Prepared in cooperation with the City of Crystal Lake, Illinois

Hydrologic Influences on Water Levels at Three Oaks Recreation Area, Crystal Lake, Illinois, April 14 through September 27, 2016

Scientific Investigations Report 2018–5105

U.S. Department of the Interior
U.S. Geological Survey

Cover photographs:

Front: View of Three Oaks Recreation Area (South Lake) from James R. Rakow Road, September, 27, 2016.
Back: View of Three Oaks Recreation Area (South Lake) from James R. Rakow Road, September 27, 2016.

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DAVID BERNHARDT, Acting Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Contents

Figures

Tables

Conversion Factors and Abbreviations

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
liter per second (L/s)	15.85	gallon per minute (gal/min)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)

Datum

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

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

Abbreviations

ILWATER	Illinois State Geological Survey website database
ISWS	Illinois State Water Survey
Kh	horizontal hydraulic conductivity
MP	measuring point
NAVD88	North American Vertical Datum of 1988
TORA	Three Oaks Recreation Area
USGS	U.S. Geological Survey

Hydrologic Influences on Water Levels at Three Oaks Recreation Area, Crystal Lake, Illinois, April 14 through September 27, 2016

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Abstract

Hydrologic influences on water levels were investigated at Three Oaks Recreation Area (TORA), a former sand-and-gravel quarry converted into recreational lakes in Crystal Lake, Illinois. From 2009 to 2015, average water levels in the lakes declined nearly 4 feet. It was not clear if these declines were related to variations in weather (precipitation or evaporation) or other hydrologic influences such as municipal supply pumping or nearby quarry operations. Data were collected using three approaches to determine the possibility of such hydrologic influences. First, water levels were collected at 15-minute intervals at three wells equipped with pressure transducers from April 14 through September 27, 2016. The continuous data allowed assessment of lake and well water-level responses to precipitation, pumping influences, and quarry operations. Second, a single-day synoptic water-level survey was completed to create a water-table map to determine groundwater flow directions. Third, single-well aquifer tests (slug tests) were completed on the three data-collection wells to estimate the aquifer's horizontal hydraulic conductivity. Collectively, these data were used to estimate the velocity and volume of water entering and exiting TORA.

Groundwater levels increase rapidly in response to precipitation at wells adjacent to TORA, but the higher levels are lost quickly to discharge between precipitation events. There were minimal to no pumping influences from the nearby municipal supply wells evident in the hydrographs. Nearby quarry dredging operations also did not appear to directly affect the water levels at wells adjacent to TORA. The calculations that compare the inflows to the outflows at the TORA indicate that evaporation may be the dominant hydrologic influence; therefore, the TORA would be particularly vulnerable to periods of drought conditions.

Introduction

In 2009, the City of Crystal Lake, Illinois, converted an unused sand and gravel quarry within the city limits into a recreation area for swimming and beach activities named the Three Oaks Recreation Area (TORA). The TORA is located south of U.S. Highway 14 and west of State Highway 31 in McHenry County (fig. 1). The TORA consists of two lakes, North Lake and South Lake, with groundwater generally moving from north to south, hereafter referred to as "downgradient." The TORA is surrounded by residential, commercial, and industrial development, which obtain water supplies from the City of Crystal Lake's municipal supply wells. Ongoing quarry operations are located south of the TORA. The U.S. Geological Survey (USGS), in cooperation with the City of Crystal Lake, conducted a local hydrologic investigation of the TORA, with data collected from April 14 to September 27, 2016. The data were collected to identify the influences from precipitation, nearby groundwater withdrawals, and nearby quarry operations on water levels at the TORA and to quantify the velocity and volume of groundwater flow entering and exiting the TORA. This investigation will provide the necessary information to Crystal Lake's resource managers for lake-management, planning, and configuration decisions.

Figure 1. Three Oaks Recreation Area, downgradient quarries, and well locations in Crystal Lake, Illinois.

Purpose and Scope

The purpose of this report is to describe hydrologic influences on water levels at the TORA in Crystal Lake, Illinois. This report is to provide Crystal Lake's resource managers with an understanding of how precipitation, groundwater withdrawals, and nearby quarry operations may be affecting lake levels and water quality in the TORA. USGS collected continuous (15-minute) water-level data within and near the TORA from April 14 to September 27, 2016 to identify water-level responses to precipitation events, groundwater withdrawals, and quarry operations. Additionally, a synoptic water-level survey was completed to establish water-level elevations, hydrologic flow paths, and hydraulic gradients in the TORA and estimate groundwater velocity and volumetric flow rates. Single-well aquifer tests were completed at selected wells to estimate hydraulic conductivity. All collected data were compared to develop calculations that estimate the rate and volume of groundwater flow entering and exiting the TORA from April 14, 2016, to September 27, 2016.

Previous Investigations at Three Oaks Recreation Area

A water-level model for the TORA was used to estimate a maximum historical lake stage of 866 feet (ft) and a minimum stage of 856 ft (Hey and Associates, Inc., written commun., August 31, 2015). Hey and Associates, Inc., also indicated that water levels at the TORA would decrease if the nearby quarry water level fell below 849 ft. The model used by Hey and Associates, Inc., was a water-level model that does not consider geology or aquifer properties. Water-level models use only water-budget inputs such as precipitation and evaporation to predict lake water levels.

Crystal Lake and Hey and Associates, Inc., collected daily groundwater and surface water level data from 2009 through 2015 (Hey and Associates, Inc., written commun., September 11, 2015). These data were compared to the continuous water-level data available from a nearby (4 miles [mi] southwest) well (421122088222701–43N7E-23.1d, 16–GRF–I) in the McHenry County Groundwater Monitoring Well Network. This comparison indicated that the average-annual water levels at the TORA appeared to have been declining since 2009 similar to 16–GRF–I (fig. 2). In general, the average-annual water levels of the two lakes were consistent with those in well 16–GRF–I from 2009 to 2010. From 2013 to 2014, the water level in the well decreased slightly while it remained the same in the two lakes. However, in 2015, the water levels at North and South Lake declined by about 3 ft, while the average annual water-level changes at well 16–GRF–I were less than 1 ft, potentially indicating the TORA water-level declines were unrelated to regional influences.

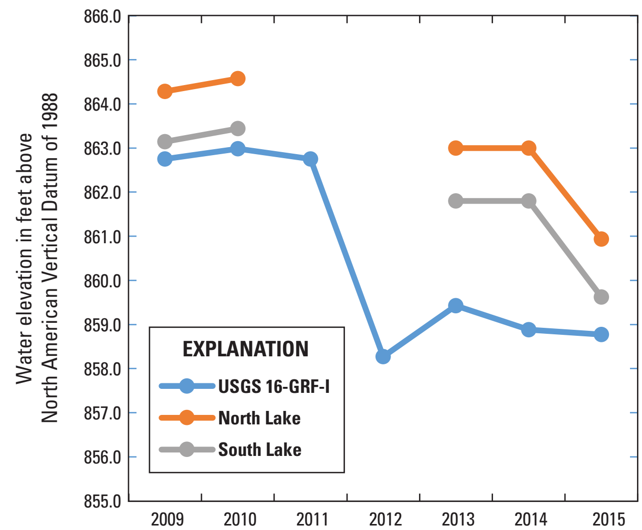


Figure 2. Average annual water levels at North Lake and South Lake of the Three Oaks Recreation Area and McHenry County observation well, 421122088222701–43N7E-23.1d, 16–GRF–I from 2009 to 2015. (Source: North and South Lake data from Hey and Associates, written commun., 2014; observation well data from U.S. Geological Survey, 2016).

Bathymetric (lakebed) measurements completed by the Illinois Department of Natural Resources Fisheries division (Vic Santucci, written commun., February 23, 2006) determined that North Lake had an average depth of 23 ft with a maximum depth of 40 ft and South Lake had an average depth of 19 ft with a maximum depth of 41 ft toward the eastern half of the lake (fig. 3). The lakebeds have a tiered, stair-step configuration that grades deeper toward the center of the lake and shallows toward the shores. This is the result of previous quarry operations at the TORA with the configuration dictated by the amount of fine-grained (clays and silts) deposits encountered during mining operations. It is common for quarry operators to avoid mining fine-grained deposits because they clog equipment and are not salable. Where encountered, the dragline or dredger is moved until sand and gravel is found. The surface area of North Lake is about 1,437,000 square feet (ft^2; 33 acres) and South Lake of the TORA is about 12,271,000 ft^2 (281.7 acres) for a total of 13,708,000 ft^2 (Vic Santucci, written commun., 2006). The volume of surface water at North Lake was estimated at 760 acre-feet (33,110,000 cubic feet [ft^3]). The volume of surface water at South Lake was estimated to be 5,384 acre-feet (234,540,000 ft^3) (Vic Santucci, written commun., 2006).

