

Prepared in cooperation with the Indiana Department of Natural Resources

Hydrology and Water Quality of a Dune-and-Swale Wetland Adjacent to the Grand Calumet River, Indiana, 2019–22



Scientific Investigations Report 2023–5122

Cover. From Clark Road looking west at a wetland cell in the Clark and Pine Nature Preserve. Photograph by Shawn Naylor, U.S. Geological Survey

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By Shawn Naylor and Amy M. Gahala

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km ²)
gallon (gal)	3.785	liter (L)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

A water year is the period from October 1 to September 30 and is designated by the year in which it ends.

Abbreviations

EPA	U.S. Environmental Protection Agency
ET ₀	reference evapotranspiration
USGS	U.S. Geological Survey
VOC	volatile organic compound

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Abstract

Adverse ecological and water-quality effects associated with industrial land-use changes are common for littoral wetlands connected to river mouth ecosystems in the Grand Calumet River-Indiana Harbor Canal Area of Concern. These effects can be exacerbated by recent high Lake Michigan water levels that are problematic for wetland restoration. Wetlands in the adjacent Clark and Pine Nature Preserve and Pine Station Nature Preserve are intended to mitigate wetland destruction in the area of concern by restoring residual dune-and-swale wetlands and preserving habitat for endangered and threatened plant species. Physical hydrology and water-quality monitoring of restored wetland cells at the preserves were initiated during 2019 to evaluate changes after wetland restoration efforts in 2015 and near record-low water levels in early 2013. Lake Michigan water levels rose steadily between late 2013 and 2018 to record-high water levels in 2019 and 2020. In this report, precipitation, evapotranspiration, and groundwater and surface-water levels are analyzed to better understand wetland inundation controls and flow directions in restored northern dune-and-swale wetland settings relative to the Grand Calumet River. Continuous specific conductance data and discrete water-quality samples were collected and analyzed to provide a synoptic view of water quality for the restored wetlands.

High Lake Michigan water levels affected Grand Calumet River stage and shallow groundwater elevations in the study area after the onset of peak lake levels in June 2019, that persisted through summer 2020, before finally receding in September 2020. Grand Calumet River stage peaked soon after lake levels in July 2019, whereas groundwater elevations in the study area peaked in October 2019. Specific conductance values in closed-basin wetland cells in the western and central parts of the nature preserves indicated a dilution trend and contrasted those of interconnected wetland cells along an eastern corridor, where alterations to wetland cells were more pronounced. Monitoring results indicate that varying seasonal wetland inundation trends with low stands in autumn have returned after high water table conditions owing to high water levels on Lake Michigan. Wetland water balance results during

the study period indicated that the wetland ecosystem partially moderated flooding during high lake levels through summer evapotranspiration.

Introduction

Restored wetland ecosystems provide many benefits, such as reduced downstream flooding, improved water quality, increased biodiversity, increased wildlife habitat, and greater carbon sequestration (Cowdery and others, 2019). Wetland restoration efforts aim to restore hydrologic and ecological functions, but achieving these goals is challenging where industrial development has substantially altered the surrounding landscape and hydrologic conditions. Land-use changes substantially alter wetland vegetation, and hydrochemical alterations can promote the dominance of plant species with poor habitat value (Larson and others, 2013). The Grand Calumet River-Indiana Harbor Canal Area of Concern in northwestern Indiana was established under the Great Lakes Water Quality Agreement of 1987 (International Joint Commission, 1987) to prioritize the area for restoration because of water-quality and ecosystem impairments. In addition to past anthropogenic effects, Great Lakes river mouths and adjacent wetlands represent a complex natural continuum between river- and lake-dominated hydrologic settings requiring careful consideration of cyclical mixing dynamics for effective restoration efforts (Mazur and others, 2019).

The Clark and Pine Nature Preserve and the adjacent Pine Station Nature Preserve (referred to collectively as “the preserves” in this report; [fig. 1](#)) were established as part of wetland restoration activities by trustee agencies in the natural resource damage assessment in the Grand Calumet River-Indiana Harbor Canal Area of Concern. These wetlands are intended to mitigate damage to other wetlands in the area of concern by restoring residual dune-and-swale wetlands and preserving several State endangered and threatened plant and animal species. The preserves are a restored dune-and-swale wetland complex between Lake Michigan and the Grand Calumet River ([fig. 1](#)) and are surrounded by industry in Gary, Indiana (Kay and others, 1997). The preserves encompass

320 acres, and the corresponding habitat hosts substantial plant biodiversity and a large assemblage of endangered plant and animal species (Indiana Heritage Data Center, 2021). At least 24 rare plants, including *Arctostaphylos uva-ursi* (bearberry), several varieties of *Orchidaceae* (orchid), *Buchnera americana* (blue heart), and *Betula papyrifera* (paper birch); and 12 rare animals, including *Ambystoma laterale* (blue-spotted salamander) and *Acris blanchardi* (cricket frog), are within the preserves (Indiana Heritage Data Center, 2021). Hydroperiods (periods when wetland soils are inundated with water) are key controls on the viability of plant communities in restored wetlands. Considering the emerging effects of increasing extreme precipitation and temperature events on hydrologic regimes, restored wetland ecosystems have varying resilience to shifting water budgets depending on their design features and landscape position relative to groundwater flow patterns (Cassatt and Wilcox, 2020).

After record-low water levels in early 2013 (about 576 feet [ft]), water levels in Lake Michigan (fig. 2) and other Great Lakes rose steadily between late 2013 and 2018 to near record-high levels (about 582 ft; Gronewold and Rood, 2019). Researchers monitoring Lake Ontario wetland ecosystems between 2009 and 2019 documented a loss of ecosystem diversity with a decrease in meadow marsh, shrub, and upland vegetation guilds and an increase in *Typha latifolia* (cattail) coverage at higher wetland cell elevations in 2019 (Smith and others, 2021). Future climate simulations predict increasing winter and spring precipitation through the end of the century for Chicago and the Great Lakes regions (Hayhoe and others, 2010), highlighting the need for water-level monitoring and assessment of wetland ecosystems adjacent to Lake Michigan.

Purpose and Scope

This report summarizes the physical hydrology and water-quality characteristics of restored wetland cells at the preserves that were monitored between 2019 and 2022. One priority is to understand how precipitation patterns and groundwater or surface-water interactions affect wetland hydroperiods. Groundwater and surface-water levels are analyzed to better understand hydraulic gradients and flow directions in restored northern dune-and-swale wetland settings adjacent to the Grand Calumet River. In addition to quantifying wetland inundation patterns that control wetland habitat and plant species diversity (Keddy and Reznicek, 1986), postreclamation (2019–22) continuous specific conductance data and discrete water-quality results throughout the project area provide a synoptic view of water quality at the restored wetlands. This U.S. Geological Survey (USGS) study addresses high-priority issues including providing data to quantify changes in water quantity relative to areas with native and restored ecosystems and identifying hydrologic characteristics that relate to transitions between ecosystem states.

Hydrologic Setting

Wetlands at the preserves are dune-and-swale wetland complexes (also known as ridge and swale) in the embayments of the Great Lakes and are composed of a series of beach ridges separated by narrow swales (Albert and others, 2005). Swales (depressions) containing the northernmost wetland cells of the preserves are approximately 1 mile (mi) south of the Lake Michigan shoreline (fig. 1). According to Albert and others (2005), dune-and-swale complexes adjacent to Lake Michigan vary in their degree of hydrologic connection to the lake with some maintaining connection for thousands of feet inland. The preserves are part of the Calumet lacustrine plain of northwestern Indiana where substantial drainage alterations of the Grand Calumet River were done to support development during the late 19th and early 20th centuries, including diverting the Grand Calumet River several hundred feet to the south when Gary Harbor was dug in 1906 (Kay and others, 1997).

Shedlock and others (1993, 1994) studied the hydrogeology of the Great Marsh region east of the preserves and demonstrated that wetland surface waters are usually derived from local subsurface flow systems (fig. 3). The local flow regimes are recharged through the dune complexes and discharged by seepage into wetlands and streams (fig. 3), such as the Grand Calumet River, with additional water loss owing to evapotranspiration. These natural flow patterns are locally affected for some swale wetland cells in the preserves that have been widened in places by previous sand mining operations (see fig. 4, northern cells in Pine Station Nature Preserve). Also, the naturally undulating dune-and-swale topography has been leveled by historical sand mining in the vicinity of monitoring well P14 (Emily Stork, Indiana Department of Natural Resources, written commun., 2021). Furthermore, the natural closed-basin configuration of swale wetland cells is altered where sand mining and drainage alterations have crosscut dunes such as the north-south trending wetland cell and low-lying area in the vicinity of monitoring wells P4 and P5 (mapped water body not shown in fig. 4).

The dunes and swales at the preserves were originally formed 3,200 to 4,500 years ago when Lake Michigan was more than 13 ft higher than today and receding from Tolleston Beach (Argyilan and others, 2014). The higher elevation dune ridges at the preserves mark previous intermittent reaches of the Lake Michigan shoreline. Lake Michigan water levels fluctuate with a periodicity of about 33 years and an even greater pronounced rise in water levels with a periodicity of about 160 years (Baedke and Thompson, 2000). Based on geologic observations, the recent 2019 and 2020 increase in Lake Michigan water levels likely mark a recurrence of the approximate 33-year lake cycle (last rise in water level was in 1986; fig. 2).

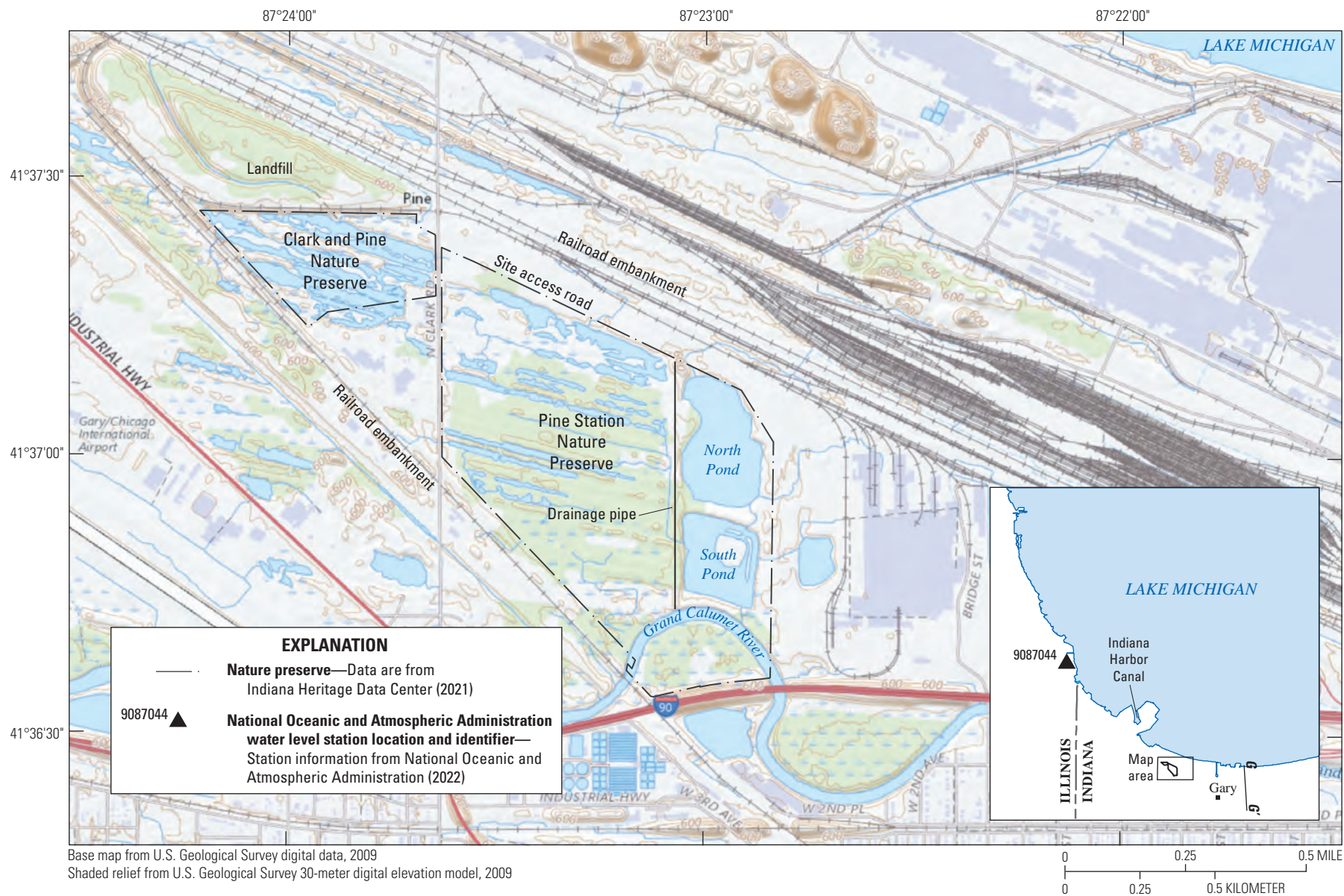


Figure 1. Map showing Clark and Pine Nature Preserve and Pine Station Nature Preserve study area in the Grand Calumet River-Indiana Harbor Canal Area of Concern near Gary, Indiana.

