Prepared in cooperation with the National Park Service

# Hydrologic Data and Groundwater-Flow Simulations in the Brown Ditch Watershed, Indiana Dunes National Lakeshore, Near Beverly Shores and Town of Pines, Indiana

Scientific Investigations Report 2015–5141

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

USGS Stream Gage Brown Ditch at Beverly Shores, IN (USGS 04095154), taken on June 11, 2013, by David C. Lampe.

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SALLY JEWELL, Secretary

**U.S. Geological Survey**
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

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## Figures

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# Conversion Factors

[Inch/Pound to International System of Units[

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Flow rate | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3/d$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| inch per month (in/month) | 25.4 | millimeter per month (mm/month) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | Mass | |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| | Pressure | |
| pound per square inch ($lb/in^2$) | 6.895 | kilopascal (kPa) |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | Hydraulic gradient | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as:
°C = (°F – 32) / 1.8.

# Datum

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

Selected altitudes include a reference to the National Geodetic Vertical Datum of 1929 (NGVD 29), as specifically described in the report text.

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

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

Time is referenced to Eastern Standard Time.

# Abbreviations and Acronyms

| | |
|---|---|
| CSS | composite scaled sensitivities |
| IDNR | Indiana Department of Natural Resources |
| INDU | Indiana Dunes National Lakeshore |
| $K_h$ | horizontal hydraulic conductivity |
| ks | surficial sand aquifer |
| $K_v$ | vertical hydraulic conductivity |
| lidar | light detection and ranging |
| NOAA | National Oceanic and Atmospheric Administration |
| NPS | National Park Service |
| PVC | Polyvinyl chloride |
| RMSE | root mean square error |
| USGS | U.S. Geological Survey |

# Hydrologic Data and Groundwater-Flow Simulations in the Brown Ditch Watershed, Indiana Dunes National Lakeshore, Near Beverly Shores and Town of Pines, Indiana

By David C. Lampe

## Abstract

The U.S. Geological Survey (USGS) collected data and simulated groundwater flow to increase understanding of the hydrology and the effects of drainage alterations on the water table in the vicinity of Great Marsh, near Beverly Shores and Town of Pines, Indiana. Prior land-management practices have modified drainage and caused changes in the distribution of open water, streams and ditches, and groundwater abundance and flow paths.

Collected hydrologic data indicate that the majority of water entering Great Marsh flows from the southern dune ridge beneath Town of Pines, Indiana. Groundwater flow is intercepted by Brown Ditch in the eastern portion of the study area and Derby Ditch in the western portion of the study area. A smaller amount of groundwater from the northern dune ridge beneath Beverly Shores also contributed water to Great Marsh. Continuous groundwater-level data collected indicate that the predominant north-south groundwater-flow gradients vary during the course of the year due to increased levels of precipitation or during periods of drainage obstructions. Continuous surface-water discharge and surface-water elevation were measured at three USGS streamgages, one each on Brown, Kintzele and Derby Ditches. The monthly mean discharge statistics indicate that during the period of record—June 2012 to September 2013—streamflow in Kintzele Ditch was lowest during July 2012 and highest during April 2013. In Derby Ditch, streamflow also was lowest during July 2012 and highest during April 2013.

Periods of relatively high and low groundwater levels during August 1982, March 2013, and April 2014 were examined and simulated by using MODFLOW and companion software. Results from the simulation of conditions during March 2013 include that nearly 100 percent of all water entering the area simulating Town of Pines is from recharge. Of all the water simulated to enter the eastern and western portions of Great Marsh, nearly 20 and 18 percent, respectively, flows from Town of Pines to the western and eastern portions of Great Marsh. The dune ridges beneath Town of Pines and to a lesser extent beneath Beverly Shores are a major source of recharge to the surficial aquifer and Great Marsh.

Results from the simulation of the conditions of April 2014 include that, despite increases in the amount of water entering Great Marsh due to a beaver-dam-modified hydrologic condition, there is still virtually zero simulated groundwater flow from Great Marsh to Town of Pines. The volume of water simulated to be entering the zone representing Beverly Shores decreased by 0.43 cubic foot per second from the results of the March 2013 simulation. This simulated difference in water budgets can be attributed to increased simulated recharge in Great Marsh and Town of Pines. Effects of the inclusion of the beaver dam included the increase of the simulated water table and simulated inundated area upstream of the beaver dam due to the effects of ponding surface water.

Results from the simulation scenario that includes six proposed pool-riffle control structures in Brown Ditch under the hydrologic conditions of March 2013 indicate areas inundated by water are larger, including areas just to the north of the entrance of Brown Ditch into Great Marsh, and areas north of the confluence of Brown and Kintzele Ditches.

Results from the scenario simulating the increase of the Lake Michigan water level to the historical high of May 31, 1998, showed inundated areas of Great Marsh south of Beverly Shores enlarged on both sides of Lakeshore County Road with the greatest enlargement simulated to be southeast of the intersection of Lakeshore County Road and Beverly Drive. For the scenario simulating the decrease of the Lake Michigan water level to the historical low of December 23, 2007, results show little change from the original March 2013 inundated area.

The results of this study can be used by water-resource managers to understand how surrounding ditches affect water levels in Great Marsh and other inland wetlands and residential areas. The groundwater model developed can be applied to answer questions about how alterations to the drainage system in the area affects water levels in the public and residential areas surrounding Great Marsh. The modeling methods developed in this study provide a template for other studies of groundwater flow and groundwater/surface-water interactions within the shallow surficial aquifer in northern Indiana, and in similar hydrologic settings that include surficial sand aquifers in coastal areas.

# Introduction

The Indiana Dunes National Lakeshore (INDU) was formally established in 1973 as part of a continuing effort to preserve the dunes and wetlands along the southern shore of Lake Michigan in northwestern Indiana (fig. 1). The National Park Service (NPS) is charged with preserving and managing the aesthetic, scientific, and recreational resources of the INDU. Industrial and urban development during the 19th and 20th centuries has substantially modified the study area. Changes to the natural drainage system and other cultural disturbances have affected the hydrology of the lake-wetland complex in the vicinity of Great Marsh near the town of Beverly Shores and Town of Pines (fig. 2). The NPS and other resource managers in the area require an improved understanding of the hydrology in the vicinity of Great Marsh in order to understand the effects of drainage alterations on the water levels of Great Marsh and on the water table in the neighboring residential areas.

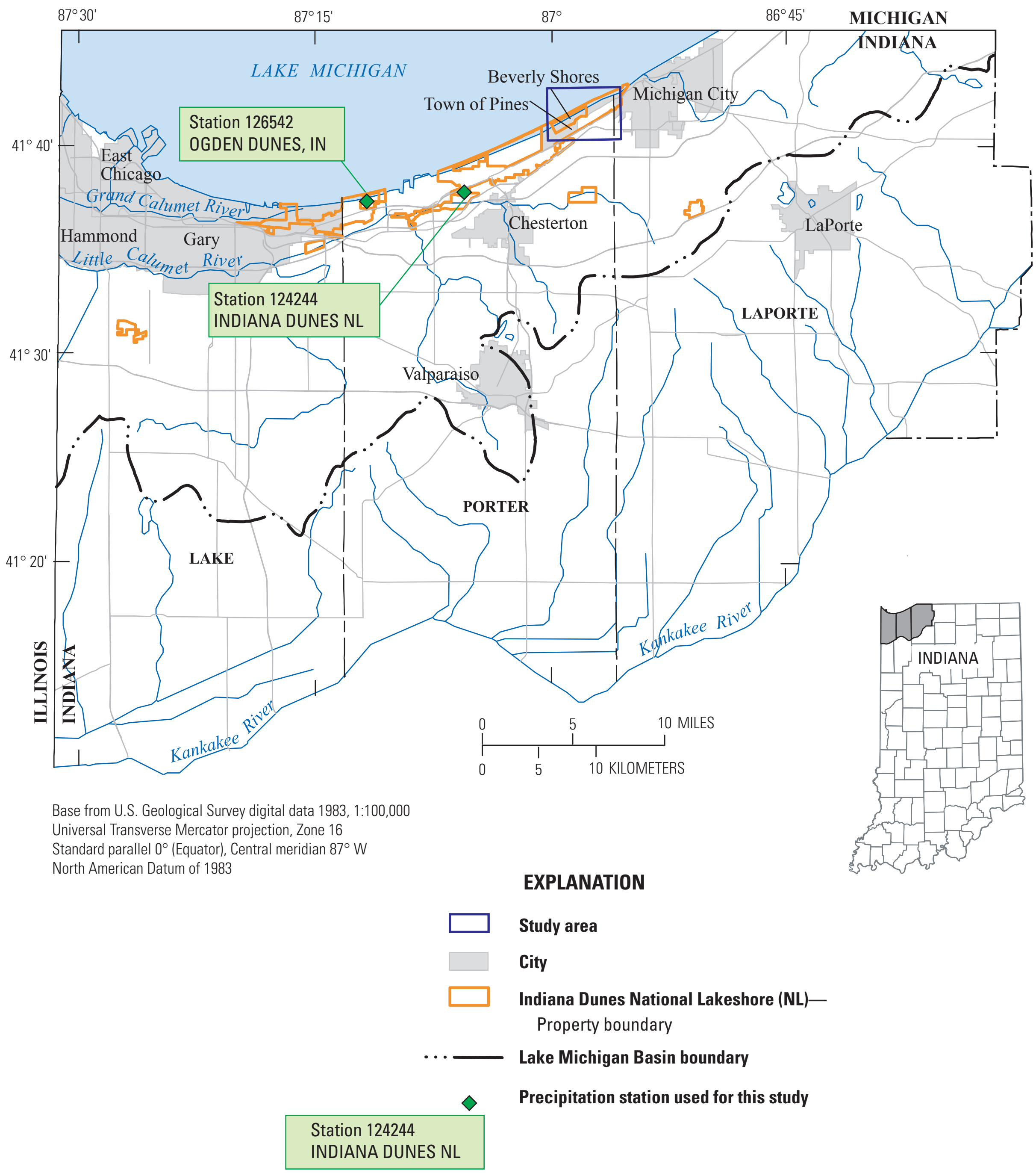



**Figure 1.** Location of study area, Lake Michigan Basin, and weather stations near the Indiana Dunes National Lakeshore, northwestern Indiana.

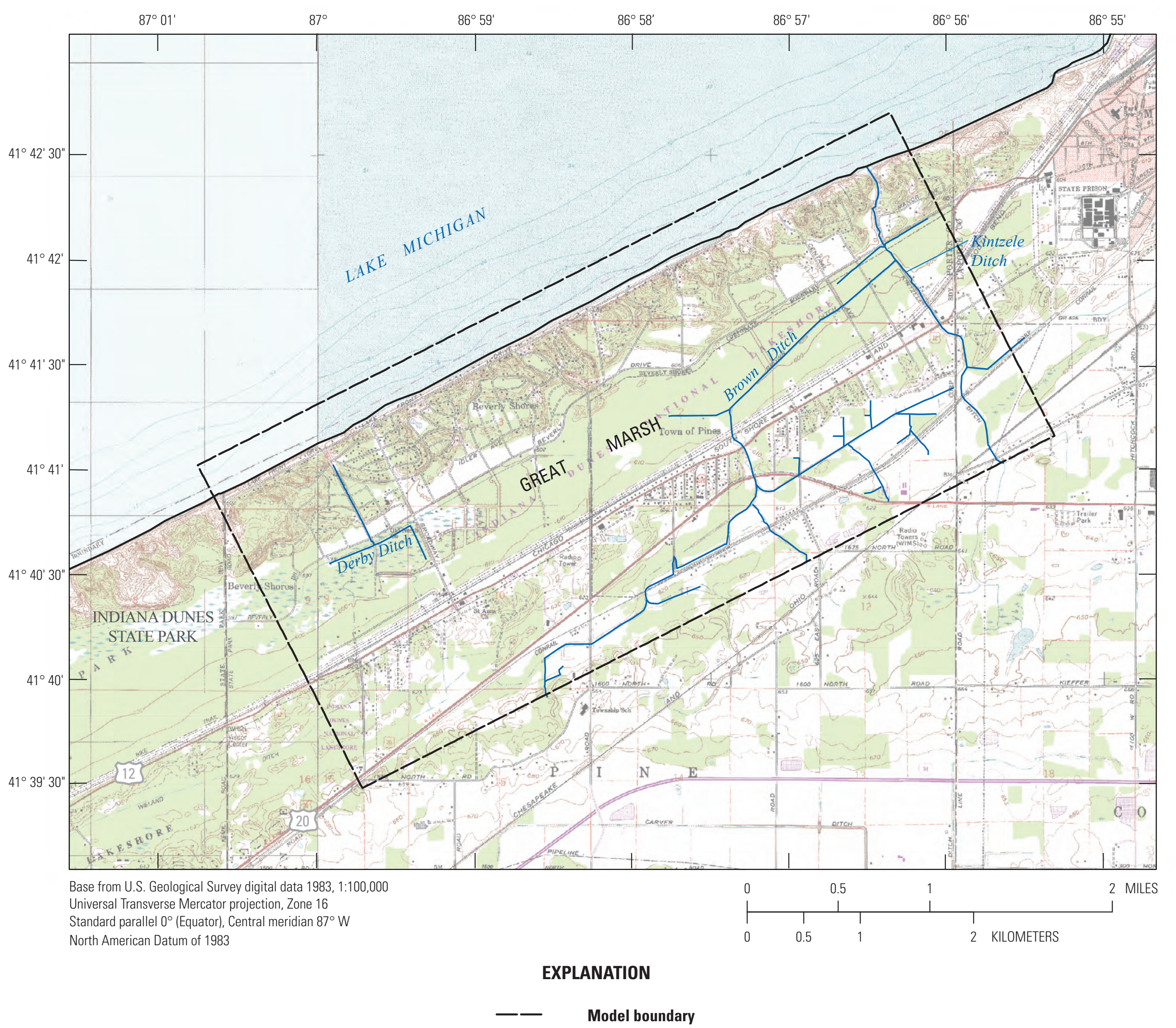



**Figure 2.** Location of study area and surrounding hydrologic and cultural features near the Indiana Dunes National Lakeshore, northwestern Indiana.

