accumulating wetlands fed by circumneutral to alkaline groundwater with high concentrations of calcium and low dissolved oxygen (Leete et al., 2005). In Minnesota, calcareous fens are defined using a combination of their hydrology, soil, water chemistry, and vegetation (Table 1). Calcareous fens are protected under Minnesota Statute 103G.223 because of the presence of several threatened calciphytic plant species including the sterile sedge (Carex sterilis), beaked spike-rush (Eleocharis rostellata), hair beak-rush (Rhynchospora capillacea), whorled nut-rush (Scleria verticillata), and common valerian (Valeriana edulis var. ciliate) (Eggers & Reed, 2011; MNDNR, 2016).

Figure 1. Photo of Sanders Fen North, a calcareous fen that was studied in detail as a part of this project. Author photo, June 20, 2019.

Table 1. Technical criteria for calcareous fen identification in Minnesota.

Hydrology	
Stable, typically upwelling groundwater flows sufficient to maintain soil saturation	
Soils	
Presence of a histosol or histic epipedon (organic soil), potentially with calcium carbonate precipitates	
Water Chemistry	
Calcium	> 30 mg/L
pH	> 6.7
Alkalinity	> 1.65 meq/L (> 82.5 mg/L $CaCO_3$)
Specific Conductance	> 500 µS/cm
Dissolved Oxygen	< 2 mg/L
Vegetation	
Exceedance of index score based on presence of calciphytic plants listed and scored in MNDNR (2016)	

(Compiled from Leete et al., 2005; MNDNR, 2016)

Although vegetation assemblages and water chemistry parameters in calcareous fens have been well described, there is a general paucity of research on their hydrology. Calcareous fens are found in a wide variety of hydrogeomorphic settings across Minnesota. These settings include in the Driftless Area of southeastern Minnesota, the Minnesota River valley, morainal complexes of southwestern and central Minnesota, Glacial Lake Agassiz beach ridges in northwestern Minnesota, and the Lake Agassiz Peatlands of northern Minnesota. Of the 296 identified calcareous fens in Minnesota at the time of this writing (MNDNR, 2019, Native Plant Communities), only a few have been the focus of detailed hydrologic investigations (Almendinger and Leete, 1998a, 1998b; Komor, 1994; Pavlish, 2004).

This investigation evaluates the hydrology and hydrogeology of two calcareous fen in the Lake Agassiz Beach ridge complex that are typical of the fens in this particular hydrogeomorphic setting. This will allow for a better understanding of the hydrologic mechanisms controlling the presence of calcareous fens and their unique biota that includes several threatened plant species.

The hydrology, water chemistry, and geologic setting of these fens are used to test three hypotheses regarding fen hydrology:

1. Calcareous fens associated with Agassiz beach ridges are completely fed by surficial beach ridge aquifers;
2. Calcareous fens associated with Agassiz beach ridges are primarily fed by water from confined aquifers;
3. Calcareous fens associated with Agassiz beach ridges are primarily fed by surficial aquifers except during dry periods, when water from buried aquifers helps sustain them.

The hypotheses were tested through a detailed study of the physical, chemical, and isotopic hydrology of two beach ridge calcareous fens as well as a statistical analysis of landscape factors describing calcareous and non-calcareous fens along Minnesota's Lake Agassiz beach ridges.

Background

In a study of fens in the Minnesota River Valley, Almendinger and Leete (1998a, 1998b) show that fens are commonly associated with permeable, coarse-grained deposits in topographic settings that allow substantial vertical hydraulic head gradients. Such fens need not depend on the local presence of carbonate bedrock and depend instead on shallow calcareous deposits (whether unconsolidated or not) in the recharge area. Although upward ground-water flow exists beneath all of the fens studied by Almendinger and Leete (1998a, 1998b), Komor (1994), and Pavlish (2004), the total depth of the flow system that actually contributes ground water to the fens is unknown and site-specific. Komor (1994) used stable-isotope analysis of water to demonstrate that some ground water emerging at Savage Fen in the Minnesota River Valley probably recharged on the adjacent bluffs from ponds about 2 km from the fen; in addition, the young age of ground water at Savage Fen suggested short ground water travel time from the recharge area supporting the nearby recharge.

Literature on calcareous fens outside of Minnesota generally focuses on the vegetation and chemical characteristics of fen water. Locations of these studies include the north-central and northeastern United States (Bedford & Godwin, 2003; Bowles et al., 2005; Miner & Ketterling, 2003), southern Canada (Duval et al., 2012), and England (Boyer & Wheeler, 1989). In a water budget study of three calcareous fens near Toronto, Ontario, Canada, Duval and Waddington (2018) conclude that calcareous fens need not sit in groundwater discharge zones, the geomorphic setting commonly deemed necessary for fen development (Almendinger & Leete, 1998b; Amon et al., 2002). Instead, calcareous fens in their investigation were dominated by stream recharge and precipitation with minor groundwater contributions to only one of the fens (Duval and Waddington, 2018). A fen’s hydrogeomorphic setting is an important control on the movement of water into and through the fen (Duval & Waddington, 2018), and since fens are found in a variety of unique landscape settings (Almendinger & Leete, 1998b; Duval & Waddington, 2018; Thompson, 1992), research on the different settings is vital to better understand fen function and occurrence.

Minnesota calcareous fens fall into three general groups based on hydrology and peat landforms: 1) Peat domes sustained by localized, small areas of upwelling groundwater where conductive sediments penetrate a confining unit to a confined aquifer with above-surface hydraulic heads (Figure 2a); 2) Peat aprons at seepage faces with diffuse groundwater discharge (Figure 2b); and 3) Spring ponds with discharging groundwater (Aaseng et al., 2005; Leete et al., 2005). Coring through the peat into the underlying mineral soil showed that sand and gravel was present under all but one calcareous fen in the study by Almendinger and Leete (1998b), indicating that coarse inorganic substrate allows large amounts of groundwater to discharge at the fen. Beach ridges, bluffs, incised valleys, and morainal complexes can provide hydrogeologic settings that create springs and seeps conducive to the formation of calcareous fens (Almendinger and Leete, 1998b).

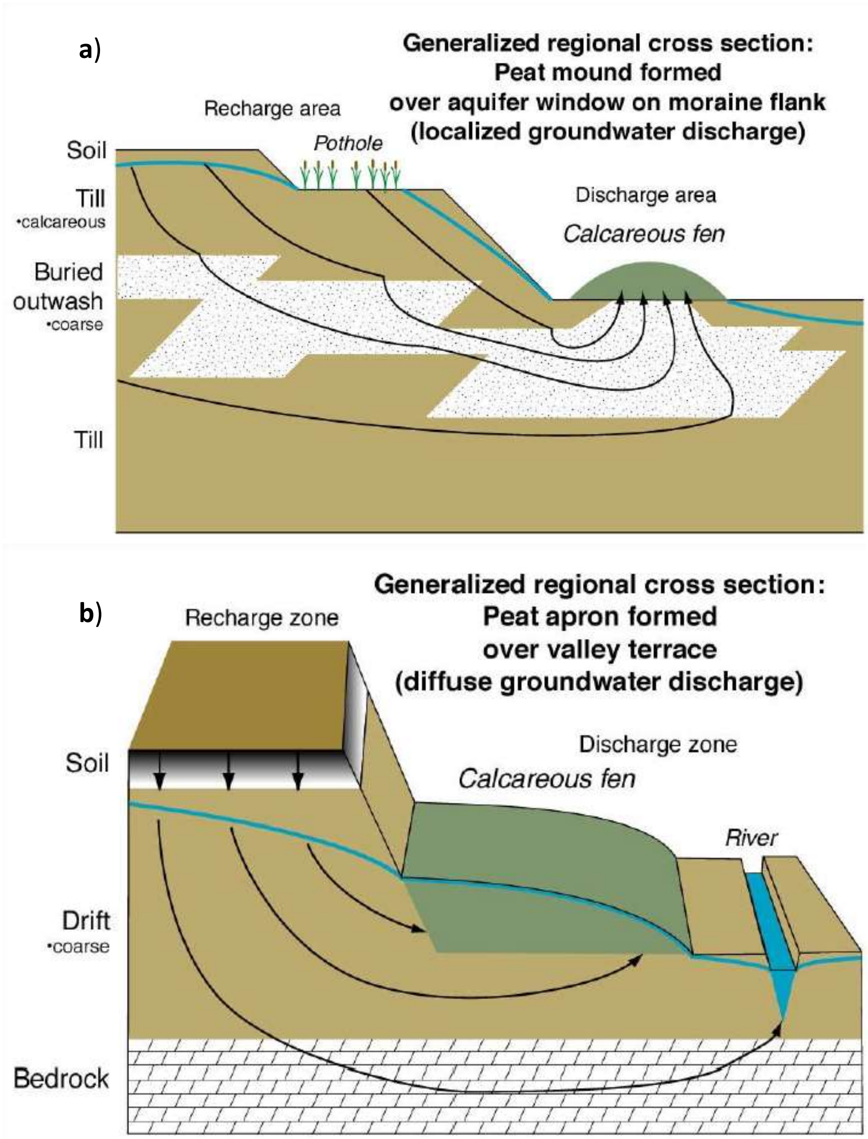

*Figure 2. MNDNR conceptual models of calcareous fen hydrology including groundwater flow paths for **a**) a morainal aquifer window setting and **b**) a river valley terrace setting (MNDNR, 2017).*

The Agassiz beach ridge fens that are the focus of this investigation are located immediately downslope of Glacial Lake Agassiz beach ridges, where gentle slopes intersect groundwater-bearing, beach-ridge surficial aquifers. As the coarse-grained, high-permeability beach sediments thin on the down-slope edge, a seepage face is present.

These beach ridges and the underlying sediments are a result of glacial processes (Cowdery et al., 2008, 2019).

Much of northwestern Minnesota's glacial sediments were deposited during the Wisconsinan glaciation of the Laurentide Ice Sheet beginning 75,000 years ago. Advance and retreat of various glacial lobes including the Wadena, Red River, and most recently (14,000 years ago) the Des Moines lobe left a complex stratigraphy of regionally extensive calcium carbonate-rich, fine-grained tills interspersed with smaller, localized outwash and coarser-grained deposits (Lehr & Hobbs, 1992; Minnesota Geological Survey, 2017). Throughout the region, the regionally extensive tills act as a confining layer over localized confined aquifers that are found at depths ranging from around 20 to over 200 feet (MN County Well Index, 2019). As the Des Moines Lobe retreated past a continental divide at Browns Valley, Minnesota, meltwater built up behind the glacier forming Glacial Lake Agassiz from approximately 11,500 years ago through 9,500 years ago in Northwestern Minnesota (Teller, 1987; Thorleifson, 1992). As outlets fluctuated throughout the lake's history, a series of beach ridges were formed at decreasing shoreline elevations along the lake's margin, the eastern shoreline traversing northwestern Minnesota in a largely north-south direction. These beach ridges consist of wave-worked sands and gravels left behind at the lake margin after waves winnowed away fine-grained sediments (Cowdery et al., 2008; Thorleifson, 1992). These sand and gravel beach ridges form surficial aquifers up to 35 feet thick, up to several hundred feet wide, and tens to hundreds of miles long. Occasionally, these beach ridges lie atop previously deposited sands and gravels, increasing the surficial aquifer thickness to up to 80 feet and occasionally providing connections to deeper sand and gravel aquifers (Cowdery et al., 2008).

Beach-seep wetlands (seepage wetlands) within the Glacial Ridge National Wildlife Refuge in northwestern Minnesota were studied as a part of a comprehensive hydrologic investigation of prairie reconstruction around Lake Agassiz beach ridges (Cowdery et al., 2008, 2019). Cowdery and others (2008) characterized the beach-seep wetlands as fed by groundwater seepage from the thin, surficial beach ridge aquifers (Figure 3). This a result of the higher local slope (~0.01), the proximity of the beach-seep fens to the beach ridges, and a high recharge of up to 25 inches/year over the beach ridge aquifers. Fifty-three identified calcareous fens are located along the beach face-to-foreshore transition zone of Minnesota’s Glacial Lake Agassiz beach ridges and are often associated with other types of seepage wetlands rather than forming a continuous calcareous fen complex (Aaseng et al., 2005; Cowdery et al., 2008, 2019).

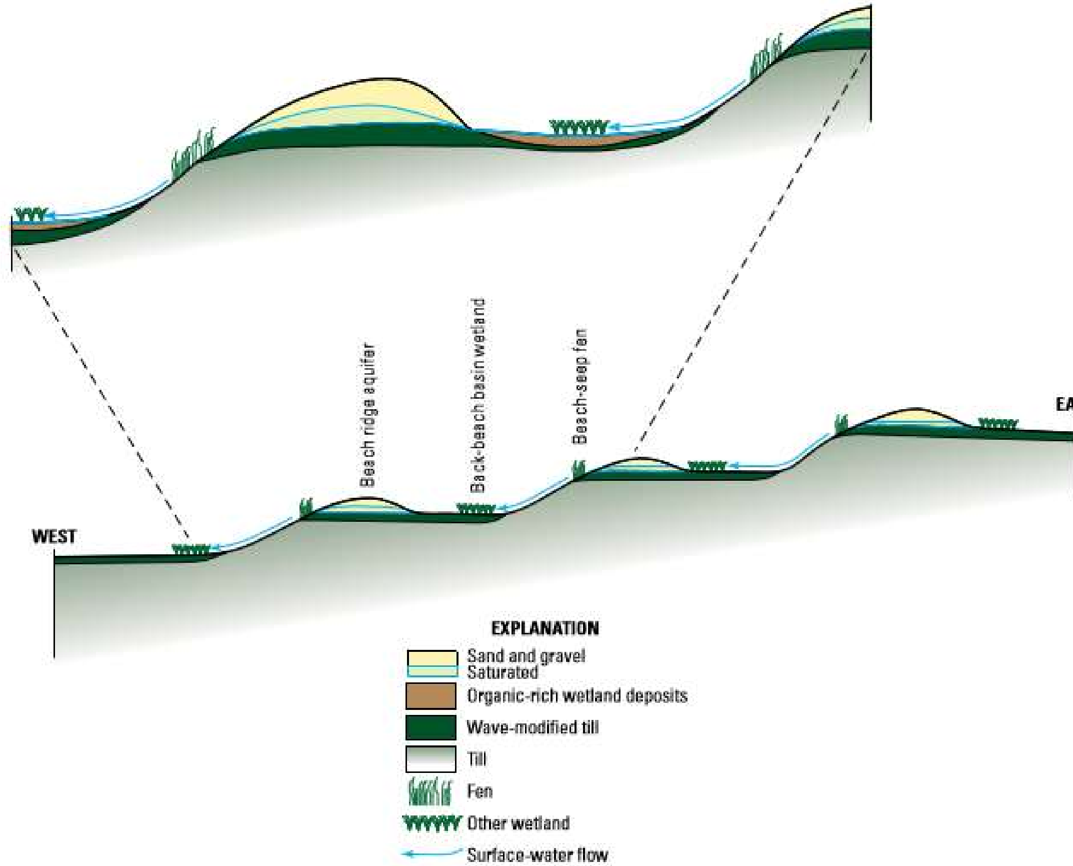

Figure 3. Cross section of typical beach seep wetlands at the base of a glacial lake beach ridge in the Glacial Ridge National Wildlife Refuge (Cowdery et al., 2008).

Mining of gravel from below beach ridges (and subsequent disturbance of near-surface aquifers and confining units) has led to research on gravel mining's impact on calcareous fens. This includes studies on the hydrologic impacts of a gravel mine on a Clay County, MN calcareous fen system (Merritt et al., 2002; Pavlish, 2004). Groundwater modeling of a gravel pit and the nearby Felton Prairie calcareous fens shows sub-water table mining results in a five-meter drop in hydraulic head below the fens (Merritt, et al., 2002). Because of complicated subsurface glacial geology, Pavlish (2004) was unable to generate conclusive hydraulic head maps of the system and called for conservative management of the fens because of potential linkages between the surficial and deep groundwater.

Two hydrogeologic investigations involving high-capacity pump tests have been conducted in the vicinity of two beach ridge calcareous fens in Norman County: the Agassiz-Nelson and Spring Creek 25 fens (Braun, 2014; Summit, 2015). These studies determined hydrogeologic properties of the confined aquifer and aquitard. However, neither of the studies demonstrated any hydrologic connection between the confined and surficial beach-ridge aquifers or the fens.

Study Sites

The Lake Agassiz beach ridge hydrogeomorphic setting hosts a myriad of wetlands, including 53 identified calcareous fens and hundreds of other wetlands of various types. To evaluate the hydrology of calcareous fens in this setting, two sites were chosen for detailed hydrologic analysis. In addition, 53 calcareous fens and 26 non-calcareous fens along the beach ridges of northwestern Minnesota were part of a multivariate analysis of landscape factors that potentially control fen occurrence. The two detailed study sites are Sanders Fen North, west of Thief River Falls, MN, in Pennington County and Agassiz-Nelson Fen, near Gary, MN, in Norman County (Figure 4).

Figure 4. Study fen locations within Minnesota.

The hydrologic investigations involved assessment of the geomorphology of the beach ridges, surficial aquifers, confined aquifers, and wetland characteristics. Based on assessment of the hydrology, wells were installed at both sites (Table 2). Existing wells also were monitored; detailed logs for existing wells can be found in Appendix A. **Error! Reference source not found.** is a generalized cross section of the fen and beach ridge found at both sites. It also includes generalized locations of wells installed in transects across both sites.

Table 2. Construction specifications for all wells at both Sanders Fen North and Agassiz Nelson Fen.

Well Name	MN Well ID	Install Date	Ground Surface Elev (ft)	Well Depth (ft)	Screen Len (ft)	Screen from (ft):	Screen to (ft):	Casing Dia. (in)	Screened Location
Sanders Fen North									
SC0		6/25/2019	1101.53	9.58	5	4.58	9.58	2	Beach Ridge Aquifer
SC1		6/25/2019	1096.06	4.39	1.87	2.52	4.39	2	Sand Apron Up-Ridge of Fen
SC4		6/20/2019	1094.06	3.65	0.98	2.67	3.65	2	Sand Apron Up-Ridge of Fen
SC7D		6/25/2019	1092.07	6.1	1.31	4.79	6.1	2	Sand Apron below Fen
SC7S		6/20/2019	1091.92	3.78	2.3	1.48	3.78	2	Base of Fen Peat
SC9		6/25/2019	1090.93	8.05	1.5	6.55	8.05	2	Sand Apron below Fen
SCF		7/29/2019	1091.83	1.1	1.1	0	1.1	2	Fen Surface Water
SN0		6/25/2019	1101.71	9.3	5	4.3	9.3	2	Beach Ridge Aquifer
SN2		6/26/2019	1096.86	3.52	0.98	2.54	3.52	2	Sand Apron Up-Ridge of Fen
SN6D		6/26/2019	1092.62	6.68	1.5	5.18	6.68	2	Sand Apron below Fen
SN6S		6/26/2019	1092.71	3.98	2	1.98	3.98	2	Base of Fen Peat
580065	580065	10/9/1998	1118	224	4	220	224	4	Confined Aquifer
244122	244122	5/6/1992	1105	13	5	8	13	2	Beach Ridge Aquifer

Table 2 *(cont.)*. *Construction specifications for all wells at both Sanders Fen North and Agassiz Nelson Fen.*

Well Name	MN Well ID	Install Date	Ground Surface Elev (ft)	Well Depth (ft)	Screen Len (ft)	Screen from (ft):	Screen to (ft):	Casing Dia. (in)	Screened Location
Agassiz-Nelson Fen									
NS0		6/27/2019	1050.73	9	5	4	9	2	Beach Ridge Aquifer
NS3		7/18/2019	1048.97	5.42	2	3.42	5.42	2	Sand Apron Up-Ridge of Fen
NC0		6/26/2019	1051.63	9.1	5	4.1	9.1	2	Beach Ridge Aquifer
NCSP3	276847	7/9/2015	1046.92	4.37	4.37	0	4.37	2	Sand Apron Up-Ridge of Fen
NN0		6/26/2019	1051.82	8.7	5	3.7	8.7	2	Beach Ridge Aquifer
NN3		6/26/2019	1046.08	2.83	2	0.83	2.83	2	Sand Apron Up-Ridge of Fen
DNR Deep 3	278583	6/21/2018	1043.4	5.75	0.5	5.25	5.75	1.25	Sand Apron below Fen
North Nest									
SP2	276845	8/6/2014	1064.01	5.5	2	3.5	5.5	1.25	Surface Sand at Nest
SMW2	806836	8/6/2014	1063.87	16	5	11	16	2	Intermediate Confining/Fine Sands
SMW3	806837	8/6/2014	1063.88	38	5	33	38	2	Intermediate Confining/Fine Sands
NMW*	801345	6/22/2015	1064.25	102	20	82	102	2	North Confined Aquifer
South Aquifer									
SP1	276844	8/7/2014	1051.51	5.3	2	3.3	5.3	1.25	Surface Sand at Nest
SMW1	806835	8/7/2014	1051.48	43	5	38	43	2	Intermediate Confining/Fine Sands
SMW (SMWR)**	801346	6/22/2015	1051.26	86	5	81	86	2	South Confined Aquifer
804872	804872	6/22/2015	1069.65	66	7	59	66	2	South Confined Aquifer
W-5	791080	9/13/2012	1059.9	101	30	71	101	12	South Confined Aquifer
*Replacing well 276843 drilled 4/22/2013									
**Replacing well 276841 drilled 4/12/2013									

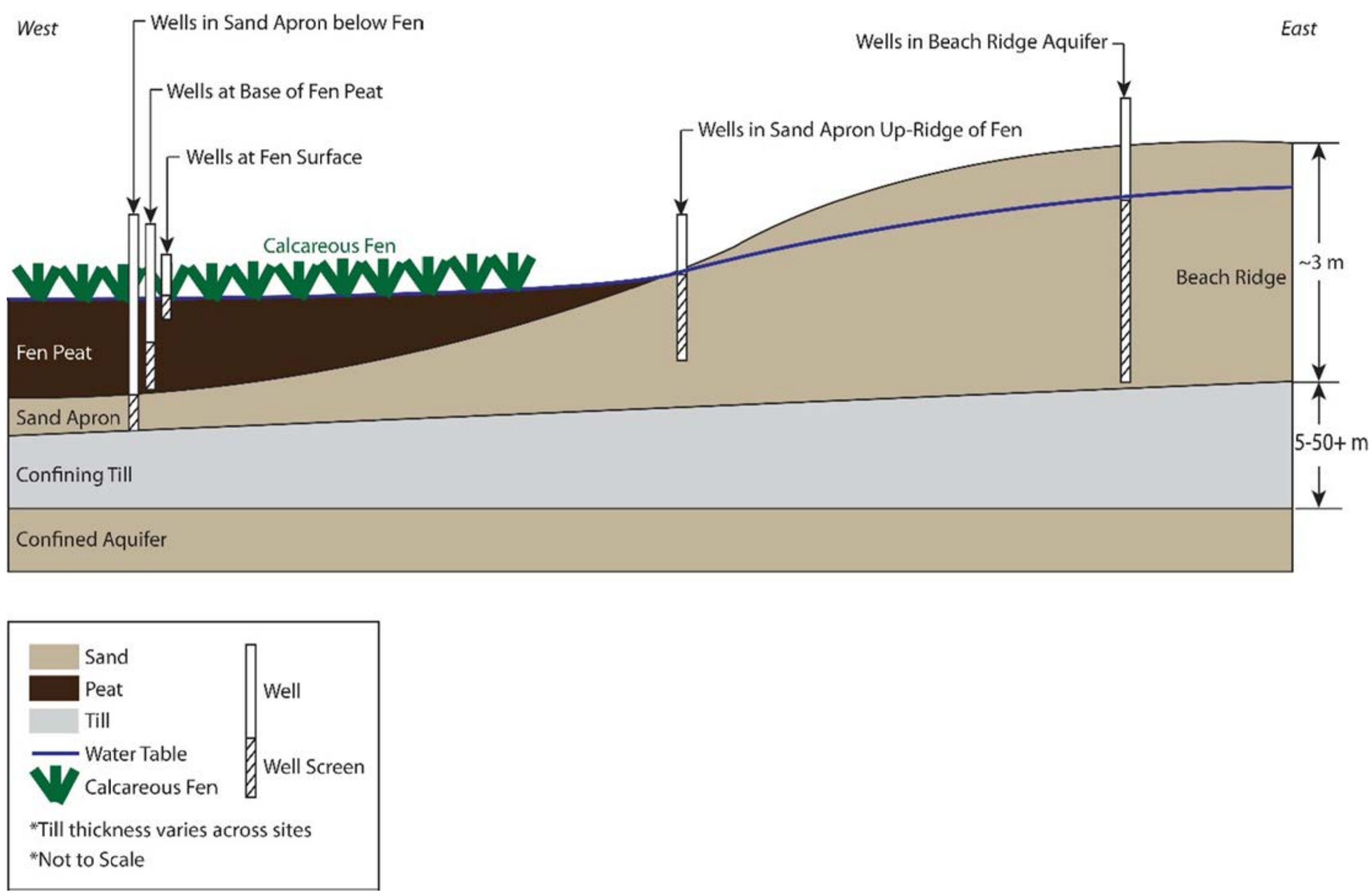

Figure 5. Typical cross section of a calcareous fen and beach ridge and the locations of surficial system wells.

Sanders Fen North was selected for study because it is a typical beach-ridge fen, under private ownership, and the owners encouraged this investigation. Two transects of piezometers were installed across the fen and up the beach ridge: transect SC (Sanders Central) and transect SN (Sanders North) (Figure 6). The SC transect passes through high-quality calcareous fen. The SN transect passes through low-quality calcareous fen that is overgrown with trees and shrubs. Peat thicknesses gathered using a peat probe increase from around 2 feet at the upgradient edge of the fen to up to 6 feet at the downgradient edge. Depths are consistently 4-5 feet along the fen's central axis. Most domestic wells in the area are at around 200 ft depth, as this is the first major confined aquifer, so a domestic well (MN well ID 580065) one mile east of the fen site was sampled for chemistry and isotopic data on the area's confined aquifer. The Minnesota DNR also monitors a well in the beach ridge at the corner of the property (MN well ID 244122) by taking tape water level measurements several times per year.

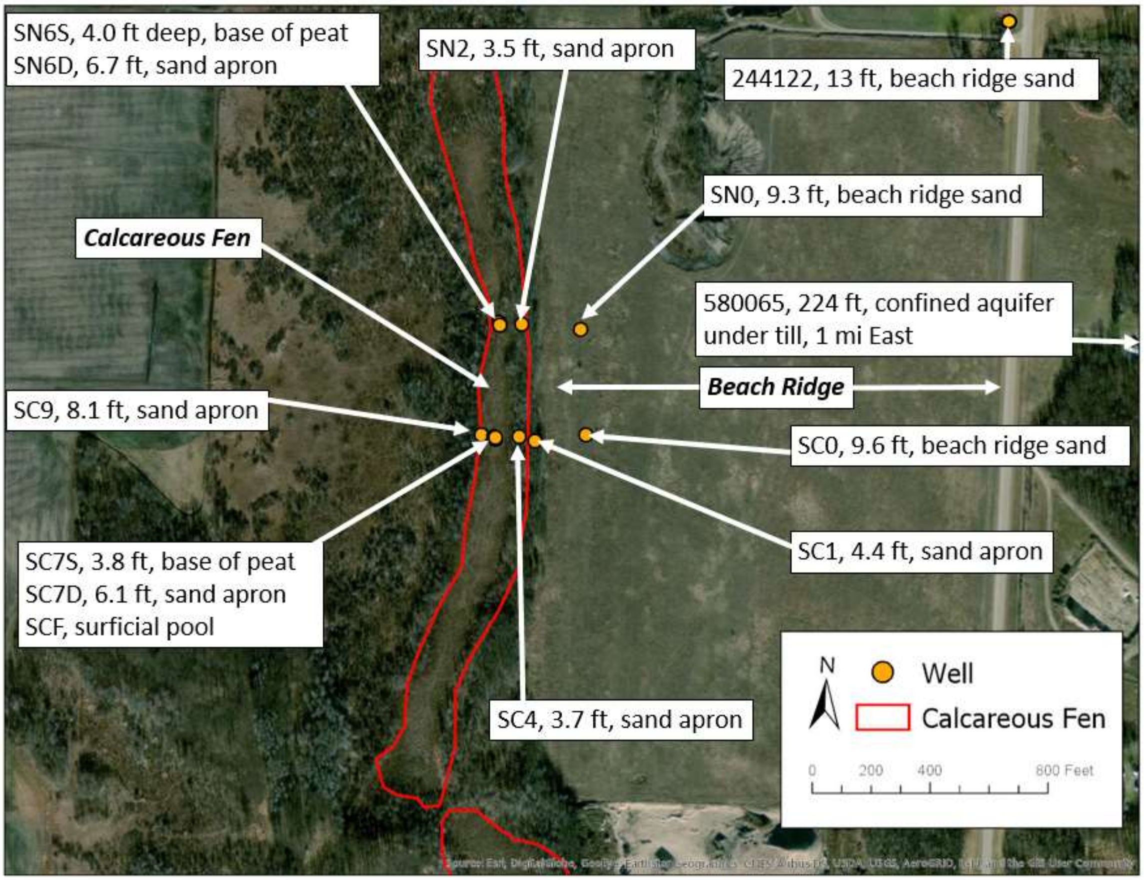

Figure 6. Locations and depths of wells at Sanders Fen North near Thief River Falls, MN.

Agassiz-Nelson fen was selected for study because of previous study data being available at the site and the fen system quality. Three transects of piezometers were installed at this site in the beach ridge and sand apron upgradient of the fen: transect NN (Agassiz-Nelson North), transect NC (Agassiz-Nelson Central), and transect NS (Agassiz-Nelson South) (Figure 7). Water chemistry and isotope samples were also taken from 3 surficial puddles in the fen. The fen itself is on state land, and as a result of delays in the permitting process, access to install wells was not granted in time for summer and fall monitoring. Water level data from a state-installed well in the sand below the fen, well DNR Deep 3, were included in this study. Two existing nests of wells from earlier pump tests are at the site: a north nest and a south nest (Figure 7). Well SMW is grouted closed. To monitor the aquifer penetrated by SMW, a replacement well was used: MN well ID# 804872. This well penetrates the same aquifer as SMW and heads were found to be consistently only 1.5 feet higher than in SMW (Summit, 2015). Peat depths in the fen increase from 1.5 feet at the upgradient edge of the fen to 4 feet at the downgradient edge, with depths along the fen's central axis consistently being around 3 feet.

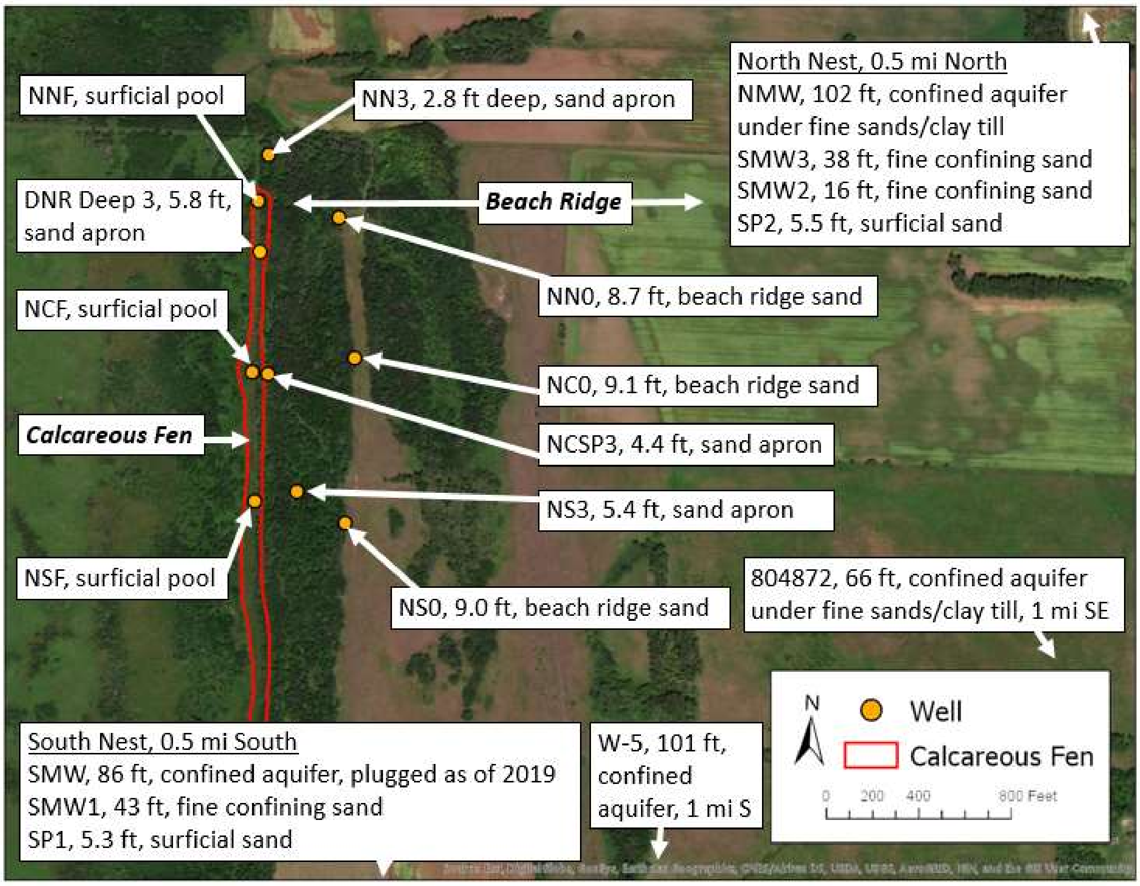

Figure 7. Locations and depths of wells at Agassiz-Nelson Fen near Gary, MN.

There were two pump tests performed at the Agassiz Nelson Fen site. The first, by Braun Intertec (2014) found that when a well north of well NMW was pumped, well NMW responded to pumping but SMW did not. Only wells in the confined aquifer were monitored for this pump test; the surficial system was not monitored.

The second test by Summit Envirosolutions (2015) found that when well W-5 (MN well ID 791080; south of well SMW) was pumped, wells SMW, SMW1, and 804072 all responded while well NMW and other deep wells north of that well did not respond. The surficial beach ridge system near the fen (well NCSP3) also did not respond to pumping, indicating the confined aquifer is not connected to the surficial beach ridge system in the vicinity of the Agassiz-Nelson fen. Well SMW1 is screened in fine sand at the base of the upper confining unit. It is just above a lens of sand 5-10 feet thick and separated from the pumped aquifer by 5-10 foot clay layer at both the south nest and well W-5. There is a sand lens at similar depth (about 40 ft) at well W-5. The Summit pump test was conducted in the winter when the surface was frozen. When well W-5 was pumped at a high rate during the summer, bubbling was observed at the surface around the outside of the casing, suggesting the well is not sealed properly. Because of this, when the well was pumped in the deeper sand (70-100 ft depth) during the Summit test it may have pulled water from the 40 foot deep sand through the leaky seal around the casing (Summit, 2015). This could result in the small response in well SMW1 during the pump test (Figure 8) rather than water being pulled through the confining clays. Summit (2015) also suggested the connection could be a result of construction issues, but they suggested the issues may be with SMW. The lack of response between the two nest sites during both pump tests indicates that there are two different confined aquifers below the fen site separated by a barrier boundary, one of the aquifers being penetrated by the north nest, the other by the south.

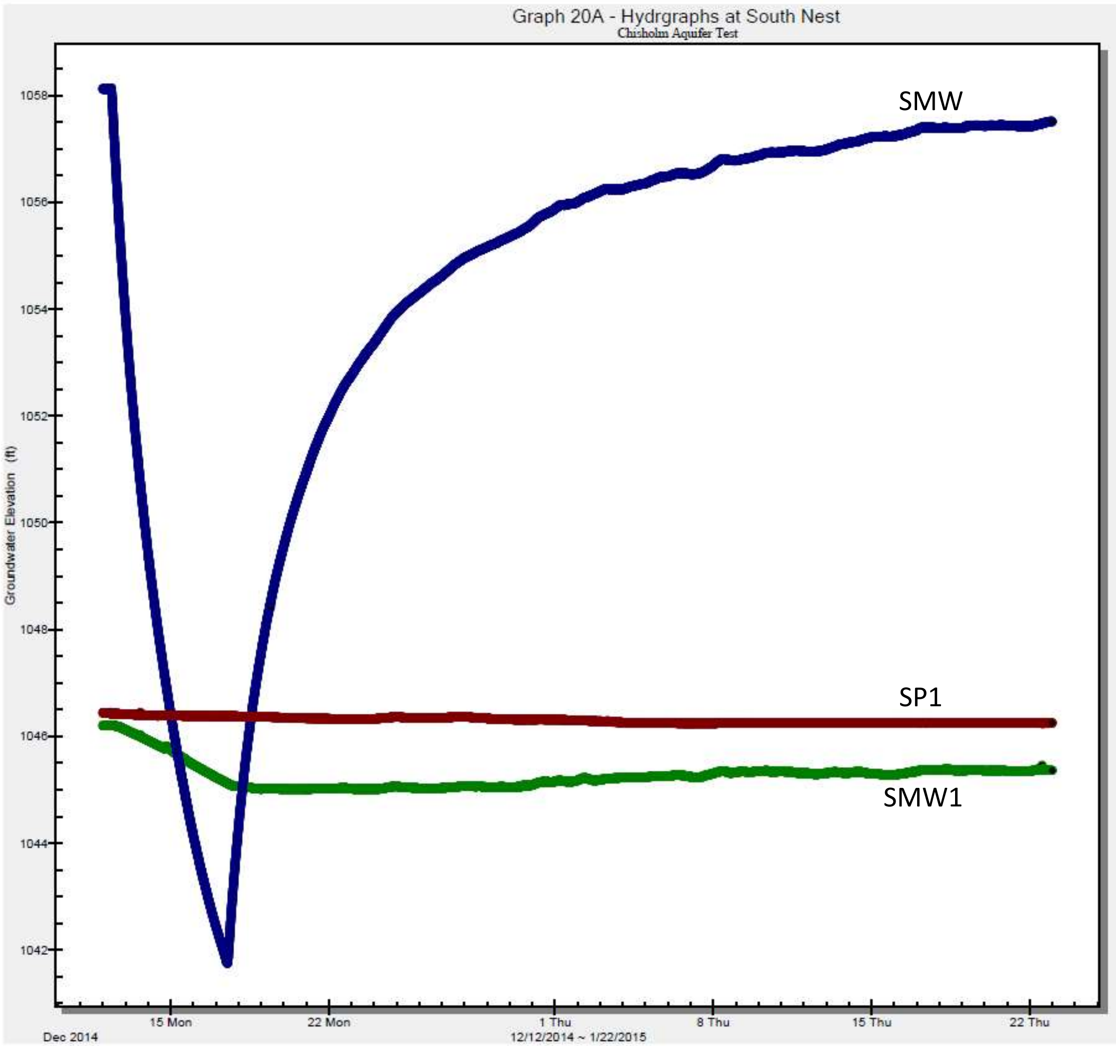

Figure 8. South nest well responses to Summit pump test (figure from Summit Envirosolutions, 2015).

Methods

A combination of hydrologic, chemical, and isotopic investigations were used to determine the hydrology at Sanders Fen and Agassiz-Nelson Fen.

Field Hydrology

Monitoring wells were installed between late June and mid-July, 2019, in transects moving across the fen and up the beach ridge at both sites. Wells were constructed of 2 inch PVC pipe with 0.01 inch screen slot size. Table 2 has well dimension details. In the beach ridge, holes were drilled with a trailer-mounted, gas-powered drill rig. Wells in and adjacent to the fen were hand-dug using a peat auger. Wells were developed using a surge block and were bailed following construction. All well collars were surveyed to a common datum: preexisting well NCSP3 at Agassiz-Nelson Fen and well SC0 at Sanders Fen.

Pressure transducers were installed in all constructed wells and preexisting monitoring wells described above at Agassiz-Nelson Fen. These transducers are unvented, so a barometric pressure logger was deployed at each site to allow for barometric pressure corrections. Readings were taken every 15 minutes from the time of installation. Before reading out transducer data, a depth to water measurement was taken from a marked point on each well collar to allow water levels to be tied to a true reference elevation. Water levels from transducers were tied to this elevation and added to the hydrograph record for the corresponding well.

Because of land access issues, the only well hydrology data collected from within Agassiz-Nelson Fen are from Minnesota DNR-installed well Agassiz-Nelson Deep 3 (MN well ID 278583).

This well is screened in the sand below the fen. The Minnesota DNR collected water levels every hour from June through October of 2019 and the data are publically available (MN DNR Cooperative Groundwater Monitoring, 2019).

Rainfall data for both sites were gathered from the Minnesota Community Collaborative Rain, Snow, and Hail network. At Agassiz-Nelson Fen, data from station Twin Valley 0.1 NE (station ID MN-NR-1; 10 miles south of the fen) were used for the entire study duration. At Sanders Fen North, data from Thief River Falls 0.3 NW (MN-PG-4; 8 miles east of the fen) were used unless a day was missing, then for that day data from Goodridge 7.4 SW (MN-PG-3; approximately 18 miles east of the fen) were used. Gauge-collected rainfall is recorded each day between 6 and 8 AM.

