

ASSESSING THE ROLE OF GEOLOGIC SETTING ON THE
HYDROLOGY AND GROUND WATER GEOCHEMISTRY OF
FENS IN THE GLACIATED MIDWESTERN UNITED STATES

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Submitted to the faculty of the University Graduate School
in partial fulfillment of the requirements
for the degree
Master of Science
in the Department of Earth Sciences,
Indiana University

May 2007

Accepted by the Faculty of Indiana University, in partial fulfillment of the requirements for the degree of Master of Science.

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ACKNOWLEDGEMENTS

I would like to acknowledge my advisory committee for their input and assistance with data interpretation. An extended gratitude to Dr. Lenore Tedesco is appropriate for the wide array of support she has provided for this project. The Indiana Department of Natural Resources, Division of Nature Preserves was kind enough to grant access to some remarkable wetland communities. Thanks to John Bacone and Tom Swinford for their continued interest and encouragement with Indiana fen research. Indy Parks allowed for the sample collection at Southwestway Park and Holliday Park. Don Miller and Andrew Mertz deserve many thanks for their support. Access to the Ritchey Woods Natural Area was granted by the Town of Fishers Department of Parks and Recreation. A special thanks to Danesa Stoltz for promoting the research at Ritchey Woods. The Graduate Student Organization in the School of Science at IUPUI provided a research grant to aid in the field work and transportation efforts. Field and lab work would not have been possible without the assistance of friends and colleagues, especially Vince Hernly, Jeremy Webber, Cheryl Nazareth, Sarah Sutor, Travis Erny, Ryan McAtee, and Denise Pascual. GIS and cartography efforts would not have been possible without the support of Mr. Jeremy Webber. The composite staff of the Center for Earth and Environmental Science at IUPUI is deserving of my appreciation for all of their expertise, advice, field logistics, travel, and research supplies.

ABSTRACT

Dustin Graves

ASSESSING THE ROLE OF GEOLOGIC SETTING ON THE HYDROLOGY AND GROUND WATER GEOCHEMISTRY OF FENS IN THE GLACIATED MIDWESTERN UNITED STATES

A water quality investigation of several fens located in the temperate glaciated Midwestern United States, near the southern limit of fen occurrence, was conducted to assess the role of geologic setting on the hydrogeochemical signature of fens and to compare hydrogeochemistry of fens located in different geographic and geologic settings. The five studied fens, located in the Central Till Plain physiographic region of Indiana, receive ground water sourced from glacial tills with very similar petrologic composition. These wetlands are hydrogeomorphically classified as slope wetlands with dominant ground water input. More specifically, these sites are inter-till / intra-till type fens (Type Ia and Ib) or outwash terrace type fens (Type II). Shallow ground water was collected just prior to surface interception (source water), and again after discharging into each fen (fen water) and measured for a suite of cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) and anions (HCO_3^- , SO_4^{2-} , NO_3^- , NO_2^- , PO_4^{3-} , and Cl^-). Fen water hydroperiods showed similar dynamics, despite some variation in the hydrologic input of these systems (source water).

Central Indiana fens are recognized as Ca^{2+} , Mg^{2+} , and HCO_3^- dominated systems. Fen water showed substantial evolution from source water at each study site, evidently the result of carbonate and gypsum dissolution dynamics. However, when only fen water is analyzed, results suggest that ground water of the southern fens represents geochemical similarity, with the exception of anthropogenic influence. The greatest geochemical

variation among central Indiana fens can be attributed to Na^+ and Cl^- , which has been linked to road salt contamination at two of the study sites.

This hydrogeochemical study also reveals that fens (slope wetlands) within this particular geologic setting of central Indiana show strong geochemical similarities to fens located throughout the temperate Northern Hemisphere. However, statistical analyses provide evidence that the parameters of Ca^{2+} , HCO_3^- , and SO_4^{2-} account for the greatest variation among these wetland communities, suggesting that calcium carbonate and gypsum dissolution dynamics are primarily fen specific while other parameters remain relatively homogenous across a wide geographical range.

Lenore P. Tedesco, Ph. D.

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INTRODUCTION

Fens can be generally described as ground water-charged wetlands. Amon et al. (2002) characterized fens as wetlands that typically maintain water saturation of the root zone throughout the growing season due to the presence of ground water seeps and have carbon-accumulating substrates including organic and/or carbonate deposition. Godwin et al. (2002) simply describe fens as communities of calciphilic vegetation reliant upon ground water input. Fens maintain a rare status in the glaciated yet temperate Midwestern United States due to the unique natural setting of these ecotones and the depletion thereof (Hunt et al. 1999; Amon et al. 2002). The sustenance of these wetland communities relies upon the combination of landscape, climate, geology, and hydrology (Amon et al. 2002). In the United States, fens are most commonly located in areas of prominent Wisconsinan deposition (Minnesota, Wisconsin, northern Illinois, northern Indiana, and northwest Ohio) which provides abundant coarse-grained glacial outwash deposits comprising large recharge zones. Fens located in this area of the temperate Midwestern USA are also supported by abundant precipitation and lower evapotranspiration rates than other areas that might support fen development, such as the Great Plains and regions blanketed only with pre-Wisconsinan deposits (Amon et al. 2002).

Fens generally occur at topographic and/or stratigraphic breaks on the land surface. Such geomorphic settings typically provide for hydrologic gradients that support ground water seeps to the surface (Amon et al. 2002). Attempts to associate fens with specific geomorphic settings have been suggested; however these associations tend only to be regionally applicable (Richardson et al. 1994; Carpenter 1995; Almendinger and

Leete 1998; Godwin et al. 2002). Thompson et al. (1992) proposed a fen classification scheme that incorporates fen geomorphology and source of water. Among the fen types recognized in this classification are the intra-till and inter-till fens and outwash terrace fens. Figure 1 provides a general geologic cross section of these fen types modified from Thompson et al. (1992), with a typical ground water recharge flow arrow. Based on the hydrogeomorphic sub-classification scheme, which encompasses all types of wetlands and not just fens, the central Indiana fens included in this study are recognized as slope wetlands with dominant ground water input with a consistent annual hydroperiod (Brinson 1993; Smith et al. 1995; Cole et al. 1997). This specific characterization bestows more of a hydrologic function and would therefore be of utilization for wetland managers and the regulatory community.

Many of the hydrogeochemical studies on fens throughout the Northern Hemisphere tend to focus on impacts of land use and associated vegetation (Wilcox 1986; Panno et al. 1999) and often neglect the influence of the geologic setting on wetland function. Other studies have focused on spatial geochemical dynamics of wetlands (Bernaldez and Benayas 1992; Hite and Cheng 1996) but did not include a range of data from other studies to statistically evaluate the relationships of wetland ground water chemistry on a large geographical scale. Stewart et al. (1993) conducted a baseline chemical study of Indiana fens however did not investigate the role of stratigraphy or geomorphology of the specific fen sites, and focused on the surface water geochemistry. Amon et al. (2002) were unable to discover any significant trends or consistent hydrogeochemical dynamics in temperate zone fens, and found it difficult to apply water chemistry data to an overall definition of such wetlands. However, local

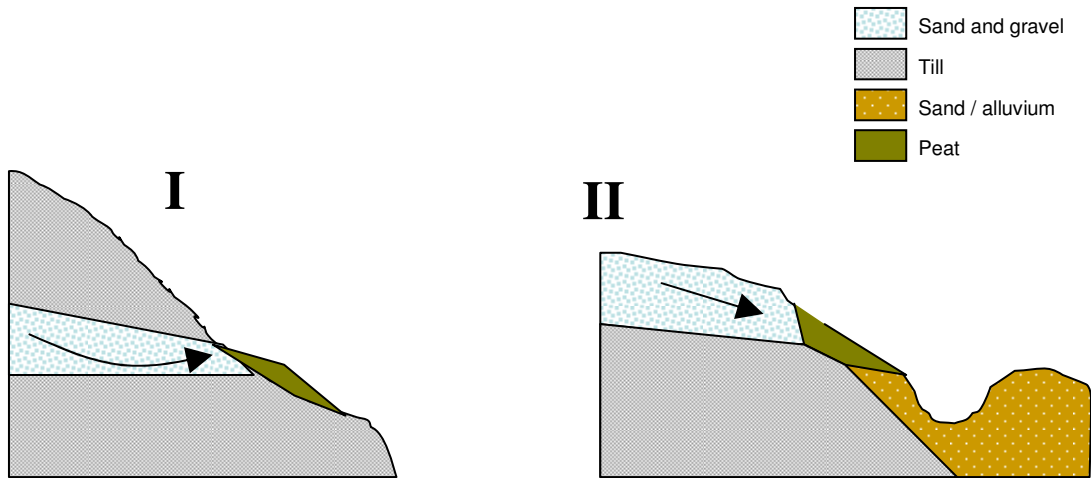


Figure 1. Schematic diagram showing the generalized hydrogeomorphic and stratigraphic setting of the central Indiana fens. Arrows represent ground water flow. Type I are considered inter-till or intra-till fens while Type II are considered outwash terrace fens. Schematics modified from Thompson et al. (1992).

environmental gradients were found to correlate to hydrogeologic setting (HGS) in New York state (Godwin et al. 2002). A similar correlation is sought with the central Indiana fens and their respective hydrogeologic settings.

Indiana ranks among the highest in states suffering from wetland loss in the USA, with an estimated 87% depletion since the onset of European settlement (Mitsch and Gosselink 2000). As most of Indiana's wetlands have been lost to development or farming (Robb 2002), the desire and obligation to protect and restore remaining wetlands as unique habitats to Indiana has become vital to a healthy natural environment.

Temperate zone fens are found in these glaciated environments that are very suitable for farming, and have more recently become areas of widespread urban development (Amon and Briuer 1993).

The fens selected for this study are located just north of the Wisconsin glacial maximum, placing these sites among the southern-most fens of the glaciated Midwestern USA (Figure 2). South of the Wisconsin glacial front, fen occurrence is extremely rare (Amon et al. 2002). This study seeks to document the relationship of fen water chemistry with the general hydrology, stratigraphy, and geomorphology associated with the wetland, and attempt to assign a relatively predictive hydrologic and geochemical signature to slope wetlands within the temperate glaciated Midwest. A determination of ground water geochemical evolution from the source aquifer to the zone of prevalent wetland vegetation and/or surface saturation is also discussed. Such an investigation also provides for a hydrogeomorphic and geochemical characterization of some of the southern-most existing fen communities in the glaciated Midwest. Furthermore, a comparison of fen geochemical data from a broad geographic range aims to enhance our

understanding of some of the underlying geochemical dynamics that control fen ground water chemistry.

BACKGROUND

Climate and Geology

This fen geochemical study was conducted at five sites in central Indiana (Figure 2). Central Indiana lies in the northern mid-latitudes and is characterized by a temperate climate. This region typically receives 84 – 86 cm of precipitation annually on average (<http://www.worldclimate.com>, 2004). The average annual temperature in this part of the state is 11.2 degrees Celsius. According to the Indiana State Climate Office (2004) the average maximum temperature is 29.7 degrees Celsius (in July) and the mean minimum temperature, occurring in January, is -8.2 degrees Celsius.

Sedimentary units of Paleozoic age, which dip gently to the southwest, comprise the bedrock geology of central Indiana. Few bedrock exposures crop out in this area as extensive glacial deposits of Pleistocene age rest atop the Paleozoic rocks (Hall 1999). Outcrops that do occur tend to persist in stream valleys where incision predominates.

The five study sites lie within the physiographic province of the Central Till Plain of Indiana (Figure 2). The surficial sediments at the specific study sites are recognized as Pleistocene Wisconsinan glacial deposits, with some Quaternary alluvium and loess (Hall 1999). All fens included in this investigation derive ground water from a stratigraphic break in the surficial glacial deposits, specifically the Trafalgar Formation. Furthermore, the Trafalgar Formation contains a notable petrologic homogeneity in central Indiana (Harrison 1959), including an abundance of carbonate material.

Two of the study sites (Ritchey Woods and Southwestway Park, Figures 2C and 2E, respectively) are recharged by a sand and gravel aquifer unit within the Trafalgar

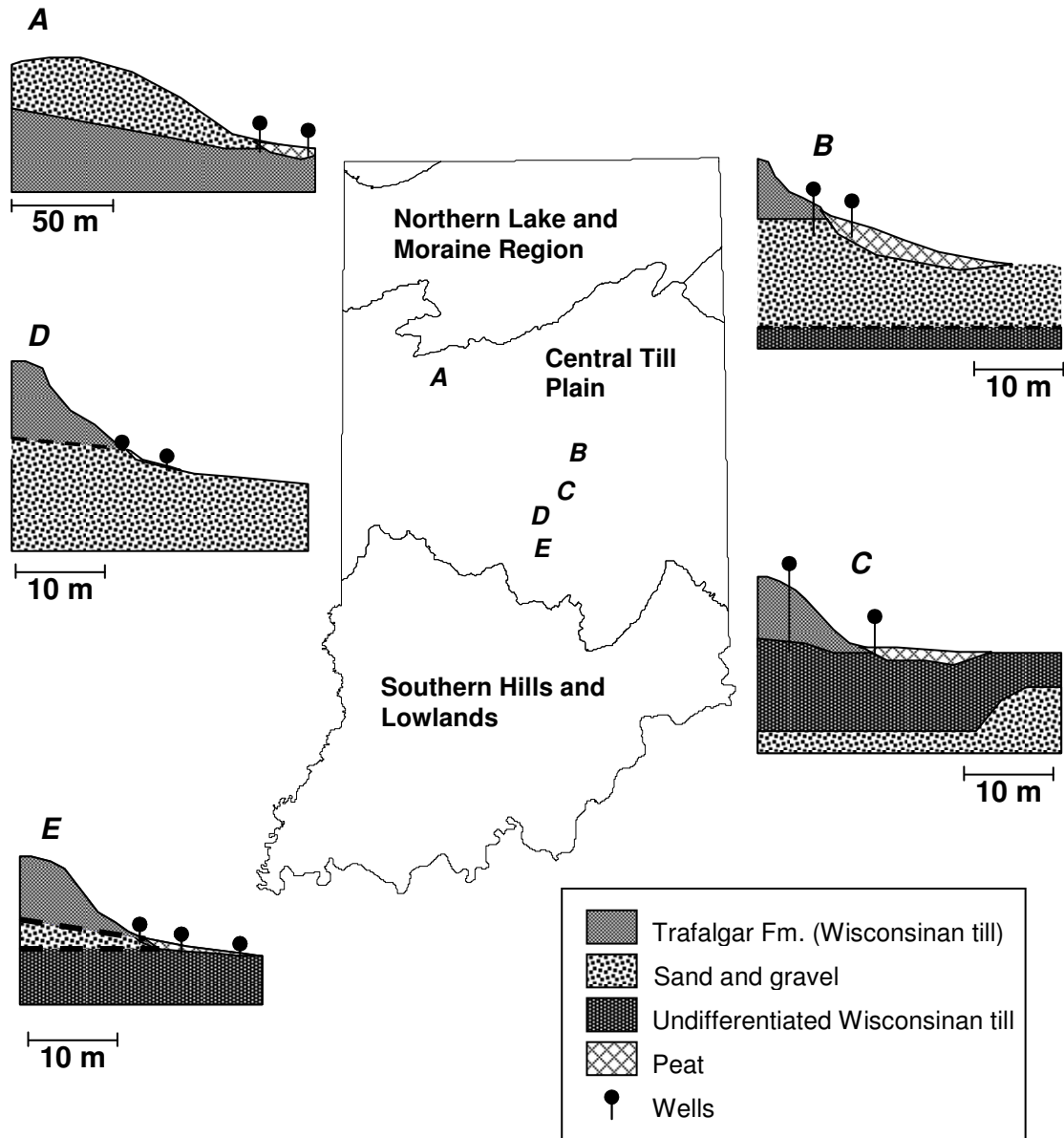


Figure 2. Physiographic map of Indiana showing the location of the five study sites with respective cross sections. The southern boundary of the Central Till Plain marks the southern extent of Wisconsinan glacial deposition. **A.** Prophetstown State Park; **B.** Mounds State Park; **C.** Ritchey Woods; **D.** Holliday Park; **E.** Southwestway Park.

Formation and are therefore characterized as intra-till type fens (Type Ia). Mounds State Park and Holliday Park fens are the result of ground water recharge sourced from the geologic contact between the overlying Trafalgar Formation and the underlying pre-Wisconsinan deposits, deeming the characterization of inter-till type fens (Type Ib) (Figures 2B and 2D, respectively). The fen located at Prophetstown State Park is recognized as an outwash terrace type fen (Type II) (Figure 2A).

Central Indiana Study Sites

Site selection for this study was based on the general stratigraphy and regional distribution of the wetlands, which allowed for a geochemical investigation of several sites that are located in a comparable geologic setting. All sites are hydrogeomorphically recognized as slope wetland systems (Smith et al. 1995; Cole et al. 1997) and have distinguishable fen hydrology with ground water as the dominant hydrologic input to the wetlands. Furthermore, the hydrologic input to each of the central Indiana fens is associated with a stratigraphic break associated with the Trafalgar Formation. These wetland communities are among the southern-most recognizable fens in the glaciated Midwestern United States and exist within a geologic niche that provides for relatively large recharge aquifers near the land surface with abundant rainfall to support fen hydrology via such shallow ground water aquifers. Figure 2 displays the geographical distribution of the central Indiana study sites.

Other Fen locations

Geochemical data from the central Indiana fens described above are compared to data from other fens throughout the Northern Hemisphere. This section provides a

general background of the other sites that are included in this comparative analysis of fen geochemistry.

The Savage Fen complex is found within central Minnesota along the Minnesota River. Savage Fen is a calcareous fen with ground water supplied from dolomitic bedrock and carbonate-rich glacial till (Komor 1994). A fen-wetland complex in northern Illinois, investigated by Panno et al. (1999), is sustained by ground water seepage near the base of a Wisconsinan kamic morainal complex, and fed by calcareous ground water under artesian conditions. Hite and Cheng (1996) investigated the geochemistry of a constructed fen in Greene County, Ohio that was emplaced in unconsolidated glacial deposits atop of limestone and shale. Based on the depth to bedrock (30 m), it is inferred that ground water input to this fen is sourced from the glacial deposits. High Creek Fen, located in South Park, Colorado, is sustained by calcareous ground water closely related to the dominant parent material in the watershed (Cooper, 1995). Paleozoic sedimentary rocks exist near the ground surface at High Creek fen, and are capped by Pleistocene outwash deposits. A fen complex in the central part of the Netherlands, located within a poldered river plain, was investigated by Wassen et al. (1990). This fen complex is associated with Pleistocene glacial deposits, and is sustained by ground water input sourcing from an adjacent Pleistocene moraine. Fen geochemical data was also investigated for a wide range of New York fens (Godwin et al. 2002), however limited geologic data could be recovered from this investigation.

FIELD METHODS

Fen surveying incorporated aerial photography and geologic maps to determine the geologic and geomorphic framework of each site prior to field investigation. Aerial photography of each site attained from the Indiana Spatial Data Portal (2005) was analyzed and manipulated using Arc 9.0 Geographical Information System to provide a vantage that was used for preliminary site investigation. A straight-rod soil probe and a hollow barrel core auger were used for substrate description in the field, including soil type, peat thicknesses, and preliminary determination of ground water level. The basic stratigraphic data was used to determine the location and depth of the shallow ground water monitoring wells and piezometers. The targeted zone for monitoring well locations was the ground water seep found at the toe of a slope. At each study site, the ground water seep was affiliated with a stratigraphic anomaly associated with the Trafalgar formation (Gray 1989; Brown et al. 1998).

At least two shallow ground water monitoring wells were installed at each site. One well was positioned upslope from the fen at each study site in order to capture “source water” prior to discharge, which provided aquifer chemistry characteristics. At least one well was positioned within the organic substrate of each fen which provided a comparison of the “fen water” relative to the “source water.” The wells consist of five centimeter diameter polyvinyl chloride (pvc) pipe with at least a 24 cm perforation at the bottom portion of each well (Appendix A). The overall depth of well placement depended on ground water level, but ranged from 0.5 – 2.0m. At least three piezometer nests were also installed at each fen (five piezometer nests at Ritchey Woods) that follows the same linear transect as the aforementioned wells. Piezometer nests consist of

two or three piezometers composed of 1.5 cm diameter pvc with 20 cm slotted ends that were advanced to various depth intervals (ranging from 0.5 – 1.8 m). Each well or piezometer was sand packed and sealed with bentonite in order to eliminate the influence of surface runoff in the monitoring wells.