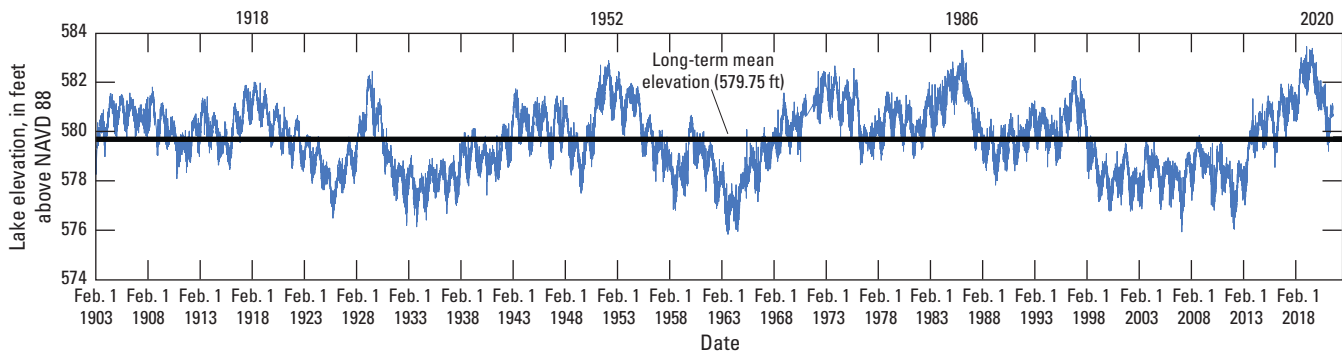


Figure 2. Graph showing daily mean water levels in Lake Michigan measured at the National Oceanic and Atmospheric Administration water level observation station CMT12 (9087044) at the Calumet Harbor, Illinois. The bold black line is the long-term mean lake elevation (579.75 ft). Station location shown on [figure 1](#).

Description of Study Area

In addition to the effects of artificial drainage and sand aggregate mining, railroad embankments and industrial facilities adjacent to the preserves have affected the hydrology and water quality. Based on metals concentrations of sediments at the preserves (Sparks, 2019) and previous work to characterize fill materials in the region (Kay and others, 1997), fly ash and steel slag were used as fill material for roadways (including the preserves' access road) and railroad embankments along the northern and southwestern borders of the nature preserves. Also, atmospheric deposition of particulate matter emitted from surrounding industrial sources is a source of metals input (Sweet and others, 1998). Surrounding industrial facilities, including three U.S. Environmental Protection Agency (EPA) Superfund sites (U.S. Environmental Protection Agency, 2022b) within 0.25 mi of the preserves are potential sources of groundwater contamination.

Before the Indiana Department of Natural Resources acquired the preserves in 1993, the site had a history of industrial uses that were summarized in a written communication from the Indiana Department of Natural Resources Grand Calumet regional ecologist (Emily Stork, Indiana Department of Natural Resources, written commun., 2020). The preserves were primarily used for sand mining operations between the 1950s and 1980s ([fig. 1](#)). Within the preserves, approximately 47 acres represent a mostly undisturbed dune-and-swale hydrogeologic setting (see wetland cells in the vicinity of monitoring wells C1, C3, and C4; [fig. 4](#)). The natural dune ridges and swales vary in height or depth, width, and slope, producing variable soil moisture conditions that support a highly diverse continuum of natural communities. The remaining dunes and swales were altered by the sand mining industry from the 1950s to the 1980s, scraping away dunes down to the water table (Emily Stork, Indiana Department of Natural Resources, written commun., 2021). These large, linear features are now expansive, flat stretches of swales more uniform in width and depth than the previous formations and are referred to as scrapes.

The sand scrapes created an unintended benefit for many of the unique and endangered species that thrive in the preserves. In some places, the scrapes provided a larger habitat for emergent plant species tolerant to changes between dry conditions and inundation (Emily Stork, Indiana Department of Natural Resources, written commun., 2021). The native plants that assembled there created a community consistent with those in pannes (calcareous intradunal ponds; Hiebert and others, 1986). Contrasting wet and dry periods have naturally excluded invasive plant species that do not tolerate these divergent soil conditions. The undisturbed swales are home to the most diverse native species and have proven exceptionally resilient to the pressures of invasive species, such as *Phragmites australis* (common reed) and *Rhamnus frangula* (glossy buckthorn).

At the onset of this study, the resilience of these swales and their corresponding habitat was threatened by unintended consequences resulting from renovation of a brick storm sewer. In the 1930s, the brick-lined drainage pipe was installed by the steel industries to the north through the Pine Station Nature Preserve to discharge directly into the Grand Calumet River (Sparks, 2019). Along the eastern edge of the Pine Station Nature Preserve, the south-flowing drainage pipe likely drained the wetlands toward the Grand Calumet River ([fig. 1](#)) before the 2015 restoration. During the postreclamation period, the river is the primary drainage capturing surface water (runoff) and groundwater discharge from the wetlands. Since restoration work made the drainage pipe ([fig. 1](#)) impermeable, water levels at the Pine Station Nature Preserve have risen to levels not previously observed by current nature preserve staff (Emily Stork, Indiana Department of Natural Resources, oral commun., 2021). Wetland water levels may stabilize and remain high, thereby adversely affecting wetland inundation patterns that control wetland habitat and plant species diversity (Keddy and Reznicek, 1986).

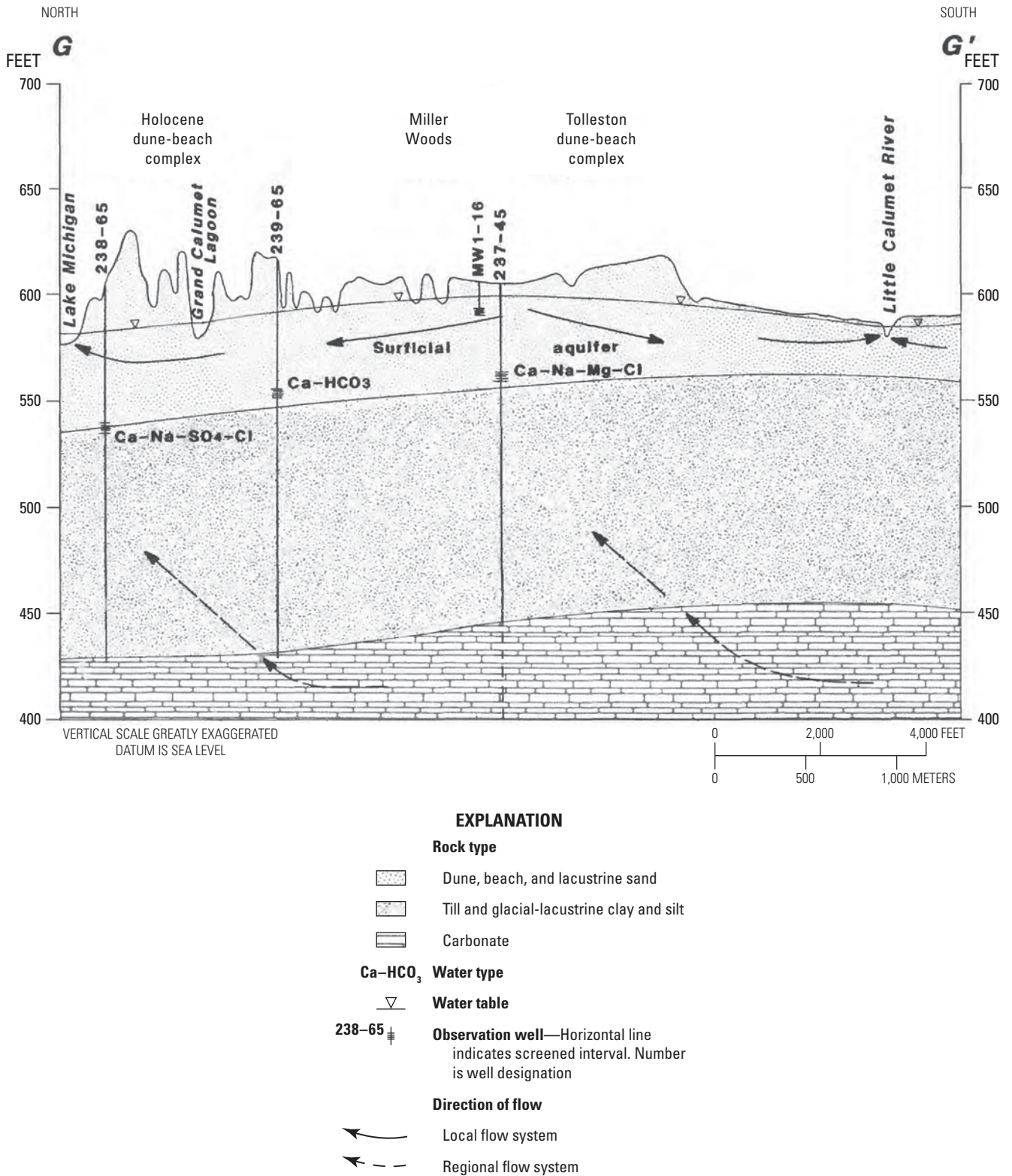


Figure 3. Hydrogeologic cross section showing groundwater flow paths approximately 5 miles east of the Clark and Pine Nature Preserve and Pine Station Nature Preserve study area near Gary, Indiana. Modified from Shedlock and others, 1994. Location of cross section shown on figure 1. Ca, calcium; Na, sodium; SO₄, sulfate; Cl, chloride; Ca-HCO₃, calcium bicarbonate; Mg, magnesium.

Methods

The water budget of restored wetlands at the preserves was quantified with continuous (one reading every 15 minutes) and discrete (monthly) monitoring of water-budget components including precipitation (rainfall), evapotranspiration, and water-level elevations at surface-water and groundwater monitoring locations. Wetland water quality was evaluated using continuous specific conductivity and water temperature measurements as well as discrete (one-time) sampling for major ions, trace elements, nutrients, and volatile organic compounds (VOCs). All data collected as part of this study, including physical hydrologic data and water-quality data, are published in the National Water Information System (U.S. Geological Survey, 2023). Station numbers or names in [table 1](#) can be used to find data in the National Water Information System.

Monitoring Sites

Nineteen monitoring wells were installed and developed using a surge block, in August 2019, with screen intervals crossing the hyporheic zone of the dunes and swales throughout the preserves ([table 1](#)). An additional monitoring well (P16, USGS well 413644087230601) was installed in September 2020 to provide data near where the wetlands can directly interact with the Grand Calumet River depending on the river's stage ([fig. 4](#); [table 1](#)). Monitoring wells were constructed using 2-inch (in.) diameter galvanized steel pipe connected to stainless steel well points with 3-ft 80-mesh well screens. The well assemblies were manually driven into the ground until refusal, which typically was less than 12 ft below land surface. The wells were generally positioned along the periphery of inundated areas so that the screened intervals would represent the hyporheic zones of wetland cells within scrapes and swales. Monitoring wells were redeveloped using a bailer in August 2020 and May 2021.

In addition to monitoring wells, surface-water monitoring included three water-quality sampling sites established during an August 2020 sampling event (C3–SW, S13–Confluence, S13–Discharge; [table 1](#)). A staff gage (S15) was installed in the North Pond in September 2020 for measuring pond water levels. Meteorological monitoring was initiated in September 2019 with the installation of a weather station near monitoring well P9 ([fig. 4](#)).