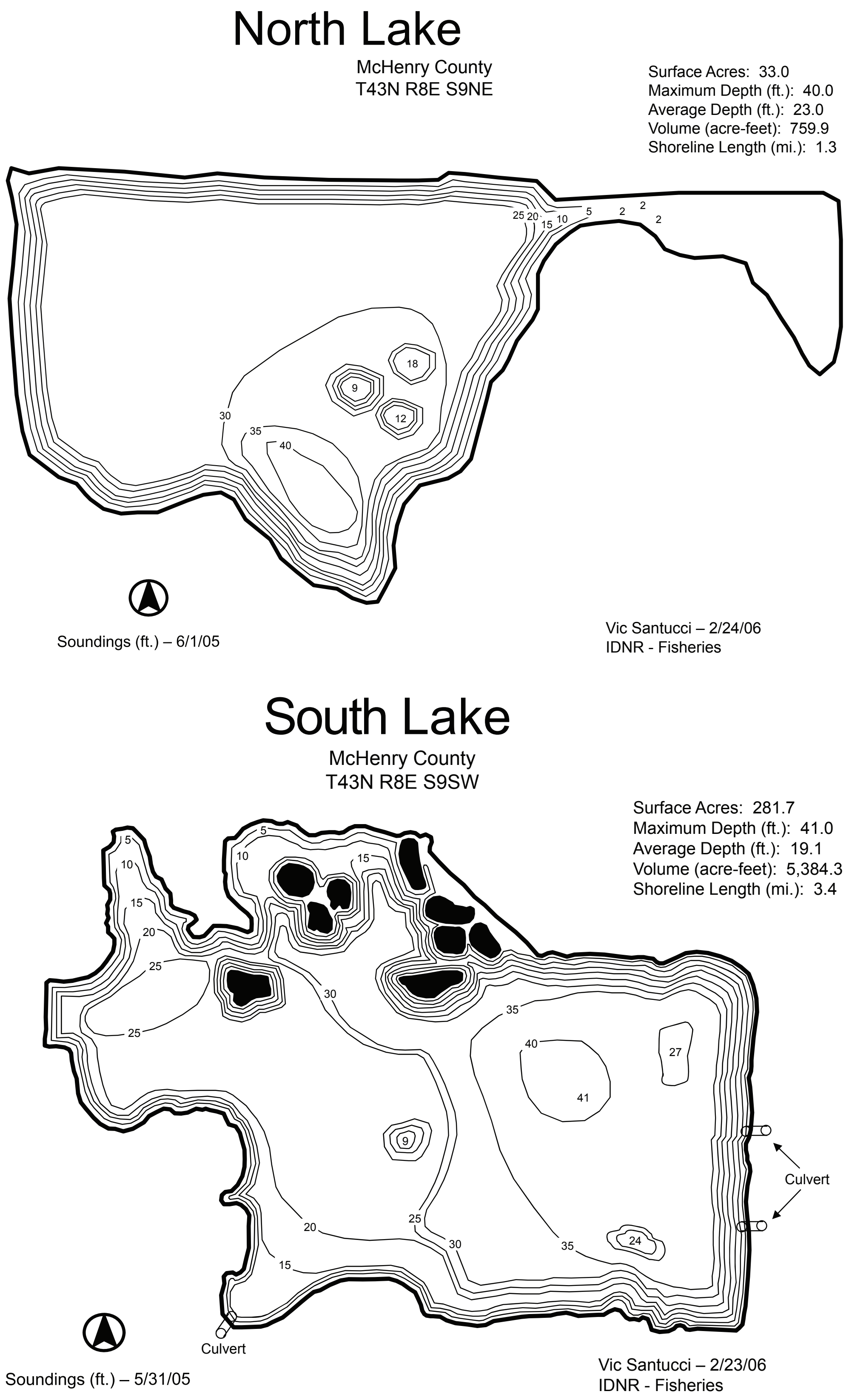


Figure 3. Bathymetry, in feet (ft) below water surface, of *A*, North and *B*, South Lake at the Three Oaks Recreation Area, Crystal Lake, Illinois. (Figures sourced from Vic Santucci, Illinois Department of Natural Resources (IDNR), written commun., 2006).

Description of Study Area

The land topography surrounding the TORA is hilly with elevations ranging from 905 ft to 940 ft (North American Vertical Datum of 1988 [NAVD88]) toward the north, and relatively flat toward the west with elevations ranging from 895 ft to 901 ft NAVD88. South of the TORA, the land slopes gently until steep gradients are encountered just before the Fox River.

There are no streams or constant sources of drainage into the TORA. Three culverts direct stormwater runoff from the roads into the recreational area; two culverts are located on the east side of South Lake (draining storm runoff from Pingree Road [Rd]), and one is located on the southwest side of South Lake (draining storm runoff from Virginia and James R. Rakow Rd). Two additional culverts parallel to the southern shoreline of South Lake along an earthen berm direct stormwater runoff from James R. Rakow Rd (hereafter referred to as Rakow Rd) where, the stormwater runoff passively infiltrates into the groundwater along Rakow Rd. Stage and flow data are not available for these culverts during the period of study. A culvert connects North Lake and South Lake to the TORA, and historical water levels indicate that water elevation at North Lake is generally less than 1 ft higher than South Lake. Therefore, velocity and volume calculations presented in the Water Levels and Quantification of Flow section of this report include only the square feet and volume of South Lake.

Geology

The geologic units of interest to this investigation consist of: (1) an approximately 70 ft thick fractured bedrock of Silurian age that pinches out toward the south (Reinertsen and others, 1993) overlain by (2) proglacial outwash of the Wisconsin Episode that includes less than 80 ft of till, fine-grained deposits up to 38 ft thick (Haeger Member), and coarse-grained outwash deposits (Henry Formation) less than 10 ft to more than 180 ft thick (Curry, 2005a). From a larger areal perspective, the sequence of coarse-grained outwash deposits (Henry Formation) thicken toward the northwest and gradually thin toward the south and east of the TORA toward the Fox River. Much of the coarse-grained deposits of the Henry Formation have been mined (Curry, 2005b). The fine-grained deposits of the Woodstock Moraine and Barlina Moraine increase toward the Fox River.

Well logs from several wells in the vicinity of the TORA are available from the Illinois State Geological Survey website database (ILWATER; Illinois State Geological Survey, 2016). North of the TORA, layers of sand and gravel extend to approximately 70 ft below land surface with clay encountered at depths of 50 to 70 ft to bedrock and bedrock encountered at about 250 ft below land surface. West of the TORA, well logs noted interbeds of sandy clays followed by silts and brown clay at about 89 ft below land surface. Depth to bedrock west of the TORA is approximately 230 ft below land surface. Southwest of the TORA, well logs noted the presence of about 60 ft of sand and gravel, underlain by about 150 ft of clay and bedrock that occurs at 217 ft below land surface. Southeast of the TORA, sand and gravel thickens, extending to depths ranging from 104 ft to 130 ft below land surface. The well logs located along Rakow Rd primarily show sand and gravel about 70 ft below land surface overlain by a thin (0 to 8 ft) layer of brown sandy clay.

Water Use and Quarry Operations

There are two supply wells (Crystal Lake wells 12 and 13) about 170 ft apart from each other, located about 1,200 ft west of the TORA, and about 800 ft southeast of the USGS observation well 42130108819150—43N8E-8.2c. This USGS observation well is referred to in this report as 8.2c. The supply wells are both open to the shallow bedrock aquifer at 250 ft depth according to well logs available on ILWATER (Illinois State Geological Survey, 2016). Daily pumping records from supply wells 12 and 13 were provided by the City of Crystal Lake Public Works Department (written commun., November 2, 2016) for most of the period of study (May 15, 2016, through October 1, 2016). The cumulative extraction rates for the supply wells ranged from 0 to 1,275,000 gallons per day, with an average extraction rate of 101,000 gallons from Crystal Lake well 12 and 233,000 gallons from Crystal Lake well 13 and a cumulative average of 334,000 gallons per day from January 2009 through May 2016 (fig. 4) (City of Crystal Lake, written commun., June 1, 2016). Withdrawal rates have decreased from an average of 111,000 to 75,000 gallons for Crystal Lake well 12 and from an average of 286,000 to 98,000 gallons for Crystal Lake well 13 from July 2014 to May 2016. Several other municipal supply wells open to the shallow bedrock aquifer are located north, west, and east of the TORA according to ILWATER. About 15 private (residential) water-supply wells are present northeast of the TORA according to ILWATER. Approximately five commercial wells are located just north of the TORA. No known industrial supply wells are located within the vicinity of the TORA (Illinois State Geological Survey, 2016; U.S. Geological Survey, 2016).

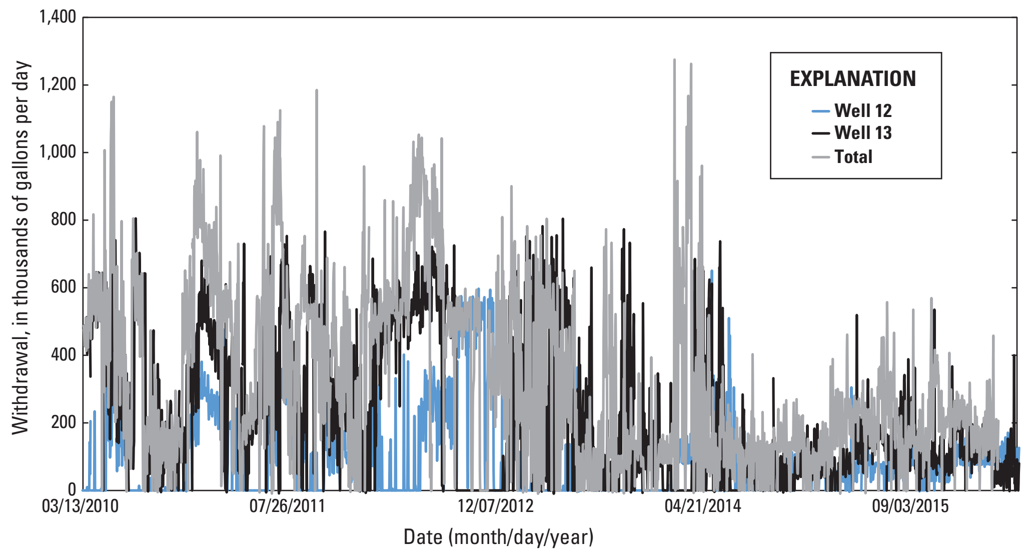


Figure 4. Daily pumping rates for supply wells 12 and 13 from January 2010 to May 2016, in Crystal Lake, Illinois.