Field Chemistry and Isotope Sampling

The entire monitoring well network at both fen sites was sampled twice, first on July 29-30, 2019, and second on October 19-20, 2019. MN DNR well Deep 3 was not sampled. For wells in low water-yield material, the well was pumped dry before sampling. Three well volumes of water were pumped out of higher-yield wells before sampling. Sampling procedures follow Alexander and Alexander (2015). Cation and anion samples were collected in 15mL polypropylene centrifuge tubes after being filtered through a 0.22 micron PES filter. Cation samples were pre-preserved with 2 drops of reagent-grade HCl in July and with 170 µL of reagent- grade nitric acid in October. Alkalinity samples were collected in 250 mL glass BOD bottles with no headspace. Samples for stable isotope analysis were collected in the same 15mL centrifuge tubes with no headspace and were sealed with parafilm as an extra precaution against contaminating leakage. In October, seven samples were collected for tritium analysis, each in a 1L HDPE bottle. General water quality parameters including temperature, pH, specific conductivity, dissolved oxygen, and oxidation-reduction potential (July) were collected using a calibrated Hydrolab MS-5 sonde. Cation, anion, isotope, and alkalinity samples were kept on ice after sampling and were transferred to a refrigerator as soon as possible.

Cation and anion samples were sent to the Research Analytical Lab at the University of Minnesota in St. Paul, MN. Cations were analyzed using an ICP-OES, anions using an IC. Stable isotopes $\delta^{2}H$ (deuterium) and $\delta^{18}O$ were analyzed on a Picarro L2130-I with a High Precision Vaporizer (A0211) at the University of Minnesota-Duluth. Tritium samples were analyzed at the Tritium Laboratory at the University of Miami, Miami, FL. Alkalinity titrations were performed in triplicate following the Hach 8203 (2018) digital titration method at the University of Minnesota-Duluth.

Quality control and quality assurance measures include calculating charge balances on cation and anions for agreement, using all sampling equipment according to instructions, calibrating the Hydrolab sonde before use, and the collection of 3 field duplicate and 2 field blank samples (9% of total samples). The lab also performed some duplicate runs for cation and anion samples.

Stable isotopes were plotted in dual-isotope space as $\delta^{2}H$ versus $\delta^{18}O$ over a local meteoric water line from Grand Forks, North Dakota (Matheny & Gerla, 1996). This line is comparable to a line from Princeton, Minnesota used by Cowdery et al., (2008) in their study of beach ridge hydrology in the region. Stable isotope (δ18O and δD) analysis of water provides a powerful tool for determining the source of water to wetlands. A local meteoric water line is needed to identify the isotopic signature of rainwater in the region and compare it to water in the fens and surrounding aquifers. Several rainfall samples were collected during September 2019 to verify the local meteoric water line and identify the isotopic signature of rainwater at this time of year.

Tritium, a radioactive isotope of hydrogen, is used to estimate the age of groundwater. Tritium at approximately 10 TU is naturally found in waters with recent atmospheric contact in the north-central United States. Decades-old or older waters will not have tritium; it will quickly decay to a more stable form as a result of its 12.5-year half-life (Clark, 2015).

Major ion chemistry data are plotted on a Piper diagram. This diagram is a powerful way to distinguish different water chemistry provinces. Major cations (Ca, Mg, Na, and K) and anions (sulfate, chloride, carbonate, and bicarbonate) are plotted on ternary diagrams as percent milliequivalents for each ion out of the respective total for cations or anions. The ternary diagrams for cations and anions are projected to a single diamond-shaped diagram that distinguishes water chemistry provinces.

To discriminate groundwater originating from beach-ridge and confined aquifers, average beach ridge water concentrations were subtracted from all well water concentrations. This leaves waters with differing chemistries from the beach ridges as anomalies when plotted as bar graphs. Concentrations were normalized so the highest for each analyte is 1.

A mixing model also can be used to discriminate the proportion of water entering the fen from the confined aquifers compared to the beach ridge aquifers. Using water chemistry and stable isotope data from wells in the beach ridge aquifer and in the confined aquifer as endpoints, the proportion each makes up in the water entering the fen can be calculated using equation 1.

Equation 1:

$$(Confined\ Aquifer) * A + (Beach\ Ridge\ Aquifer) * B = (Water\ Entering\ Fen)$$

Where A and B are proportions of water from the confined and beach ridge aquifers respectively that result in the chemical or isotopic signature of the water entering the fen. A and B must add up to 100%.

Proportions are calculated for several chemical and isotopic analytes and then averaged.

Resistivity Survey

An electrical resistivity profile was collected at each fen site on November 2, 2019 to distinguish substrate sediment types below the beach ridge and fen. A Supersting R8 system was used to collect the survey. A dipole-dipole method survey at 4m spacing was collected at each site. Electrode connection with the ground was aided by dousing the contact with salt water when needed. The 220-m long transects were collected along transect SC at Sanders Fen and transect NC at Agassiz-Nelson fen. Transects started just past the downgradient edge of the fen and continued up the beach ridge. Data were inverted using AGI EarthImager software.

Rockworks Model

A static model of the regional subsurface geology around the Agassiz-Nelson and Sanders Fens was generated using Rockworks 17. A 20 mile by 20 mile square centered on each fen was modeled. All verified and unverified wells in the Minnesota County Well index falling within this square were input to the Rockworks model. Unverified wells were included because they greatly increase well coverage density; given the overall statistical confidence, a small number of incorrect well locations will have minimal impact on the result. Well stratigraphic logs were interpreted on a binary aquifer/non-aquifer basis. Model resolution was 200 meters by 200 meters horizontally and 1 meter vertically. A 3-dimensional model of aquifers and aquitards in the study area was generated for each site using Lateral Blending the Rockworks 17 Lithology modeler. This modeling method extrudes the well log lithology to one third of the distance between two logs and then randomly assigns a value to the middle third of the distance. It is the recommended method for sites with high subsurface heterogeneity (Rockware Inc., variously dated).

Statistical Chemistry Model

Chemistry records were input into a principal component, multivariate factor analysis to identify patterns in the dataset. For a factor analysis, a matrix is formed of n observations with a corresponding set of p variables. Principal component analysis will reduce the data to a set of L variables (factors) where $L<p$. Each of these L components will describe a proportion of the overall variance as a function of a weighted combination of the original variables. For these analyses, a varimax normalized rotation was performed on the factor axes (Davis, 2011).

For the chemistry data, analytes for both the July and October sampling trips were included as variables (for a complete list, see Appendix C). All chemistry variables that had no variation—the value was below detection limit for all or all but one or two wells—were removed from the analysis. 56 chemical variables remained for analysis. Data on both sampling trips were available for 26 wells. After analyzing which chemical parameters loaded on each factor, how each well scored on the major factors was plotted to distinguish different water chemistry provinces among the wells.

GIS and statistical analysis of beach ridge fens

Calcareous fens and associated non-calcareous fens occur along the entire Lake Agassiz beach ridge complex, and the landscape and hydrologic variables controlling calcareous fen distribution have heretofore not been evaluated. Therefore, 53 calcareous fens and 26 non-calcareous wetlands located in similar geomorphic settings at the base of beach ridges were selected for study. Thirty-one variables were extracted using GIS and are listed in Table 3 (see Appendix C for full list and extraction method). These 31 variables and the corresponding 53 calcareous and 26 non-calcareous fen observations were analyzed by principal components analysis. Factor scores were plotted, with calcareous and non-calcareous fens delineated.

Table 3. General list of variables analyzed in principal component analysis of 53 calcareous and 26 non-calcareous beach ridge fens (See Appendix C for full list).

- Landsat 8-based thermal infrared and RGB values
- NAIP17 imagery RGB values
- Distances to roads, gravel pits, and streams
- Width, length, and area of fen
- Fen elevation
- Fen location
- Cross sectional area and volume of beach ridge associated with fen
- Beach ridge land use
- Depth to first confined aquifer
- Soil hydraulic conductivity of beach ridge and fen

Results

Hydrology

At Sanders Fen, hydraulic heads in wells along both the SC transect (Figure 9) and the SN transect (Figure 10) all respond synchronously to rainfall and recharge events. Table 4 presents the hydraulic gradients between the higher beach ridge heads and the lower heads in the sand apron below the fen. It also presents gradients from the sand below the fen into the peat base. The SC transect through the high-quality calcareous fen has a stronger upward gradient from the sand beneath the peat up into the base of the peat than the scrubbier SN transect (Table 4). Along the SC transect, the well in the sand below the fen (SC7D) has a higher amplitude response to rainfall events than the well in the base of the peat (SC7S) (Figure 9).

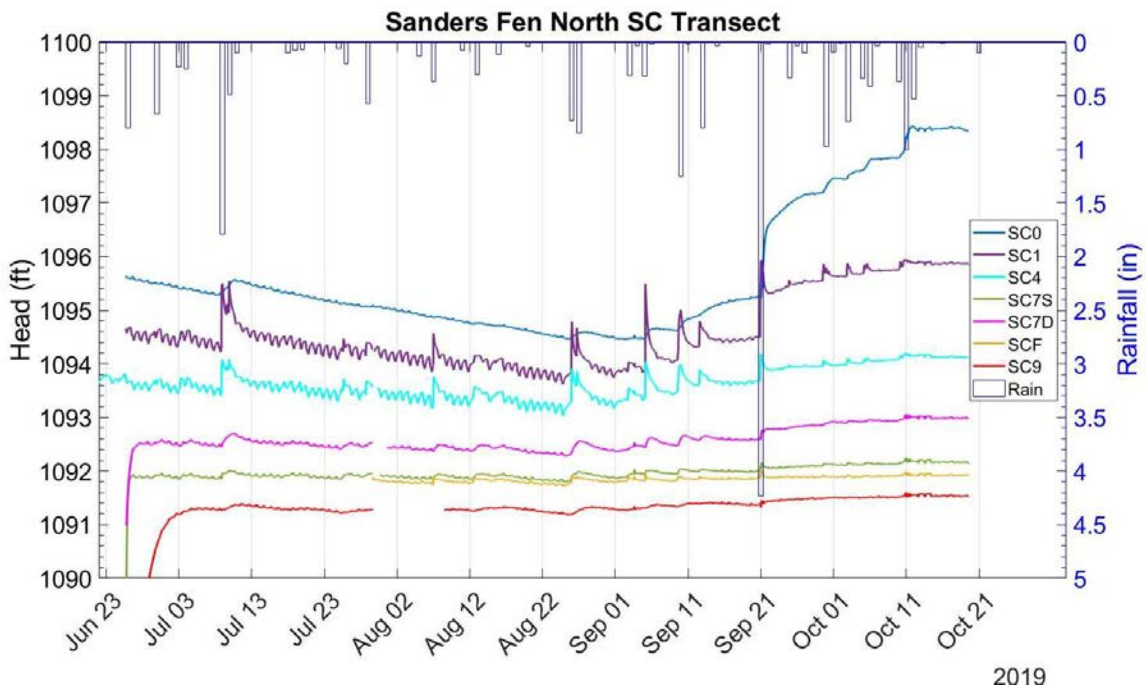

Figure 9. Sanders Fen North SC transect hydrograph with rainfall at Thief River Falls, MN.

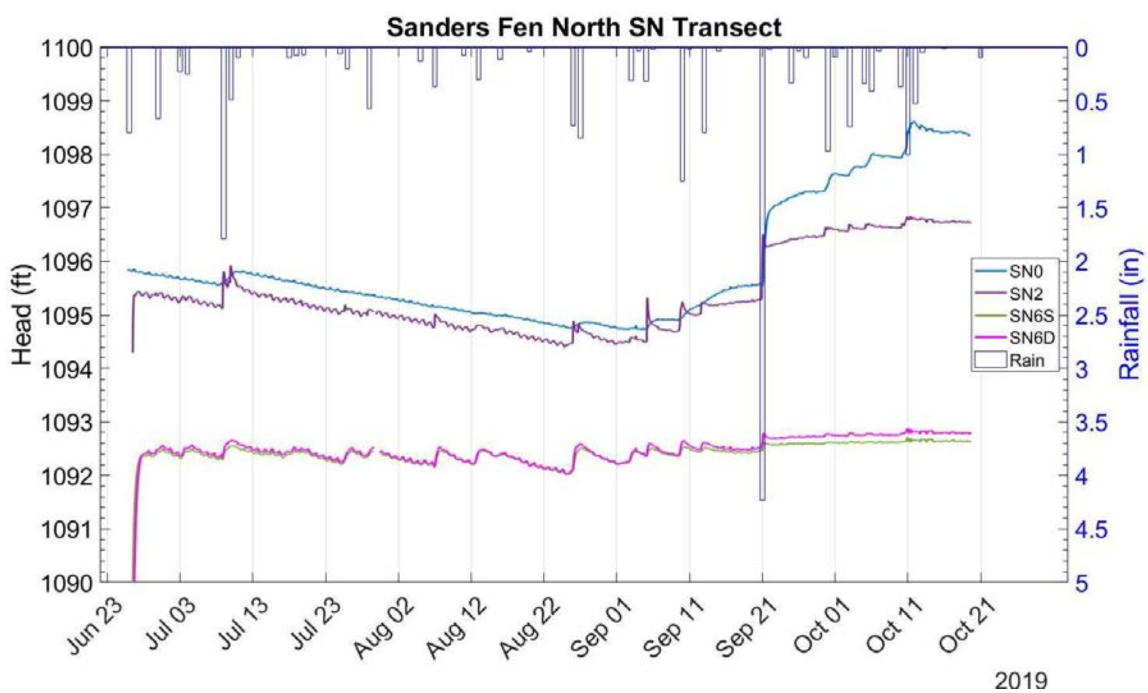

Figure 10. Sanders Fen North SN transect hydrograph with rainfall at Thief River Falls, MN.

Table 4. Hydraulic gradients between surficial wells at Sanders Fen for 8/10/19 and 10/18/19 at noon. Both selected times are at periods of stability in the hydrographs.

Gradients (ft/ft)	From Beach Ridge to Sand Below Fen		From Sand Below Fen into Peat Base	
	SC Transect	SN Transect	SC Transect	SN Transect
8/10/19 12:00	0.008	0.010	0.20	0.006
10/18/19 12:00	0.018	0.020	0.31	0.049

Table 5 and Figure 11. Sanders Fen North SC transect hydrograph for July 8-9, 2019 storm with rainfall at Thief River Falls, MN. & Figure 12 show the hydrograph timing and amplitude response for all of the installed wells at Sanders Fen North for two storms: July 8-9, 2019 and August 25-26, 2019. Water levels in the wells in the sand apron adjacent to the fen and the surface water in the fen rose first in response to rainfall. The water table is near the land surface for these wells. Water levels in the beach ridge aquifers took from 30-90 minutes to respond to rainfall and the response is spread over a longer time. There is a larger vadose zone at these wells. Water levels in the sand under the fen responded similarly to the beach ridge aquifer and with a higher amplitude than the wells above them in the base of the peat.

Table 5. Hydrograph timing and amplitudes in response to two rainfall events at Sanders Fen North.

		Sanders Fen North (2.3" rain 7/8-9/19)			**Sanders Fen North** (1.6" rain 8/25-26/19)		
Well Location	Well	Time to Peak (hr)	Time to respond after first well response (min)	Water level rise from start to peak (ft)	Time to Peak (hr)	Time to respond after first well response (min)	Water level rise from start to peak (ft)
Beach Ridge Aquifer	SC0	43.25	30	0.31	39.25	30	0.13
Sand Apron Upgradient	SC1	3.25	15	0.29	2.25	15	0.95
Sand Apron Upgradient	SC4	3.50	0	0.61	2.50	15	0.62
Base of Peat	SC7S	27.00	30	0.14	22.75	30	0.14
Sand Below Fen	SC7D	41.25	45	0.24	29.25	45	0.24
Sand Below Downgradient Edge Fen	SC9	63.50	165	0.12	64.25	105	0.15
Fen Surface	SCF	Not Installed			2.50	0	0.14
Beach Ridge Aquifer	SN0	43.75	0	0.29	42.00	90	0.11
Sand Apron Upgradient	SN2	4.25	0	0.70	2.75	15	0.42
Base of Peat	SN6S	31.00	30	0.26	26.00	30	0.44
Sand Below Fen	SN6D	29.25	45	0.31	23.75	45	0.48

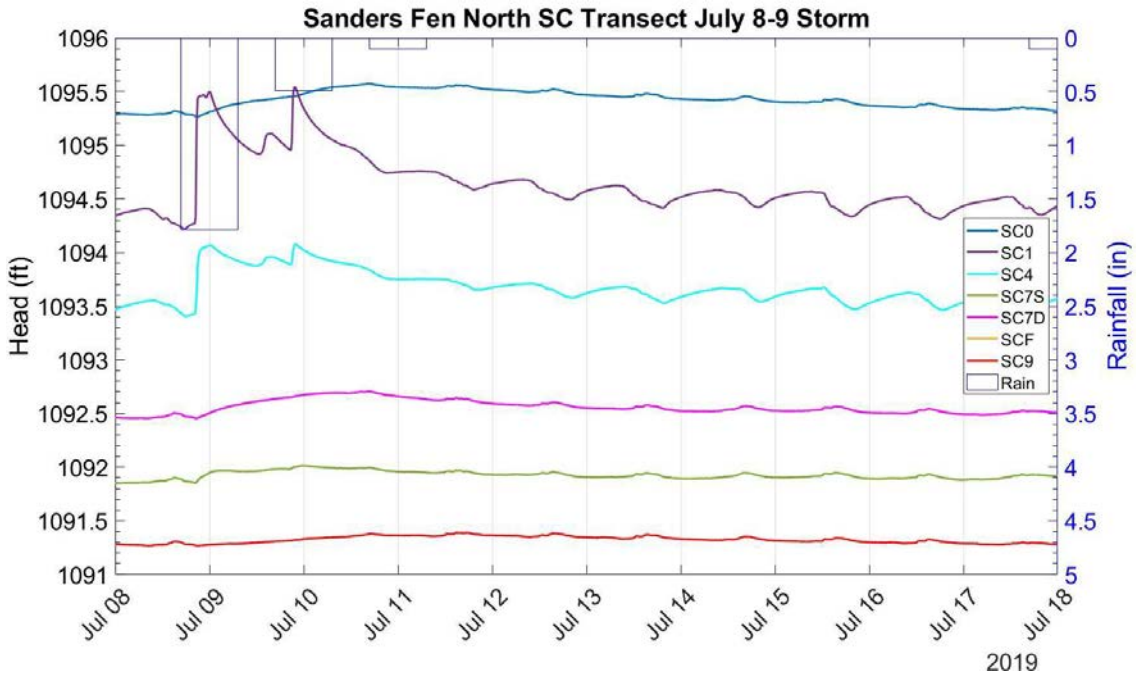

Figure 11. Sanders Fen North SC transect hydrograph for July 8-9, 2019 storm with rainfall at Thief River Falls, MN.

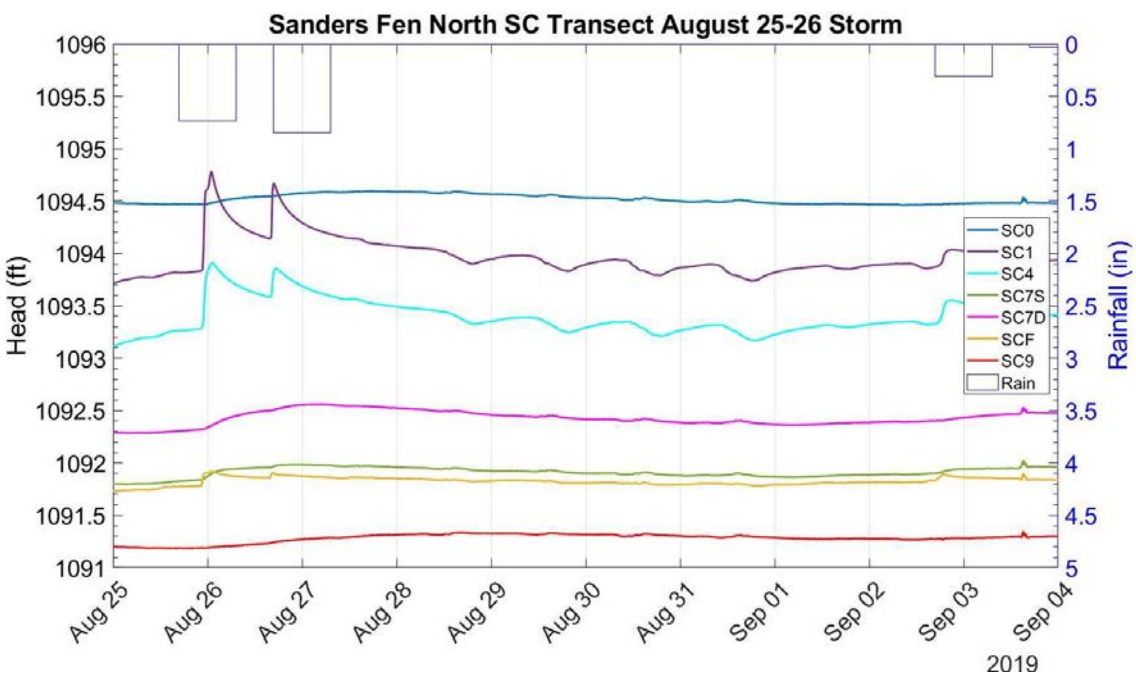

Figure 12. Sanders Fen North SC transect hydrograph for August 25-26, 2019 storm with rainfall at Thief River Falls, MN.

At Agassiz-Nelson Fen, the wells in the sand apron adjacent to the fen and well DNR Deep 3 below the fen respond to rainfall events similarly to the beach ridge (Figure 13-Figure 15). The gradients between the higher heads in the beach ridge and the lower heads in the sand below/adjacent to the fen on Agassiz-Nelson transects are presented in Table 6. Well DNR Deep 3 in the sand below the fen has heads higher than the ground surface.

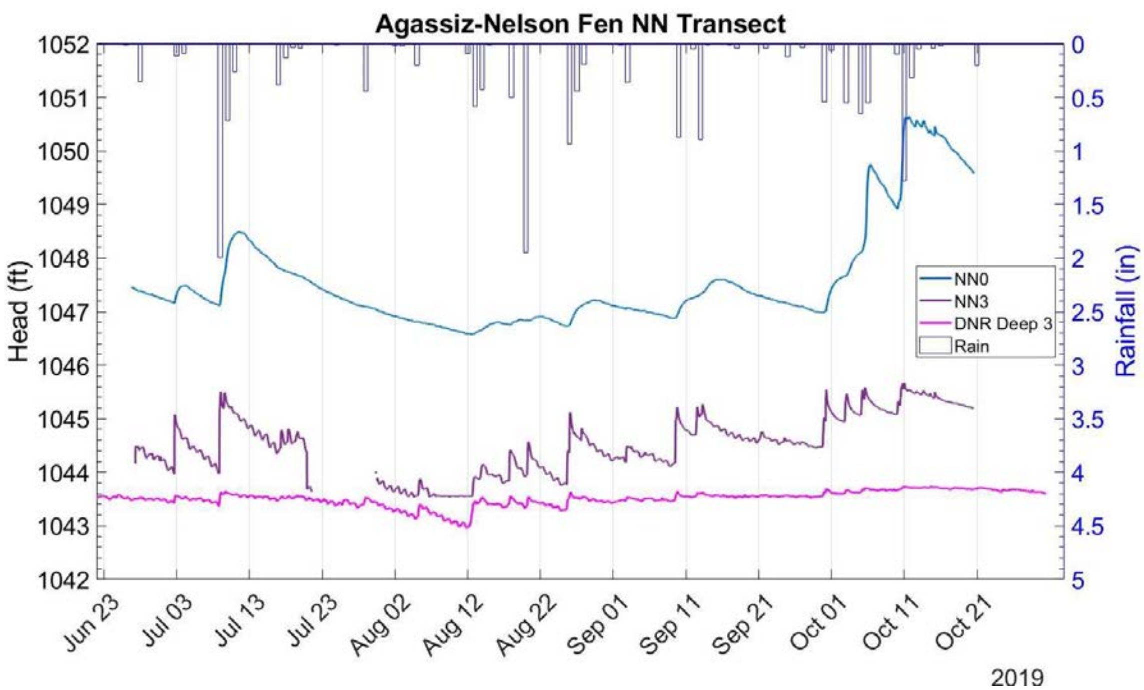

Figure 13. Agassiz-Nelson Fen NN transect hydrograph with rainfall at Twin Valley, MN.

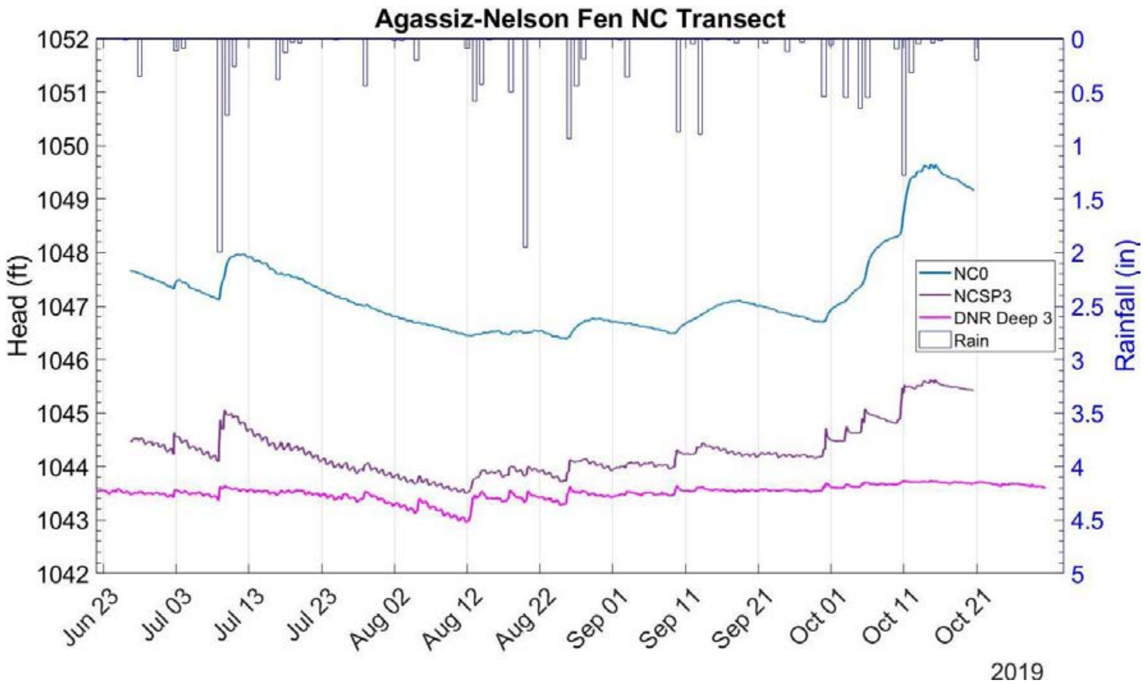

Figure 14. Agassiz-Nelson Fen NC transect hydrograph with rainfall at Twin Valley, MN. DNR Deep 3 well is also included on this figure because of the spotty record of well NN3.

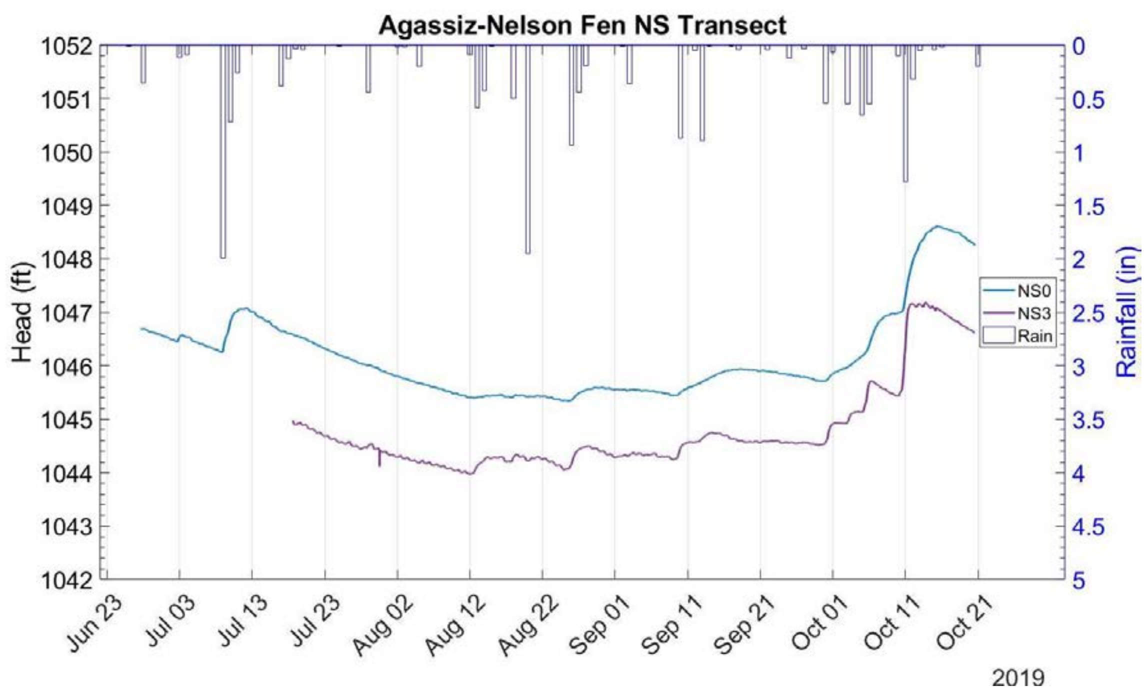

Figure 15. Agassiz-Nelson Fen NS transect hydrograph with rainfall at Twin Valley, MN.

Table 6. Hydraulic gradients between surficial wells at Agassiz-Nelson Fen for 8/10/19 and 10/18/19 at noon. Both selected times are at periods of stability in the hydrographs.

Gradients (ft/ft)	From Beach Ridge to Sand Below or Adjacent to Fen		
	NN0 to DNR Deep 3	NC0 to NCSP3	NS0 to NS3
8/10/2019 12:00	0.010	0.008	0.007
10/18/2019 12:00	0.017	0.010	0.008

The north nest, about 0.5 miles north of Agassiz-Nelson fen, has a downward gradient from surficial sand well SP2 (Figure 16) through the 16 (SMW2) and 38 ft (SMW3) deep wells in the intermediate fine confining sands, to the deep confined aquifer at 102 ft (well NMW).

At the south nest, about 0.5 miles south of Agassiz-Nelson fen, there is a small downward gradient from well SP1 in the surficial sand (Figure 17) to well SMW1. There is an upward gradient from well 804872 to well SMW1 (Figure 17). The static hydraulic heads found in both north and south well nests during this study agree with those found by Summit (2015).

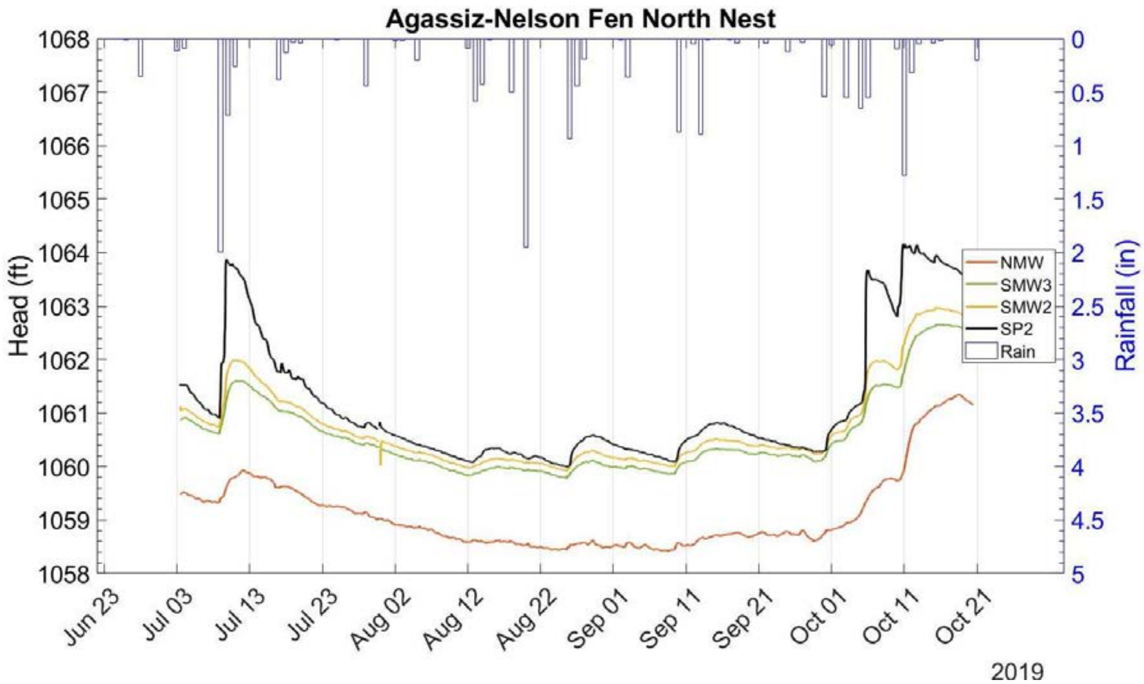

Figure 16. Agassiz-Nelson Fen north nest hydrograph with rainfall at Twin Valley, MN

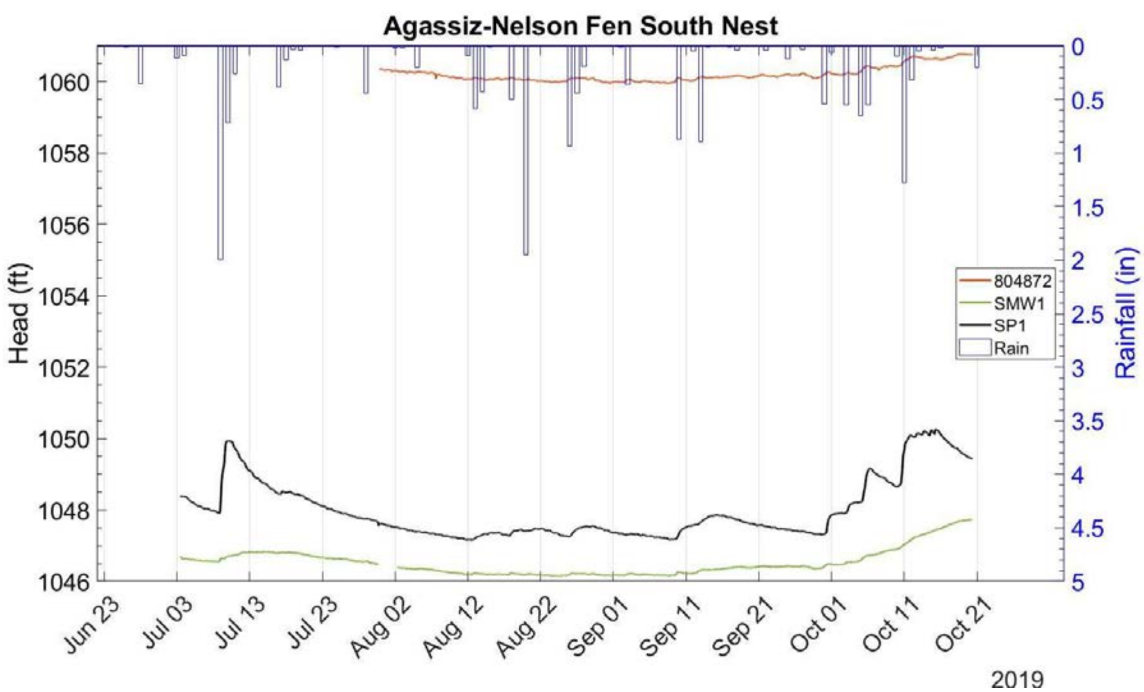

Figure 17. Agassiz-Nelson Fen south nest hydrograph with rainfall at Twin Valley, MN.

Table 7 and Figure 18-Figure 21 show the timing and amplitude response of well hydrographs at Agassiz-Nelson Fen in response to two storms: July 8-9, 2019 and August 25-26, 2019. The wells in the sand apron adjacent to the fen that are screened closer to the land surface responded first to the rainfall. Well DNR Deep 3 responded on a similar time scale to the wells in the sand adjacent to the fen (Figure 18-Figure 19). The beach ridge aquifer responded just over an hour later for the July storm and nearly 10 hours later for the August storm when less rain fell and vegetation was further developed. At the north nest, all wells respond to the rainfall events, with response muting with depth (Figure 20). At the south nest, the larger July storm lead to a small response in well SMW1 (Figure 21), but for the smaller August storm a response could not be distinguished in well SMW 1 or the deeper well 804872.

Table 7. Hydrograph timing and amplitudes in response to two rainfall events at Agassiz-Nelson Fen.

		Agassiz-Nelson Fen (2.6" rain at Twin Valley 7/8-9/19)			**Agassiz-Nelson Fen** (1.4" rain at Twin Valley 8/25-26/19)		
Well Location	Well	Time to Peak (hr)	Time to respond after first well response (min)	Water level rise from start to peak (ft)	Time to Peak (hr)	Time to respond after first well response (min)	Water level rise from start to peak (ft)
Beach Ridge Aquifer	NN0	63.75	75	1.37	77.50	555	0.47
Sand Apron Upgradient	NN3	4.50	0	1.53	10.75	0	1.34
Beach Ridge Aquifer	NC0	58.50	75	0.85	103.25	570	0.34
Sand Apron Upgradient	NCSP3	5.00	0	0.76	12.75	0	0.39
Beach Ridge Aquifer	NS0	60.25	75	0.81	98.50	660	0.23
Sand Apron Upgradient	NS3	Not Installed			64.25	30	0.43
Sand Beneath Fen	DNR Deep 3	5.00	15	0.22	11.00	45	0.24
Surficial Sand at S Nest	SP1	26.00	75	2.01	72.75	675	0.29
Confining Unit S Nest	SMW1	76.75	90	0.23	No/minimal response		
Confined Aquifer S Nest	804872	Not Installed			No/minimal response		
Surficial Sand at N Nest	SP2	23.00	15	2.96	77.75	510	0.57
Confining Unit N Nest 16 ft deep	SMW2	49.75	30	1.22	75.25	675	0.28
Confining Unit N Nest 38 ft deep	SMW3	55.75	30	0.92	74.00	750	0.24
Confined Aquifer N Nest	NMW	75.00	180	0.54	63.50	1305	0.09

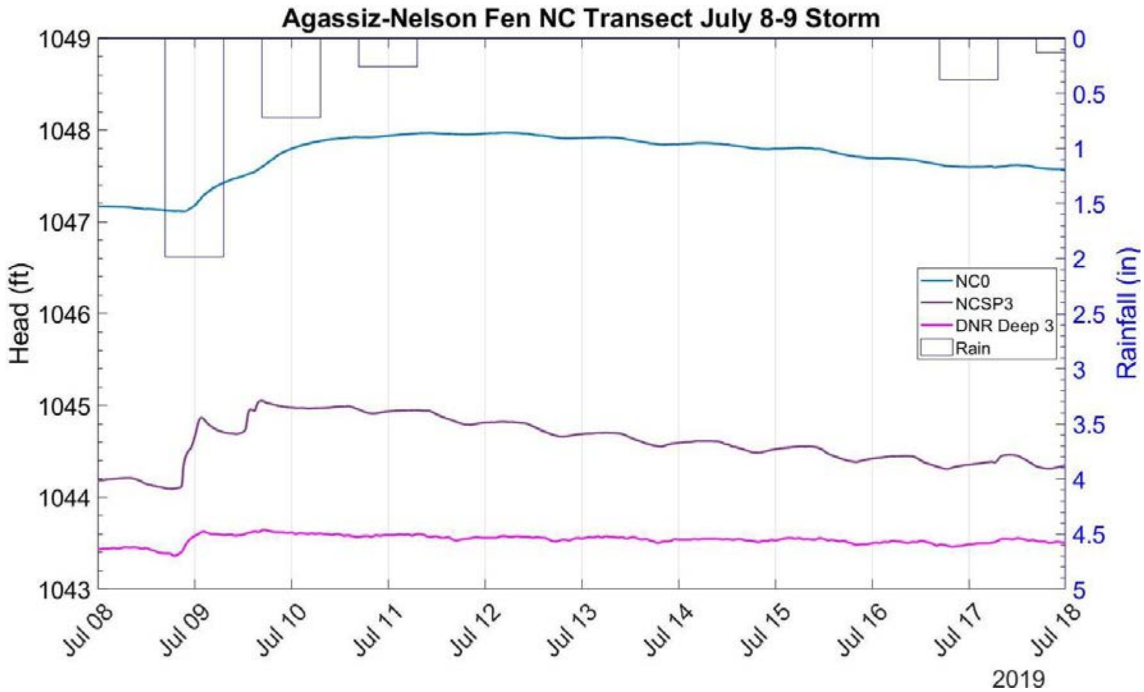

Figure 18. Agassiz-Nelson Fen NC transect hydrograph for July 8-9, 2019 storm with rainfall at Twin Valley, MN.