Monitoring Water-Level Elevations and Water Quality

Monthly discrete and 15-minute continuous groundwater levels were measured from September 2019 through June 2021. Nine monitoring wells were equipped with pressure transducers to automate the collection of depth-to-water data, and four of these wells were also equipped with specific

conductivity and temperature sensors ([table 1](#)). Two of the nine pressure transducers were added in October 2020 to initiate continuous monitoring at monitoring wells P7 and P16 ([fig. 4](#); [table 1](#)). Continuous water-level data were recorded using atmospherically vented pressure transducers and following standard procedures described by Freeman and others (2004). Monthly groundwater-level measurements were collected at discrete data-type wells ([table 1](#)) by manually measuring depth-to-water using a calibrated electronic measuring tape and following procedures outlined by Cunningham and Schalk (2011). Water-level measurements from 12 additional wells adjacent to the study area ([app. 1](#)) were collected during autumn 2019 and 2020 and used for potentiometric surface mapping.

Continuous specific conductance and water temperature were recorded at monitoring wells C4, P5, P8, and P12 ([fig. 4](#); [table 1](#)) to quantify seasonal patterns of dissolved ions in shallow groundwater. In Situ Aqua Troll 200 Data Logger pressure transducers, with internally logged water level, water temperature, and specific conductance sensors, were checked quarterly with 500 and 1,000 microsiemens per centimeters at 25 degrees Celsius ($\mu\text{S}/\text{cm}$) potassium chloride (KCl) standards. Sensors were recalibrated if calibration checks indicated sensor measurement differences greater than 3 percent or 5 $\mu\text{S}/\text{cm}$ (whichever is greater) from the standards (U.S. Geological Survey, 2019). In Situ Aqua Troll 200 Data Logger thermistors (site sensors) were factory calibrated prior to deployment. Periodic temperature checks of the site sensors were conducted using one or more field monitor sensor(s) that was verified against a National Institute of Standards and Technology traceable thermistor. Temperature checks using the field monitor sensor(s) indicated that the site sensor temperature readings were stable and within the USGS criterion of 0.2 degree Celsius (Wilde, 1998).

Monthly surface-water levels were measured at a staff gage (S15; [fig. 4](#)) that was installed in the North Pond to record and compare fluctuations relative to adjacent wetland cells. A monitoring well (P11; [fig. 4](#)) was installed along the western bank of the South Pond to record and compare monthly water-level fluctuations of the South Pond relative to the North Pond, adjacent wetland cells (in the vicinity of P5 and P10; [fig. 4](#)), and the Grand Calumet River to the south. Grand Calumet River stage and discharge were monitored using the USGS streamgage Grand Calumet River at Industrial Highway at Gary, Ind. (station 04092677; [fig. 4](#)) with a gage height record from October 1991 to September 2022. The S13–Discharge sampling site is at the lined discharge pipe. The S13–Confluence sampling site is where runoff flows into the Grand Calumet River from a small channel at the wetland-river boundary. The C3–SW sampling site is in the wetland cell in the northwest corner of the study area, near monitoring well C3.

Table 1. Monitoring sites installed at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana, for water years 2020–22.

[Data are from U.S. Geological Survey (2023). ft, foot; bls, below land surface; NP, nature preserve; IN, Indiana; WL, water level; N, nutrient; MI, major ion; TE, trace element; VOC, volatile organic compound; SpC, specific conductance; T, temperature; Met, meteorological; NA, not applicable]

U.S. Geological Survey (USGS) site			Site type	Data type	Well depth (ft bls)
Number	Name	Field identifier			
413720087233901	USGS well C1 at Clark and Pine NP near Gary, IN	C1	Monitoring well	Continuous (WL) Discrete (N, MI, TE, VOC)	10.7
413726087235201	USGS well C2 at Clark and Pine NP near Gary, IN	C2	Monitoring well	Discrete (N, MI, TE)	8.37
413725087240601	USGS well C3 at Clark and Pine NP near Gary, IN	C3	Monitoring well	Discrete (WL)	8.25
413726087241100	Clark and Pine NP site C3–SW near Gary, IN	C3–SW	Surface water	Discrete (N, MI, TE, VOC)	NA
413721087235801	USGS well C4 at Clark and Pine NP near Gary, IN	C4	Monitoring well	Continuous (WL, SpC, T) Discrete (N, MI, TE)	7.95
413718087233701	USGS well P1 at Pine Station NP near Gary, IN	P1	Monitoring well	Discrete (N, MI, TE, VOC)	8.30
413715087232101	USGS well P2 at Pine Station NP near Gary, IN	P2	Monitoring well	Continuous (WL) Discrete (N, MI, TE, VOC)	8.68
413710087230601	USGS well P3 at Pine Station NP near Gary, IN	P3	Monitoring well	Discrete (WL, N, MI, TE)	10.7
413703087230501	USGS well P4 at Pine Station NP near Gary, IN	P4	Monitoring well	Discrete (WL, N, MI, TE, VOC)	11.3
413654087230501	USGS well P5 at Pine Station NP near Gary, IN	P5	Monitoring well	Continuous (WL, SpC, T) Discrete (N, MI, TE, VOC)	11.5
413700087233101	USGS well P6 at Pine Station NP near Gary, IN	P6	Monitoring well	Discrete (N, MI, TE)	8.27
413653087232201	USGS well P7 at Pine Station NP near Gary, IN	P7	Monitoring well	Continuous (WL) Discrete (N, MI, TE, VOC)	7.51

Table 1. Monitoring sites installed at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana, for water years 2020–22.—Continued

[Data are from U.S. Geological Survey (2023). ft, foot; bls, below land surface; NP, nature preserve; IN, Indiana; WL, water level; N, nutrient; MI, major ion; TE, trace element; VOC, volatile organic compound; SpC, specific conductance; T, temperature; Met, meteorological; NA, not applicable]

U.S. Geological Survey (USGS) site			Site type	Data type	Well depth (ft bls)
Number	Name	Field identifier			
413705087231601	USGS well P8 at Pine Station NP near Gary, IN	P8	Monitoring well	Continuous (WL, SpC, T) Discrete (N, MI, TE)	8.04
413709087231601	USGS well P9 at Pine Station NP near Gary, IN	P9	Monitoring well	Discrete (WL)	7.42
413650087230601	USGS well P10 at Pine Station NP near Gary, IN	P10	Monitoring well	Discrete (WL, N, MI, TE, VOC)	8.32
413649087230301	USGS well P11 at Pine Station NP near Gary, IN	P11	Monitoring well	Discrete (WL, N, MI, TE)	8.36
413657087231201	USGS well P12 at Pine Station NP near Gary, IN	P12	Monitoring well	Continuous (WL, SpC, T)	7.60
413643087231301	USGS well P13 at Pine Station NP near Gary, IN	P13	Monitoring well	Discrete (N, MI, TE)	8.36
413704087233101	USGS well P14 at Pine Station NP near Gary, IN	P14	Monitoring well	Continuous (WL) Discrete (N, MI, TE)	8.62
413711087233601	USGS well P15 at Pine station NP near Gary, IN	P15	Monitoring well	Discrete (WL)	8.36
413644087230601	USGS well P16 at Pine Station NP near Gary, IN	P16	Monitoring well	Continuous (WL)	7.74
413642087230600	Pine Station NP site S13—Confluence near Gary, IN	S13—Confluence	Surface water	Discrete (N, MI, TE, VOC)	NA
413644087230300	Pine Station NP site S13—Discharge near Gary, IN	S13—Discharge	Surface water	Discrete (N, MI, TE, VOC)	NA
413655087230201	Staff gage S15 at Pine Station NP near Gary, IN	S15	Surface water	Discrete (WL)	NA
413709087231602	Pine Station NP Met Station near Gary, IN	Met Station	Meteorological station	Continuous	NA

Rainfall and Evapotranspiration Monitoring

A weather station (fig. 4; table 1) equipped with a pyranometer (incoming solar radiation), anemometer (wind speed), tipping bucket rain gauge (rainfall), thermometer, and relative humidity sensor, was installed to continuously monitor each parameter every 15 minutes. Reference evapotranspiration (ET_0) is calculated using a daily time step for meteorological variables (air temperature, relative humidity, wind speed, and solar radiation) following the method described by Allen and others (1998).

Discrete Water-Quality Sampling

Discrete water-quality samples were collected from 15 monitoring wells (fig. 4; table 1) and at three of the surface-water monitoring sites in August 2020 (fig. 4; table 1). Field parameters were measured, and water-quality samples were analyzed for major ions, trace elements, and nutrients. A subset (10) of water-quality samples was analyzed for volatile organic compounds. Samples were collected following the methods described in the USGS “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, variously dated). The sampling was conducted using a Fultz submersible pump, with the pump intake placed within the screened interval of the wells. The pump discharge tubing was attached to a flow-through chamber with a YSI multiparameter sonde for measuring pH, specific conductance, water temperature, and dissolved oxygen during sampling. Turbidity was measured using a Hach field turbidity meter. To ensure samples were representative of the aquifer, three well volumes of water were purged by pumping from the well at a rate of less than 0.15 gallon per minute, and a water sample was collected after stabilization of the field parameters.

Alkalinity of the groundwater samples was determined by collecting a filtered sample and conducting a titration in the field using the inflection-point method (Rounds, 1998). Three surface-water samples were collected and analyzed for major ions, trace elements, nutrients, and VOC. A peristaltic pump was used to collect field samples with the tubing intake placed in the surface water about 2 inches from the wetland cell bottom (at C3–SW) or streambed (at S13–Confluence) and about 1 ft into the discharge from S13–Discharge. Field parameters were measured with the multiparameter sonde by placing the sonde directly in the surface water feature and allowing the meter readings to equilibrate. Water-quality samples were analyzed by the USGS National Water Quality Laboratory in Denver, Colorado. Major ions, nutrients, and trace elements were analyzed using the methods described in Fishman and Friedman (1989), Fishman (1993), and Garbarino and others (2006). Volatile organic compound samples were analyzed at the USGS National Water Quality Laboratory by purge and trap gas chromatography with quadrupole mass-spectrometric detection (Connor and others, 1998).

Results

Grand Calumet River and Lake Michigan Water Levels

As shown in figure 2, Lake Michigan approached an all-time-high water level above 582.5 ft at Calumet Harbor, Ill., (National Oceanic and Atmospheric Administration, 2022 [NOAA] station 9087044; location shown in fig. 1;) in 2019–20 for the period of record, and high water levels are also indicated by lake-stage measurements at the nearby Chicago Lock monitoring site (USGS station 04087440; not shown). Monthly average lake levels were above 582.25 ft between May and August 2020. The Grand Calumet River generally flows west toward the Indiana Harbor Canal from the USGS streamgage Grand Calumet River at Industrial Highway at Gary, Ind. (station 04092677; fig. 4) along the southern edge of the study area. However, the high water levels on Lake Michigan coincided with the Grand Calumet River stage starting in October 2019, and this coincidental relation endured with a near-zero gradient until May 2020 and again from October 2020 until April 2021 (fig. 5). During these “coupling phases” (fig. 5), the gradient between the USGS streamgage at Gary, Ind. (04092677) and the NOAA lake-stage monitoring site at Calumet Harbor, Ill. (9087044; National Oceanic and Atmospheric Administration, 2022) was less than ($<$) 0.25 ft for a sustained period (more than [$>$] 1 month).

Wetland Groundwater Levels

Groundwater-elevation trends along the eastern edge of the Pine Station Nature Preserve (fig. 6) are generally consistent with water-level patterns observed throughout the study area. Water levels were low in early autumn 2019 (mean water level for wells P3, P4, P5, P10, and P11 was 586.2 ft in September 2019) when monitoring was initiated but rose markedly in November 2019 (mean water level for wells P3, P4, P5, P10, and P11 was 587.7 ft in November 2019) and remained high until late summer 2020 (mean water level for wells P3, P4, P5, P10, and P11 was 587.2 ft in July and August 2020). This period of heightened groundwater levels coincides with high water levels on Lake Michigan and the Grand Calumet River shown in figure 5, but lagged the lake and river increases by 4 to 5 months.