Sample Acquisition and Analyses

Sample frequency followed a six to eight week regimen from March of 2005 to May of 2006 providing a relatively consistent temporal resolution of the hydrology and geochemical dynamics in each fen. Water samples were extracted from each of the shallow ground water wells using nalgene polyvinyl chloride tubing fastened to a 60 ml syringe via a three-way stopcock. Samples were syringed into 250 ml acid washed nalgene bottles and immediately placed in a cooler on ice for transport back to the laboratory. Water samples were filtered within 48 hours of collection using Whatman 0.7 μm glass microfibre filter paper and frozen until ready for analysis.

A YSI 600 XLM Multi Parameter Water Quality Monitoring probe was used to measure temperature, pH, and specific conductivity (SpC) in the field. A YSI 600 LS Multi Parameter Water Quality Monitor sonde calibrated for collection of water level and temperature on a 15 minute interval was installed in the source water well of each fen in order to monitor source water levels at each site. Water level measurements for all other wells and piezometers were recorded using a Solinst 101M mini water level meter. Total station surveying, used in combination with topographic maps, provided specific elevation control for each fen.

Data Analyses

Ground water geochemistry was characterized for major cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) using a Dionex DX500 ion chromatograph with CS15 column and methasulfonic acid eluent. Silica and anion analyses (SO_4^{2-} , NO_3^- , NO_2^- , PO_4^{3-} , NH_3^- , Cl^-) were performed by colorimetry using a Konelab 20 Photometric Analyzer. Alkalinity and bicarbonate values were determined via ion balance with an endpoint titration as an accuracy check (Fritz 1994). Field blanks and laboratory blanks were included in each analytical procedure for quality control and assurance. Appendix B provides a more detailed description of the analytical procedures and detection limits for each parameter. Precipitation data was collected from the nearest accessible weather station for each site via the Indiana State Climate Office (2004) and compared to each groundwater hydrograph.

Principal Component Analyses (PCA) and Discriminant Analyses were performed with the data set using PAST software (Hammer et al. 2001) in order to determine variations in the data among the five study sites. These statistical analyses were also employed to compare fen data from several different studies from a wide geographical range. This investigation included fen geochemical data from New York (Godwin et al. 2002), Minnesota (Komor 1994), Illinois (Panno et al. 1999), Ohio (Hite and Cheng 1996), Colorado (Cooper 1995), and the Netherlands (Wassen et al. 1990). This multi-region fen geochemical investigation involved only studies that included major cation (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anion (HCO_3^- , NO_3^- , SO_4^{2-} , Cl^-) measurements in order to maintain consistency in statistical applications and analyses.

RESULTS

Geology and Hydrogeology

The central Indiana study sites are all associated with a stratigraphic contact involving the Wisconsinan Trafalgar Formation. Each fen is hydrologically supplied by a shallow aquifer consisting of non-cohesive granular soils. Organic deposits, including peat or muck, exist in each fen in varying thicknesses, ranging from <10 cm (Holliday Park) to >2 m (Mounds State Park). Most sites also contained calcium carbonate deposits (tufa) that was variably distributed within the organic deposits. Table 1 provides a summary of organic deposit thicknesses at each fen.

“Source water” levels, acquired from the source water well at each fen, exhibit some variation among the study sites with an overall range of 1.5 m below ground surface (bgs) to 0.5 m above ground surface. Hydrographs from the source water aquifer of each site are included as Figures 3A – 3E. Each site exhibits a rapid response to precipitation events, in most cases raising the water table by 5 – 10 cm, but in rare cases, as characterized at Ritchey Woods, nearly a meter of fluctuation is associated with enduring precipitation events.

A hydrologic summary for each site is shown in Table 2. Source water levels for the Type Ia and Ib fens (Southwestway Park, Holliday Park, Ritchey Woods, and Mounds State Park) range from <1.63 m below ground surface to 0.22 m above ground surface. Source water levels for the Type II fen (Prophetstown State Park) generally show more fluctuation than the Type Ia and Ib fens and range from 60 cm below ground surface to 50 cm above ground surface. Water levels in SWW1 were always above ground surface

Table 1. Organic substrate thickness summary from the central Indiana study sites.

Site	Type	Max. Observed Thickness (m)
Southwestway Park	Hemic Peat	1.0
Holliday Park	Silty Muck	0.40
Ritchey Woods	Silty Muck	1.45
Mounds State Park	Fibric Peat	>2.0
Prophetstown State Park	Hemic Peat	0.75

Southwestway Park

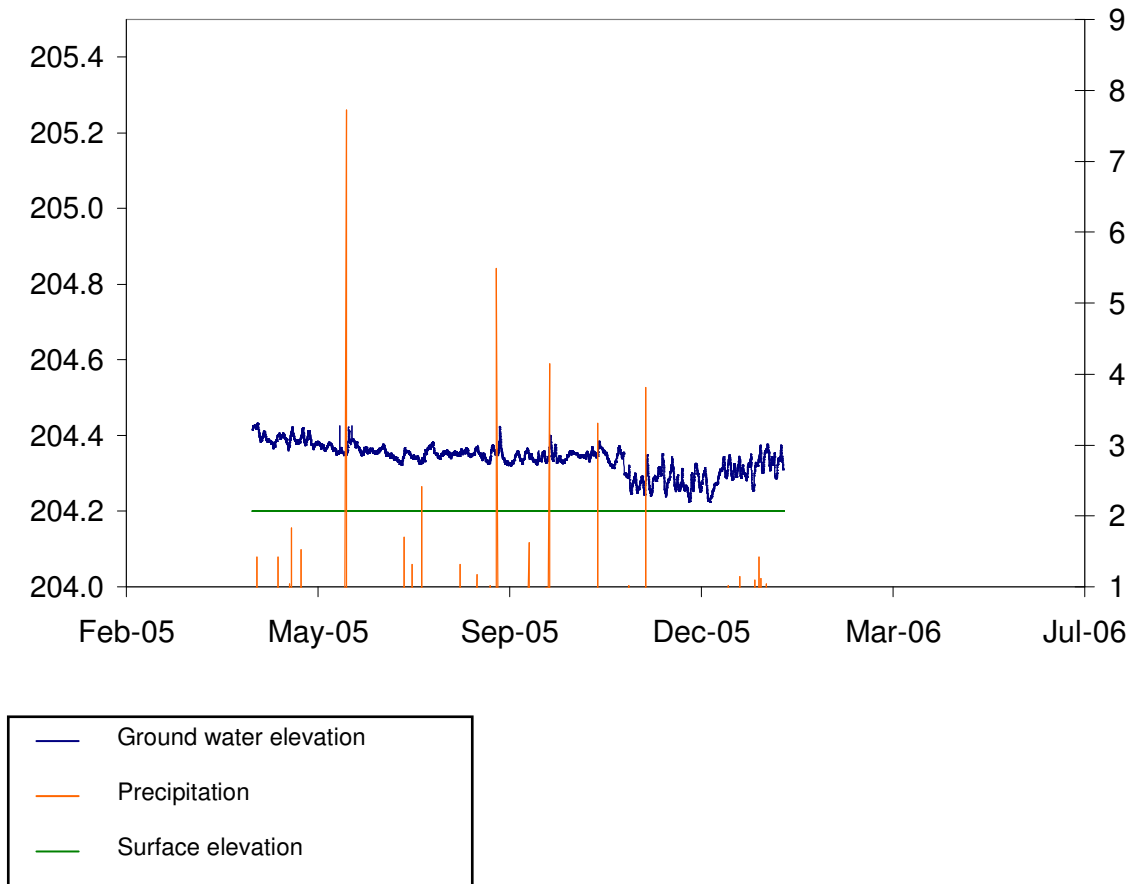


Figure 3A. Source water hydrograph for Southwestway Park displaying ground water elevation versus precipitation and surface elevation.

Holliday Park Hydrograph

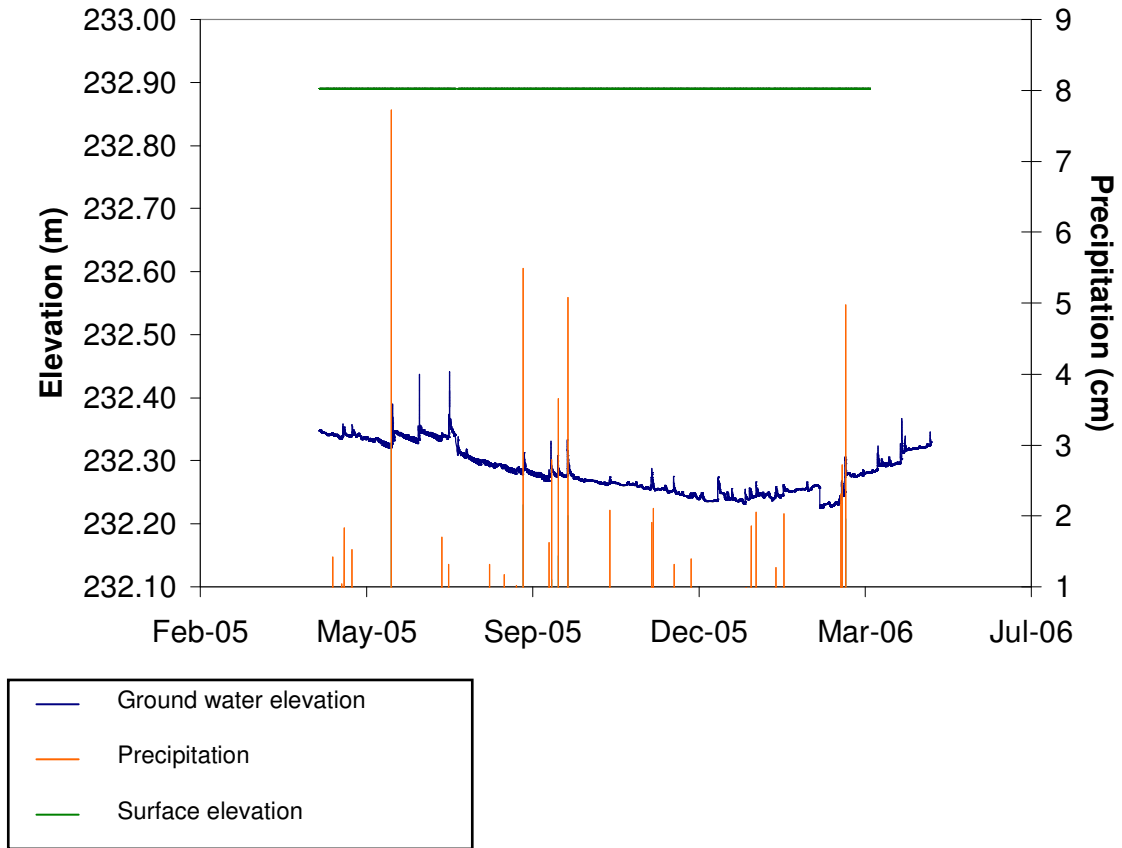


Figure 3B. Source water hydrograph for Holliday Park displaying ground water elevation versus precipitation and surface elevation.

Ritchey Woods Hydrograph

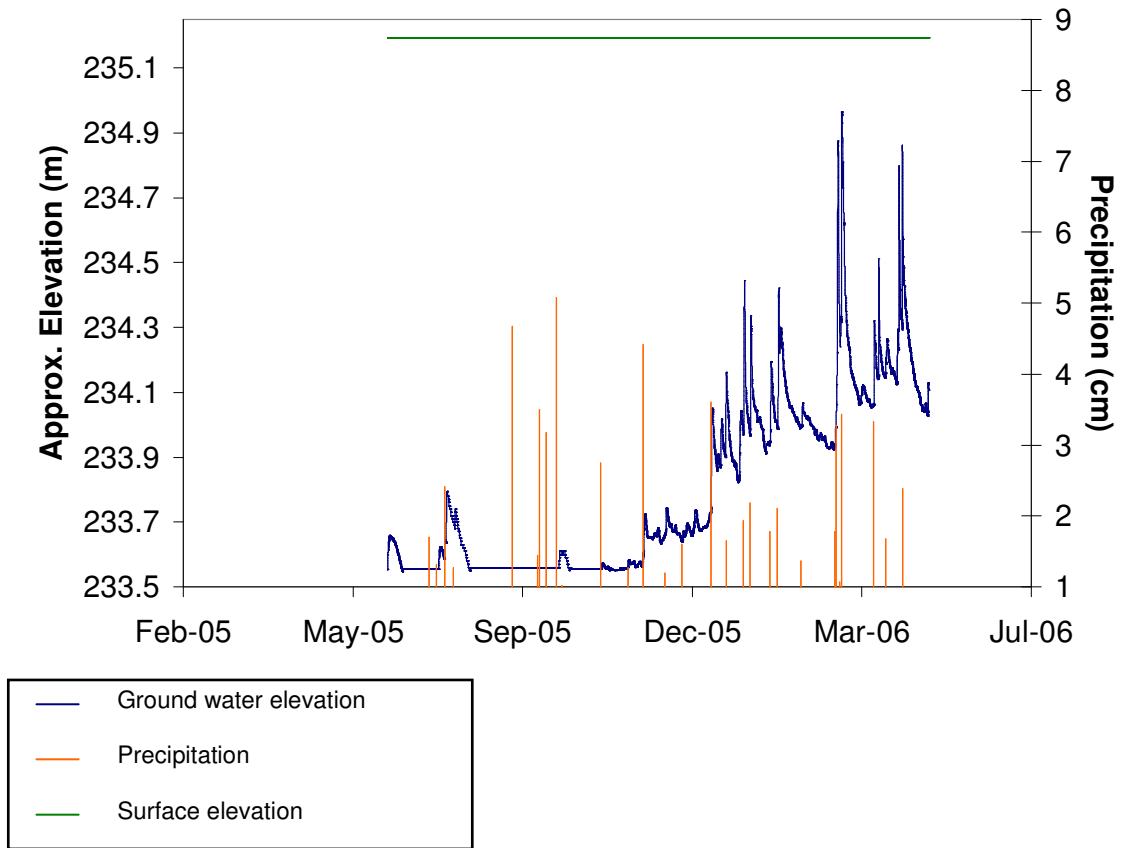


Figure 3C. Source water hydrograph for Ritchey Woods displaying ground water elevation versus precipitation and surface elevation.

Mounds State Park Hydrograph

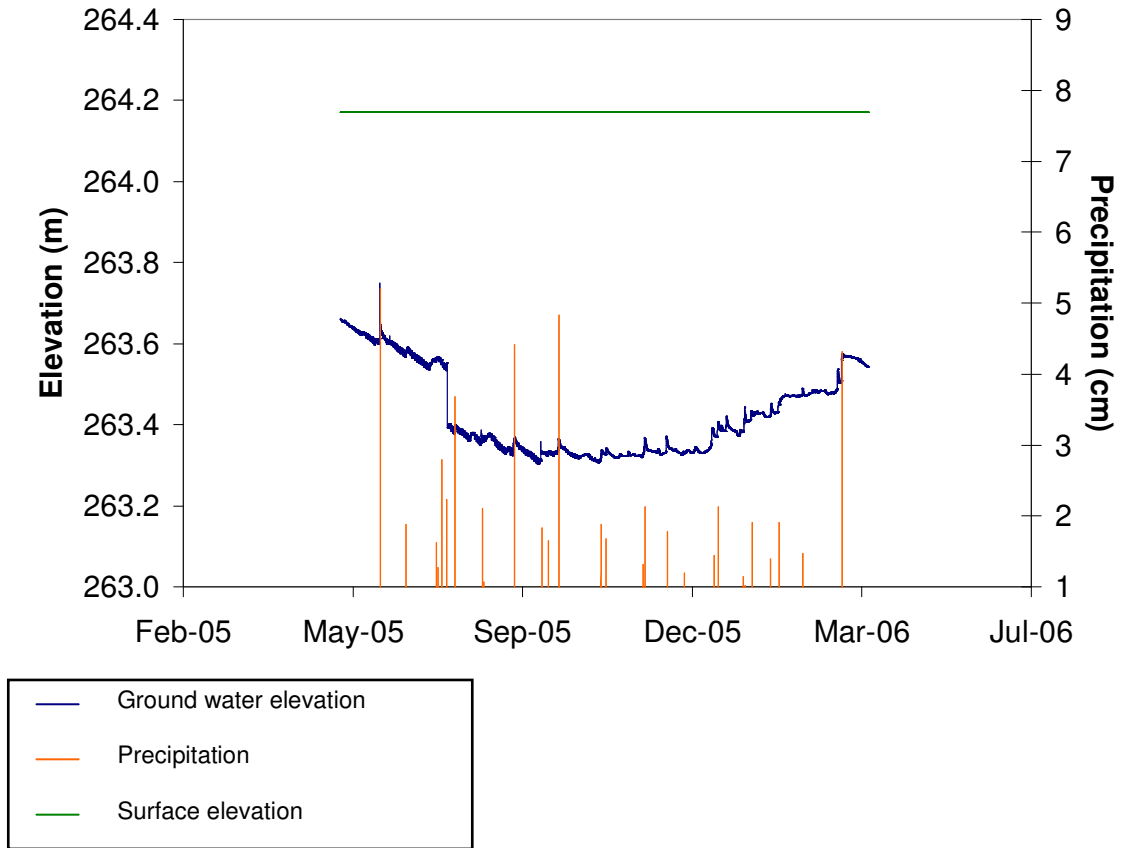


Figure 3D. Source water hydrograph for Mounds State Park displaying ground water elevation versus precipitation and surface elevation. The sudden drop of ground water elevation in July of 2005 is due to calibration of the data logger and is not representative of environmental conditions.

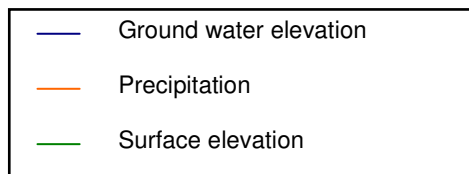
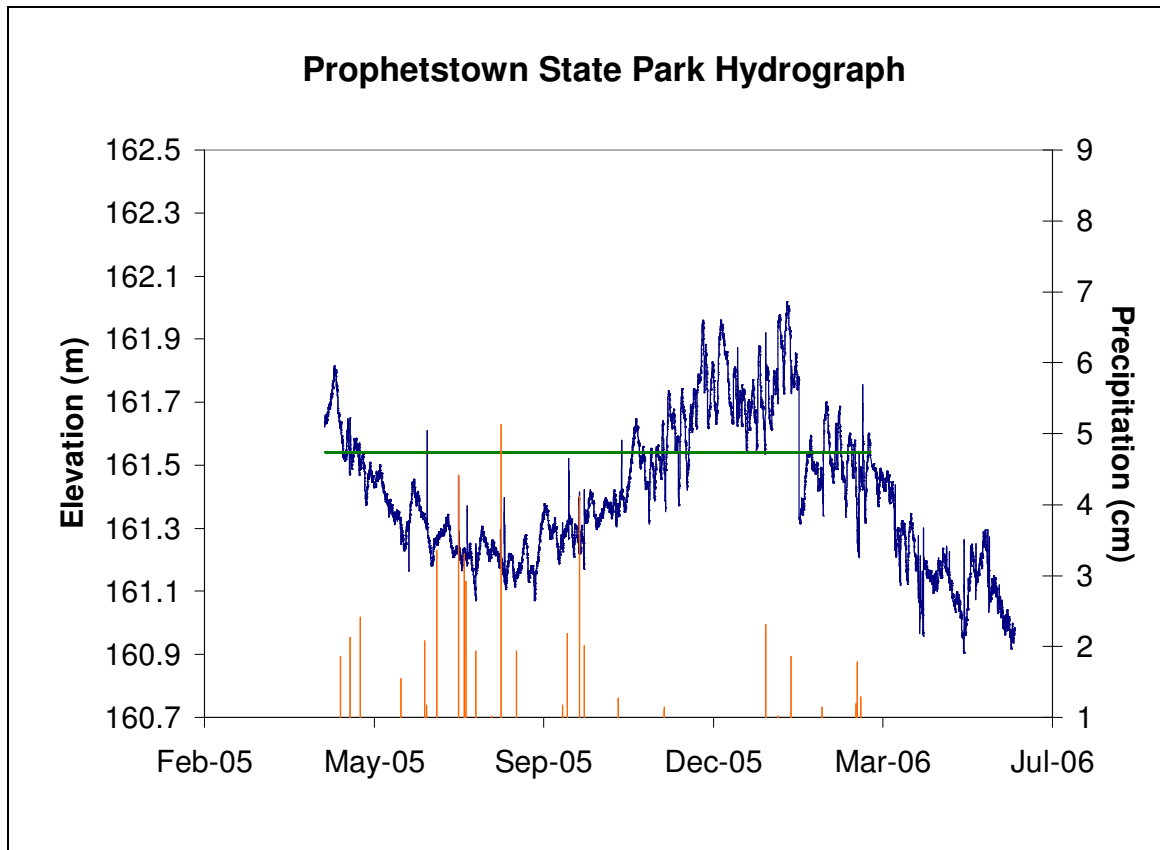


Figure 3E. Source water hydrograph for Prophetstown State Park displaying ground water elevation versus precipitation and surface elevation.

and had little variability during the 2005 – 2006 sampling season, ranging from 2 – 22 cm above ground surface. However, fluctuations were more significant in the winter months (December – February) (Figure 3A). Holliday Park source water also maintained a relatively consistent ground water table in the 2005 – 2006 sampling period, ranging from 43 – 67 cm bgs with the lowest levels generally occurring during the winter months (Figure 3B). Ground water levels in the source water well at Ritchey Woods (RW1) display the most fluctuation among all study sites, ranging from <1.63 m bgs to 0.3 meters bgs. Water levels in RW1 were below measuring capabilities (1.63 m bgs) for the majority of the summer 2005 sampling season (Figure 3C) then began to rise in the winter and spring months. The hydrograph from the source water well at Mounds State Park (M1) also displays minimal fluctuation, as the water table ranges from 38 – 88 cm bgs throughout the duration of data collection (Figure 3D). Prophetstown State Park water table elevations show a great deal of temporal variation, ranging from 60 cm bgs to 50 cm above ground surface during the 2005 – 2006 sampling season with water table increases in the autumn and winter that are not correlative to local rainfall.