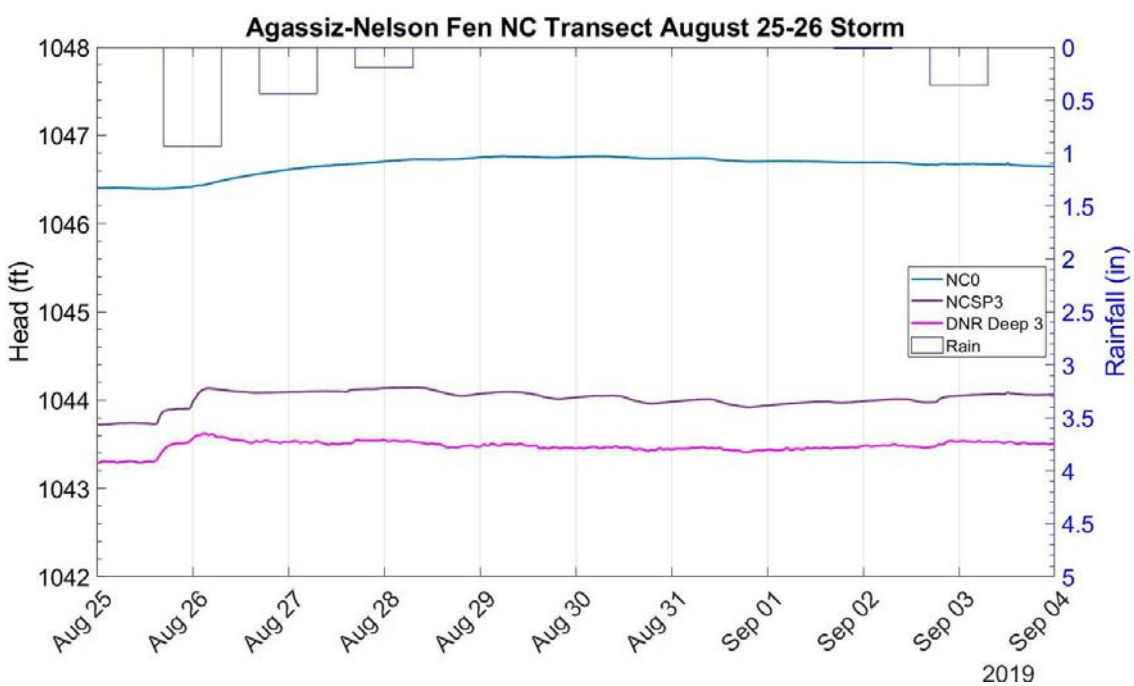

Figure 19. Agassiz-Nelson Fen NC transect hydrograph for August 25-26, 2019 storm with rainfall at Twin Valley, MN.

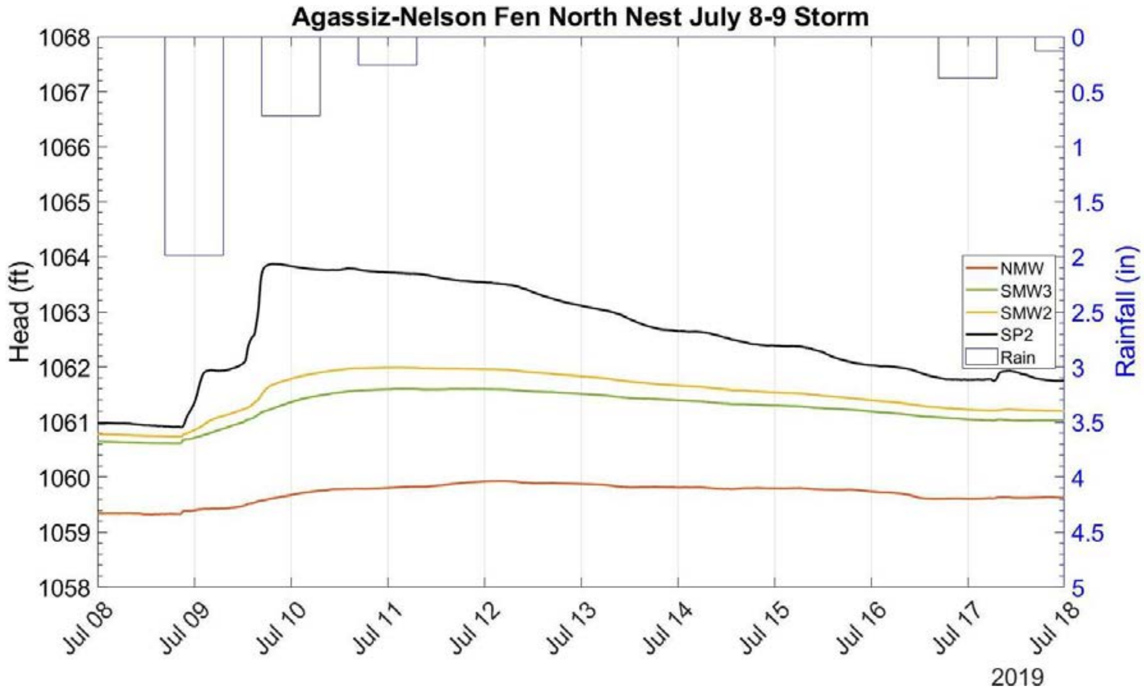

Figure 20. Agassiz-Nelson Fen North Nest hydrograph for July 8-9, 2019 storm with rainfall at Twin Valley, MN.

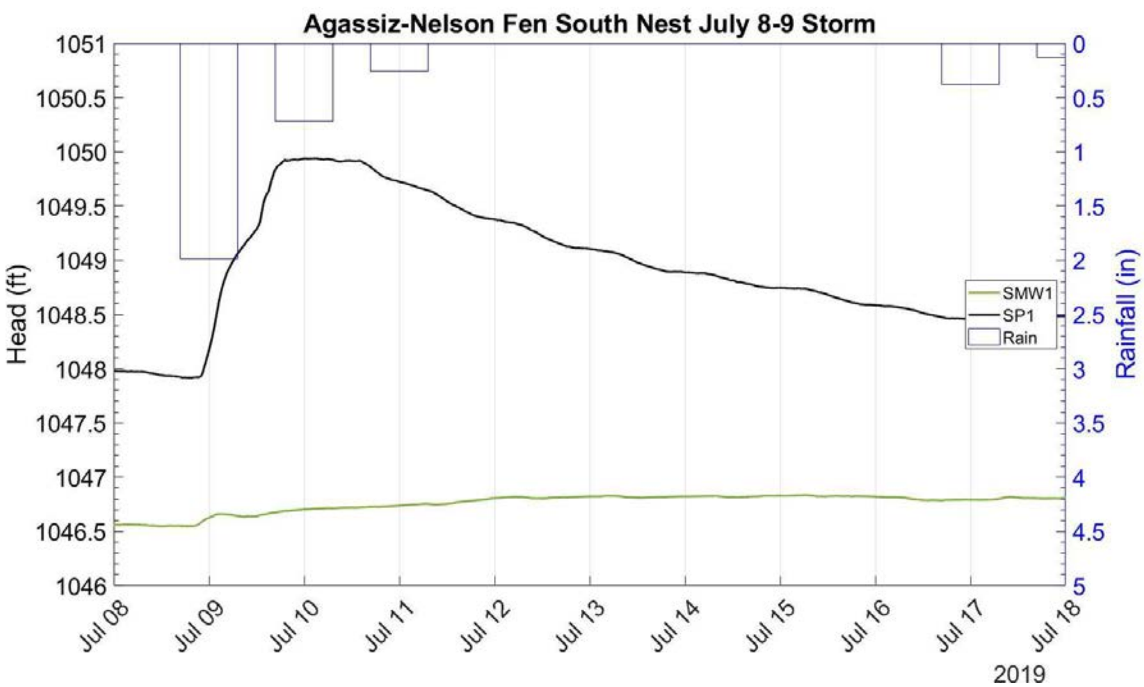

Figure 21. Agassiz-Nelson Fen South Nest hydrograph for July 8-9, 2019 storm with rainfall at Twin Valley, MN.

The DNR monitoring well (ID 244122) at Sanders Fen is used to address saturated thickness in beach-ridge aquifers over long timescales; the beach ridge aquifer has had a continuously saturated zone since records began in 1995. The well has not had water levels below an elevation of 1099 feet (Figure 22). Clay was encountered at an elevation of 1092 ft. There has always been at least 7 feet of saturated zone in the beach ridge at this location.

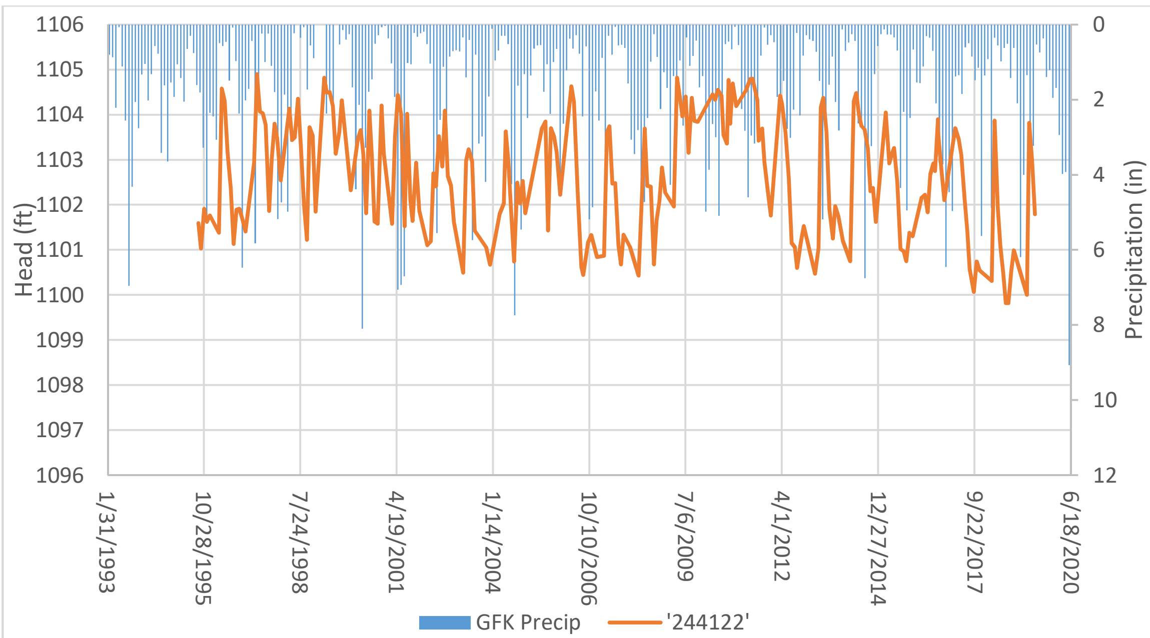

Figure 22. Water levels in MN DNR well 244122 since 1995. Monthly rainfall at the National Weather Service in Grand Forks, ND (ID USC00323621) is included.

Water Chemistry

Full chemistry results are tabulated in Appendix B. Water chemistry data was plotted on Piper diagrams. At Sanders Fen, for both the July (Figure 23) and October (Figure 24) samplings, well 580065 in the confined aquifer has a distinct general chemistry with larger proportions of sodium, potassium, sulfate, and chloride and a lower proportion of calcium. All of the other wells, including the beach ridge aquifer and all wells in and below the fen have similar chemistries with high carbonate and calcium/magnesium proportions. At Agassiz-Nelson fen (Figure 25-Figure 26), the wells in the beach ridge aquifer and those in the sand adjacent to the fen, which hydraulically behave like well DNR Deep 3 below the fen, all have similar general chemistries with high carbonate and calcium/magnesium proportions. The intermediate-depth and confined wells at the north nest have a different chemistry from the surface system, and plot intermediate between the surficial wells and the two confined wells at the south nest. At the south nest, well SMW1 has a higher proportion of sulfate than well 804872 in the confined aquifer below.

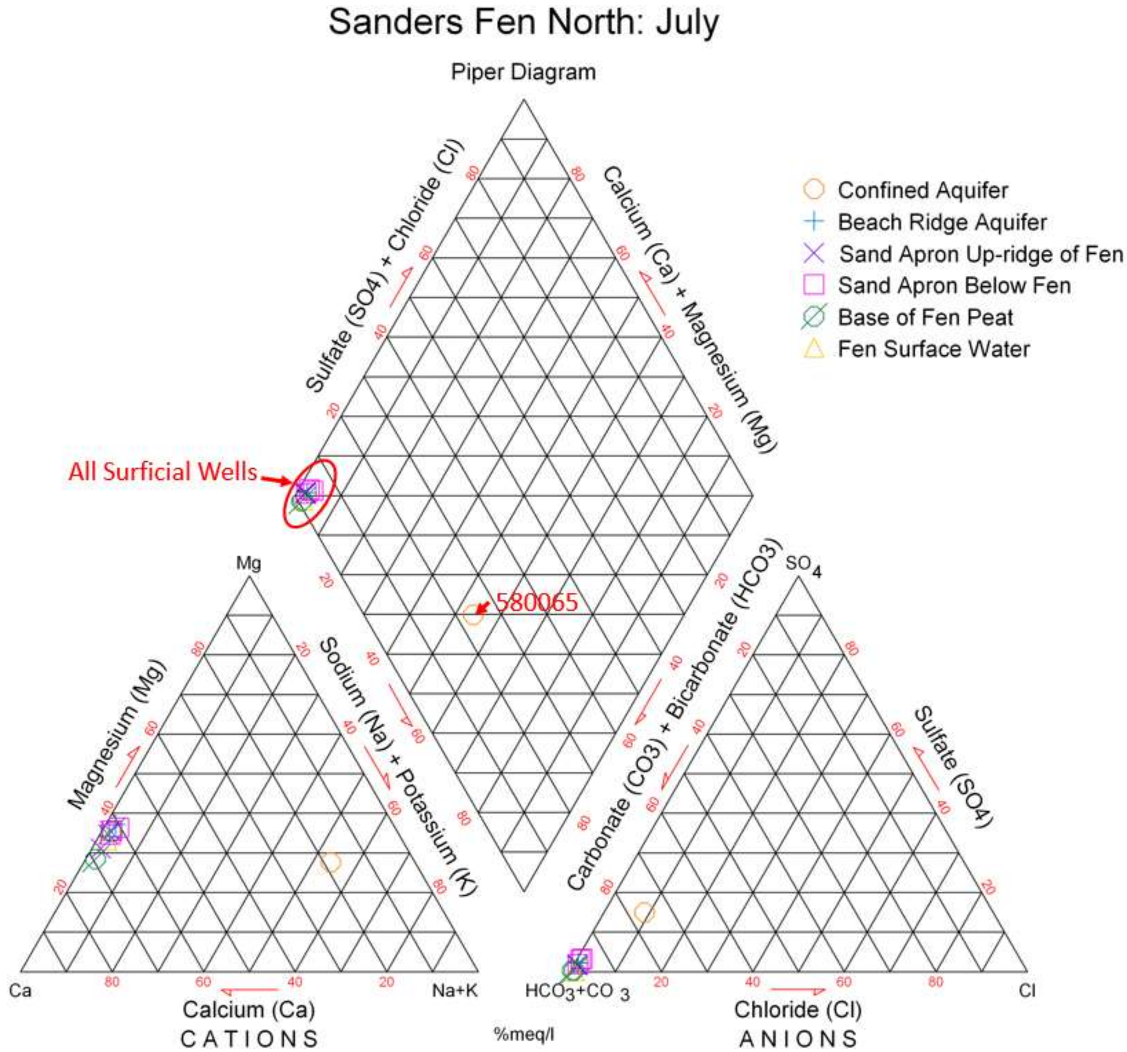

Figure 23. Piper diagram of major ion water chemistry for Sanders Fen from July 2019 samples.

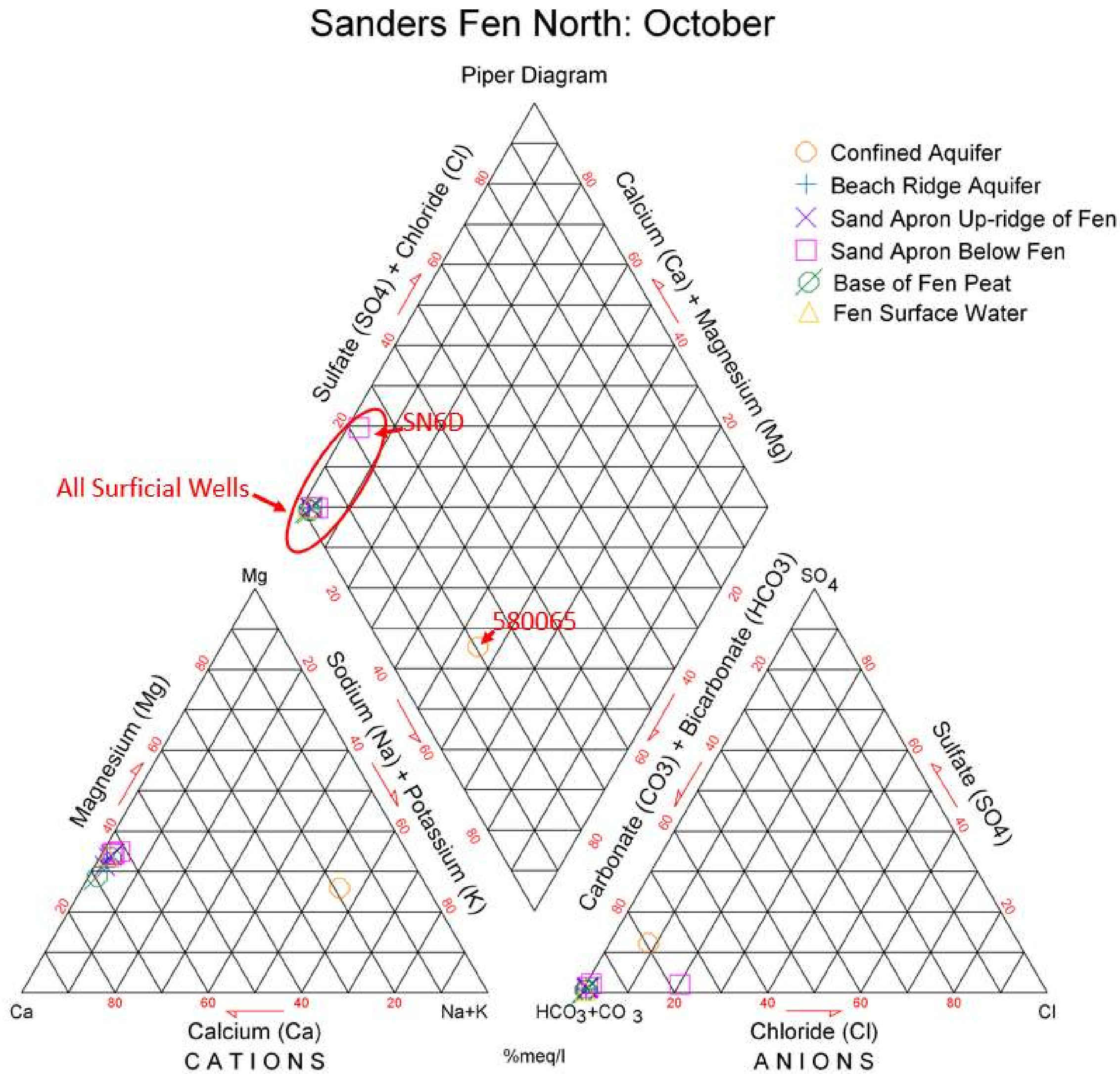

Figure 24. Piper diagram of major ion water chemistry for Sanders Fen from October 2019 samples.

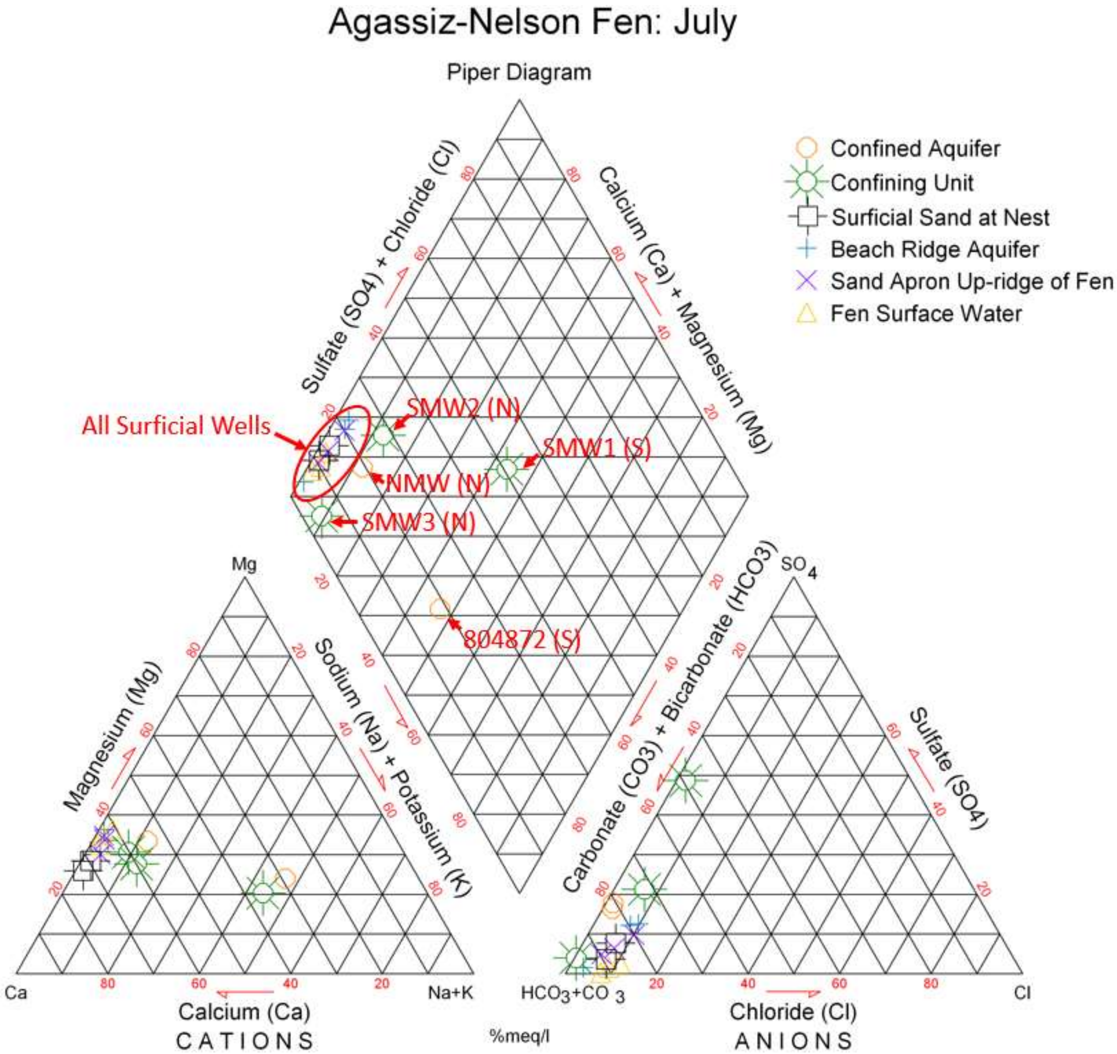

Figure 25. Piper diagram of major ion water chemistry for Agassiz-Nelson Fen from July 2019 samples.

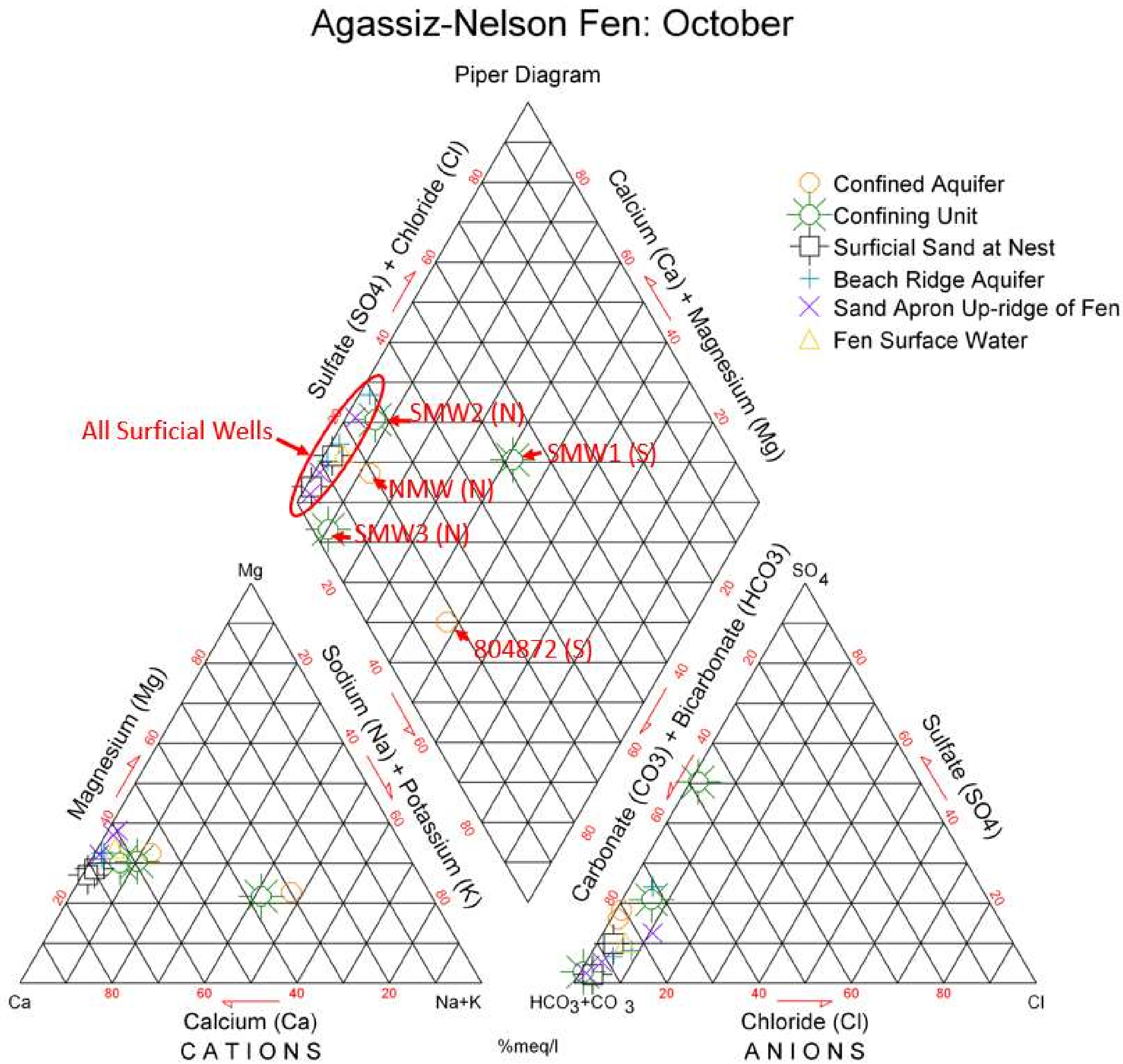

Figure 26. Piper diagram of major ion water chemistry for Agassiz-Nelson Fen from October 2019 samples.

Normalizing and plotting selected metal and anion concentrations as anomalies from the average beach ridge aquifer water gives similar results. Waters with chemistry similar to the beach ridge aquifer have anomalies close to zero. All surficial wells, including those in and below the fen at both sites plot near zero, while the deep aquifer and intermediate confining unit wells plot with large deviations from zero (Figure 27-Figure 30).

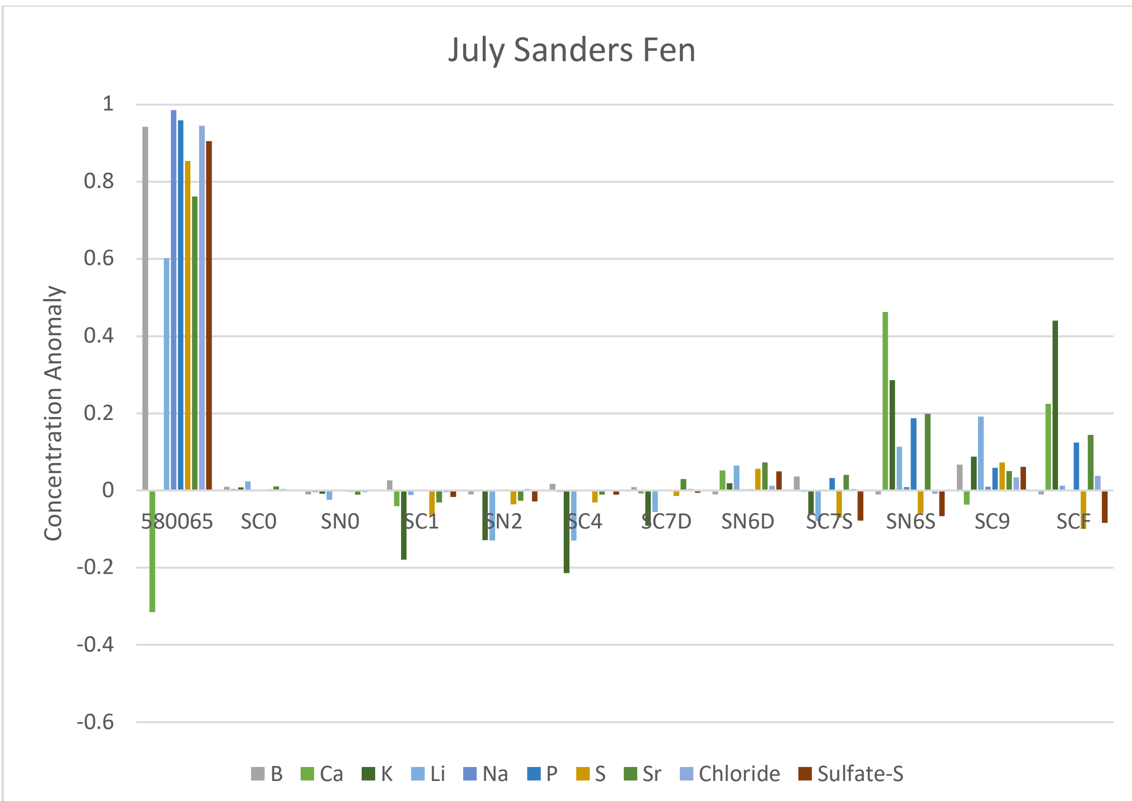

Figure 27. Selected concentration anomalies of metals and anions from beach ridge aquifer water for Sanders Fen during July 2019.

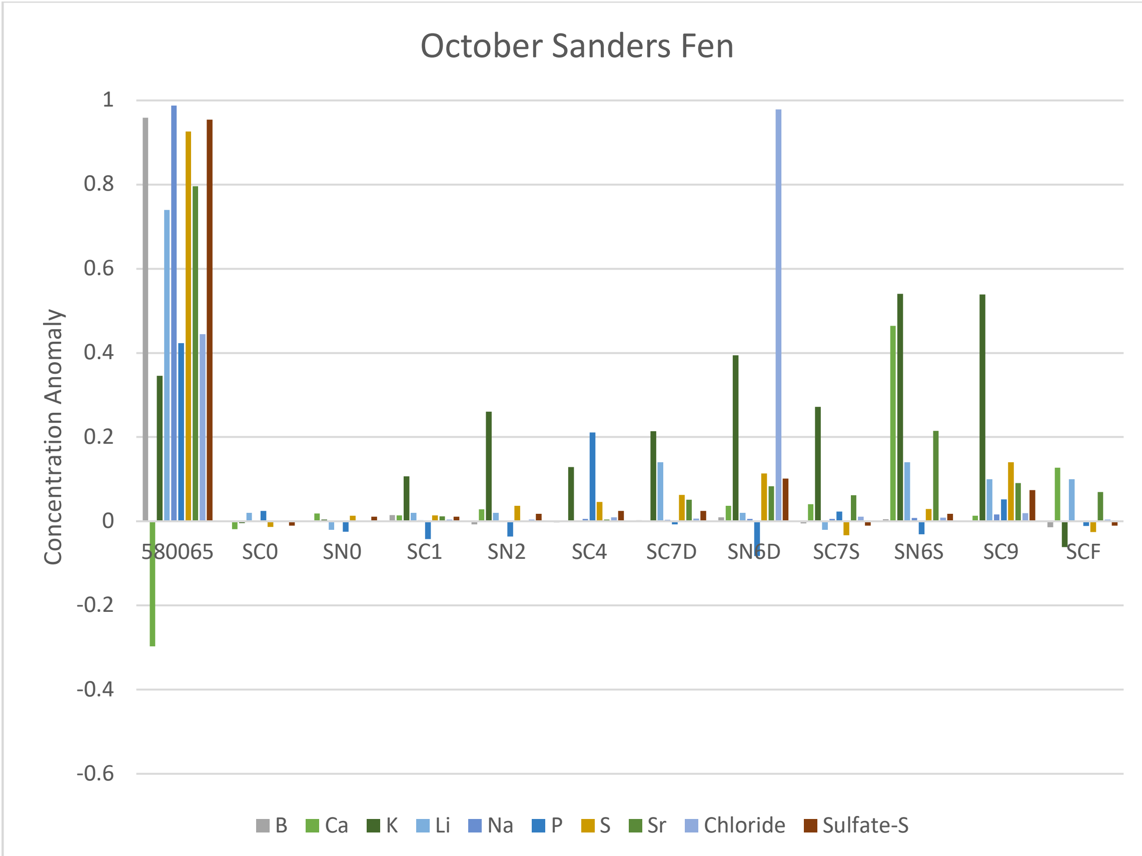

Figure 28. Selected concentration anomalies of metals and anions from beach ridge aquifer water for Sanders Fen during October 2019.

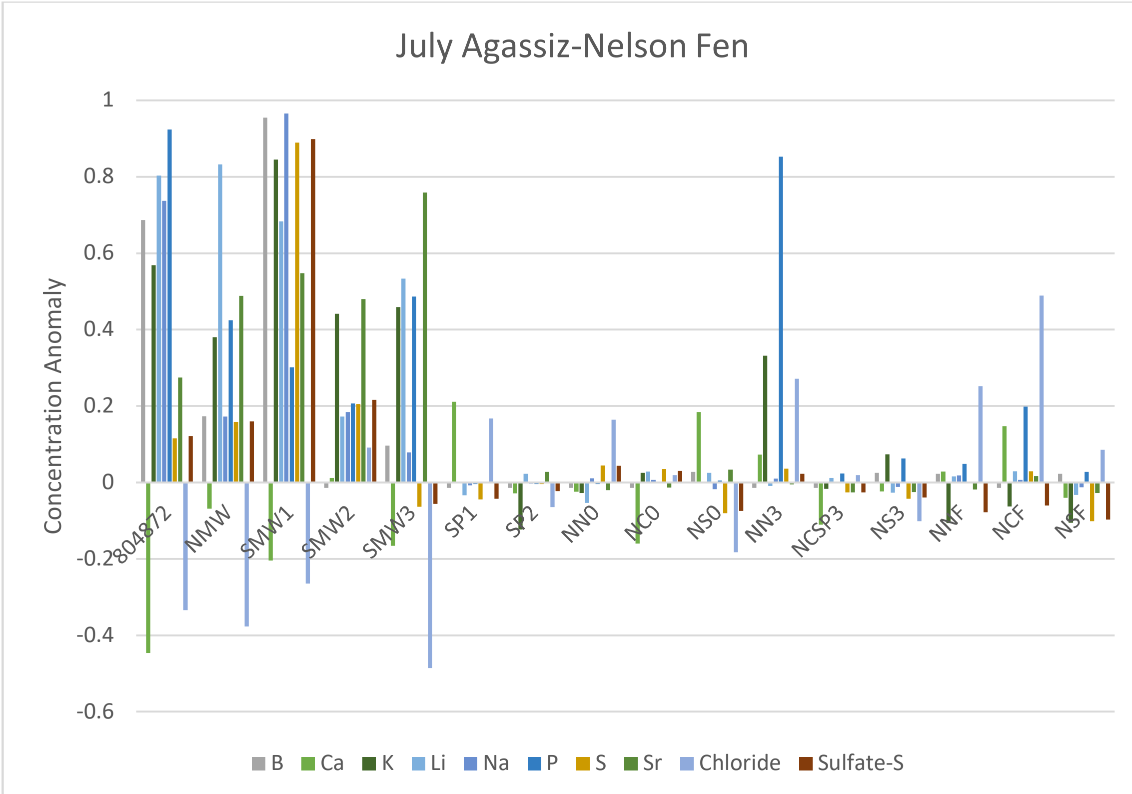

Figure 29. Selected concentration anomalies of metals and anions from beach ridge aquifer water for Agassiz-Nelson Fen during July 2019.

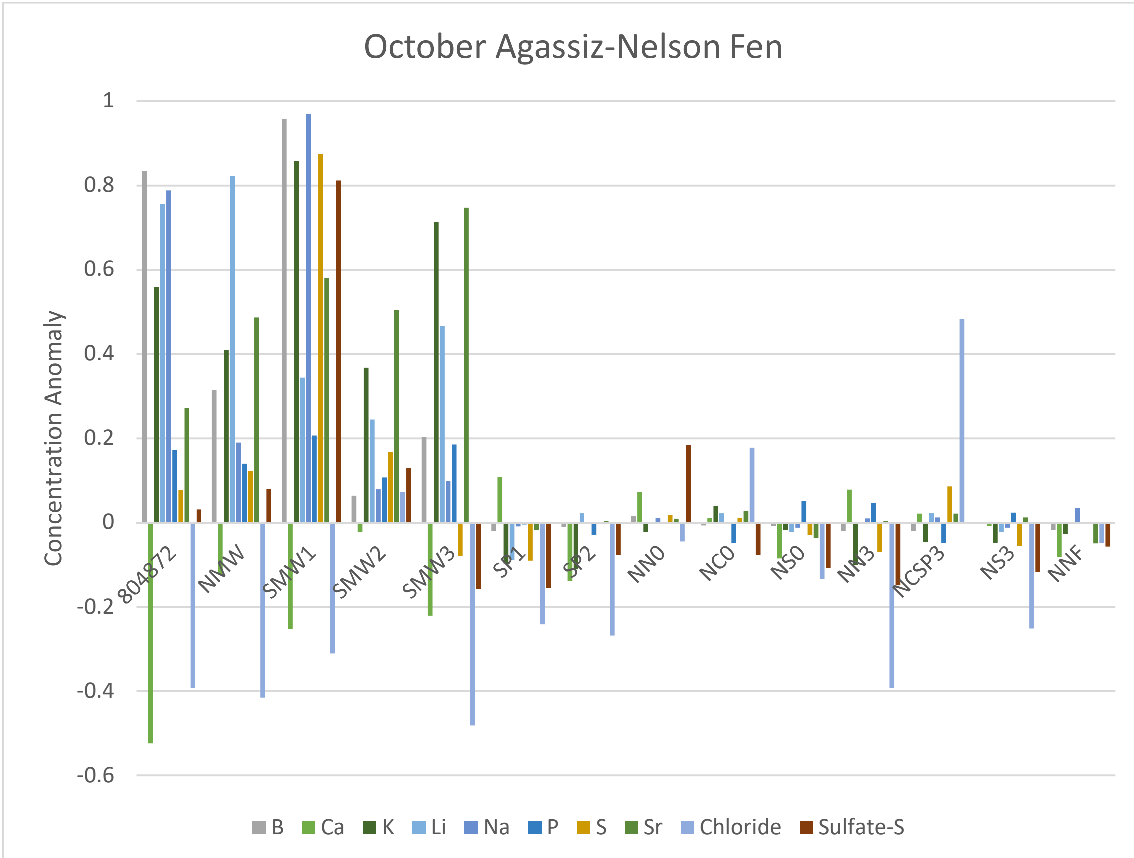

Figure 30. Selected concentration anomalies of metals and anions from beach ridge aquifer water for Agassiz-Nelson Fen during October 2019.

Finally, when the entire suite of chemistry data collected during both sampling events at both fen sites are input into a principal component factor analysis, a distinct divide again arises between all of the surficial wells and the wells in the deeper aquifers. Twelve factors were extracted. Two factors describe more than 10% of the variance, with factor 1 describing 22.5% and factor 2 describing 12% (Full results in appendix C). Factor 1 is loaded by mainly group 1A and 2A metals that are fairly conservative in the environment (eg. Li, Sr, K, Na) along with B, S, and SO4. Factor 2 is loaded by specific conductance and the calcium-carbonate system ions: Ca, Mg, and Alkalinity (carbonate). When plotting how each well scores on factor 2 versus factor 1, nearly all wells break into quartiles following their site and depth (Figure 31). Factor 2 simply divides the wells into their sites, with Agassiz-Nelson Fen wells plotting above the horizontal dividing line (Figure 31) and Sanders Fen wells below. Factor 2's division shows waters at Agassiz-Nelson are a bit richer in calcium/magnesium and carbonate than Sanders Fen waters. Factor 1, loaded by conservative metals, divides deep and intermediate wells to the right of the vertical line and surficial wells to the left (Figure 31). All 3 north nest wells (SMW2, SMW3, and NMW) plot much closer to the surficial wells than the south nest wells (SMW1, 804872). At Sanders Fen, confined aquifer well 580065 plots away from the rest of the surficial wells based on factor 1.