The nearby quarry is situated directly south of South Lake and will be referred to as the downgradient quarry for the remainder of this report. The following descriptions of the downgradient quarry operations and plans were from conversations with the downgradient quarry Plant Manager on May 5, 2016. The downgradient quarry has two active mining areas (pits): Franke and Allendale (fig. 5). Franke is the larger of the two pits and is located just south of Rakow Rd (and South Lake). The second pit, Allendale, is located east of Pingree Rd and south of Rakow Rd. Franke is approximately 45 to 50 ft deep and is currently being excavated via dredging operations. The dredge extracts sediment and water at a rate of 500 tons per hour for 8 hours a day, typically 5 days per week, according to the downgradient quarry Plant Manager (Jack Luccetti, oral commun., May 5, 2016). All fine-grained deposits are avoided and not mined because it damages the mining equipment. The water is redirected back into the same pit (Franke) while the sediment is removed by way of conveyor belt (fig. 6). The water in Franke and Allendale is not drained. Prior to July 2015, Franke and Allendale were mined using a dragline at an approximate rate of 250 tons per hour. Dredging operations commenced after July 2015 and are expected to continue until all minable sand and gravel is extracted from Franke to a depth of approximately 55 ft, which is estimated to take about 5 years.

Allendale is approximately 25 ft deep. An additional 25 ft is planned to be mined to similar depths as Franke using the dredge, after the mining of Franke is complete (fig. 5). Currently (2017), there remains approximately 25 ft of sand and gravel above the water table at Allendale that also is planned to be mined. Furthermore, it is possible that this area may be mined below the water table to similar depths as the rest of Allendale.

Other previously mined surface-water bodies located on the downgradient quarry property are Perch Lake and Big Lake (fig. 5). These previously mined pits were not mined as deeply as Franke and Allendale because the increase in fine-grained deposits was encountered at shallower depths (approximately 12 ft), according to the downgradient quarry Plant Manager (Jack Lucchetti, oral commun., May 5, 2016). These lakes are drained through culverts toward Larson Fen and Crystal Creek, due to a lack of storage capacity within the quarry site according to the Plant Manager (Jack Lucchetti, oral communication, May 5, 2016).

Other activities at the downgradient quarry include a wash area where the sand and gravel are washed before being dried and sorted (fig. 1). The water that is used to wash the sand and gravel is sourced from a pond, and the used water is pumped to a settlement pond upgradient and allowed to return by gravity to a pump house pond to be reused. The water is pumped at a rate of 2,500 gallons per minute from the pump house when in operation (fig. 1) (Jack Lucchetti, oral commun., November 2016).

The area to the west of Franke, south of S. Virginia Rd (fig. 5), and northwest of Perch Lake is an older quarry that is currently being filled with clean construction material and debris owned by Consolidated Materials, Inc. No measurements were obtained in this area. Additional quarry operations owned by a different company are located further south of Big Lake and east of Route 31 but were not included in this investigation due to a lack of access. It is probable that operations at these additional quarries will be limited to depths similar to Big Lake and Perch Lake due to the increase in fine-grained deposits and thinning of the overlying sand and gravel alluvium toward the south.

Figure 5. Downgradient quarry and proposed expansion plans at Allendale in Crystal Lake, Illinois.

Figure 6. Dredge operations in Franke at the downgradient quarry in Crystal Lake, Illinois.

Hydrogeology

The coarse-grained outwash deposits of the Henry Formation comprise the Haeger-Beverly Unit. The Haeger-Beverly Unit is the primary aquifer unit for shallow groundwater flow in the TORA (Meyer and others, 2013). The Haeger-Beverly Unit is underlain primarily by fine-grained deposits of the Tiskilwa Formation (till) deposited by the Woodstock and Barlina Moraines. Underlying the till is the fractured bedrock aquifer, which can be hydraulically connected to the shallower Haeger-Beverly Unit where the Tiskilwa Formation is absent.

The TORA lakes and downgradient quarries are known as flow-through pits or pit lakes. Groundwater flows through the TORA lakes and downgradient quarries by entering from the north, along with surface-water runoff, and exiting the TORA at the southern portions of the lakes (fig. 7). Pit lakes are a source of groundwater recharge but can also have a greater loss from evaporation because of their open water characteristics. Pit lakes are a lake boundary system that receives precipitation, loses water to evaporation, and allows groundwater to enter and leave the lake. Pit lakes are also zones of infinite permeability, in that the velocity of the water within the pit is not limited by a matrix of sediment or rock. An increase in the velocity can alter the groundwater flow paths (Younger and others, 2012). Green and others (2005) published one of the first and only comprehensive studies on the hydraulic impacts of quarries and gravel pits. In that study of five limestone quarries and two sand and gravel pits, the effects of quarry operations on water levels at the sand and gravel pit mines were determined to be minimal; however, that study also showed that groundwater-flow directions were diverted away from a nearby fen because of one of the excavated gravel pits. Therefore, the downgradient quarry operations and expansion plans could potentially alter the groundwater-flow directions at TORA.

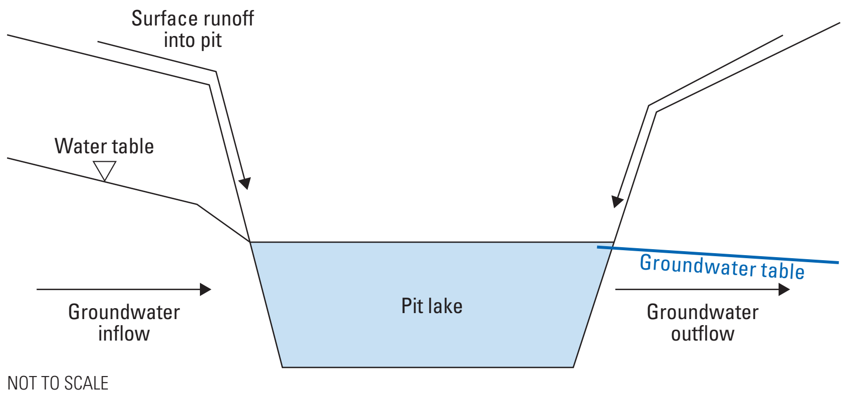


Figure 7. Conceptual drawing of a flow-through pit, representative of the groundwater system at the Three Oaks Recreation area and the downgradient quarries in Crystal Lake, Illinois.

Hydrologic Data Collection

On April 7, 2016, an observation well (Rakow Rd well) was installed by the Testing Service Corporation slightly north of Rakow Rd about 25 ft from the southern shoreline of South Lake (fig. 1). The Rakow Rd well monitors the groundwater exiting the TORA. The well was installed at a depth of 38 ft below land surface. The geology described in the well log showed a brown sandy clay to a depth of 8 ft, followed by coarse-grained outwash deposits approximately 30 ft in thickness. The identified geology is consistent with existing well logs available from the Illinois State Geological Survey (2016) ILWATER database. South Lake well is an existing well owned and maintained by the City of Crystal Lake and is located about 10 ft from the northern shoreline of South Lake (fig. 1). The South Lake well has a depth 8.82 ft below land surface with a 5-ft screen interval at the bottom of the well. The existing USGS well 8.2c is located about 1,200 ft west of South Lake and is 46.1 ft below land surface with a 5-ft screen interval at the bottom of the well. The South Lake well and 8.2c well represent the upgradient groundwater entering the TORA. These three wells were equipped with vented pressure transducers and data were collected from April 14, 2016, to September 27, 2016 (referred to as the period of record) and processed according to Cunningham and Schalk (2011). The transducers continuously measured and recorded water levels at 15-minute intervals to catalog water-level responses to precipitation, pumping, and quarry operations. The data are available in the USGS National Water Information System (U.S. Geological Survey, 2016).

Daily precipitation data were obtained from a rain gage at Crystal Lake Waste Water Treatment Plant 2, approximately 1.5 mi west of the TORA (The Weather Company, 2016) (fig. 1). Daily precipitation for the period of record ranged from 0.00 to 1.47 inches (in.) for a total of 22.06 in. Evaporation was estimated from Roberts and Stall (1967), which reported monthly average evaporation for the state of Illinois. Near the study area, the evaporation for the months April through September totaled 25.2 in. The volume of precipitation and evaporation was determined by converting the inches to feet and multiplying by the surface area of North and South Lake (13,708,000 ft^2). Precipitation added 25,222,720 ft^3 to TORA and evaporation removed 28,786,800 ft^3 from TORA. Evaporation exceeded precipitation during the period of record by about 14 percent.

On May 5, 2016, synoptic water-level measurements within about a 2-mi radius of TORA were collected by the USGS from observation wells and surface-water sites including the downgradient quarry property (table 1). Table 2 lists the pertinent well construction details for the observation wells measured for the synoptic water-level event, and the water-level data are available in the USGS NWIS (U.S. Geological Survey, 2016). A calibrated electronic sounding tape obtained depth-to-water readings. A Trimble™ R8 GNSS global positional system with an accuracy of approximately +/– 1.5 centimeter was used to determine the elevation of the land surface and the surface water-level elevation referenced to NAVD88. For groundwater level measurements, the measuring point (MP) height was measured, recorded, and added to the land-surface elevation to calculate MP elevation. Groundwater elevations were calculated by subtracting the depth to water from MP elevation.

Surface water-level measurements at TORA and the downgradient quarries were collected at seven surface-water (SW) sites (table 1; fig. 1). The water-surface elevation was determined with the Trimble™ R8 GNSS global positional system on May 5, 2016, using a Virtual Reference System Real-Time Network based on the single-base Real Time Kinematic method (Rydlund and Densmore, 2012.) The data are available in the USGS NWIS (U.S. Geological Survey, 2016).

Table 1. Surveyed groundwater and surface water-level measurements near the Three Oaks Recreation Area, Crystal Lake, Illinois, May 5, 2016.