Water levels within each fen (fen water) remained consistent over the duration of the study period. The water table within each fen typically has a 25 cm range of fluctuation on an annual temporal scale, and tends to stay within approximately 30 cm of the ground surface. Depth to ground water was most variable at Southwestway Park in well SWW2, ranging from 42 cm bgs to 5 cm bgs, a fluctuation of 37 cm. Ground water at Holliday Park (well H2) was located deeper than any of the other fens, with an average of 32 cm bgs. Figure 4 provides water level data in relation to surface elevation for each of the fen water wells. Fen water levels recorded at each site ranged from 42 cm

Table 2. Water level summary for the central Indiana fens.

Site	Well	Water Type	Min.	Max.	Mean	Median
SOUTHWESTWAY PARK	SWW1	Source	0.02	0.22	0.14	0.15
	SWW2	Fen	-0.42	-0.05	-0.17	-0.13
	SWW3	Fen	-0.14	0.04	-0.05	-0.06
HOLLIDAY PARK	H1	Source	-0.65	-0.47	-0.61	-0.61
	H2	Fen	-0.38	-0.27	-0.32	-0.33
RITCHEY WOODS	RW1	Source	bd	-0.30	-1.40	-1.52
	RW2	Fen	-0.18	0.04	-0.05	-0.01
MOUNDS STATE PARK	M1	Source	-0.80	-0.40	-0.74	-0.79
	M2	Fen	-0.14	0.07	-0.02	-0.01
PROPHETSTOWN STATE PARK	P1	Source	-0.60	0.50	-0.13	-0.16
	P2	Fen	-0.26	-0.03	-0.17	-0.19

**All values reported in meters relative to ground surface (i.e. -.05 = 5 cm below ground surface)*

***bd = below detection*

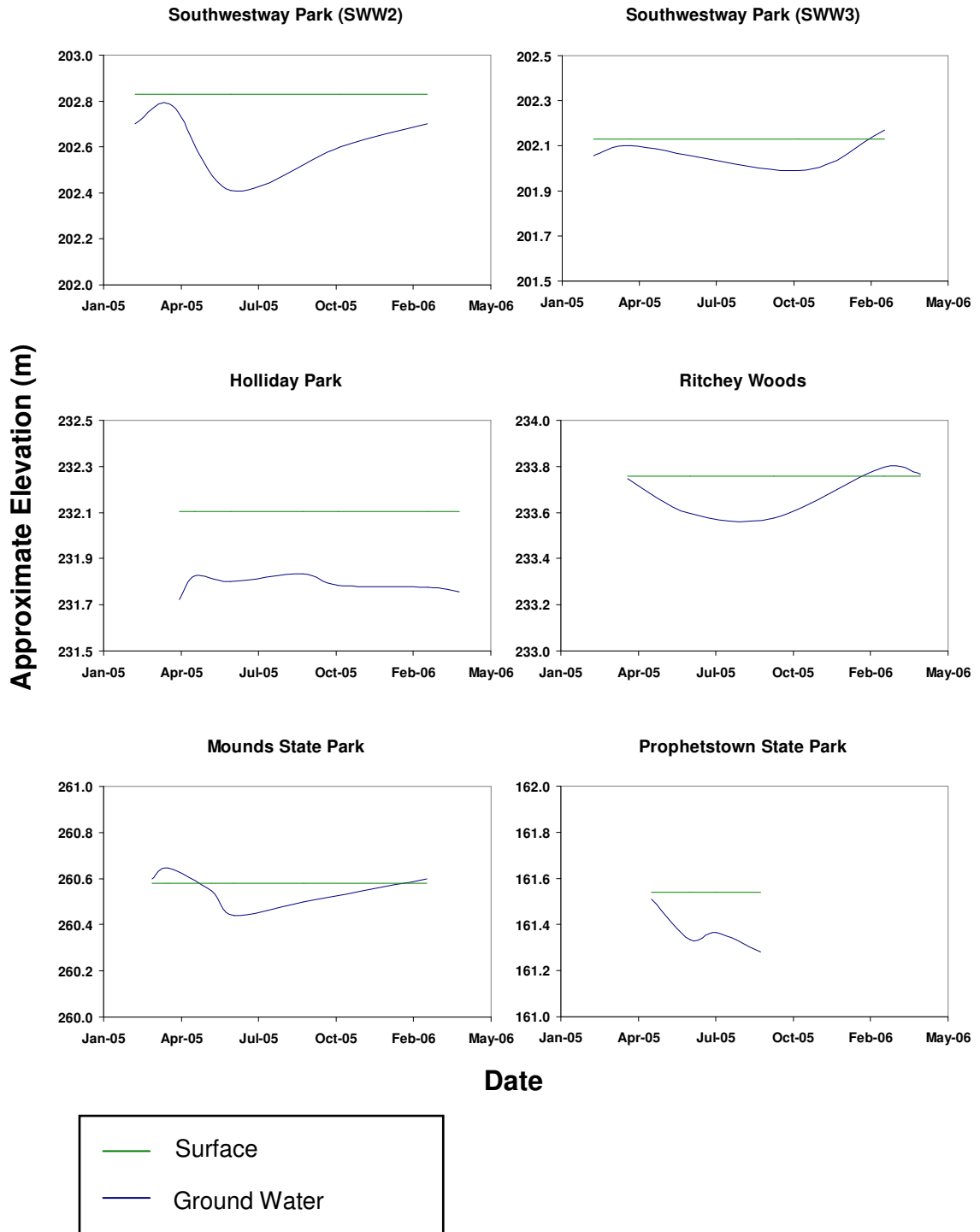


Figure 4. Hydrographs from fen water wells showing the water table elevation in relation to surface elevation. These values are placed on a 1 m vertical scale. The data collection spans approximately one year, with the exception of Prophetstown State Park, where fen water level data was only included for the growing season of 2005.

bgs to 7 cm above ground surface, with an overall median value of 15 cm bgs. Table 2 provides a hydrologic summary of each study site.

Figures 5A – 5E show the hydraulic head values, general ground water flow, and hydrologic input to each of the study sites. Hydraulic head values and hydrologic input to each fen remain relatively consistent throughout the sampling season. The hydrologic input to Southwestway Park is a combination of throughflow from the sand and gravel outwash unit upslope of the fen, and upwelling from deeper portions of the shallow aquifer. Hydrology of Holliday Park, Mounds State Park, and Prophetstown State Park show little evidence of an upwelling component. Hydrologic input to these sites originates from the aquifer upslope of the fen. Ritchey Woods represents very little throughflow from the upslope aquifer, but is fed primarily by upwelling ground water from below the fen (Figure 5C).

Geochemistry

Table 3 provides a summary of the geochemical data from the studied central Indiana fens, including range, mean and median for each parameter. All analytical and field data collected from each of the study sites is included as Appendix C. The central Indiana fens are ground water dominated systems with circumneutral pH (5.88 – 7.77). Ca^{2+} , Mg^{2+} , and HCO_3^- comprise the dominant ground water geochemical components of these wetlands (Figure 6). Ca^{2+} values range from 33 – 131 mg/L, Mg^{2+} values range from 10 – 50 mg/L, and HCO_3^- (alkalinity) range from 71 – 405 mg/L for the central Indiana fens (Table 3). However, elevated Na^+ concentrations are noted at Holliday Park (16 – 57 mg/L) and Mounds State Park (27 – 81 mg/L) fens compared to the other fens in the study (2 – 9 mg/L). Elevated chloride concentrations are also observed at Holliday

Southwestway Park

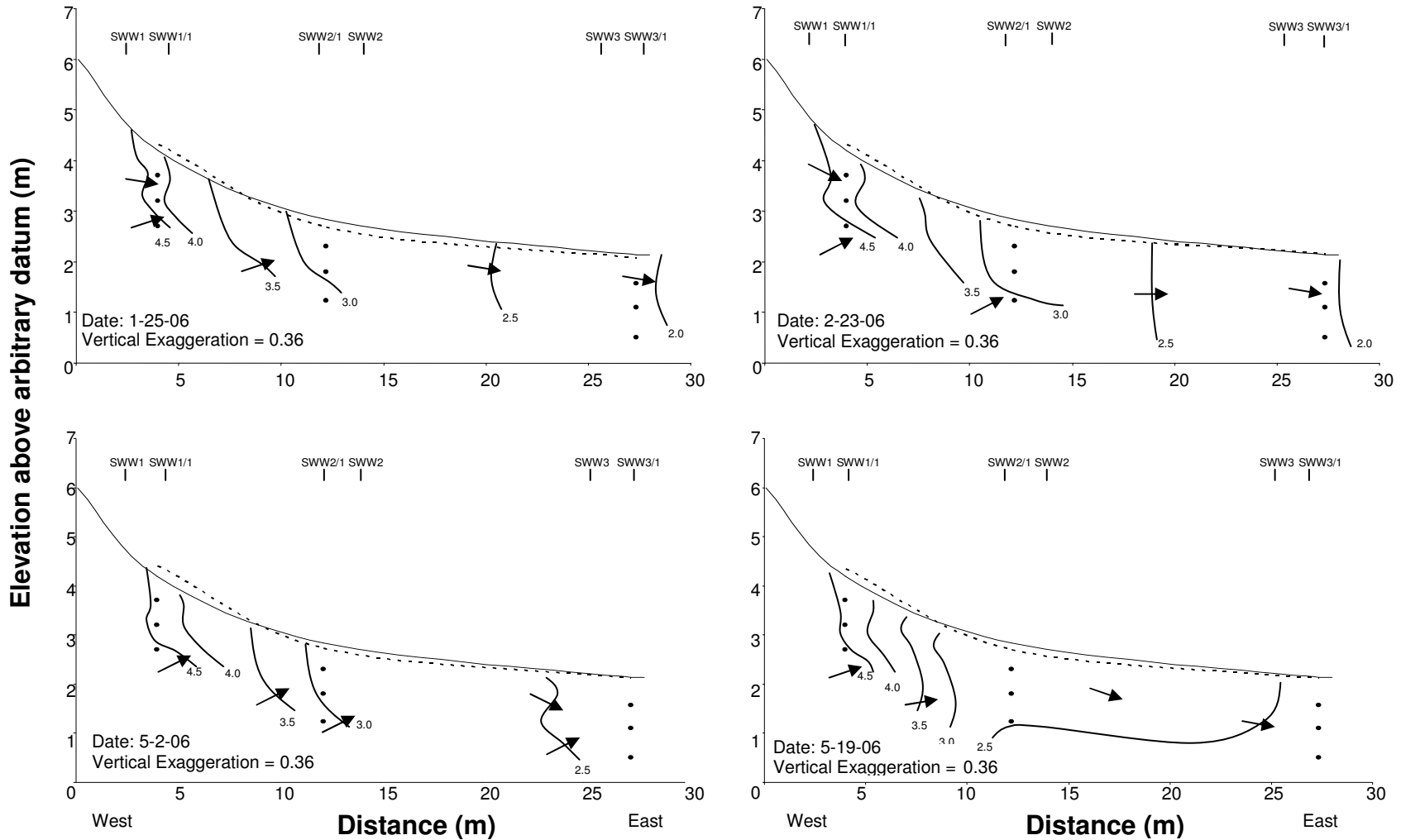
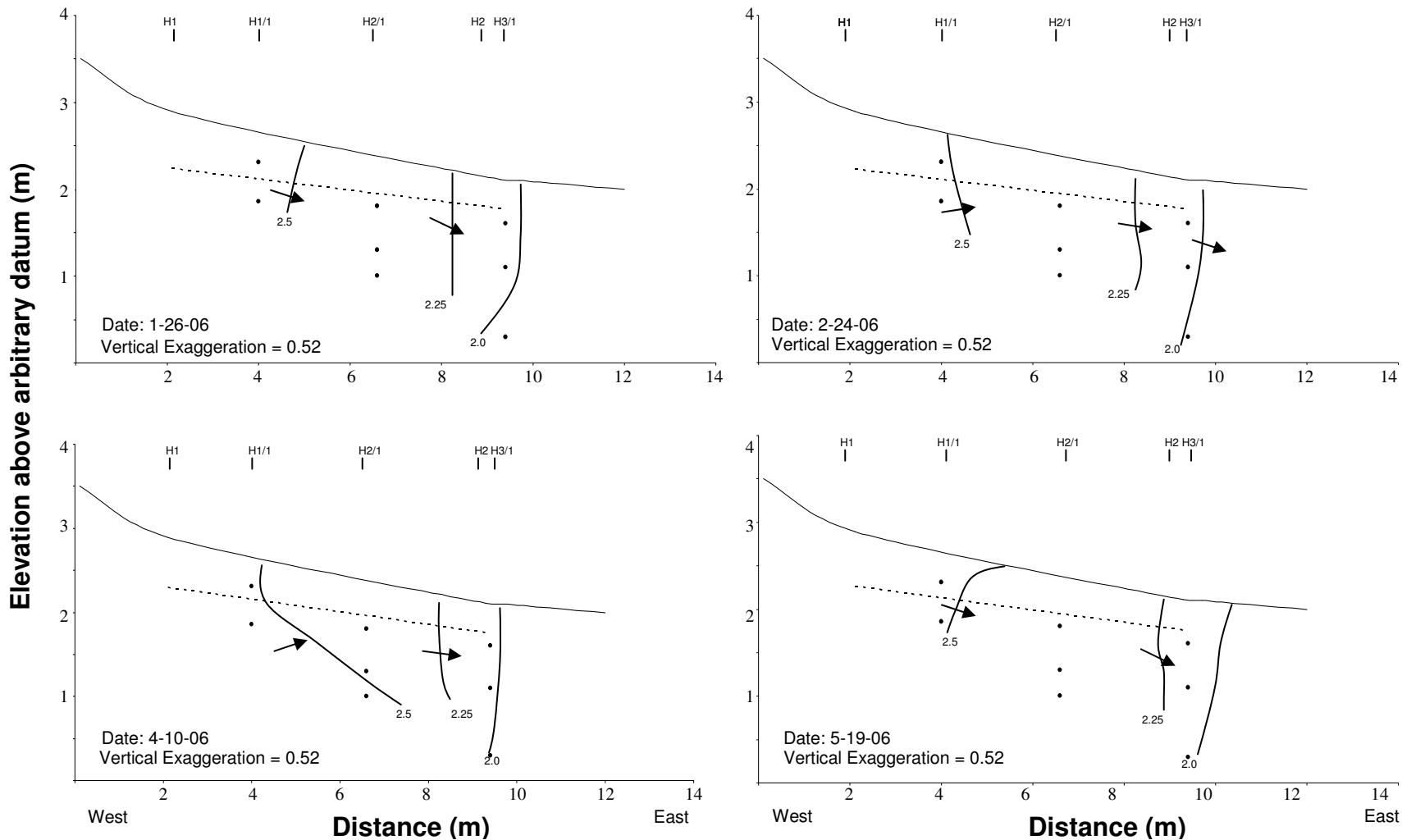


Figure 5A. Vertical cross section along the main transect of Southwestway Park displaying equipotential lines and hydraulic head values of the ground water in the fen. The dashed line represents water level; dots represent piezometer slot zones; arrows represent general flow direction; piezometer and well identification are labeled at the top of each cross section.

Holliday Park



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Figure 5B. Vertical cross section along the main transect of Holliday Park displaying equipotential lines and hydraulic head values of the ground water in the fen. The dashed line represents water level; dots represent piezometer slot zones; arrows represent general flow direction; piezometer and well identification are labeled at the top of each cross section.

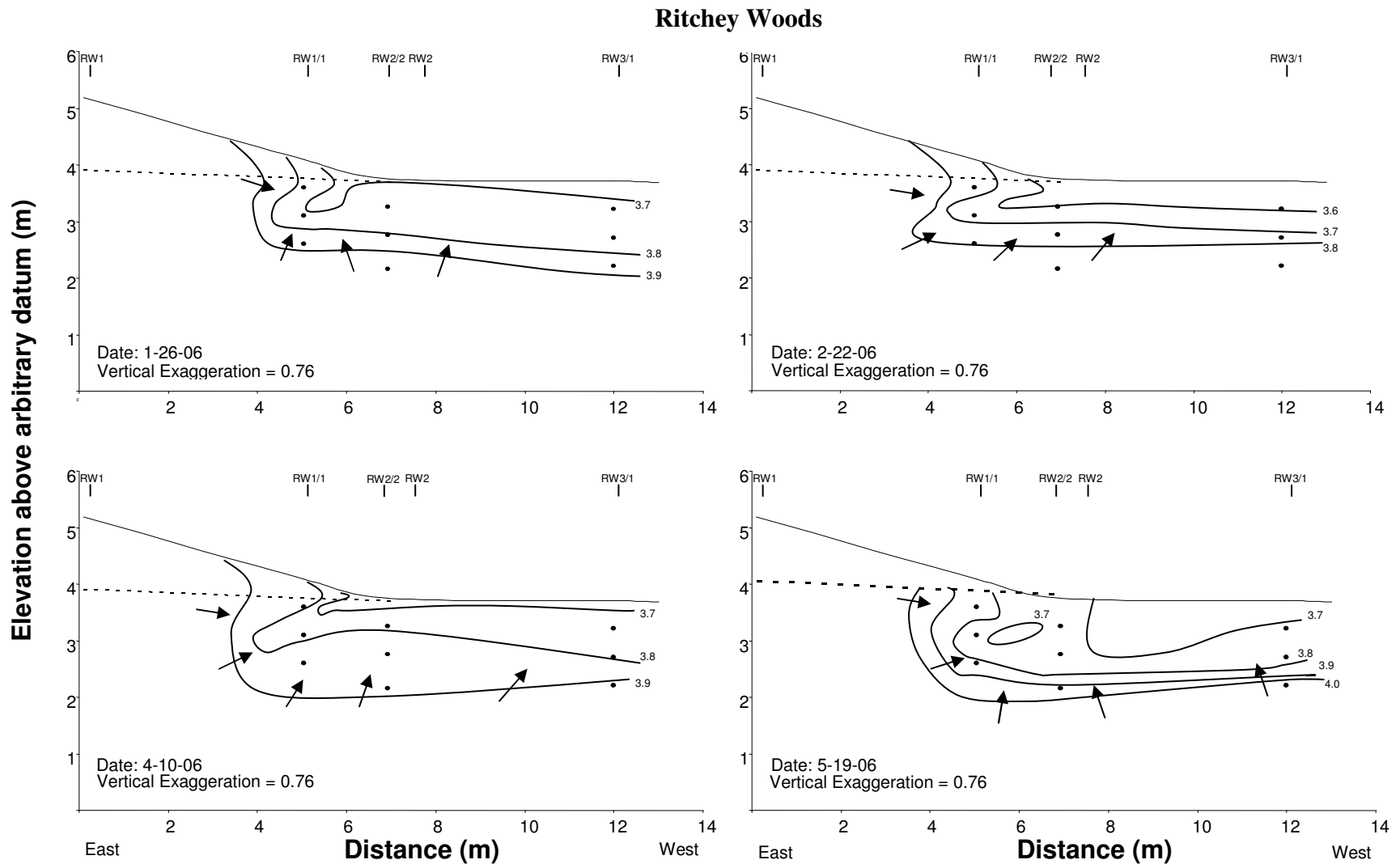


Figure 5C. Vertical cross section along the main transect of Ritchey Woods displaying equipotential lines and hydraulic head values of the ground water in the fen. The dashed line represents water level; dots represent piezometer slot zones; arrows represent general flow direction; piezometer and well identification are labeled at the top of each cross section.