The shallow groundwater divide, between water that flows north into Lake Michigan and water that migrates south into the Grand Calumet River, is generally indicated by potentiometric contours shown in figure 7 that delineate shallow aquifer water-level elevations in the vicinity of the preserves. The transient nature of the divide during the high lake and river stand is indicated by monitoring wells P3 and P4 water-level trends in figure 6 that inverted in September 2020 (P4 water level fell below P3 water level and

remained below it for the duration of the study). Furthermore, a change in hydraulic gradients is indicated by the shifting groundwater divide between autumn 2019 and autumn 2020 (fig. 7). Seasons are divided based on the months of December to February (winter), March to May (spring), June to September (summer), and October to November (autumn). The highest groundwater elevations are consistently recorded

near monitoring well C2 (fig. 7) along the northern edge of the Clark and Pine Nature Preserve. The topographic high near monitoring well C2 is a groundwater recharge area. Water entering the groundwater flow system here typically flows perpendicular to potentiometric contours toward the Grand Calumet River to the south (fig. 7).

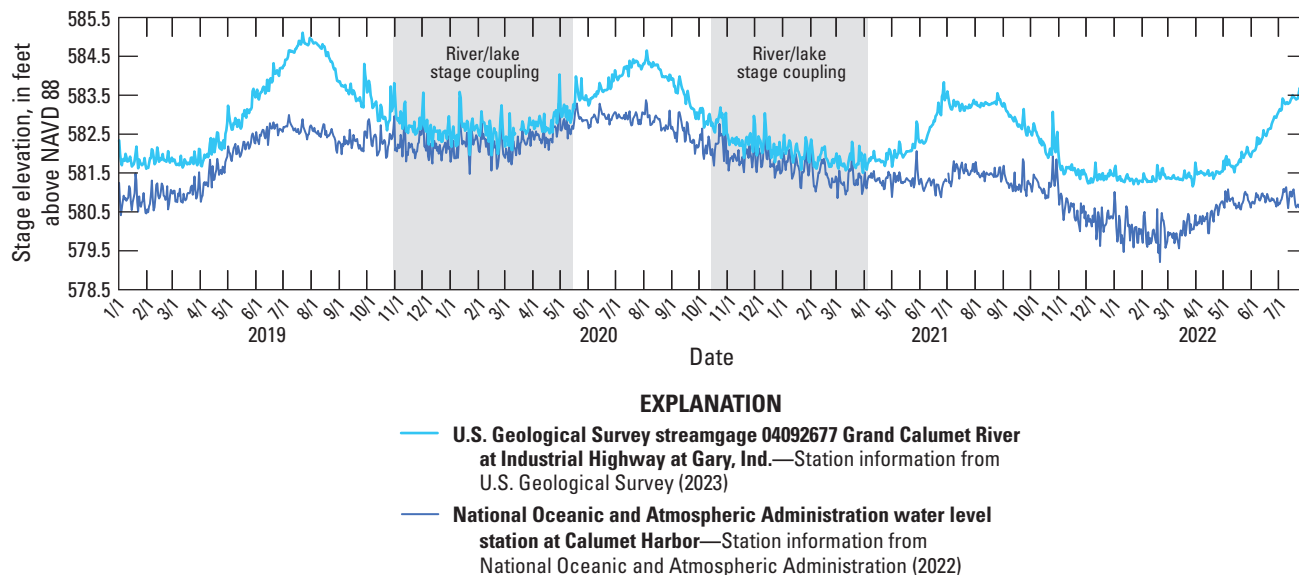


Figure 5. Graph showing daily mean stage at Grand Calumet River at Industrial Highway at Gary, Indiana (U.S. Geological Survey streamgage 04092677) and daily mean Lake Michigan water levels measured at the National Oceanic and Atmospheric Administration Calumet Harbor, Illinois (station 9087044), for calendar years 2019–22. NAVD 88, North American Vertical Datum of 1988.

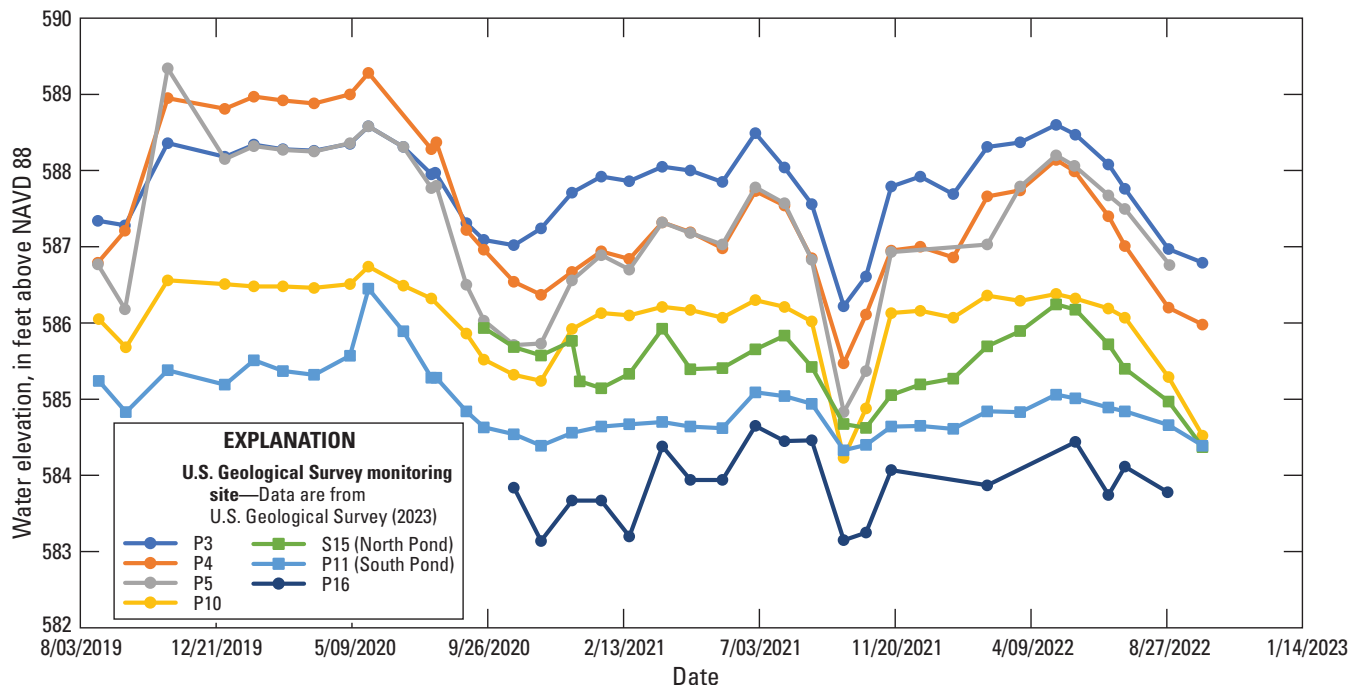


Figure 6. Groundwater hydrographs for five monitoring wells along the eastern edge of the study area plotted with North and South Pond water levels at Pine Station Nature Preserve near Gary, Indiana. The hydrographs are derived from monthly discrete water levels. The North Pond staff gage (S15) and monitoring well P16 near the bank of the Grand Calumet River were installed in September 2020, approximately 1 year after monitoring was initiated at other sites. NAVD 88, North American Vertical Datum of 1988.

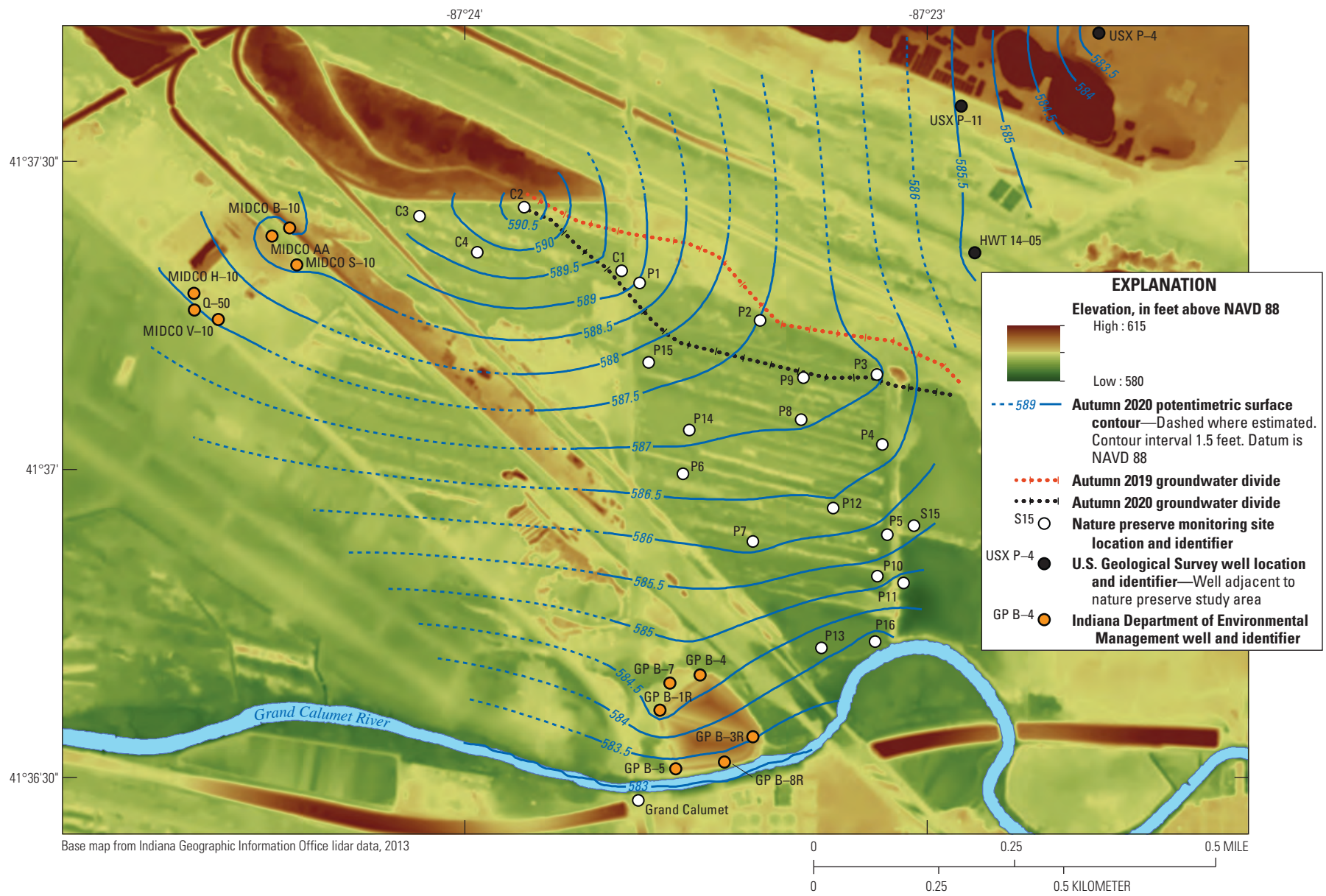


Figure 7. Map showing potentiometric contours at the Clark and Pine Nature Preserve and the Pine Station Nature Preserve near Gary, Indiana. NAVD 88, North American Vertical Datum of 1988.

Rainfall and Evapotranspiration

Measured rainfall and calculated ET_0 indicated that hydrologic conditions were partially driven by meteorological patterns at the preserves during the study period (September 2019–June 2022). Rainfall trends were compared with 30-year normal precipitation data (1991–2020) from a nearby weather station (not shown) at Indiana Dunes National Park (National Oceanic and Atmospheric Administration, 2021; Station ID USC00124244). Even though water year 2020 (October 1, 2019–September 30, 2020) had near-normal precipitation (39.16 inches per year) based on 30-year normal precipitation, the distribution pattern included an abnormally wet spring (16.27 in.) followed by below-average rainfall in the summer (table 2). Dry conditions persisted into water year 2021 (October 1, 2020–September 30, 2021) with below-average precipitation during the autumn, winter, and spring seasons (table 2). Calculated ET_0 exceeded rainfall for water year 2021 by 7 in. (table 2), indicating a net loss of water from the study area owing to meteorological conditions. With rainfall exceeding ET_0 by only 1.4 in. during water year 2022, it is likely that ET_0 -driven water loss plays an important role in lowering shallow groundwater and wetland water levels throughout the region during periods when wetlands are affected by high water levels in the Grand Calumet River and Lake Michigan.