The U.S. Geological Survey (USGS) provides reliable scientific information to describe the interaction of hydrologic systems and assists in understanding their effects on natural lands and adjacent property. In most instances, these efforts involve documenting and analyzing the effects of widely recognized phenomena such as surface-water and groundwater flow and quality. On occasion, they involve relatively small-scope studies of previously unrecognized phenomena, such as the use of groundwater-flow simulations to understand interactions of changes in groundwater drainage with wetland water levels and the potential for groundwater flooding. The USGS works within its strategic science direction and with its partner organizations, such as the NPS, to document these emerging hazards and to ensure that scientific methods are applied effectively to better understand these phenomena at INDU and in similar hydrologic settings that include surficial sand aquifers in coastal settings.

The USGS, in cooperation with the NPS, has been studying flow and water quality in the surficial aquifer at INDU since 1973. The USGS initially studied the area in cooperation with the NPS to determine shallow groundwater flow and the effects of drainage modification in reaches of Brown Ditch on water levels within the surficial sand aquifer in INDU and Town of Pines (Shedlock and Harkness, 1984).

That evaluation used a two-dimensional finite-difference groundwater-flow model. During 2007–10, the USGS, in cooperation with the NPS, investigated the effect of natural and human-affected hydrologic processes on changes in groundwater and surface-water levels and groundwater-flow directions in nearby parts of a dune-beach complex in and around Beverly Shores, Indiana (Buszka and others, 2011). In May 2012, the USGS initiated an investigation in cooperation with the NPS to evaluate the hydrology in the vicinity of Great Marsh that included measurement of surface-water and groundwater levels, the measurement of continuous discharge from Brown and Kintzele Ditches, and development of a steady-state groundwater-flow model similar to that documented by Shedlock and Harkness (1984). An updated understanding of the hydrologic system was needed to (1) manage and restore Great Marsh, and (2) understand the effects on the hydrologic system and the surrounding residential and natural areas that result from drainage modifications and wetland restorations that have been made, are planned, or are hypothetical. This investigation by the USGS and its partners will aid in comprehending how natural and human-affected hydrologic processes affect shallow groundwater levels in an unconfined surficial aquifer surrounding and beneath Great Marsh in the INDU in Porter County, Indiana.

## Purpose and Scope

This report describes interpretation of hydrologic data, and development and use of a groundwater-flow model in simulations to show how natural and human-affected hydrologic processes affect shallow groundwater levels in an unconfined surficial aquifer surrounding and beneath Great Marsh. The groundwater-flow model was developed to be available, if needed, as a tool to help evaluate future management actions.

Water levels were measured during May 2012–December 2013 to understand flow directions in the surficial aquifer and establish a consistent reference to compare with and quality assure results from the groundwater-flow simulations. Continuous water-level and weather data also are presented and interpreted to characterize the transient groundwater-flow system and identify steady-state water-level periods in the surficial aquifer.

The purpose of the calibrated groundwater model is to numerically represent groundwater/surface-water interactions in the shallow hydrologic system of the area surrounding Great Marsh so that various simulations can be made that represent different drainage modifications. The model was calibrated to a relatively wet hydrologic condition to examine the specific effects on the surrounding land uses. Four different scenarios were completed:

- A simulation of the effects of a beaver dam installed in the main channel of Brown Ditch upstream of Central Avenue on the surrounding water table. Results of the simulation are compared to data collected on April 29, 2014, while such a beaver dam was present.
- A simulation of the effects of six proposed pool-riffle structures and spillways that could be installed in the main channel of Brown Ditch downstream of highway US-12 to restore wetlands.
- Simulations of the effects of record high Lake Michigan lake levels (stage) on the water table within Great Marsh to represent conditions typical of recent Lake Michigan level variations.
- A simulation of the effects of a record low Lake Michigan stage on the water table within the Great Marsh to represent conditions typical of recent Lake Michigan level variations.

The study evaluates the potential effects of drainage modifications and changes to the levels of Lake Michigan on the surrounding residential and natural areas by comparing simulation results for each scenario to baseline conditions or the results of another scenario. Water-table distributions for each simulation are compared with the altitudes of hypothetical subgrade structures (basements, roadbeds, or railbeds) in the model area.

## Description of Study Area

The study area is in northeastern Porter County in northwestern Indiana (fig. 1). The investigation is focused principally on an area that includes portions of INDU, the town of Beverly Shores, and Town of Pines, and is bounded on the west by Indiana Dunes State Park, the north by Lake Michigan, the east by Michigan City, Indiana, and the south by portions of highway US-20 and Brown Ditch (fig. 2). As of the 2010 census, the populations of Beverly Shores and Town of Pines were 613 and 708, respectively (U.S. Census Bureau, 2013). Great Marsh, the largest interdunal wetland near the Lake Michigan shore at INDU, crosses through the study area (fig. 2). Derby Ditch drains portions of the residential area of Beverly Shores and wetlands within the dune-beach complex to Lake Michigan. Brown Ditch drains portions of Town of Pines residential area and portions of Great Marsh north of US-12 and south of Beverly Drive in INDU to Kintzele Ditch. Kintzele Ditch drains Brown Ditch, portions of the residential area of Town of Pines, and eastern portions of Great Marsh to Lake Michigan.

Land use in the study area is principally residential along streets in Beverly Shores and Town of Pines, and is a mixture of residential and commercial uses along US-12 and US-20. Principal transportation land uses that cross the study area consist of US-12 and US-20, paved and unpaved secondary roads, and railroads. Parts of the study area in INDU and adjacent parkland are maintained as natural and restored wetlands, wooded dune, and swale environments.

The climate along the southern shore of Lake Michigan, including the study area, is characterized by hot, humid summers and cold winters. The mean precipitation is approximately 36 inches per year (in/yr), including approximately

30 to 40 in/yr of snowfall (Midwestern Regional Climate Center, 2014). Monthly mean precipitation is lowest in February (approximately 1.5 inches [in.]) and highest in June and July (approximately 3.8 in.). The mean January temperature is 24 degrees Fahrenheit (°F), and the mean July temperature is 73 °F (National Oceanic and Atmospheric Administration, 1982; Greeman, 1995).

Development of Beverly Shores and the surrounding areas began in the mid to late 1800s with the draining of several thousand acres of Great Marsh for residential use, use as cranberry bogs and production of other agriculture, and in raising cattle. Prior to development, the eastern portion of Great Marsh had two distinctive natural landmarks, the exact location of each is unknown: Fish Lake (presumably located in the eastern half of the study area), and Tamarack Bog (presumably located in the southern-central portion of the study area) (Plampin and Hamilla, 2011, as cited by Daniel Mason, written commun., 2014). These natural landmarks were drained by ditches that were the predecessors of modern day Brown and Kintzele Ditches, which were dug sometime prior to 1921. In the late 1920s, the construction of roads to allow for the development of housing within the area began to divide the drained areas of Great Marsh. Such development also included the installation of low embankments, drainage pipe, ditches, and culverts. Residential homes were developed largely in the dunes and interdunal wetlands between Great Marsh and Lake Michigan, although some were built in or on the periphery of Great Marsh. Many of the homes were built with below-land-surface basements that are equipped with sump pumps to maintain a dry subsurface space. When Congress authorized INDU in the mid-1960s, much of the acreage in Beverly Shores between US-12 and the residential part of the dune-beach complex was included within INDU. Areas along US-12 and in Beverly Shores were later excluded from INDU. Many of the roads that were built through Great Marsh for residential development were abandoned between 1979 and 2005.

Possible future modifications to the local hydrologic system east of Lakeshore County Road may include limiting the discharge from Brown Ditch with the creation of flow-control structures that would allow water to pool on the upstream side. A potential side effect could be a rise in water levels in the surficial aquifer; a rise in the water table could result in groundwater flooding of subgrade structures in surrounding residential areas. Owing to a relatively shallow water table in the area surrounding Great Marsh, there is a potential for several areas to be susceptible to groundwater flooding in response to rapid infiltration of precipitation into the surficial aquifer:

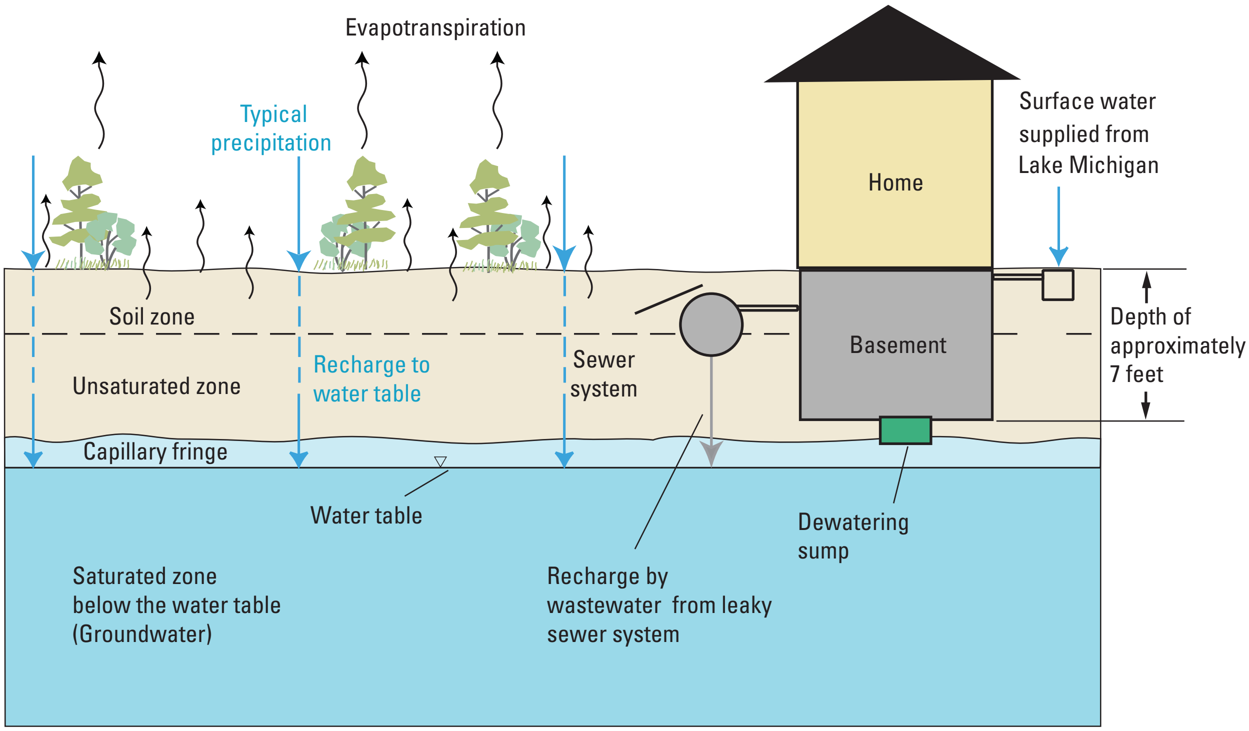
- *Northernmost residential areas in Town of Pines along US-12.* The US-12 corridor lies just to the south of Great Marsh. Changes in the water-level elevation due to increased or heavy precipitation may lower or flatten the hydrologic gradient in this area and in the process increase the associated travel time of groundwater flowing north from Town of Pines to areas of Great Marsh.
- *Residential areas in southern parts of Beverly Shores.* Low-lying areas immediately north of Beverly Drive and Great Marsh, especially those with subgrade structures, can be subject to groundwater flooding because of the relatively shallow water table. Parts of these areas experienced groundwater flooding during periods of relatively high precipitation in 2006–8.

Two conceptual diagrams illustrate typical interactions of precipitation and recharge with changes in groundwater levels in a hypothetical unconfined sand aquifer (figs. 3 and 4). Precipitation that falls on the land surface, minus losses from evaporation and plant transpiration (evapotranspiration), can pond at the land surface, run off into surface water, or infiltrate through the unsaturated zone to groundwater as recharge (fig. 3). Discharge of water from septic systems, leaky sewers, or irrigation systems also can contribute to recharge. A building and its basement can be vulnerable to infiltration and groundwater flooding of the basement if the water table rises above the basement floor (estimated for the purpose of this investigation to occur approximately 7 feet (ft) below the land surface) or sump underdrain and if the sump pump is unable to withdraw sufficient water to lower the groundwater level below basement floors and maintain dry conditions (fig. 3).

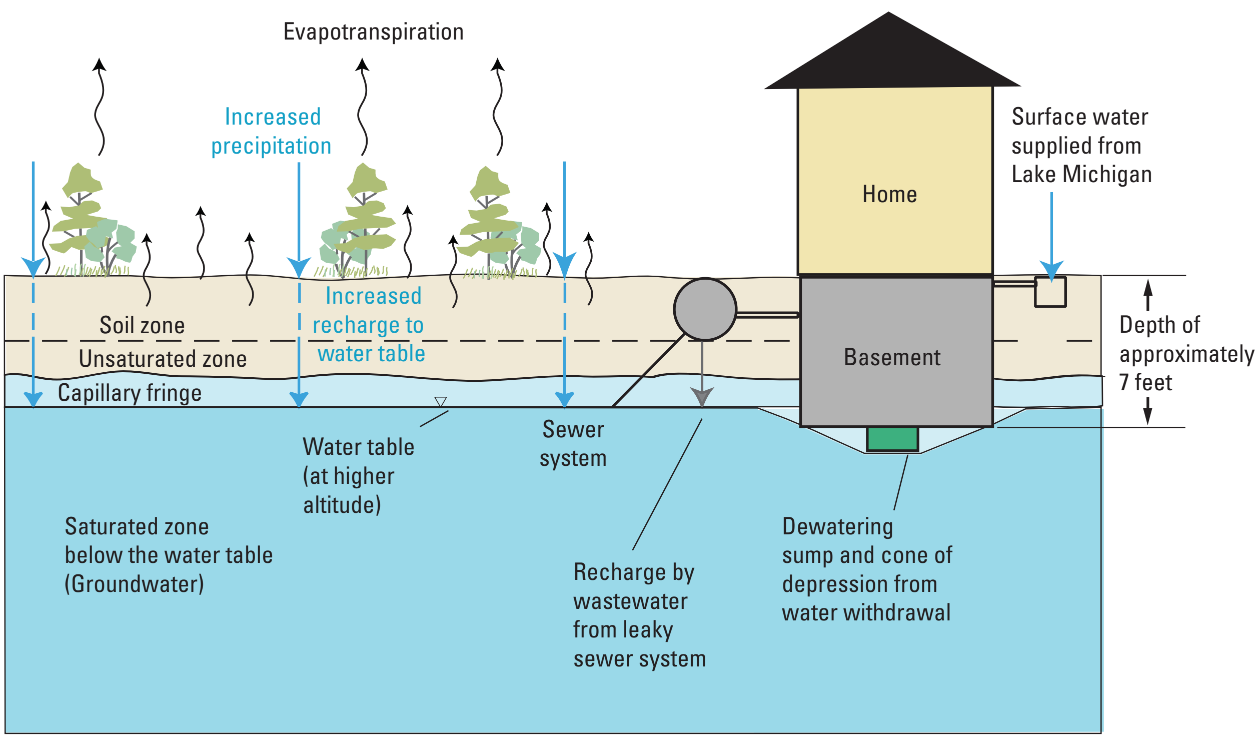
Outflow from the conceptualized surficial aquifer shown in figure 4 occurs in the form of groundwater seepage directly to ditches, wetlands, and lakes, such as Lake Michigan (fig. 4*A*) and indirectly to those surface-water bodies through ditches or subsurface drains (fig. 4*B*), or to the atmosphere by seasonal processes such as transpiration (fig. 3). Withdrawals from the aquifer occur when water is pumped from shallow wells in the surficial aquifer for domestic supply and lawn irrigation or by sump pumps used for dewatering basements and areas near building foundations (fig. 3*B*). Sump withdrawals of groundwater are typically discharged within the same property, so these withdrawals may be essentially recycled. Withdrawals from sumps would lower groundwater levels near the building and slightly raise nearby groundwater levels where the water is discharged but would produce little overall change in groundwater levels or flow, particularly beyond the immediate area of the property (fig. 3).