Mounds State Park

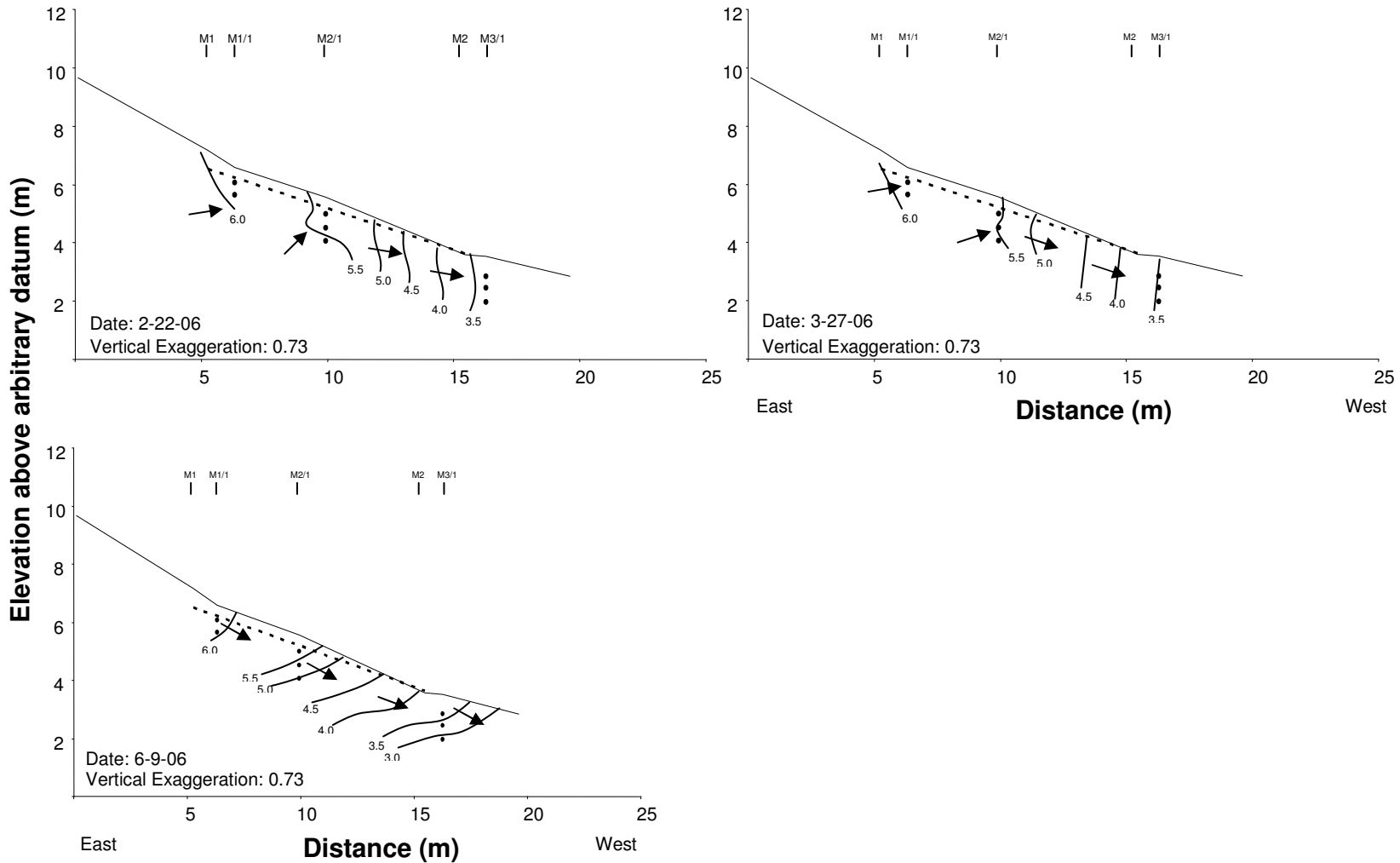


Figure 5D. Vertical cross section along the main transect of Mounds State Park displaying equipotential lines and hydraulic head values of the ground water in the fen. The dashed line represents water level; dots represent piezometer slot zones; arrows represent general flow direction; piezometer and well identification are labeled at the top of each cross section.

Prophetstown State Park

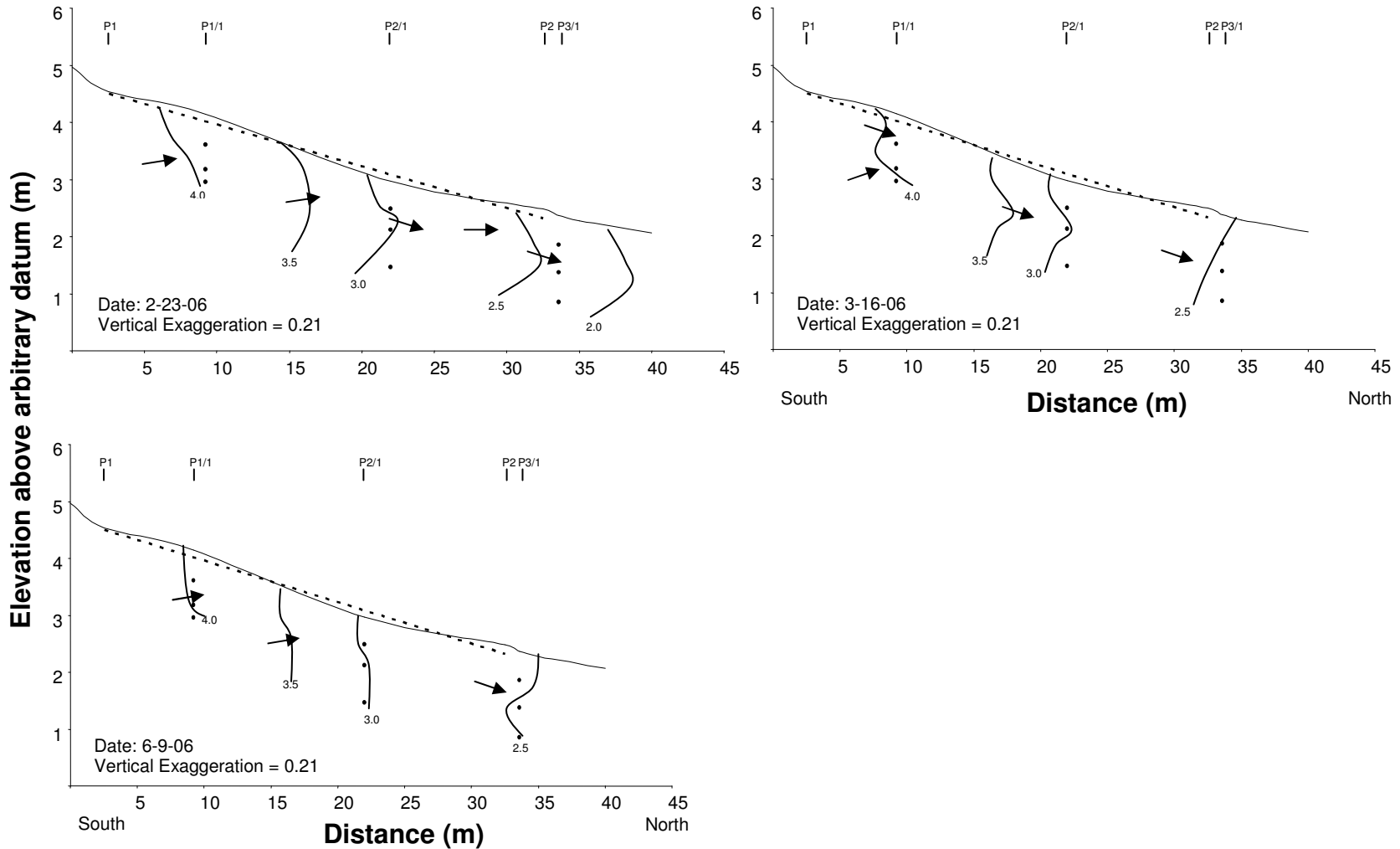


Figure 5E. Vertical cross section along the main transect Prophetstown State Park displaying equipotential lines and hydraulic head values of the ground water in the fen. The dashed line represents water level; dots represent piezometer slot zones; arrows represent general flow direction; piezometer and well identification are labeled at the top of each cross section.

Table 3. Summary of analytical results for central Indiana fens.

SITE	WELL		PARAMETER													
			Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	NH ₃ -N	NO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₂	O-PO ₄ ²⁻	HCO ₃ ⁻	SiO ₂	SpC	pH
SOUTHWESTWAY PARK	SWW1	Min	40.53	17.13	3.35	<0.01	<0.01	<0.01	31.30	9.65	<0.01	<0.003	171.52	5.80	0.676	7.03
		Max	66.20	35.08	6.58	2.80	0.53	0.53	58.80	16.90	0.01	0.004	270.06	8.38	0.809	7.77
		Mean	54.01	31.16	4.53	1.12	0.11	0.16	45.07	13.62	0.01	0.003	214.15	7.07	0.710	7.32
		Median	57.65	33.57	3.88	<0.01	0.05	0.08	50.33	14.30	<0.01	0.003	204.56	6.51	0.699	7.26
		N	6	6	6	5	8	9	10	10	8	4	6	9	10	10
	SWW2	Min	40.01	22.50	3.11	<0.01	<0.01	<0.01	1.70	8.07	<0.01	0.008	184.15	5.40	0.549	6.97
		Max	83.06	46.02	6.57	<0.01	0.19	0.16	138.40	15.20	0.01	<0.003	323.27	7.85	0.902	7.47
		Mean	54.53	35.81	4.42	<0.01	0.09	0.10	40.13	9.93	0.01	0.013	262.21	6.48	0.764	7.13
		Median	46.12	36.52	4.19	<0.01	0.08	0.11	35.60	9.20	0.01	0.011	280.06	6.49	0.833	7.04
		N	6	6	6	6	8	8	9	9	7	7	6	7	9	9
	SWW3	Min	42.00	17.67	2.91	<0.01	0.01	0.02	22.03	4.21	<0.01	0.003	211.65	4.70	0.567	6.97
		Max	82.40	37.10	4.23	<0.01	0.14	0.16	59.28	8.60	0.02	0.017	266.41	6.71	0.751	7.43
		Mean	56.55	29.70	3.46	<0.01	0.08	0.11	33.61	6.32	0.01	0.008	236.66	5.74	0.652	7.15
		Median	49.43	33.12	3.11	<0.01	0.07	0.11	28.87	6.26	0.01	0.008	235.99	5.80	0.652	7.12
		N	5	5	5	5	8	6	8	8	7	7	5	7	8	8
HOLLIDAY PARK	H1	Min	53.02	21.20	15.80	1.03	<0.01	0.70	24.50	36.09	<0.01	0.005	159.11	2.36	0.819	6.83
		Max	69.25	39.45	56.50	2.98	0.17	2.98	57.13	59.38	0.04	0.083	405.46	8.16	0.996	7.22
		Mean	71.60	35.25	28.02	2.34	0.06	1.72	38.96	48.99	0.01	0.034	261.65	6.12	0.911	7.01
		Median	61.97	38.41	25.31	2.80	0.05	2.09	36.40	48.18	0.01	0.014	262.56	6.81	0.905	6.97
		N	5	5	7	7	8	9	9	9	8	3	5	8	9	9
	H2	Min	52.59	19.60	22.92	1.24	<0.01	0.94	42.69	48.63	<0.01	<0.003	175.17	4.60	0.883	7.07
		Max	120.74	40.49	30.02	3.02	0.07	2.68	93.30	60.74	0.02	0.016	386.67	8.74	0.953	7.45
		Mean	70.31	35.83	26.16	2.68	0.03	1.63	60.78	56.59	0.01	0.007	239.41	7.17	0.916	7.28
		Median	65.85	38.71	26.11	2.94	0.03	1.34	59.36	57.82	0.01	0.006	225.91	7.53	0.914	7.30
		N	8	8	8	7	6	9	10	10	8	6	8	8	9	9

Table 3 (cont.). Summary of analytical results for central Indiana fens.

SITE	WELL		PARAMETER													
			Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	NH ₃ -N	NO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₂	O-PO ₄ ²⁻	HCO ₃ ⁻	SiO ₂	SpC	pH
RITCHEY WOODS	RW1	Min	43.36	28.89	2.03	<0.01	<0.01	0.00	11.60	3.42	<0.01	<0.003	215.80	2.10	0.57	5.88
		Max	91.62	33.25	6.21	2.80	0.52	0.26	31.57	15.40	0.02	0.180	328.02	16.69	2.24	7.48
		Mean	60.24	30.83	3.45	0.47	0.18	0.13	22.19	6.78	0.01	0.050	258.84	7.41	0.91	6.81
		Median	58.75	30.30	2.72	<0.01	0.16	0.15	23.37	5.57	<0.01	0.030	255.85	7.20	0.71	6.91
		N	5.00	5.00	6.00	6.00	7.00	9.00	7.00	8.00	6.00	6.00	5.00	8.00	8.00	8.00
	RW2	Min	41.30	17.24	3.19	<0.01	0.02	0.01	34.50	5.63	<0.01	<0.003	199.06	4.90	0.07	6.87
		Max	130.50	38.01	6.50	2.79	1.35	0.22	66.49	9.83	0.03	<0.003	369.34	8.57	0.87	7.47
		Mean	70.87	33.41	4.53	0.35	0.36	0.11	49.96	7.77	<0.01	<0.003	247.20	7.07	0.64	7.25
		Median	59.19	35.57	4.35	<0.01	0.11	0.09	49.45	7.71	0.01	<0.003	235.33	7.60	0.70	7.29
		N	8.00	8.00	8.00	8.00	8.00	9.00	9.00	9.00	7.00	7.00	6.00	9.00	8.00	8.00
MOUNDS STATE PARK	M1	Min	56.78	22.30	27.10	3.36	0.03	0.00	21.50	61.88	<0.01	<0.003	176.11	2.53	0.85	6.39
		Max	89.85	48.03	51.30	4.57	0.41	0.32	90.06	131.00	0.01	0.090	336.68	7.99	2.24	7.26
		Mean	72.04	35.85	39.29	3.76	0.14	0.10	47.57	93.94	<0.01	0.040	239.96	5.81	1.16	6.88
		Median	73.40	37.07	36.83	3.53	0.08	0.08	44.33	92.53	<0.01	0.020	233.91	6.76	1.04	6.90
		N	7.00	7.00	7.00	7.00	8.00	8.00	8.00	8.00	8.00	8.00	5.00	7.00	8.00	8.00
	M2	Min	42.80	22.60	69.90	0.00	0.14	0.06	34.25	147.80	<0.01	<0.003	70.51	4.00	1.10	6.98
		Max	93.60	49.73	80.60	4.31	0.27	0.09	69.87	185.46	0.01	0.020	288.91	7.93	1.29	7.45
		Mean	73.24	40.18	74.49	2.13	0.20	0.07	51.00	164.83	<0.01	0.010	196.48	6.05	1.25	7.15
		Median	76.74	44.77	74.00	3.26	0.19	0.06	49.89	165.50	<0.01	0.010	189.12	6.10	1.28	7.14
		N	7.00	7.00	7.00	7.00	8.00	6.00	8.00	8.00	8.00	8.00	7.00	7.00	8.00	8.00

Table 3 (cont.). Summary of analytical results for central Indiana fens.

SITE	WELL		PARAMETER													
			Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	NH ₃ -N	NO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₂	O-PO ₄ ²⁻	HCO ₃ ⁻	SiO ₂	SpC	pH
PROPHETSTOWN STATE PARK	P1	Min	32.73	10.00	1.84	<0.01	0.01	0.08	12.71	4.00	<0.01	<0.003	108.29	3.48	0.241	6.70
		Max	39.60	16.11	3.91	<0.01	0.36	0.46	32.40	10.50	0.01	0.017	134.45	5.02	0.680	7.74
		Mean	36.65	12.84	2.87	<0.01	0.17	0.31	22.40	7.44	0.01	0.005	121.37	4.18	0.392	7.09
		Median	37.63	12.40	2.86	<0.01	0.16	0.33	23.12	7.40	<0.01	0.004	121.37	4.00	0.255	6.96
		N	3	3	3	3	5	5	5	5	5	5	2	5	4	4
	P2	Min	43.34	18.35	3.82	<0.01	0.04	0.07	3.88	6.45	<0.01	<0.003	181.49	3.45	0.490	6.71
		Max	87.70	27.90	8.74	10.40	4.58	0.22	137.50	16.60	0.02	0.156	184.46	8.30	0.805	7.49
		Mean	71.54	23.88	6.76	3.47	0.92	0.12	52.76	9.20	0.01	0.029	182.975	5.25	0.639	7.09
		Median	77.55	25.40	7.25	<0.01	0.21	0.10	25.95	7.80	0.01	0.005	182.975	4.90	0.643	7.08
		N	4	3	4	3	6	6	6	6	6	6	5	6	2	6

*All values reported in mg/L except for SpC and pH

**SpC = Specific Conductance reported in ms/cm

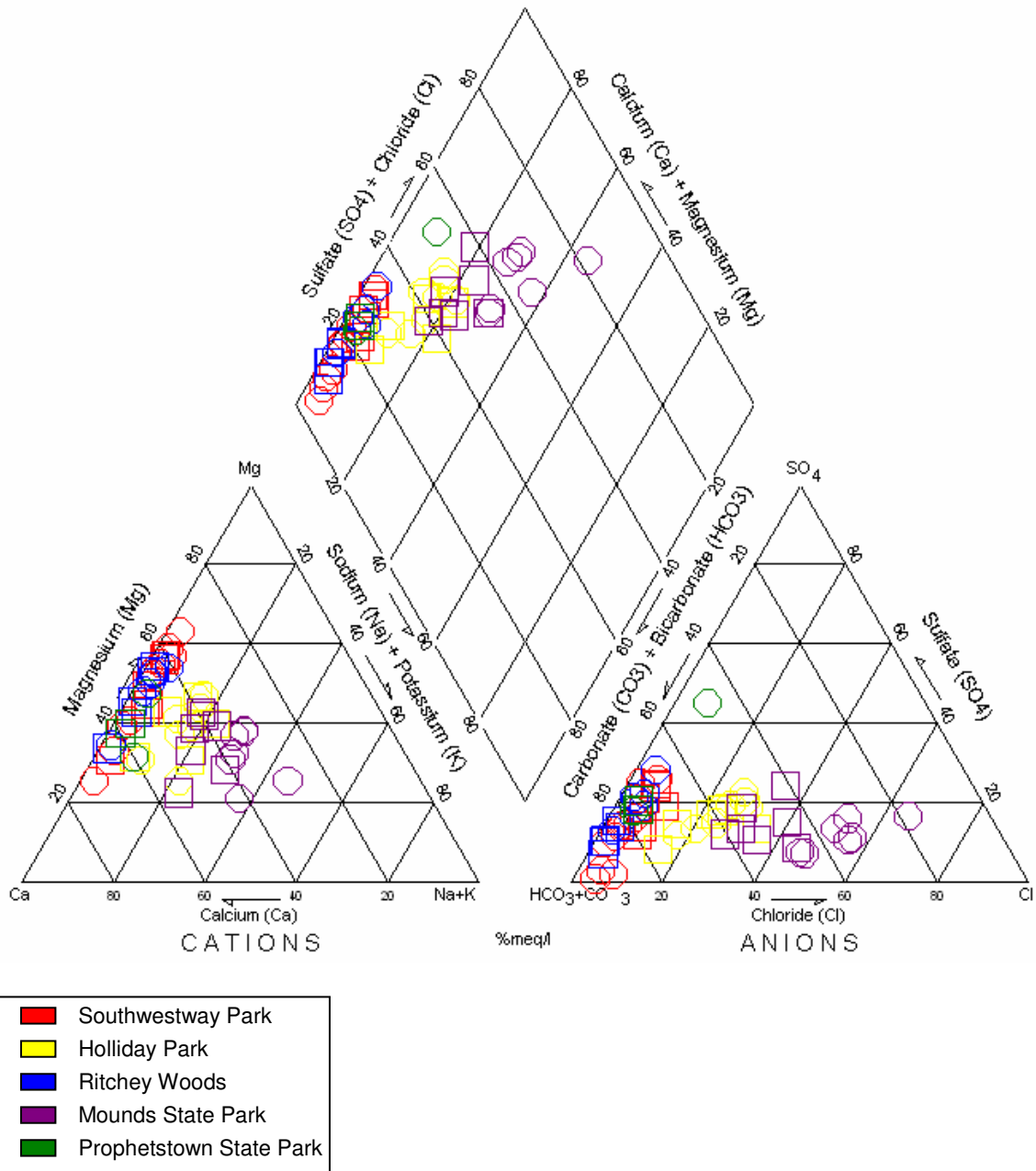


Figure 6. Piper diagram showing the ion distribution of ground water from central Indiana fens. The data represented in the piper diagram includes both source water and fen water from each central Indiana study site. Source water is represented with squares while fen water is represented with octagons. Most of the study sites are characterized as Ca^{2+} , Mg^{+} , and HCO_3^{-} dominated systems, with the exception of Mounds State Park and to a lesser degree Holliday Park.