Specific Conductance

Solute concentrations in closed-basin wetlands are often affected by evaporation and dilution effects (LaBaugh and others, 2016), and specific conductance trends at three of four monitoring wells (fig. 8) indicate these effects at preserve wetland cells (higher specific conductance values indicate more ions in water). Groundwater levels are generally inversely related to specific conductance at monitoring wells P8 (September 22 to November 22, 2020; fig. 8B), P12 (September 22 to November 22, 2020; fig. 8C) and C4 (August 22 to October 22, 2021; fig. 8D) suggesting that

solute concentration increases when water levels are low. Groundwater in wetland cells monitored by these wells is typically diluted during high water levels, resulting in lower specific conductance values (fig. 8B–D).

Alternatively, the specific conductance data closely follow water level patterns at monitoring well P5 (fig. 8A); increases in groundwater elevation in March 2021 and July 2021 coincide with increases in specific conductance. This suggests that there is a more active flow regime along the eastern edge of the preserves, and that the connected wetland cells are diluted following wet periods that bring water high in solutes into the eastern basin where connected wetland cells are present. For example, groundwater level, water temperature, and specific conductance data collected at monitoring well P5 leading up to and following an October 2021 rainstorm (fig. 9) provide a detailed “snapshot” of coupled groundwater/surface-water dynamics and water quality. The increase in water level following the late-October precipitation is accompanied by a decrease in water temperature (indicating cool meteoric water recharging the shallow aquifer) and accompanying increase in specific conductance (about 140 $\mu\text{S}/\text{cm}$), indicating increasing solute concentrations in surface water and groundwater flowing north-to-south in the vicinity of monitoring well P5.

A statistical analysis of continuous specific conductance and water-level data was conducted to quantitatively assess trends for these parameters. The Spearman’s rank correlation coefficient is used because it does not assume normal distribution of data and is suitable to assess linear and nonlinear relations between variables (Haque and others, 2018). For monitoring well P5, the Spearman’s rank correlation coefficient is 0.63 ($p < 0.001$) indicating a positive trend between water level and specific conductance. Alternatively, for monitoring well C4, the Spearman’s rank correlation coefficient is -0.30 ($p < 0.001$) suggesting an inverse relation between water level and specific conductance (when water level increases, specific conductance decreases), consistent with dilution effects associated with rising water levels.

Table 2. Primary water budget components at Pine Station Nature Preserve near Gary, Indiana, for water years 2020–22.

[Data are from U.S. Geological Survey (2023). Evapotranspiration calculated following the daily time step approach described by Allen and others (1998) using wind speed, air temperature, relative humidity, and solar radiation data collected at the site weather station. ET₀, reference evapotranspiration; in., inch]

Season	Indiana dunes precipitation 30-year normals (in.)	Water year 2020		Water year 2021		Water year 2022	
		Rainfall (in.)	ET ₀ (in.)	Rainfall (in.)	ET ₀ (in.)	Rainfall (in.)	ET ₀ (in.)
Autumn	6.51	3.72	3.87	4.27	4.12	7.72	3.24
Winter	6.47	6.73	2.79	3.85	2.60	4.55	3.13
Spring	10.16	16.27	8.98	6.45	10.14	11.22	9.36
Summer	16.02	12.09	19.72	13.57	18.87	11.98	18.35
Year	39.16	38.81	35.37	28.14	35.72	35.47	34.07

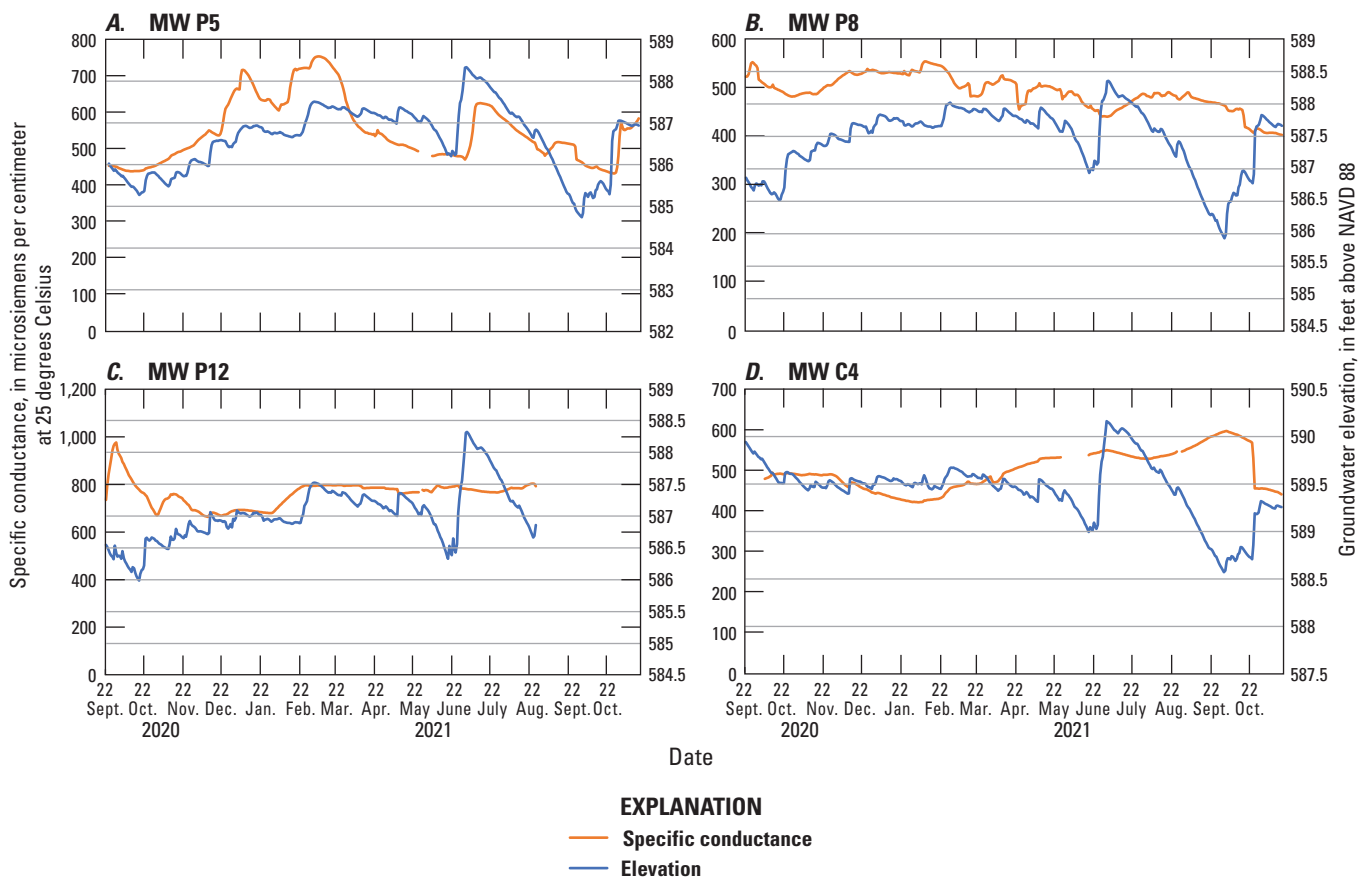


Figure 8. Graphs showing continuous specific conductance and groundwater elevation in monitoring wells A, MW P5, B, MW P8, C, MW P12, and D, MW C4 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana. NAVD 88, North American Vertical Datum of 1988.

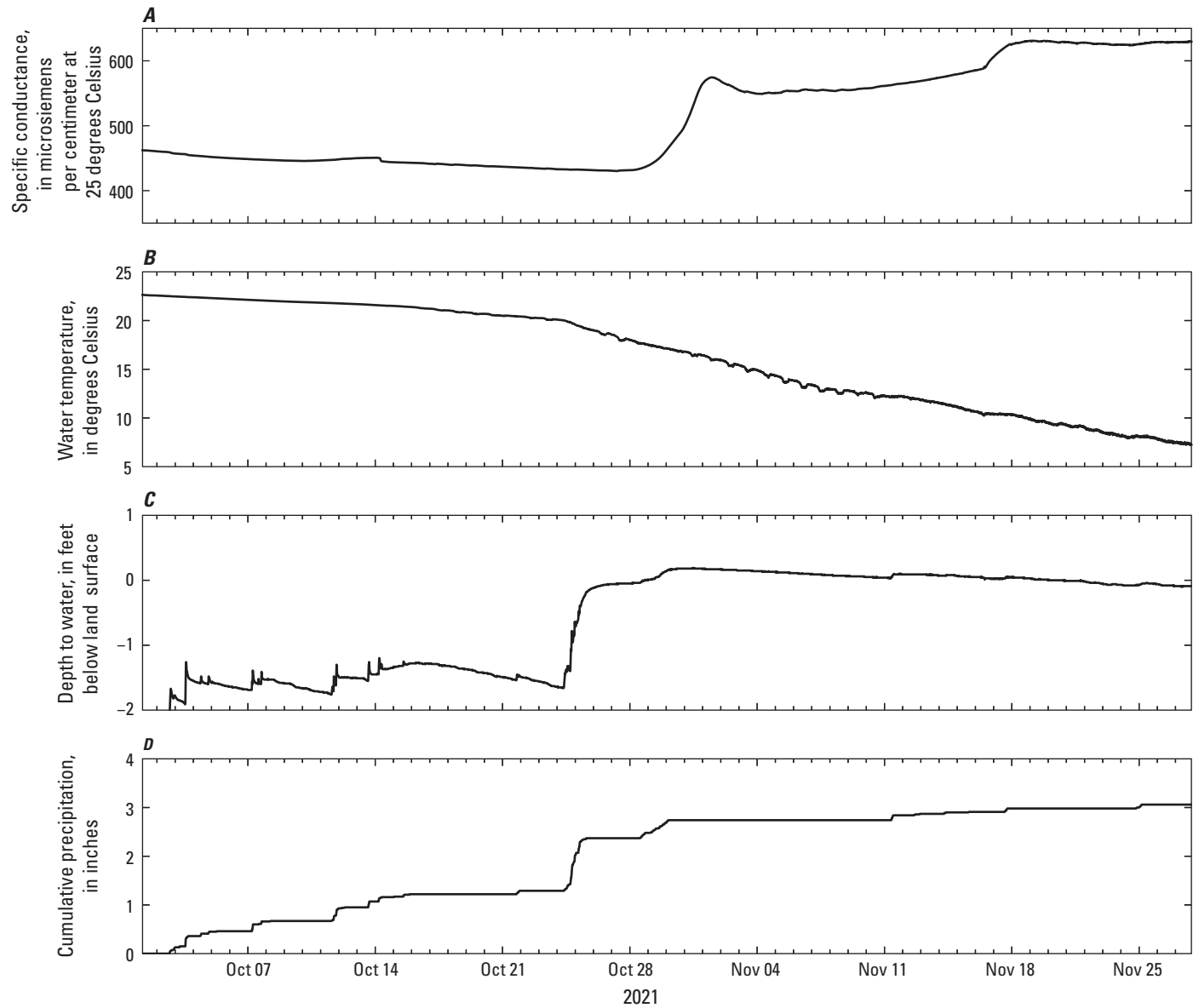


Figure 9. Graphs of continuous *A*, specific conductance, *B*, water temperature, and *C*, depth to groundwater at U.S. Geological Survey well MW P5 leading up to and following *D*, a rainstorm in late October 2021 at the Clark and Pine Nature Preserve and the Pine Station Nature Preserve near Gary, Indiana.

Discrete Water-Quality Sampling

Major Ions and Nutrients

Ions in groundwater at the preserves primarily consist of calcium and magnesium as the major cations and bicarbonate as the major anion (fig. 10; table 3), indicating sources from interactions with the bedrock limestone and dolomite aquifers, consistent with a previous study of shallow groundwater adjacent to southwestern Lake Michigan (Cherkauer and Zvibleman, 1981). These results contrast data from a study in the vicinity of Cowles Bog, approximately 15 mi east of the study area, that indicated shallow groundwater higher in sulfate anions (including dilute calcium sulfate) for shallow dune and intradunal wetland aquifers (Shedlock and others, 1993).