The rate and volume of groundwater flow through a porous medium, such as in an unconfined sand aquifer, are directly proportional to the slope of the water-level surface (gradient) and the conductive characteristics of the aquifer to water (hydraulic conductivity). A water-table altitude can rise because of increased amounts of recharge or decreased amounts of groundwater outflow. Recharge can increase when more precipitation falls, when snow melts, or when water brought into an area increases infiltration to the water table. Discharge of groundwater from the hypothetical aquifer can decrease if flow to a ditch is reduced by clogging from debris or beaver dams, causing water levels to rise in an area of typical groundwater discharge, such as a lake, ditch, or wetland (fig. 4*C*).

*A.* **Conceptual diagram of parts of the water budget under the dune-beach complex, dry-weather (October 2002) conditions**

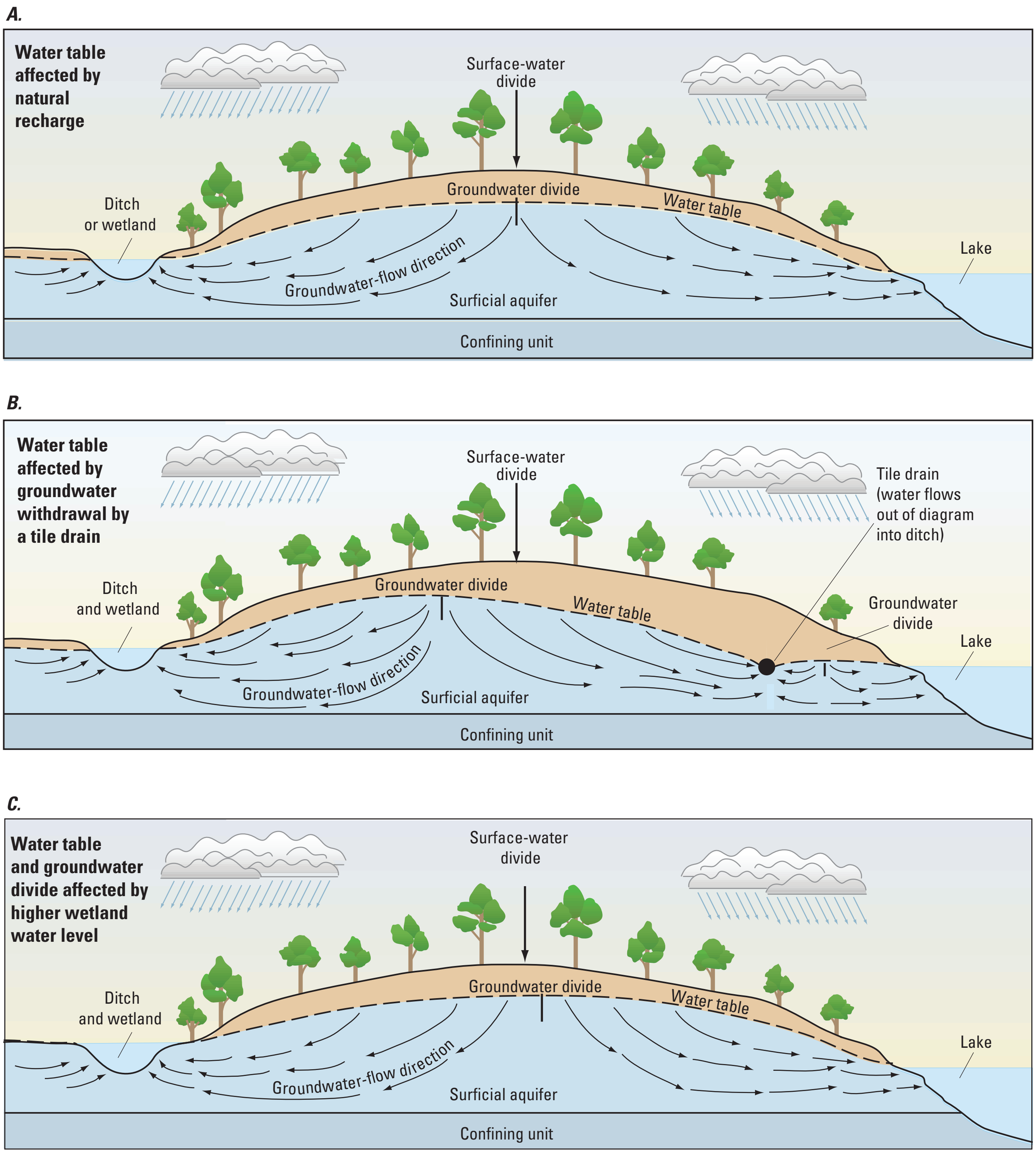



*B.* **Conceptual diagram of parts of the water budget under the dune-beach complex, wet-weather (March 2011) conditions**




Diagrams modified from Alley and others (1999, fig. 4, p. 6).

**Figure 3.** Interactions of precipitation with recharge and groundwater levels in a hypothetical unconfined sand aquifer. (Note that precipitation in *A* is less than in *B*.)




Diagrams reproduced and modified from Grannemann and others (2000, fig. 5, p. 5).

**Figure 4.** Generalized groundwater flow. *A*, Under natural conditions. *B*, Affected by tile drain flow. *C*, Affected by surface-water-level change in adjacent discharge ditch. (Note that surface-water and groundwater divides coincide in *A* but not in *B* or *C*.)

# Groundwater and Surface-Water Resources

Many factors affect the hydrology in the study area. Groundwater flow is influenced by the hydraulic properties of the geologic units that constitute the local aquifers, in addition to the timing and quantity of recharge. Topography, streams, ditches and wetlands, and climate affect surface-water flow. Groundwater- and surface-water flow systems are in close hydraulic connection, especially in the highly permeable surficial geologic materials.

## Hydrogeologic Setting

The study area lies within the Calumet Lacustrine Plain physiographic province (Malott, 1922). Gray (2000) refers to the same area as the Lake Michigan Border. The province is characterized by dune-beach complexes—areas that contain many individual dunes with total relief of 50–100 ft between the tops and bottoms of adjacent dune lowlands, but with water tables that do not follow the dune topography because of the highly permeable dune materials (fig. 5). These dune-beach complexes were deposited over the area formerly occupied by glacial Lake Chicago, formed during the Holocene Epoch, and represent relic shorelines from when post-Pleistocene Lake Chicago receded (Hartke and others, 1975). Great Marsh and associated interdunal wetlands occupy an elongated lowland between these dune-beach complexes (fig. 6).

Groundwater resources in the study area are made up of the Calumet Aquifer system[1] and, to a lesser extent, the Lacustrine Plain Aquifer system[1] (fig. 7) and one underlying bedrock aquifer system (the Silurian-Devonian Carbonate Aquifer system[1]).

The hydrogeologic framework of the study area consists of two unconsolidated aquifers that are included in the Calumet Aquifer system—the surficial aquifer and the basal sand aquifer—typically separated by variable thicknesses of glacial till and lacustrine clay and silt (table 1; Shedlock and others, 1994, fig. 10). The aquifer materials beneath the study area are made up of approximately 0–110 ft of unconsolidated glacial, lacustrine, eolian, and paludal sediments that were deposited on a bedrock surface modified by pre-Pleistocene erosion. The unconsolidated material is thinnest in areas in the northeast part of the study area near the intersection of Kintzele Ditch with Lake Michigan; it is generally thickest beneath the Beverly Shores duneland that parallels Lake Michigan. The underlying bedrock consists of the Antrim and Ellsworth Shale of Late Devonian to Early Mississippian age underlain by Devonian limestones and dolomites of the Muscatatuck Group.

The surficial aquifer consists primarily of lacustrine and wind-blown sands and is commonly called the Calumet aquifer (Hartke and others, 1975; Shedlock and others, 1994). The saturated thickness of the surficial aquifer in the study area ranges from approximately 0 to greater than 30 ft. In much of the central part of the study area, lowland areas generally have relatively thin (from less than 1 to about 8 ft) wetland deposits of muck, peat, calcareous clay, and other organic sediments at the surface. These organic deposits are associated with back-barrier deposits and other former wetland areas associated with higher levels of the post-Pleistocene Lake Chicago (Shedlock and others, 1994; Thompson, 1987). Generally, the surficial aquifer is unconfined throughout most of the study area. In some areas, however, buried organic sediments may function as local confining layers for underlying parts of the surficial aquifer and also may create perched water tables.

The basal sand aquifer in the INDU is described as interbedded clay, sand, gravel, and till by Shedlock and others (1994, p. 16), who state that its extent is less well known than that of other aquifers in the area. Several deep drilled wells intersect the basal sand aquifer within the study area (table 2, fig. 8).

The thickness of the surface organic material in Great Marsh was measured by Thompson (1987) using vibracores collected within the study area that ranged from 0.8 to 5.4 ft thick. Cores with the thickest organic intervals were collected near the center of the study area along Lakeshore County Road, and the core with the thinnest interval was collected in the eastern portion of the study area northwest of the confluence of Brown and Kintzele Ditches. Little other information is available regarding the thickness, areal distribution, and composition of the surficial organic sediments throughout the study area. The pattern in organic thickness is consistent with patterns found in similar study areas and consistent with their formation in wetland environments on the landward side of former beach ridges identified in this area (Lampe and Bayless, 2013; Thompson, 1992).

[1] Aquifer-system names are local usage; see Beaty (1994).

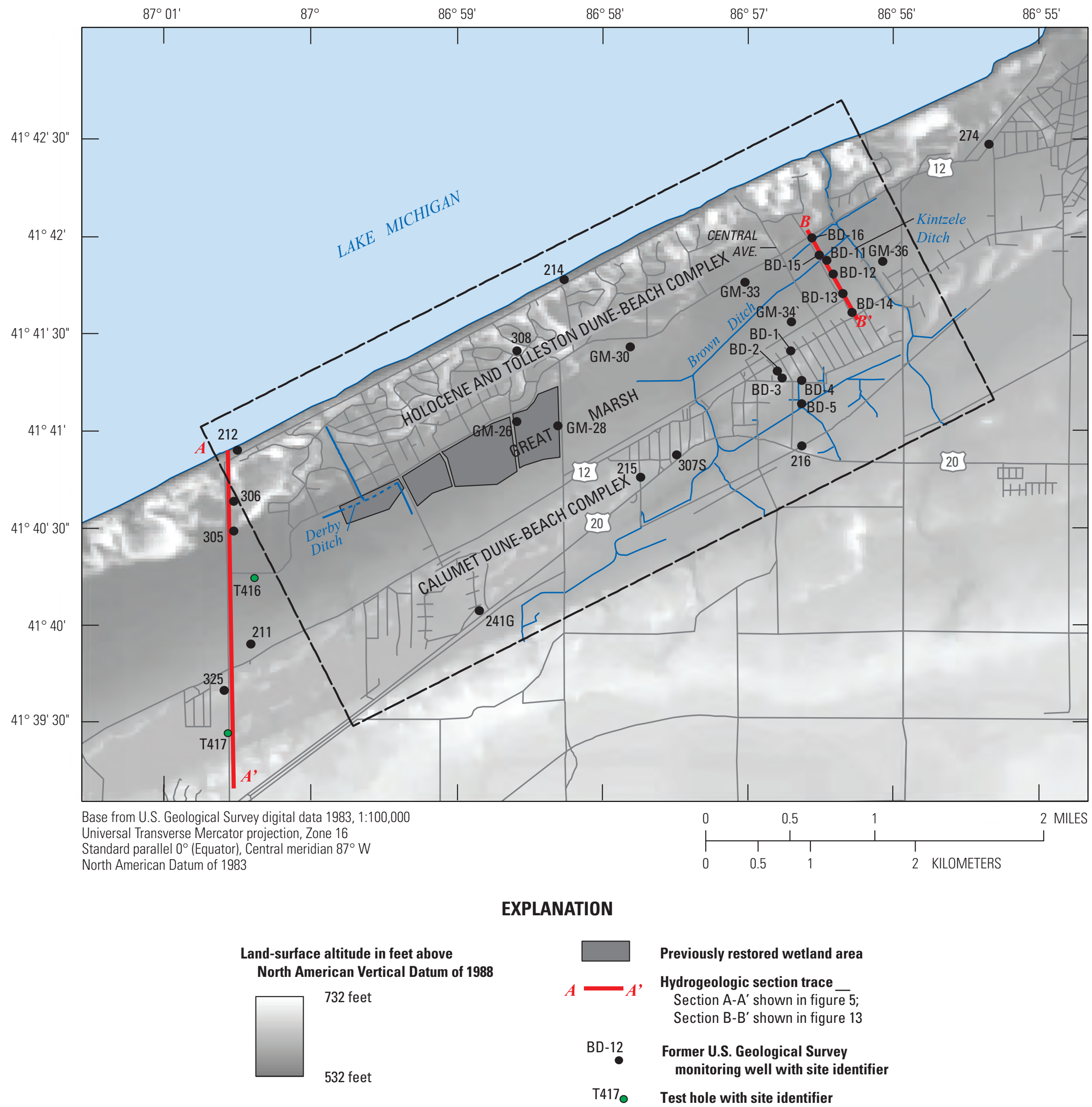



**Figure 5.** Location of study area, hydrologic cross sections, former monitoring wells, and surface-water features in the Great Marsh study area, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana.