[USGS, U.S. Geological Survey; Rd, Road; SW, surface water; NAVD88, North American Vertical Datum of 1988; IL, Illinois; N, North; S, South]

USGS station identification number	USGS station name	USGS field identifier	Water elevation, in feet above NAVD88
		Groundwater	
421317088182301	43N8E-9.5f	South Lake well[1]	861.54
421320088181001	43N8E-9.3f	North Lake well	861.77
421244088180201	43N8E-9.2a	Rakow Rd well[1]	853.77
421143088180101	43N8E-21.2g	Storage-Well	829.20
421301088191501	43N8E-8.2c	8.2c[1]	875.34
421402088173501	43N8E-3.7d	3.7d	881.29
421228088160701	43N8E-14.5f	14.5f	842.48
421052088184101	43N8E-28.6g	28.6g	799.55
		Surface water	
421320088181002	North lake at Three Oaks at Crystal Lake, IL	North Lake SW	862.20
421317088182201	South Lake N at Three Oaks Crystal Lake, IL	South Lake northern SW	861.16
421244088180202	South Lake S at Three Oaks at Crystal Lake, IL	South Lake southern SW	861.13
421220088175601	Franke Lake at Quarry at Crystal Lake, IL	Franke	847.49
421217088173301	Allendale Lake at Quarry at Crystal Lake, IL	Allendale	840.68
421132088175201	Big Lake Lake at Quarry at Crystal Lake, IL	Big Lake	823.51
421144088181501	Perch Lake Lake at Quarry at Crystal Lake, IL	Perch Lake	832.98

[1]Observation well equipped with pressure transducer to collect 15-minute continuous water-level data.

Table 2. Observation well-construction data for wells near the Three Oaks Recreation Area, Crystal Lake, Illinois.

[USGS, U.S. Geological Survey; Rd, Road; ?, unknown]

USGS station identification number	USGS station name	USGS field identifier	Land-surface elevation, in feet above North American Vertical Datum 1988	Measuring-point elevation, in feet above North American Vertical Datum 1988	Depth of open interval, in feet below land surface
421317088182301	43N8E-9.5f	South Lake well[1]	863.6	866.69	6–8.82
421320088181001	43N8E-9.3f	North Lake well	865.6	869.16	6–8.82
421244088180201	43N8E-9.2a	Rakow Rd well[1]	868	871.06	28–38
421143088180101	43N8E-21.2g	Storage-Well	834.6	836.709	?–21.5
421301088191501	43N8E-8.2c	8.2c[1]	900	899.7	41.1–46.1
421402088173501	43N8E-3.7d	3.7d	920	919.6	53.7–58.7
421228088160701	43N8E-14.5f	14.5f	870	869.5	53.2–58.2
421052088184101	43N8E-28.6g	28.6g	800	799.5	33.9–38.9

[1]Observation well equipped with pressure transducer to collect 15-minute continuous water-level data.

Analysis of Influences

Water-Level Responses to Precipitation Events

Daily precipitation data (fig. 8) were available from the Wastewater Treatment Plant 2 (The Weather Company, 2016). From April 14, 2016 to September 27, 2016, total precipitation was 22.06 in. Based on the area of North and South Lake (13,708,000 ft^2) and the amount of total precipitation (1.84 ft), the amount of rain added to South Lake at the TORA was 25,222,720 ft^3 for the period of study.

Precipitation events greater than 0.1 ft raised the water level at the South Lake and Rakow Rd wells by about 0.2 ft or greater. Water levels within the South Lake well increased rapidly by a few tenths of a foot after a precipitation event, but the increased water levels were followed by very rapid recession between precipitation events (fig. 9). The rapid water-level increase because of precipitation indicates the infiltration rate is fast and the recharge is a localized short path (Conlon and others, 2005). A rapid increase in water levels is expected because of the surficial geology of sand and gravel and the short distance the infiltrating rain must travel to reach the water table at this shallow well (8.82 ft below land surface).

Observation wells 8.2c and the Rakow Rd well are deeper (38 and 46.1 ft below land surface, respectively) with a larger unsaturated zone (height of soil above water table) than the South Lake well. Deeper wells with large unsaturated zones are generally less responsive to precipitation due to the greater distance the infiltrating water needs to travel. Water levels at observation well 8.2c show very little response to precipitation (fig. 10). Precipitation events larger than 0.10 ft, increased the water level at times by about 0.20 ft or less at this location. In addition, water levels decreased gradually between precipitation events. Water levels in Rakow Rd well showed a moderate response to precipitation during the period of record (fig. 11).

Water-level elevations at South Lake well can be considered a proxy for the uppermost column of surface water at South Lake due to its short distance (10 ft) to the shoreline and shallow depth (8.82 ft). The South Lake well water levels fluctuated between 861.33 ft to 861.72 ft above NAVD88 during April 14, 2016 to September 27, 2016. Water-level trends during the period of record showed an increase at South Lake well of 0.13 ft (fig. 9) and 0.63 ft at Rakow Rd well (fig. 11). The water levels at 8.2c ranged from 876.13 ft to 876.71 ft above NAVD88 and decreased by 0.58 ft during the period of record, indicating limited recharge from precipitation. South Lake well also had a greater decrease (–0.46 ft) in water elevation during a period with fewer precipitation events (June 13, 2016 to July 20, 2016) than the other two wells (well 8.2c and the Rakow Rd well). The larger fluctuations of water levels between precipitation events at South Lake and the smaller overall increase in water level for the period of record at South Lake well than at the other two wells may be indicative of the influence of evaporation. The water-level increase at the Rakow Rd well may be indicative of the seepage of surface water through the lakebed into the groundwater, along with flow surrounding TORA, precipitation and surface runoff. Therefore, it is possible that at least some of the gains at the Rakow Rd well could represent the loss of water from South Lake.

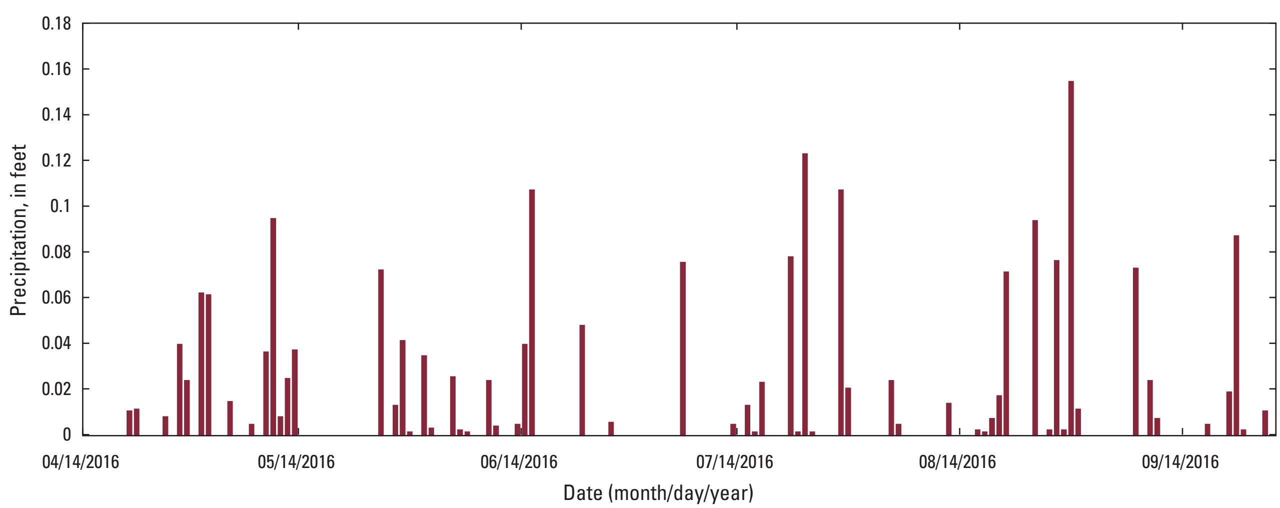


Figure 8. Daily precipitation data from the rain gage at the Crystal Lake Waste Water Treatment Plant 2 (WWTP2) near the Three Oaks Recreation Area, Illinois, April 14, 2016, to September 27, 2016.

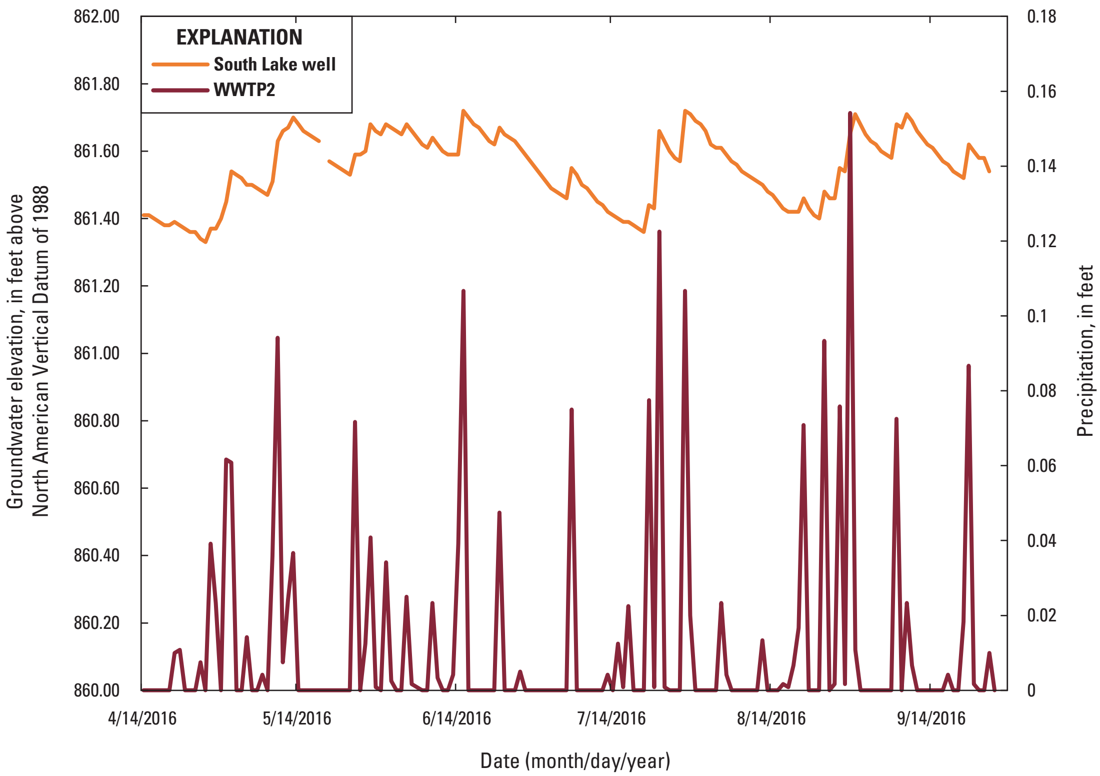


Figure 9. Daily water levels at South Lake well and daily precipitation from the Waste Water Treatment Plant 2 (WWTP2) rain gage, Crystal Lake, Illinois, from April 14, 2016, to September 27, 2016.