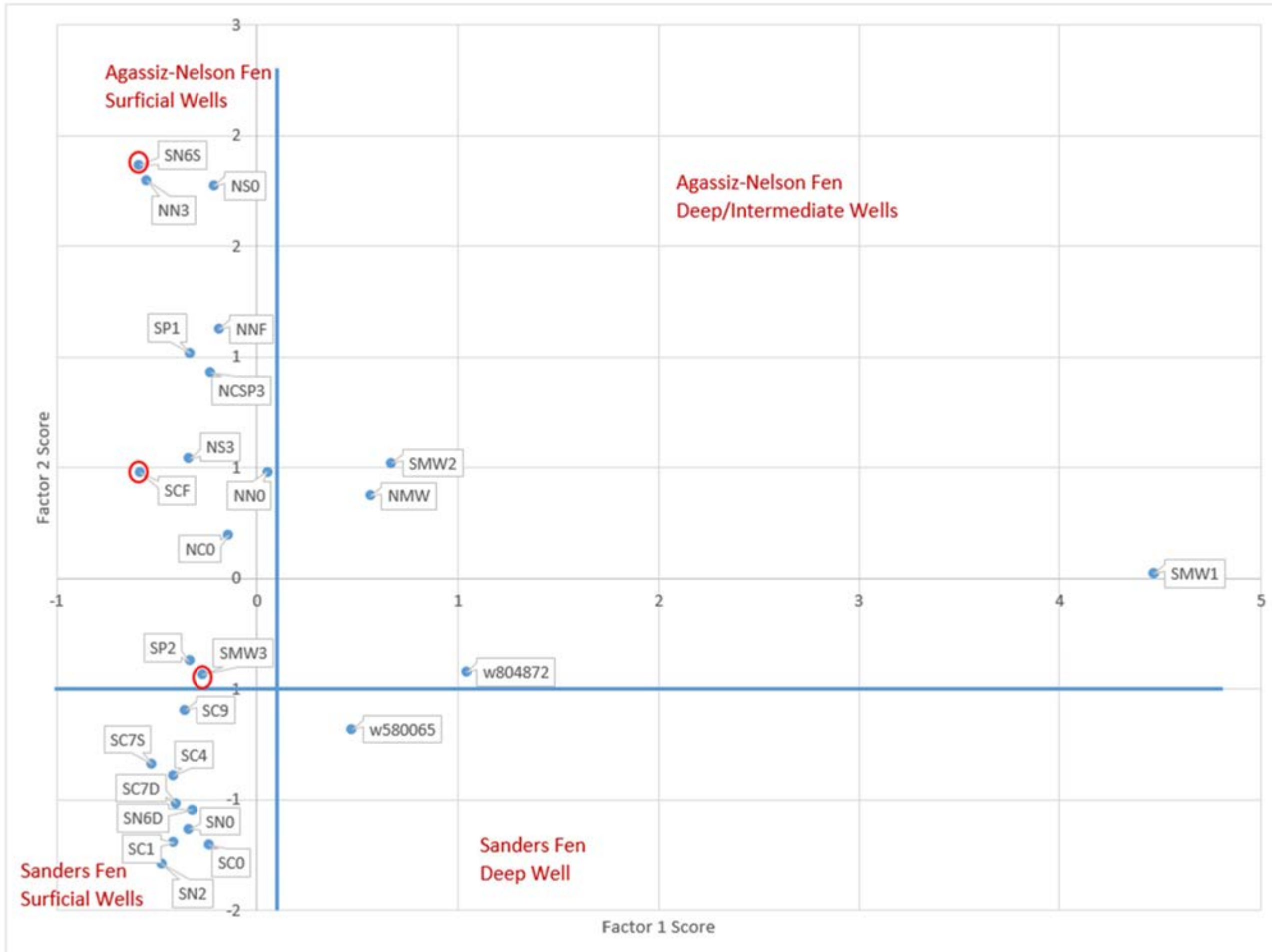

Figure 31. Factor scores for all wells sampled at both fen sites divided into quartiles based on depth and site. Exceptions to the major divisions are circled.

There were no appreciable concentrations in field blanks samples for ions of interest. Field duplicate samples and lab duplicate samples had overall errors of less than 7%, with two exceptions. The July lab duplicate for well SC9 had an error of 16% and the October lab duplicate for well SMW1 had an error of 13%--largely a result of increases in small concentrations leading to a large error. Charge balance errors did not exceed an acceptable 13%, with average charge balance errors for both months being 8%. More details on quality assurance and control are in Appendix B.

Stable Isotopes

Water samples collected at both fen sites were analyzed for stable isotopes $\delta^{18}O$ and $\delta^{2}H$ (deuterium). For full tabulated results see Appendix B. When plotted in dual-isotope space (Figure 32-Figure 35), all samples plot along the Grand Forks, ND meteoric water line (Matheny & Gerla, 1996). The wells at the Agassiz-Nelson north nest plot closer to the surficial wells during both samplings. The deepest well, NMW, plots with the surficial wells, while the intermediate depth wells are slightly lighter than the surficial water samples. The tightly confined south nest wells have an even lighter signature, as does the confined aquifer at Sanders Fen. The wells in, below, or next to the fen at both sites during both samplings plot with the beach ridge aquifer values, which also is similar to the rainfall isotope values collected during September (Figure 36) where δ18O values are between -9.5 and -12.

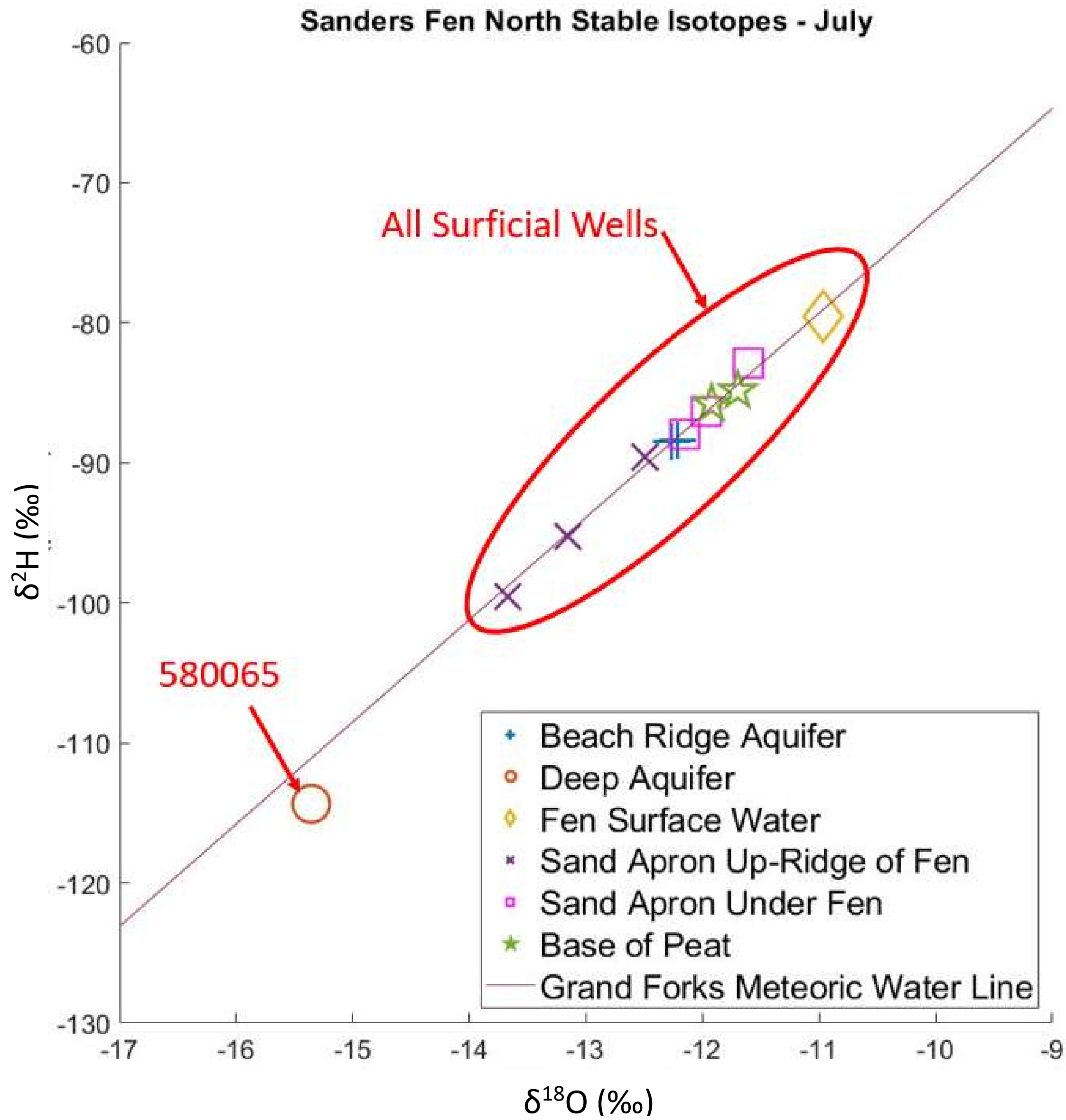

Figure 32. Stable isotopes at Sanders Fen North for samples collected July 2019.

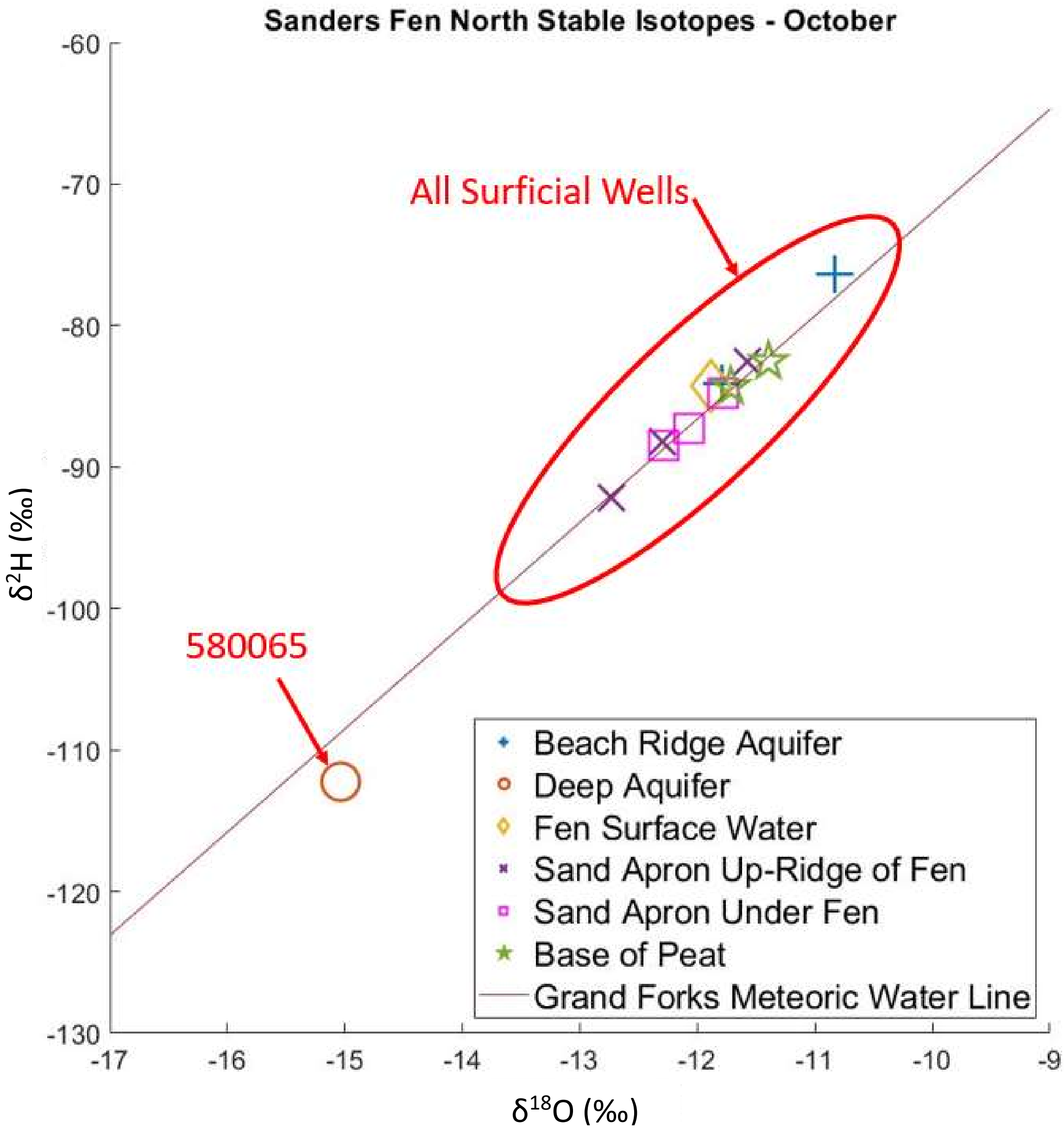

Figure 33. Stable isotopes at Sanders Fen North for samples collected October 2019.

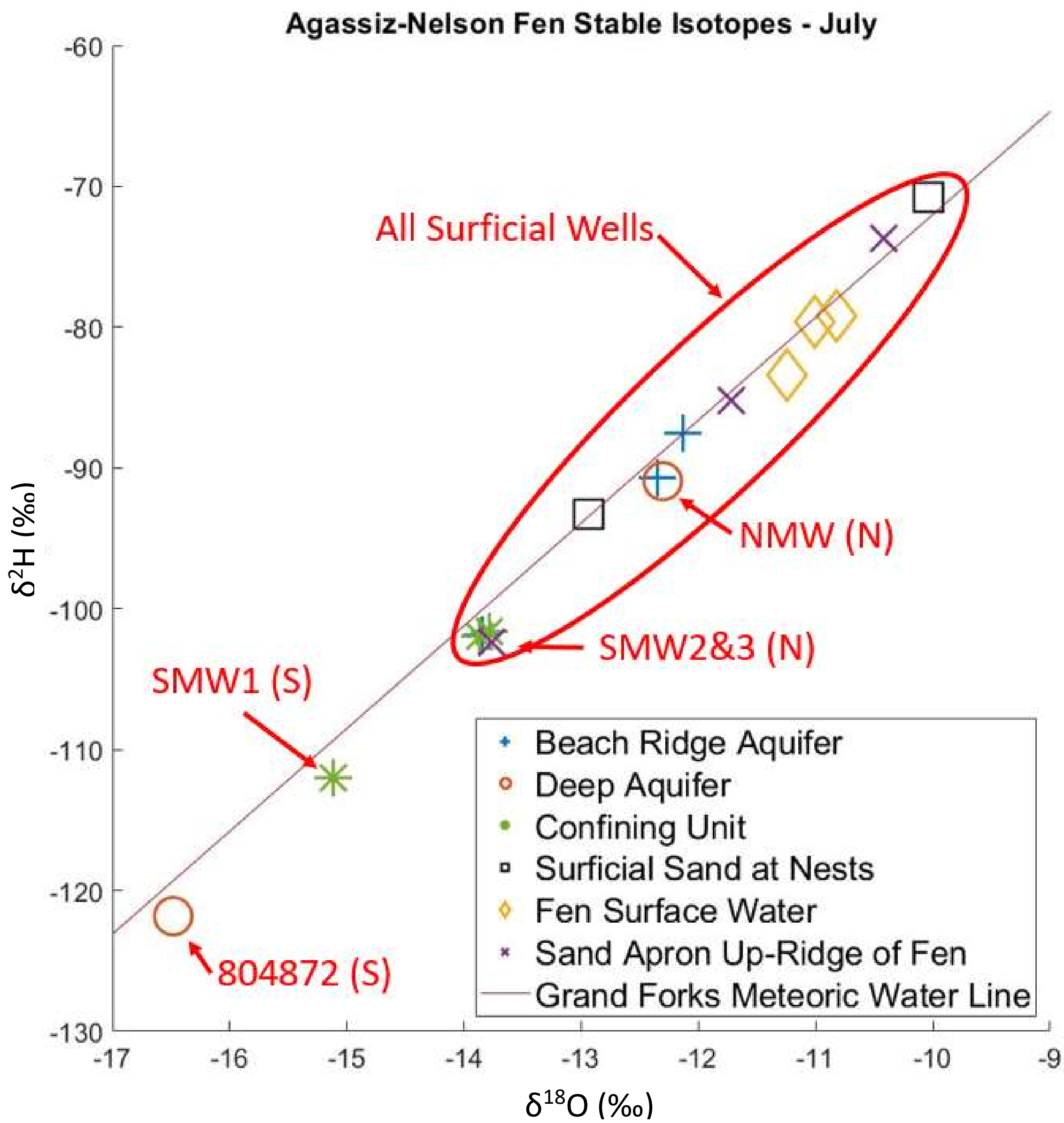

Figure 34. Stable isotopes at Agassiz-Nelson Fen for samples collected July 2019.

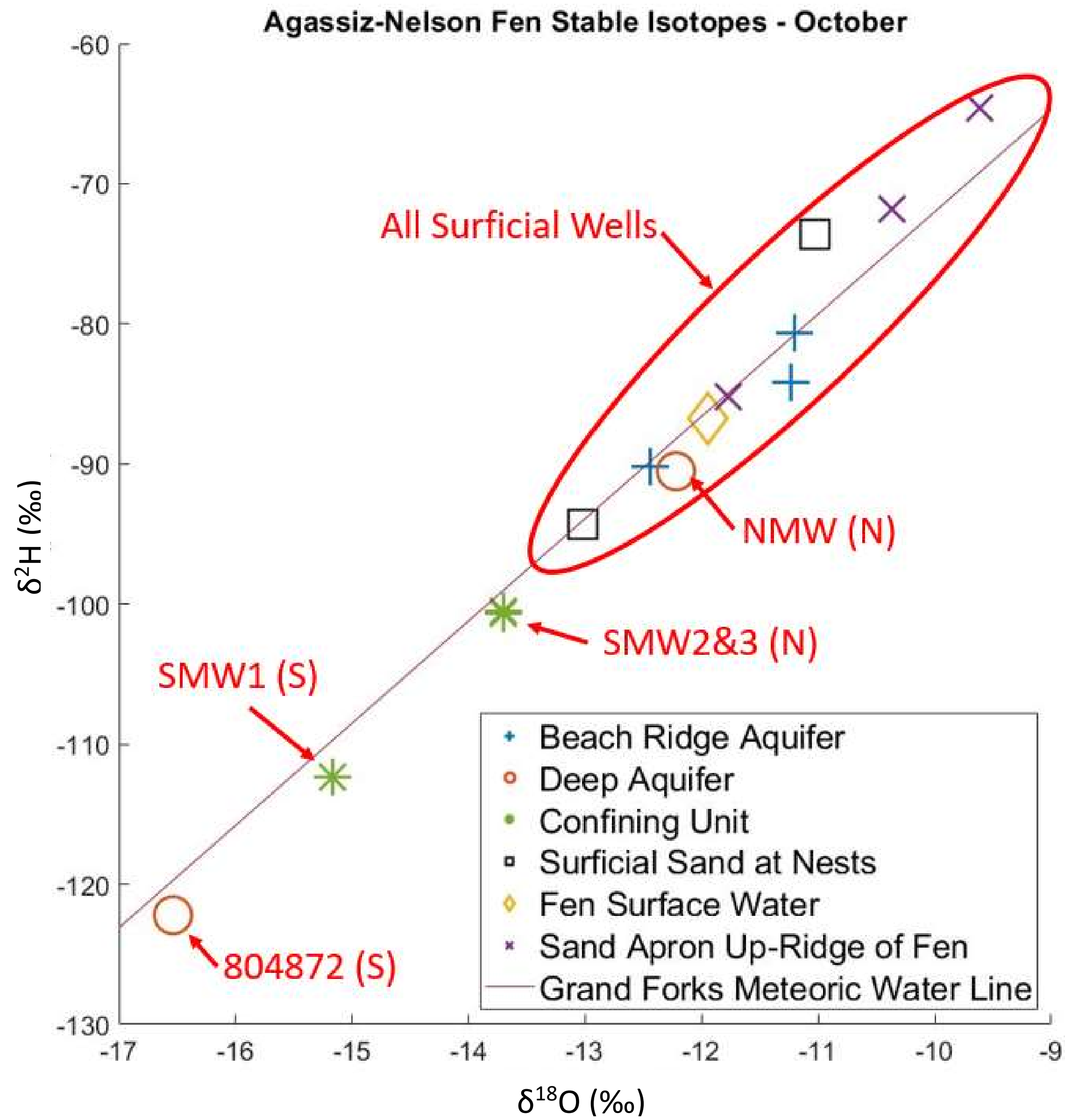

Figure 35. Stable isotopes at Agassiz-Nelson Fen for samples collected October 2019.

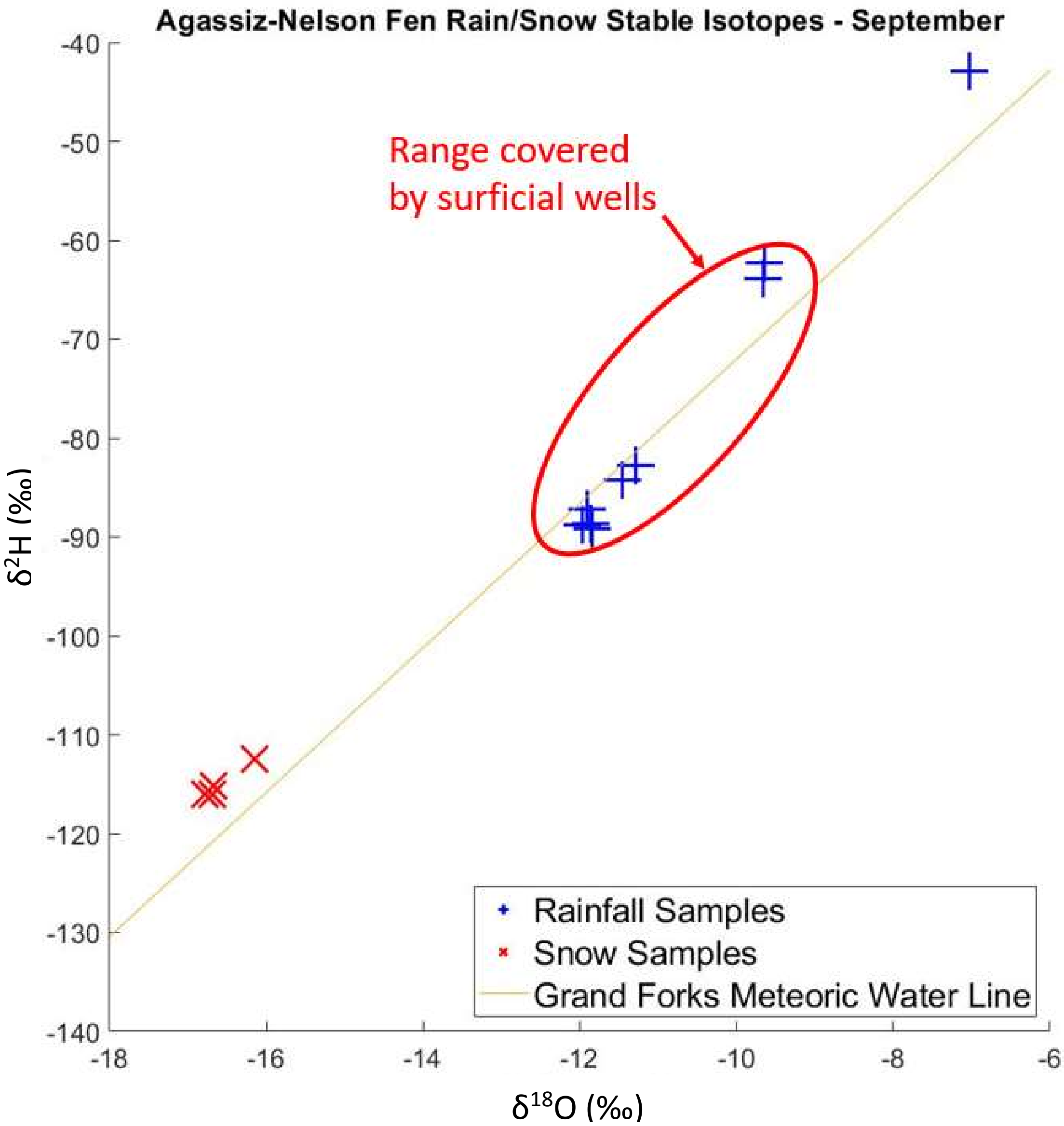

Figure 36. Rainfall and snow samples collected near Agassiz-Nelson Fen during September 2019.

Mixing Model

A mixing model helps determine the proportion of water entering the fen from the beach ridge compared to the confined aquifer (Table 8). At Sanders Fen North, well SC0 in the beach ridge aquifer and well 580065 in the confined aquifer were used as mixing endpoints for well SC7D in the sand below the fen. At Agassiz-Nelson Fen, well NC0 in the beach ridge aquifer and well 804872 in the south confined aquifer were used as mixing endpoints for well NCSP3 in the sand immediately adjacent to the fen. The north nest at Agassiz-Nelson Fen was not used because of the downward gradient to the deep aquifer. Mixing models using stable isotopes, several conservative metal concentrations (B, Ca, Li, Na, Sr) and chloride concentrations were averaged for each site and month.

Table 8. Proportions of water entering Sanders Fen North and Agassiz-Nelson Fen from the beach ridge aquifer compared to the confined aquifer.

Fen	Month	% Deep	% Beach Ridge
Sanders Fen North	July	-6	106
Sanders Fen North	October	5	95
Agassiz-Nelson Fen	July	-6	106
Agassiz-Nelson Fen	October	-6	106

Tritium

Seven wells were sampled for radioactive tritium (hydrogen-3) during October 2019 (Figure 37). Wells 580065, 804872, and NMW are in confined aquifers and have the lowest counts. The four wells with higher counts are in the surficial system.

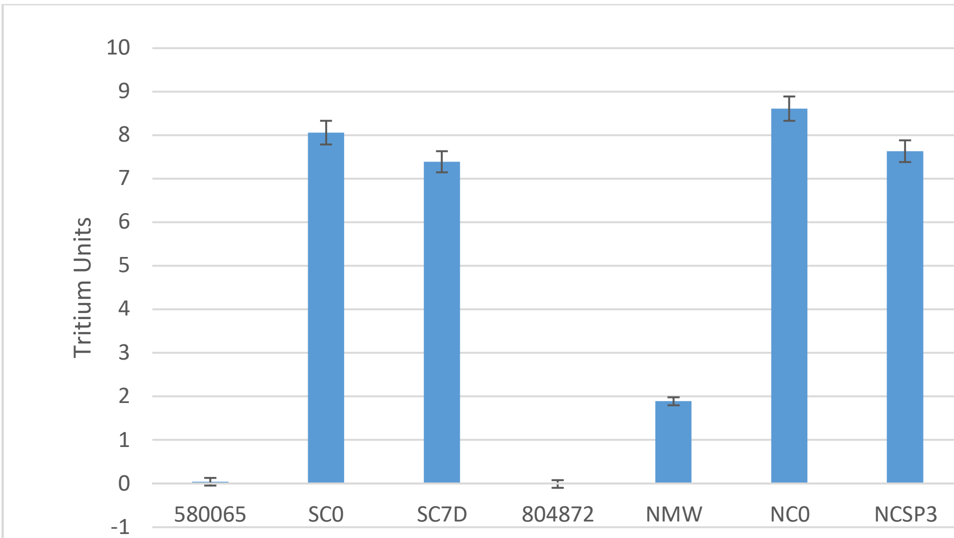

Figure 37. Tritium counts in waters from sampled wells in October 2019. Error bars capture one standard deviation of counting error.

Rockworks Model

The glacial subsurface of a 20 mile by 20 mile square region centered on each of the two study fens, when modeled in three dimensions using well-log stratigraphy data, is highly heterogeneous. Aquifers start and end irregularly across the region. Figure 38-Figure 41 are cross sections through the entire 20 mile by 20 mile square model illustrating the irregularity of the glacial substrate around both fen sites. Videos of more slices through the models are included in supplementary materials

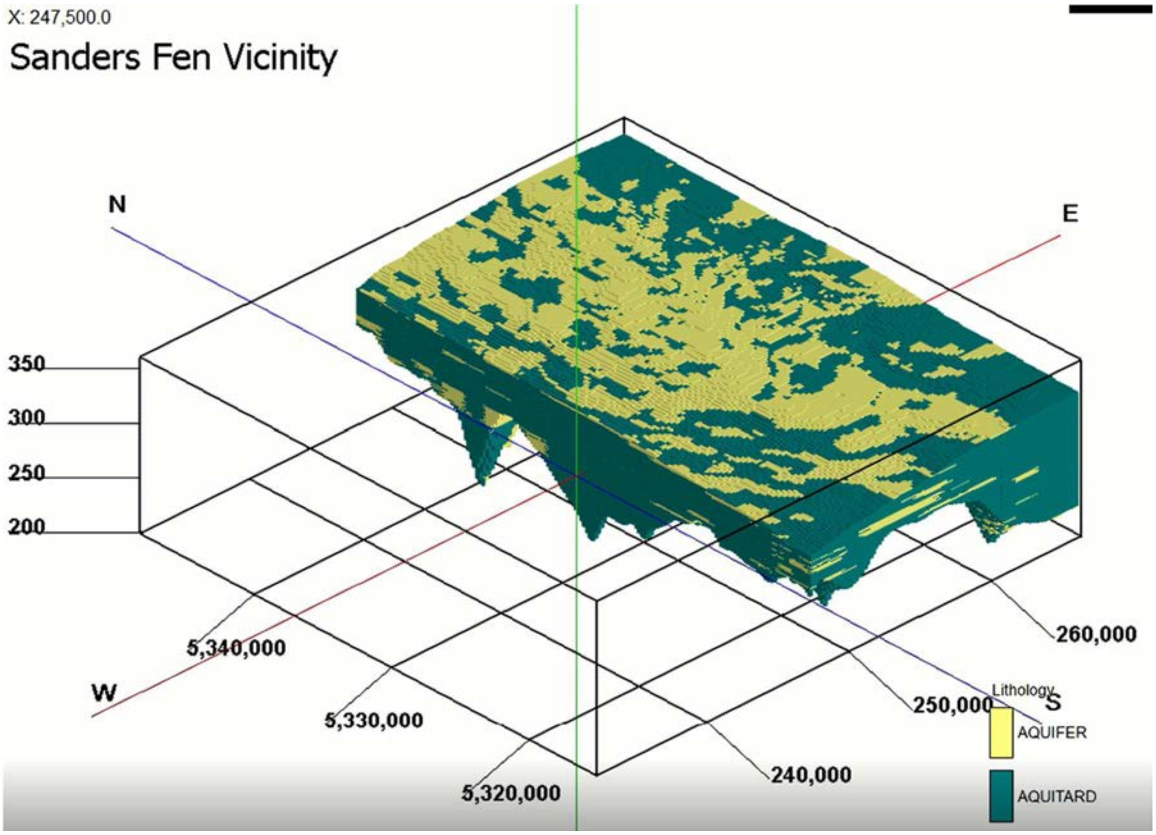

Figure 38. North-south cross-section through Sanders Fen Rockworks 3D model. Sanders Fen is located at the intersection of the axis lines. Vertical exaggeration 64x. Units in meters. Horizontal values are UTM Zone 15N Extended.

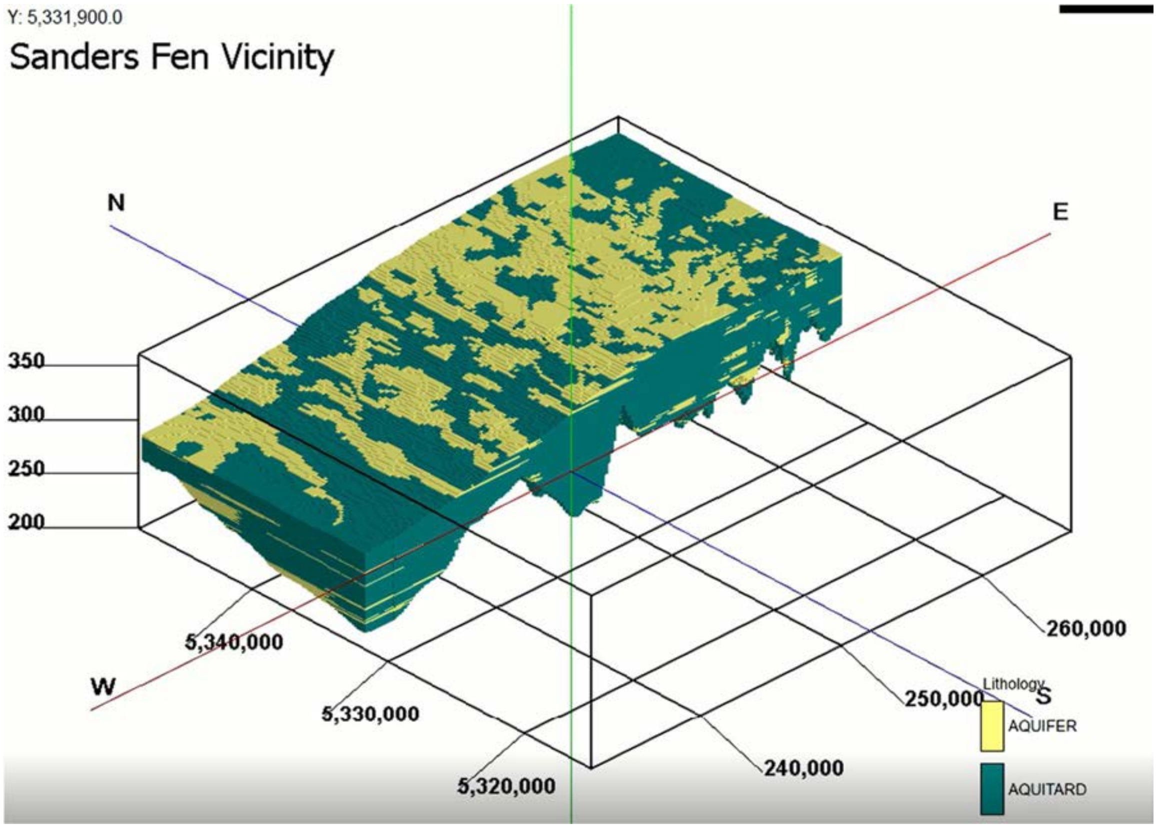

Figure 39. East-west cross-section through Sanders Fen Rockworks 3D model. Sanders Fen is located at the intersection of the axis lines. Vertical exaggeration 64x. Units in meters. Horizontal values are UTM Zone 15N Extended.

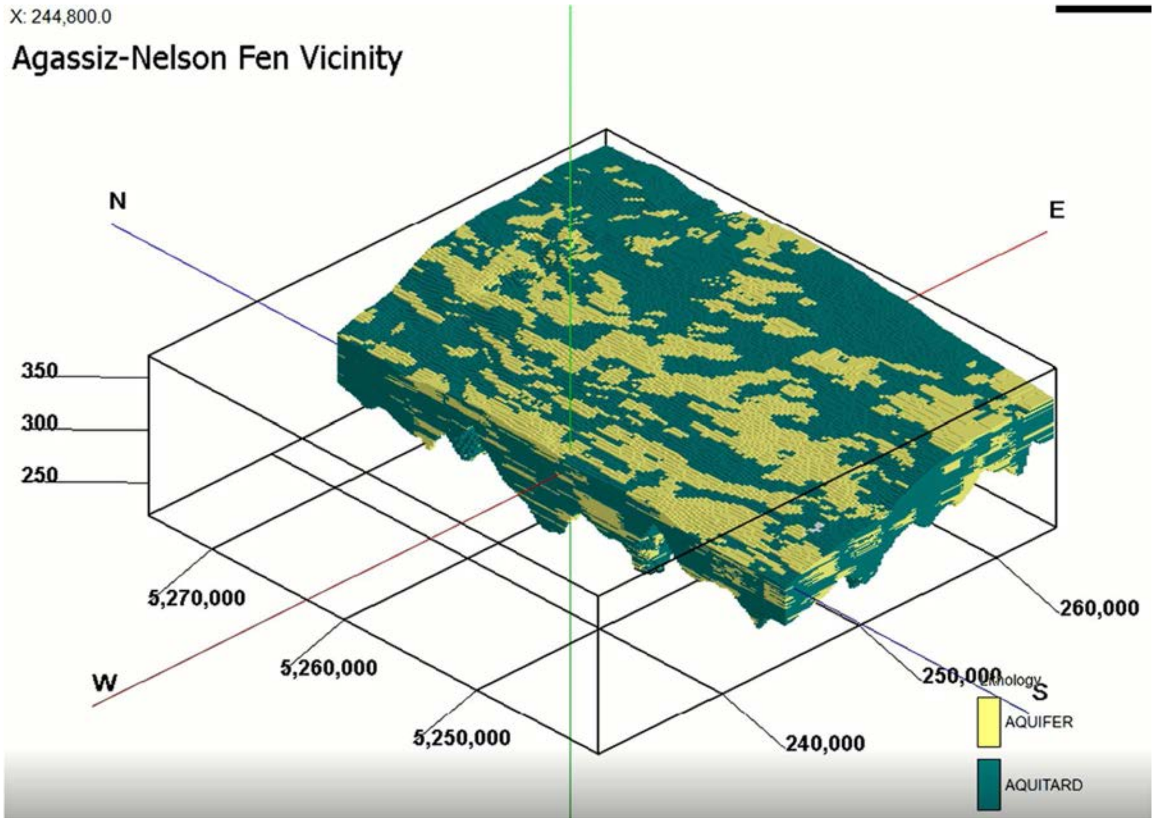

Figure 40. North-south cross-section through Agassiz-Nelson Fen Rockworks 3D model. Agassiz-Nelson Fen is located at the intersection of the axis lines. Vertical exaggeration 64x. Units in meters. Horizontal values are UTM Zone 15N Extended.

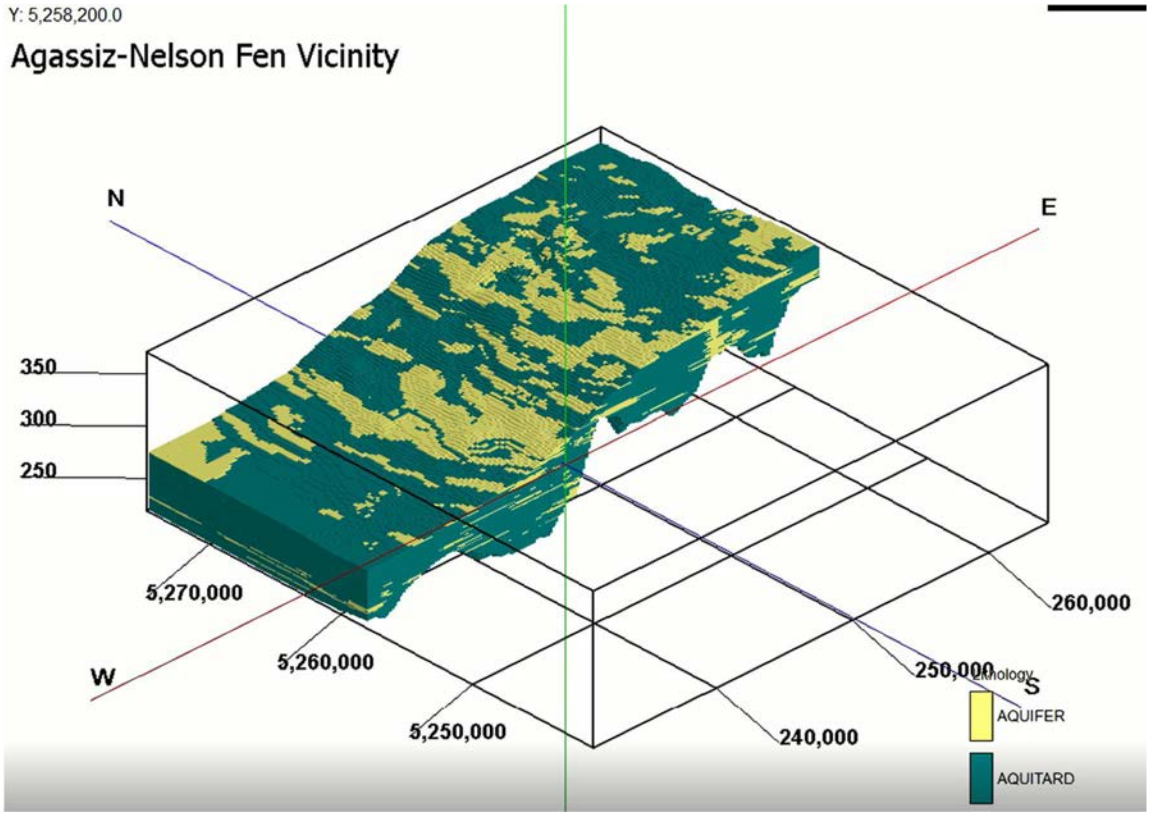

Figure 41. East-west cross-section through Agassiz-Nelson Fen Rockworks 3D model. Agassiz-Nelson Fen is located at the intersection of the axis lines. Vertical exaggeration 64x. Units in meters. Horizontal values are UTM Zone 15N Extended.

Zooming the model to a 3.75 mile (6km) by 3.75 mile square area centered on each fen and creating fence diagrams reveals more about the subsurface lithology directly below each fen. At Sanders Fen (Figure 42), directly below the fen (at the center of the diagram) there is only aquitard material and the first major aquifer, mainly to the east of the fen, is at 200 ft depth.