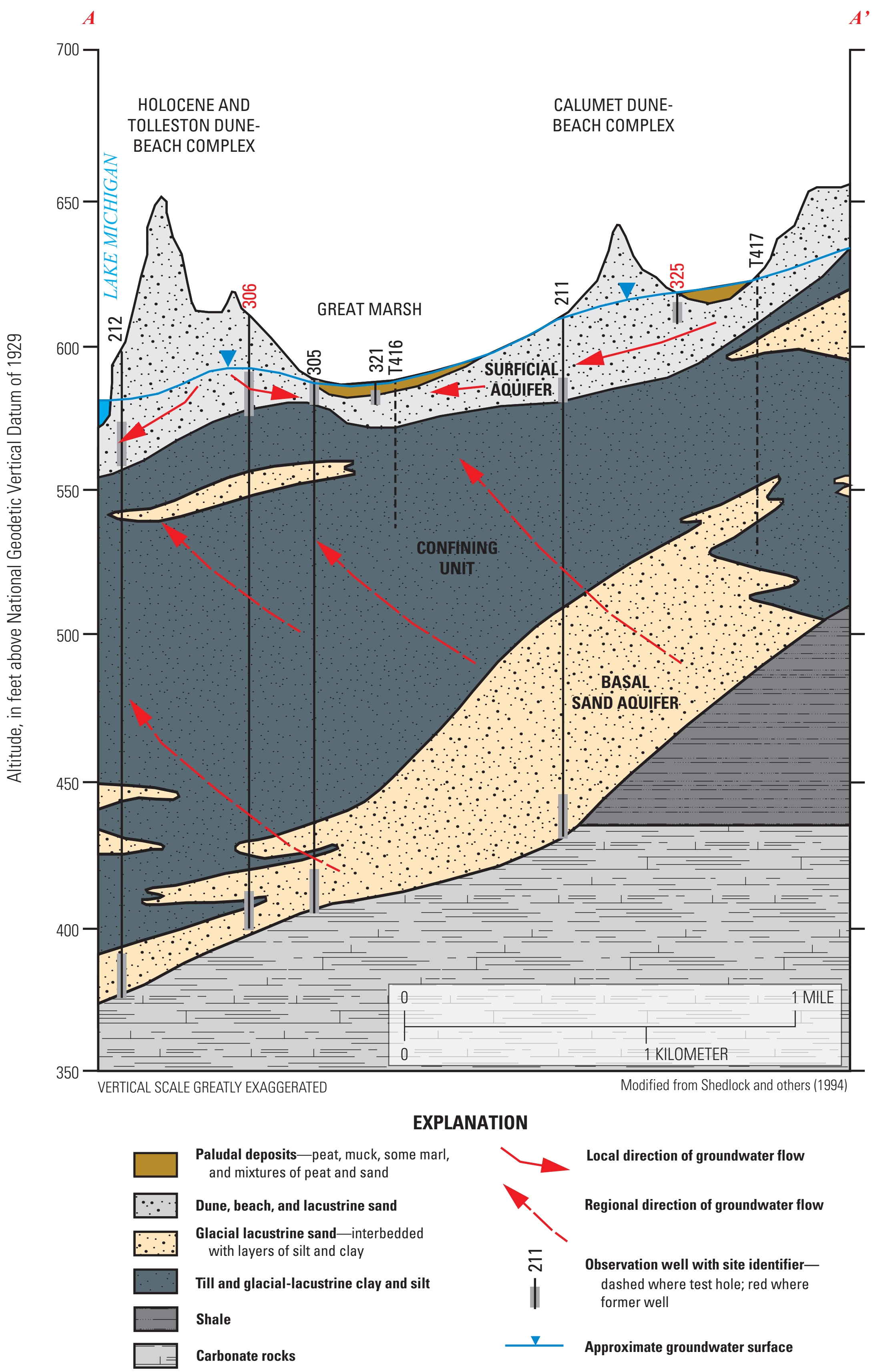



**Figure 6.** Hydrogeologic section ***A–A′*** showing the surficial aquifer, confining unit, basal sand aquifer, underlying shale and carbonate bedrock, and local and regional directions of groundwater flow (modified from Shedlock and others, 1994); section trace is shown in fig. 5.

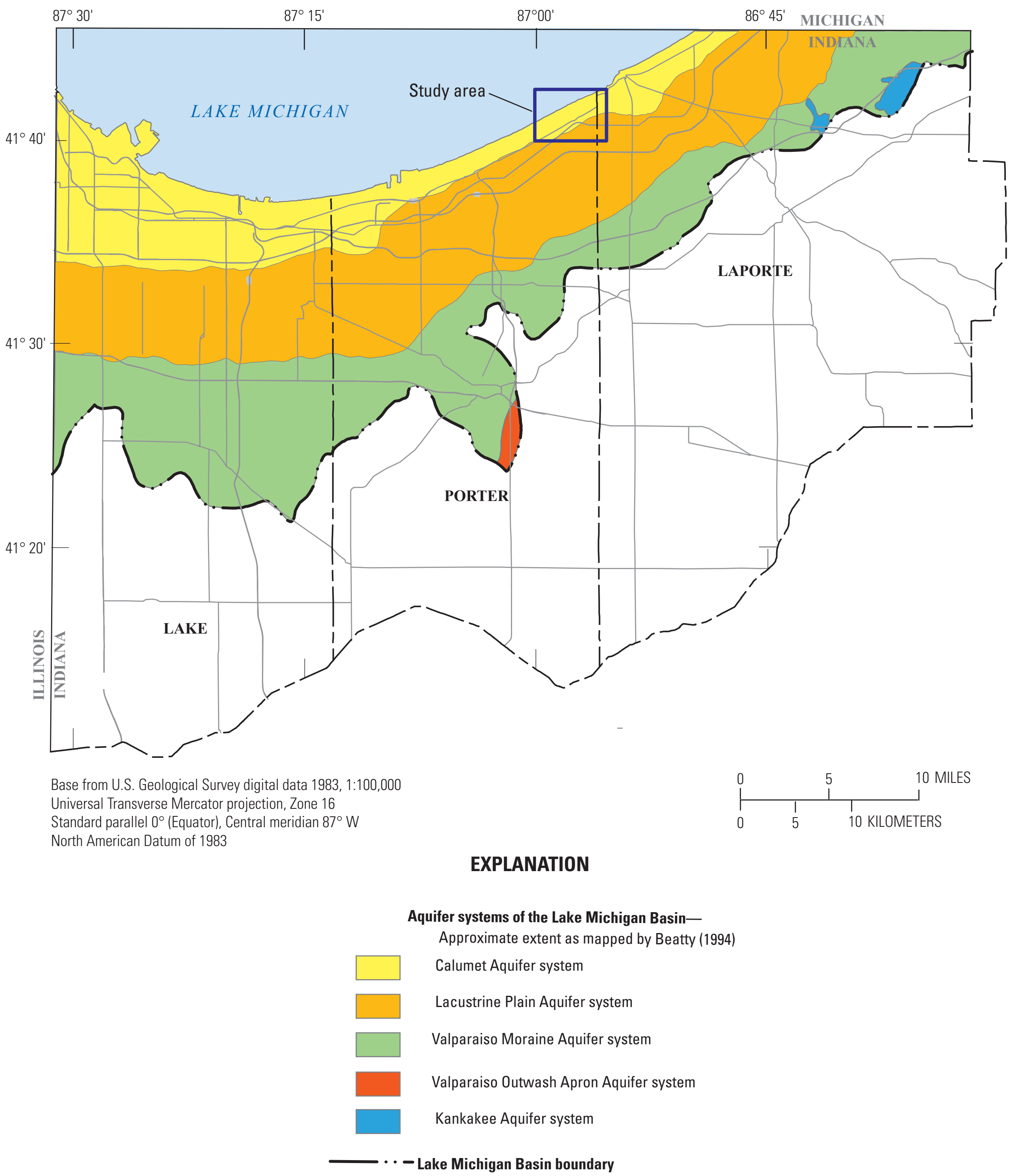



**Figure 7.** Unconsolidated aquifer systems in the Lake Michigan region and the study area, northwestern Indiana. Definitions of aquifer-system characteristics can be found in Beaty (1994, pl. 2).

**Table 1.** Lithostratigraphy of the study area in the context of northwestern Indiana hydrogeologic units.

| Lithostratigraphic descriptions | Hydrogeologic-framework designation | |
|---|---|---|
| | This report and Shedlock and others (1994) | Beaty (1994) |
| Fine- to medium-grained dune, beach, eolian, and lacustrine sands and gravels (of Holocene and Pleistocene age) | Surficial aquifer | Calumet aquifer system |
| Glacial and lacustrine sands of Pleistocene age, with interbedded clays and silts, including tills of the Lake Border Moraine | Confining units,<br>Subtill aquifer,<br>Confining units,<br>Basal sand aquifer | Lacustrine Plain aquifer system |
| Shale and carbonate rocks of Early Mississippian, Devonian, and Silurian age | Bedrock aquifer | Silurian-Devonian carbonate aquifer system |

**Table 2.** Characteristics of groundwater-monitoring wells in the study area.

[USGS, U.S. Geological Survey; dd mm ss, degrees minutes seconds; NAVD 88, North American Vertical Datum of 1988; WL, discrete water level; PVC, polyvinyl chloride; CWL, continuous water level; GEO, geologic; —, not applicable; SS, stainless steel]

| Well name | USGS station-identification number | Latitude (dd mm ss) | Longitude (dd mm ss) | Type of data collected | Date installed (month/year) | Method of installation | Land-surface datum (feet above NAVD 88) | Measur-ing-point elevation (feet above NAVD 88) | Casing material | Casing diameter (inches) | Well depth (feet below land-surface datum) | Well-screen length (feet0 | Depth from land surface to bottom of well screen (feet below land-surface datum) | Aquifer intersected by well screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Privately owned monitoring wells used during study | | | | | | | | | | | | | | |
| MW101 | 414056086573701 | 41 40 56.13 | 86 57 36.97 | WL | 07/2006 | Auger | 619.0 | 618.71 | PVC | 2 | 26 | 10 | 26 | Surficial |
| MW102 | 414050086574501 | 41 40 50.36 | 86 57 45.38 | WL, CWL | 07/2006 | Auger | 625.3 | 628.45 | PVC | 2 | 29 | 10 | 29 | Surficial |
| MW103 | 414059086574101 | 41 40 59.69 | 86 57 41.36 | WL | 07/2006 | Auger | 615.4 | 615.09 | PVC | 2 | 24 | 10 | 24 | Surficial |
| MW104 | 414103086572701 | 41 41 03.11 | 86 57 27.36 | WL, CWL | 07/2006 | Auger | 620.6 | 622.45 | PVC | 2 | 25 | 10 | 25 | Surficial |
| MW106 | 414125086563301 | 41 41 25.38 | 86 56 33.07 | WL | 07/2006 | Auger | 619.7 | 621.56 | PVC | 2 | 26 | 10 | 26 | Surficial |
| MW107 | 414125086562301 | 41 41 24.60 | 86 56 23.36 | WL, CWL | 07/2006 | Auger | 615.4 | 617.5 | PVC | 2 | 19 | 10 | 19 | Surficial |
| MW109 | 414116086563101 | 41 41 15.59 | 86 56 30.53 | WL | 07/2006 | Auger | 612.2 | 614.12 | PVC | 2 | 21 | 10 | 21 | Surficial |
| MW110 | 414129086563601 | 41 41 28.52 | 86 56 35.61 | WL, CWL | 07/2006 | Auger | 617.4 | 619.48 | PVC | 2 | 22 | 10 | 22 | Surficial |
| MW116 | 414052086575501 | 41 40 51.65 | 86 57 54.53 | WL | 07/2006 | Auger | 617.9 | 617.54 | PVC | 2 | 23 | 10 | 23 | Surficial |
| MW120 | 414059086581601 | 41 40 59.09 | 86 58 15.61 | WL | 07/2006 | Auger | 605.0 | 606.98 | PVC | 2 | 18 | 10 | 18 | Surficial |
| MW123 | 414107086573501 | 41 41 06.85 | 86 57 34.99 | WL, CWL | 07/2006 | Auger | 612.0 | 613.66 | PVC | 2 | 23 | 10 | 23 | Surficial |
| Pre-existing USGS monitoring wells used during study | | | | | | | | | | | | | | |
| 203S | 414212086555602 | 41 42 11 | 86 55 56 | WL | 07/1979 | Auger | 601.67 | 600.95 | PVC | 4 | 33 | 5 | 33 | Surficial |
| 203D | 414212086555601 | 41 42 11 | 86 55 56 | GEO | 07/1979 | Auger | 602 | — | PVC | 4 | 191 | 5 | 191 | Basal sand |
| 211S | 413957087002602 | 41 39 54 | 87 00 25 | WL | 05/1979 | Auger | 611 | 610.85 | PVC | 4 | 21 | 5 | 21 | Surficial |
| 211D | 413957087002601 | 41 39 54 | 87 00 25 | GEO | 05/1979 | Auger | 611 | — | PVC | 4 | 175 | 5 | 175 | Basal sand |
| 212G | 414057087003003 | 41 40 54 | 87 00 30 | WL | 10/1979 | Auger | 602 | 601.31 | PVC | 2 | 24 | 3 | 24 | Surficial |
| 212D | 414057087003000 | 41 40 54 | 87 00 30 | GEO | 10/1979 | Auger | 602 | NA | PVC | 4 | 210 | 5 | 210 | Basal sand |
| 213G | 414041086592003 | 41 40 39 | 86 59 18 | WL | 10/1979 | Auger | 600.17 | 600.17 | Steel | 2 | 12 | 3 | 12 | Surficial |
| 213D | 414041086592000 | 41 40 41 | 86 59 18 | GEO | 10/1979 | Auger | 600.5 | — | PVC | 4 | 133 | 5 | 133 | Basal sand |
| 305D | 414029087003201 | 41 40 29 | 87 00 33 | GEO | 09/1981 | Auger | 599 | — | PVC | 4 | 156 | | 156 | Basal sand |
| 305B | 414029087003204 | 41 40 30 | 87 00 33 | WL | 11/1985 | Hand driven | 601 | 597.74 | SS | 2 | 6 | 3 | 6 | Surficial |
| 321 | 414017087002701 | 41 40 17 | 87 00 26 | WL | 08/1984 | Hand driven | 596 | 598.94 | SS | 2 | 5 | 3 | 5 | Surficial |
| GM-21 | 414013087000701 | 41 40 13 | 87 00 07 | WL | 07/1979 | Hand driven | 598.7 | 600.58 | SS | 2 | 5 | 3 | 5 | Surficial |
| GM-25 | 414050086590501 | 41 40 52.8 | 86 59 06.0 | WL | 07/1979 | Hand driven | 596.7 | 599.61 | SS | 2 | 8 | 3 | 8 | Surficial |
| GM-27 | 414046086583601 | 41 40 40.83 | 86 58 36.90 | WL | 08/1979 | Hand driven | 609.16 | 610.22 | SS | 2 | 6 | 3 | 6 | Surficial |