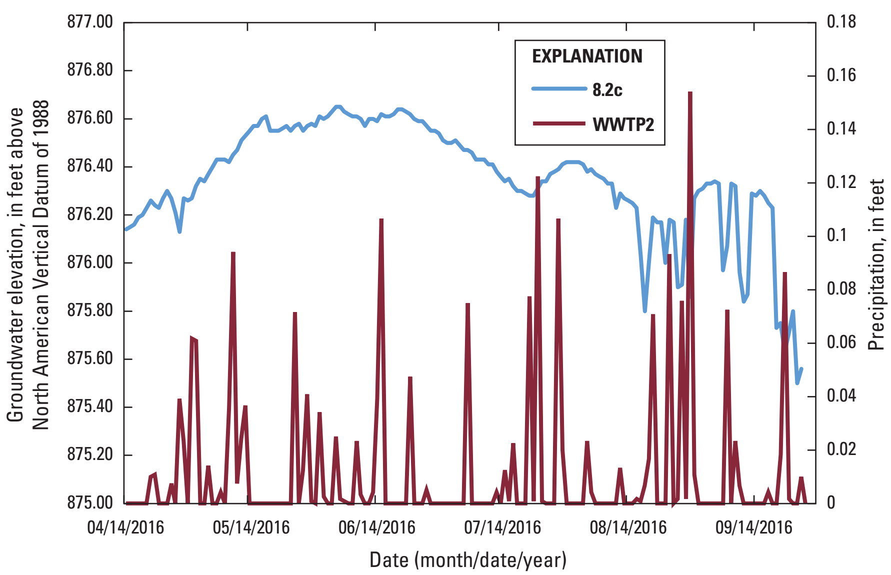


Figure 10. Daily water levels at well 8.2c and precipitation from the rain gage at Waste Water Treatment Plant 2 (WWTP2), in Crystal Lake, April 14, 2016, to September 27, 2016.

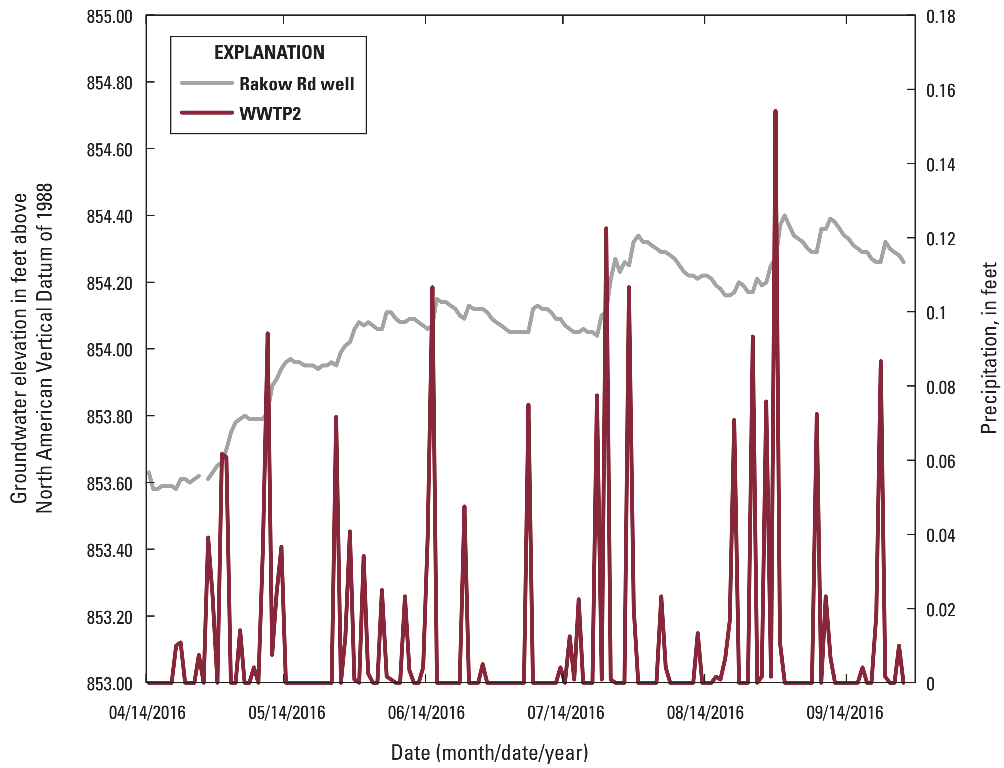


Figure 11. Daily water levels at the Rakow Road well and precipitation from the rain gage at Waste Water Treatment Plant 2 (WWTP2), in Crystal Lake, Illinois, April 14, 2016, to September 27, 2016.

Water-Level Responses to Withdrawals

In order to identify water-level responses related to the nearby withdrawals from the supply wells, total daily water withdrawal in gallons per day by the supply wells 12 and 13 were compared to the water levels at each well. These supply wells are open to the shallow bedrock aquifer and are not screened into the glacial aquifer. However, several areas throughout McHenry County show hydraulic connectivity between these two aquifers in areas where the till is absent (Meyer and others, 2013). These two supply wells pumped an average of 169,000 gallons of water per day and withdrew a total of 22,984,000 gallons from May 15, 2016, to September 27, 2016 (Crystal Lake Public Works Department written commun., December 2, 2016).

Minimal pumping influences were observed in observation well 8.2c throughout the period of study (fig. 12). The water-level drawdown caused by pumping, which was determined by comparing groundwater levels before and after the onset of pumping, is as little as a few hundredths of a foot (0.03 ft) and not a substantial influence on water levels at the TORA. Larger water-level changes were observed in 8.2c toward the latter half of the data collection effort from around August 12, 2016, to September 27, 2016, (fig. 12). These larger water-level changes did not coincide with withdrawals from the supply wells 12 and 13. The cause of these later water-level fluctuations could be related to other pumping influences, although there are no known residential or industrial pumping wells in this area. Pumping influences were not observed in South Lake well or Rakow Rd well.

Water-Level Responses to Quarry Operation Activities

Continuous water-level data collected from the South Lake well and Rakow Rd well did not show any instance of being directly affected by dredging operations at the downgradient quarry. However, indirect effects on the TORA water levels may occur as quarry operations continue to remove sand and gravel at Franke and expand vertically and horizontally at Allendale. The removal of additional sand and gravel at both Allendale and Franke will increase the permeability downgradient and further decrease the downgradient water elevations, which could then cause declining water levels at the TORA.