Park (36 – 61 mg/L) and Mounds State Park (62 – 185 mg/L) in excess of other sites (3 – 17 mg/L). Figures 7 and 8 show Na^+ and Cl^- ranges as box plots for each studied fen. Nutrients, including nitrate (NO_3^-) (0 – 2.98 mg/L), ortho-phosphate (O-PO_4^{3-}) (0 – 0.18 mg/L), nitrite (NO_2^-) (0 – 0.04 mg/L), and ammonia ($\text{NH}_3\text{-N}$) (0 – 4.58 mg/L), are not detected in substantial amounts. Sulfate (SO_4^{2-}) values are highly variable among the central Indiana fens, ranging from 2 – 138 mg/L (Table 3).

Discriminant analysis results indicate discrimination between source water and fen water at each Indiana fen (Figure 9). An overlap of the source water and fen water would suggest minimal variation among the data, however each fen exhibits a substantial segregation. Table 4 provides a generalized summary of the variance at each study site, as derived from Principal Component Analysis (PCA). HCO_3^- and SO_4^{2-} present the heaviest loadings upon the primary components that control this discrimination, with the exception of Mounds State Park where some of the variance is explained by Cl^- . HCO_3^- comprises the most variance at Southwestway Park, Holliday Park, Ritchey Woods, and Mounds State Park (Type Ia and Ib fens) accounting for 65% – 89% of the total variance at these sites. However, the variance at Prophetstown State Park (Type II fen) is predominantly controlled by SO_4^{2-} .

PCA was used to evaluate the geochemical variation among the five studied central Indiana fens using the parameters of pH, specific conductivity, cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), anions (HCO_3^- , NO_3^- , SO_4^{2-} , Cl^-), and silica (SiO_2). This analysis was conducted for each site with all ground water samples (Figure 10), only source water samples (Figure 11), and only fen water samples (Figure 12). The PCA scatter plots

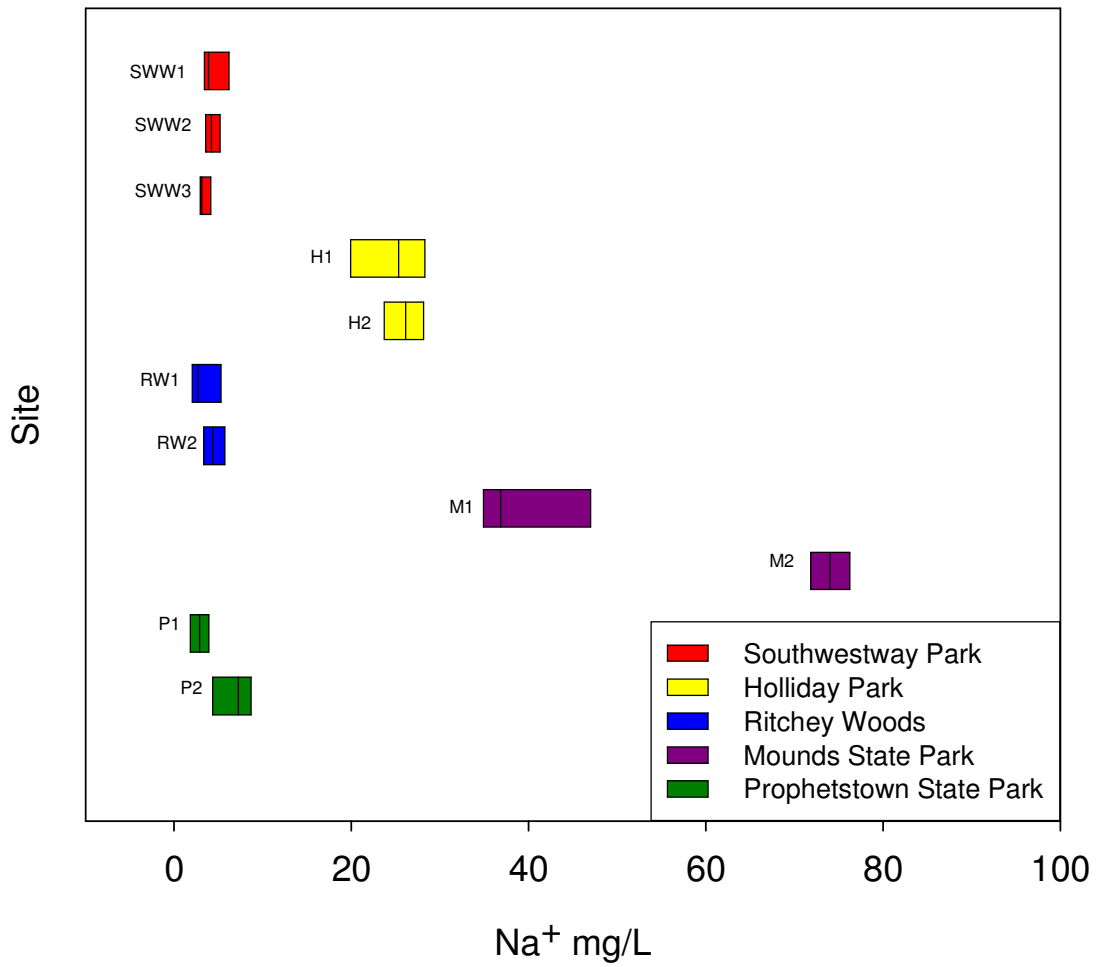


Figure 7. Box plots with median lines showing ranges of sodium values (Na⁺) in central Indiana fens. Source water wells are suffixed with a number 1 while fen water values are suffixed with numbers 2 or 3. Note the elevated concentrations of Na⁺ at both the Holliday Park and Mounds State Park fens.

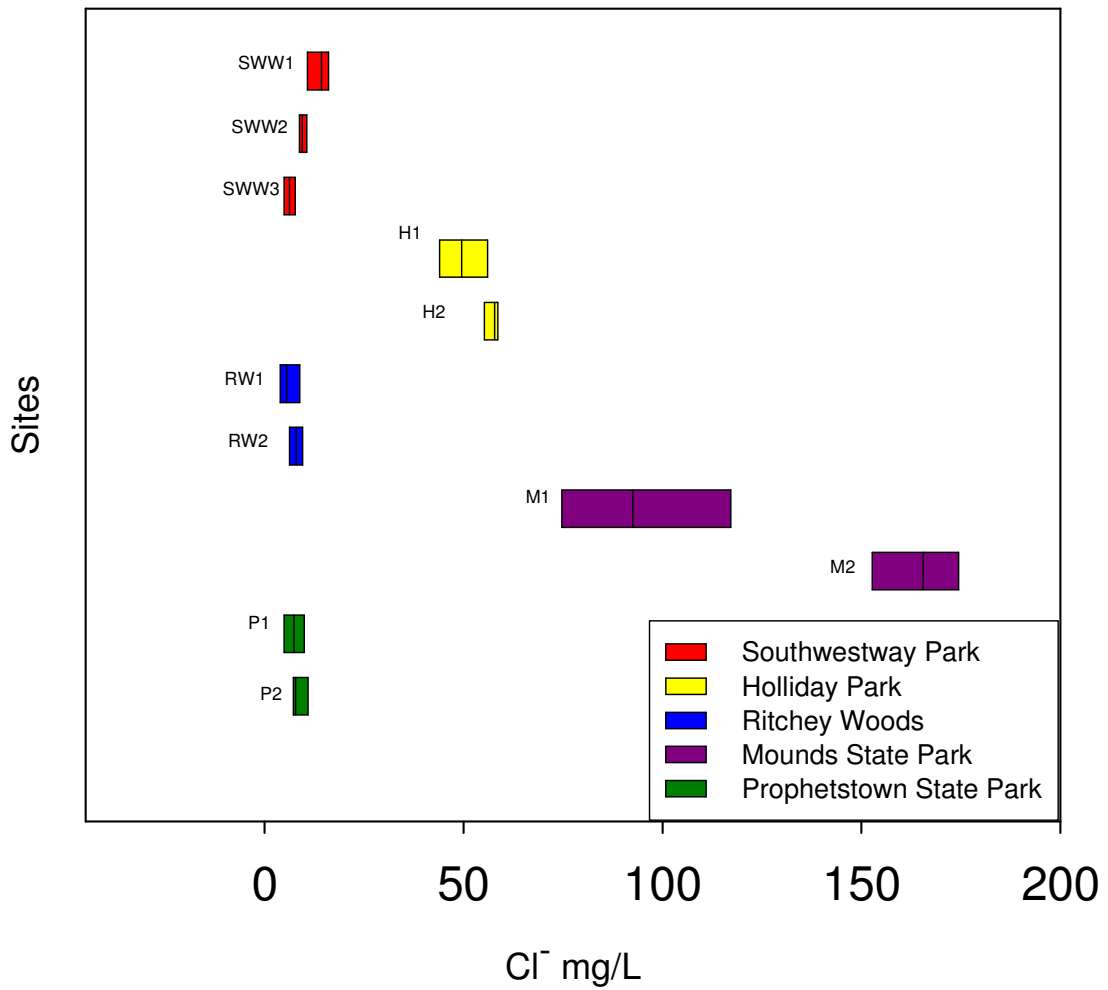


Figure 8. Box plots with median lines showing ranges of chloride values (Cl⁻) in central Indiana fens. Source water wells are suffixed with a number 1 while fen water values are suffixed with numbers 2 or 3. Note the elevated concentrations of Cl⁻ at both the Holliday Park and Mounds State Park fens.

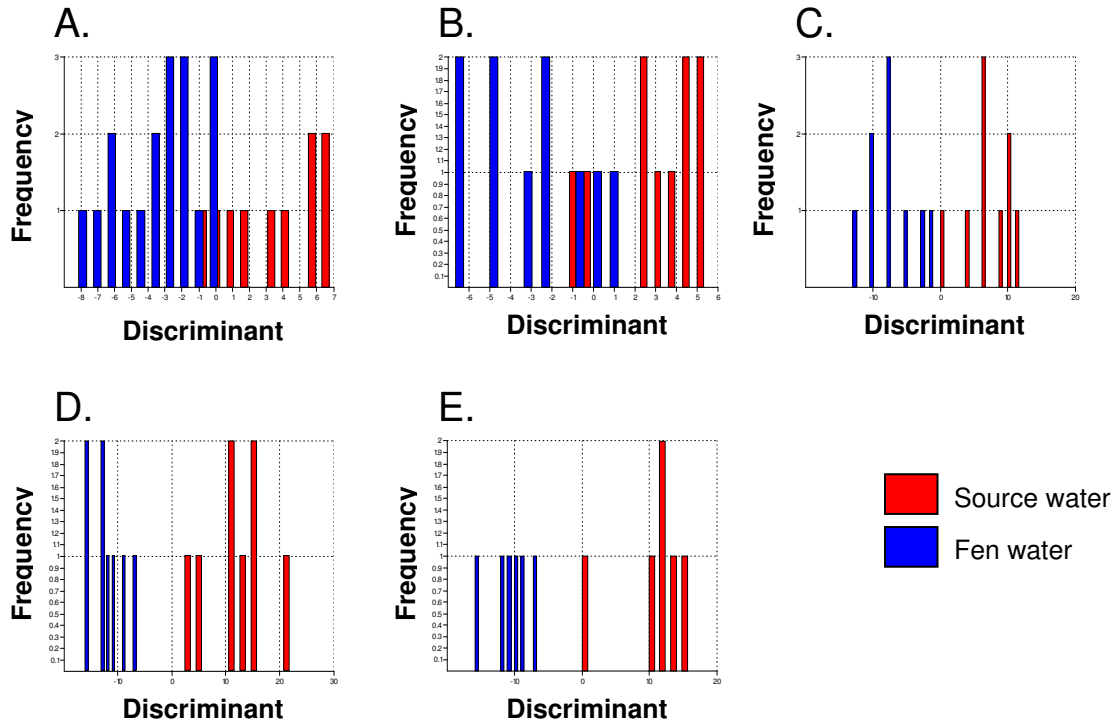


Figure 9. Discriminant Analysis results for source water vs. fen water at each respective study site. A. Southwestway Park; B. Holliday Park; C. Ritchey Woods; D. Mounds State Park; E. Prophetstown State Park.

Table 4. Summary of the variance of source water vs. fen water for each study site derived using principal component analysis. SWW = Southwestway Park; H = Holliday Park; RW = Ritchey Woods; M = Mounds State Park; P = Prophetstown State Park.

Site	Component	% Variance	Dominant Parameter	Parameter Loading Factor
SWW	1	65%	HCO ₃ ⁻	0.96
	2	28%	SO ₄ ²⁻	0.95
H	1	89%	HCO ₃ ⁻	0.99
	2	8%	SO ₄ ²⁻	0.97
RW	1	86%	HCO ₃ ⁻	0.99
	2	12%	SO ₄ ²⁻	0.99
M	1	66%	HCO ₃ ⁻	0.94
	2	27%	Cl ⁻	0.88
P	1	80%	SO ₄ ²⁻	0.99
	2	19%	HCO ₃ ⁻	0.98

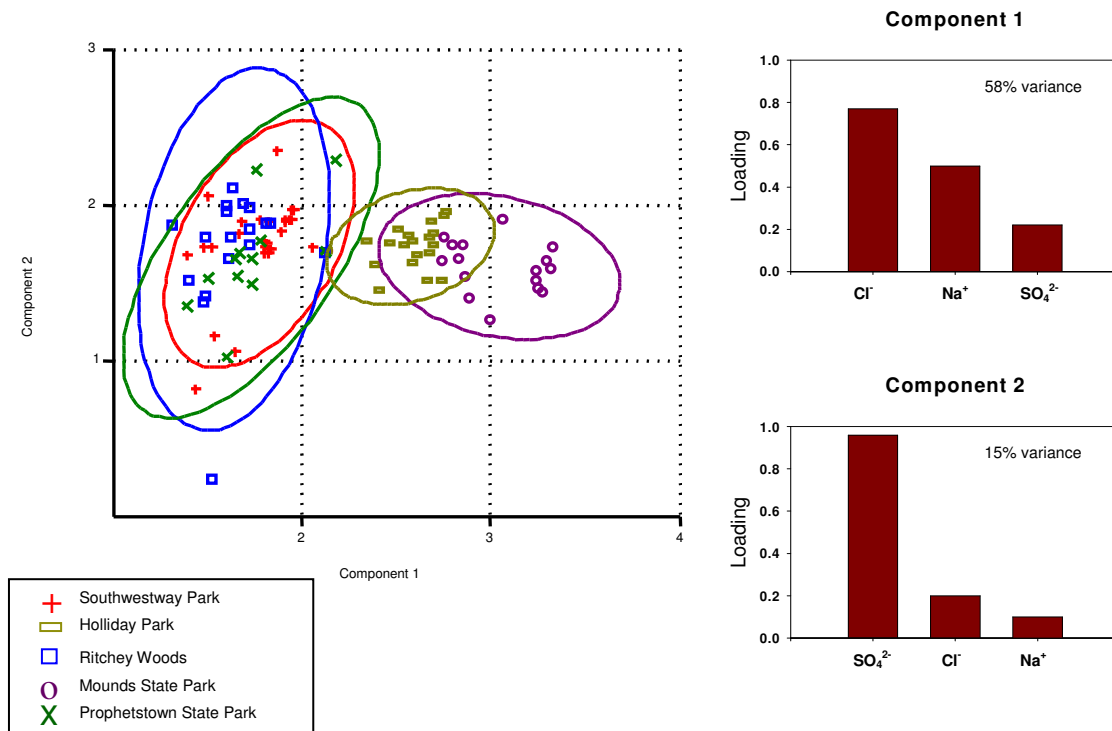


Figure 10. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Fen and source water are combined* here and all primary parameters are used as classifiers. Component 1 is responsible for 58% of the variance among the data and Cl⁻ and Na⁺ are the parameters with the heaviest loading on this component. 15% of the variance is explained by component 2, primarily driven by SO₄²⁻.

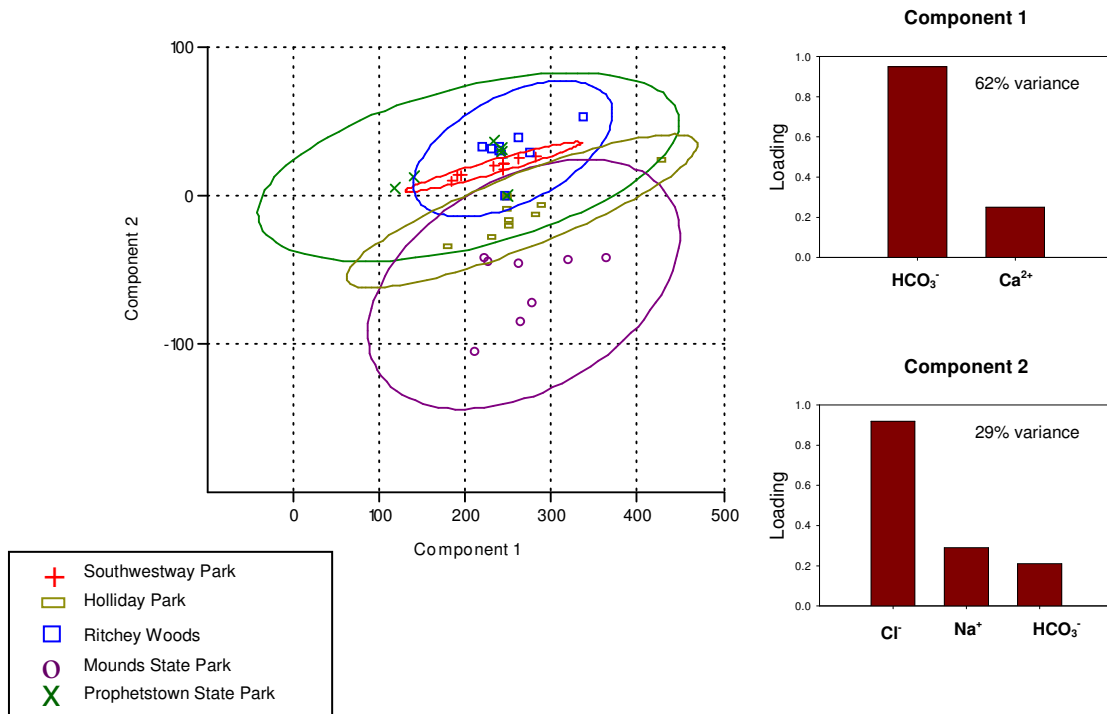


Figure 11. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Only source water* is shown here and all primary parameters are used as classifiers. Component 1 is responsible for 62% of the variance among the data and HCO_3^- and Ca^{2+} are the parameters with the heaviest loading on this component. 29% of the variance is explained by component 2, primarily driven by Cl^- .