**Table 2.** Characteristics of groundwater-monitoring wells in the study area.—Continued

[USGS, U.S. Geological Survey; dd mm ss, degrees minutes seconds; NAVD 88, North American Vertical Datum of 1988; WL, discrete water level; PVC, polyvinyl chloride; CWL, continuous water level; GEO, geologic; —, not applicable; SS, stainless steel]

| Well name | USGS station-identification number | Latitude (dd mm ss) | Longitude (dd mm ss) | Type of data collected | Date installed (month/year) | Method of installation | Land-surface datum (feet above NAVD 88) | Measuring-point elevation (feet above NAVD 88) | Casing material | Casing diameter (inches) | Well depth (feet below land-surface datum) | Well-screen length (feet0 | Depth from land surface to bottom of well screen (feet below land-surface datum) | Aquifer intersected by well screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pre-existing USGS monitoring wells used during study—Continued | | | | | | | | | | | | | | |
| GM-31 | 414121086571001 | 41 41 18.95 | 86 57 12.25 | WL | 08/1979 | Hand driven | 609.26 | 611.40 | SS | 2 | 9 | 3 | 9 | Surficial |
| GM-35 | 414151086562701 | 41 41 51 | 86 56 27 | WL | 08/1979 | Hand driven | 597.33 | 598.12 | SS | 2 | 6 | 3 | 6 | Surficial |
| GM-37 | 414207086561601 | 41 42 07 | 86 56 16 | WL | 08/1979 | Hand driven | 595.2 | 596.66 | SS | 2 | 5 | 3 | 5 | Surficial |
| 549 | 414115086585401 | 41 41 15.2 | 86 58 54.1 | WL | 04/2008 | Direct-push drill rig | 604.62 | 605.83 | Steel | 2 | 21 | 2.3 | 21 | Surficial |
| 551 | 414126086585101 | 41 41 26.3 | 86 58 51.1 | WL | 07/2008 | Direct-push drill rig | 607.22 | 609.62 | Steel | 2 | 15 | 2.2 | 15 | Surficial |
| 552 | 414125086583901 | 41 41 25.5 | 86 58 39.5 | WL | 07/2008 | Direct-push drill rig | 620.04 | 622.47 | Steel | 2 | 28 | 1.8 | 28 | Surficial |
| 553 | 414109086585001 | 41 41 09.5 | 86 58 50.8 | WL | 07/2008 | Direct-push drill rig | 607.12 | 609.46 | Steel | 2 | 15 | 2.2 | 15 | Surficial |
| 554 | 414102086584801 | 41 41 02.0 | 86 58 48.9 | WL | 07/2008 | Direct-push drill rig | 600.8 | 602.97 | Steel | 2 | 17 | 2.5 | 17 | Surficial |
| 555 | 414059086593401 | 41 40 59.2 | 86 59 34.8 | WL | 07/2005 | Direct-push drill rig | 609.05 | 611.86 | Steel | 2 | 19 | 2.2 | 19 | Surficial |
| 556 | 414101086593901 | 41 41 01.2 | 86 59 39.5 | WL | 07/2008 | Direct-push drill rig | 604.79 | 606.95 | Steel | 2 | 21 | 2 | 21 | Surficial |
| 557 | 414104086594101 | 41 41 04.3 | 86 59 41.2 | WL | 07/2008 | Direct-push drill rig | 609.57 | 611.95 | Steel | 2 | 18 | 2.2 | 18 | Surficial |
| 558 | 414108086594101 | 41 41 08.3 | 86 59 41.7 | WL | 07/2008 | Direct-push drill rig | 605.11 | 607.65 | Steel | 2 | 15 | 2.2 | 15 | Surficial |
| 559A | 414049086592801 | 41 40 49.2 | 86 59 28.4 | WL | 08/2008 | Direct-push drill rig | 599.62 | 601.78 | Steel | 2 | 12 | 2.5 | 12 | Surficial |
| 559B | 414049086592802 | 41 40 49 | 86 59 28 | WL | 11/2008 | Direct-push drill rig | 598.47 | 600.93 | Steel | 2 | 6 | 2.5 | 6 | Surficial |
| 560 | 414100086591801 | 41 41 00.4 | 86 59 18.1 | WL | 07/2008 | Direct-push drill rig | 607.44 | 610.04 | Steel | 2 | 15 | 1.1 | 15 | Surficial |
| 562 | 414112086591701 | 41 41 12.6 | 86 59 17.9 | WL | 07/2008 | Direct-push drill rig | 605.16 | 607.73 | Steel | 2 | 12 | 2.2 | 12 | Surficial |

**Table 2.** Characteristics of groundwater-monitoring wells in the study area.—Continued

[USGS, U.S. Geological Survey; dd mm ss, degrees minutes seconds; NAVD 88, North American Vertical Datum of 1988; WL, discrete water level; PVC, polyvinyl chloride; CWL, continuous water level; GEO, geologic; —, not applicable; SS, stainless steel]

| Well name | USGS station-identification number | Latitude (dd mm ss) | Longitude (dd mm ss) | Type of data collected | Date installed (month/year) | Method of installation | Land-surface datum (feet above NAVD 88) | Measuring-point elevation (feet above NAVD 88) | Casing material | Casing diameter (inches) | Well depth (feet below land-surface datum) | Well-screen length (feet0 | Depth from land surface to bottom of well screen (feet below land-surface datum) | Aquifer intersected by well screen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USGS monitoring wells installed for this study | | | | | | | | | | | | | | |
| 601 | 414114086581601 | 41 41 13.7 | 86 58 16.4 | WL | 05/2012 | Hand driven | 603.27 | 606.16 | Steel | 2 | 18 | 3 | 18 | Surficial |
| 602 | 414130086580301 | 41 41 29.8 | 86 58 04.0 | WL | 05/2012 | Hand driven | 603.41 | 606.16 | Steel | 2 | 8 | 3 | 8 | Surficial |
| 603 | 414132086574101 | 41 41 31.30 | 86 57 41.3 | WL, CWL | 05/2012 | Hand driven | 603.51 | 606.54 | Steel | 2 | 6 | 5 | 6 | Surficial |
| 604 | 414140086571501 | 41 41 41.1 | 86 57 15.9 | WL | 05/2012 | Hand driven | 598.77 | 601.22 | Steel | 2 | 4 | 3 | 4 | Surficial |
| 605 | 414152086564901 | 41 41 52.28 | 86 56 48.87 | WL | 05/2012 | Hand driven | 596.38 | 599.28 | Steel | 2 | 9 | 3 | 9 | Surficial |
| 606 | 414124086574101 | 41 41 26.4 | 86 57 40.7 | WL, CWL | 05/2012 | Hand driven | 602.19 | 604.92 | Steel | 2 | 9 | 3 | 9 | Surficial |
| 607 | 414200086563402 | 41 42 00.09 | 86 56 34.04 | WL, CWL | 05/2012 | Hand driven | 593.64 | 596.77 | Steel | 2 | 8 | 3 | 8 | Surficial |
| 608 | 414154086563102 | 41 41 55.7 | 86 56 33.7 | WL, CWL | 05/2012 | Hand driven | 594.63 | 598.47 | Steel | 2 | 9 | 3 | 9 | Surficial |
| 609 | 414139086574101 | 41 41 38.6 | 86 57 41.2 | WL, CWL | 05/2012 | Hand driven | 603.03 | 605.67 | Steel | 2 | 5 | 3 | 5 | Surficial |
| 610 | 414146086562301 | 41 41 45.3 | 86 56 21.7 | WL, CWL | 05/2012 | Hand driven | 605.25 | 607.40 | Steel | 2 | 6 | 3 | 6 | Surficial |

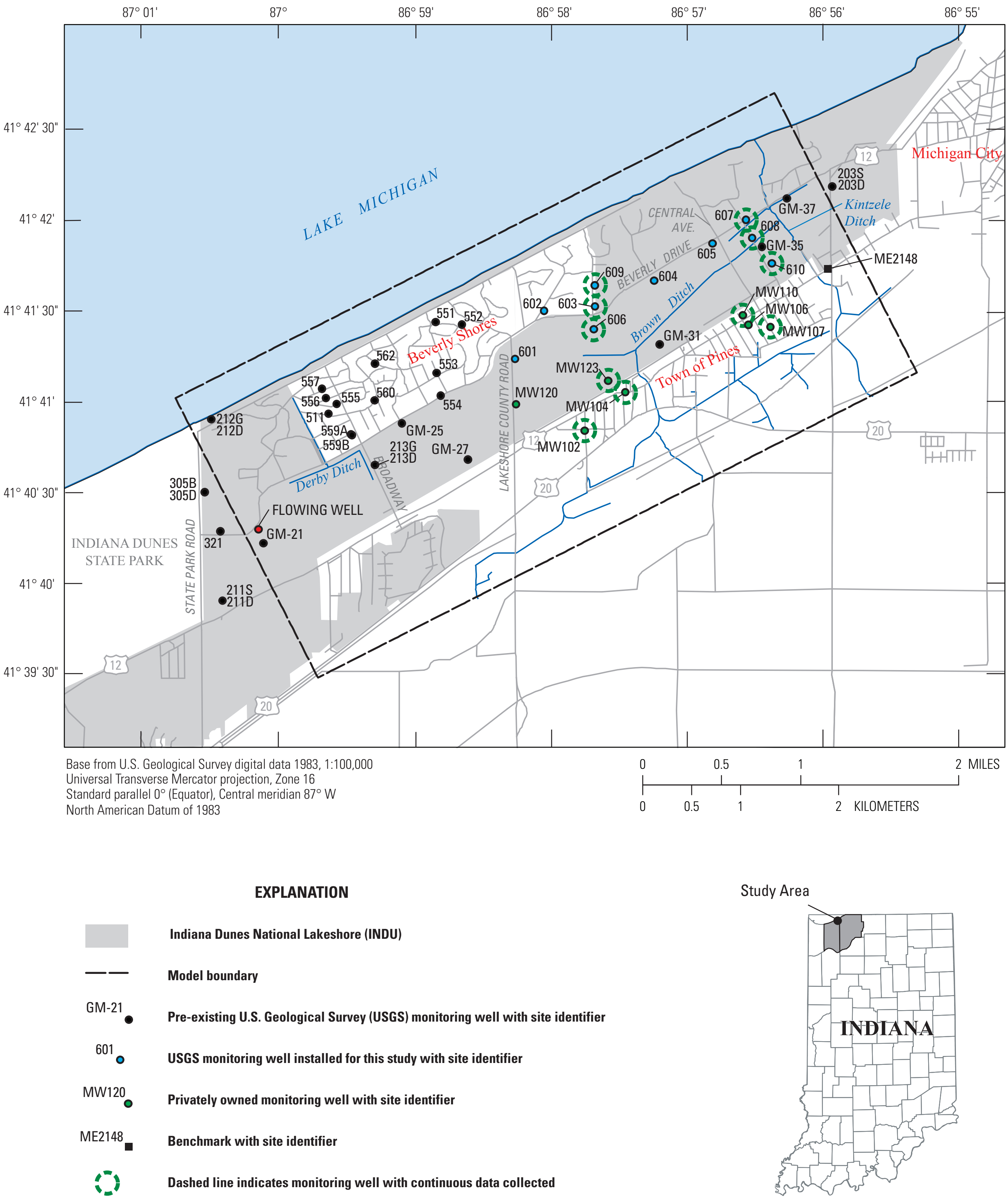



**Figure 8.** Location of study area and groundwater-data-collection sites in the Great Marsh study area, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana.

## Methods of Investigation

A data-collection network was installed in the study area to measure both discrete and continuous groundwater and surface-water altitudes and streamflow discharge. Groundwater-flow modeling relied on these data and hydrogeologic data from previous investigations for its calibration and verification. Most of the hydrogeologic interpretations in this report are based on data collected from sites shown in figures 8 and 9, particularly the following:

- Lithologic and discrete water-level data collected from four monitoring wells and lithologic and continuous water-level data collected from six monitoring wells installed in May 2012 for this study (table 2).
- Lithologic and discrete water-level data collected from six monitoring wells and continuous water-level data collected from five monitoring wells previously installed (July 2006) and operated in Town of Pines by AECOM environmental consultants for previous studies in the area (table 2) (AECOM, 2010).
- Lithologic or discrete water-level data collected from 30 monitoring wells installed by the USGS before 2007 for previous studies in the area (table 2).
- Artesian groundwater discharge measured from the "flowing well," a well developed in the basal sand aquifer near Beverly Shores (fig. 8).
- Surface-water stage (water level) obtained from seven surface-water monitoring sites, discrete discharge obtained from eight surface-water monitoring sites established for this study, and continuous discharge at three USGS streamgages (table 3).