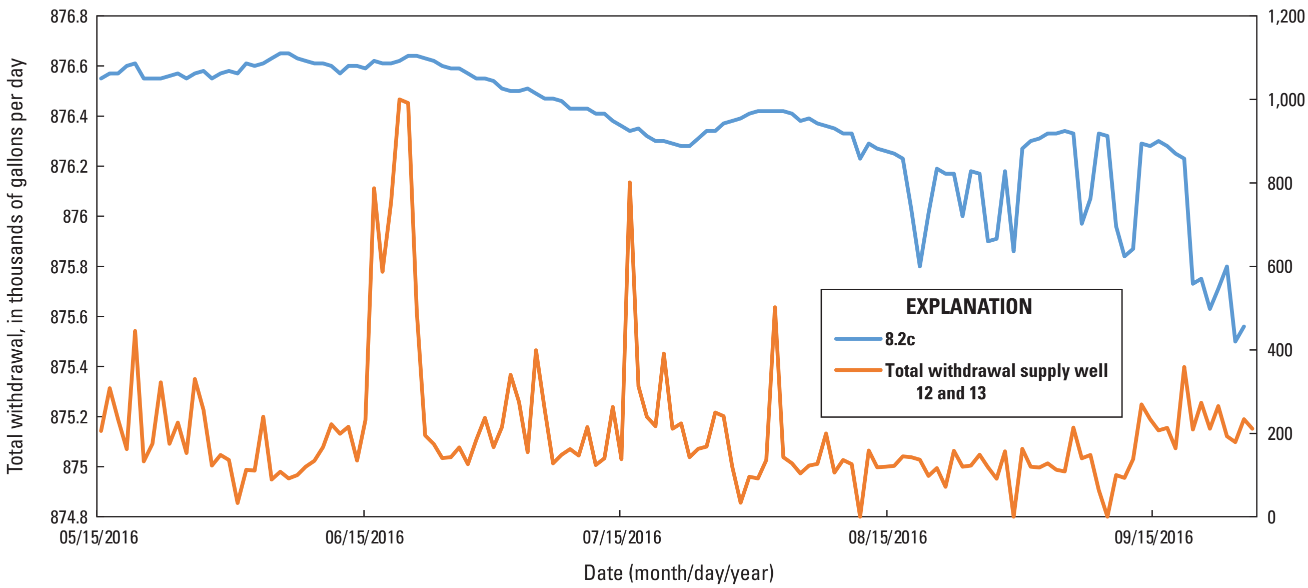


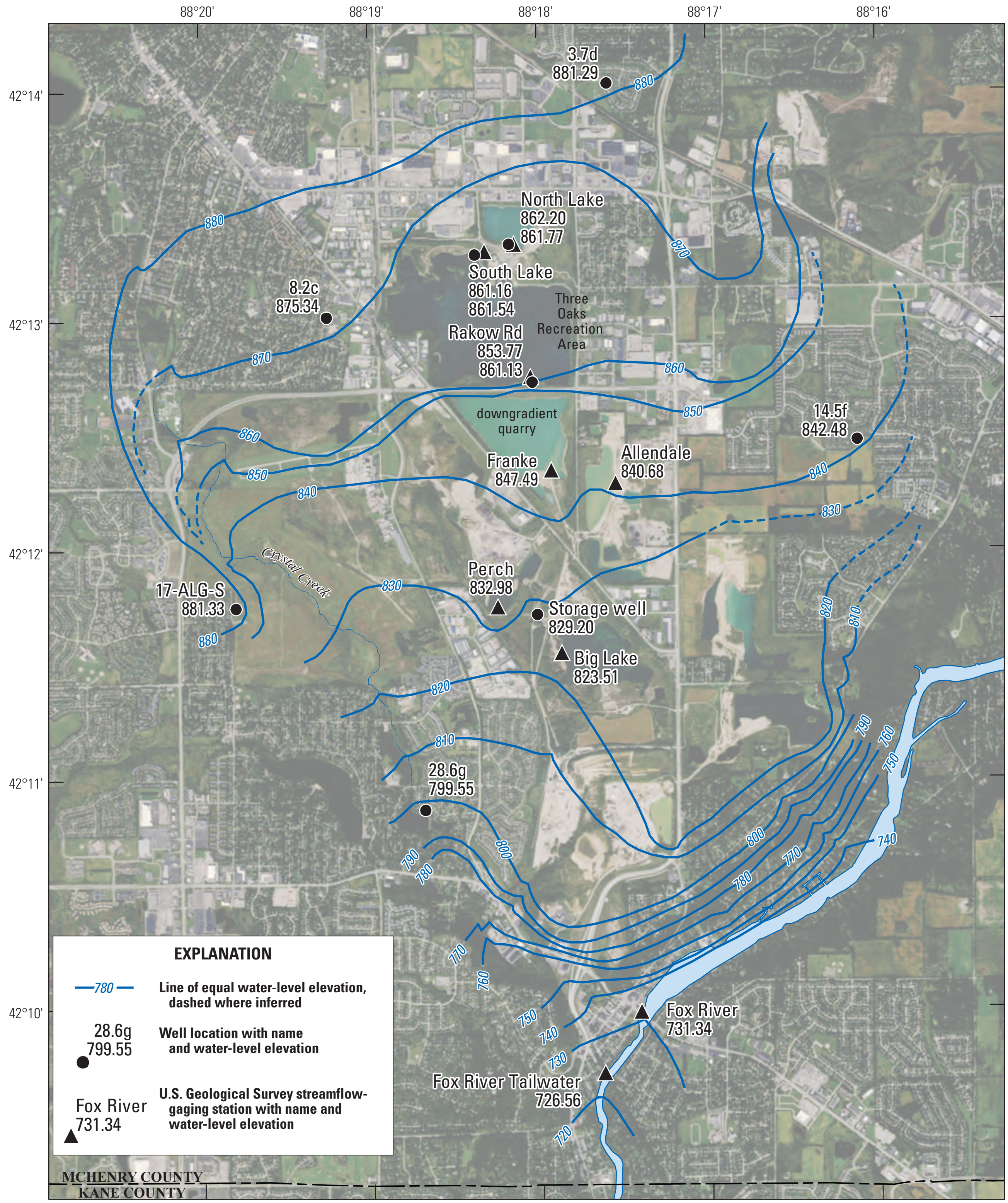
Figure 12. Daily water levels at observation well 8.2c and total daily pumping by supply wells 12 and 13 in Crystal Lake, Illinois, May 15, 2016, to September 27, 2016.

Water Levels and Quantification of Flow

Water-Table Map

On May 5, 2016, surface- and groundwater-level measurements were collected to create a water-table map to identify the groundwater flow direction and the horizontal hydraulic gradients (fig. 13). The water-level elevations were located on a map and lines of equal elevation were drawn between the points. Topographic elevation data from Google Earth Pro® were used to estimate the water-level elevation at ungaged creeks and along the steep slopes toward the Fox River. The direction of flow is perpendicular to the contoured lines. Groundwater flow direction is generally northwest to southeast toward the Fox River.

The difference in surface-water elevation between South Lake southern SW and Franke was 13.65 ft. The large difference was created in part by the removal of the sands and gravels at Franke that had previously provided the matrix for the groundwater to flow and to be stored. Removing the sand and gravel reduced the storage capacity of the aquifer and increased this hydraulic gradient and groundwater-flow velocity between the two surface-water bodies. The horizontal hydraulic gradient, or slope, of the water table in an unconfined aquifer is the change in water level over the distance between the two water levels along the direction of flow. It is a unitless value as it measures feet over feet. The horizontal hydraulic gradient affects the velocity of the water. There was one area where the water levels drop substantially within a relatively short distance. The horizontal hydraulic gradient between the surface-water elevation at the southern shoreline of South Lake and Rakow Rd well was calculated to be 0.29, where a 7.36 ft change in water-level elevation occurs over a distance of about 25 ft. The steep drop from the surface-water elevation to the groundwater over the short distance also indicates the presence of lower-permeable material such as clays, silts, and organics that act to reduce the flow of surface water infiltrating into the groundwater and exiting South Lake (Gandy and others, 2004). The lakebed of South Lake likely consists of fine-grained deposits that were stirred into suspension by previous quarry operations and subsequently settled out and formed a thin layer of clays and silts. The presence of fine-grained deposits was confirmed by the Illinois State Water Survey (ISWS) from sediment grab samples using a clamshell sampler dropped from a boat collecting 13 samples of lakebed sediment from South Lake at various locations about 30 ft from the southern shoreline. The clamshell sampler can only collect up to about 4 in. of sediment from the lakebed, therefore the full thickness of the lakebed material is unknown. The ISWS also confirmed that at the areas away from the shoreline of South Lake, the lakebed (at least the upper 4 in. of the lakebed) consist of clay, silts, and organic matter, whereas coarser materials (sands and gravels) were predominately found toward the shoreline (Illinois State Water Survey, oral commun., 2016).



Base map image is the intellectual property of Esri and is used herein under license.

Datum of measured water-level elevations is in feet above the North American Vertical Datum of 1988.
Inferred water-level elevations were estimated from topographic elevation data from Google Earth Pro®

0 0.25 0.5 0.75 1 MILE
0 0.25 0.5 0.75 1 KILOMETER

Figure 13. Water-table map in the vicinity of the Three Oaks Recreation Area, Crystal Lake, Illinois, May 5, 2016.

Additionally, the USGS used a handheld auger to collect geologic samples to a depth of nearly 2 ft at three locations along South Lake's shorelines near the Rakow Rd well. The uppermost 4 to 6 in. of the shorelines augured were coarse-grained sand with some clays that progressed to sand and gravel with less clay at depth, indicating that fine-grained deposits line the lakebed but the upper portion near the shoreline has less clay. This is because waves and scour may stir up the clays and silts lining the southern shoreline of South Lake allowing the upper portion to be more permeable than the lower portion of the lakebed. It should be noted that the northern shoreline is also subject to having more permeable sediments than areas of the lakebed away from the shoreline. This is in part because of beach activities along the northern shoreline, and the steep bathymetry (fig. 3) along much of the eastern half of South Lake, potentially limiting the deposits of fine-grained material. Along the southern shoreline of South Lake, the areas of thin or absent clays and silts in the upper portion of the southern shoreline would create a preferential flow path to the underlying coarser materials for the surface water to infiltrate into the groundwater along James Rakow Rd and into Franke. The thickness and distribution of this upper portion of coarser materials is unknown. Figure 14 illustrates how effectively the low-permeable layer at the bottom of South Lake impedes groundwater flow toward Franke. Note the steep drop-off in water level from South Lake to Rakow Rd well. This represents the higher hydraulic gradient at this location.

Groundwater Flow

The horizontal hydraulic conductivity (Kh) controls the rate at which fluid will transport horizontally through the geology. The Kh was determined from single well aquifer tests, referred to hereafter as slug-tests, in an effort to calculate the rate of groundwater flow in and out of the TORA from South Lake. Tests were done at the Rakow Rd on April 26, 2016, and on May 20th, at South Lake and 8.2c wells by USGS personnel. Slug-tests were conducted following guidelines and selected procedural guidelines for conducting an instantaneous change in head test with a mechanical slug and submersible pressure transducer presented in Groundwater Technical Procedures Document GWPD 17 (Cunningham and Schalk, 2011). Water levels of the slug tests at Rakow Rd well had an oscillatory response, which were analyzed using the KGS-High K option in a spreadsheet provided by Keith Halford (U.S. Geological Survey, written commun., 2016) based on methods described in Butler and others (2003). The other two slug-test results were analyzed with the Bouwer and Rice (1976) method for determining hydraulic conductivity in an unconfined aquifer. The saturated aquifer thickness at South Lake and Rakow Rd well was estimated to be 55 ft thick for the saturated sand and gravel, and 48 ft at the 8.2c well. The average Kh of the Haeger-Beverly aquifer north and west of the TORA is one to two orders of magnitude lower than the Kh of the Haeger-Beverly aquifer to the south of the TORA along Rakow Rd (table 3).