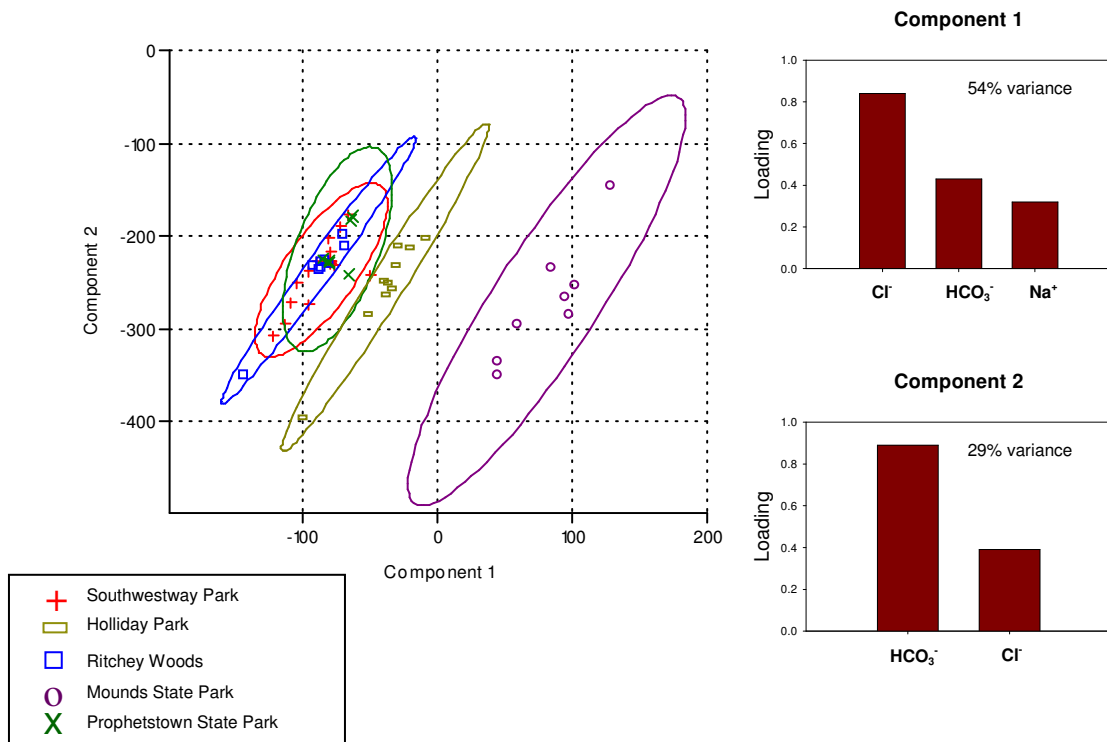


Figure 12. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Only fen water* is shown here and all primary parameters are used as classifiers. Component 1 is responsible for 54% of the variance among the data and Cl⁻, HCO₃⁻, and Na⁺ are the parameters with the heaviest loading on this component. 29% of the variance is explained by component 2, primarily driven by HCO₃⁻.

show that the Holliday Park and Mounds State Park fens are geochemically distinct from the other study sites (Figures 10, 11, and 12). Furthermore, the parameters of Na^+ and Cl^- are responsible for segregating these sites from the other studied fens, providing for most of the variance among the fen geochemistry. SO_4^{2-} is also responsible for some of the variation when source water and fen water are combined for each site and analyzed, however HCO_3^- and Ca^{2+} are the other driving variables when source water and fen water are investigated individually.

When the parameters responsible for the heaviest loadings on components 1 and 2 of the PCA, Na^+ and Cl^- , are removed from the data set, all central Indiana fens show geochemical similarity, or overlap of the confidence ellipses (Figures 13, 14, and 15). While ground water geochemistry is very similar among the Indiana fens after the removal of Na^+ and Cl^- , the variation that does remain can be attributed mostly to HCO_3^- , and SO_4^{2-} , and to a lesser degree Ca^{2+} and Mg^{2+} , which have the heaviest loadings on the components. These parameters are found to control the variation among the data in source water, fen water, and the combination thereof.

Comparison of Fen Geochemical Studies

Major cation (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anion (HCO_3^- , NO_3^- , SO_4^{2-} , Cl^-) ground water geochemistry generated from this study was compared to the fen ground water geochemical data of several studies using Principal Component Analysis (PCA) (Figure 16). This multi-region fen geochemical investigation involved only studies that included major cation (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anion (HCO_3^- , NO_3^- , SO_4^{2-} , Cl^-) measurements in order to keep statistical applications and analyses consistent. It should be noted that only

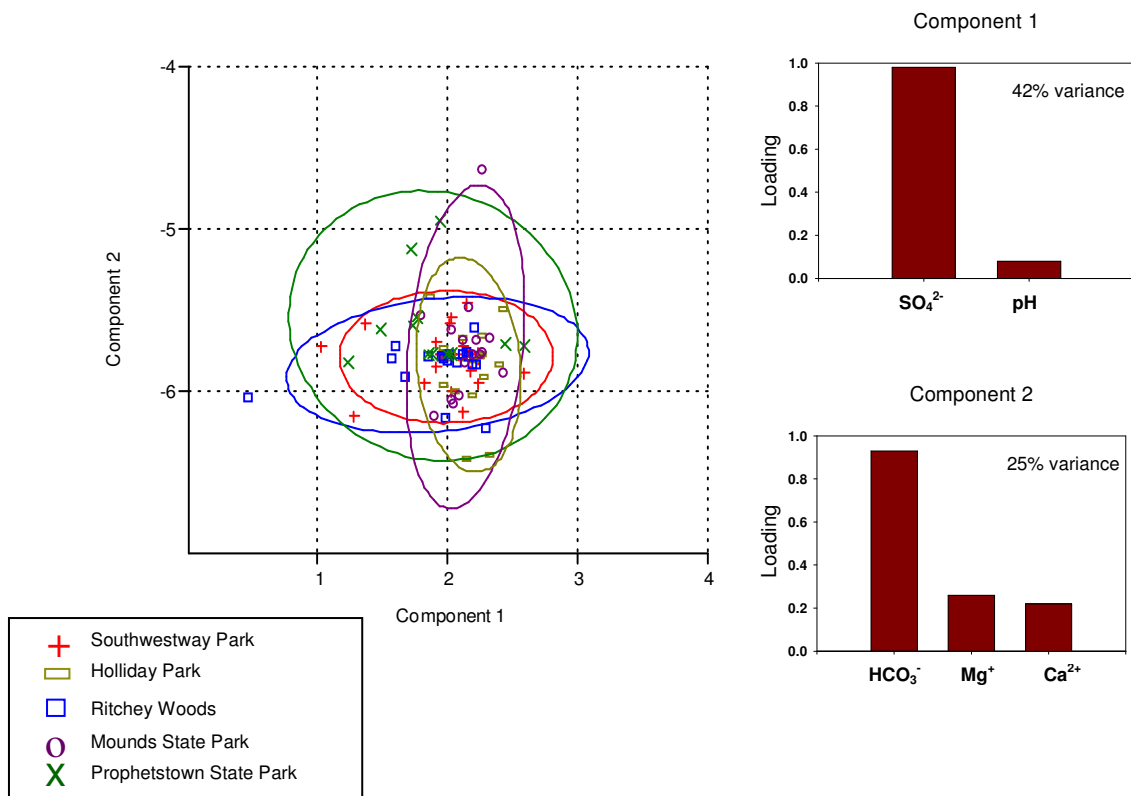


Figure 13. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Both source and fen water* are combined for this representation and Na^+ and Cl^- have been removed from the data set; all other parameters are used as classifiers. Component 1 is responsible for 42% of the variance among the data, driven primarily by SO_4^{2-} and component 2 explains 25% of the variance, driven mostly by HCO_3^- .

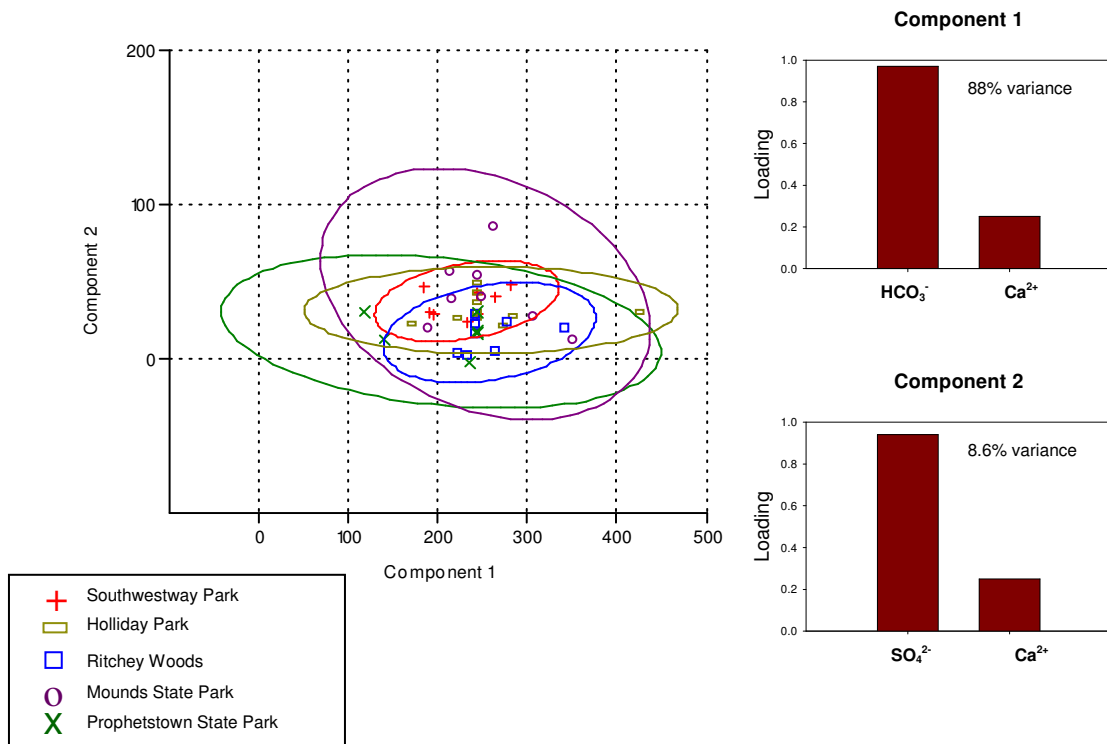


Figure 14. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Only source water is shown in this representation and Na^+ and Cl^- have been removed from the data set; all other parameters are used as classifiers.* Component 1 is responsible for 88% of the variance among the data, driven primarily by HCO_3^- and component 2 explains 8.6% of the variance, driven mostly by SO_4^{2-} .

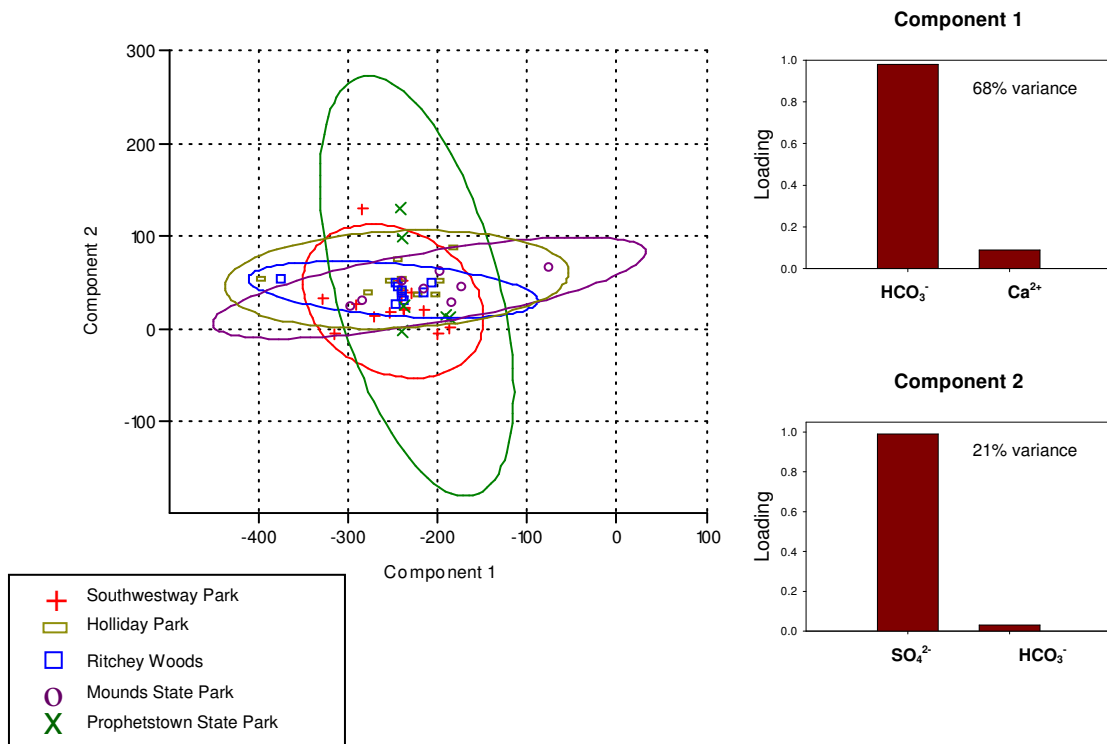


Figure 15. Principal Component Analysis scatter plot using variance – covariance matrix of central Indiana fen data with 95% confidence ellipses. *Only fen water* is shown in this representation and Na^+ and Cl^- have been removed from the data set; all other parameters are used as classifiers. Component 1 is responsible for 68% of the variance among the data, driven primarily by HCO_3^- and component 2 explains 21% of the variance, driven mostly by SO_4^{2-} .

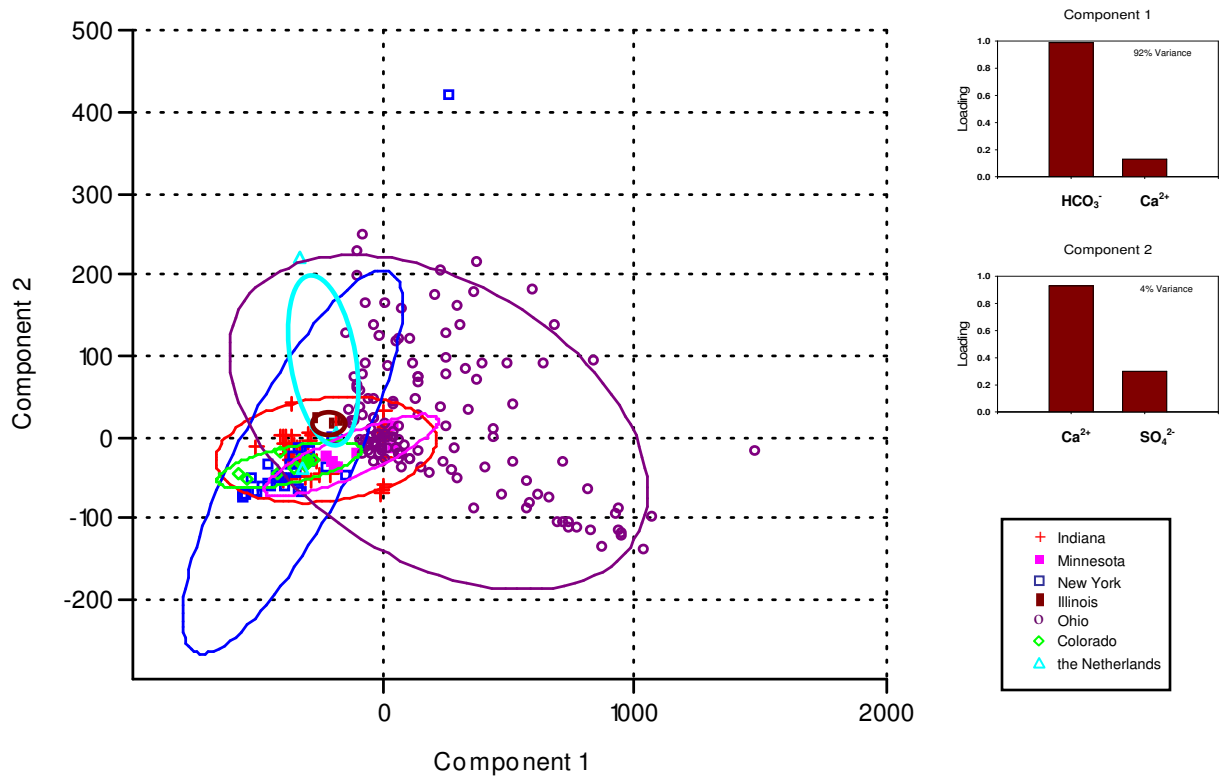


Figure 16. Principal Component Analysis scatter plot using variance – covariance matrix of a multi-region fen data set with 95% confidence ellipses. Only the major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (HCO_3^- , NO_3^- , SO_4^{2-} , Cl^-) are used in this representation. Component 1 is responsible for 92% of the variance and is largely driven by HCO_3^- while component 2 explains 4% of the variance and is driven by Ca^{2+} and SO_4^{2-} .

fen water data from the Indiana fens was included in the comparison in order to maintain consistency with other fen studies. This investigation included fen data from a variety of geological settings, from numerous fens in New York state (Godwin et al. 2002), and calcareous fens in the Minnesota River basin (Komor 1994), to other Pleistocene deposit related fens in northern Illinois (Panno et al. 1999), and western Ohio (Hite and Cheng 1996). Data was also analyzed from a mountain fen in South Park, Colorado, associated with bedrock geology (Cooper 1995), and from a poldered river plain fen complex in the Netherlands (Wassen et al. 1990). The geochemical data from Ohio (Hite and Cheng, 1996) was sampled from a recently constructed fen. All other fen data was collected from naturally occurring wetlands.

PCA analysis of multiple fen geochemical data display, with 95% confidence intervals, that a strong overlap of fen geochemistry exists, implying that fen geochemistry is largely homogenous over a wide geographical and geological range. Although the cation and anion data from the multi-region fen study shows correlation among the included fens, variation among the data can be attributed to HCO_3^- (component 1), and Ca^{2+} (component 2). Fen geochemical data representing the strongest deviation from the other data sets was collected from a constructed fen in Ohio (Hite and Cheng 1996).

DISCUSSION

Hydrogeology

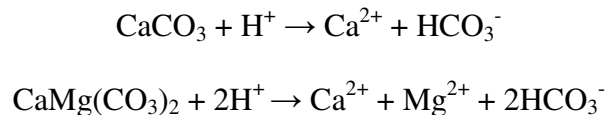
Hydraulic head measurements from the winter of 2005 and spring 2006 suggest that the hydrologic input to the central Indiana fens is a combination of throughflow from the shallow aquifer upslope of the fens (source water) and upwelling, which provides ground water from below the fens. Hydraulic head measurements from Southwestway Park suggest that ground water is supplied from both the sand and gravel upslope of the fen and from upwelling, while the hydrogeology of Holliday Park, Mounds State Park, and Prophetstown State Park represents a throughflow ground water supply, suggesting that little or no upwelling from below the fen is present. However, the fen at Ritchey Woods is almost entirely fed by upwelling ground water. The source water hydrographs (Figures 5A – 5E) show that the Type II fen (Prophetstown State Park) generally displays more variation in water table elevations than the Type Ia and Ib fens. Since the Type II, outwash terrace fen, is supplied by an unconfined aquifer, it is not surprising that the water table fluctuates more than the Type Ia and Ib fens, supplied by a confined aquifer.