Chloride concentrations in monitoring wells were generally below 10 milligrams per liter (mg/L), but concentrations were greater than 10 mg/L at wells P2, P3, P4, P6, P11, and P13 (table 3). Road salt (deicers) may be applied along Clark Road but not along the access road. Other sources of chloride beyond deicers are water softener effluent, wastewater effluent, livestock runoff, landfills, agricultural chemicals, and ancient brines (Panno and others, 2006). The source of chloride can be determined through a chloride-to-bromide (Cl:Br) ratio analysis. Chloride and bromide are conservative in groundwater and transport through the aquifer with limited interaction, transformation, or attenuation with aquifer materials (Panno and others, 2006; Davis and others, 1998). Sources of bromide can be from septic tanks, deicers, agricultural chemicals, industrial solvents, and gasoline additives, but concentrations are typically 40 to 80,000 times less than chloride concentrations; thus, small changes elicit large variations in the ratios of chloride to bromide (Davis and others, 1998). The end members and source mixing curves were developed from the northern glacial aquifer by Panno and others (2005) and Mullaney and others (2009). The Cl:Br ratio for each sample location was plotted along the mixing curves to evaluate potential sources (fig. 11). The proximity of the Cl:Br ratio plotted near or on a mixing-curve line indicates a possibility that the end member is a potential source of the chloride. The results indicate that the preserve samples are predominately interacting with dilute groundwater. The sample plots for the S13–Discharge monitoring site between the animal waste and halite curves indicate a different source of water compared with other sampling locations throughout the preserves.

Nutrient concentrations in samples collected at the preserves in August 2020 are generally low, and data for nitrogen species (table 4) indicate reducing conditions in shallow groundwater. Phosphorus, measured as orthophosphate in milligrams per liter, is less than 0.10 mg/L in all well samples. The pH of samples is near neutral (6.5 to 7.6 and does not appear to influence nutrient concentrations). Dissolved oxygen in all wells is less than or equal to 1 mg/L,

a further indication of reducing conditions favorable for ammonia as the dominant nitrogen compound. Groundwater concentrations of nitrate (nitrate plus nitrite) are at or below the detection limit (0.04 mg/L) in all wells, and surface-water concentrations are less than 1 mg/L. Concentrations of nitrite in groundwater are less than 0.01 mg/L in all samples. Nitrite concentrations are highest in surface-water samples from the steel discharge pipe (well S13–Discharge, 0.123 mg/L) and Grand Calumet River confluence (well S13–Confluence, 0.036 mg/L). Ammonia as nitrogen is the dominant nitrogen species with the highest concentrations at wells P14 (3.38 mg/L) and P6 (3.83 mg/L) in the west-central part of the study area (fig. 4). According to Kay and others (1997), slag deposits produced from manufacturing iron and steel are commonly used as fill in the area surrounding the preserves and are a potential source of elevated ammonia concentrations.

Trace Elements

Iron and manganese concentrations in groundwater samples are elevated at several of the well locations (fig. 12; table 5) indicating that these trace elements are being retained in wetland cells, supporting the water filtration function of wetlands in the study area. Iron exceeds the EPA drinking water secondary maximum contaminant level (SMCL; U.S. Environmental Protection Agency, 2018) of 300 micrograms per liter ($\mu\text{g/L}$) for all the groundwater samples, ranging from 962 $\mu\text{g/L}$ (well C2) to 32,800 $\mu\text{g/L}$ (well P6). None of the surface-water samples (wells C3–SW, S13–Confluence, S13–Discharge) exceed the EPA drinking water SMCL for iron, or the chronic aquatic life criteria for iron (1,000 $\mu\text{g/L}$; U.S. Environmental Protection Agency, 2022a). Forty percent (6 of 15) of groundwater samples exceed the USGS health-based screening level of 4,000 $\mu\text{g/L}$ for iron (Norman and others, 2018; U.S. Geological Survey, 2022). Manganese concentrations range from 132 $\mu\text{g/L}$ (well C2) to 1,490 $\mu\text{g/L}$ (well P14) in groundwater samples, exceeding the USGS health-based screening level of 300 $\mu\text{g/L}$ in 67 percent of groundwater samples (10 of 15). The EPA has not established aquatic life criteria for manganese. None of the sites sampled in this study are used as a source for potable drinking water.

Zinc concentrations are also elevated in many of the monitoring wells with elevated iron and manganese (table 5). Zinc ranges from 223 $\mu\text{g/L}$ (well P3) to 29,400 $\mu\text{g/L}$ (well P14) in the groundwater wells, and from less than detection limits to 2.1 $\mu\text{g/L}$ in surface-water samples. Zinc does not have an established maximum contaminant level (MCL), but it does have a USGS noncancer health-based screening level of 2,000 $\mu\text{g/L}$ that was exceeded at four monitoring wells (P6, P11, P13 and P14; Norman and others, 2018). The one detection of zinc in a surface-water sample is well below the acute and chronic aquatic life criteria of 120 $\mu\text{g/L}$ (criteria include an adjustment for hardness; U.S. Environmental Protection Agency, 2022a).

Aluminum ranges from <3.0 to 21.0 $\mu\text{g/L}$ in groundwater samples and from 4.0 to 27.0 $\mu\text{g/L}$ in surface-water samples (table 5). Aluminum is detected at elevated concentrations

at P14 (fig. 4; table 5) but may be sourced from historical activities near the site or naturally occurring in minerals associated with dune sands.

Arsenic concentrations range from 0.86 to 59.6 $\mu\text{g/L}$ with a median of 7 $\mu\text{g/L}$ (table 5) for all monitoring sites and exceed the EPA drinking water MCL of 10 $\mu\text{g/L}$ in 53 percent of groundwater samples (8 of 15). The distribution appears somewhat sporadic and may be associated with higher iron concentrations (table 5) because arsenic bonds readily to iron (Guo and others, 2013). Arsenic occurs naturally but can also be anthropogenic and result from agricultural chemicals, metal alloys, glass industries, and coal-burning power plants (Han and others, 2003).

Boron concentrations range from 56 to 4,690 $\mu\text{g/L}$ (table 5) with a median of 263 $\mu\text{g/L}$ and are generally higher in monitoring wells (P2, P3, P4, P5, P11; fig. 4) along the access road separating the North and South Ponds from the Pine Station Nature Preserve wetland cells (fig. 4). Boron is commonly found in coal combustion residue leachate (Naylor and others, 2012), in construction and demolition debris (Xu and others, 2020), and may be leaching from the coal fly ash and other materials that were used to build the access road. Other sources of boron are from manufacturing of glass, ceramics, fertilizers, and detergents (Paternoster, 2019), which may be in this heavily industrialized part of Gary. As a conservative geochemical element, boron transports readily through surface water and groundwater without substantial interaction with biota, evaporation, volatilization, oxidation-reduction reactions, mineral precipitation, or dissolution (Buszka and others, 2007). High boron concentrations are measured at monitoring wells P7 (1,250 $\mu\text{g/L}$) and P13 (619 $\mu\text{g/L}$), which are away (0.25 to 0.5 mi) from the access road (fig. 1), indicating that there may be additional sources along the western part of the Pine Station Nature Preserve.

Groundwater concentrations of lithium (table 5) are also higher along the access road at wells P2 (65.2 $\mu\text{g/L}$) and P3 (32.6 $\mu\text{g/L}$). This is consistent with previous research noting the occurrence of high-lithium-content fly ash (Hu and others, 2018), but lithium is also used in ceramic, glass, and alloy production (Lindsey and others, 2021). Lithium is toxic to some plants and aquatic organisms at 60 to 100 $\mu\text{g/L}$ (Hem, 1985; Kszos and Stewart, 2003).

Volatile Organic Compounds

Discrete water-quality samples were analyzed for a total of 84 VOCs, and 20 of these VOCs were detected at least once at 7 monitoring wells and 3 surface-water locations (table 6). The surface-water samples had a higher occurrence of VOCs than the groundwater samples. The S13–Confluence site had the highest number of detections at 11 detections; the S13–Discharge pipe site had 9 detections; and the C3–SW site (fig. 4) had 6 detections. The C3–SW sampling site is in the northwest corner of the Clark and Pine Nature Preserve and is downgradient from an elevated landfill north of the study area (fig. 7). All concentrations were below regulatory and

nonregulatory water-quality benchmarks. No VOC compound was detected at more than three sites, but bromodichloromethane, trichloromethane, acetone, and methyl ethyl ketone were detected at all three surface-water sampling sites (table 6).

Quality Assurance

Quality-assurance and quality-control samples were collected to evaluate and control bias in the analytical results. One equipment blank and one replicate were collected during the August 2020 water-quality sample collection in accordance with the USGS “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, variously dated). The equipment blank and replicate samples were analyzed for major ions, trace elements, and volatile organic compounds. Barium (2.10 $\mu\text{g/L}$), calcium (0.042 mg/L), lead (0.04 $\mu\text{g/L}$), strontium (1.83 $\mu\text{g/L}$), and zinc (3 $\mu\text{g/L}$) had detections in the equipment blank, but concentrations were generally below the concentrations detected in the environmental samples, except for lead. Therefore, the results for these compounds are included in the results section, and lead results are qualified as estimated. Copper was detected in the equipment blank at a concentration of 17.5 $\mu\text{g/L}$.

Three VOC concentrations (1,2,4-trimethylbenzene, ethylbenzene, and m-xylene plus p-xylene) were detected in the equipment blank but were below their reporting limits of 0.016 $\mu\text{g/L}$, 0.018 $\mu\text{g/L}$, and 0.08 $\mu\text{g/L}$, respectively. Trichloroethylene was detected in the equipment blank at a concentration of 0.041 $\mu\text{g/L}$, which is above the environmental sample concentration (less than 0.025 $\mu\text{g/L}$). Detections of these compounds in environmental samples are not presented in the results section. For the replicate results, the relative percent difference, calculated as the difference in the environmental and replicate concentration divided by the mean of the two concentrations, was less than 10 percent for all except for three constituents. Ammonia as nitrogen, nitrite as nitrogen, and selenium had replicate differences greater than 10 percent, and some compounds were detected in either the environmental sample or the replicate, but not both (isopropylbenzene, 1,3,5-trimethylbenzene, copper, and nickel). Detections in either the sample or the replicate, but not both, were still considered as potential detections and are included in the data analyses (except for copper) and interpretations because the concentrations were generally low and within the detection limits of the laboratory analytical methods (Foreman and others, 2021).

Table 3. Major ions and dissolved solids in water-quality samples collected in August 2020 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

[mg/L, milligram per liter; CaCO₃, calcium carbonate; NA, not applicable; NS, not sampled; E, estimated]

U.S. Geological Survey site field identifier (see table 1)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Chloride-to-bromide ratio	Sulfate (mg/L)	Fluoride (mg/L)	Field alkalinity (mg/L as CaCO ₃)	Dissolved solids (mg/L)
C1	76.6	20.5	3.70	3.58	3.06	0.030	102	0.05	0.34	324	329
C2	77.2	30.8	4.47	3.11	7.13	0.035	204	3.98	0.43	195	204
C3-SW	51.6	13.3	1.86	1.41	2.82	0.017	166	0.50	0.36	NA	193
C4	51.1	20.7	2.61	4.53	1.60	0.014	114	2.94	0.48	300	227
P1	73.9	25.0	3.52	5.14	3.35	0.014	239	0.04	0.35	306	319
P2	90.2	23.1	18.3	23.8	18.9	0.058	326	6.21	0.67	331	421
P3	64.6	24.1	NA	27.6	19.8	E0.049	404	0.12	0.79	326	397
P4	64.8	23.9	12.2	10.5	10.8	E0.023	470	7.77	0.55	281	323
P5	53.3	19.1	7.78	9.39	7.41	E0.031	239	0.07	0.61	230	287
P6	104	38.4	13.1	5.38	17.2	0.063	273	0.11	1.08	473	536
P7	41.4	14.7	8.11	7.01	5.58	0.029	192	0.05	0.50	189	217
P8	69.6	33.9	10.3	3.43	6.77	E0.033	205	0.04	1.00	318	340
P9	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P10	63.5	16.1	10.1	3.48	9.06	E0.034	266	1.28	0.88	226	266
P11	67.9	15.1	8.60	5.11	11.0	0.026	423	29.3	0.84	222	297
P12	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P13	85.5	22.4	9.41	3.61	10.5	E0.037	284	0.66	0.68	NA	369
P14	96.1	22.3	6.21	8.14	8.66	E0.068	127	0.07	0.64	399	459
P15	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P16	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S13-Confluence	43.0	13.8	16.5	2.67	28.0	0.077	364	38.7	0.42	NA	225
S13-Discharge	80.2	11.2	35.4	2.39	84.6	0.041	2,060	117	0.17	NA	406
Laboratory detection limits	0.022	0.01	0.40	0.30	0.02	0.01	NA	0.02	0.01	NA	NA