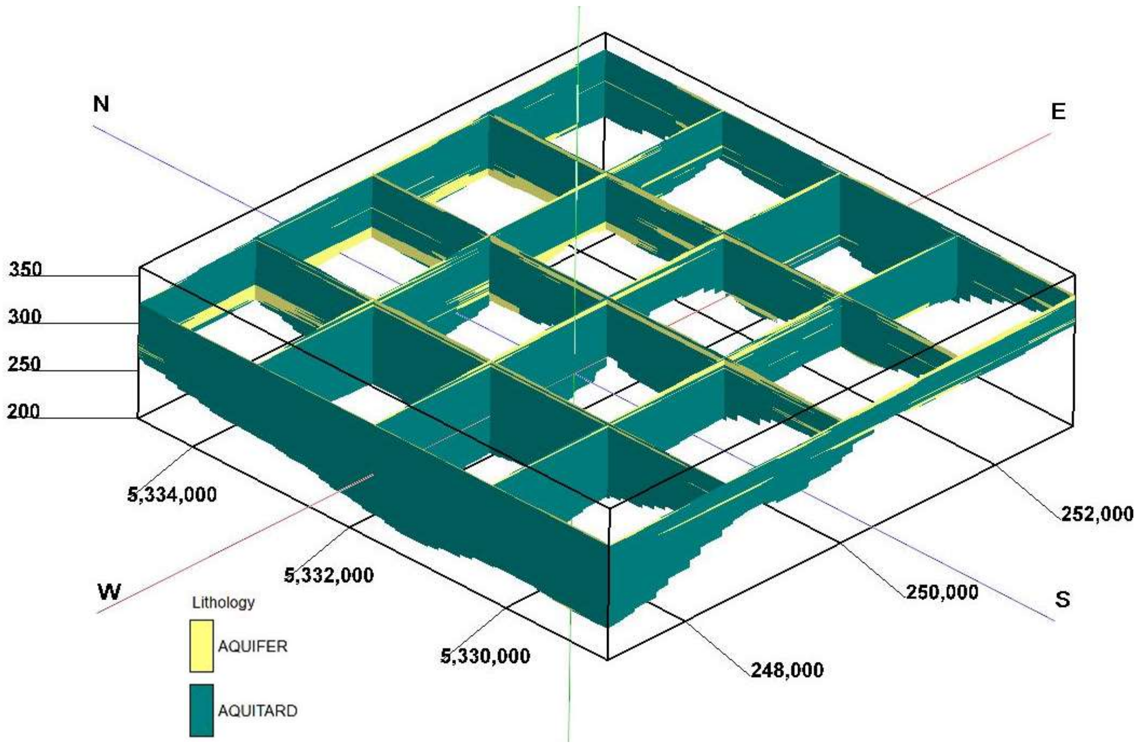

Figure 42. Fence diagram of stratigraphy in immediate area around Sanders Fen. Sanders Fen is located at the center. Vertical exaggeration 10x. Units in meters. Horizontal values are UTM Zone 15N Extended.

At Agassiz-Nelson Fen, the model captures the more complicated pattern of aquifers and aquitards in the area (Figure 43). A gap falls between the aquifer systems north of the fen and south of the fen, though the exact location is unclear because of the coarseness of the model. South of the fen, where the south nest is located, a thin layer of sand where SMW1 is located is separated by an aquitard from the thicker aquifer penetrated by well 804872, SMW, and well W-5, pumped in the Summit (2015) test. The model also captures the complicated stratigraphy at the north nest, with inter-fingering patches of aquifer material extending from the surface to well NMW's depth.

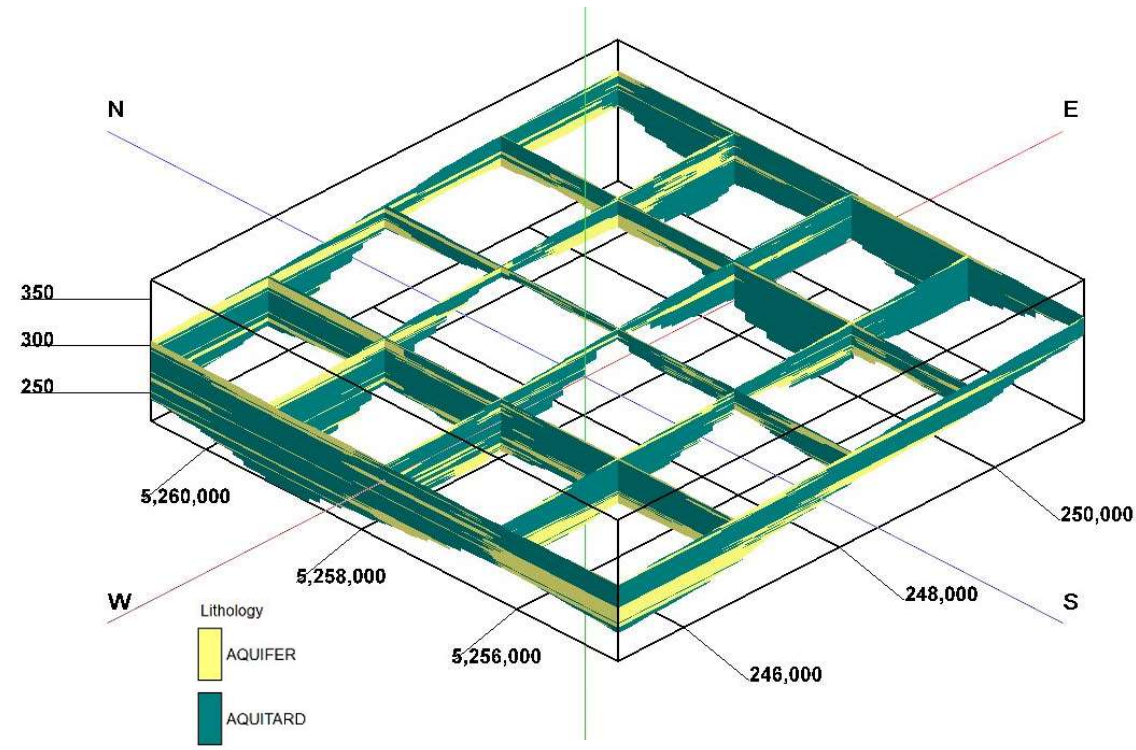

Figure 43. Fence diagram of stratigraphy in immediate area around Agassiz-Nelson Fen. Agassiz-Nelson Fen is located at the center. Vertical exaggeration 10x. Units in meters. Horizontal values are UTM Zone 15N Extended.

Resistivity Survey

Geophysical sections generated using electrical resistivity provide a more refined picture of the stratigraphy below the fens. Higher resistivity values tend to signify sands, while lower values signify clays and saturated materials. At Sanders Fen (Figure 44), the highest resistivity values are at the right side of the profile, corresponding to the location of the beach ridge. Moving left towards the fen, resistivity values decrease slightly as the water table gets closer to the surface. There is a clear horizon at about 10-15 ft (3-5 meters) depth where there is a drop in resistivity that continues with relatively lower resistivity values to the depth of the profile at 170 ft (52 meters).

At Agassiz-Nelson Fen (Figure 45), there is a clear horizon of higher resistivity in the upper 7-15 ft (2-5 meters) across the entire length. This high-resistivity layer is underlain by a layer of lower resistivity that is about 25 ft (8 meters) thick. At approximately 30-35 ft (10 meters) depth, there is increased resistivity again continuing to approximately 100 ft (30m) depth. Both modeled profiles have RMS errors below 5%, meaning the modeled profiles match the collected data well.

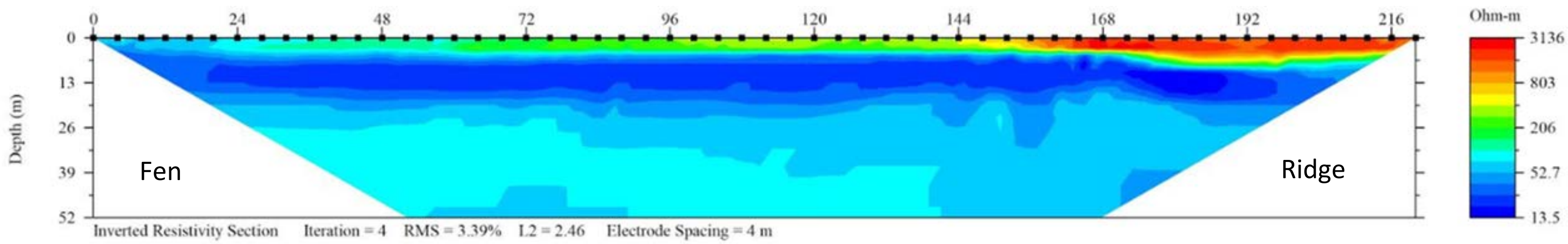

Figure 44. Sanders Fen modeled electrical resistivity profile. Notice the different resistivity scale compared to Figure 45.

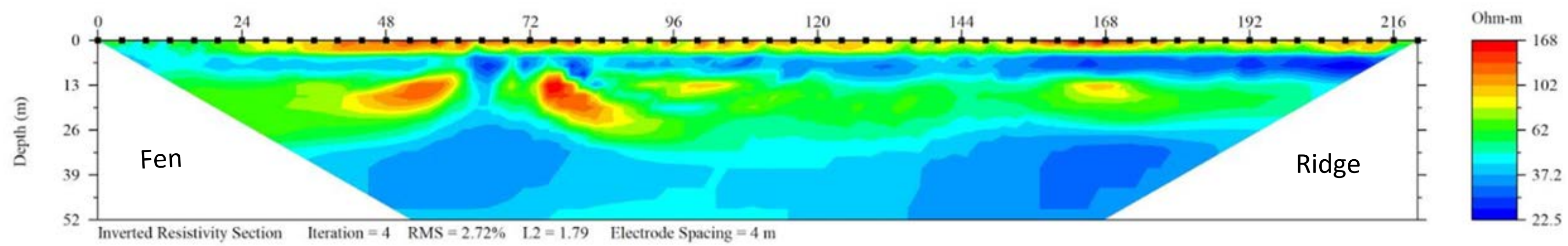

Figure 45. Agassiz-Nelson Fen modeled electrical resistivity profile. Notice the different resistivity scale compared to Figure 44.

Beach Ridge Fens GIS and Statistical Analysis

A statistical analysis of 53 beach ridge calcareous fens and 26 non-calcareous beach ridge wetlands was used to help understand the importance of beach ridges for calcareous fen occurrence. Nine factors were extracted from the input landscape variables. See Appendix C for detailed results. Table 9 displays what environmental variables each of the extracted factors describe.

Table 9. Description of factors extracted using a principal component analysis to describe calcareous fen occurrence.

Factor	Loaded variables
1	NAIP imagery red, green, and blue coloring
2	Saturated hydraulic conductivity of beach ridges
3	More northerly fens are colder and have larger depth to confined aquifer. This is the only factor that depth to confined aquifer has a loading greater than 0.25 (at 0.59).
4	The inverse relationship between the beach ridge being covered by crops or natural prairie
5	Saturated hydraulic conductivity of the soil in and downgradient of the fen
6	Area of the fen and the length perpendicular (and parallel) to the beach ridge increase together.
7	Aspect ratio of the fen—length parallel over perpendicular to the beach ridge
8	Beach ridge volume and cross sectional area (the volume divided by the length parallel to ridge front)
9	Relationship between Landsat summer red, green, and Thermal Infrared (TIR)

To determine whether there is a difference between calcareous and non-calcareous fens among the factors, factor scores were input into a *t*-test to determine if there is a statistically significant difference between the means of the calcareous fens and non-calcareous fens (Table 10). *P*-values less than 0.05 mark significant differences between calcaerous and non-calcaereous fens. Factor 2 (12% of the variance), which describes the hydraulic conductivity of the beach ridge, and Factor 4 (6% of the variance), which describes whether the beach ridge is covered in prairie or crops, were the only two factors that statistically discriminate calcareous and non-calcareous fens. The calcareous fens scored higher on Factor 2, which corresponds to higher beach ridge conductivities. The calcareous fens also scored higher on Factor 4, which corresponds to more prairie coverage and less crop coverage. On average, the calcareous fens have 51% crop and 34% prairie coverage, while the non-calcareous fens have 66% crop and 26% prairie coverage.

Table 10. P-values for each factor in the calcareous fen occurrence multivariate analysis.

Factor	*p*-value
1	0.610
2	0.022
3	0.349
4	0.036
5	0.194
6	0.488
7	0.290
8	0.364
9	0.990

Discussion

The hydrology, chemistry, isotope, geophysical, and modeling data collected as a part of this study support the hypothesis that the surficial beach ridge aquifers are the primary source of water feeding calcareous fens. Both Sanders Fen North and Agassiz-Nelson Fen, the two primary study sites, are intricately linked to their beach ridge and a part of the same hydrologic system. The study captured both relatively dry or average months at the beginning of the monitoring season (June-August) and very wet months at the end (September-October) (Table 11). September was the wettest on record since 1941.

Table 11. Monitoring season monthly rainfall compared to climatic data (NOAA NCEI, 2019).

Month	Year	Precip (in)	Mean Precip (in) 1981-2010	Anomaly (in)	Wetness Rank (of 79) 1941-2019
10	2019	3.48	1.93	1.55	5
9	2019	8.15	2.05	6.1	1
8	2019	2.65	2.88	-0.23	39
7	2019	3.5	3.15	0.35	25
6	2019	1.67	3.48	-1.81	66
5	2019	1.72	2.67	-0.95	47

At Sanders Fen, the wells in the sand beneath the fen peat, at the base of the fen peat, and in the sand apron upgradient of the fen all respond to natural hydrologic forcing as a system with the wells in the beach ridge surficial aquifer (Figure 9). High heads in the beach ridge provide the potential needed to drive water from the sand below the fen up into the base of the fen peat (Figure 46). The nest of wells in the fen show that there is indeed an upward gradient of water from this sand into the base of the fen peat (Figure 9). The lack of a strong upward gradient in the northern scrubby-quality fen transect (Figure 10) may result in this location's scrubbier quality. The wells below the fen responded to the two analyzed rainfall events as a system with the beach ridge aquifer and the sand apron upgradient of the fen (Figure 11Figure 12). The wells below the fen started having increases in head not long after the upgradient sand-apron wells first responded to the rainfall. The beach ridge took longer to respond and reach a peak because of the increased distance water needs to travel to reach the water table at these wells, but the drawn out response in the beach ridge sustains a more drawn out response in the sand below the fen (Figure 11Figure 12). The high-frequency, low amplitude fluctuations that occur approximately daily in the hydrographs are a result of either evapotranspiration or earth tides, which occur when the moon causes the earth to swell and contract (see Appendix D for more information).

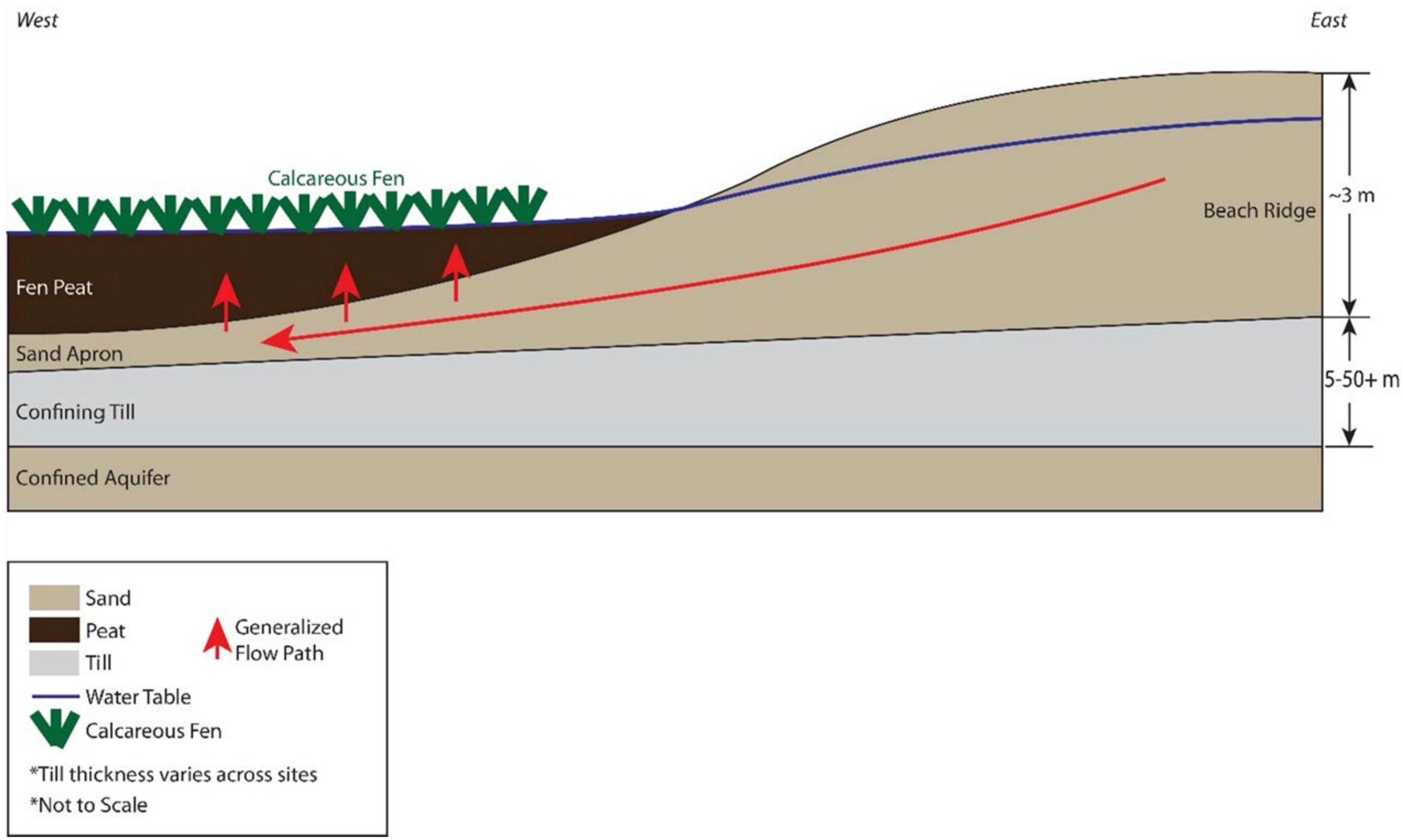

Figure 46. Hydrology of Beach Ridge Calcareous Fens. Arrows are generalized water flow paths.

The water chemistry is similar in all of the surficial wells—including the wells in and below the fen, upgradient of the fen, and in the beach ridge aquifer (Figure 23Figure 24Figure 27Figure 28). In the resistivity profile at this site (Figure 44), the beach ridge and surficial sand are clear as a horizon of higher resistivity at the surface with very high resistivity values at the right in the figure corresponding to the beach ridge. Below this, there are lower resistivity values that typically signify clay to the 170-ft depth of the survey. The 200-foot-deep confined aquifer sampled at the site has a different chemistry: it has higher concentrations of stable tracer metals such as lithium, sodium, potassium, and strontium (Figure 27-Figure 28). It also has higher proportions of sulfate and chloride than the surficial wells (Figure 23Figure 24). In the multivariate analysis of the chemistry samples (Figure 31), confined aquifer well 580065 has statistically different factor 1 chemistry (loaded by conservative cations) than all of the surficial wells including those in and below the fen. Wells SCF and SN6S plotted with the higher-alkalinity Agassiz-Nelson Fen wells based on factor 2 (Figure 31). Higher factor 2 scores mean higher calcium-carbonate concentrations. Well SCF monitors the fen surface water. Well SN6S monitors the peat in the scrubby fen transect. Both wells potentially could see surface evaporation, which increases alkalinity by increasing concentration. Stable isotopes also separate the confined aquifer from the surficial system (Figure 32Figure 33). While all data points plot on the local meteoric water line, the confined aquifer water is much lighter than the surficial system. Interestingly, the wells near the ground surface do not plot off the local meteoric water line with an evaporative isotopic signature (Figure 32Figure 33). Water in the confined aquifer recharged at an earlier time, as water from well 580065 has no tritium (Figure 37). The beach ridge aquifer (well SC0) and the sand below the fen (well SC7D) have water with tritium counts above 7 TU, signifying recent recharge (Figure 37).

The confined aquifer, mainly east of the fen, is separated from the surface by 200 feet of confining till and is the first major aquifer underneath the Sanders Fen study area—evidenced by well logs and the Rockworks model (Figure 42) and the lack of a zone of higher electrical resistivity marking sand for 150 feet below the fen (Figure 44). This aquifer may not even extend underneath the fen, as there is a distinct lack of wells immediately west of the fen at any depth—there is no aquifer present to access through drilling. Based on the similarities between the water entering the fen and the beach ridge water and the differences from the confined aquifer, along with the high depth to any confined aquifer, Sanders Fen North is fed by and intricately linked to its associated beach ridge (Figure 46). The results of the averaged chemical and isotopic mixing model (Table 8) highlight the link between the fen and the beach ridge aquifer. During July, 100% of the water is coming from the beach ridge. During October, water enters the fen matches the beach ridge at 95%, though because October was a wet month (Table 11), the beach ridge still likely was providing all of the water to the fen and the 5% matching the deep aquifer is error.

The simultaneous hydrologic response of wells in the beach-ridge aquifer, those immediately adjacent to, and the DNR well beneath Agassiz-Nelson Fen indicate that water feeding Agassiz-Nelson Fen also comes from the beach ridge aquifer (Figure 46). Well DNR Deep 3 in the sand below the fen acts hydrologically as a system with the wells in the sand adjacent to the fen and in the beach ridge aquifer (Figure 13Figure 14). This well in the sand below the fen also has hydraulic head above the ground surface, indicating an upward gradient from sand below the fen into the peat. All surficial wells respond as a system to rainfall events (Figure 18-Figure 19). The wells in the sand apron upgradient of the fen respond first, as the water table is closer to the surface at these wells. The beach ridge takes longer to respond because of the greater depth to the water table. Well DNR Deep 3 below the fen begins responding to both analyzed storms soon after the sand-apron wells adjacent to the fen as a part of the surficial system. DNR Deep 3 well also has a small rise in head during the fall recharge pulse in late September. All of these surficial wells, just as at Sanders Fen, respond to surficial hydrologic forcing events. All of the surficial wells have similar water chemistry (Figure 25Figure 26Figure 29Figure 30) and isotopic signatures (Figure 34Figure 35). As at Sanders Fen North, the wells at the fen surface interestingly do not show an evaporative isotopic signal. Also, though the surficial well isotope samples fall within the range covered by the rainfall samples collected in September (Figure 36), it must be noted that the isotopic signature of rainfall varies temporally and neither the July nor October sampling event is covered by these rainfall samples. Thus, the collected rainfall samples only give a general estimate of the isotopic composition of rainfall for the region. All of the surficial wells fall in the general range covered by rainfall (Figure 34Figure 35). Water in the beach ridge aquifer (well NC0) and the sand apron adjacent to the fen (well NCSP3) have tritium counts above 7 TU, signifying recent recharge (Figure 37).

The stratigraphy below the fen at this site is more complex and there are two potential sources of deeper, confined groundwater: one to the north of the fen and one to the south (Figure 47). Both confined systems were monitored and can be ruled out as sources of water to the fen for different reasons. Based on pump tests by Braun (2014) and Summit (2015), the north and south aquifers are not connected; there is a barrier boundary between the two somewhere in the vicinity of Agassiz-Nelson fen.

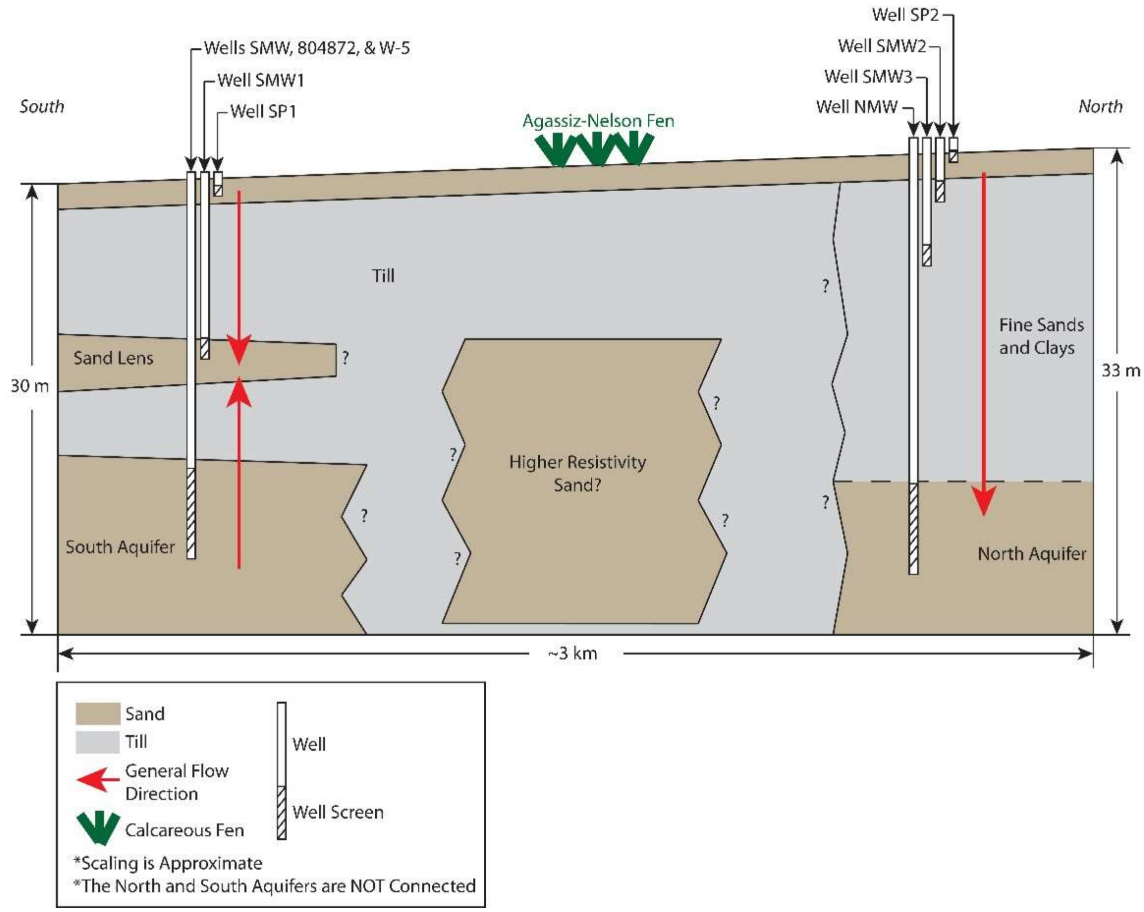

Figure 47. Confined aquifer system at Agassiz-Nelson Fen.

The south aquifer, starting at about 70-80 feet deep, is overlain by 10 feet of till, 5-10 feet of sand (monitored), and then till again until the upper 5 feet of surficial sands (Figure 47). The confined south aquifer is artesian, giving it potential to be forcing water to the fen at the surface. However, the chemistry in this aquifer is again very different. There are higher concentrations of conservative tracer metals and sulfates (Figure 25Figure 26Figure 29Figure 30). The stable isotope samples collected from this aquifer are lighter than the surficial system (Figure 34Figure 35). The water in this aquifer must have recharged at an earlier time, as no tritium was found in well 804872 (Figure 37). Well SMW1, nestled in 5-10 feet of sand and separated from the confined aquifer below by till, has water with an ever larger proportion of sulfate and an even more different chemical signature from the surficial wells in the multivariate chemistry analysis presented in Figure 31. The confining layer between this sand lens and the confined aquifer must be tight, as around 10 feet of head are lost over the short interval of till in between (Figure 17). Also, the hydraulic gradient flips to being downward from the surface into this sand lens (Figure 17). All of the potential from the artesian head in the south aquifer is lost in the confining unit. Any small increases in head in the intermediate sand during summer rainfall events (Figure 21) can be explained by the increased weight of the water in the surficial sands increasing the overlying pressure, as the response is the correct order of magnitude. A change in overlying total stress (+0.7 ft pure water) is proportional to a change in head in the confined aquifer (+0.2 ft) from equation 2.

Equation 2: $\Delta\sigma_T = \Delta\sigma_e + \Delta P$ (Fetter, 2001)

Where: $\Delta\sigma_T$ is total stress ($\rho g \Delta H$), $\Delta\sigma_e$ is effective stress ($zero$), ΔP is change in pressure in the confined aquifer ($\rho g \Delta h$), ρ is the density of water, g is gravitational acceleration, H is the added load in length units, and h is the head in the confined aquifer in length units.

Though all depths see an increase in head during the fall recharge pulse (Figure 17), the magnitude in the confined system is much lower and the response is dampened in time. It takes time for the loading signal to reach this aquifer. The lack of response in surficial wells during the Summit (2015) pump test of the south aquifer also supports the lack of a surface-confined aquifer connection. The small intermediate layer of sand did respond, but is likely the result of faulty construction of the pumping well W-5. Well W-5 likely pulled water down through a leak along the casing, reducing the head slightly in the intermediate sands rather than pulling water through the tight till in between (Summit, 2015). These hydraulic observations and the very different chemistry and isotopic signatures suggest that the south aquifer is not a source of water to Agassiz-Nelson Fen—if the aquifer even reaches the vicinity below the fen. The average chemical and isotopic mixing model (Table 8) also supports this conclusion. During both the July and October sampling events, the water entering the fen matches that in the beach ridge at 100%.

The north aquifer, starting at around 80 feet deep, is overlain by a complex system of inter-fingering fine sands and till (Figure 47). There is a downward hydraulic gradient to this aquifer from the surface (Figure 16). This alone eliminates this aquifer as a source of water for the fen: it isn't driving water upward to the fen. All four nest wells respond more to rainfall events (Figure 20) than the comparable south nest wells (Figure 21), likely a result of a combination of recharge and increased pressure from increased loading above. The chemistry and isotopic signatures of the waters in the intermediate fine sands and in the north aquifer also support the downward movement of water from the surface at this site. The chemistry (Figure 25Figure 26Figure 29Figure 30) and isotopic signature (Figure 34Figure 35) of waters in the intermediate fine sands and in the confined aquifer are closer to that of the surface than at the south aquifer. The confined aquifer (well NMW) has approximately 2 TU of tritium (Figure 37). This also suggests recharge is reaching this aquifer; this value is slightly greater than the zero tritium in the other confined aquifers. Although the chemistry and isotopic signature at this aquifer is closer to that of the surface, the downward hydrologic gradient provides a mechanism for this observation. This downward gradient also explains why well SMW3 was an outlier in the chemistry multivariate analysis (Figure 31), as it may be recharged from the surface. Interestingly, well SMW2, which is closer to the surface (16ft deep) than SMW3 (38ft deep), plots with the deeper wells (Figure 31).

The stratigraphic model captures the two different aquifer systems to the north and south of Agassiz-Nelson Fen (Figure 43) and the complex nature of the glacial substrate around this site. The electrical resistivity survey at this site identified an area of slightly increased resistivity marking what likely is fine sand at depths from around 30 to 100 feet overlain by a till layer (Figure 45). Further investigations are needed to verify the location of the boundary between the two confined aquifer systems and which, if any, system extends below the fen and which, if either, is being captured by the higher resistivity values.

This research supports the hydrologic model for beach ridge-seep wetlands described by Cowdery and others (2008) in their study at the nearby Glacial Ridge National Wildlife Refuge. Water stored in the beach ridges feeds fens at the foreshore/beach slope transition. The fens also follow the generalized model for seepage face calcareous fens described by Almendinger & Leete (1998b). The fens form at a break in slope where water from a higher recharge area (the beach ridge) emerges at the base of the slope face. The geomorphic setting of calcareous fens is indeed important for its location: there is a reason that calcareous fens found in northwestern Minnesota are all found along the beach ridge foreshore/beach slope transition zone. The presence of the beach ridge provides the essential recharge and hydraulic head gradient. Confined aquifers could potentially be a good source of water for calcareous fens: they provide a constant source of water to support the wetland community. Cowdery and others (2008; 2019) found that some beach ridge aquifers dried up. Some beach ridges are big enough or a stable enough water source to support calcareous fens year-round. The beach ridge feeding Sanders Fen has had a fully saturated zone at its base since monitoring began in 1995 (Figure 22). This could be an important distinction: beach ridges that provide a constant source of water are more likely to be associated with calcareous fens, while those that dry up occasionally are associated with intermittently inundated wetlands or no wetlands at all.

The multivariate analysis of landscape factors around northwestern Minnesota's beach ridge fens (Table 9) also supports this landscape model. The hydraulic conductivity of the beach ridge and higher prairie coverage compared to crop coverage on the beach ridge were the only factors that emerged as delineators between calcareous and non-calcareous fens (Table 10). Higher conductivity beach ridges are associated with calcareous fens. These higher conductivities allow water to flow from the ridge to support the calcareous fen at the ridge's base. The association of higher prairie coverage and lower crop coverage on the beach ridge with calcareous fens may highlight the importance of maintaining native prairie coverage on beach ridges above calcareous fens, however the mechanism for this is unknown and bears further research. No other landscape factors emerged as important for delineating between calcareous and non-calcareous fens. This further highlights the importance of the beach ridge aquifers for calcareous fens. Depth to confined aquifer had no impact on occurrence, except corresponded to an increase in depth to confined aquifer at more northerly sites (Factor 3 in Table 9). The lack of confined aquifer influence on beach ridge calcareous fens aligns with the results of the Sanders Fen North and Agassiz-Nelson Fen studies.

The description of the hydrology and landscape setting specifically for calcareous fens along sand beach ridges done in this study supplements and adds to the general description beach seep wetlands by Cowdery and others (2008; 2019). Literature specifically on calcareous fens is largely limited to their vegetation, peat, and chemical compositions. This study adds a detailed study of the sand and gravel beach ridge calcareous fen setting to the hydrologic work on river terrace and morainal calcareous fen settings by Almendinger & Leete (1998b), providing another hydrologic model for calcareous fens found throughout the world.

Conclusion

This study sought to determine the source of water feeding calcareous fens along northwestern Minnesota's beach ridges. Three hypotheses were tested about the source of the water: whether it comes primarily from the surficial beach ridge aquifer system, primarily from confined/deep sources, or from a mix of the two sources. A combination of hydrologic, chemical, isotopic, geophysical, modeling, and statistical techniques were employed to analyze in detail two calcareous fens: Sanders Fen North and Agassiz-Nelson Fen. Water levels below both fens responded as a system with the other surficial wells at both sites, including the beach ridge aquifers. Chemistry and isotopic results at both fens also matched the surficial systems. Electrical resistivity surveys at both sites confirmed the presence of a confining till layer below the sands that extend below both fens. A variety of chemical, isotopic, and hydrological reasons rule out the confined aquifers as sources. Since the beach ridge aquifers rarely dry up, they provide a lasting source of water for the fen. The heterogeneous nature of the glacial substrate below these fens and the landscape association between calcareous fens and beach ridges highlights this important relationship. This subsurface heterogeneity results in a lack of confined aquifer systems as a viable water source for many calcareous fens. The surficial beach ridge aquifers are always found up-gradient of calcareous fens in this region and are key water sources for the calcareous fens.

Future areas of study include better determining the glacial stratigraphy below Agassiz-Nelson Fen to better constrain the locations of both the north and south aquifers. Also, collecting more hydrologic and chemical data from in and below Agassiz-Nelson Fen would help confirm the model of the site's hydrologic system. Further investigations of the role of land use and native prairie coverage on beach ridges and their relation to calcareous fen occurrence also would be important for the preservation of these communities.

The intricate link between calcareous fens and beach ridges in northwestern Minnesota can be applied to other calcareous fens around the world found along the seepage face of sand ridges. The water stored in the sand beach ridges is vital for sustaining a water source for the calcareous fens and the unique suite of flora that they host.

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Appendix A: Well Construction Logs

Minnesota Unique Well Number

244122

County Pennington
Quad Viking SE
Quad ID 395D

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 07/27/1994
Update Date 06/14/2018
Received Date

Well Name	Township	Range	Dir Section	Subsection
DNR OB 57003	153	44	W 6	DDDDDC

Elevation 1105 **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOPSOIL	0	2		
SAND, FINE-MED.	2	5		
SAND, FINE	5	13		
CLAY, PEBBLY	13	17	GRAY	
CLAY, PEBBLY WITH	17	20		

Remarks
DNR OBWELL 57003.

Well Depth 20 ft. **Depth Completed** 13 ft. **Date Well Completed** 05/06/1992

Drill Method Auger (non-specified) **Drill Fluid**

Use monitor well **Status** Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below** 0 ft.

Casing Diameter **Weight**
2 in. To 8 ft. lbs./ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** plastic **Make**

Diameter	Slot/Gauze	Length	Set	
2 in.		5 ft.	8 ft.	13 ft.

Static Water Level
2 ft. land surface Measure 05/06/1992

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite		2 ft.	7 ft.
neat cement		ft.	2 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP 0 Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat pebbly sand/silt/clay Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:12,000) (>15 meters)
System UTM - NAD83, Zone 15, Meters X 250585 Y 5332138
Unique Number Verification Site Plan Input Date 06/12/2017

Angled Drill Hole

Well Contractor

U.S. Geol Survey	M0113	STARK, J.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 244122

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

276844

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 02/05/2016
Update Date 02/05/2016
Received Date

Well Name	Township	Range	Dir Section	Subsection
SP-1	145	45	W 1	BAAAAA

Elevation 1051.5 **Elev. Method** Surveyed

Address

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SURFICAL DEPOSITS	0	6		

Remarks

THIS UNIQUE NUMBER GIVEN TO MN DNR TO TRACK THIS WELL.

Well Depth 6 ft. **Depth Completed** 5.3 ft. **Date Well Completed**

Drill Method **Drill Fluid**

Use environ. bore hole **Status** Sealed

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Open Hole From ft. To ft.

Screen? ☒ **Type** **Make**
Diameter Slot/Gauze Length Set
in. 2 ft. 3.3 ft. 5.3 ft.

Static Water Level

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☐ Yes ☐ No ☒ Not Specified

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☐ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer
Last Strat Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248519 Y 5256423
Unique Number Verification Info/GPS from data Input Date 02/05/2016

Angled Drill Hole

Well Contractor
Minnesota Dept. of Natural MNDNR
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 276844

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

276845

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 02/05/2016
Update Date 02/05/2016
Received Date

Well Name	**Township**	**Range**	**Dir Section**	**Subsection**
SP-2	146	45	W 25	ACCCCD

Elevation 1064.0 **Elev. Method** Surveyed

Address

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SURFICIAL DEPOSITS	0	6		

Remarks
THIS UNIQUE NUMBER GIVEN TO MN DNR TO TRACK THIS WELL.

Well Depth	**Depth Completed**	**Date Well Completed**
6 ft.	5.5 ft.	

Drill Method **Drill Fluid**

Use environ. bore hole **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Open Hole From ft. To ft.

Screen? ☒ **Type** **Make**

Diameter	Slot/Gauze	Length	Set	
in.		2 ft.	3.5 ft.	5.5 ft.

Static Water Level

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☐ Yes ☐ No ☒ Not Specified

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☐ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer
Last Strat Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248653 Y 5258880
Unique Number Verification Info/GPS from data Input Date 02/05/2016

Angled Drill Hole

Well Contractor
Minnesota Dept. of Natural MNDNR
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 276845

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

276847

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 02/05/2016
Update Date 02/05/2016
Received Date

Well Name	Township	Range	Dir Section	Subsection
SP-3R	146	45	W 36	BACCBB

Elevation 1046.9 **Elev. Method** Surveyed

Address

Well Depth 5 ft. **Depth Completed** 4.5 ft. **Date Well Completed** 07/09/2015

Drill Method Bucket Auger **Drill Fluid**

Use environ. bore hole **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
PEAT, MOIST	0	1		
SAND, F-CRS	1	2	DK. BRN	
SAND & GRAVEL, WET	2	5		

Open Hole From ft. To ft.

Screen? ☒ **Type** plastic **Make**

Diameter	Slot/Gauze	Length	Set
2 in.	10	5 ft.	ft. 4.5 ft.

Static Water Level
3.1 ft. land surface Measure 07/09/2015

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☐ Yes ☐ No ☒ Not Specified

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☐ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat sand +larger Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248181 Y 5257764
Unique Number Verification Info/GPS from data Input Date 02/05/2016

Remarks
THIS UNIQUE NUMBER GIVEN TO MN DNR TO TRACK THIS WELL.
WELL CONSTRUCTED BY SUMMIT ENVIROSOLUTIONS.
WELL ON KEITH CHISHOLM PROPERTY.

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Summit Envirosolutions	1305	

Minnesota Well Index Report

276847

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

278583

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 07/11/2018
Update Date 07/11/2018
Received Date

Well Name	Township	Range	Dir Section	Subsection
A-NELSON DEEP 146	45	W	36	BBADDA

Elevation 1043.4 Elev. Method Surveyed

Address

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
FABRIC PEAT	0	2		
SAPRIC PEAT	2	3		
MED-CRS SAND SOME	3	6		

Remarks
THIS UNIQUE NUMBER GIVEN TO DNR-KEYLOR ANDREWS TO TRACK THIS WELL.
SEE DETAILED RECORD IN MGS FILES.
DRILLERS: K. ANDREWS, R. NELSON, & M. WALKER.
SCREEN: JOHNSON DRIVE POINT.

Well Depth 5.75 ft. Depth Completed 5.75 ft. Date Well Completed 06/21/2018
Drill Method Drill Fluid

Use piezometer Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☐ Above/Below 3.25 ft.

Casing Diameter Weight
1.2 in. To 5.3 ft. lbs./ft.

Open Hole From ft. To ft.
Screen? ☒ Type other Make JOHNSON

Diameter	Slot/Gauze	Length	Set	
1.2 in.	10	0.5 ft.	5.2 ft.	5.7 ft.

Static Water Level

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☐ Yes ☐ No ☒ Not Specified

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☐ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☐ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☐ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat sand+larger Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248166 Y 5257921
Unique Number Verification Info/GPS from data Input Date 07/11/2018

Angled Drill Hole

Well Contractor

Minnesota Dept. of Natural	MNDNR	SEE REMARKS
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 278583

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

580065

County Pennington
Quad Viking SE
Quad ID 395D

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 12/01/2000
Update Date 05/08/2019
Received Date

Well Name	Township	Range	Dir Section	Subsection
PYLE, SCOTT	153	44	W 8	DDABBA

Elevation 1118 Elev. Method LiDAR 1m DEM (MNDNR)

Address

C/W RR 5 BOX 115-B THIEF RIVER FALLS MN 56701

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
SOIL	0	1	BLACK	SOFT
SAND	1	6	RED	SOFT
CLAY	6	75	GRAY	SOFT
GRAVEL & CLAY	75	220	GRAY	HARD
SAND	220	224	RED	SOFT

Remarks

DRILLING FLUID: SUPER GEL X

Well Depth	Depth Completed	Date Well Completed
224 ft.	224 ft.	10/09/1998

Drill Method Non-specified Rotary Drill Fluid Other

Use domestic Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight Hole Diameter
4 in. To 222 ft. lbs./ft. 6.5 in. To 224 ft.