Although the source water flow path, prior to discharging into the fens, may be unique at some sites, the water-table fluctuations within each fen were minimal, resulting in very similar hydroperiods at each of these slope wetlands. The similarities in hydrology of each of the study sites exist in combination with the similarities shown among the geologic or geomorphic setting of each fen. It is evident that the geologic setting of these slope wetlands provides for a consistent hydroperiod, despite some deviations in the hydrologic input to each fen.

Geochemistry

Ground water geochemistry exhibits substantial discrimination from the source water to fen water at each of the central Indiana fens. HCO_3^- and SO_4^{2-} present the heaviest loadings upon the primary components that control this discrimination. This variation in geochemistry may be due to an evolution of the water as it interacts with the root zone in the fen, anaerobic microbes, and atmospheric gases (Komor 1994; Hite and Cheng 1996). HCO_3^- is the primary variant at the Type Ia and Ib fens, while SO_4^{2-} is the primary variant at the Type II fen.

Haynos (1991) suggested that HCO_3^- concentrations in a wetland-related aquifer system in Ohio were controlled by the dissolution of calcite and dolomite via the following reactions:



Due to the pH values that were measured from the central Indiana fens (5.58 – 7.74), the CO_3^- species of dissolved inorganic carbon, and dissolved hydroxide ions, are not present in substantial quantities in this ground water (Hem 1989). Therefore, alkalinity is comprised almost entirely of HCO_3^- . If HCO_3^- (alkalinity) concentrations are solely sourced from carbonate mineral dissolution, then $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and alkalinity would have a 1:1 equivalent ratio. A plot of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ versus alkalinity (Figure 17) shows that all of the alkalinity in the ground water can be attributed to carbonate mineral dissolution. Although the reduction of ferric iron and reactions involving organic acids

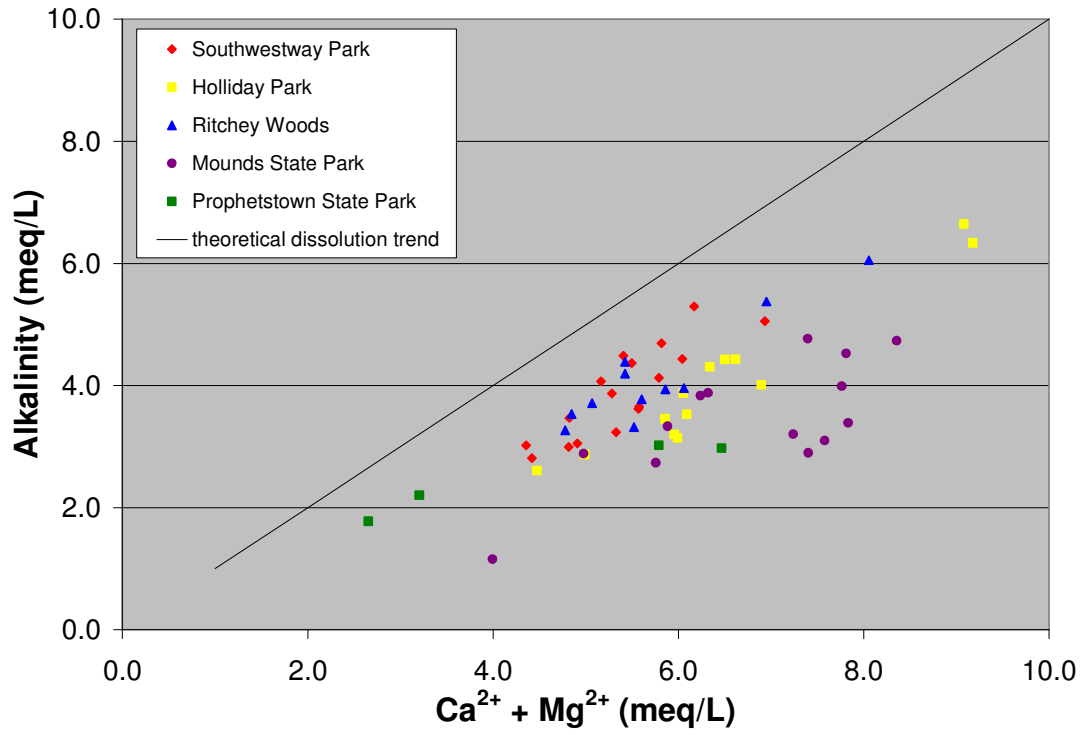


Figure 17. Comparison between the theoretical dissolution trend of calcite and dolomite and analytical results. Data includes both source and fen water results.

could result in the production of HCO_3^- in the subsurface, these contributions are minimal and are ignored for the purposes of this quantification (Hite and Cheng 1996).

In the same manner that calcite and dolomite control HCO_3^- values, it is likely that gypsum (anhydrite) dissolution would supply SO_4^{2-} to these systems via the following reaction:



If gypsum (anhydrite) is responsible for all of the SO_4^{2-} in these systems, then SO_4^{2-} and the remaining Ca^{2+} , after carbonate dissolution is quantified and removed, should also have a 1:1 equivalent ratio (Figure 18). Nearly all SO_4^{2-} is accounted for using this relationship. Other SO_4^{2-} contributions to these systems would likely include pyrite oxidation (Panno et al. 1999; Nordstrum 2005) or atmospheric deposition.

The hydraulic head measurements from the spring of 2006 suggest that the sampled fen water is a combination of shallow ground water throughflow derived from the aquifer upslope from the fen (source water) and upwelling ground water from deeper zones of the aquifer. Therefore, there may be substantial differences in the flow path and/or residence time between source water and fen water, particularly at Southwestway Park and Ritchey Woods, the sites exhibiting the greatest degree of upwelling. Production of carbon dioxide and organic acids via biological productivity, geochemical processes that facilitate carbonate dissolution, should be more prevalent in the fen water due to the increased interaction with the root zone (Hite and Cheng 1996). However, HCO_3^- is not consistently in higher concentration in the fen water versus the source water (Figure 19). This inconsistency could be explained as carbonate mineral precipitation

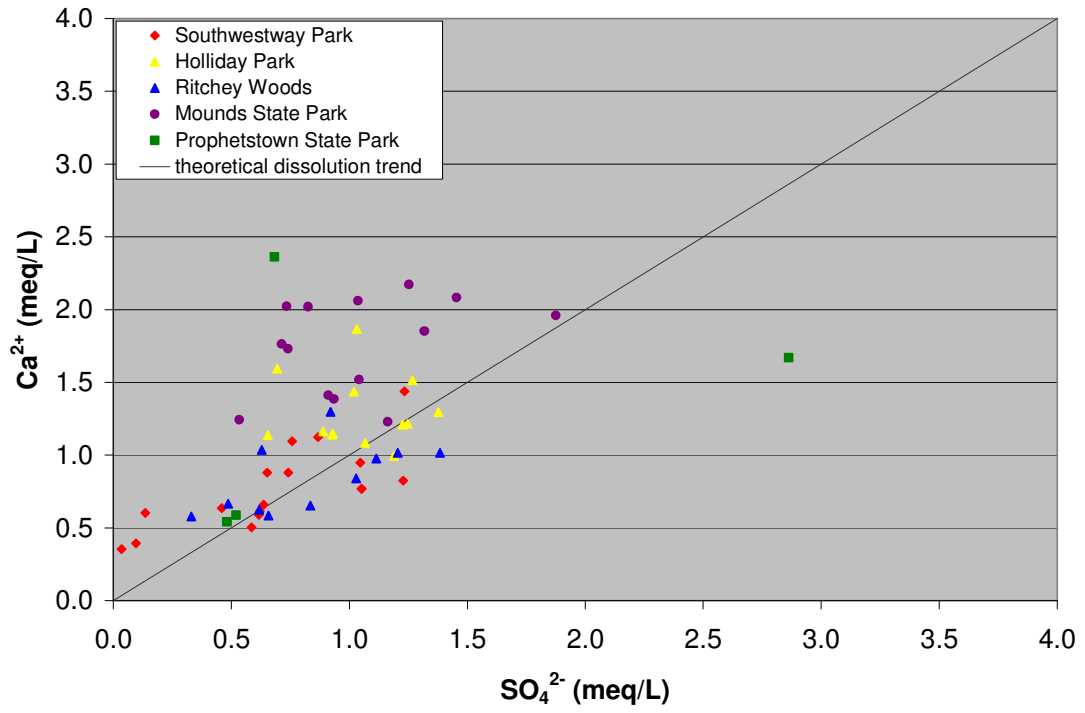


Figure 18. Comparison between theoretical dissolution trend of gypsum and analytical values. Data includes both source and fen water results.

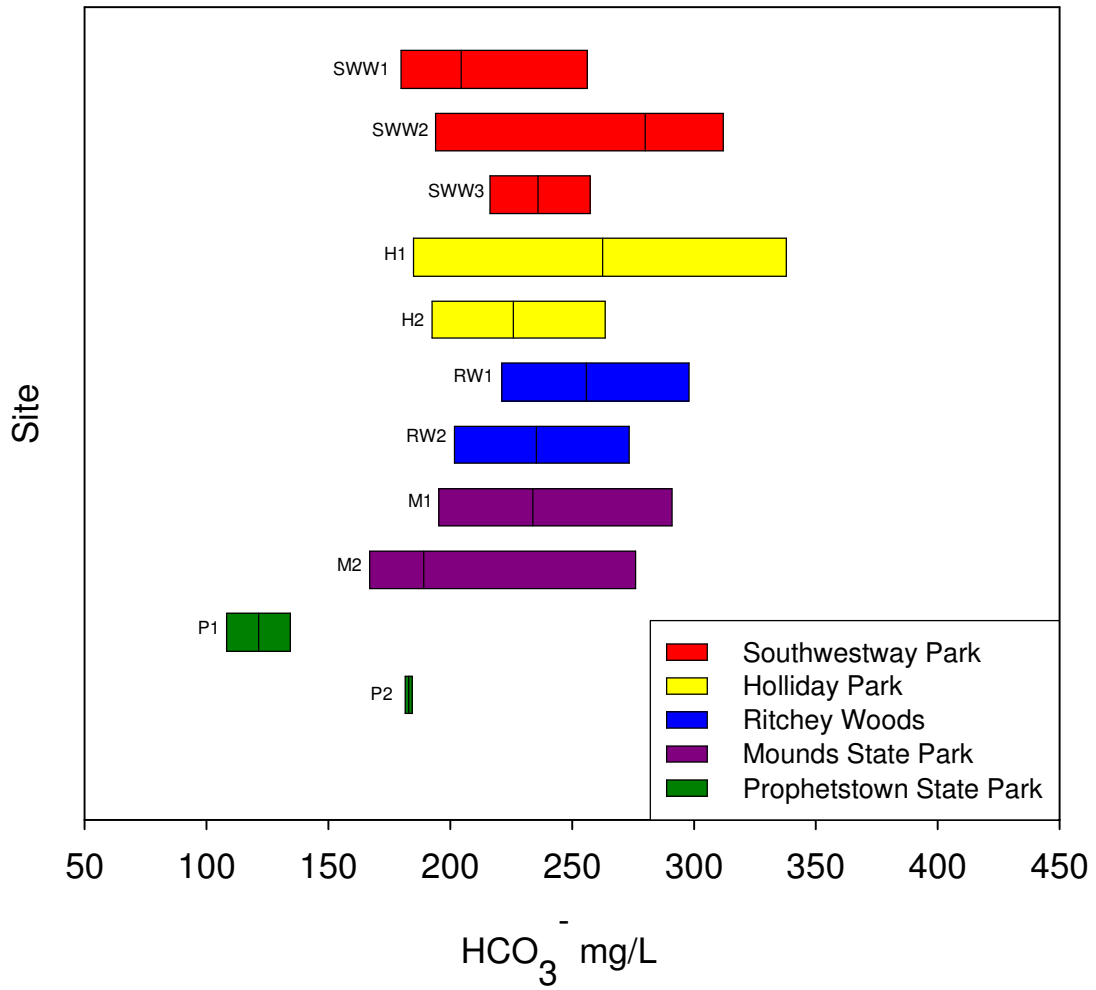


Figure 19. Box plots with median lines representing the bicarbonate values at the central Indiana fens. Source water wells are suffixed with a number 1 while fen water values are suffixed with numbers 2 or 3.

within the fen, associated with CO₂ outgassing of the shallow ground water as it discharges to interact with the fen root zone. It is also possible that the variation from source water to fen water is the signature of varying flow paths and/or residence time between these two waters.

The PCA results from the central Indiana fen geochemical data show that Holliday Park and, to a greater degree, Mounds State Park does not share similarity with the other fens. Further, it is evident that Cl⁻ and Na⁺ are responsible for the variation among the fens. If these parameters are the product of aquifer mineral dissolution, then a correlation between the two would be unlikely. However, if these parameters are sourced from an anthropogenic influence, such as the dissolution of road salt (NaCl), then they would represent a 1:1 equivalent ratio (Figure 20). Although the relationship among Na⁺ and Cl⁻ do not fall perfectly along the theoretical dissolution trend, a linear relationship among these parameters is evident and nearly all of the Na⁺ is explained. The excess Cl⁻ is closely related to the remaining (Ca²⁺ + Mg²⁺), which would demonstrate a 2:1 equivalent theoretical dissolution trend, after carbonate mineral and gypsum dissolution values are removed (Figure 21). This relationship suggests that road salt contamination is a primary influence on both Holliday Park and Mounds State Park. Other variations among the fen data is driven by SO₄²⁻ when source water and fen water are combined and analyzed, and by HCO₃⁻ and Ca²⁺ when source water and fen water are analyzed individually. This suggests that SO₄²⁻ is more variable between the source “aquifer” water and the fen “wetland” water when study sites are compared, and less variable

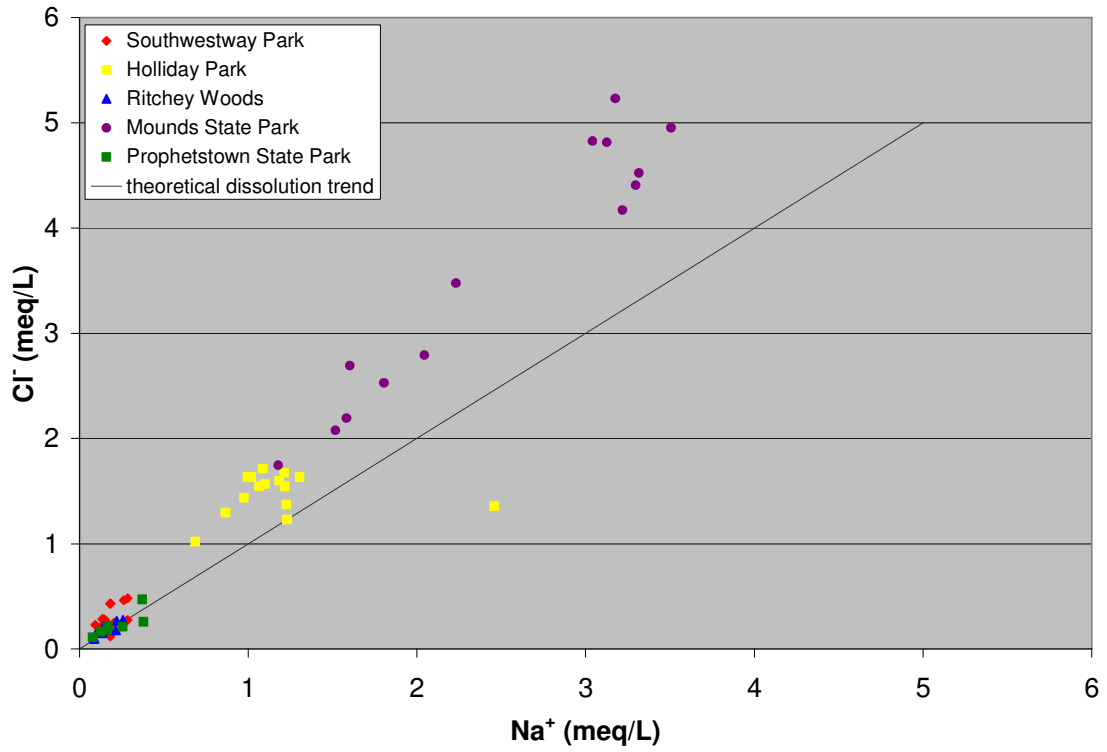


Figure 20. Comparison between theoretical dissolution trend of sodium chloride (NaCl) and analytical results. Data includes both source and fen water results.

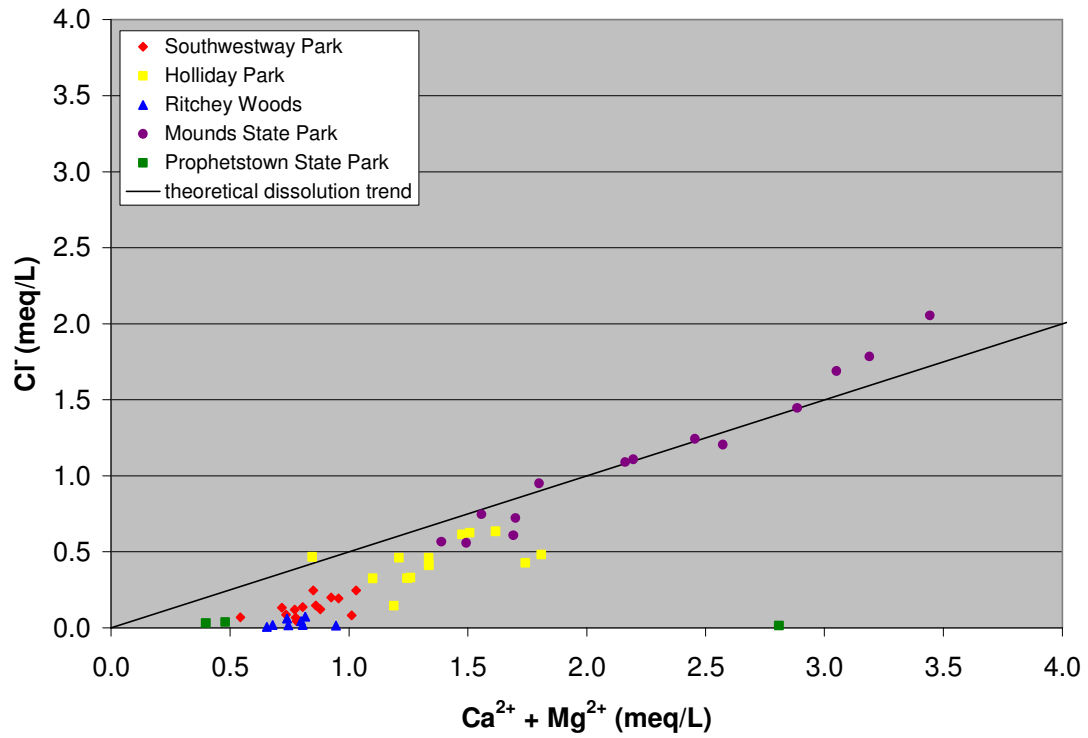


Figure 21. Comparison between the theoretical dissolution trend of CaCl₂ and MgCl₂ and analytical values, after carbonate mineral, gypsum, and sodium chloride (NaCl) have been quantitatively removed.

within the source “aquifer” or within the fen “wetland” when sites are compared to each other.

If Na^+ and Cl^- are then removed from the data set, the geochemical 95% confidence ellipses from the five central Indiana fens show a substantial overlap, suggesting that fens located in a similar geologic setting display very similar geochemical signatures, with exception of aquifer contamination. Furthermore, parameters that are responsible for variation (after the removal of Na^+ and Cl^-) remain consistent *within* both source and fen water, and are recognized as the same parameters that are responsible for the deviation *between* source water and fen water, that being HCO_3^- , Ca^{2+} , and SO_4^{2-} . This suggests the dynamics that geochemically distinguish source water from fen water at each site are also prevalent within each respective realm of ground water, and that this biogeochemical signature is consistent among all five central Indiana fens.