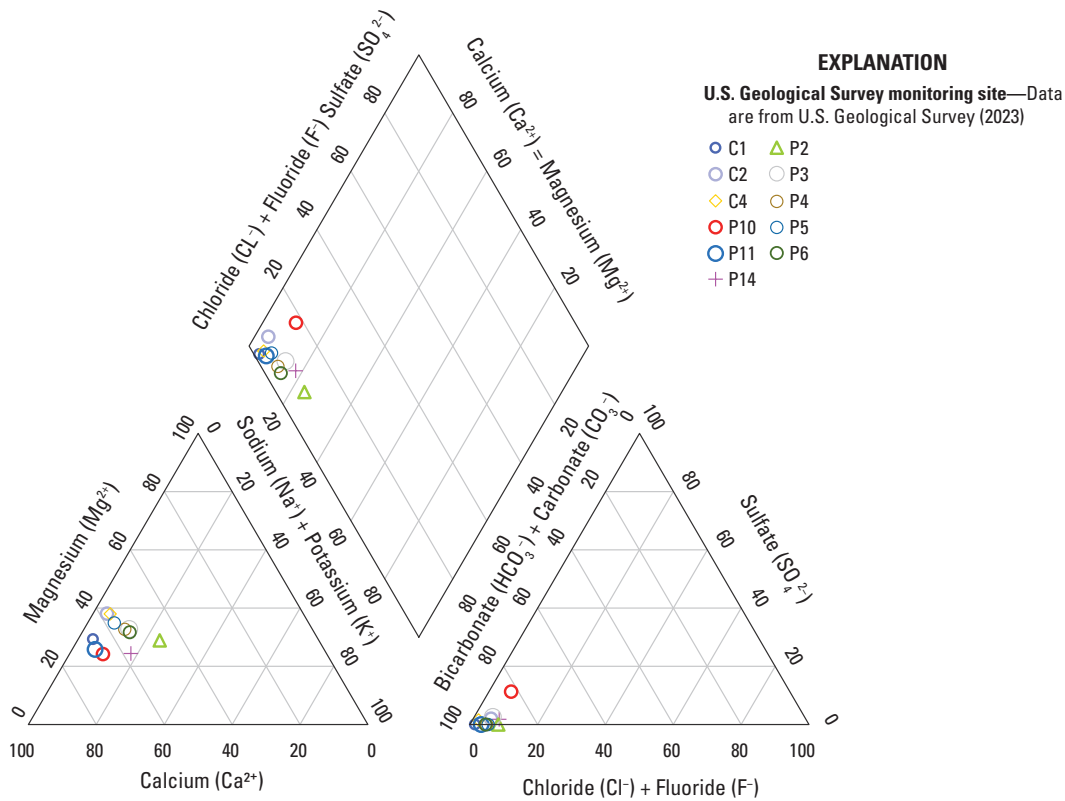


Figure 10. Piper diagram of major ions detected in groundwater samples collected in August 2020 at the Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

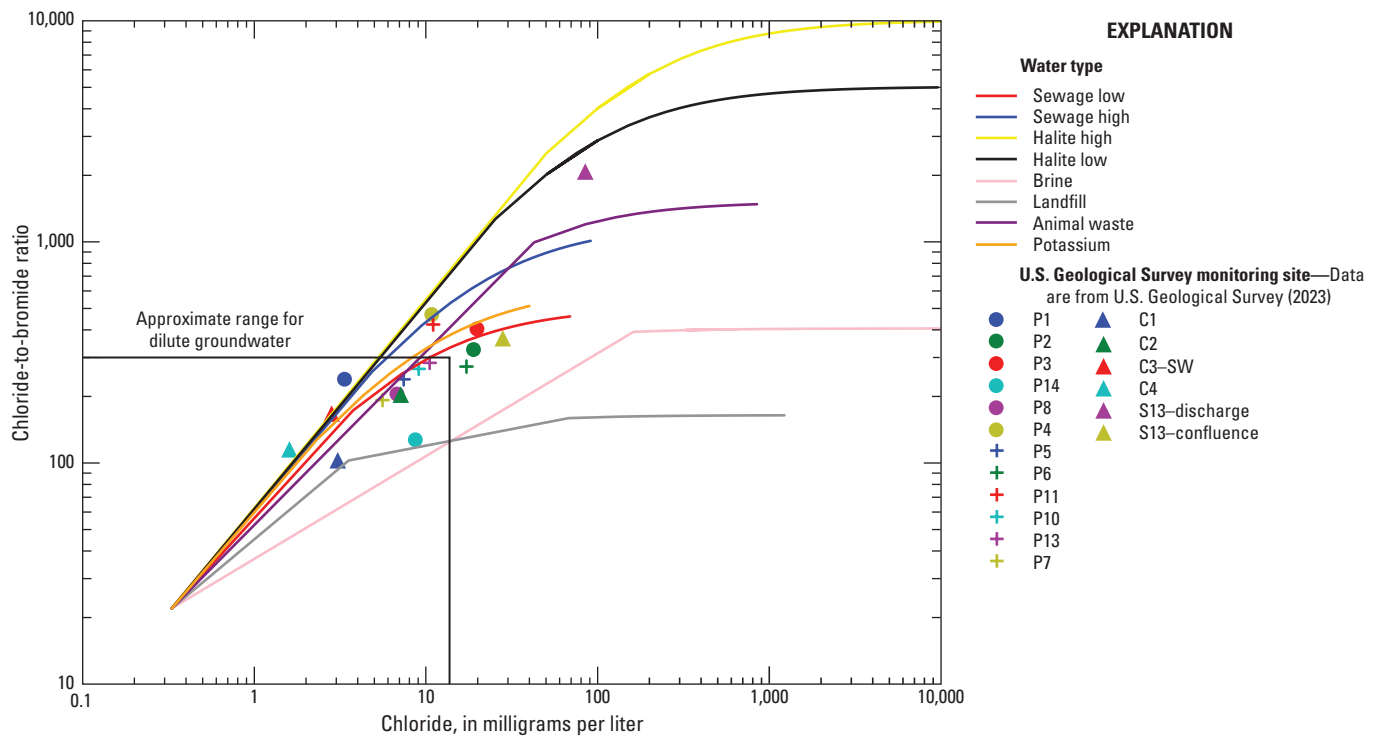


Figure 11. Graph showing the relation of chloride-to-bromide ratios to chloride concentrations, with mixing curves representing sources of chloride, for samples collected in August 2020 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

Table 4. Nutrient, pH, and dissolved oxygen concentrations in water-quality samples collected in August 2020 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; NA, not available; NS, not sampled; —, not applicable]

U.S. Geological Survey site field identifier (see table 1)	Ammonia (mg/L as N)	Nitrite (mg/L as N)	Nitrate plus nitrite (mg/L as N)	Orthophosphate (mg/L as P)	pH	Dissolved oxygen (mg/L)
C1	0.15	0.001	<0.04	<0.004	6.8	0.30
C2	0.06	<0.001	<0.04	0.004	7.6	1.0
C3–SW	<0.01	<0.001	0.04	<0.004	NA	NA
C4	0.14	<0.001	<0.04	<0.004	7.5	0.70
P1	0.24	0.002	<0.04	<0.004	7.2	0.30
P2	0.03	0.002	<0.04	0.004	6.8	0.30
P3	0.69	0.001	<0.04	0.019	7.1	0.30
P4	0.74	0.002	<0.04	0.043	7.0	0.30
P5	0.70	0.002	<0.04	<0.004	7.2	0.30
P6	3.83	<0.001	<0.04	0.007	6.6	0.30
P7	0.33	0.002	<0.04	0.037	7.5	0.80
P8	0.89	0.001	<0.04	0.023	7.1	0.30
P9	NS	NS	NS	NS	NS	NS
P10	0.19	0.001	<0.04	0.012	7.0	0.60
P11	0.19	0.002	<0.04	0.009	7.4	0.70
P12	NS	NS	NS	NS	NS	NS
P13	0.21	0.003	<0.04	0.005	7.0	0.80
P14	3.38	0.007	<0.04	0.005	6.5	0.30
P15	NS	NS	NS	NS	NS	NS
P16	NS	NS	NS	NS	NS	NS
S13–Confluence	0.23	0.036	0.32	<0.004	7.6	8.7
S13–Discharge	0.11	0.123	0.25	<0.004	7.5	6.5
Laboratory detection limits	0.01	0.001	0.04	0.004	—	—

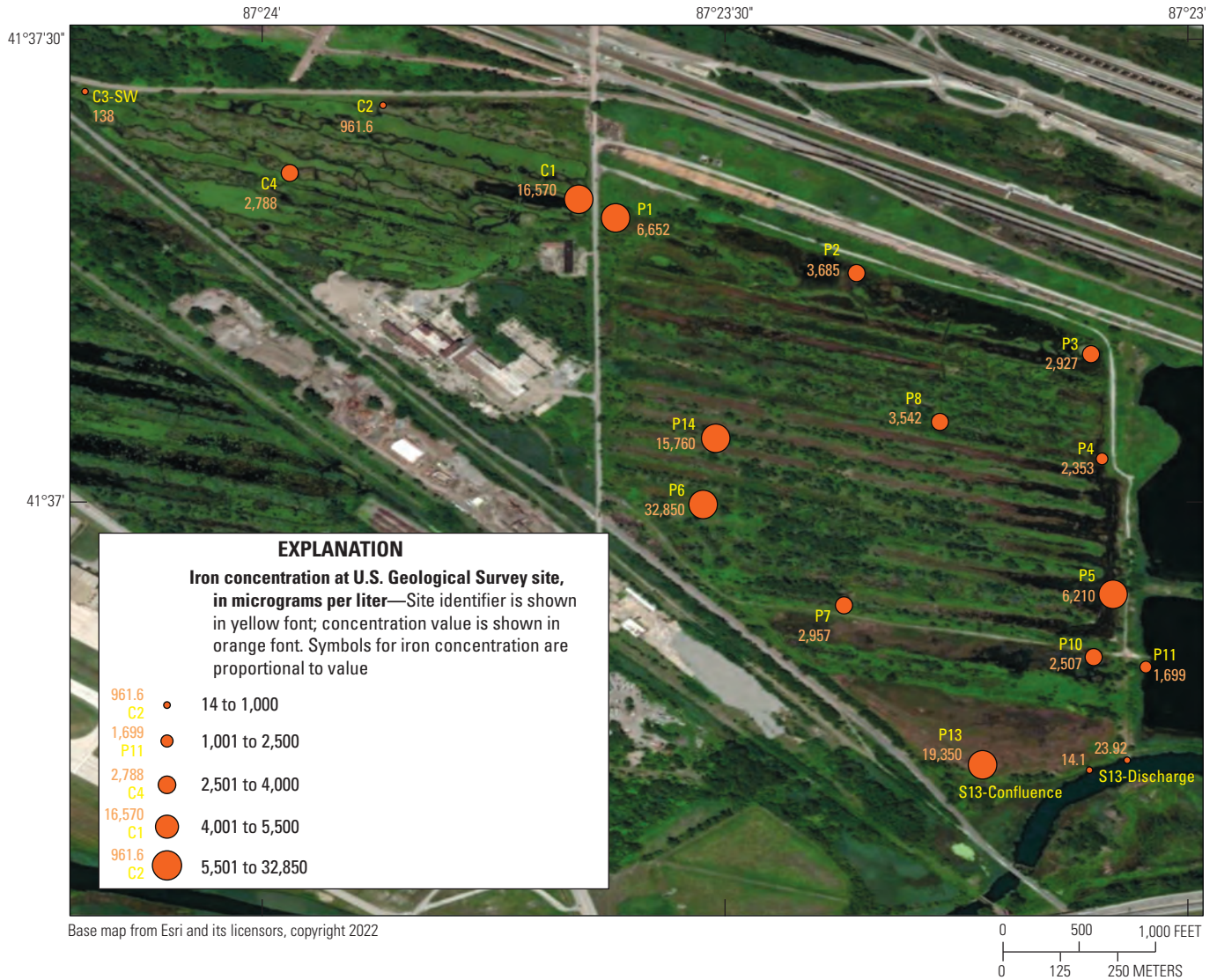


Figure 12. Map showing iron concentrations in groundwater and surface-water samples collected in August 2020 at the Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

Table 5. Concentrations of selected trace elements in water-quality samples collected in August 2020 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