Open Hole From ft. To ft.

Screen? ☒ Type stainless Make JOHNSON

Diameter	Slot/Gauze	Length	Set	
4 in.	30	4 ft.	220 ft.	224 ft.

Static Water Level

63 ft. land surface Measure 10/06/1998

Pumping Level (below land surface)

75 ft. 0.5 hrs. Pumping at 10 g.p.m.

Wellhead Completion

Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
high solids bentonite	3 Sacks	0 ft.	60 ft.

Nearest Known Source of Contamination

78 feet West Direction Barnyard Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned

Does property have any not in use and not sealed well(s)? ☒ Yes ☐ No

Variance

Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous

First Bedrock Aquifer Quat. buried
Last Strat sand-red Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method GPS SA Off (averaged) (15 meters)
System UTM - NAD83, Zone 15, Meters X 252015 Y 5330811
Unique Number Verification Plat Book Input Date 05/06/2019

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Erickson D. Well Co.	57261	ERICKSON, D.

Minnesota Well Index Report 580065

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

791080

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 12/12/2012
Update Date 02/11/2016
Received Date 10/15/2012

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	145	45	W 1	ADAADC

Elevation 1059.9 **Elev. Method** Surveyed

Address

Well 340TH AV GARY MN 56545
Contact 2578 340TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOPSOIL	0	3	BLACK	SOFT
CLAY	3	20	BROWN	HARD
CLAY	20	34	GRAY	HARD
SAND	34	38	GRAY	MEDIUM
CLAY	38	60	GRAY	HARD
(SANDY) CLAY ROCKS	60	70	GRAY	HARD
SAND (SHARP) ROCK	70	101	VARIED	HARD

Remarks
DRILLERS: DON KLIMEN & JUSTIN KLIMEK.
PRODUCTION WELL 5.

Well Depth 101 ft. **Depth Completed** 101 ft. **Date Well Completed** 09/13/2012
Drill Method Non-specified Rotary **Drill Fluid** Bentonite

Use irrigation **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Casing Diameter **Weight** **Hole Diameter**
12 in. To 71 ft. 50 lbs./ft. 17. in. To 101 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** stainless **Make** JOHNSON

Diameter	Slot/Gauze	Length	Set
12 in.	70	30 ft.	71 ft. 101 ft.

Static Water Level
1 ft. land surface Measure 09/13/2012

Pumping Level (below land surface)
71 ft. 6 hrs. Pumping at 400 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☐ Casing Protection ☒ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
other		0 ft.	50 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☐ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand+larger Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 249288 Y 5255918
Unique Number Verification Info/GPS from data Input Date 02/11/2016

Angled Drill Hole

Well Contractor
Klimek Bros. Well Drilling, 1864 SEE REMARKS
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 791080

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

801345

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 03/31/2014
Update Date 02/11/2016
Received Date 02/19/2014

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM	146	45	W 25	ACCCCD

Elevation 1064.7 **Elev. Method** Surveyed

Address

Well 300TH AV GARY MN 56545
Contact 2578 340TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOPSOIL	0	2	BLACK	SOFT
CLAY (SANDY)	2	10	BROWN	MEDIUM
CLAY	10	78	GRAY	HARD
SAND SHARP	78	102	GRAY	MEDIUM

Remarks
THIS IS THE SECOND WELL RECONSTRUCTED IN THE SAME BOREHOLE. THE FISRT WELL HAS UNIQUE NO. 276843 AND WAS DRILLED 4-22-2013. NORTH MONITORING WELL.

Well Depth 102 ft. **Depth Completed** 102 ft. **Date Well Completed** 06/22/2015
Drill Method Non-specified Rotary **Drill Fluid** Bentonite

Use environ. bore hole **Status** Active

Well Hydrofractured? **Yes** ☐ **No** ☐ **From** **To**

Casing Type Single casing **Joint**
Drive Shoe? **Yes** ☐ **No** ☐ **Above/Below**

Casing Diameter **Weight** **Hole Diameter**
2 in. To 82 ft. 1 lbs./ft. 6.2 in. To 102 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** plastic **Make** JET STREAM

Diameter	Slot/Gauze	Length	Set	
2 in.	30	20 ft.	82 ft.	102 ft.

Static Water Level
16 ft. land surface Measure 06/22/2015

Pumping Level (below land surface)
82 ft. 2 hrs. Pumping at 15 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
neat cement	1	Sacks	ft.	ft.
bentonite	12	Sacks	ft. 72	ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248651 Y 5258877
Unique Number Verification Info/GPS from data Input Date 08/18/2014

Angled Drill Hole

Well Contractor

Klimek Bros. Well Drilling,	1864	KLIMEK, D.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 801345 Printed on 02/12/2020 HE-01205-15

Minnesota Unique Well Number

801346

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 03/31/2014
Update Date 02/11/2016
Received Date 02/19/2014

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	145	45	W 1	BAAAAA

Elevation 1051.8 Elev. Method Surveyed

Address

Well 280TH AV GARY MN 56545
Contact 2578 340TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOPSOIL	0	2	BLACK	SOFT
SANDY (CLAY)	2	8	BROWN	MEDIUM
CLAY	8	10	BROWN	MEDIUM
CLAY	10	51	GRAY	HARD
SAND	51	55	GRAY	MEDIUM
CLAY	55	60	GRAY	HARD
SAND (FINE)	60	74	GRAY	MEDIUM
SAND	74	86	GRAY	MEDIUM
	86			

Remarks

TWO OTHER WELLS WERE DRILLED UNDER THIS UNIQUE NUMBER THEY NOW HAVE THEIR OWN UNIQUE NUMBERS. 276841 WAS DRILLED 4-12-2013 AND SEALED 6-15-2015 BY 1864.
276841 WAS DRILLED 10-14-2015 IT FAILED AND 801346 WAS RECONSTRUCTED IN THE SAME HOLE.
SOUTH MONTORIN WELL REPLACEMENT.

Well Depth 86 ft. **Depth Completed** 86 ft. **Date Well Completed** 06/22/2015

Drill Method Non-specified Rotary Drill Fluid Bentonite

Use environ. bore hole Status Active

Well Hydrofractured? Yes ☐ No ☐ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☐ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 76 ft. 1.1 lbs./ft. 6.2 in. To 86 ft.

Open Hole From ft. To ft.

Screen? ☒ Type plastic Make JET STREAM

Diameter	Slot/Gauze	Length	Set	
2 in.	10	10 ft.	76 ft.	86 ft.

Static Water Level
8 ft. land surface Measure 06/22/2015

Pumping Level (below land surface)
76 ft. 2 hrs. Pumping at 10 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
neat cement	16 Sacks	ft.	66 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248520 Y 5256428
Unique Number Verification Info/GPS from data Input Date 08/18/2014

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Klimek Bros. Well Drilling,	1864	KLIMEK, D.

Minnesota Well Index Report 801346 Printed on 02/12/2020 HE-01205-15

Minnesota Unique Well Number

804872

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 103I

Entry Date 12/30/2014
Update Date 01/15/2016
Received Date 06/29/2015

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	145	44	W 6	BDBCAC

Elevation 1069.6 **Elev. Method** Surveyed

Address

Contact 2578 340TH ST GARY MN 56545
Well 350TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOPSOIL	0	1	BLACK	SOFT
CLAY	1	9	BROWN	MEDIUM
CLAY	9	50	GRAY	HARD
SAND ROCK (SHARP)	50	66	VARIED	MEDIUM

Remarks

Well Depth 66 ft. **Depth Completed** 66 ft. **Date Well Completed** 06/22/2015

Drill Method Non-specified Rotary **Drill Fluid** Bentonite

Use environ. bore hole **Status** Active

Well Hydrofractured? Yes ☐ No ☐ **From** **To**

Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Casing Diameter **Weight** **Hole Diameter**
2 in. To 59 ft. 1 lbs./ft. 6.2 in. To 66 ft.

Open Hole From ft. To ft.
Screen? ☒ **Type** plastic **Make** JET STREAM

Diameter	Slot/Gauze	Length	Set	
2 in.	10	5 ft.	59 ft.	66 ft.

Static Water Level
10 ft. land surface Measure 06/22/2015

Pumping Level (below land surface)
59 ft. 2 hrs. Pumping at 10 g.p.m.

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount		From	To
bentonite	9	Sacks	ft. 49	ft.
neat cement	1	Sacks	ft.	ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☒ Yes ☐ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand+larger Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 249766 Y 5255850
Unique Number Verification Info/GPS from data Input Date 12/30/2014

Angled Drill Hole

Well Contractor
Klimek Bros. Well Drilling, 1864 KLIMEK, D.
Licensee Business Lic. or Reg. No. Name of Driller

Minnesota Well Index Report 804872 Printed on 07/15/2019 HE-01205-15

Minnesota Unique Well Number

806835

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 11/12/2014
Update Date 02/11/2016
Received Date 10/02/2014

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	145	45	W 1	BAAAAD

Elevation 1051.4 Elev. Method Surveyed

Address

Contact 2489 350TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL-FINE MED.	0	2	BLK/BRN	MEDIUM
MED. COARSE SAND	2	6	BROWN	MEDIUM
MED. COARSE SAND	6	8	BRN/GRY	HARD
CLAY	8	14	GRAY	HARD
CLAY	14	26	GRAY	HARD
CLAY	26	28	GRAY	MEDIUM
CLAY/SANDY SILT	28	30	GRAY	MEDIUM
SANDY SILT	30	36	GRAY	HARD
FINE SAND	36	44	GRAY	HARD

Remarks
CASING PROTECTION: 6" PROTOP.
SMW-1.
SHALLOW MONITORING WELL 1.

Well Depth 44 ft. Depth Completed 43 ft. Date Well Completed 08/07/2014
Drill Method Auger (non-specified) Drill Fluid

Use piezometer Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 38 ft. lbs./ft. 8.2 in. To ft.

Open Hole From ft. To ft.
Screen? ☒ Type plastic Make TIMCO

Diameter	Slot/Gauze	Length	Set	
2 in.	10	5 ft.	38 ft.	43 ft.

Static Water Level
7 ft. land surface Measure 08/07/2014

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	3 Sacks	4 ft.	36 ft.
neat cement	2 Sacks	ft.	4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. buried
Last Strat sand-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:24,000) (15 meters or
System UTM - NAD83, Zone 15, Meters X 248519 Y 5256421
Unique Number Verification Info/GPS from data Input Date 12/30/2014

Angled Drill Hole

Well Contractor

Thein Well Co., Inc.	1337	WIEBER, A.
Licensee Business	Lic. or Reg. No.	Name of Driller

Minnesota Well Index Report 806835

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

806836

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH

WELL AND BORING REPORT

Minnesota Statutes Chapter 1031

Entry Date 11/12/2014
Update Date 02/11/2016
Received Date 10/02/2014

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	146	45	W 25	ACCCCD

Elevation 1063.8 **Elev. Method** Surveyed

Address

Contact 2489 380TH ST GARY MN 56454

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL FINE-MED.	0	2	BLK/BRN	SOFT
FINE MED. SAND	2	4	BRN/WHT	MEDIUM
FINE MED. SAND-SILTY	4	6	BROWN	MEDIUM
SILTY CLAY	6	8	GRAY	MEDIUM
SILTY CLAY	8	16	GRAY	HARD

Remarks
CASING PROTECTION: 6" PROTOP.
SMW-2.
SOUTH MW-2.

Well Depth 16 ft. **Depth Completed** 16 ft. **Date Well Completed** 08/06/2014

Drill Method Auger (non-specified) **Drill Fluid**

Use piezometer **Status** Active

Well Hydrofractured? Yes ☐ No ☒ **From** **To**

Casing Type Single casing **Joint**
Drive Shoe? Yes ☐ No ☐ **Above/Below**

Casing Diameter **Weight** **Hole Diameter**
2 in. To 11 ft. lbs./ft. 8.2 in. To ft.

Open Hole From ft. To ft.

Screen? ☒ **Type** plastic **Make** TIMCO

Diameter	Slot/Gauze	Length	Set	
2 in.	10	5 ft.	11 ft.	16 ft.

Static Water Level
8 ft. land surface Measure 08/06/2014

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	0.25 Sacks	4 ft.	10 ft.
neat cement	2 Sacks	ft.	4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat silt+clay-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:12,000) (>15 meters)
System UTM - NAD83, Zone 15, Meters X 248652 Y 5258881
Unique Number Verification Info/GPS from data Input Date 12/30/2014

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Thein Well Co., Inc.	1337	WIEBER, A.

Minnesota Well Index Report 806836

Printed on 02/12/2020
HE-01205-15

Minnesota Unique Well Number

806837

County Norman
Quad Flaming
Quad ID 308A

MINNESOTA DEPARTMENT OF HEALTH
WELL AND BORING REPORT
Minnesota Statutes Chapter 1031

Entry Date 11/12/2014
Update Date 02/11/2016
Received Date 10/02/2014

Well Name	Township	Range	Dir Section	Subsection
CHISHOLM,	146	45	W 25	ACCCCD

Elevation 1064.4 Elev. Method LiDAR 1m DEM (MNDNR)

Address

Contact 2489 380TH ST GARY MN 56545

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
TOP SOIL-FIRM MED.	0	2	BLK/BRN	SOFT
FINE MED. SAND	2	4	BRN/WHT	MEDIUM
FINE MED. SAND SILTY	4	6	BROWN	MEDIUM
SILTY SAND	6	8	GRAY	MEDIUM
SILTY SAND	8	16	GRAY	HARD
FINE SAND	16	26	GRAY	HARD
FINE SAND-SILTY CLAY	26	28	GRAY	HARD
FINE SAND-SILT	28	32	GRAY	HARD
FINE SAND	32	36	GRAY	HARD
FINE SAND-CLAY	36	38	GRAY	HARD

Remarks
CASING PROTECTION: 6" PROTOP.
SMW-3.
SOUTH MW-3.

Well Depth 38 ft. Depth Completed 38 ft. Date Well Completed 08/06/2014
Drill Method Auger (non-specified) Drill Fluid

Use piezometer Status Active

Well Hydrofractured? Yes ☐ No ☒ From To

Casing Type Single casing Joint
Drive Shoe? Yes ☐ No ☒ Above/Below

Casing Diameter Weight Hole Diameter
2 in. To 33 ft. lbs./ft. 8.2 in. To ft.

Open Hole From ft. To ft.
Screen? ☒ Type plastic Make TIMCO

Diameter	Slot/Gauze	Length	Set	
2 in.	10	5 ft.	33 ft.	38 ft.

Static Water Level
7 ft. land surface Measure 08/06/2014

Pumping Level (below land surface)

Wellhead Completion
Pitless adapter manufacturer Model
☒ Casing Protection ☐ 12 in. above grade
☐ At-grade (Environmental Wells and Borings ONLY)

Grouting Information Well Grouted? ☒ Yes ☐ No ☐ Not Specified

Material	Amount	From	To
bentonite	3 Sacks	4 ft.	32 ft.
neat cement	2 Sacks	ft.	4 ft.

Nearest Known Source of Contamination
feet Direction Type
Well disinfected upon completion? ☐ Yes ☒ No

Pump ☒ Not Installed Date Installed
Manufacturer's name
Model Number HP Volt
Length of drop pipe ft Capacity g.p. Typ

Abandoned
Does property have any not in use and not sealed well(s)? ☐ Yes ☒ No

Variance
Was a variance granted from the MDH for this well? ☐ Yes ☒ No

Miscellaneous
First Bedrock Aquifer Quat. Water
Last Strat clay+sand-gray Depth to Bedrock ft
Located by Minnesota Geological Survey
Locate Method Digitization (Screen) - Map (1:12,000) (>15 meters)
System UTM - NAD83, Zone 15, Meters X 248654 Y 5258881
Unique Number Verification Info/GPS from data Input Date 12/30/2014

Angled Drill Hole

Well Contractor

Licensee Business	Lic. or Reg. No.	Name of Driller
Thein Well Co., Inc.	1337	WIEBER, A.

Minnesota Well Index Report 806837

Printed on 02/12/2020
HE-01205-15

Appendix B: Full Chemistry and Isotopes Results

July Sampling				*Sonde-Measured Properties*	
	Sample Date	**Sample Time**	**Amount Flushed**	**Sonde Measurement Location**	**Water Temp**
					°C
LOD					
Sanders Fen					
580065	7/29/2019	9:10:00 PM	3 well vol	in cup	9.68
580065 LD					
SC0	7/29/2019	7:25:00 PM	3 well vol	in cup	14.06
SC1	7/29/2019	7:00:00 PM	dry+more	in hole	14.1
SC4	7/29/2019	6:45:00 PM	dry+more	in hole	13.91
SC7D	7/29/2019	4:55:00 PM	dry+more	in hole	10.05
SC7S	7/29/2019	6:05:00 PM	dry+more	in hole	14.51
SC9	7/29/2019	4:20:00 PM	dry+more	in cup	19.21
SC9 LD					
SCF	7/29/2019	5:45:00 PM	3 well vol	in hole	20.36
SN0	7/29/2019	1:00:00 PM	3 well vol	in hole	14.66
SN2	7/29/2019	7:45:00 PM	dry+more	in hole	12.7
SN6D	7/29/2019	3:22:00 PM	dry+more	in hole	9.15
SN6S	7/29/2019	3:45:00 PM	dry+more	in hole	10.65
Agassiz-Nelson Fen					
804872	7/30/2019	7:25:00 PM	3 well vol	in hole	8.47
SMW1	7/30/2019	5:45:00 PM	3 well vol	in hole after 30 min refill	9.99
SP1	7/30/2019	4:40:00 PM	dry+more	in cup	18.58
NMW	7/30/2019	9:05:00 PM	3 well vol	in hole	8.89
NMW FD	7/30/2019	9:10:00 PM			
SMW3	7/30/2019	8:25:00 PM	3 well vol	in hole	8.03
SMW2	7/30/2019	9:20:00 PM	3 well vol	in hole	9.19
SP2	7/30/2019	8:45:00 PM	3 well vol	in cup	16.32
SP2 LD					
NS0	7/30/2019	3:00:00 PM	3 well vol	in hole	13.62
NS3	7/30/2019	12:35:00 PM	dry+more	in cup	21.79
NSF	7/30/2019	11:30:00 AM	3 well vol	in hole	17.35
NC0	7/30/2019	2:25:00 PM	3 well vol	in hole	13.32
NC0 FD	7/30/2019	2:30:00 PM			
NCSP3	7/30/2019	12:15:00 PM	3 well vol	in hole	16.06
NCF	7/30/2019	11:05:00 AM	3 well vol	in hole	21.26
NN0	7/30/2019	2:00:00 PM	3 well vol	in hole	17.15
NN3	7/30/2019	10:35:00 AM	dry+more	in cup	17.7
NNF	7/30/2019	10:00:00 AM	3 well vol	in hole	17.71
NNF LD					

FB = Field Blank
FD = Field Duplicate
LD = Lab Duplicate
LOD = Detection Limit

*Duplicates averaged for plotting and analyses

July Sampling						*Alkalinity*
	Specific Conductance	**pH**	**DO**	**DO**	**Oxid-Red Potential**	Alkalinity 1
	µS/cm		%saturation	mg/L	mV	mg/L CaCO3
LOD						
Sanders Fen						
580065	666.3	7.52	10	1.09	183	286
580065 LD						
SC0	463.6	7.08	n	n	282	240
SC1	436	6.97	58.1	5.74	258	226
SC4	470.8	6.78	10.7	1.06	166	242
SC7D	451.3	6.93	31.6	3.42	113	251
SC7S	457	6.9	30.3	2.97	59	245
SC9	469.6	7.32	n	n	344	262
SC9 LD						
SCF	628.5	6.68	30	2.6	68	343
SN0	436.7	6.74	29.3	2.86	296	228
SN2	447.8	6.9	22.6	2.3	162	226
SN6D	520.6	6.94	12.8	1.42	222	256
SN6S	782.9	6.68	58.1	6.21	105	417
Agassiz-Nelson Fen						
804872	635.3	7.29	3.5	0.39	143	297
SMW1	930.2	7.19	69.8	7.58	302	275
SP1	776.2	6.86	n	n	134	384
NMW	556.7	7.12	0.7	0.08	31	317
NMW FD						
SMW3	554.9	7.13	1.1	0.13	134	286
SMW2	659	7	4.6	0.51	117	284
SP2	652.9	6.9	28.1	2.65	233	237
SP2 LD						
NS0	837.1	6.62	17.7	1.77	298	437
NS3	667	6.96	n	n	201	309
NSF	680.5	6.63	0.9	0.08	11	324
NC0	563.7	6.88	57.1	5.74	283	234
NC0 FD						
NCSP3	591.4	6.87	5	0.47	179	273
NCF	492.2	6.66	17.4	1.48	84	364
NN0	631.8	6.8	36.7	3.4	267	245
NN3	708.9	7.11	n	n	272	271
NNF	725.1	6.59	20.7	1.9	51	350
NNF LD						

FB = Field Blank
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LD = Lab Duplicate
LOD = Detection Limit

July Sampling					*Cations/Metals*	
	Alkalinity 2	Alkalinity 3	**Alkalinity Avg**	Alkalinity Standard Dev	**Al**	**As**
	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	mg/L	mg/L
LOD					<0.011	<0.021
Sanders Fen						
580065	283	290	286	3.5	0.039	<0.021
580065 LD						
SC0	236	242	239	3.1	0.079	<0.021
SC1	218	223	222	4.0	0.069	<0.021
SC4	240	236	239	3.1	0.064	<0.021
SC7D	256	259	255	4.0	0.073	<0.021
SC7S	249	251	248	3.1	0.078	<0.021
SC9	251	247	253	7.8	0.085	<0.021
SC9 LD					0.094	<0.021
SCF	337	333	338	5.0	0.081	<0.021
SN0	224	231	228	3.5	0.082	<0.021
SN2	227	230	228	2.1	0.080	<0.021
SN6D	266	255	259	6.1	0.095	<0.021
SN6S	449	426	431	16.5	0.067	<0.021
Agassiz-Nelson Fen						
804872	296	304	299	4.4	0.081	0.030
SMW1	272	271	273	2.1	0.071	<0.021
SP1	383	380	382	2.1	0.066	<0.021
NMW	319	321	319	2.0	0.058	0.024
NMW FD					0.058	0.026
SMW3	299	296	294	6.8	0.070	<0.021
SMW2	296	290	290	6.0	0.101	<0.021
SP2	235	241	238	3.1	0.062	<0.021
SP2 LD						
NS0	440	452	443	7.9	0.055	<0.021
NS3	296	303	303	6.5	0.087	<0.021
NSF	321	322	322	1.5	0.068	<0.021
NC0	231	232	232	1.5	0.063	<0.021
NC0 FD					0.071	<0.021
NCSP3	269	273	272	2.3	0.068	<0.021
NCF	364	359	362	2.9	0.077	<0.021
NN0	236	245	242	5.2	0.067	<0.021
NN3	276	272	273	2.6	0.079	<0.021
NNF	347	354	350	3.5	0.064	<0.021
NNF LD						

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LOD = Detection Limit

July Sampling

	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.016	<0.003	<0.001	<0.124	<0.003	<0.003	<0.002	<0.003	<0.002
Sanders Fen									
580065	0.339	0.082	<0.001	30.635	<0.003	<0.003	<0.002	<0.003	0.426
580065 LD									
SC0	0.023	0.060	<0.001	74.499	<0.003	<0.003	<0.002	<0.003	0.011
SC1	0.028	0.039	<0.001	68.363	<0.003	<0.003	<0.002	<0.003	0.020
SC4	0.025	0.036	<0.001	73.543	<0.003	<0.003	<0.002	<0.003	0.233
SC7D	0.022	0.056	<0.001	72.928	<0.003	<0.003	<0.002	<0.003	0.107
SC7S	0.032	0.060	<0.001	73.491	<0.003	<0.003	<0.002	<0.003	0.023
SC9	0.025	0.066	<0.001	69.205	<0.003	<0.003	<0.002	0.005	0.016
SC9 LD	0.060	0.068	<0.001	68.653	<0.003	<0.003	<0.002	0.005	0.011
SCF	<0.016	0.106	<0.001	104.899	<0.003	<0.003	<0.002	<0.003	0.924
SN0	<0.016	0.049	<0.001	73.401	<0.003	<0.003	<0.002	<0.003	<0.002
SN2	<0.016	0.039	<0.001	74.069	<0.003	<0.003	<0.002	<0.003	0.065
SN6D	<0.016	0.064	<0.001	81.125	<0.003	<0.003	<0.002	<0.003	0.110
SN6S	<0.016	0.114	<0.001	137.677	<0.003	<0.003	<0.002	<0.003	0.033
Agassiz-Nelson Fen									
804872	0.379	0.044	<0.001	49.274	<0.003	<0.003	<0.002	<0.003	0.346
SMW1	0.518	0.094	<0.001	84.142	<0.003	<0.003	<0.002	<0.003	0.010
SP1	<0.016	0.086	<0.001	143.929	<0.003	0.004	<0.002	<0.003	1.496
NMW	0.109	0.121	<0.001	102.596	<0.003	<0.003	<0.002	<0.003	1.656
NMW FD	0.117	0.123	<0.001	104.847	<0.003	<0.003	<0.002	<0.003	1.685
SMW3	0.073	0.386	<0.001	89.739	<0.003	<0.003	<0.002	<0.003	0.849
SMW2	<0.016	0.386	<0.001	115.211	<0.003	<0.003	<0.002	<0.003	0.548
SP2	<0.016	0.096	<0.001	109.536	<0.003	<0.003	<0.002	<0.003	0.148
SP2 LD									
NS0	0.038	0.057	<0.001	140.063	<0.003	<0.003	<0.002	<0.003	<0.002
NS3	0.036	0.083	<0.001	110.201	<0.003	0.005	<0.002	<0.003	0.228
NSF	0.035	0.058	<0.001	107.792	<0.003	<0.003	<0.002	<0.003	1.166
NC0	<0.016	0.040	<0.001	91.567	<0.003	<0.003	<0.002	<0.003	<0.002
NC0 FD	<0.016	0.040	<0.001	89.600	<0.003	<0.003	<0.002	<0.003	0.002
NCSP3	<0.016	0.032	<0.001	97.643	<0.003	<0.003	<0.002	0.004	0.024
NCF	<0.016	0.071	<0.001	134.801	<0.003	<0.003	<0.002	<0.003	1.554
NN0	<0.016	0.054	<0.001	110.080	<0.003	<0.003	<0.002	<0.003	0.003
NN3	<0.016	0.081	<0.001	124.096	<0.003	<0.003	<0.002	0.003	0.025
NNF	0.035	0.059	<0.001	117.671	<0.003	<0.003	<0.002	<0.003	0.606
NNF LD									

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July Sampling

	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.094	<0.005	<0.007	<0.001	<0.002	<0.030	<0.004	<0.009	<0.008
Sanders Fen									
580065	2.717	0.022	27.869	0.012	0.002	101.509	<0.004	0.220	<0.008
580065 LD									
SC0	2.754	0.009	27.714	0.043	<0.002	1.516	<0.004	<0.009	<0.008
SC1	1.848	0.008	22.638	0.024	<0.002	1.275	<0.004	<0.009	<0.008
SC4	1.679	0.006	25.352	0.063	<0.002	1.364	<0.004	<0.009	<0.008
SC7D	2.274	0.007	25.281	0.022	<0.002	1.577	<0.004	0.010	<0.008
SC7S	2.408	0.007	25.284	0.015	<0.002	1.596	<0.004	0.016	<0.008
SC9	2.940	0.011	25.408	0.180	0.003	2.449	<0.004	0.016	<0.008
SC9 LD	3.340	0.014	25.025	0.189	0.002	2.468	0.008	0.027	<0.008
SCF	4.855	0.009	32.618	0.357	<0.002	1.584	<0.004	0.036	<0.008
SN0	2.677	0.008	23.912	0.107	<0.002	1.397	<0.004	<0.009	<0.008
SN2	2.093	0.006	20.870	0.376	<0.002	1.307	<0.004	<0.009	<0.008
SN6D	2.806	0.010	27.085	0.658	<0.002	1.810	<0.004	0.010	<0.008
SN6S	4.103	0.011	34.137	0.091	<0.002	2.386	<0.004	0.050	<0.008
Agassiz-Nelson Fen									
804872	5.967	0.042	24.544	0.111	0.012	87.131	<0.004	0.125	<0.008
SMW1	8.253	0.037	28.899	0.413	0.020	112.886	<0.004	0.047	<0.008
SP1	1.277	0.006	31.321	0.407	<0.002	2.996	0.015	<0.009	<0.008
NMW	4.335	0.044	38.247	0.166	0.004	23.166	<0.004	0.063	<0.008
NMW FD	4.490	0.044	38.797	0.169	0.004	23.564	<0.004	0.063	<0.008
SMW3	5.067	0.031	27.692	0.103	0.003	12.809	<0.004	0.070	<0.008
SMW2	4.917	0.015	32.284	0.311	0.005	24.668	<0.004	0.035	<0.008
SP2	0.258	0.008	27.166	0.017	<0.002	3.512	<0.004	<0.009	<0.008
SP2 LD									
NS0	1.294	0.008	49.153	0.006	<0.002	1.942	<0.004	0.010	<0.008
NS3	1.885	0.006	36.576	1.767	<0.002	2.539	0.006	0.017	<0.008
NSF	0.404	0.006	36.169	0.151	<0.002	2.428	<0.004	0.013	<0.008
NC0	1.458	0.008	29.970	0.020	<0.002	4.713	<0.004	0.010	<0.008
NC0 FD	1.516	0.009	28.540	0.028	<0.002	4.482	<0.004	<0.009	<0.008
NCSP3	1.139	0.008	31.326	0.095	<0.002	3.742	<0.004	0.012	<0.008
NCF	0.759	0.009	40.501	0.219	<0.002	4.611	<0.004	0.034	<0.008
NN0	1.048	<0.005	31.083	0.038	<0.002	5.111	<0.004	<0.009	<0.008
NN3	4.014	0.007	34.009	0.218	<0.002	4.976	<0.004	0.116	<0.008
NNF	0.398	0.008	42.883	0.098	<0.002	5.936	<0.004	0.016	<0.008
NNF LD									

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July Sampling								*Anions*
	Rb	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**	**HCO3 (from Alk)**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.004	<0.020	<0.005	<0.003	<0.001	<0.001	<0.001	< 2.5
Sanders Fen								
580065	<0.004	15.006	11.531	0.378	0.002	<0.001	0.007	349
580065 LD								
SC0	<0.004	2.245	10.276	0.094	0.002	<0.001	0.008	292
SC1	<0.004	1.221	10.091	0.079	0.002	<0.001	0.010	271
SC4	<0.004	1.739	9.785	0.086	0.002	0.002	0.008	292
SC7D	<0.004	1.977	11.206	0.101	0.002	0.002	0.012	312
SC7S	<0.004	1.133	12.058	0.105	0.002	<0.001	0.009	303
SC9	<0.004	3.260	11.068	0.107	0.002	<0.001	0.015	309
SC9 LD	<0.004	3.324	11.543	0.111	0.005	<0.001	0.017	
SCF	<0.004	0.698	21.113	0.145	0.002	<0.001	0.012	412
SN0	<0.004	2.142	11.008	0.086	0.002	0.001	0.007	278
SN2	<0.004	1.656	13.273	0.080	0.002	<0.001	0.012	278
SN6D	<0.004	3.037	13.732	0.118	0.002	<0.001	0.022	316
SN6S	<0.004	1.327	14.293	0.165	0.002	<0.001	0.014	525
Agassiz-Nelson Fen								
804872	<0.004	19.988	16.942	0.350	0.002	<0.001	0.016	365
SMW1	<0.004	88.639	13.256	0.535	0.002	0.010	0.012	333
SP1	<0.004	5.807	7.113	0.162	0.001	<0.001	6.587	466
NMW	<0.004	23.726	17.103	0.490	0.002	<0.001	0.008	389
NMW FD	<0.004	23.852	17.331	0.499	0.002	<0.001	0.009	
SMW3	<0.004	4.084	17.308	0.678	0.002	<0.001	0.010	358
SMW2	<0.004	27.920	15.342	0.489	0.003	0.003	0.017	354
SP2	<0.004	9.422	11.774	0.182	0.002	<0.001	2.479	290
SP2 LD								
NS0	<0.004	2.646	10.218	0.186	0.001	<0.001	0.006	540
NS3	<0.004	5.952	15.405	0.147	0.002	0.001	0.014	369
NSF	<0.004	0.754	12.168	0.144	0.002	<0.001	0.009	393
NC0	<0.004	13.179	11.710	0.157	0.002	<0.001	0.008	283
NC0 FD	<0.004	12.612	11.839	0.152	0.002	<0.001	0.009	
NCSP3	<0.004	7.439	12.372	0.146	0.002	<0.001	0.013	331
NCF	<0.004	12.348	15.987	0.175	0.002	<0.001	0.020	442
NN0	<0.004	13.730	12.429	0.150	0.002	<0.001	0.009	295
NN3	<0.004	12.924	14.642	0.160	0.002	0.001	0.106	333
NNF	<0.004	9.510	15.198	0.151	0.001	<0.001	0.019	427
NNF LD								

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July Sampling

	Bromide	Chloride	Fluoride	Nitrate-N	Nitrite-N	Phosphate-P	Sulfate-S
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sanders Fen							
580065	< 0.1	23.6	< 0.1	< 0.1	< 0.1	< 0.1	17.8
580065 LD	< 0.1	23.5	< 0.1	< 0.1	< 0.1	< 0.1	18.2
SC0	< 0.1	1.4	< 0.1	0.4	< 0.1	< 0.1	1.7
SC1	< 0.1	1.2	< 0.1	0.2	< 0.1	< 0.1	1.4
SC4	< 0.1	1.3	< 0.1	< 0.1	< 0.1	< 0.1	1.5
SC7D	< 0.1	1.4	< 0.1	0.1	< 0.1	< 0.1	1.6
SC7S	< 0.1	1.4	< 0.1	< 0.1	< 0.1	< 0.1	0.3
SC9	< 0.1	2.1	< 0.1	0.1	< 0.1	< 0.1	2.8
SC9 LD	< 0.1	2.1	< 0.1	0.1	< 0.1	< 0.1	2.8
SCF	< 0.1	2.2	< 0.1	< 0.1	< 0.1	< 0.1	0.2
SN0	< 0.1	1.2	< 0.1	0.1	< 0.1	< 0.1	1.7
SN2	< 0.1	1.4	< 0.1	< 0.1	< 0.1	< 0.1	1.2
SN6D	< 0.1	1.6	< 0.1	0.1	< 0.1	< 0.1	2.6
SN6S	< 0.1	1.1	< 0.1	< 0.1	< 0.1	< 0.1	0.5
Agassiz-Nelson Fen							
804872	< 0.1	5.6	< 0.1	< 0.1	< 0.1	< 0.1	19.2
SMW1	< 0.1	7.8	< 0.1	< 0.1	< 0.1	< 0.1	86.3
SP1	< 0.1	21.5	< 0.1	1	< 0.1	< 0.1	5
NMW	< 0.1	4.2	< 0.1	< 0.1	< 0.1	< 0.1	22.4
NMW FD	< 0.1	4.3	< 0.1	< 0.1	< 0.1	< 0.1	22.7
SMW3	< 0.1	0.8	< 0.1	< 0.1	< 0.1	< 0.1	3.9
SMW2	< 0.1	19.1	< 0.1	< 0.1	< 0.1	< 0.1	27.4
SP2	< 0.1	14.2	< 0.1	13.9	< 0.1	< 0.1	6.8
SP2 LD	< 0.1	14.1	< 0.1	14.2	< 0.1	< 0.1	6.8
NS0	< 0.1	10.4	< 0.1	1.5	< 0.1	< 0.1	2.3
NS3	< 0.1	13	< 0.1	1.4	< 0.1	< 0.1	5.3
NSF	< 0.1	18.9	< 0.1	< 0.1	< 0.1	< 0.1	0.3
NC0	< 0.1	18	< 0.1	5.6	< 0.1	< 0.1	12
NC0 FD	< 0.1	15.6	< 0.1	4.9	< 0.1	< 0.1	10.7
NCSP3	< 0.1	16.8	< 0.1	< 0.1	< 0.1	< 0.1	6.5
NCF	< 0.1	31.7	< 0.1	< 0.1	< 0.1	< 0.1	3.5
NN0	< 0.1	21.4	< 0.1	5.8	< 0.1	< 0.1	12.5
NN3	< 0.1	24.8	< 0.1	4.2	< 0.1	< 0.1	10.7
NNF	< 0.1	24.2	< 0.1	< 0.1	< 0.1	< 0.1	2
NNF LD	< 0.1	24.2	< 0.1	< 0.1	< 0.1	< 0.1	2

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LOD = Detection Limit

July Sampling	*Stable Isotopes*			
	δ¹⁸O	**δ²H**	**δ¹⁸O Precision**	**δ²H Precision**
	per mil	per mil	per mil	per mil
LOD				
Sanders Fen				
580065	-15.36	-114.36	0.01	0.13
580065 LD				
SC0	-12.27	-88.45	0.02	0.13
SC1	-13.16	-95.24	0.05	0.33
SC4	-12.50	-89.62	0.02	0.25
SC7D	-11.60	-82.87	0.05	0.54
SC7S	-11.92	-85.79	0.04	0.30
SC9	-11.97	-86.33	0.03	0.19
SC9 LD				
SCF	-10.97	-79.56	0.02	0.10
SN0	-12.22	-88.38	0.01	0.10
SN2	-13.67	-99.54	0.04	0.38
SN6D	-12.16	-87.96	0.07	0.64
SN6S	-11.70	-84.86	0.04	0.34
Agassiz-Nelson Fen				
804872	-16.48	-121.83	0.05	0.34
SMW1	-15.12	-111.97	0.02	0.32
SP1	-10.04	-70.79	0.02	0.13
NMW	-12.32	-91.12	0.02	0.18
NMW FD	-12.29	-90.75	0.03	0.18
SMW3	-13.78	-101.58	0.01	0.03
SMW2	-13.87	-101.95	0.04	0.14
SP2	-12.94	-93.28	0.06	0.54
SP2 LD				
NS0	-12.14	-87.55	0.05	0.35
NS3	-10.42	-73.66	0.04	0.11
NSF	-11.01	-79.64	0.01	0.15
NC0	-14.23	-104.90	0.03	0.16
NC0 FD	-13.46	-98.78	0.03	0.15
NCSP3	-13.76	-102.37	0.02	0.22
NCF	-10.82	-79.22	0.02	0.11
NN0	-12.35	-90.71	0.02	0.16
NN3	-11.72	-85.20	0.02	0.02
NNF	-11.24	-83.36	0.02	0.09
NNF LD				

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LOD = Detection Limit

October Sampling

	Sample Date	Sample Time	Amount Flushed	*Sonde-Measured Properties* Sonde Measurement Location	Water Temp
					°C
LOD					
Sanders Fen					
580065	10/19/2019	11:00:00 AM	3 well vol	flowing into bucket	8.17
580065 LD					
SC0	10/19/2019	11:45:00 AM	3 well vol	in hole	11.22
SC1	10/19/2019	2:15:00 PM	dry+more	in hole	11.77
SC4	10/19/2019	1:50:00 PM	dry+more	in hole	12.38
SC4 FD	10/19/2019	2:00:00 PM			
SC7D	10/19/2019	3:15:00 PM	dry+more	in hole	9.35
SC7D FB	10/19/2019	6:00:00 PM			
SC7S	10/19/2019	3:00:00 PM	dry+more	in hole	9.48
SC9	10/19/2019	3:30:00 PM	dry+more	in hole	8.72
SCF	10/19/2019	1:00:00 PM	3 well vol	in hole	10.34
SN0	10/19/2019	12:00:00 PM	3 well vol	in hole	11.65
SN0 LD					
SN2	10/19/2019	4:00:00 PM	dry+more	in hole	11.79
SN6S	10/19/2019	4:15:00 PM	dry+more	in hole	9.9
Agassiz-Nelson Fen					
804872	10/20/2019	9:50:00 AM	3 well vol	in hole	10.53
SMW1	10/20/2019	9:00:00 AM	dry+more	in hole	8.21
SMW1 LD					
SP1	10/20/2019	8:35:00 AM	3 well vol	in cup	8.94
NMW	10/20/2019	11:30:00 AM	3 well vol	in hole	8.17
NMW LD					
SMW3	10/20/2019	10:45:00 AM	3 well vol	in hole	8.44
SMW2	10/20/2019	11:45:00 AM	dry+more	in hole	11
SP2	10/20/2019	10:55:00 AM	3 well vol	in cup	11.78
NS0	10/20/2019	2:40:00 PM	3 well vol	in hole	11.76
NS3	10/20/2019	1:25:00 PM	3 well vol	in hole	10.6
NC0	10/20/2019	3:00:00 PM	3 well vol	in hole	11.52
NCSP3	10/20/2019	1:55:00 PM	3 well vol	in hole	10.17
NN0	10/20/2019	3:20:00 PM	3 well vol	in hole	12.55
NN0 LD	10/20/2019	3:35:00 PM			
NN3	10/20/2019	12:35:00 PM	3 well vol	in hole	10.41
NNF	10/20/2019	12:50:00 PM	3 well vol	in hole	9.09