Lithology, as referred to in this report, is defined by the relative grain size or texture of geologic materials encountered during drilling. "Continuous record" indicates data collected hourly or more frequently. "Discrete data" indicates measurements made occasionally and not on a set time period.

The lithology data from monitoring wells primarily used within the study area were augmented by lithologic information from 27 records from the Water Well Record Database maintained by the Indiana Department of Natural Resources (IDNR)-Division of Water (Indiana Department of Natural Resources, 2014).

All methods used for drilling, finishing, and developing monitoring wells installed for this study were consistent with USGS procedures and techniques as described in Holmes and others (2001) and Lapham and others (1997). Hand-driven wells were installed by using an 85-pound (lb) fencepost-type driver. Well casings were galvanized steel pipe and stainless steel mesh screens. All monitoring wells used in the study were composed of polyvinyl chloride (PVC) plastic, galvanized or stainless steel casings, and screens of varying diameter (table 2).

Measuring points for most surface-water-stage measurement sites (table 3) consisted of staff gages or painted or lightly chiseled marks on culvert tops that facilitated consistent tape measurements down to the water surface (fig. 10). .

Vertical control on measuring-point altitudes was established with an automatic (pendulum) level and leveling rod by using standard methods and procedures (U.S. Geological Survey, 1966). Measuring-point altitudes for all newly installed monitoring wells, some pre-existing wells, and most surface-water stage-measurement sites in the study area (tables 2 and 3) were tied to a single first-order benchmark (ME2148, fig. 8) by using a starting altitude referenced to North American Vertical Datum of 1988 (NAVD 88). Measuring-point altitudes derived by using this benchmark are considered accurate to ± 0.01 ft. Measuring-point altitudes for the 500 series observation wells, and observation wells 203S, 212G, 213G, 211S, 321, 305B, GM-21, and GM-25 were originally referenced from National Geodetic Vertical Datum of 1929 (NGVD 29) in previous investigations (Buszka and others 2011). These NGVD 29 altitudes were converted to NAVD 88 referenced altitudes using a correction factor obtained from the National Geodetic Survey VERTCON tool (Mulcare, 2004). The reported correction factor was evaluated by running an automatic level line from the established first-order benchmark referenced to NAVD 88 to a previously established reference point referenced to NGVD 29 to ensure that the difference between measured elevations agreed within 0.01 ft to the reported correction factor. Well-construction information and measuring-point altitudes for wells in the AECOM Town of Pines network were taken from the Remedial Investigation report for the Pines Area of Investigation prepared by AECOM (2010). Two observation wells in the AECOM network (MW123 and MW104) were included in the optical level line establishing the measuring point altitudes of the new observation wells, and altitudes determined during that effort agreed with altitudes reported by AECOM.

Water levels in monitoring wells and at surface-water stage-measurement sites were measured with an electric water-level tape or graduated folding rule. All water-level measurements are considered accurate to ± 0.01 ft and were made by using standard methods and procedures of the USGS (Cunningham and Schalk, 2011). The stage values for the elevation of Lake Michigan water surface were obtained at a National Oceanic and Atmospheric Administration (NOAA) monitoring site at Calumet Harbor, Illinois (National Oceanic and Atmospheric Administration, 2011), approximately 18 miles (mi) northwest of the study area.

Continuous record water-level data at groundwater-observation wells were measured at 1-hour increments during June 2012–August 2013 at 11 sites within the study area (fig. 8). Vented 10-pounds per square inch ($1b/in^2$) pressure transducers were installed in wells MW102, MW104, MW107, MW110, MW123, 603, 606, 607, 608, 609, and 610. Accuracy of the transducer measurements of water levels was approximately ± 0.01 ft. Transducer measurements of water levels were adjusted for mechanical drift by linearly averaging the difference between the transducer and electrical tape measurements over the period between electrical tape measurements.

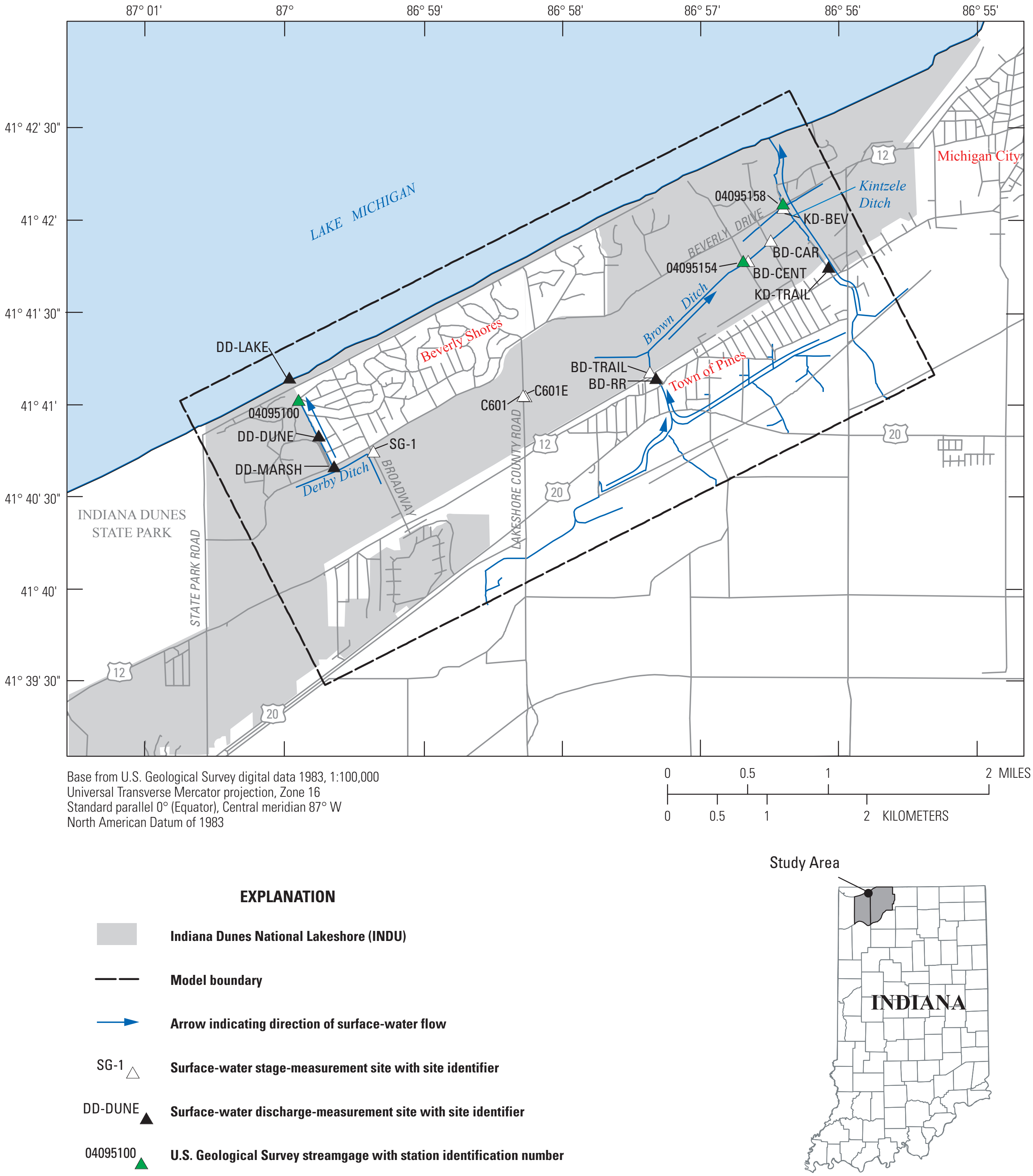



**Figure 9.** Location of study area and surface-water data-collection sites in the Great Marsh area, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana.

**Table 3.** Characteristics of surface-water data-collection sites in the study area.

[USGS, U.S. Geological Survey; dd mm ss, degrees minutes seconds; NAVD 88, North American Vertical Datum of 1988; WL, discrete water level; Q, discrete stream discharge; —, not applicable; CQ, continuous discharge]

| Site name | USGS station-identification number | Latitude (dd mm ss) | Longitude (dd mm ss) | Type of data collected | Date established (month/year) | Measuring-point elevation (feet above NAVD 88) | Surface-water body | Measurement location |
|---|---|---|---|---|---|---|---|---|
| BD-CAR | 414153086562902 | 41 41 53.39 | 86 56 29.65 | WL | 1979 | 591.36 | Brown Ditch | Staff gage in Brown Ditch east side of culvert on Carolina Avenue |
| BD-CENT | 414146086563901 | 41 41 46.89 | 86 56 39.50 | WL | 1979 | 599.79 | Brown Ditch | Top rim of east side of culvert where Brown Ditch flows under Central Avenue |
| KD-BEV | 414204086562401 | 41 42 04 | 86 56 24 | WL | 1982 | 586.24 | Kintzele Ditch | Staff gage in Kintzele Ditch south of Beverly Drive |
| SG-1 | 414045086592202 | 41 40 45 | 86 59 22 | WL | 12/2007 | 595.72 | Great Marsh | Staff gage in Great Marsh southeast of intersection of Beverly Drive and Broadway |
| C601 | 414103086581701 | 41 41 02.9 | 86 58 16.8 | WL | 12/2009 | 601.13 | Great Marsh | Staff gage just north of culvert on west side of Lakeshore County Road |
| C601E | 414103086581702 | 41 41 03.19 | 86 58 16.03 | WL | 05/2012 | 602.38 | Great Marsh | Staff gage just north of culvert on east side of Lake-shore County Road |
| BD-TRAIL | 414110086572201 | 41 41 10.53 | 86 57 22.13 | WL, Q | 1979 | 612.79 | Brown Ditch | Bridge over Brown Ditch on Calumet Trail. Measuring point is V-notch carved into top of north handrail approximately 10 feet west of the terminus of handrail |
| KD-TRAIL | 414149086560800 | 41 41 49 | 86 56 08 | Q | 1973 | — | Kintzele Ditch | 75 feet downstream of Calumet Trail |
| DD-LAKE | 414107086592800 | 41 41 06.97 | 86 59 58.30 | Q | 1973 | — | Derby Ditch | Just north of culvert where Derby Ditch flows into Lake Michigan |
| DD-DUNE | 414050086594701 | 41 40 50.05 | 86 59 47.08 | Q | 03/2013 | — | Derby Ditch | Approximately 1,000 feet south of Beverly Drive |
| DD-MARSH | 414038086593901 | 41 40 38.96 | 86 59 39.52 | Q | 03/2013 | — | Derby Ditch | Just north of Beverly Drive |
| 04095154 | 04095154 | 41 41 46.60 | 86 56 39.92 | CQ | 05/2012 | 594.18 | Brown Ditch | USGS streamgage located on the west side of Central Avenue |
| 04095158 | 04095158 | 41 42 04.81 | 86 56 24.67 | CQ | 05/2012 | 585.16 | Kintzele Ditch | USGS streamgage located on the north side of Beverly Drive |
| 04095100 | 04095100 | 41 41 02 | 86 59 55 | CQ | 1978 | 583.90 | Derby Ditch | USGS streamgage located on the south side of Fairwater Avenue |

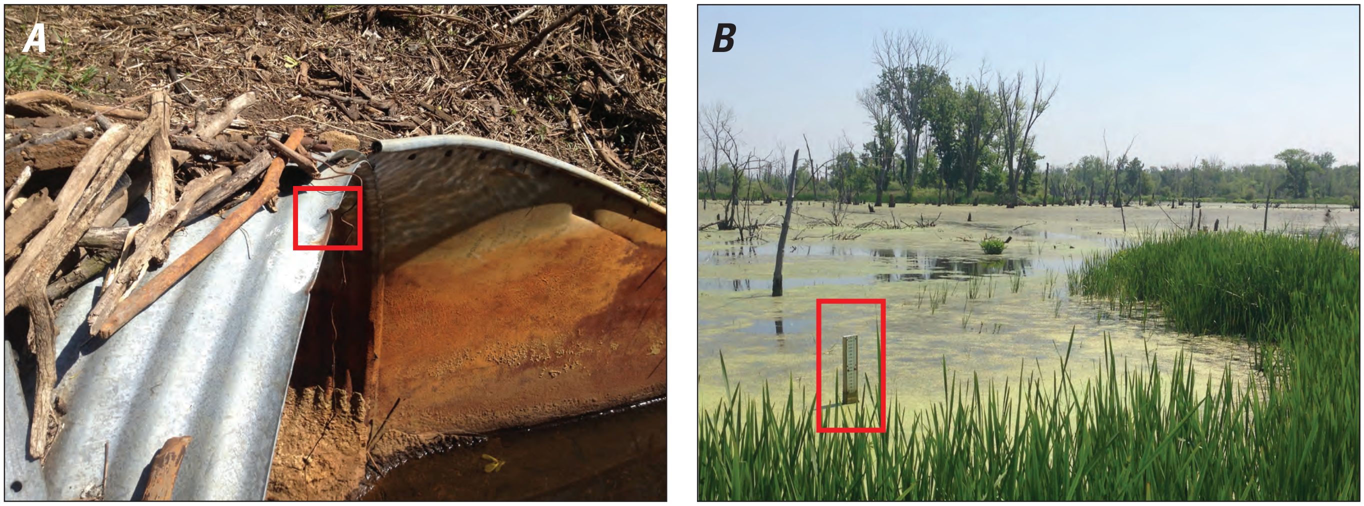



**Figure 10.** Photographs showing typical surface-water measurement sites. *A*, Stable culvert end at site BD-CENT. *B*, Staff gage at site SG1

Artesian groundwater discharge was measured from the "flowing well," a well developed in the basal sand aquifer near Beverly Shores (fig. 8). Discharge from the well is continuous to the land surface and, for the purposes of this study, is considered a point of recharge to the surficial aquifer. Discharge measurements were made using a graduated cylinder and stop watch. Seven consecutive measurements were made on September 3, 2013. Results of the measurements were averaged to determine the average discharge from the basal sand aquifer from the well. Discharge from the well for the purposes of this study is assumed to be relatively constant and the measurement made on September 3, 2013 to be representative for the period of investigation.