This evidence supports the primary hypotheses that source water and fen water are geochemically distinct, yet fen water geochemistry represents similarity among fens located in a similar geologic setting. Therefore, biogeochemical dynamics in fen ground water is consistent among fens located along the Trafalgar till stratigraphic contact with older till (pre-Wisconsinan or Wisconsinan) packages.

Comparison of Fen Geochemical Studies

Fen geochemistry appears to be largely homogenous on a wide geographical scale. The PCA analysis results display a relatively strong homogeneity among fen geochemical data. The data set responsible for the greatest heterogeneity among the several fen studies included in this investigation was from a constructed fen in Greene County, Ohio (Hite and Cheng 1996), perhaps explained by a decreased amount of

weathering, alkaline mineral leaching, or carbonate precipitation in the fen. Therefore, it is practical that this young fen is more concentrated in Ca^{2+} and HCO_3^- , the parameters shown to have the greatest loading on the variation among the geochemical comparison. Although fen geochemistry shows significant similarity among several studied fens, the dynamics of carbonate mineral and gypsum dissolution appear to be fen-specific and are responsible for geochemical variation among this type of wetland. Godwin et al. (2002) also found that HCO_3^- , and to a lesser degree Ca^{2+} was best correlated to individual landscape properties in New York fens, supporting the inference that carbonate mineral dissolution is primarily fen specific.

The limited fluctuation in the “fen water” hydroperiods of central Indiana, as well as overall statistical similarity of these wetlands falls in accordance with the suggestions proposed by Cole et al. (1997). Cole and his coauthors noted that “Wetlands in comparable regional hydrogeomorphic subclasses should show similar characteristics ...i.e., the frequency and duration of saturation or inundation...and selected water quality signatures.” The consistency of these parameters as indicated by this study could provide beneficial insight to regulatory officials, wetland managers, and wetlands restorationists. If potential wetland creation or restoration sites were geochemically investigated and results indicated that parameters other than HCO_3^- , Ca^{2+} , and SO_4^{2-} were responsible for variations, then the site may not be indicative of a natural fen setting, or there is possibly an aquifer contamination. Furthermore, if natural fens, often recognized as pristine environments, were found to have geochemical variability driven by parameters other than HCO_3^- , Ca^{2+} , and SO_4^{2-} , then a land use influence might be targeted as a potential degradation source.

CONCLUSIONS

The central Indiana fens included in this study are characterized as slope wetlands with dominant ground water input. More specifically, these fens are recognized as inter-till (Type Ia) or intra-till type fens (Type Ib) or as outwash terrace type fens (Type II). Although the source water aquifer levels at each study site represents some variation, the fen water hydroperiods are comparable among central Indiana fens, with a mean depth to ground water at 15 cm. Furthermore, it is evident that this hydrogeomorphic subclass of slope wetlands, located along a comparable geologic contact, share very similar hydroperiod dynamics, displaying minor variations within each fen despite some deviation in hydrologic input, specifically a greater variation in source water table elevations in the Type II fens.

There exists distinct segregation in the ground water geochemistry between the aquifer source water and fen water for the central Indiana fens. Variation is primarily driven by HCO_3^- in the Type Ia and Ib fens, while SO_4^{2-} is the primary variant in the Type II fen. Although the variation in the geochemistry appears to be controlled by carbonate dissolution dynamics (via biological productivity) and gypsum dissolution, it is also possible that aquifer residence time and/or flow path of the ground water sustaining the fen is responsible for some of the geochemical variation.

Anthropogenic influence was observed at two of the study sites (Holliday Park and Mounds State Park) and identified as road salt contamination. Although CaCl_2 and MgCl_2 appear to contribute minimally to this contamination, NaCl was observed as the primary constituent of the dissolved salt. When PCA was used to analyze the variation in fen geochemistry, Holliday Park and Mounds State Park represented the greatest

variation between the fens. However, when NaCl was removed from the data set, source water, fen water, and the combination of the two all show a strong overlap in geochemistry, indicating homogeneity of fens within a similar geologic setting. This evidence also suggests that the biogeochemical dynamics are consistent among fens that are located along a similar stratigraphic contact.

Furthermore, when the fen ground water geochemical data from central Indiana was compared to similar data from a broad geographical range, similar trends were observed. Fen geochemistry appears to share significant similarity on a wide geographical, and hence geological, setting. However, the variation that was observed between fen geochemical studies can be attributed to carbonate and gypsum dissolution, a biogeochemical signature that appears to be fen specific.

The similarities observed in the hydroperiod of central Indiana fens, as well as the statistical similarity among ground water geochemistry of fens, provides evidence that wetlands fulfilling a similar hydrogeomorphic niche among a broad geographical range do conform to very similar characteristics, as suggested by Cole et al. (1997). It is plausible that wetlands inhabiting this particular niche within the glaciated Midwest will yield very similar geochemical response, in the absence of aquifer contamination. This data provides a useful geochemical background data set and analysis for temperate zone fens and slope wetlands within the glaciated Midwest. Such findings could be further tested among differing hydrogeomorphic subclasses and possibly extrapolated for the beneficial use of wetland scientists and managers.

APPENDIX A

Well and Piezometer Data

Well-Piezometer ID	Type	Date of Installation	Zone	UTM East	UTM North	Depth (m bgs)	Screen length (m)
SW1	well	1/25/2005	slope/source	565140	4389886	1.65	0.24
SW2	well	1/25/2005	fen/middle	565163	4389886	0.69	0.24
SW3	well	1/25/2005	fen/east	565178	4389884	0.52	0.24
SW1/1	piezometer	10/3/2005	slope/source	565140	4389886	1.50	0.20
SW1/2	piezometer	10/3/2005	slope/source	565140	4389886	1.00	0.20
SW1/3	piezometer	10/3/2005	slope/source	565140	4389886	0.50	0.20
SW2/1	piezometer	10/3/2005	fen/middle	565163	4389886	1.60	0.20
SW2/2	piezometer	10/3/2005	fen/middle	565163	4389886	1.00	0.20
SW2/3	piezometer	10/3/2005	fen/middle	565168	4389886	0.50	0.20
SW3/1	piezometer	10/3/2005	fen/east	565178	4389884	1.63	0.20
SW3/2	piezometer	10/3/2005	fen/east	565173	4389884	1.00	0.20
SW3/3	piezometer	10/3/2005	fen/east	565178	4389884	0.56	0.20
H1	well	2/18/2005	slope/source	572002	4413881	1.02	0.24
H2	well	2/18/2005	fen	572005	4413876	1.07	0.24
H1/2	piezometer	10/31/2005	slope/source	572002	4413881	0.94	0.20
H1/3	piezometer	10/31/2005	slope/source	572002	4413881	0.49	0.20
H3/1	piezometer	10/31/2005	fen/middle	572000	4413876	1.30	0.20
H3/2	piezometer	10/31/2005	fen/middle	572000	4413881	1.00	0.20
H3/3	piezometer	10/31/2005	fen/middle	572000	4413881	0.50	0.20
H2/1	piezometer	10/31/2005	fen/east	572005	4413876	1.80	0.20
H2/2	piezometer	10/31/2005	fen/east	572005	4413876	1.00	0.20
H2/3	piezometer	10/31/2005	fen/east	572005	4413876	0.50	0.20
RW1	well	3/3/2005	slope/source	581915	4421512	1.98	0.70
RW2	well	na	fen	581909	4421514	0.82	0.71
RW1/1	piezometer	10/3/2005	slope/source	581903	4421513	1.50	0.20
RW1/2	piezometer	10/3/2005	slope/source	581903	4421513	1.00	0.20
RW1/3	piezometer	10/3/2005	slope/source	581903	4421513	0.50	0.20
RW2/1	piezometer	10/3/2005	fen	581901	4421513	1.60	0.20
RW2/2	piezometer	10/3/2005	fen	581901	4421513	1.00	0.20
RW2/3	piezometer	10/3/2005	fen	581901	4421513	0.50	0.20
RW3/1	piezometer	10/3/2005	fen	581896	4421512	1.50	0.20
RW3/2	piezometer	10/3/2005	fen	581896	4421512	1.00	0.20
RW3/3	piezometer	10/3/2005	fen	581896	4421512	0.50	0.20
RW4/1	piezometer	10/3/2005	fen	581896	4421507	1.50	0.20
RW4/2	piezometer	10/3/2005	fen	581896	4421507	0.90	0.20
RW4/3	piezometer	10/3/2005	fen	581896	4421507	0.50	0.20
RW5/1	piezometer	10/3/2005	fen	581896	4412517	1.45	0.20
RW5/2	piezometer	10/3/2005	fen	581896	4412517	1.00	0.20
RW5/3	piezometer	10/3/2005	fen	581896	4412517	0.50	0.20

Well-Piezometer ID	Type	Date of Installation	Zone	UTM East	UTM North	Depth (m bgs)	Screen length (m)
M1	well	3/4/2005	slope/source	617533	4439600	1.30	0.24
M2	well	3/4/2005	fen	617522.5	4439600	2.01	0.42
M1/2	piezometer	2/3/2006	slope/source	617533	4439600	0.93	0.2
M1/3	piezometer	2/3/2006	slope/source	617533	4439600	0.49	0.2
M2/1	piezometer	2/3/2006	fen	na	na	1.51	0.2
M2/2	piezometer	2/3/2006	fen	na	na	1.06	0.2
M2/3	piezometer	2/3/2006	fen	na	na	0.57	0.2
M3/1	piezometer	2/3/2006	fen	na	na	1.55	0.2
M3/2	piezometer	2/3/2006	fen	na	na	1.07	0.2
M3/3	piezometer	2/3/2006	fen	na	na	0.67	0.2
P1	well	3/16/2005	slope/source	na	na	0.66	0.24
P2	well	3/16/2005	fen	na	na	0.53	0.24
P1/1	piezometer	2/2/2006	slope/source	na	na	1.20	0.2
P1/2	piezometer	2/2/2006	slope/source	na	na	0.98	0.2
P1/3	piezometer	2/2/2006	slope/source	na	na	0.54	0.2
P2/1	piezometer	2/2/2006	fen	na	na	1.51	0.2
P2/2	piezometer	2/2/2006	fen	na	na	0.85	0.2
P2/3	piezometer	2/2/2006	fen	na	na	0.49	0.2
P3/1	piezometer	2/2/2006	fen	na	na	1.52	0.2
P3/2	piezometer	2/2/2006	fen	na	na	1.00	0.2
P3/3	piezometer	2/2/2006	fen	na	na	0.52	0.2

*na = not available

APPENDIX B

Laboratory Methodology and Detection Limits

Parameter tested	Analysis Equipment	Analysis Method	Detection limits
Magnesium (Mg ²⁺)	DX500 Ion Chromatograph (Dionex)	Column CS15 Methasulfanic Acid	0.49
Potassium (K ⁺)	DX500 Ion Chromatograph (Dionex)	Column CS15 Methasulfanic Acid	0.008
Calcium (Ca ²⁺)	DX500 Ion Chromatograph (Dionex)	Column CS15 Methasulfanic Acid	1.3
Sodium (Na ⁺)	DX500 Ion Chromatograph (Dionex)	Column CS15 Methasulfanic Acid	0.85
Chloride (Cl ⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	EPA method 325.2	0.33
Ammonia (NH ₃ ⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	EPA method 350.1	0.016
Nitrite (NO ₂ ⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	EPA method 354.1	0.004
Nitrate (NO ₃ ⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	Hydrazine Reduction method (EPA Method 353.3)	0.026
Phosphate (PO ₄ ³⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	ascorbic acid method (EPA method 365.2)	0.003
Sulfate (SO ₄ ²⁻)	Konelab 20 Photometric Analyzer (ESTanalytical)	EPA method 375.4	0.064

Parameter tested	Analysis Equipment	Analysis Method	Detection limits
Silica (SiO ₂)	Konelab 20 Photometric Analyzer (ESTanalytical)	EPA method 370.1	0.013
Bicarbonate (HCO ₃ ⁻)	Hach Digital Titrator	Ion balance	10
Alkalinity (as mg/L CaCO ₃)	Hach Digital Titrator	Ion balance	10

APPENDIX C

Tabulated Analytical and Field Data

Site	Well	Parameter														
		NH ₃ -N	Alkalinity	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	NO ₂	SiO ₂	O-PO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	pH	SpC	
Southwestway Park	SW1	0.03	143.00	13.20	50.70	0.080	0.014	6.30	0.004	60.30	17.13	2.80	4.26	7.2	0.715	
		0.06	128.70	14.30	50.40	0.075	0.007	5.80	0.003	61.30	33.20	2.80	6.05	7.03	0.809	
		0.04	143.60	14.30	58.80	0.100	0.007	6.40	0.003	66.20	33.30	?	6.58	7.18	0.692	
		0.53	132.00	15.35	36.40	0.065	0.006	6.01	<0.003	?	?	?	?	7.28	0.697	
		0.06	127.86	16.31	35.56	0.050	<0.004	8.38	<0.003	?	?	?	?	7.32	0.701	
		?	133.00	16.90	31.30	0.058	0.004	8.22	<0.003	?	?	?	?	7.55	0.681	
		?	?	?	?	?	?	?	?	?	?	?	?	?	7.23	0.743
	SW2	0.08	148.40	10.80	138.40	0.071	0.007	5.80	0.015	71.20	22.50	<0.01	4.73	7.47	0.696	
		0.09	151.40	9.20	43.90	0.106	0.008	6.80	0.011	50.10	44.60	?	6.57	7.22	0.673	
		0.07	152.60	8.70	35.60	0.157	0.009	5.40	0.011	?	?	?	?	7.01	0.85	
		0.14	135.60	8.89	6.49	0.106	0.011	5.41	0.011	?	?	?	?	7	0.866	
		0.10	151.36	9.82	1.70	0.077	<0.001	7.85	<0.003	?	?	?	?	6.97	0.866	
		?	?	?	?	?	?	?	?	?	?	?	?	?	7.01	0.902
		?	?	?	?	?	?	?	?	?	?	?	?	?	7.04	0.833
	SW3	0.13	147.20	8.60	44.80	0.110	0.009	5.80	0.006	82.40	17.67	<0.01	4.02	7.24	0.595	
		0.06	143.80	5.60	26.60	0.122	0.015	5.80	0.012	60.00	26.40	?	4.23	7.43	0.578	
		0.06	150.60	5.50	27.80	0.106	0.017	4.70	0.017	?	?	?	?	7.03	0.733	
		0.14	139.90	4.73	59.28	0.115	0.011	5.23	0.008	?	?	?	?	7.01	0.751	
		0.08	130.50	4.21	22.03	0.161	<0.004	5.46	<0.003	?	?	?	?	7.05	0.567	
		?	?	?	?	?	?	?	?	?	?	?	?	?	6.97	0.686

Site	Well	Parameter													
		NH ₃ -N	Alkalinity	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	NO ₂	SiO ₂	O-PO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	pH	SpC
Holiday Park	H1	0.04	158.30	56.20	24.50	0.149	0.006	7.50	0.014	54.66	21.20	<0.01	27.91	7.1	0.956
		0.02	147.70	45.10	30.30	1.075	0.017	2.90	0.005	?	?	1.50	56.50	7.11	0.914
		0.17	132.70	59.38	31.44	0.695	0.041	2.36	<0.003	?	?	2.78	28.30	6.97	0.976
		0.11	136.29	48.18	36.40	1.264	0.004	6.12	<0.003	?	?	?	?	6.83	0.905
		0.05	131.45	43.60	41.75	2.131	0.007	5.94	0.083	?	?	?	?	6.92	0.996
	H2	0.07	151.54	57.80	93.30	0.943	0.023	7.50	0.012	67.70	19.60	2.98	30.02	7.18	0.937
		0.04	148.62	58.90	82.90	1.090	0.008	6.60	0.009	64.00	34.72	2.85	28.00	7.45	0.945
		0.03	139.99	57.87	49.00	1.344	0.012	4.60	<0.003	72.90	34.80	<0.01	28.20	7.36	0.891
		0.03	125.30	54.76	44.67	2.179	0.015	7.57	<0.003	?	?	?	?	7.07	0.912
		0.02	139.42	48.63	42.69	2.287	<0.004	6.30	<0.003	?	?	?	?	7.3	0.953
Ritchey Woods	RW1	0.07	166.66	15.40	0.00	0.160	<0.004	7.40	0.056	60.70	29.10	<0.01	4.96	5.88	2.24
		0.05	154.93	4.60	13.00	0.114	0.017	2.10	0.007	123.00	32.54	2.80	6.21	6.48	1.032
		0.52	152.74	9.71	11.60	0.256	<0.004	6.62	0.180	?	?	?	?	6.72	0.791
		0.28	?	6.23	15.90	0.155	<0.004	4.09	0.083	?	?	?	?	6.96	0.755
		0.17	?	?	?	0.168	?	7.00	<0.003	?	?	?	?	?	?
	RW2	0.05	150.07	8.20	57.70	0.077	0.008	5.60	0.003	69.60	17.24	<0.01	5.07	7.38	0.694
		0.02	141.51	6.00	34.50	0.090	0.009	4.90	0.004	41.30	33.00	2.80	5.96	7.19	0.721
		1.35	140.06	9.58	45.82	0.101	0.029	5.72	<0.003	130.50	36.60	?	6.50	6.87	0.867
		0.84	144.63	9.83	40.08	0.208	0.005	7.20	<0.003	?	?	?	?	7.13	0.78
		0.35	?	?	?	0.209	?	7.89	<0.003	?	?	?	?	?	?

Site	Well	Parameter													
		NH ₃ -N	Alkalinity	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	NO ₂	SiO ₂	O-PO ₄ ²⁻	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	pH	SpC
Mounds State Park	M1	0.03	187.82	131.00	21.50	0.321	<0.004	4.80	0.090	59.30	24.51	4.57	47.00	6.94	1.099
		0.11	154.46	99.00	25.60	0.120	0.006	2.80	0.006	89.85	22.30	3.53	41.50	6.39	2.238
		0.41	141.38	89.61	35.56	0.091	0.007	2.53	<0.003	78.20	31.30	3.38	36.40	6.7	1.135
		0.28	137.36	77.72	44.89	0.061	<0.004	6.85	0.073	73.40	?	3.36	34.90	6.7	1.057
		0.20	135.55	73.67	43.76	0.062	0.003	6.67	0.015	?	?	?	?	6.85	0.892
		?	?	?	?	?	?	?	?	?	?	?	?	?	7.12
	M2	0.19	138.78	151.60	69.00	0.068	0.007	5.40	0.004	42.80	22.60	3.63	74.00	6.98	1.098
		0.27	156.83	147.80	50.00	0.063	0.007	4.00	0.017	77.10	23.20	3.74	75.80	7.16	1.293
		0.22	141.72	156.20	39.63	0.065	0.006	4.02	0.005	84.00	44.00	3.26	76.23	7.12	1.248
		0.22	140.26	160.30	34.25	0.059	<0.004	6.37	0.004	93.60	44.77	4.31	80.60	7.16	1.233
		0.18	137.37	175.56	35.27	0.087	<0.004	5.82	?	?	?	?	?	7.15	1.285
?	?	?	?	?	?	?	?	?	?	?	?	?	7.45	1.284	
Prophetstown State Park	P1	0.28	136.36	9.50	32.40	0.460	0.014	3.90	0.004	39.60	10.00	?	3.91	6.97	0.68
		0.36	142.68	10.50	18.80	0.208	0.009	4.00	0.004	?	?	?	?	6.94	?
		0.04	86.86	7.40	12.71	0.083	<0.004	3.48	<0.003	?	?	?	?	7.74	?
		?	?	?	?	?	?	?	0.017	?	?	?	?	?	?
	P2	0.12	145.06	7.90	19.10	0.219	0.014	5.00	0.006	85.10	18.35	10.40	5.92	7.49	0.615
		0.07	135.36	7.70	17.30	0.094	0.012	4.80	0.003	70.00	27.90	?	8.74	6.93	0.805
		0.41	144.72	7.47	3.88	0.075	0.011	5.45	<0.003	87.70	?	?	8.57	6.71	0.741
		0.29	131.65	9.09	105.98	0.101	<0.004	4.53	0.004	?	?	?	?	7.22	0.67
		4.58	117.40	16.60	137.50	0.090	0.017	3.45	0.156	?	?	?	?	?	?

Notes

-All values reported in mg/L

- ? = Data Not Available

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