FB = Field Blank
FD = Field Duplicate
LD = Lab Duplicate
LOD = Detection Limit

*Duplicates averaged for plotting and analyses

October Sampling					*Alkalinity*	
	Specific Conductance	**pH**	**DO**	**DO**	Alkalinity 1	Alkalinity 2
	µS/cm		% saturation	mg/L	mg/L CaCO3	mg/L CaCO3
LOD						
Sanders Fen						
580065	658.6	8.58	1.1	0.13	289	288
580065 LD						
SC0	412	8.28	85.1	8.91	213	214
SC1	436.5	8.33	45.2	4.68	242	242
SC4	415.2	8.24	17.3	1.77	242	234
SC4 FD					232	236
SC7D	423.4	8.34	31.8	3.48	229	229
SC7D FB					<2	<2
SC7S	448.1	8.42	23.2	2.55	243	242
SC9	445	8.93	82.1	9.01	236	237
SCF	578.7	8.23	9.8	1.06	281	285
SN0	424.7	8.39	73.6	7.62	231	233
SN0 LD						
SN2	428.1	8.67	30.1	3.12	230	230
SN6S	706.3	8.11	15.6	1.7	405	398
Agassiz-Nelson Fen						
804872	635.6	8.43	12.3	1.31	300	304
SMW1	898.7	8.18	42	4.73	251	251
SMW1 LD						
SP1	721.4	7.55	22.1	2.44	386	388
NMW	686.1	8.19	0.6	0.07	315	312
NMW LD						
SMW3	539.2	8.26	16.3	1.82	285	288
SMW2	699.1	8.18	40.6	4.27	294	289
SP2	545.5	7.96	22.7	2.34	261	258
NS0	618	8.25	12.8	1.32	287	285
NS3	654.2	8.47	36.2	3.73	318	321
NC0	709.9	8.29	37.1	3.86	297	304
NCSP3	795.7	8.38	1.2	0.12	310	306
NN0	737.4	8.36	43.3	4.38	290	290
NN0 LD					<2	<2
NN3	889.1	8.57	5.5	0.59	394	398
NNF	661.6	8.01	47.7	5.26	284	290

FB = Field Blank
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LOD = Detection Limit

October Sampling				*Cations/Metals*	
	Alkalinity 3	**Alkalinity Avg**	Alkalinity Standard Dev	**Al**	**As**
	mg/L CaCO3	mg/L CaCO3		mg/L	mg/L
LOD				<0.009	<0.010
Sanders Fen					
580065	291	289	1.5	0.071	<0.010
580065 LD				0.076	<0.010
SC0	213	213	0.6	0.063	<0.010
SC1	242	242	0.0	0.058	<0.010
SC4	240	239	4.2	0.087	<0.010
SC4 FD	233	234	2.1	0.069	<0.010
SC7D	229	229	0.0	0.058	<0.010
SC7D FB	<2	<2	0.0	0.069	<0.010
SC7S	243	243	0.6	0.065	<0.010
SC9	233	235	2.1	0.07	<0.010
SCF	282	283	2.1	0.053	<0.010
SN0	233	232	1.2	0.069	<0.010
SN0 LD					
SN2	232	231	1.2	0.065	<0.010
SN6S	396	400	4.7	0.07	<0.010
Agassiz-Nelson Fen					
804872	300	301	2.3	0.062	0.026
SMW1	256	253	2.9	0.07	<0.010
SMW1 LD				0.067	<0.010
SP1	379	384	4.7	0.068	<0.010
NMW	316	314	2.1	0.069	0.021
NMW LD					
SMW3	289	287	2.1	0.194	0.015
SMW2	296	293	3.6	0.062	<0.010
SP2	257	259	2.1	0.061	<0.010
NS0	289	287	2.0	0.066	<0.010
NS3	321	320	1.7	0.078	<0.010
NC0	302	301	3.6	0.077	0.011
NCSP3	307	308	2.1	0.064	<0.010
NN0	294	291	2.3	0.068	<0.010
NN0 LD	<2	<2	0.0	0.063	<0.010
NN3	400	397	3.1	0.061	<0.010
NNF	287	287	3.0	0.075	<0.010

FB = Field Blank

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LOD = Detection Limit

October Sampling

	B	Ba	Be	Ca	Cd	Co	Cr	Cu
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.011	<0.001	<0.001	<0.105	<0.005	<0.003	<0.002	<0.001
Sanders Fen								
580065	0.409	0.082	<0.001	30.861	<0.005	0.1	<0.002	0.002
580065 LD	0.416	0.086	<0.001	32.549	<0.005	0.109	<0.002	<0.001
SC0	0.017	0.047	<0.001	68.747	<0.005	0.106	<0.002	0.003
SC1	0.023	0.042	<0.001	73.056	<0.005	0.097	<0.002	0.003
SC4	0.016	0.033	<0.001	71.169	<0.005	0.133	<0.002	0.005
SC4 FD	0.016	0.032	<0.001	71.418	<0.005	0.142	<0.002	0.004
SC7D	0.018	0.049	<0.001	71.024	<0.005	0.1	<0.002	0.002
SC7D FB	<0.011	<0.001	<0.001	0.618	<0.005	0.113	<0.002	0.002
SC7S	0.015	0.055	<0.001	76.612	<0.005	0.1	<0.002	0.003
SC9	0.017	0.068	<0.001	72.969	<0.005	0.11	<0.002	0.005
SCF	<0.011	0.056	<0.001	88.146	<0.005	0.093	<0.002	0.002
SN0	0.017	0.038	<0.001	73.723	<0.005	0.097	<0.002	0.004
SN0 LD								
SN2	0.014	0.036	<0.001	74.988	<0.005	0.096	<0.002	0.003
SN6S	0.019	0.105	<0.001	132.96	<0.005	0.093	<0.002	0.002
Agassiz-Nelson Fen								
804872	0.446	0.043	<0.001	49.058	<0.005	0.128	<0.002	0.003
SMW1	0.509	0.077	<0.001	84.128	<0.005	0.138	<0.002	0.003
SMW1 LD	0.51	0.079	<0.001	86.225	<0.005	0.146	<0.002	<0.001
SP1	<0.011	0.039	<0.001	133.29	<0.005	0.127	<0.002	0.003
NMW	0.182	0.119	<0.001	102.53	<0.005	0.132	<0.002	0.003
NMW LD								
SMW3	0.125	0.291	<0.001	89.429	<0.005	0.122	<0.002	0.018
SMW2	0.054	0.209	<0.001	115.97	<0.005	0.137	<0.002	0.003
SP2	0.016	0.082	<0.001	100.49	<0.005	0.126	<0.002	0.003
NS0	0.017	0.042	<0.001	107.53	<0.005	0.138	<0.002	0.005
NS3	0.02	0.053	<0.001	117.73	<0.005	0.129	<0.002	0.005
NC0	0.018	0.042	<0.001	120.39	<0.005	0.119	<0.002	0.005
NCSP3	<0.011	0.047	<0.001	121.66	<0.005	0.12	<0.002	0.006
NN0	0.029	0.046	<0.001	128.62	<0.005	0.128	<0.002	0.004
NN0 LD	<0.011	<0.001	<0.001	0.839	<0.005	0.13	<0.002	0.003
NN3	<0.011	0.061	<0.001	129.31	<0.005	0.132	<0.002	0.004
NNF	0.012	0.053	<0.001	107.89	<0.005	0.119	<0.002	0.008

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October Sampling

	Fe	K	Li	Mg	Mn	Mo	Na	Ni
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.001	<0.094	<0.002	<0.007	<0.001	<0.001	<0.015	<0.001
Sanders Fen								
580065	0.408	2.641	0.023	25.051	0.019	0.003	100.75	<0.001
580065 LD	0.415	2.712	0.027	27.531	0.019	0.002	108.53	<0.001
SC0	0.006	1.513	0.007	20.885	0.008	<0.001	1.185	<0.001
SC1	0.01	1.883	0.007	22.989	0.033	<0.001	1.465	0.001
SC4	0.251	2.047	0.006	22.998	0.071	<0.001	1.895	0.004
SC4 FD	0.198	1.865	0.007	22.928	0.066	<0.001	1.699	0.002
SC7D	0.013	2.238	0.01	23.254	0.011	<0.001	1.594	0.001
SC7D FB	0.007	<0.094	<0.002	0.035	0.008	<0.001	0.155	0.001
SC7S	0.004	2.432	0.006	24.226	0.017	0.001	1.841	0.002
SC9	0.012	3.32	0.009	25.122	0.165	0.004	2.913	0.003
SCF	0.499	1.323	0.009	28.122	0.213	<0.001	1.429	0.001
SN0	0.006	1.542	0.006	22.807	0.012	<0.001	1.27	<0.001
SN0 LD								
SN2	0.215	2.393	0.007	21.501	0.187	<0.001	1.297	0.002
SN6S	0.026	3.324	0.01	33.301	0.072	<0.001	2.083	<0.001
Agassiz-Nelson Fen								
804872	0.337	5.555	0.042	22.636	0.119	0.014	85.988	0.002
SMW1	0.141	7.812	0.022	30.61	0.495	0.018	103.46	0.001
SMW1 LD	0.129	8.045	0.025	30.327	0.523	0.023	106.54	<0.001
SP1	1.008	0.358	0.004	30.533	0.369	<0.001	2.31	0.006
NMW	1.923	4.371	0.045	36.589	0.164	0.005	23.205	0.002
NMW LD								
SMW3	0.764	6.784	0.029	27.809	0.113	0.004	13.588	0.003
SMW2	0.238	4.038	0.019	33.53	0.239	0.004	11.52	0.002
SP2	0.136	0.249	0.009	25.05	0.494	0.002	2.943	0.002
NS0	0.022	0.991	0.007	32.087	0.019	<0.001	2.005	0.001
NS3	0.005	0.748	0.007	34.396	0.015	<0.001	1.977	0.002
NC0	<0.001	1.434	0.009	36.525	0.017	<0.001	3.31	0.002
NCSP3	0.048	0.766	0.009	47.235	0.064	<0.001	4.5	0.002
NN0	0.006	0.954	0.008	36.457	0.021	<0.001	4.373	0.001
NN0 LD	0.058	<0.094	<0.002	0.043	0.009	<0.001	0.186	0.001
NN3	0.036	0.326	0.008	47.437	0.038	0.001	4.274	0.003
NNF	0.04	0.914	0.008	35.267	0.015	<0.001	6.8	0.001

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LOD = Detection Limit

October Sampling

	P	Pb	Rb	S	Si	Sr	Ti	V
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.004	<0.003	<0.002	<0.027	<0.004	<0.001	<0.001	<0.002
Sanders Fen								
580065	0.512	<0.003	<0.002	14.263	11.371	0.365	0.002	<0.002
580065 LD	0.532	<0.003	<0.002	14.756	12.427	0.394	0.003	<0.002
SC0	0.314	<0.003	<0.002	0.881	9.402	0.078	0.002	<0.002
SC1	0.279	<0.003	<0.002	1.271	10.718	0.082	0.002	<0.002
SC4	0.393	<0.003	<0.002	1.748	10.016	0.079	0.002	0.003
SC4 FD	0.429	<0.003	<0.002	1.737	9.951	0.079	0.002	<0.002
SC7D	0.297	<0.003	<0.002	1.977	11.723	0.097	0.002	0.007
SC7D FB	0.289	<0.003	<0.002	0.061	0.029	0.001	<0.001	<0.002
SC7S	0.313	<0.003	<0.002	0.593	12.175	0.101	0.002	<0.002
SC9	0.328	<0.003	<0.002	3.108	12.54	0.112	0.002	<0.002
SCF	0.295	<0.003	<0.002	0.702	12.897	0.104	0.002	<0.002
SN0	0.288	<0.003	<0.002	1.263	9.262	0.077	0.002	<0.002
SN0 LD								
SN2	0.282	<0.003	<0.002	1.61	10.728	0.077	0.002	<0.002
SN6S	0.285	<0.003	<0.002	1.492	13.938	0.159	0.002	<0.002
Agassiz-Nelson Fen								
804872	0.482	<0.003	<0.002	18.995	16.712	0.335	0.002	<0.002
SMW1	0.474	<0.003	<0.002	94.501	11.592	0.516	0.002	<0.002
SMW1 LD	0.525	<0.003	<0.002	93.595	12.191	0.547	0.005	0.002
SP1	0.394	<0.003	<0.002	3.295	6.407	0.15	0.001	<0.002
NMW	0.466	<0.003	<0.002	23.363	16.76	0.472	0.002	<0.002
NMW LD								
SMW3	0.489	0.005	<0.002	4.238	17.151	0.638	0.008	<0.002
SMW2	0.45	<0.003	<0.002	27.501	16.632	0.483	0.001	0.002
SP2	0.382	<0.003	<0.002	11.778	10.151	0.164	0.002	<0.002
NS0	0.422	<0.003	<0.002	8.948	10.31	0.138	0.001	<0.002
NS3	0.408	<0.003	<0.002	6.56	15.989	0.169	0.002	<0.002
NC0	0.372	<0.003	<0.002	12.816	12.329	0.179	0.001	<0.002
NCSP3	0.372	<0.003	<0.002	19.811	13.92	0.175	0.002	<0.002
NN0	0.395	<0.003	<0.002	13.485	12.397	0.167	0.001	<0.002
NN0 LD	0.371	<0.003	<0.002	0.073	0.041	0.002	<0.001	<0.002
NN3	0.42	<0.003	<0.002	5.2	16.46	0.164	0.002	<0.002
NNF	0.396	<0.003	<0.002	11.503	11.576	0.13	0.002	<0.002

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October Sampling		Anions					
	Zn	**HCO3- (from Alk)**	**Bromide**	**Chloride**	**Fluoride**	**Nitrate-N**	**Nitrite-N**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
LOD	<0.002	<2.5	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sanders Fen							
580065	0.016	353	< 0.1	21.5	1.2	< 0.1	< 0.1
580065 LD	0.015		< 0.1	21.7	1.2	< 0.1	< 0.1
SC0	0.01	260	< 0.1	1	< 0.1	0.3	< 0.1
SC1	0.018	295	< 0.1	1.2	< 0.1	0.3	< 0.1
SC4	0.02	291	< 0.1	1.5	1.2	0.2	< 0.1
SC4 FD	0.014	285	< 0.1	1.4	1.2	0.2	< 0.1
SC7D	0.012	279	< 0.1	1.3	< 0.1	0.2	< 0.1
SC7D FB	0.01	<2.5	< 0.1	< 0.1	< 0.1	0.2	< 0.1
SC7S	0.015	296	< 0.1	1.5	< 0.1	0.2	< 0.1
SC9	0.022	287	< 0.1	1.9	1.2	0.3	< 0.1
SCF	0.011	345	< 0.1	1.2	< 0.1	0.2	< 0.1
SN0	0.013	283	< 0.1	1	< 0.1	0.3	< 0.1
SN0 LD			< 0.1	1	< 0.1	0.3	< 0.1
SN2	0.017	281	< 0.1	1.2	< 0.1	0.2	< 0.1
SN6S	0.012	488	< 0.1	1.4	< 0.1	< 0.1	< 0.1
Agassiz-Nelson Fen							
804872	0.011	368	< 0.1	3.8	1.2	< 0.1	< 0.1
SMW1	0.016	308	< 0.1	6.3	1.1	< 0.1	< 0.1
SMW1 LD	0.019						
SP1	3.005	469	< 0.1	8.4	< 0.1	0.3	< 0.1
NMW	0.019	383	< 0.1	3.1	< 0.1	< 0.1	< 0.1
NMW LD			< 0.1	3.1	< 0.1	< 0.1	< 0.1
SMW3	0.239	351	< 0.1	1.1	< 0.1	0.3	< 0.1
SMW2	0.017	357	< 0.1	18	1.1	< 0.1	< 0.1
SP2	3.274	316	< 0.1	7.6	1.2	2.3	< 0.1
NS0	0.013	350	< 0.1	11.7	< 0.1	2.1	< 0.1
NS3	0.02	390	< 0.1	8.1	< 0.1	< 0.1	< 0.1
NC0	0.016	367	< 0.1	21.2	< 0.1	5.6	< 0.1
NCSP3	0.018	375	< 0.1	30.5	< 0.1	4.8	< 0.1
NN0	0.013	355	< 0.1	14.4	< 0.1	< 0.1	< 0.1
NN0 LD	0.012	<2.5	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
NN3	0.036	485	< 0.1	3.8	1.1	1	< 0.1
NNF	0.034	350	< 0.1	14.3	< 0.1	< 0.1	< 0.1

FB = Field Blank
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LOD = Detection Limit

October Sampling			*Stable Isotopes*			
	Phosphate-P	**Sulfate-S**	**$\delta^{18}O$**	**$\delta^{2}H$**	**$\delta^{18}O$ Precision**	**$\delta^{2}H$ Precision**
	mg/L	mg/L	per mil	per mil	per mil	per mil
LOD	< 0.1	< 0.1				
Sanders Fen						
580065	< 0.1	14.2	-15.04	-112.24	0.03	0.27
580065 LD	< 0.1	14.3				
SC0	< 0.1	0.5	-11.79	-84.13	0.02	0.22
SC1	< 0.1	0.8	-12.29	-88.19	0.04	0.52
SC4	< 0.1	1	-12.76	-92.36	0.01	0.11
SC4 FD	< 0.1	1	-12.70	-92.01	0.02	0.06
SC7D	< 0.1	1	-12.08	-87.27	0.01	0.08
SC7D FB	< 0.1	< 0.1				
SC7S	< 0.1	0.5	-11.72	-84.32	0.03	0.11
SC9	< 0.1	1.7	-11.79	-84.82	0.02	0.12
SCF	< 0.1	0.5	-11.88	-84.27	0.02	0.12
SN0	< 0.1	0.8	-10.83	-76.37	0.03	0.23
SN0 LD	< 0.1	0.8				
SN2	< 0.1	0.9	-11.57	-82.58	0.01	0.11
SN6S	< 0.1	0.9	-11.39	-82.54	0.02	0.10
Agassiz-Nelson Fen						
804872	< 0.1	18.7	-16.54	-122.21	0.03	0.32
SMW1	< 0.1	85.1	-15.17	-112.33	0.04	0.19
SMW1 LD						
SP1	< 0.1	2.8	-13.02	-94.30	0.02	0.21
NMW	< 0.1	22.8	-12.22	-90.52	0.03	0.11
NMW LD	< 0.1	22.9				
SMW3	< 0.1	2.7	-13.70	-100.53	0.03	0.32
SMW2	< 0.1	27	-13.70	-100.67	0.01	0.15
SP2	< 0.1	9.5	-11.03	-73.61	0.03	0.24
NS0	< 0.1	6.9	-12.45	-90.17	0.04	0.08
NS3	< 0.1	6	-10.36	-71.80	0.03	0.25
NC0	< 0.1	9.5	-11.24	-84.14	0.05	0.25
NCSP3	< 0.1	16.1	-11.77	-85.22	0.01	0.06
NN0	< 0.1	31.7	-11.20	-80.70	0.03	0.21
NN0 LD	< 0.1	< 0.1				
NN3	< 0.1	3.4	-9.61	-64.58	0.03	0.35
NNF	< 0.1	11.2	-11.95	-86.71	0.05	0.31

FB = Field Blank
FD = Field Duplicate
LD = Lab Duplicate
LOD = Detection Limit

September Samples	*Stable Isotopes*				
	$\delta^{18}O$	**$\delta^{2}H$**	**$\delta^{18}O$ Precision**	**$\delta^{2}H$ Precision**	**amt in 15mL vial**
	per mil	per mil	per mil	per mil	mL
Rain Samples					
PR1	-9.66	-63.82	0.02	0.44	14.00
PR2	-11.97	-88.81	0.03	0.28	14.50
PR3	-11.91	-87.23	0.04	0.50	14.00
PR4	-7.03	-42.89	0.01	0.23	6.00
PR5	-9.64	-62.29	0.03	0.17	14.00
PR6	-11.87	-88.61	0.06	0.71	15.00
PR7	-11.29	-82.82	0.01	0.17	14.00
PR8	-11.46	-84.19	0.04	0.21	15.00
PR9	-11.85	-89.16	0.00	0.11	12.50
Snow Samples					
PS1	-16.70	-116.06	0.02	0.29	15.00
PS2	-16.15	-112.49	0.03	0.20	15.00
PS3	-16.79	-116.03	0.01	0.09	15.00
PS4	-16.68	-115.17	0.02	0.25	15.00

*Collected near Agassiz-Nelson Fen

September Samples	*Tritium*	
	TU	**TU Error**
580065	0.04	0.09
SC0	8.06	0.27
SC7D	7.39	0.24
804872	-0.01	0.09
NMW	1.89	0.09
NC0	8.61	0.28
NCSP3	7.63	0.25

*Error is 1 standard deviation

QA/QC

Major Ion Charge Balance

Ca, Mg, Na, K, Cl, SO4, HCO3, NO3

	July				October			
	Sum Cations	Sum Anions	Difference	Charge Balance Error	Sum Cations	Sum Anions	Difference	Charge Balance Error
	meq/L	meq/L	meq/L	%	meq/L	meq/L	meq/L	%
Sanders Fen								
580065	8.31	7.51	0.79	5.0	8.37	7.28	1.08	6.9
SC0	6.13	4.95	1.18	10.7	5.24	4.34	0.90	9.4
SC1	5.38	4.57	0.80	8.1	5.65	4.94	0.71	6.7
SC4	5.86	4.92	0.94	8.7	5.58	4.85	0.73	7.0
SC7D	5.85	5.25	0.60	5.4	5.58	4.69	0.89	8.7
SC7S	5.88	5.02	0.86	7.8	5.96	4.95	1.01	9.3
SC9	5.70	5.30	0.40	3.7	5.92	4.88	1.04	9.6
SCF	8.11	6.84	1.27	8.5	6.81	5.74	1.07	8.5
SN0	5.76	4.71	1.05	10.1	5.65	4.74	0.91	8.8
SN2	5.52	4.68	0.84	8.3	5.63	4.72	0.91	8.8
SN6D	6.43	5.39	1.03	8.8	6.03	6.50	-0.47	-3.7
Average			*0.9*	*7.7*			*0.8*	*7.3*
Agassiz-Nelson Fen								
804872	8.42	7.34	1.08	6.9	8.19	7.30	0.89	5.8
SMW1	11.70	11.08	0.62	2.7	11.53	10.55	0.98	4.4
SP1	9.92	8.63	1.30	7.0	9.27	8.11	1.16	6.7
NMW	9.48	7.91	1.56	9.0	9.25	7.80	1.45	8.5
SMW3	7.44	6.15	1.29	9.5	7.52	5.96	1.56	11.6
SMW2	9.60	8.05	1.55	8.8	9.15	8.06	1.09	6.4
SP2	7.86	6.60	1.26	8.7	7.21	6.15	1.06	7.9
NS0	11.15	9.40	1.75	8.5	8.12	6.65	1.47	10.0
NS3	8.67	6.86	1.81	11.7	8.81	7.01	1.80	11.4
NSF	8.47	7.00	1.47	9.5				
NC0	7.17	6.20	0.97	7.2	9.19	7.61	1.59	9.4
NCSP3	7.64	6.32	1.32	9.4	10.17	8.37	1.81	9.7
NCF	10.28	8.36	1.92	10.3				
NN0	8.30	6.64	1.66	11.1	9.63	8.21	1.42	8.0
NN3	9.31	7.13	2.18	13.3	10.55	8.33	2.22	11.8
NNF	9.67	7.81	1.86	10.6	8.61	6.85	1.76	11.4
Average			*1.5*	*9.0*			*1.4*	*8.8*
Overall Average			*1.2*	*8.5*			*1.2*	*8.1*

*Duplicates averaged for calculation; some only have duplicates of cations or anions

QA/QC

Duplicate Sample Agreement

Percent error in duplicates from original

	July						October				
	580065	NC0	NMW	NNF	SC9	SP2	580065	SC4	NMW	SMW1	SN0
	LD	FD	FD	LD	LD	LD	LD	FD	LD	LD	LD
Al		11.5	0.8		11.6		7.0	-20.7		-4.3	
As		LOD	7.3		LOD		LOD	LOD		LOD	
B		LOD	7.3		142.4		1.7	0.0		0.2	
Ba		0.4	1.6		3.4		4.9	-3.0		2.6	
Be		LOD	LOD		LOD		LOD	LOD		LOD	
Ca		-2.1	2.2		-0.8		5.5	0.3		2.5	
Cd		LOD	LOD		LOD		LOD	LOD		LOD	
Co		LOD	LOD		LOD		9.0	6.8		5.8	
Cr		LOD	LOD		LOD		LOD	LOD		LOD	
Cu		LOD	LOD		13.9		LOD	-20.0		LOD	
Fe		LOD	1.7		-32.9		1.7	-21.1		-8.5	
K		4.0	3.6		13.6		2.7	-8.9		3.0	
Mg		-4.8	1.4		-1.5		9.9	-0.3		-0.9	
Mn		43.1	2.0		5.0		0.0	-7.0		5.7	
Mo		LOD	8.2		-18.3		-33.3	LOD		27.8	
Na		-4.9	1.7		0.8		7.7	-10.3		3.0	
Ni		LOD	LOD		LOD		LOD	-50.0		LOD	
P		LOD	-0.1		68.1		3.9	9.2		10.8	
Pb		LOD	LOD		LOD		LOD	LOD		LOD	
Rb		LOD	LOD		LOD		LOD	LOD		LOD	
S		-4.3	0.5		2.0		3.5	-0.6		-1.0	
Si		1.1	1.3		4.3		9.3	-0.6		5.2	
Sr		-3.1	1.9		3.8		7.9	0.0		6.0	
Ti		1.3	0.0		95.4		50.0	0.0		150.0	
V		LOD	LOD		LOD		LOD	LOD		LOD	
Zn		16.1	14.8		14.8		-6.3	-30.0		18.8	
Fluoride	LOD	LOD	LOD	LOD	LOD	LOD	0.0	0.0	LOD		LOD
Chloride	-0.4	-13.3	2.4	0.0	0.0	-0.7	0.9	-6.7	0.0		0.0
Nitrite-N	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD		LOD
Bromide	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD		LOD
Sulfate-S	2.2	-10.8	1.3	0.0	0.0	0.0	0.7	0.0	0.4		0.0
Nitrate-N	LOD	-12.5	LOD	LOD	0.0	2.2	LOD	0.0	LOD		0.0
Phosphate-P	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD		LOD
Overall Average	***0.9***	***1.9***	***3.0***	***0.0***	***16.7***	***0.5***	***5.0***	***-6.4***	***0.2***	***13.3***	***0.0***

*Calculated by subracting duplicate from original and dividing by original

QA/QC

Field Blank Samples

Comparison to minimum concentration from all other samples

October

	NN0 FB	SC7D FB	Minimum	LOD		
Al	0.063	0.069	0.053	<0.009	mg/L	
As	<0.010	<0.010	LOD	<0.010	mg/L	
B	<0.011	<0.011	LOD	<0.011	mg/L	
Ba	<0.001	<0.001	0.032	<0.001	mg/L	
Be	<0.001	<0.001	LOD	<0.001	mg/L	
Ca	0.839	0.618	30.861	<0.105	mg/L	
Cd	<0.005	<0.005	LOD	<0.005	mg/L	
Co	0.13	0.113	0.063	<0.003	mg/L	
Cr	<0.002	<0.002	LOD	<0.002	mg/L	
Cu	0.003	0.002	LOD	<0.001	mg/L	
Fe	0.058	0.007	LOD	<0.001	mg/L	*
K	<0.094	<0.094	0.249	<0.094	mg/L	
Li	<0.002	<0.002	0.004	<0.002	mg/L	
Mn	0.009	0.008	0.008	<0.001	mg/L	
Mo	<0.001	<0.001	LOD	<0.001	mg/L	
Na	0.186	0.155	1.185	<0.015	mg/L	
Ni	0.001	0.001	LOD	<0.001	mg/L	
P	0.371	0.289	0.258	<0.004	mg/L	
Pb	<0.003	<0.003	LOD	<0.003	mg/L	
Rb	<0.002	<0.002	LOD	<0.002	mg/L	
S	0.073	0.061	0.593	<0.027	mg/L	
Si	0.041	0.029	6.407	<0.004	mg/L	
Sr	0.002	0.001	0.077	<0.001	mg/L	
Ti	<0.001	<0.001	0.001	<0.001	mg/L	
V	<0.002	<0.002	LOD	<0.002	mg/L	
Zn	0.012	0.01	0.01	<0.002	mg/L	
Fluoride	< 0.1	< 0.1	LOD	<0.1	mg/L	
Chloride	< 0.1	< 0.1	1	<0.1	mg/L	
Nitrite-N	< 0.1	< 0.1	LOD	<0.1	mg/L	
Bromide	< 0.1	< 0.1	LOD	<0.1	mg/L	
Sulfate-S	< 0.1	< 0.1	0.5	<0.1	mg/L	
Nitrate-N	< 0.1	0.2	LOD	<0.1	mg/L	
Phosphate-P	< 0.1	< 0.1	LOD	<0.1	mg/L	
Alk Avg	<2	<2	213	<2	mg/L CaCO3	

Analytes where blank has noticibly higher concentration than lowest of other samples

*Most Samples higher than blank for Fe

**Deionized water was used for blank samples

Appendix C: Detailed Multivariate Statistics Results

Table C1. Factor loadings for varimax-normalized principal component analysis of water chemistry data from July and October sampling trips.

Variable	Fact. 1	Fact. 2	Fact. 3	Fact. 4	Fact. 5	Fact. 6	Fact. 7	Fact. 8	Fact. 9	Fact. 10	Fact. 11	Fact. 12
Oct_Al	-0.03	-0.06	0.94	0.07	0.02	-0.15	0.00	0.08	-0.01	0.00	0.01	-0.11
Oct_As	0.22	-0.06	0.14	0.91	0.06	0.03	0.09	-0.04	0.04	0.02	0.25	0.01
Oct_B	0.81	-0.12	0.05	0.30	0.05	-0.13	0.43	-0.01	0.00	0.07	0.06	-0.13
Oct_Ba	0.12	0.07	0.88	-0.03	0.00	0.31	0.11	-0.14	0.03	0.02	0.23	-0.01
Oct_Ca	-0.15	0.80	0.08	-0.14	-0.16	0.13	-0.36	0.10	-0.12	-0.01	0.00	0.25
Oct_Co	0.41	0.44	0.22	0.14	-0.10	-0.25	0.01	0.07	0.29	-0.07	-0.03	0.56
Oct_Cu	-0.21	0.08	0.85	0.10	0.11	-0.20	-0.16	0.07	0.00	-0.12	-0.05	0.05
Oct_Fe	0.11	0.07	0.22	0.35	-0.22	-0.06	0.02	-0.01	0.00	0.02	0.81	0.00
Oct_K	0.69	-0.22	0.45	0.24	0.13	0.21	0.04	-0.13	0.09	-0.08	0.11	-0.29
Oct_Li	0.50	-0.03	0.31	0.61	0.13	0.02	0.27	-0.13	0.02	0.03	0.39	0.03
Oct_Mg	0.04	0.80	0.04	-0.05	0.22	0.00	-0.01	0.04	-0.36	-0.12	0.08	0.32
Oct_Mn	0.42	-0.08	-0.02	-0.05	-0.66	0.42	-0.09	0.03	-0.28	-0.02	0.10	-0.13
Oct_Mo	0.92	-0.06	0.05	0.30	-0.04	0.09	0.05	0.00	0.11	-0.10	-0.06	-0.08
Oct_Na	0.78	-0.10	-0.02	0.19	0.05	-0.17	0.53	-0.02	-0.04	0.07	0.03	-0.12
Oct_P	0.55	0.29	0.40	0.20	-0.02	-0.27	0.42	0.07	0.04	0.05	0.14	0.29
Oct_S	0.97	0.13	0.01	-0.07	0.00	0.02	-0.07	-0.03	-0.10	-0.02	0.00	0.10
Oct_Si	0.12	0.24	0.40	0.41	0.46	0.49	0.22	0.11	-0.20	-0.02	0.12	0.10
Oct_Sr	0.62	0.11	0.65	0.16	0.03	0.08	0.22	-0.05	-0.05	0.04	0.28	0.07
Oct_Zn	-0.10	0.08	-0.01	-0.02	-0.95	-0.08	0.03	0.05	0.01	0.04	0.06	0.17
Oct_Fluoride	0.40	-0.07	-0.03	0.05	-0.20	0.20	0.61	-0.15	0.18	-0.24	-0.20	0.29
Oct_Chloride	0.04	0.11	-0.05	-0.14	-0.01	0.04	0.06	0.05	-0.88	0.03	-0.03	-0.06
Oct_Sulfate-S	0.95	0.15	-0.01	-0.08	0.03	0.02	-0.07	-0.03	-0.08	0.01	0.01	0.17
Oct_Nitrate-N	-0.12	0.24	0.00	0.10	-0.05	-0.25	-0.20	-0.20	-0.60	-0.15	-0.31	0.31
Oct_Temp	-0.33	-0.07	-0.22	0.03	0.01	0.02	-0.25	-0.09	0.19	0.27	-0.53	0.47
Oct_SpC	0.48	0.77	0.00	0.01	0.00	0.00	0.17	0.06	-0.23	0.00	0.04	0.20
Oct_pH	-0.09	-0.35	-0.06	0.07	0.62	0.14	0.32	0.07	-0.07	-0.41	-0.27	0.03
Oct_DO	0.05	-0.38	-0.05	-0.33	0.04	0.02	-0.34	0.12	0.31	-0.42	-0.25	0.02
Oct_Alk Avg	-0.08	0.83	0.05	0.16	-0.15	0.08	0.26	0.12	-0.07	0.05	0.12	-0.04
Jul_Al	-0.05	-0.19	0.00	-0.02	0.10	0.77	-0.25	0.31	0.05	-0.23	-0.12	-0.03
Jul_As	0.24	-0.05	-0.11	0.90	0.04	0.04	0.16	-0.02	0.11	0.02	0.12	0.01
Jul_B	0.85	-0.11	-0.02	0.23	0.04	-0.15	0.37	0.02	0.02	0.03	-0.02	-0.16
Jul_Ba	0.11	0.12	0.80	-0.12	-0.05	0.41	0.09	-0.07	0.11	0.07	0.23	0.05
Jul_Ca	-0.17	0.83	0.07	-0.14	-0.28	0.12	-0.35	0.06	0.08	0.10	0.04	0.04

Jul_Co	-0.09	0.20	0.00	-0.02	-0.17	-0.07	-0.01	0.92	0.07	0.04	0.05	0.02
Jul_Cu	-0.09	-0.04	-0.03	-0.02	0.06	0.03	0.04	-0.03	-0.05	-0.95	-0.07	-0.04
Jul_Fe	0.01	0.21	0.22	0.21	-0.29	-0.05	0.02	0.10	0.11	0.06	0.84	-0.02
Jul_K	0.67	0.00	0.21	0.21	0.18	0.44	0.14	-0.06	0.20	-0.05	0.12	-0.25
Jul_Li	0.66	-0.06	0.30	0.55	0.07	0.01	0.16	-0.10	0.04	-0.04	0.31	-0.09
Jul_Mg	0.00	0.81	0.05	-0.02	0.14	-0.20	-0.13	0.07	0.02	0.11	0.12	-0.05
Jul_Mn	0.06	0.10	-0.01	-0.04	0.03	0.28	-0.05	0.92	-0.08	0.05	0.02	-0.06
Jul_Mo	0.95	-0.02	-0.03	0.21	-0.02	0.11	-0.02	0.02	0.10	-0.02	-0.09	-0.07
Jul_Na	0.82	-0.08	-0.01	0.16	0.04	-0.11	0.50	-0.02	-0.02	0.07	0.03	-0.10
Jul_P	0.25	0.08	0.12	0.21	0.17	-0.07	0.88	-0.08	-0.02	0.07	0.13	-0.08
Jul_S	0.97	0.11	0.00	-0.07	-0.02	0.08	0.00	-0.01	-0.03	-0.01	0.03	0.12
Jul_Si	0.11	0.22	0.24	0.36	0.38	0.52	0.06	0.08	0.00	0.18	0.27	-0.03
Jul_Sr	0.60	0.11	0.66	0.17	0.00	0.08	0.20	-0.09	-0.01	0.07	0.30	0.02
Jul_Ti	0.17	-0.27	0.15	0.02	0.07	0.55	0.08	-0.18	0.06	-0.66	-0.14	-0.03
Jul_Zn	-0.09	0.18	-0.08	-0.07	-0.88	-0.17	0.00	0.17	0.05	-0.04	0.23	-0.01
Jul_Chloride	0.08	0.56	-0.06	-0.24	-0.13	-0.21	0.36	0.12	-0.25	0.03	0.03	0.45
Jul_Sulfate-S	0.98	0.08	0.01	-0.07	-0.01	0.08	0.04	0.00	-0.04	-0.01	0.03	0.11
Jul_Nitrate-N	-0.11	0.12	-0.02	0.03	-0.50	0.03	0.05	-0.11	-0.16	0.13	-0.35	0.58
Jul_Temp	-0.38	0.28	-0.34	-0.25	-0.10	-0.08	-0.12	0.44	0.18	-0.28	-0.11	0.26
Jul_SpC	0.51	0.76	0.01	-0.08	-0.24	-0.06	0.14	0.08	0.02	0.15	-0.11	-0.15
Jul_pH	0.40	-0.35	0.17	0.18	0.04	0.01	0.63	0.10	-0.08	-0.36	0.11	0.06
Jul_ORP	0.16	-0.13	-0.08	-0.17	-0.07	-0.14	-0.02	0.06	-0.09	-0.39	-0.69	0.15
Jul_Alk avg	-0.02	0.75	0.06	0.11	-0.11	-0.11	0.01	-0.01	0.19	0.12	0.14	-0.51
Expl.Var	12.7	6.81	5.17	3.85	3.75	2.84	3.87	2.38	2.03	2.47	3.50	2.32
Prp.Totl	0.23	0.12	0.09	0.07	0.07	0.05	0.07	0.04	0.04	0.04	0.06	0.04

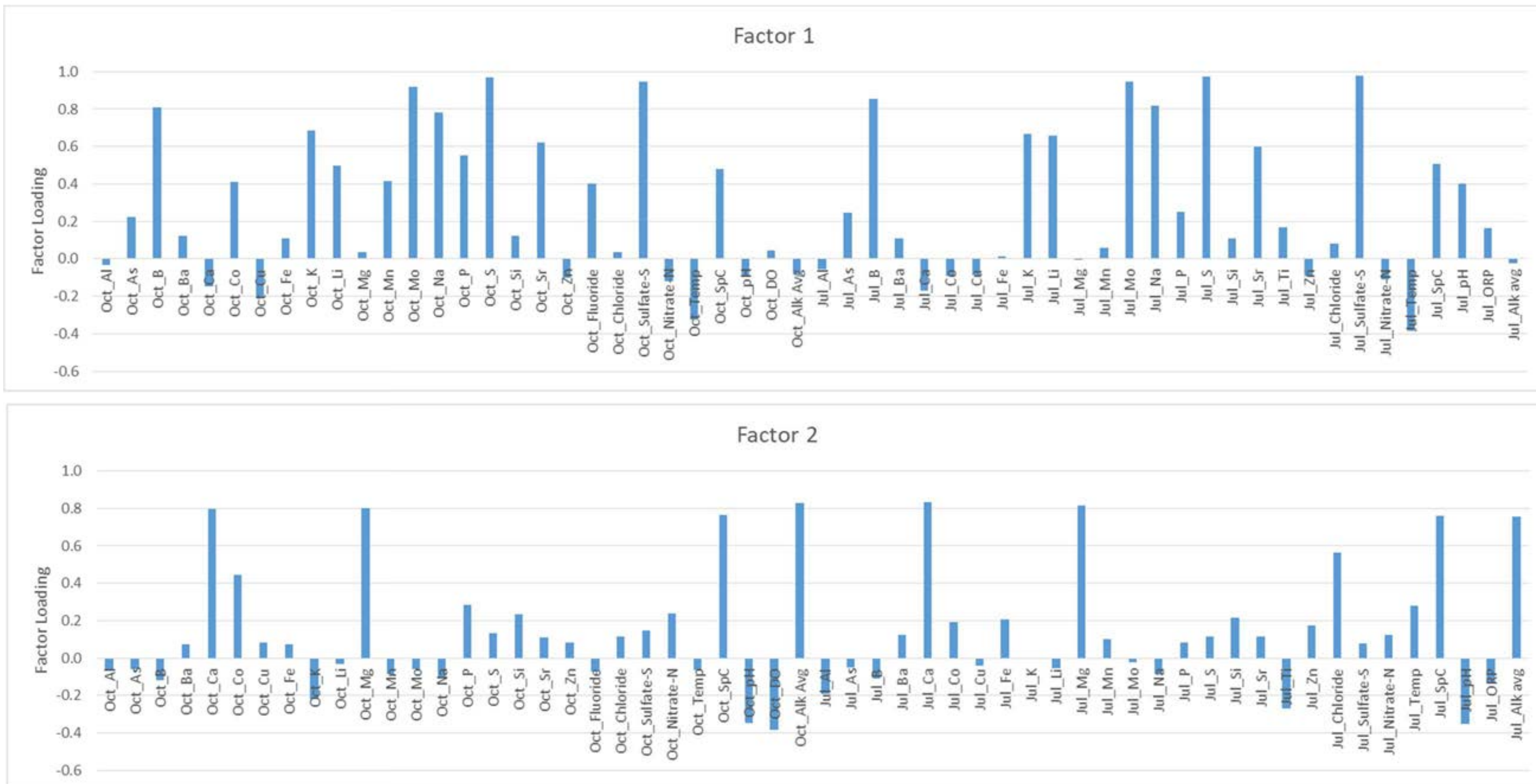

Figure C1. Bar chart of factor loadings from July and October Sampling Trips

Table C2. Factor scores for varimax-normalized principal component analysis of water chemistry data from July and October sampling trips.