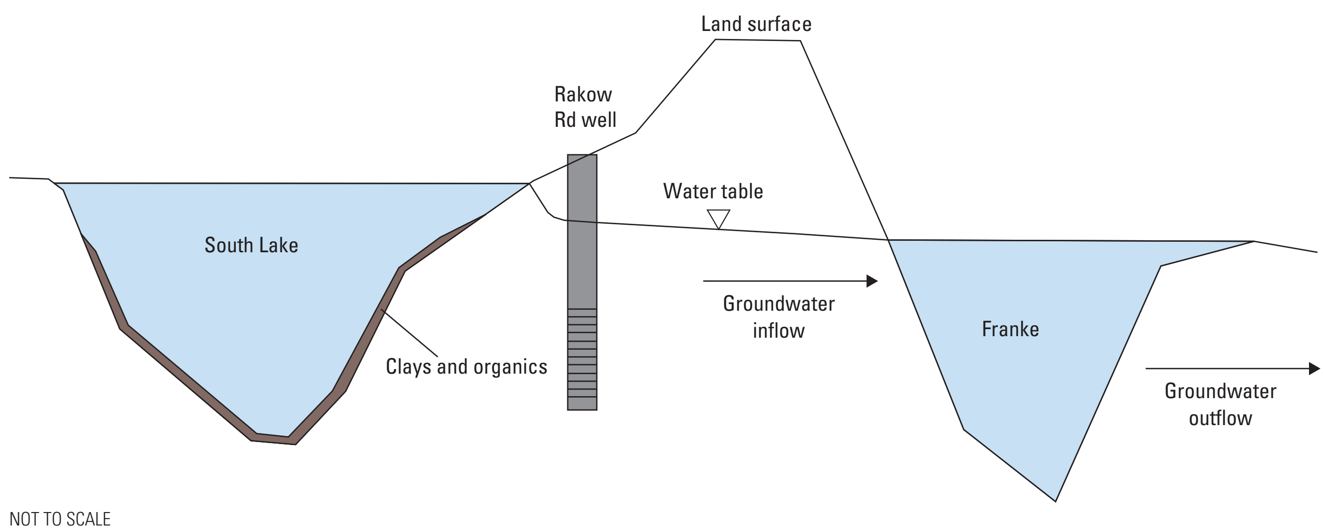


Figure 14. Conceptual illustration of water levels at South Lake of the Three Oaks Recreation Area and the downgradient quarry, in Crystal Lake, Illinois.

Table 3. Horizontal hydraulic conductivity calculated from single well aquifer tests (slug tests) at select wells surrounding the Three Oaks Recreation Area, Crystal Lake, Illinois.

[USGS, U.S. Geological Survey; Rd, Road; ft, feet]

USGS station identification number	USGS station name	USGS field identifier	Average horizontal hydraulic conductivity, in ft/day
421317088182301	43N8E-9.5f	South Lake well	78
421244088182301	43N8E-9.2a	Rakow Rd well	115
421301088191501	43N9E-8.2c	8.2c	2.95

The velocity (V) of groundwater flow through the aquifer was determined from equation (1) by using water levels between paired observation wells and surface-water sites (table 4).

$$V = KhI/n \tag{1}$$

where,

- V is the velocity or rate of the groundwater flow, in feet per day;
- Kh is the horizontal hydraulic conductivity of the aquifer, in feet per day;
- I is the gradient (change in water-level elevation divided by distance), in foot per foot; and
- n is the porosity of the aquifer material through which the groundwater flows (0.38).

Previous studies indicate that the estimated porosity average for sand and gravel is 0.38 (Morris and Johnson, 1967). The estimated rate of groundwater entering from the north at South Lake well into South Lake surface water was 8.21 feet per day (ft/day) and from the west at well 8.2c into South Lake surface water was 0.02 ft/day (table 4). The velocity of groundwater flow to Franke from South Lake surface water was estimated to be about 12.11 ft/day (table 4). However, that velocity does not account for the lower permeable material such as silts, clays, and organics that line much of South Lake's lakebed. The lower permeable materials would act to limit the horizontal flow out of the flow-through lake to the upper part of the lakebed through the more permeable material. Also, because the Kh of the native sand and gravel north and west of the TORA is lower than it is at Rakow Rd, the effect of the sediments may have less influence on the velocity (and volume of inflow) than they would on the south side.

The Kh of the fine-grained material was not directly measured by the USGS. However, seepage meter measurements were collected by the ISWS and resulted in an average discharge (Q) of 0.22 ft^3/day (Illinois State Water Survey, written commun., 2016). The Kh was calculated by rearranging the Darcy equation (equation 2) to solve for Kh (Kh = Q/(A*I). There were no water levels collected at the time of the seepage measurement. Therefore, the water levels collected on May 5, 2016, were substituted to estimate the hydraulic gradient (I) which is the difference in water levels between South Lake southern SW and Rakow Rd well (7.36 ft) divided by the distance between the two locations (25 ft); A is the average area of the seepage meters, 2.76 ft^2 (ISWS, written commun., 2016). The calculated Kh of the fine-grained deposits was 0.27 ft/day. As a result, the velocity of the water transported from South Lake surface water to Rakow Rd well through the fine-grained deposits was about 0.21 ft/day (table 4). However, there may be areas of thin or absent clays where the Kh returns to that measured at Rakow Rd well of 115 ft/day. These areas are likely in the upper portion of the lakebed where wave action and scour stir up the clays and silts. This stirring can create a preferential flow path where greater amounts of lake water can drain toward the downgradient quarry.

Table 4. Velocity of groundwater flow calculations within the vicinity of the Three Oaks Recreation Area, Crystal Lake, Illinois.

[ft, feet; ft/ft, feet per feet; ft/day, feet per day; SW, surface water; Rd, Road]

Segment description	Distance, in ft	Difference in water elevation, in ft	Horizontal hydraulic gradient, in ft/ft	Horizontal hydraulic conductivity, in ft/day	Porosity for sand and gravel	Groundwater velocity, in ft/day
South Lake well to South Lake northern SW	10	0.39	0.04	78	0.38	8.21
8.2c to South Lake southern SW	5,756	14.21	0.002	2.95	0.38	0.02
South Lake southern SW to Rakow Rd well	25	7.36	0.29	0.27 [1]	0.38	0.21
Rakow Rd well to Franke	475	6.28	0.01	115	0.38	3.03
South Lake southern SW to Franke	500	13.66	0.04	115	0.38	12.11

[1]Illinois State Water Survey hydraulic conductivity applied to account for low-permeable clays and organics lining the lakebed.

Groundwater, surface water-level measurements, and *Kh* were used to calculate the volume of discharge from groundwater into South Lake and recharge from South Lake into groundwater by the solution of the Darcy Equation (Fetter, 1988). The Darcy Equation is:

$$Q = KhAI \tag{2}$$

where,

Q is the discharge, into or out of the lake, in cubic feet per day;

Kh is the horizontal hydraulic conductivity of the geologic deposits transmitting water and is equal to the mean value determined from the rising-head slug tests. *Kh* values were divided into the separate areas to fully characterize the rate of groundwater inflow and outflow at the South Lake of TORA. South Lake well *Kh* was 78 feet per day (ft/day), 8.2c well *Kh* was 2.95 ft/day, and Rakow Rd well *Kh* was 115 ft/day. The *Kh* (0.27 ft/day) from South Lake southern SW to Rakow Rd well was applied to estimate the discharge of the lake through the lakebed toward Rakow Rd well;

A is the cross-sectional area of flow between the aquifer and the lake and is equal to the length of the lakeshore along which water is being recharged or discharged multiplied by the maximum depth of the lake, 41 ft (Vic Santucci, written commun., 2006), in square feet; and

I is the horizontal hydraulic gradient, the difference in the water levels between the lake and wells divided by the distance between the well and the lakeshore, in foot per foot.

The surface-water and groundwater elevations measured on May 5, 2016, for groundwater entering (inflow) (South Lake well to South Lake northern SW and monitoring well 8.2c to South Lake southern SW) and the surface-and-groundwater exiting (outflow) TORA (South Lake southern SW to Rakow Rd well) were used to calculate the volumes of water for the period of record. Distance between the two points for the inflow to TORA from the north and west and the groundwater exiting the TORA along Rakow Rd were determined using the distance (length) measurement tool in Google Earth Pro®.

The volume of water entering and exiting the TORA per day was estimated from the Kh, horizontal hydraulic gradient, length of the north and south shorelines, maximum depth of South Lake (41 ft), as well as the area of the transect along flow direction of shoreline for inflow and outflow. The volume of flow for the period of record was estimated by multiplying the volume of flow per day by 167 days. Therefore, quantified volume for the period of record does not take into account changes in water levels that occurred between April 14 and September 27, 2016. The total inflow was subtracted from the total outflow and the difference represents the calculated change in storage at South Lake. The difference was divided by the surface area of south lake (12,270,852 ft^2) to convert the change in storage to the change in water level, in feet, for the period of record. The calculated change in water level was compared to the measured change in water level for South Lake of 0.13 ft, represented by South Lake well. Applying the maximum depth of lake (equation 2) resulted in volumes that were largely overestimated. Inflow was 164,778,327 ft^3 and outflow was 32,592,405 ft^3 over the period of 167 days. The difference (132,185,922 ft^3) was divided over the surface area of South Lake and resulted in a calculated change in feet of 10.77 ft for the period of record. The measured change in water level at South Lake was 0.13 ft and therefore, it was necessary to attempt to determine the thickness of the coarse-grained deposits where the preferential flow may be occurring. Revised volumes were determined by changing the maximum depth of South Lake (ft) for the segments with Kh of 78 ft/day and 115 ft/day to determine the potential thickness of the coarse-grained deposits not impeded by the fine-grained deposits. The thickness of the maximum depth was iteratively adjusted in only whole numbers until the calculated change in water level for the period of record was closer to the measured change in water level (0.13 ft). The refined results (table 5) indicate that the estimated thickness of the coarse-grained deposits is about 1 foot with a calculated change in water level of 0.25 ft, which is comparable to the measured change in water level of 0.13 ft. The volume of groundwater entering TORA each day was 5,915,102 ft^3/d, from the north and west, while the volume of outflow from the TORA along the south and east was 2,863,065ft^3 for the period of record (table 5; fig. 15).