Instantaneous stream discharge was measured in 2012 at four sites on Derby Ditch, two sites on Brown Ditch, and two sites on Kintzele Ditch (fig. 10). All discrete discharge measurements were measured by using an acoustic Doppler velocimeter. Discharge was calculated from continuous stream stage data at two USGS streamgages—one in Derby Ditch near the outfall to Lake Michigan (station number 04095100), and one on Kintzele Ditch at Beverly Drive (station number 04095158)—using USGS methods outlined by Rantz and others (1982). Discharge was estimated by using hydrograph comparison techniques at one USGS streamgage on Brown Ditch at Central Avenue (station number 04095154) because of complications caused by beaver dams in the ditch at the gage location (Rantz and others, 1982).

Three-dimensional groundwater flow was simulated by recreating a groundwater-flow model originally published by Shedlock and Harkness (1984) using the finite-difference groundwater-model code MODFLOW-NWT (Niswonger and others, 2011). The recreated model was checked against previously published results and then modified to better represent the current conditions found within the study area. The parameter estimation code UCODE_2005 (Poeter and others, 2005) was used to improve model calibration. Methods used during model reconstruction, modification, and calibration are discussed in detail in the section "Simulation of Groundwater Flow and Availability." A particle-tracking post-processing package for MODFLOW—MODPATH (Pollock, 2012)—was used to generate three-dimensional flow paths with different scenarios of the model for this report. MODPATH computes paths for imaginary particles of water moving through the simulated groundwater system.

## Groundwater Levels and Flow in the Surficial Aquifer

The shallow groundwater flow system is contained within the dune deposits and parallels the shoreline of Lake Michigan (fig. 5). Water-table mounds form beneath the dune-beach complexes on the north side beneath the town of Beverly Shores and on the south side beneath Town of Pines (Shedlock and others, 1994). Great Marsh, a relatively flat, low lying area, lies between both of these water-table mounds. Groundwater flows laterally away from these mounds and generally discharges to Lake Michigan to the north, the south branch of Brown Ditch to the south, Derby Ditch to the west, Kintzele Ditch to the east, and Great Marsh and the north branch of Brown Ditch in the center of the study area. The hydraulic gradient between Lake Michigan and the water-table mound beneath Beverly Shores is very steep (125 feet per mile [ft/mi], or 0.28 inches per foot) compared to hydraulic gradients between the same water-table mound and Great Marsh to the south and between the water-table mound beneath Town of Pines and Great Marsh to the north (20 ft/mi or 0.05 in/ft and 65 ft/mi or 0.15 in/ft, respectively).

Shedlock and Harkness (1984) include synoptic measurements of water-level elevation in August 5, 1982 (table 4). The authors used these measurements to evaluate the original groundwater-flow model. Synoptic measurements[2] of water-level elevation on March 27, 2013, were used to map the water table within the study area and serve as a calibration dataset for the modified groundwater model (table 5). Synoptic measurements of water-level elevation on April 29, 2014, were used to map the water table within the study area during a period of time when a beaver dam was in Brown Ditch on the upstream side of the culvert beneath Central Avenue at the site of USGS streamgage 04095154 (table 5; fig. 10).

[2] Synoptic measurements involve data collection at multiple sites in an area over a short period (often a single day) to characterize a selected seasonal or hydrologic condition.

**Table 4.** Water-level measurements made on August 5, 1982 (from Shedlock and Harkness, 1984).

[USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929]

| Site name | USGS station-identification number | Water-level altitude (feet above NGVD 29) | Abandoned as of 2014 |
|---|---|---|---|
| Groundwater measurements | | | |
| 214 | 414147086581900 | 582.91 | Yes |
| 215 | 414053086544802 | 616.06 | Yes |
| 216 | 414057086563703 | 619.69 | Yes |
| 274 | 414228086552001 | 597.91 | Yes |
| 308 | 414124086583601 | 601.5 | Yes |
| 203S | 414212086555602 | 598.5 | No |
| 211S | 413957087002602 | 610.8 | No |
| 212G | 414057087003003 | 583.6 | No |
| 213G | 414041086592003 | 597.3 | No |
| 241G | 414004086585003 | 620.98 | Yes |
| 307S | 414052086573001 | 614.83 | Yes |
| GM–25 | 414050086590501 | 597.3 | No |
| GM–26 | 414102086583601 | 599.5 | Yes |
| GM–28 | 414101086581801 | 602.85 | Yes |
| GM–30 | 414125086574801 | 604.06 | Yes |
| GM–31 | 414121086571001 | 607.48 | No |
| GM–33 | 414145086570101 | 598.05 | Yes |
| GM–34 | 414133086564201 | 608.06 | Yes |
| GM–35 | 414151086562701 | 597.33 | No |
| GM–36 | 414152086560501 | 603.3 | Yes |
| GM–37 | 414207086561601 | 595.12 | No |
| Surface-water measurements | | | |
| BD–TRAIL | 414110086572201 | 604.7 | No |
| BD–CAR | 414153086562902 | 594.46 | No |
| KD–BEV | 414204086562401 | 588.9 | No |

**Table 5.** Water-level measurements made on March 27, 2013, and April 29, 2014.

[DV, Daily value interpreted from continuous record; NAVD 88, North American Vertical Datum of 1988; NPS, National Park Service; NM, not measured; —, not applicable; USGS, U.S. Geological Survey]

| Site name | USGS station-identification number | March 27, 2013 | | April 29, 2014 | | Difference between April 2014 and May 2013 measurement |
|---|---|---|---|---|---|---|
| | | Water-level altitude (feet above NAVD 88) | Agency collecting measurement | Water-level altitude (feet above NAVD 88) | Agency collecting measurement | |
| Groundwater measurements | | | | | | |
| GM–27 | 414046086583601 | 608.51 | NPS | NM | — | — |
| GM–31 | 414121086571001 | 606.44 | NPS | 607.21 | USGS | 0.77 |
| GM–35 | 414151086562701 | 596.64 | NPS | 596.88 | USGS | 0.24 |
| GM–37 | 414207086561601 | 594.61 | NPS | NM | — | — |
| 203S | 414212086555602 | 597.82 | NPS | NM | — | — |
| 203S | 414212086555602 | 597.81 | USGS | NM | — | — |
| 211S | 413957087002602 | 610.25 | USGS | NM | — | — |
| 212G | 414057087003003 | 578.50 | USGS | NM | — | — |
| 213G | 414041086592003 | 596.97 | USGS | NM | — | — |
| 305B–7 | 414029087003204 | 596.10 | USGS | NM | — | — |
| GM–21 | 414013087000701 | 598.28 | USGS | NM | — | — |
| GM–25 | 414050086590501 | 597.21 | USGS | NM | — | — |
| MW–102 | 414050086574501 | 613.711 | USGS DV | 615.10 | USGS | 1.39 |
| MW–104 | 414103086572701 | 609.981 | USGS DV | 610.67 | USGS | 0.69 |
| MW–106 | 414125086563301 | 611.57 | USGS | 613.22 | USGS | 1.65 |
| MW–107 | 414125086562301 | 612.451 | USGS DV | 613.15 | USGS | 0.70 |
| MW–110 | 414129086563601 | 610.951 | USGS DV | 612.26 | USGS | 1.31 |
| MW–120 | 414059086581601 | 602.98 | USGS | 603.16 | USGS | 0.18 |
| MW–123 | 414107086573501 | 608.671 | USGS DV | 609.03 | USGS | 0.36 |
| 321 | 414017087002701 | 596.21 | USGS | NM | — | — |
| 511 | 414056086593801 | 598.07 | USGS | NM | — | — |
| 551 | 414126086585101 | 599.43 | USGS | NM | — | — |
| 552 | 414125086583901 | 599.68 | USGS | NM | — | — |
| 553 | 414109086585001 | 600.68 | USGS | NM | — | — |
| 554 | 414102086584801 | 598.94 | USGS | NM | — | — |
| 555 | 414059086593401 | 599.26 | USGS | NM | — | — |
| 556 | 414101086593901 | 598.75 | USGS | NM | — | — |
| 557 | 414104086594101 | 598.86 | USGS | NM | — | — |
| 559A | 414049086592801 | 597.30 | USGS | NM | — | — |
| 559B | 414049086592802 | 597.01 | USGS | NM | — | — |
| 560 | 414100086591801 | 600.72 | USGS | NM | — | — |
| 562 | 414112086591701 | 600.16 | USGS | NM | — | — |
| 601 | 414114086581601 | 603.35 | NPS | 603.28 | USGS | –0.07 |
| 602 | 414130086580301 | 602.62 | NPS | 603.39 | USGS | 0.77 |
| 604 | 414140086571501 | 598.76 | NPS | 599.45 | USGS | 0.69 |
| 605 | 414152086564901 | 596.56 | NPS | NM | — | — |

**Table 5.** Water-level measurements made on March 27, 2013, and April 29, 2014.—Continued

[DV, Daily value interpreted from continuous record; NAVD 88, North American Vertical Datum of 1988; NPS, National Park Service; NM, not measured; —, not applicable; USGS, U.S. Geological Survey]

| Site name | USGS station-identification number | March 27, 2013 | | April 29, 2014 | | Difference between April 2014 and May 2013 measurement |
|---|---|---|---|---|---|---|
| | | Water-level altitude (feet above NAVD 88) | Agency collecting measurement | Water-level altitude (feet above NAVD 88) | Agency collecting measurement | |
| | | Groundwater measurements—Continued | | | | |
| 606 | 414124086574101 | 602.47 | USGS | 602.68 | USGS | 0.21 |
| 607 | 414200086563402 | 594.08 | USGS | 594.30 | USGS | 0.22 |
| 608 | 414154086563102 | 594.69 | USGS | 594.90 | USGS | 0.21 |
| 609 | 414139086574101 | 601.74 | USGS | 602.92 | USGS | 1.18 |
| 610 | 414146086562301 | 605.24 | USGS | 605.47 | USGS | 0.23 |
| | | Surface-water measurements | | | | |
| BD–TRAIL | 414110086572201 | 602.74 | NPS | NM | — | — |
| C601 | 414103086581701 | 601.93 | NPS | 602.02 | USGS | 0.09 |
| C601E | 414103086581702 | 603.66 | NPS | 604.13 | USGS | 0.47 |
| BD–CAR | 414153086562902 | 592.06 | NPS | 591.74 | USGS | –0.32 |
| BD–CENT | 414146086563901 | 595.35 | NPS | 594.99 | USGS | –0.36 |
| KD–BEV | 414204086562401 | 586.08 | NPS | 587.5 | USGS | 1.42 |
| SG–1 | 414045086592202 | 597.04 | USGS | NM | — | — |

## Recharge

Historical precipitation data are available from two stations near the study area: Ogden Dunes, 1951–89 and INDU headquarters, 1989–2013 (fig. 11) (Midwestern Regional Climate Center, 2014). The Ogden Dunes station was discontinued on May 21, 1989, and relocated to the present INDU site, where data collection resumed on June 1, 1989. Figure 11 shows that precipitation totals in the 3 months prior to the March 2013 data collection were higher than typical and ranged from 2.34 in. in December 2012 to 3.41 in. in January 2013. Snowfall for the season was concentrated in the months of February and March, with snowpack depths reaching 8 in. during the period. Increased temperatures in late March led to melting of the snow in the weeks prior to the water-level data collection (fig. 12). The growing season, defined for this study as the period of time when the mean daily temperature exceeds the freezing point, extended from the beginning of data collection to early November 2012 and from early April to early November 2013.

## August–November 1982 Levels and Flow

During the Shedlock and Harkness (1984) observed hydrologic conditions of August 1982, groundwater generally flowed to the channels of the ditches within the study area from water-table mounds beneath the dune ridges to the north and south of Great Marsh (fig. 13). The groundwater divides generally coincided with these same dune ridges, but also included another divide that oriented northwest-southeast in the area just to the east of Lakeshore County Road.

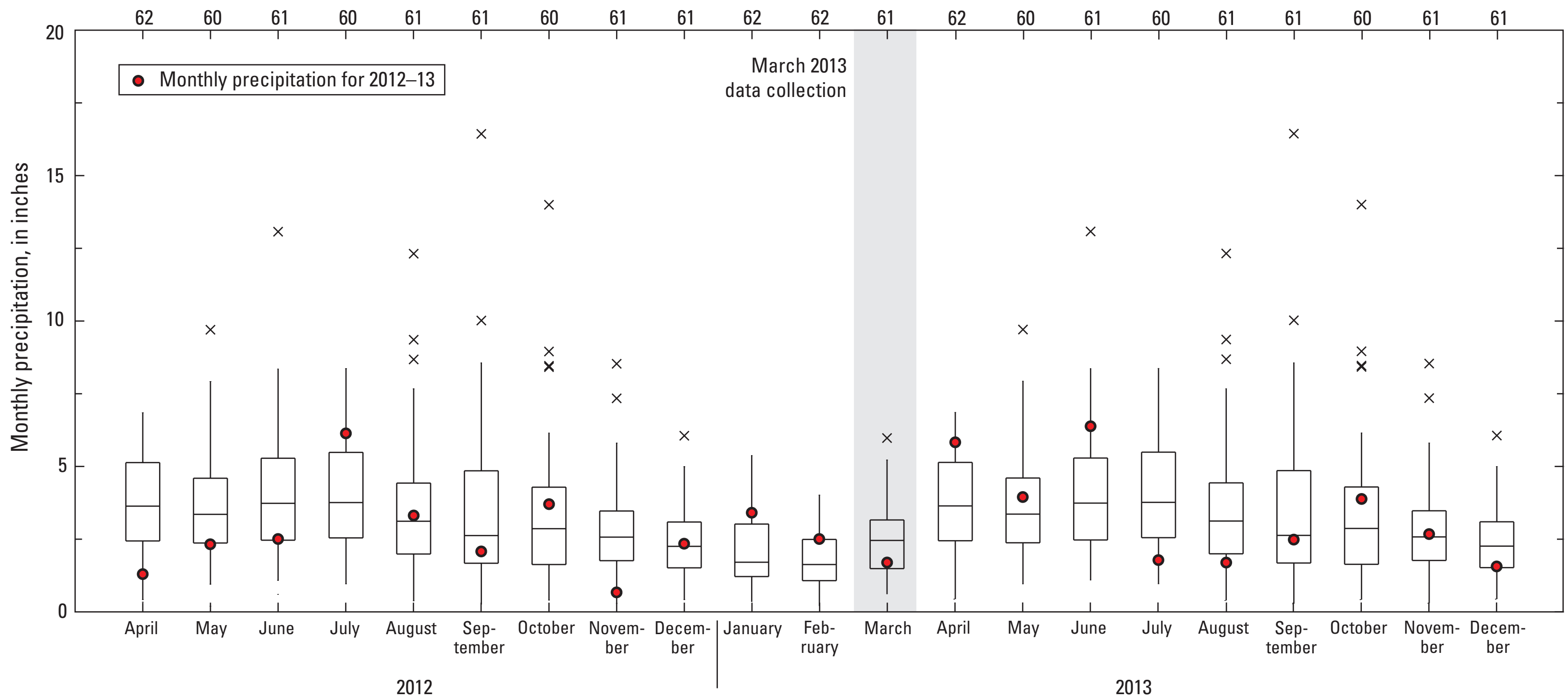
Shedlock and Harkness (1984) found that the altitude of the water-table surface roughly parallels the land surface, and that north of Brown Ditch, the water table is virtually flat. A hydrogeologic section *B-B′* along Carolina Avenue is shown in figure 14 (section location shown on fig. 5). Water levels and the approximate water-table altitude (in green) shown in the figure were measured on November 18, 1982; these wells were installed after the previously mentioned August 5, 1982, data collection. Groundwater flows north from Town of Pines and south from Beverly Shores toward Brown Ditch.