[µg/L, microgram per liter; <, less than; NS, not sampled]

U.S. Geological Survey site field identifier (see table 1)	Arsenic (µg/L)	Barium (µg/L)	Boron (µg/L)	Iron (µg/L)	Lead ¹ (µg/L)	Manganese (µg/L)	Molybdenum (µg/L)	Strontium (µg/L)	Zinc (µg/L)	Aluminum (µg/L)	Lithium (µg/L)
C1	26.6	50.2	267	16,600	<0.12	1,310	2.12	127	503	<3.0	9.60
C2	4.00	14.4	204	962	0.17	132	1.94	71.9	462	<3.0	3.76
C3–SW	0.86	27.4	159	138	0.05	52.7	0.67	90.8	2.1	4.0	8.31
C4	16.5	30	66.0	2,790	0.04	141	11.4	78.4	519	<3.0	5.29
P1	15.3	149	216	6,650	<0.16	313	0.83	125	713	<3.0	16.1
P2	4.00	61.8	4,690	3,680	<0.14	148	15.5	574	567	<21.0	65.2
P3	4.30	45.3	3,950	2,930	0.08	432	12.3	377	223	<9.0	32.6
P4	5.70	121	1,660	2,350	0.10	576	2.37	168	292	<3.0	15.6
P5	25.6	79.5	987	6,210	0.12	483	10.8	166	1,360	<45.0	23.1
P6	59.6	134	263	32,800	0.09	1,250	0.94	153	7,460	<15.0	9.22
P7	7.00	35.9	1,250	2,960	0.11	229	6.50	83.2	1,010	<36.0	10.9
P8	24.1	21.4	193	3,540	0.30	326	5.37	99	1,750	3.0	6.31
P9	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P10	10.7	15.6	668	2,510	0.02	255	11.8	91.7	667	<3.0	5.96
P11	6.20	34.4	990	1,700	0.16	479	7.85	288	2,400	<15.0	7.30
P12	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P13	18.9	60.3	619	19,400	0.02	1,070	0.67	107	7,030	<3.0	3.54
P14	5.10	90.3	99.0	15,800	0.16	1,490	1.22	109	29,400	21.0	4.75
P15	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P16	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S13–Confluence	1.20	23.4	56.0	14.1	0.07	9.24	14.9	125	<2.00	27.0	9.79
S13–Discharge	1.30	18.3	82.0	23.9	<0.12	9.14	4.80	144	<12.0	24.0	12.6
Laboratory detection limits	0.10	0.10	2.00	10.0	0.02	0.20	0.05	0.40	2.00	3.0	0.15

¹Detection in blank sample at 0.04 µg/L.

Table 6. Detected volatile organic compounds in water-quality samples collected August 2020 at Clark and Pine Nature Preserve and Pine Station Nature Preserve near Gary, Indiana.

[µg/L, microgram per liter; E, estimated; <, less than]

Volatile organic compound	C1 (µg/L)	C3-SW (µg/L)	P1 (µg/L)	P2 (µg/L)	P4 (µg/L)	P5 (µg/L)	P7 (µg/L)	P10 (µg/L)	S13-Confluence (µg/L)	S13-Discharge (µg/L)
Bromodichloromethane	<0.034	^a 0.025	<0.034	<0.034	<0.034	<0.034	<0.034	<0.034	^a 1.25	^a 0.444
Tribromomethane	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	^a 0.17	<0.14
Dibromochloromethane	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	^a 0.97	^a 0.16
Trichloromethane	<0.03	^a 0.33	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	^a 1.5	^a 0.87
Toluene	<0.20	^a 0.23	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Benzene	<0.026	<0.026	<0.026	<0.026	<0.026	^a 0.017	<0.026	<0.026	^a 0.026	<0.026
Ethylbenzene	<0.036	<0.036	<0.036	<0.036	<0.036	<0.036	<0.036	<0.036	^a 0.029	<0.036
Dichloromethane	<0.04	^a 0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Trans-1,2-Dichloroethene	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	^a 0.013
Carbon disulfide	<0.10	<0.1	<0.10	^a E0.10	<0.10	<0.10	<0.10	<0.10	<0.10	^a E0.10
cis-1,2-Dichloroethene	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	^a 0.021	^a 0.166
n-Butyl methyl ketone	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	^a 0.4
o-Xylene	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	^a 0.02	<0.032
1,2,3-Trimethylbenzene	^a 0.017	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
1,2,4-Trimethylbenzene	^a 0.033	<0.032	<0.032	<0.032	<0.032	^a 0.012	<0.032	<0.032	<0.032	<0.032
Isopropylbenzene	<0.042	<0.042	<0.042	^a 0.017	<0.042	<0.042	<0.042	^a 0.012	<0.042	<0.042
1,3,5-Trimethylbenzene	^a 0.013	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032	<0.032
Acetone	<3.4	^a 19.4	<3.4	<3.4	<3.4	<3.4	<3.4	<3.4	^a 3.6	^a 25.7
Methyl ethyl ketone	<2.0	^a 2.9	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	^a 0.8	^a 3.2
m-Xylene plus p-xylene	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	^a 0.06	<0.08

^aIndicates a detection.

Groundwater-Flow Patterns and Interactions with Surface-Water Features

The potentiometric contours in [figure 7](#) indicate that there is a groundwater divide and recharge area along the northern part of the Clark and Pine Nature Preserve and the Pine Station Nature Preserve, with groundwater in the shallow dune complex aquifer flowing south toward a discharge area adjacent to the Grand Calumet River (groundwater flow north of the recharge area is toward Lake Michigan). This shallow water-table configuration and flow is likely part of a local (<1 mi from recharge to discharge zone) flow regime (Tóth, 1963; Wilcox and others, 2020), whereas the predominant calcium-magnesium-bicarbonate groundwater chemistry ([fig. 10](#); [table 3](#)) suggests that a more regional (>3 mi from recharge to discharge zone) flow path from the south is discharging in the vicinity of the preserves consistent with a conceptual model of the groundwater-flow systems presented by Shedlock and others (1994). In contrast to shallow groundwater (upper 10 ft of saturated thickness of the surficial aquifer) east of the preserves, groundwater in the vicinity of the preserves has lower sulfate and higher magnesium concentrations suggesting that water-to-rock interactions of groundwater and dolomite bedrock are more prevalent than what Shedlock and others (1994) reported for a study area east of Gary, Indiana. The occurrence of calcium-magnesium-bicarbonate water chemistry and mixed local or regional groundwater flow (Wilcox and others, 2020) indicates unique hydrologic conditions at the preserves. Hence, the study area could represent unique growing conditions for wetland plant communities that prefer lower sulfate concentrations when compared with eastern counterparts along the Indiana Dunes National Park (Shedlock and others, 1994).

Water Quality and Wetland Ecosystem Functions

The predominant presence of ammonia as nitrogen ([table 4](#)), coupled with high iron concentrations ([fig. 12](#); [table 5](#)), indicates that reducing conditions are prevalent and that iron reduction by bacteria may be a dominant biogeochemical process in the wetlands at the preserves. Wetlands can represent sources of methane (CH₄) where persistent high water tables limit the occurrence of oxidized iron [Fe(III)], and bacteria revert to reduction of carbon dioxide as an energy source when water temperatures are sufficiently warm (Jerman and others, 2009). This highlights the importance of low water-table conditions when emergent plants are in wetland cells and iron-rich wetland substrates that are submerged during hydroperiods and exposed to air and oxygenated meteoric water during rainstorms.

Although chloride (7.41 mg/L) and sodium (7.78 mg/L) concentrations were low during the August 2020 water-quality sampling, specific conductance trends at monitoring well P5 ([figs. 8A](#) and [9](#)) suggest that surface water and shallow groundwater are transporting runoff byproducts along the eastern corridor or the north-south oriented wetland cell. Future wetland restoration efforts may entail diverting flow from the eastern wetland cell into the South Pond. Water-level elevations during the monitoring period ([fig. 6](#)) indicate that a persistent gradient exists to facilitate flow into the South Pond from the vicinity of monitoring well P5.

Summary

Adverse ecological and water-quality effects associated with industrial land-use changes are common for littoral wetlands connected to river mouth ecosystems in the Grand Calumet River-Indiana Harbor Canal Area of Concern. These effects can be exacerbated by recent high Lake Michigan water levels that are problematic for wetland restoration. Wetlands in the adjacent Clark and Pine Nature Preserve and Pine Station Nature Preserve are intended to mitigate wetland destruction in the area of concern by restoring residual dune-and-swale wetlands and preserving habitat for endangered and threatened plant species. Physical hydrology and water-quality monitoring of restored wetland cells at the preserves were initiated during 2019 to evaluate changes after wetland restoration efforts in 2015 and near record-low water levels in early 2013. Lake Michigan water levels rose steadily between late 2013 and 2018 to record-high water levels in 2019 and 2020.

High water levels on Lake Michigan influenced Grand Calumet River stage and shallow groundwater elevations at the preserves after the onset of peak lake levels (approximately 582.5 ft) in June 2019 that persisted through summer 2020. Grand Calumet River stage peaked soon after lake level at approximately 585 ft in July 2019, whereas groundwater elevations in the study area peaked in October 2019. Lake levels remained high before they began to recede in September 2020. Dry conditions at the preserves during summer 2020 persisted into water year 2021 and likely led to groundwater levels receding from their highest elevations in June 2020 before the lowering of Lake Michigan levels. This indicates that wetland water balance, especially during summer months when evapotranspiration is high, plays an important role in mediating the effects of high lake levels in the region.

The water-quality dynamics of closed-basin wetland cells in western and central preserve locations contrasts with the connected wetland cells of the eastern basin. Lithium concentrations in wells along the eastern basin (P3, P4, P5) are all above 15 micrograms per liter, whereas concentrations in western (C2, C3, C4) and central (P6, P8, P14) shallow groundwater are all less than 10 micrograms per liter. Along the northern and eastern perimeter of the wetlands, high concentrations of boron and lithium indicate that there may

be leaching from fly ash used to build the access road and the railroad embankment to the north. Hence, restoration approaches that divert shallow groundwater inflow may also be warranted to trap or incorporate toxic metals in wetland cells to prevent migration of these metals into the Grand Calumet River and other surface-water features and groundwater aquifers.

Hydrologic data collected from water years 2020 to 2022 indicate that the preserve wetlands serve essential functions related to water storage and water-quality benefits within the Grand Calumet River-Indiana Harbor Canal area of concern. The coupled occurrence of reduced nitrogen and high iron concentrations indicates that biogeochemical processes at the preserves favor iron reduction and mobilization with sustained high water levels, whereas iron oxidation occurs under variable water-table configurations and wetland hydroperiod phases. Previous work indicated that this is an important dynamic because persistently inundated wetlands can lead to conditions that favor methanogenesis and methane release. However, hydrologic monitoring from this study indicates that variable wetland hydroperiods have returned following high water-table conditions that ensued after record-high water levels in Lake Michigan in 2019–20. This is important for supporting water quality and diverse plant ecosystems.

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Appendix 1. Groundwater-Elevation Data at the Clark and Pine Nature Preserve and the Pine Station Nature Preserve Near Gary, Indiana, in Fall 2019 and 2020

Table 1.1. Groundwater-elevation data for the Clark and Pine Nature Preserve and the Pine Station Nature Preserve near Gary, Indiana, for autumn 2019 and 2020.

[Data are from Rambol U.S. Corp (2020) and Tetra Tech, Inc. (2021), which are sourced from publicly available reports submitted to the Indiana Department of Environmental Management. NA, not available]

Well name	Latitude	Longitude	Groundwater elevation, in feet	
			Autumn 2019	Autumn 2020
Q-50	41.621	-87.410	587.67	NA
GP B-1R	41.610	-87.393	587.05	585.15
GP B-3R	41.610	-87.389	584.32	583.70
GP B-4	41.611	-87.391	586.18	584.87
GP B-5	41.609	-87.392	585.36	583.61
GP B-7	41.611	-87.392	585.36	578.55
GP B-8R	41.609	-87.391	584.56	583.84
MIDCO B-10	41.623	-87.407	590.14	589.00
MIDCO S-10	41.622	-87.406	589.88	588.65
MIDCO H-10	41.621	-87.410	589.13	587.55
MIDCO V-10	41.621	-87.409	589.06	587.54
MIDCO AA	41.623	-87.406	590.15	588.14

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