The total volume of South Lake is 234,540,000 ft^3. The inflow from groundwater accounts for 3 percent while the outflow was 1 percent of the volume of South Lake. Inflow into South Lake was 52 percent greater than the outflow from South Lake. Evaporation exceeded precipitation by 14 percent. The lower permeable material creates an impediment that acts to slow down the rate at which the surface water at South Lake flows to Franke and may account for the difference in head between the two lakes. Additionally, the groundwater entering the TORA, based on these calculations, exceeds the amount of groundwater leaving the TORA likely because of the larger shoreline along the north and west of South Lake. Groundwater exits South Lake along the southern shoreline, which has a length that is about 40 percent smaller than the northern shoreline.

Table 5. Volume of flow calculations for the inflow and outflow of groundwater using horizontal hydraulic conductivity values from slug test data at the Three Oaks Recreation Area, Crystal Lake, Illinois.

[ft, feet; ft/ft, feet per feet; ft^2, feet squared; ft/day, feet per day; ft^2/day, feet squared per day; ft^3/day, cubic feet per day; SW, surface water; Rd, Road]

Segment description	Horizontal hydraulic conductivity, in ft/day	Product of horizontal hydraulic gradient and horizontal hydraulic conductivity, in ft^2/day	Length of lakeshore through which flow is occurring along flow transect, in ft	Maximum depth of South Lake, in ft	Area of transect along flow direction, in ft^2	Volume of flow, in ft^3/day	Volume in ft^3 for period of record (167 days)
Inflow							
South Lake well to South Lake northern-SW (coarse-grained deposits lining the lakebed)	78	3.04	7,823	[2]1	7,823	23,782	3,971,581
South Lake well to South Lake northern-SW (fine-grained deposits lining the lakebed)	[1]0.27	0.03	7,823	41	320,743	9,622	1,606,922
8.2c to South Lake southern-SW	2.95	0.01	4,916	41	201,556	2,016	336,599
Outflow							
South Lake southern-SW to Rakow Rd well (fine-grained deposits lining the lakebed)	[1]0.27	0.08	3,870	41	158,670	12,694	2,119,831
South Lake southern-SW to Rakow Rd well (coarse-grained deposits lining the lakebed)	115	1.15	3,870	[2]1	3,870	4,451	743,234
					inflow	5,420	5,915,102
					outflow	17,144	2,863,065
					difference	18,276	3,052,037

[1]Illinois State Water Survey hydraulic conductivity applied to account for low-permeable clays and organics lining the lakebed.

[2]Estimated thickness of sand and gravel in the upper portion of South Lake along the shoreline.

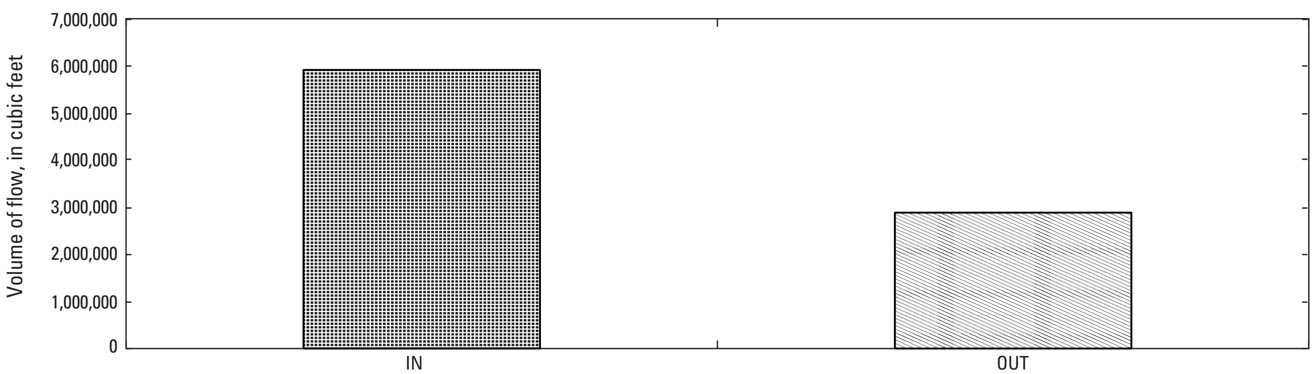


Figure 15. Volume of water entering and exiting the Three Oaks Recreation Area, Crystal Lake, Illinois, April 14, 2016, to September 27, 2016.

It is important to note that these values are generalized estimates because certain key water-balance components were not directly measured. These include: site-specific evaporation, surface-water runoff, inputs from the culverts that directly drain the surface-water runoff into South Lake, hydraulic conductivity of the low-permeable material lining the lakebed, and that the seepage measurement from the ISWS was only completed along the southern shoreline and results were assumed to be the same along the northern shoreline of South Lake. Additionally, the adjusted thickness for the coarse-grained deposits as determined by the calculations may not be the same along northern input segments as is it along the southern output segments. A full water-balance was outside the scope of this report. This study did not detect pumping influences or direct influences from the downgradient quarry. Therefore, these general estimations indicate that evaporation may be the predominant hydrologic influence on the TORA as it was estimated to have removed 14 percent more water than what precipitation added. Still, groundwater inflow exceeded the outflow to balance the losses to evaporation and outflow as shown by the measured increase in water level for the period of record. It is possible that prolonged periods of drought would be especially problematic given the loss of water to evaporation accounts for 11 percent of the volume of water of TORA.

To improve the generalized estimates, a full water balance study would help identify the effective depth and width of the lake bathymetry's sand and gravel deposits where horizontal flow occurs. Additionally, aquifer properties can be used in a groundwater model to further refine the volumes entering and exiting the TORA and to evaluate the effects of future changes in precipitation and the downgradient quarry operations.

Summary

Hydrologic influences were investigated at a former sand-and-gravel quarry that was converted to a recreational lake area in Crystal Lake, Illinois. From 2009 to 2014, average water levels have declined nearly 4 feet. It was not clear if these declines were related to variations in weather (precipitation or evaporation) or other hydrologic influences such as municipal supply pumping or quarry operations. Data were collected using three approaches to determine the possibility of such hydrologic influences. First, water levels were collected at 15-minute intervals at three wells equipped with pressure transducers from April 14 through September 27, 2016. The continuous data allowed for the assessment of responses to precipitation, pumping influences, and quarry operations. Second, a single day synoptic water-level survey was completed to create a water-table map for the determination of groundwater flow directions. Third, single-well aquifer tests (slug tests) were completed on the three data-collection wells to estimate horizontal hydraulic conductivity of the aquifer. Collectively, these data were used to estimate the velocity and volume of water entering and exiting the Three Oaks Recreation Area (TORA).

The groundwater-level responses to precipitation at South Lake well and Rakow Road (Rd) well were rapid and show that the water-level increases after precipitation events. The increase in water level was quickly lost to discharge, but overall gains during the period of record (April 14 through September 27, 2016) were observed in the South Lake well (0.13 ft) and Rakow Rd well (0.63 ft). There were minimal to no pumping influences from the nearby municipal supply wells open to the shallow bedrock aquifer evident in the hydrographs. There were also no direct hydrologic influences from the downgradient quarry observed in the hydrographs. However, indirect hydrologic influences from the downgradient quarry may occur if water levels at the quarry decline due to additional removal of the sand and gravel that acts to slow and retain the groundwater flow. The decline in water levels will increase the hydraulic gradient between the TORA and the Franke and Allendale quarry pits, which could cause water loss at the TORA.

Water-level elevations at South Lake well can be considered as a proxy for the uppermost column of surface water at South Lake. The larger fluctuations of water levels and the relatively smaller increase in water levels over the period of record at South Lake well compared to Rakow Rd well may indicate the influence of evaporation. The Rakow Rd well represents the average water level between the South Lake water level and Franke water level. At least some of the gains at Rakow Rd well could be the result of water loss from South Lake.

The synoptic water-level survey indicated that the groundwater flow direction is from northwest to southeast. There was one instance where the horizontal hydraulic gradient (0.29) was much greater than at any other location. This instance indicates a presence of lower-permeable material such as clays, silts, and organics that act to reduce the flow of surface water infiltrating to the groundwater and exiting South Lake. Higher horizontal hydraulic gradients can increase the flow velocity at which water is moved through the system.

The velocity of the groundwater entering the TORA at South Lake was 48 percent less than the velocity exiting the TORA. The volume of groundwater entering South Lake was estimated to be 52 percent greater than the water exiting South Lake along the southern shoreline toward Rakow Rd well. The longer shoreline to the north and lower-permeable materials act as a bottleneck that reduces the volume of flow exiting South Lake into Franke and may explain the difference in head between TORA and the downgradient quarries. Groundwater entering South Lake accounted for about 3 percent of the total volume of water at South Lake, while surface water exiting South Lake to Rakow Rd well and to Franke accounted for 1 percent of the total volume of South Lake. The water-level increase of 0.13 ft measured over the period of record at South Lake well was comparable to the calculated increase of 0.25 ft from the volumetric flow calculations and differences were likely due to assumptions and other unaccounted-for preferential flow paths and water balance components.

In general, water-level measurements show that direct influences from pumping or quarry operations were not observed, and comparisons of inflow and outflow show that evaporation may be the dominant hydrologic influence at the TORA. Therefore, TORA would be particularly vulnerable to prolonged periods of drought. A full water balance study would help identify the effective depth and distribution of the lake bathymetry's sand and gravel deposits where horizontal flow occurs. Additionally, aquifer properties can be used in a groundwater model to further refine the volumes entering and exiting the TORA and to evaluate the effects of future changes in precipitation and the downgradient quarry operations.

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