Well Case	Fact. 1	Fact. 2	Fact. 3	Fact. 4	Fact. 5	Fact. 6	Fact. 7	Fact. 8	Fact. 9	Fact. 10	Fact. 11	Fact. 12
580065	0.47	-0.68	-0.06	-1.05	0.43	-1.66	3.94	-0.24	-0.86	0.52	0.68	-0.52
SC0	-0.24	-1.20	-0.23	-0.44	0.23	-0.60	-0.61	-0.01	0.91	-0.06	-0.32	0.00
SN0	-0.34	-1.13	-0.24	-0.28	0.26	-0.19	-0.78	-0.05	0.73	-0.06	-0.58	-0.10
SC1	-0.42	-1.19	-0.44	-0.21	0.22	-0.41	-0.40	-0.24	0.37	0.30	-0.30	0.03
SN2	-0.48	-1.29	-0.50	-0.10	0.26	0.48	-0.35	0.15	0.10	0.49	-0.05	-0.03
SC4	-0.42	-0.89	-0.15	-0.14	0.00	-0.69	-0.06	-0.42	1.18	0.50	-0.19	0.86
SC7D	-0.41	-1.02	-0.47	-0.40	0.43	-0.18	-0.30	-0.45	0.22	0.50	0.45	-0.41
SN6D	-0.32	-1.05	-0.32	-0.09	-0.47	1.66	-0.34	0.51	-2.97	0.41	-0.06	-1.88
SC7S	-0.52	-0.84	-0.41	-0.38	0.53	0.08	-0.15	-0.26	0.30	0.42	0.42	-0.29
SN6S	-0.59	1.87	-0.06	0.07	0.02	1.05	0.12	-1.15	0.66	0.52	-0.74	-2.32
SC9	-0.36	-0.59	-0.04	-0.20	-0.01	0.47	0.43	0.00	0.77	-4.47	-0.36	-0.44
SCF	-0.59	0.48	-0.92	-0.08	0.38	1.51	-0.16	-0.07	0.69	0.60	1.10	-0.62
804872	1.04	-0.42	-0.58	3.96	-0.04	0.34	1.12	0.12	0.61	0.21	-0.83	-0.31
NMW	0.57	0.37	-0.02	1.82	0.56	-0.25	-0.71	-0.52	-0.12	-0.20	3.44	0.82
SMW1	4.47	0.02	-0.19	-1.04	-0.20	0.02	-0.73	0.19	0.14	-0.09	-0.56	-0.49
SMW2	0.67	0.52	1.05	-1.25	0.12	2.59	0.28	-0.57	0.37	0.20	0.66	1.27
SMW3	-0.27	-0.43	4.58	0.44	-0.02	-0.24	-0.04	-0.01	0.10	0.14	0.13	-0.56
SP1	-0.34	1.02	-0.44	-0.44	-3.38	-1.10	-0.15	1.17	0.38	-0.44	1.58	-0.72
SP2	-0.34	-0.37	0.05	0.25	-3.09	0.49	0.31	-0.74	-0.33	0.66	-1.07	1.76
NN0	0.05	0.48	-0.29	-0.48	0.49	-0.26	-0.44	-0.16	-0.04	0.34	-0.50	1.72
NC0	-0.14	0.20	0.15	0.43	0.19	-0.75	-0.82	-0.47	-1.87	-0.18	-0.98	1.16
NS0	-0.21	1.77	0.13	0.25	0.19	-1.64	-0.71	-0.74	0.47	0.39	-1.52	-1.03
NN3	-0.55	1.80	-0.40	-0.19	0.60	1.02	1.76	-0.08	0.18	-0.30	-0.65	1.32
NCSP3	-0.23	0.93	-0.28	0.17	0.75	-0.77	-0.63	-0.35	-2.49	-1.19	0.04	0.52
NS3	-0.34	0.54	0.20	0.11	0.79	0.15	0.02	4.40	0.20	0.43	-0.54	0.46
NNF	-0.19	1.13	-0.11	-0.76	0.73	-1.12	-0.62	-0.02	0.27	0.37	0.75	-0.19

Table C3. Landscape description factors extracted for statistical analysis of beach ridge fens.

Variable Name	Variable Meaning	Gather Method
L8_190109_TIR	Landsat 8 Thermal Infrared raster value for January 9, 2019 (winter)	Landsat tiles that had less than 1% cloud cover over entire study area selected. Pixels are 30x30m. Values were calculated by running ArcGIS's zonal statistics as table on all fen polygons.
L8_170824_B1red	Landsat 8 red color raster value for August 24, 2017 (summer)	
L8_170824_B2grn	Landsat 8 green color raster value for August 24, 2017 (summer)	
L8_170824_B3blu	Landsat 8 blue color raster value for August 24, 2017 (summer)	
L8_170824_TIR	Landsat 8 Thermal Infrared raster value for August 24, 2017 (summer)	
NAIP17_Av_B1red	NAIP 17 aerial photography red color raster value	NAIP imagery with a 1m resolution. Values were calculated by running ArcGIS's zonal statistics as table on all fen polygons.
NAIP17_Av_B2grn	NAIP 17 aerial photography green color raster value	
NAIP17_Av_B3blu	NAIP 17 aerial photography green color raster value	
Pit_NEAR_DIST	Distance to nearest gravel pit (in m)	Use ArcGIS near tool to find the distance to the nearest pit/stream/road from each fen polygon border
Stream_NEAR_DIST	Distance to nearest stream (in m)	
Road_NEAR_DIST	Distance to nearest road (in m)	
SHAPE_Area	Fen Area (sq m)	Area of each polygon in GIS
Len_Parallel_BR	Fen length parallel to beach ridge axis (m)	Measure polygon widest lengths parallel & perpendicular to beach ridge in GIS
Len_Perp_BR	Fen length perpendicular to beach ridge axis (m)	
Aspect_Ratio_Len	Aspect ratio-length parallel over perpendicular	Divide length parallel to ridge by length perpendicular
BR_CrossSecArea	Area of a cross section through the beach ridge (sq m)	Generate profile across beach ridge using 1m DEM. Start and stop profile at upgradient and downgradient edges of ridge. Generate line (regional slope) between endpoints. Subtract regional slope from profile. Calculate area in each 1m increment and sum total area.
BR_Volume	Volume of beach ridge (cu m)	Multiply cross sectional area by length of fen parallel to beach ridge axis.
Regional_Slope	Regional slope of till surface (m/m)	Slope of regional slope line generated in cross sectional area calculation
ksat_infen	Saturated hydraulic conductivity of soil in the fen (um/s)	In GIS, rasterize NRCS soil survey data for study area at 2m resolution. Values calculated by zonal statistics as table on each fen polygon
ksat_DG100	Saturated hydraulic conductivity of soil within 100m downgradient of fen (um/s)	In GIS, create lines, all from south to north on upgradient and downgradient sides of all fen polygons. Buffer lines on right side for upgradient

ksat_DG300	Saturated hydraulic conductivity of soil within 300m downgradient of fen (um/s)	and left side for downgradient at 100 and 300m. Clip rasterized 2m resolution NRCS soil survey data by buffers. Values calculated by zonal statistics as table on each buffer polygon (for each fen)
ksat_UG100	Saturated hydraulic conductivity of soil within 100m upgradient of fen (um/s)	
ksat_UG300	Saturated hydraulic conductivity of soil within 300m upgradient of fen (um/s)	
BR_avg_ksat	Saturated hydraulic conductivity of soil in the beach ridge (um/s)	In GIS, rasterize NRCS soil survey data for study area at 2m resolution. Create polygon for each fen that encompasses only the beach ridge upgradient. Values calculated by zonal statistics as table on each beach ridge polygon
NLCD16_Per_Wood_ Shrub	Percent of beach ridge covered by woods or shrubs.	In GIS, use zonal histogram to count each land use type in the NLCD16 land use layer (30m resolution, Landsat based) for each fen's beach ridge polygon. Divide land use counts by total count to get percent area. Combine similar land uses.
NLCD16_Per_Grass_ Pasture_EmWetl	Percent of beach ridge covered by grass, pasture, or emergent wetland	
NLCD16_Per_ CultivCrops	Percent of beach ridge covered by cultivated crops	
UTM15N_Easting	Easting (m) of fen center point in UTM Zone 15N coordinates (used by MN)	GIS-generated coordinates of center point of all fen polygons.
UTM15N_Northing	Northing (m) of fen center point in UTM Zone 15N coordinates (used by MN)	
Av_Surf_Elev	Average surface elevation of fen (m)	Based on 1m DEMs. Values were calculated by running ArcGIS's zonal statistics as table on all fen polygons.
Avg_Dep_to_ConfAq	Average depth to confined aquifer (ft)	Identify 3 closest wells to each fen that penetrate a confined aquifer. Use MN County Well Index stratigraphic logs to find depth to first confined sand greater than 5 ft thick. Average 3 depths.

Table C4. Factor loadings for varimax-normalized principal component analysis of all beach ridge calcareous and non-calcareous fens.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9
L8_190109_TIR	0.00	-0.19	-0.81	0.20	-0.05	-0.13	-0.21	0.18	-0.13
L8_170824_B1red	0.31	0.00	0.15	-0.05	-0.04	0.04	0.01	-0.01	0.83
L8_170824_B2grn	-0.23	0.05	0.02	-0.11	-0.45	0.08	-0.23	0.04	-0.27
L8_170824_B3grn	0.14	0.06	0.38	0.00	0.06	-0.09	-0.23	-0.05	0.69
L8_170824_TIR	0.21	0.03	-0.14	-0.16	0.11	0.27	0.18	-0.05	0.80
NAIP17_av_B1red	0.91	-0.02	0.03	0.10	0.10	-0.01	-0.02	-0.10	0.21
NAIP17_av_B2grn	0.77	0.05	-0.12	0.04	-0.01	-0.05	-0.26	0.02	0.30
NAIP17_av_B3blu	0.87	0.03	-0.01	0.08	0.13	0.08	0.01	-0.06	0.19
Pit_NEAR_DIST	0.56	-0.28	0.11	-0.02	-0.22	0.15	0.34	-0.14	0.05
Stream_NEAR_DIST	-0.32	-0.12	0.55	0.08	-0.09	0.11	-0.27	0.34	0.01
Road_NEAR_DIST	0.02	-0.31	-0.18	0.24	-0.09	0.18	-0.10	0.09	0.07
SHAPE_Area	0.04	-0.02	-0.19	0.01	-0.06	-0.94	0.02	0.06	-0.05
Len_Parallel_BR	-0.08	0.21	-0.05	0.09	-0.07	-0.64	0.51	0.23	0.00
Len_Perp_BR	-0.02	-0.02	-0.14	0.01	0.01	-0.90	-0.25	-0.07	-0.08
Aspect_Ratio_Len	-0.19	0.19	0.19	0.11	-0.17	0.20	0.77	-0.01	0.08
BR_CrossSecArea	-0.09	0.13	-0.13	0.17	-0.04	0.01	-0.06	0.89	-0.03
BR_Volume	-0.09	0.18	-0.11	0.13	0.00	-0.11	0.03	0.92	-0.06
Regional_Slope	-0.30	0.04	-0.37	-0.13	0.40	-0.14	-0.06	0.05	0.33
ksat_infen	0.00	0.13	0.04	-0.10	0.72	0.09	0.13	0.18	-0.01
ksat_DG100	0.07	0.15	0.11	0.12	0.87	0.03	-0.16	-0.14	0.03
ksat_DG300	0.04	0.07	0.12	0.10	0.87	0.02	-0.16	-0.08	-0.03
ksat_UG100	0.07	0.77	0.28	-0.05	0.21	-0.02	0.16	0.29	0.07
ksat_UG300	-0.07	0.92	-0.01	-0.01	0.03	0.01	-0.06	0.18	-0.01
BR_avg_ksat	0.03	0.92	0.08	0.06	0.13	0.01	-0.04	0.10	0.09
NLCD16_Per_Wood_Shrub	-0.35	0.53	0.18	0.12	-0.02	0.02	0.10	-0.26	-0.07
NLCD16_Per_Grass_Pasture_EmWetl	0.19	-0.11	-0.03	0.88	0.06	-0.05	0.05	0.21	-0.05
NLCD16_Per_CultivCrops	0.00	-0.15	-0.02	-0.94	-0.09	0.04	-0.07	-0.08	0.12
UTM15N_Easting	0.40	-0.21	0.44	-0.13	0.13	-0.06	0.53	-0.21	-0.17
UTM15N_Northing	0.04	0.31	0.79	-0.05	0.16	0.08	0.04	-0.08	0.21
Av_Surf_Elev	0.53	-0.30	0.22	0.10	0.15	-0.24	0.48	-0.01	-0.16
Avg_Dep_to_ConfAq	0.03	0.10	0.59	0.14	0.13	0.23	0.24	-0.16	-0.01
Expl.Var	3.60	3.25	2.84	2.00	2.69	2.49	2.07	2.27	2.33
Prp.Totl	0.12	0.10	0.09	0.06	0.09	0.08	0.07	0.07	0.08

Table C5. Factor scores for varimax-normalized principal component analysis of all beach ridge calcareous and non-calcareous fens.

Fen Case	Calcareous?	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9
CW01	no	-0.22	-0.17	-0.45	-1.40	0.59	-0.55	-0.94	-0.19	0.25
CW02	no	1.40	-0.84	-0.05	-0.12	-0.96	0.27	-0.43	-0.11	-0.10
CW03	no	0.65	-0.33	0.91	-1.63	2.41	-0.08	-0.54	0.22	-1.07
CW04	no	1.58	0.13	-0.30	0.04	-0.58	-2.35	2.16	-0.03	1.13
CW05	no	0.10	-0.74	1.02	-0.50	0.87	-0.09	0.58	-0.05	-2.59
CW06	no	-2.58	-0.22	-0.22	-0.79	-0.37	-0.18	0.32	-0.27	1.36
CW07	no	-1.12	-0.11	-0.84	-1.33	0.39	-2.07	-0.08	-0.48	1.52
CW08	no	-0.99	-0.84	-0.77	1.71	0.18	-0.48	0.13	0.37	0.75
CW09	no	-0.09	-0.99	0.80	1.17	-0.67	-4.22	-0.44	-0.61	-0.61
CW10	no	1.06	-0.41	0.21	0.05	-0.80	0.31	-1.21	0.17	-0.03
CW11	no	-0.11	-1.14	-0.81	-0.26	0.14	0.84	0.87	-0.20	-1.28
CW12	no	-0.77	1.36	-1.50	-0.11	-0.21	0.46	-0.58	-0.58	-0.53
CW13	no	1.01	4.33	-0.60	-0.61	-0.85	-0.45	-0.66	0.89	-0.13
CW14	no	-0.06	-0.22	-0.04	-0.69	-0.90	0.57	-0.42	-1.07	-1.07
CW15	no	-0.14	-0.81	-0.39	-1.04	-0.89	1.00	-0.86	0.33	0.19
CW16	no	-0.61	-0.61	-1.16	-1.61	3.98	0.49	0.17	0.29	2.81
CW17	no	-1.33	-0.80	-0.42	-0.56	-0.46	0.73	-0.61	-0.28	0.19
CW18	no	0.52	-1.12	0.68	0.69	1.72	-0.87	1.06	-0.48	-1.81
CW19	no	0.14	-1.71	0.23	-0.75	-0.16	0.36	0.36	0.19	3.78
CW20	no	-2.10	-0.81	0.56	0.66	-0.42	0.13	-0.52	-0.32	-1.52
CW21	no	1.93	-0.93	-0.66	0.77	2.60	0.95	0.30	-0.24	-0.19
CW22	no	-0.21	-0.57	-0.21	0.51	-0.25	-0.13	0.09	-0.67	-0.92
CW23	no	-0.08	-0.39	0.10	-1.49	1.62	1.00	-1.23	-0.50	-1.01
CW24	no	-0.08	-0.52	0.96	-1.26	-0.10	-0.47	0.09	0.22	0.78
CW25	no	0.21	-0.85	0.40	-1.15	-0.94	0.78	-1.04	-0.05	0.67
CW26	no	-0.26	-0.18	-1.39	1.02	-0.51	1.12	-1.00	-0.37	-0.50
Agassiz-Nelson	yes	-2.10	0.49	-0.38	0.31	-0.43	0.53	2.72	-1.06	-0.98
Agassiz-Olson WMA	yes	-0.80	-0.28	0.15	1.10	-0.45	0.53	-0.58	-0.65	-0.23
Anna Gronseth Prairie - Akron 10	yes	-0.01	-0.59	-2.32	2.20	0.43	0.14	-0.12	-0.56	-1.01
CBS Norman 1	yes	-1.10	-0.45	0.30	-0.89	-0.67	0.30	-0.43	0.03	-0.12
CBS Polk 1	yes	1.63	0.40	0.57	-1.02	-0.54	0.41	1.21	-0.04	-1.00
CBS Polk 10	yes	0.93	0.16	0.16	1.21	-0.30	0.46	0.39	-0.28	0.79
CBS Polk 11	yes	1.29	-0.01	0.06	0.40	-0.63	0.50	0.67	-0.38	1.10

CBS Polk 12	yes	0.36	-0.17	0.54	-0.83	-0.63	0.66	0.53	0.20	0.95
CBS Polk 2	yes	-0.77	0.59	-0.30	1.05	-0.72	0.25	2.80	-0.93	1.01
CBS Polk 3	yes	0.75	-0.35	0.36	1.09	-0.29	0.57	-0.04	0.16	0.50
CBS Polk 4	yes	1.92	-0.34	0.13	0.19	0.13	0.26	0.24	0.08	0.94
CBS Polk 5	yes	1.92	-0.55	1.09	-0.58	-0.67	0.35	0.07	0.31	0.31
CBS Polk 6	yes	1.18	0.07	0.37	-0.53	-0.75	0.61	-0.35	0.05	-0.45
CBS Polk 7	yes	1.56	0.17	0.24	-0.98	-0.80	0.59	-0.71	-0.05	-1.04
CBS Polk 8	yes	1.45	0.21	0.54	-0.76	-0.69	0.70	1.14	-0.04	0.61
CBS Polk 9	yes	0.80	-0.08	0.19	1.54	-0.95	0.73	0.60	0.07	0.62
CBS Red Lake 1	yes	0.61	-0.38	0.82	-0.94	-0.45	0.66	-0.33	-0.37	-0.87
Chicog WMA East-Central	yes	-0.77	0.19	-0.40	-0.09	1.30	-0.83	0.09	-0.95	0.18
Chicog WMA East-North	yes	-0.39	0.23	0.10	-0.65	0.11	0.37	-0.37	0.18	-0.62
Chicog WMA East-South	yes	0.15	0.36	-0.49	1.03	0.68	0.34	-0.77	-0.96	0.08
Chicog WMA West	yes	-0.04	4.32	-0.28	-0.19	0.60	-0.66	0.68	2.42	-0.99
Felton Prairie B Bar B Ranch	yes	-0.53	-0.81	-1.40	2.35	0.43	0.27	-0.54	1.95	0.96
Felton Prairie County Land	yes	-0.45	1.83	-1.77	-0.16	-0.34	0.70	-0.96	-0.03	-0.03
Felton Prairie Felton WMA	yes	-0.05	0.24	-1.43	-0.86	0.01	0.28	-1.62	0.24	0.02
Felton Prairie Flowing 24	yes	-0.82	-0.93	-0.49	0.66	0.10	0.06	-0.27	7.00	-0.23
Godfrey Prairie	yes	1.46	-0.15	0.89	0.93	-0.03	0.11	0.31	0.60	-0.83
Green Meadow 22	yes	-0.73	-0.80	0.88	2.09	-0.77	0.84	-1.32	-0.12	-0.34
Green Meadow 26	yes	-1.11	-0.57	0.34	-0.71	-0.81	0.69	0.48	0.54	0.06
Green Meadow 35	yes	-0.65	-0.47	0.03	-0.63	-0.24	0.05	-0.10	-0.45	0.23
Kertsonville WMA	yes	-0.88	2.04	0.52	0.84	0.35	-0.52	-1.79	-1.52	0.07
Kittleson Creek Mire	yes	0.41	0.05	-0.14	-0.41	0.52	-1.59	-0.01	-0.56	-0.44
Norden 18	yes	0.66	1.36	1.50	1.68	4.30	0.37	-0.13	-0.87	1.09
Onstad WMA	yes	-1.21	0.66	0.35	0.08	-0.34	0.15	2.65	-0.84	0.24
Pankratz Prairie South	yes	-0.01	0.12	0.55	1.05	-0.97	-0.54	-1.16	-0.56	1.19
Pembina Trail: Crookston	yes	1.21	0.21	0.18	-1.49	-0.55	0.84	0.78	-0.26	0.12

Pembina Trail: TNC	yes	0.78	-0.09	0.55	1.17	-0.85	0.72	1.54	0.15	0.46
Rothsay Prairie - Prairie View 33	yes	0.59	-0.24	-1.54	1.55	-0.50	0.51	-0.07	-0.41	-0.82
Rothsay Prairie Tanberg 16	yes	0.97	-0.75	-1.80	-0.23	-0.32	-3.63	0.41	0.14	0.21
Rothsay Prairie Tanberg 9	yes	1.04	-0.65	-1.86	-0.26	-0.16	-1.32	0.03	-0.36	-0.44
Rothsay WMA - Akron 4	yes	-0.22	-0.42	-1.76	-0.86	-0.10	-2.39	0.05	0.21	-0.61
Sanders Fen North-a	yes	-1.41	0.03	2.35	-0.65	0.60	-0.24	1.07	0.85	-0.77
Sanders Fen North-b	yes	-0.45	0.04	1.64	1.90	0.69	0.12	1.28	0.71	-0.40
Sanders Fen South	yes	-0.74	0.27	1.97	-0.46	0.28	-0.58	1.27	0.94	-0.54
Spring Creek 25	yes	-2.19	-1.05	0.36	-1.25	-0.16	0.70	0.99	0.02	-0.82
Tamarac River	yes	-0.36	0.02	2.91	0.49	-0.96	-1.27	-2.67	0.59	1.21
Thorson Prairie WMA South -a	yes	0.02	0.82	-0.16	-0.29	-0.28	0.63	-0.49	-0.38	0.42
Thorson Prairie WMA South -b	yes	0.36	0.55	-0.42	-0.72	0.53	0.59	-0.12	0.27	0.65
Thorson Prairie WMA South -c	yes	-0.67	1.26	-0.13	0.59	-0.67	0.57	-0.52	-0.64	1.96
Thorson Prairie WMA South -d	yes	-1.21	1.34	-0.50	-0.42	-0.42	0.85	0.56	-0.16	0.22
Town Hall Prairies	yes	0.46	-0.61	-2.36	-0.59	0.34	0.60	0.05	0.33	-1.67
Viking 18	yes	-0.32	0.17	1.47	0.99	1.14	0.00	-2.14	-0.58	-0.63
Viking 20	yes	-0.28	0.34	1.15	-0.56	-0.61	-1.94	-1.06	-0.32	-0.36
Viking Strip 4	yes	-0.11	1.71	0.63	0.22	0.04	-0.18	0.47	0.12	-0.03

Appendix D: Daily Water Level Fluctuations Analysis

Background and Methods

The water levels collected from the fen sites in this study have low-amplitude (~1 inch), high frequency fluctuations (ex. Figure 9, Figure 14, Figure 16Figure 17). To determine the source of these fluctuations, a multivariate principal component analysis was performed on the data.

The hydrograph data were analyzed as an average daily (midnight to midnight) signal. Records from the June/July transducer installations through the last day of August (growing season) were used. To find the average daily signal for each well, first the hydrograph signal from rainfall was subtracted. The rainfall signal was generated by taking a 24-hour moving average centered on each 15-minute observation. This moving-average hydrograph was subtracted from the raw hydrograph, leaving only non-rainfall-related fluctuations. After averaging this data from 15-minute time steps to hourly time steps, the resulting data were averaged for each hour of the day. This resulted in an average daily water level pattern given by 24 observations, one for each hour of the day, for each of 24 included wells. After the principal component multivariate analysis with a varimax normalized rotation (Davis, 2011), the resulting factors describe groups of wells that respond similarly on a daily basis, such as if they respond to evapotranspiration.

Results

The hydrographs were analyzed for patterns in their daily fluctuations during the growing season (pre-September 1). After removing the rainfall hydrograph signal and performing a principal component factor analysis on the average daily response for each well, three factors (patterns) emerged (Figure D1, details in Table D1 at end of this appendix). Factor 1 describes 46% of the variance and is loaded by the wells in the sand apron just upgradient of the fen at both sites, the fen surface water at Sanders Fen, the beach ridge aquifer wells at Agassiz-Nelson Fen, the sand beneath the fen at Agassiz-Nelson Fen, and the surficial sands at the two off-fen nests at Agassiz-Nelson Fen. Factor 2 describes 27% of the variance and is loaded by the deep and intermediate wells at the off-fen nests at Agassiz-Nelson Fen. Factor 3 describes 25% of the variance and is loaded by the beach ridge aquifer wells at Sanders Fen and the wells in the sand below the fen and at the base of the peat at Sanders Fen. These high factor 3 loadings are negative.

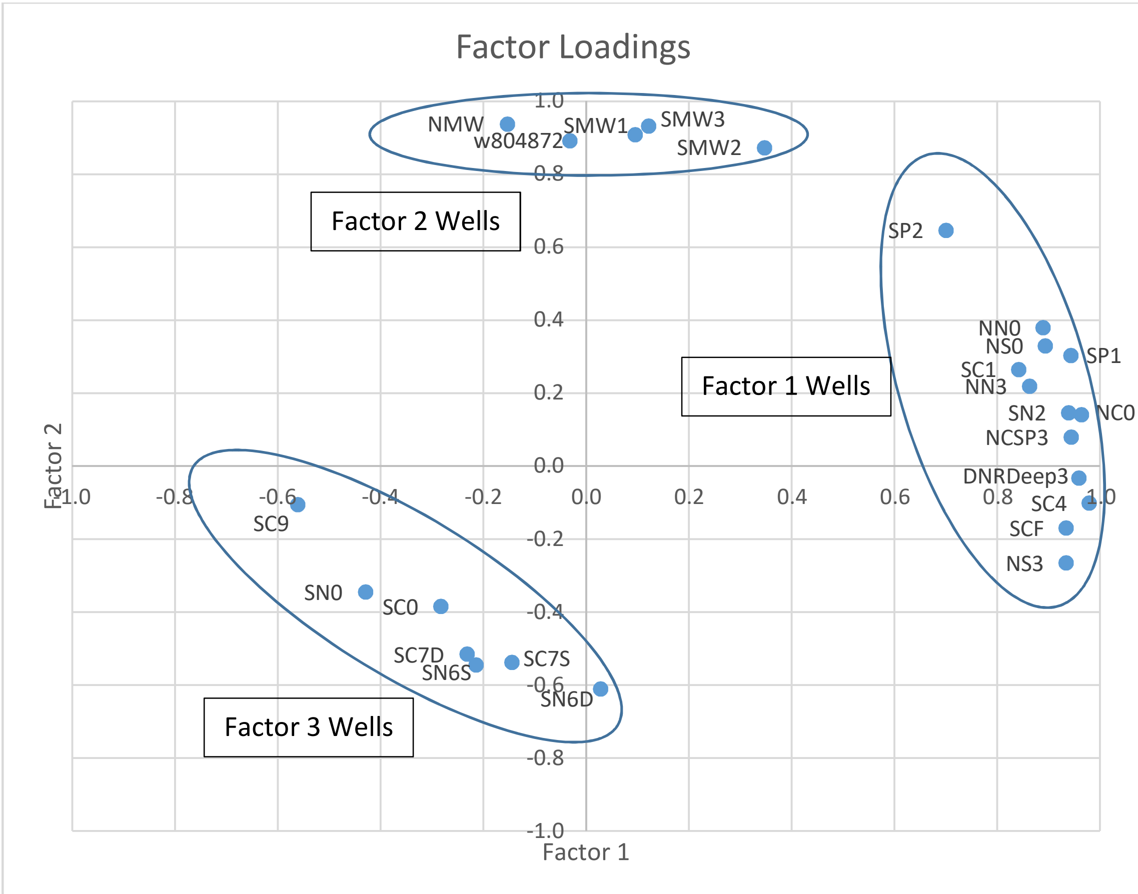

Figure D1. Factor loadings for wells based on daily water level fluctuation analysis. Plot shows only factor 2 vs factor 1, but factor 3 wells make a distinct cluster as well.

The factor scores give an idea of the daily water level pattern experienced by each group of wells described by each factor (Figure D2, details in Table D2 at the end of this appendix). Since factor 3 variables loaded negatively onto the factor, a line describing negative factor 3's pattern is also included as this better matches the water level pattern followed by these wells. Factor 1 wells fluctuate with a period of 24 hours. Factor 2 and 3 wells fluctuate with both a 24 hour period and a shorter (approximately 12 hour) period.

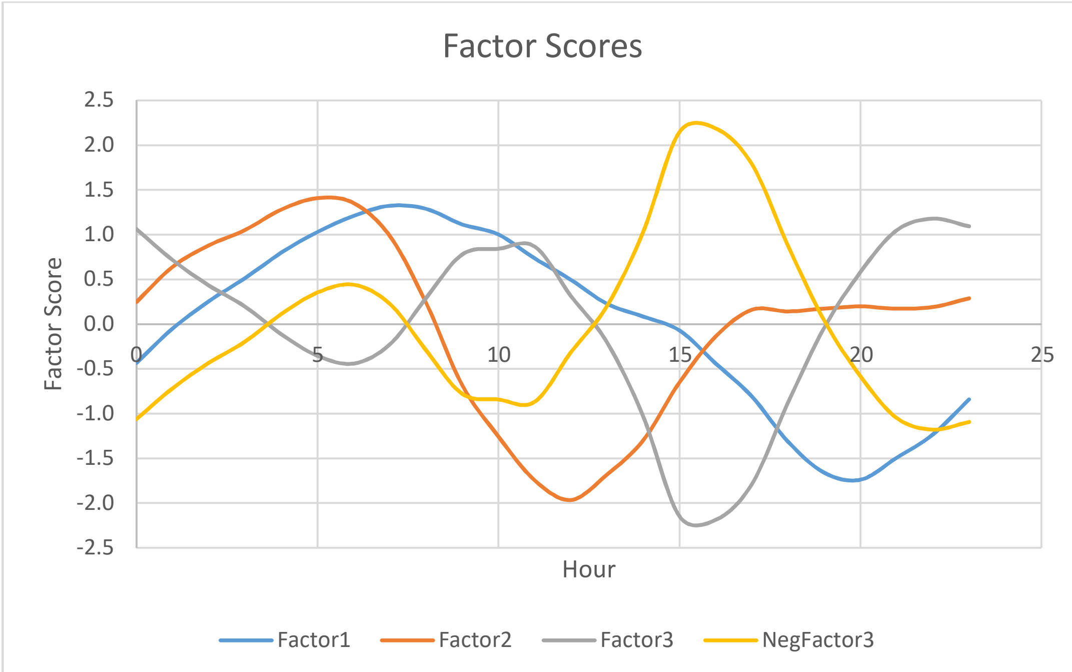

Figure D2. Factor scores showing the daily pattern followed by each factor group of wells.

Power spectrums generated using a Fast Fourier Transform (FFT) on one well from each of the three factor groups are presented in Figures D3-D5. Well SC4, used for factor 1, has one major peak with a 24 hour period (frequency 0.04 hr^{-1}). Wells SC7D and w804872, used for factors 2 and 3 respectively, have 2 major peaks with periods of 12 and 24 hours (0.04 and 0.08 hr^{-1} frequencies).

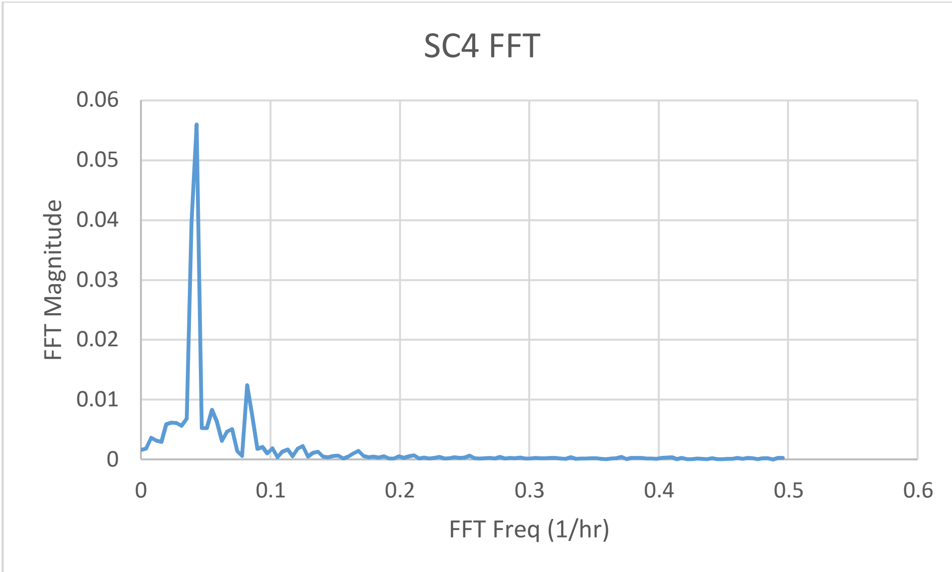

Figure D3. Fast Fourier Transform analysis for well SC4, representing factor 1.

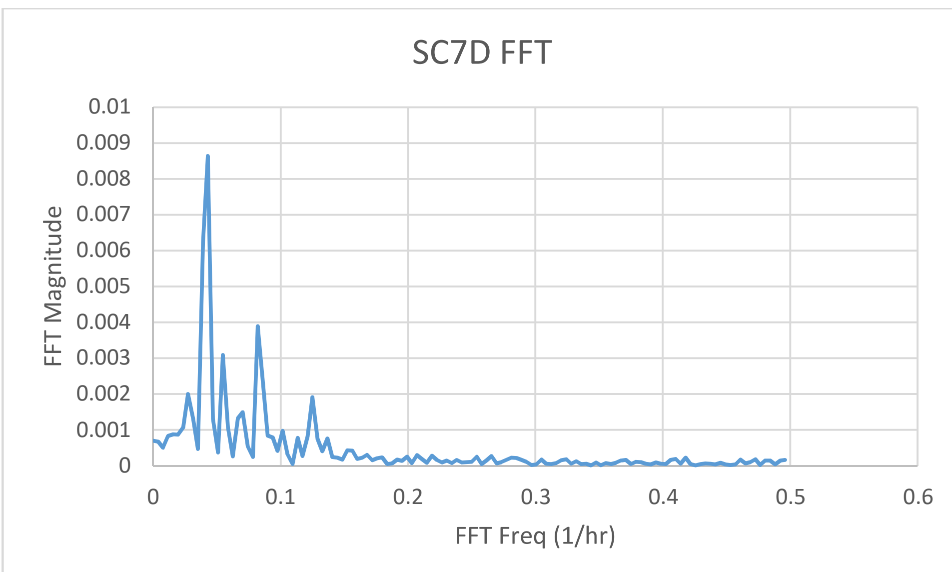

Figure D4. Fast Fourier Transform analysis for well SC7D, representing factor 2.

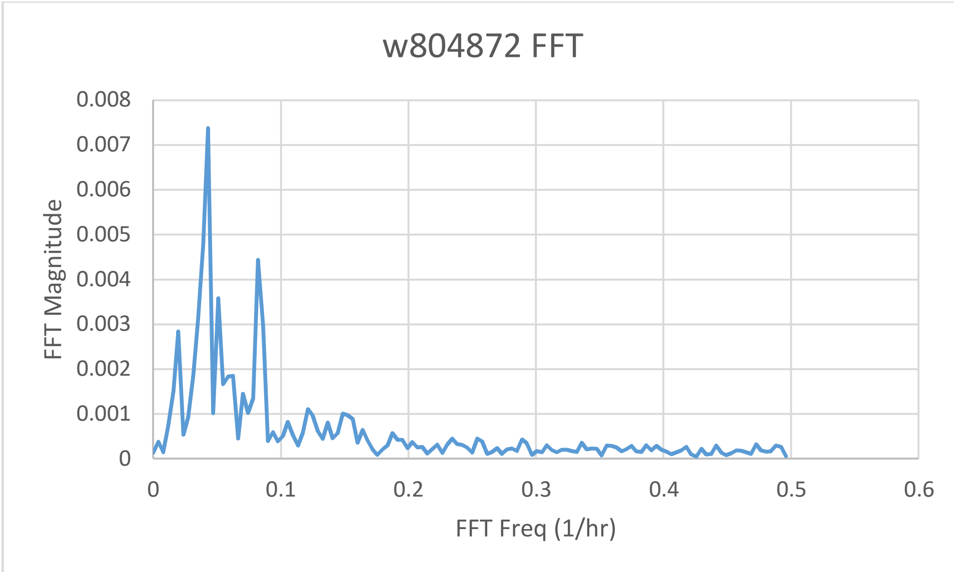

Figure D5. Fast Fourier Transform analysis for well 804872, representing factor 3.

The daily water level fluctuations of the wells at Sanders Fen respond during the growing season to either to an evapotranspiration signal with a period of 24 hours and peaking in the early morning hours or a different mechanism potentially related to earth tides. Earth tides result in a twice-daily cycle from the Earth swelling and contracting because of the moon's pull. The wells described by factor 1 are near the surface or within the expected rooting zone and follow a daily pattern of high water levels in the morning and low water levels in the late afternoon, as expected for evapotranspiration. In the FFT power analysis, there is only one major peak with a period of 24 hours (Figure D3). Factor 3 describes the wells at the base of the peat and in the sand below the peat at Sanders Fen as well as those in the beach ridge at Sanders Fen. This factor follows the pattern that you would expect for the earth tides with two cycles per day and one cycle being larger in amplitude (Figure D4). However, these wells are seemingly too shallow for feeling earth tides. They also are deeper and less likely to see an evapotranspiration signal. These factor 3 wells also follow a statistically different pattern than the deeper wells at Agassiz-Nelson Fen described by factor 2 which are more likely to see earth tides. However, both factor 2 and 3 wells have high magnitude peaks in the power spectrums (Figures D4-D5) for both 12 and 24 hour period cycles, typical of earth tides.

At Agassiz-Nelson Fen, all of the surface wells, described by factor 1, respond on a daily basis to evapotranspiration with a 24-hour period cycle (Figure D3), while all of the deep/intermediate wells at the nests, described by factor 2, respond differently with a two-cycle pattern likely related to earth-tides or pumping (Figure D4). This two-cycle pattern has one cycle with larger amplitude and the following with a smaller amplitude every day.

Table D1. Factor loadings. Varimax normalized, principal component extraction.

Well	Factor1	Factor2	Factor3
SC0	-0.28	-0.38	-0.88
SC1	0.84	0.27	0.44
SC4	0.98	-0.10	0.16
SC7S	-0.14	-0.54	-0.83
SC7D	-0.23	-0.52	-0.82
SC9	-0.56	-0.11	-0.81
SCF	0.93	-0.17	-0.22
SN0	-0.43	-0.35	-0.83
SN2	0.94	0.15	0.23
SN6S	-0.21	-0.55	-0.81
SN6D	0.03	-0.61	-0.78
NS0	0.89	0.33	0.29
NS3	0.93	-0.27	0.02
NC0	0.96	0.14	0.21
NCSP3	0.94	0.08	0.32
NN0	0.89	0.38	0.22
NN3	0.86	0.22	0.42
SP1	0.94	0.30	0.11
SMW1	0.10	0.91	0.36
w804872	-0.03	0.89	0.44
SP2	0.70	0.65	0.18
SMW2	0.35	0.87	0.27
SMW3	0.12	0.93	0.33
NMW	-0.15	0.94	0.31
DNRDeep3	0.96	-0.03	0.21
Expl.Var	11.61	6.68	6.21
Prp.Totl	0.46	0.27	0.25

Table D2. Factor Scores. Varimax normalized, principal component extraction.

Hour (Case)	Factor1	Factor2	Factor3	NegFactor3
0	-0.43	0.25	1.06	-1.06
1	-0.05	0.64	0.72	-0.72
2	0.26	0.88	0.43	-0.43
3	0.51	1.05	0.20	-0.20
4	0.80	1.28	-0.11	0.11
5	1.03	1.41	-0.35	0.35
6	1.21	1.35	-0.44	0.44
7	1.32	0.99	-0.23	0.23
8	1.29	0.24	0.29	-0.29
9	1.11	-0.68	0.78	-0.78
10	1.00	-1.26	0.84	-0.84
11	0.74	-1.74	0.87	-0.87
12	0.50	-1.97	0.32	-0.32
13	0.23	-1.68	-0.20	0.20
14	0.08	-1.30	-1.03	1.03
15	-0.07	-0.65	-2.15	2.15
16	-0.44	-0.14	-2.19	2.19
17	-0.81	0.16	-1.79	1.79
18	-1.31	0.14	-0.88	0.88
19	-1.66	0.17	-0.04	0.04
20	-1.74	0.20	0.58	-0.58
21	-1.49	0.17	1.05	-1.05
22	-1.23	0.19	1.18	-1.18
23	-0.84	0.29	1.09	-1.09