## March 2013 Levels and Flow

Water levels were measured in March 2013 to gain an understanding of the hydrologic conditions during a typical wet-weather condition in the study area. During the wet-weather conditions of March 2013, the major groundwater divides (fig. 15) generally coincided with dune ridges that parallel Lake Michigan to the north and south of Great Marsh in Beverly Shores and Town of Pines, respectively. A secondary groundwater divide trends northwest-southeast just east of Lakeshore County Road likely due to the presence of Lakeshore County Road that acts as a barrier to groundwater flow. Groundwater on the east side of this secondary divide flows toward Brown and Kintzele Ditches and ultimately Lake Michigan. Groundwater west of the secondary divide flows toward Derby Ditch and ultimately Lake Michigan.

The hydrogeologic section along Carolina Avenue (fig. 14) shows water levels in the surficial aquifer measured on March 27–28, 2013 (in blue). These water levels, except those from observation well GM-35, were measured in wells installed for this study due to the abandonment of the wells along this section used by Shedlock and Harkness (1984). The water-table surface is similar to that measured in 1982 south of Brown Ditch; the water table roughly parallels the land surface and groundwater flows north from US-12 toward Brown Ditch. While the water table north of Brown Ditch is relatively flat, the measured direction of groundwater flow has reversed from the measurements made in 1982 and now flows north from the ditch toward Beverly Shores. The hydrologic conditions during the two periods are different, which may explain the higher water levels in 2013 south of Brown Ditch, but it does not explain the flow reversal north of Brown Ditch. This reversal may be due to backwater conditions in Brown Ditch due to beaver dams.

Continuous groundwater-level data indicate that the predominant groundwater-flow gradients vary during the course of the year (fig. 16; well locations shown on fig. 8). A west to east transect of a combination of groundwater-monitoring wells and surface-water level monitoring sites indicates that the predominant flow direction is from west to east across Great Marsh, which follows the drainage gradient of Brown Ditch (fig. 16*A*). A clustering of the data points for groundwater sites 604 and 605 in October 2012 indicates stagnation of surface-water flow that may be due to increased precipitation or localized obstruction of Brown Ditch flow due to beaver dams or debris within Great Marsh. Two north-south trending transects of groundwater and surface-water sites—one on the west side of the study area east of Lakeshore County Road (fig. 16*B*), and one on the east side of the study area near Kintzele Ditch and the former Carolina Avenue extending south into Town of Pines (fig. 16*C*)—indicate the predominant groundwater-flow direction was south to north to Brown Ditch. The eastern transect shows a gradient reversal that occurs in October 2012 when groundwater flows north and away from Brown Ditch from well 608 to 607 (fig. 16*D*), which also may be due to increased precipitation or localized obstruction of surface-water flow due to beaver dams within Great Marsh. The western transect shows two different gradient reversals: one between site 609 and 606, and one between 606 and 603 (fig. 16*E*). For the period November 2012–March 2013 and a smaller period in November 2013, flow is from south to north toward site 603 in a smaller wetland area north of Great Marsh and Beverly Drive. For the period April–July 2013 and portions of August 2013, flow is from north to south toward 606 within Great Marsh.




**EXPLANATION**

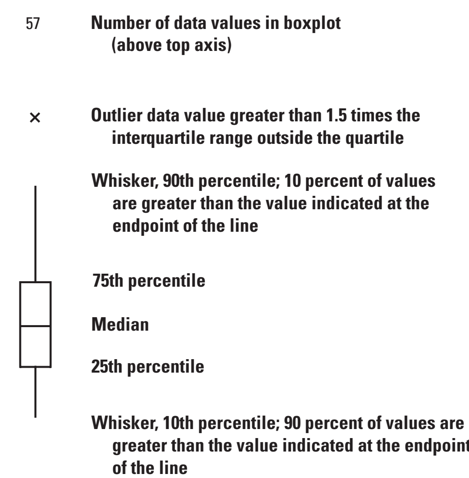



**Figure 11.** Box-and-whisker plots of monthly precipitation statistics for the combined records from the weather stations at Ogden Dunes (1951–89) and Indiana Dunes National Lakeshore, northwestern Indiana (1989–2013), and precipitation from April 2012–December 2013. (Station locations are shown in fig. 1.

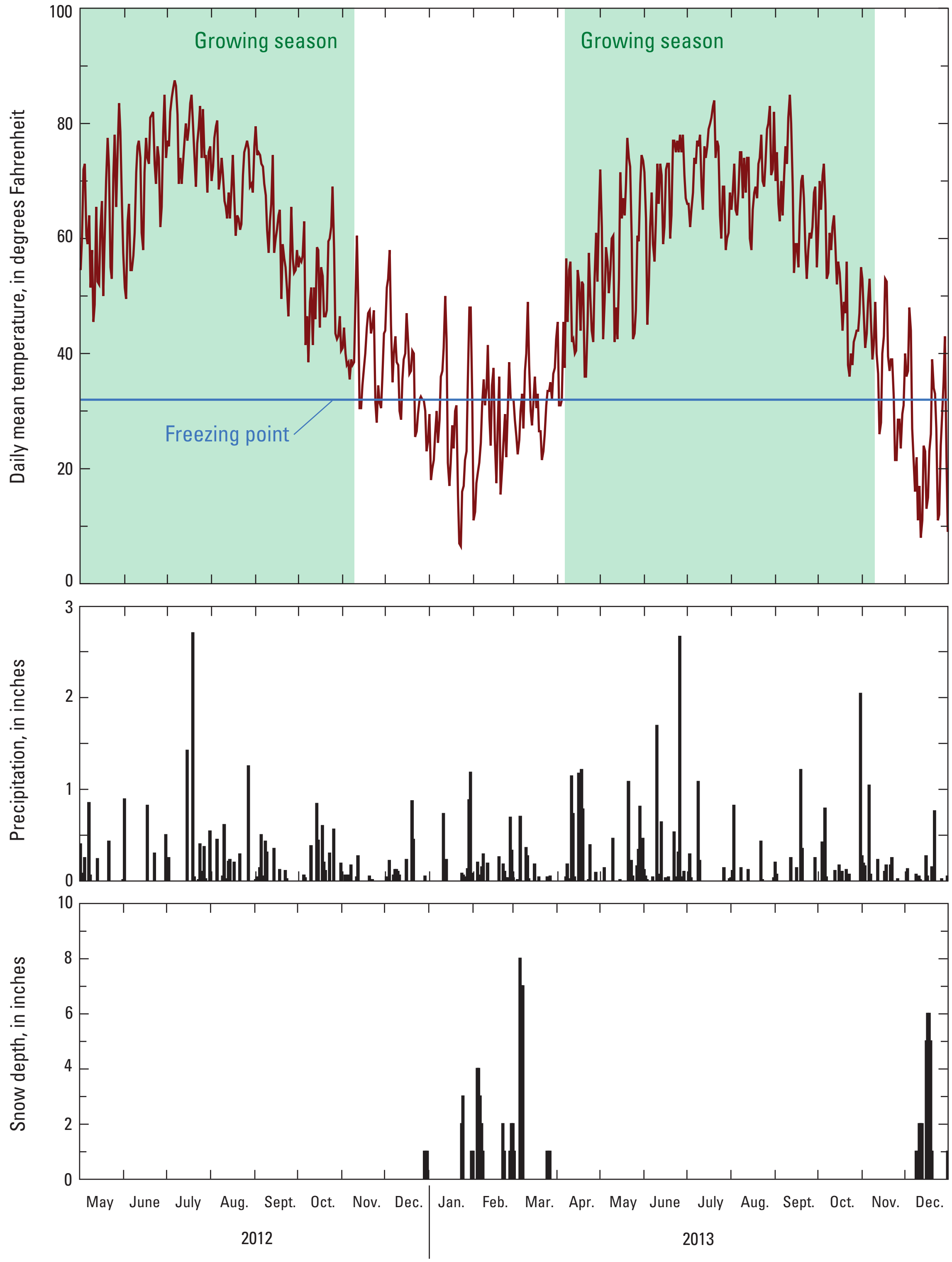
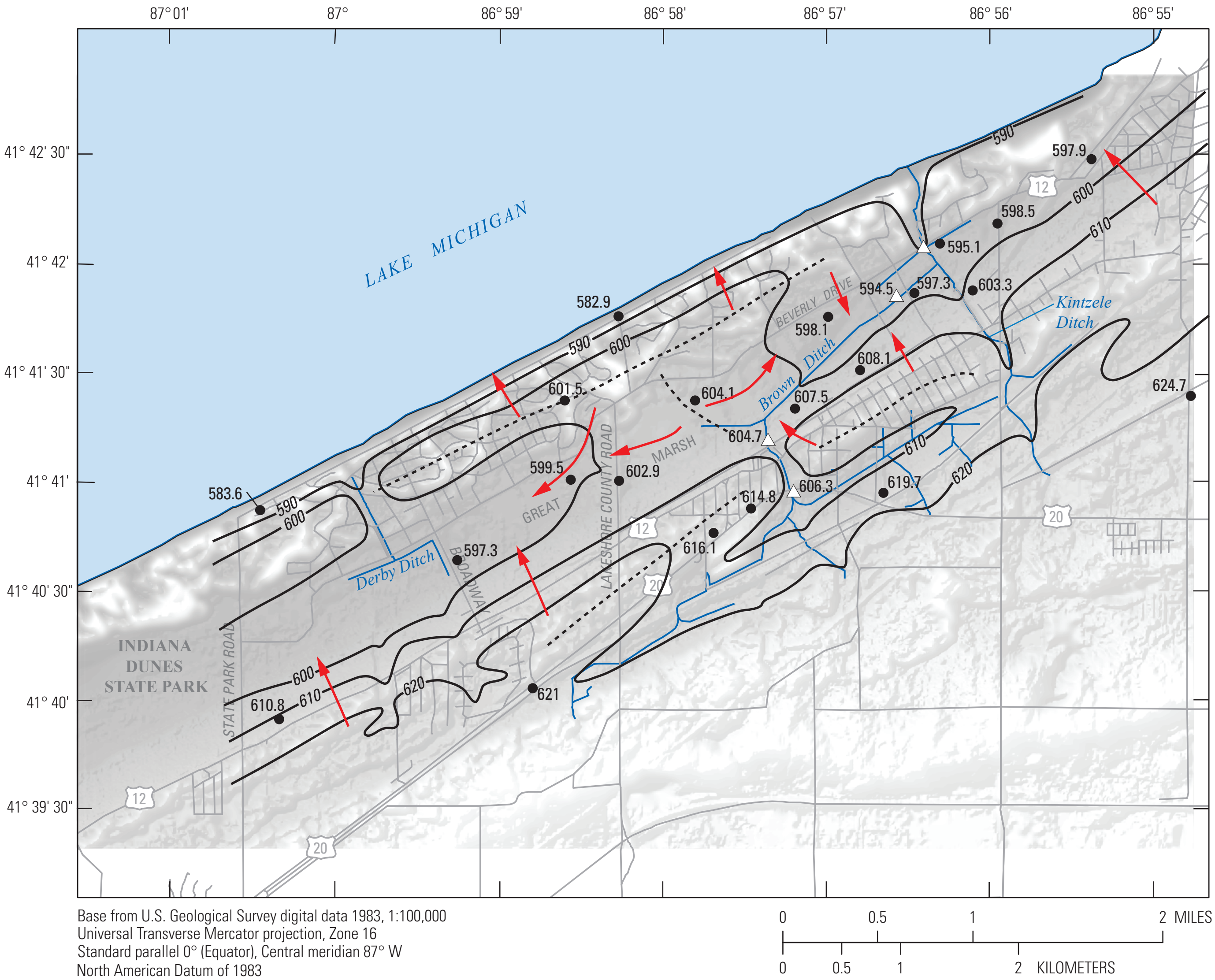



**Figure 12..** Temperature, precipitation, and snow depth from records from the weather station at Indiana Dunes National Lakeshore, northwestern Indiana, May 2012–December 2013




**EXPLANATION**

598.28 ● **Observation well, with water-level altitude on August 5, 1982, in feet above National Geodetic Vertical Datum of 1929 (NGVD 29)**

597.04 △ **Surface-water-level monitoring site, with water-level altitude on August 5, 1982, in feet above NGVD 29**

—*610*— **Water-table contour**—Shows approximate altitude of the water table in the surficial aquifer system on August 5, 1982. Contour interval is in feet above NGVD 29. Contour interval variable. Modified from Shedlock and Harkness (1984).

**Arrow indicating direction of groundwater flow inferred from water-table contours**

- - - - - **Groundwater divide**—Approximate divide in surficial aquifer, August 5, 1982

**Figure 13.** Altitude of the water table in the surficial aquifer measured on August 5, 1982, during dry-weather conditions, in the vicinity of Great Marsh, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana (modified from Shedlock and Harkness, 1984).

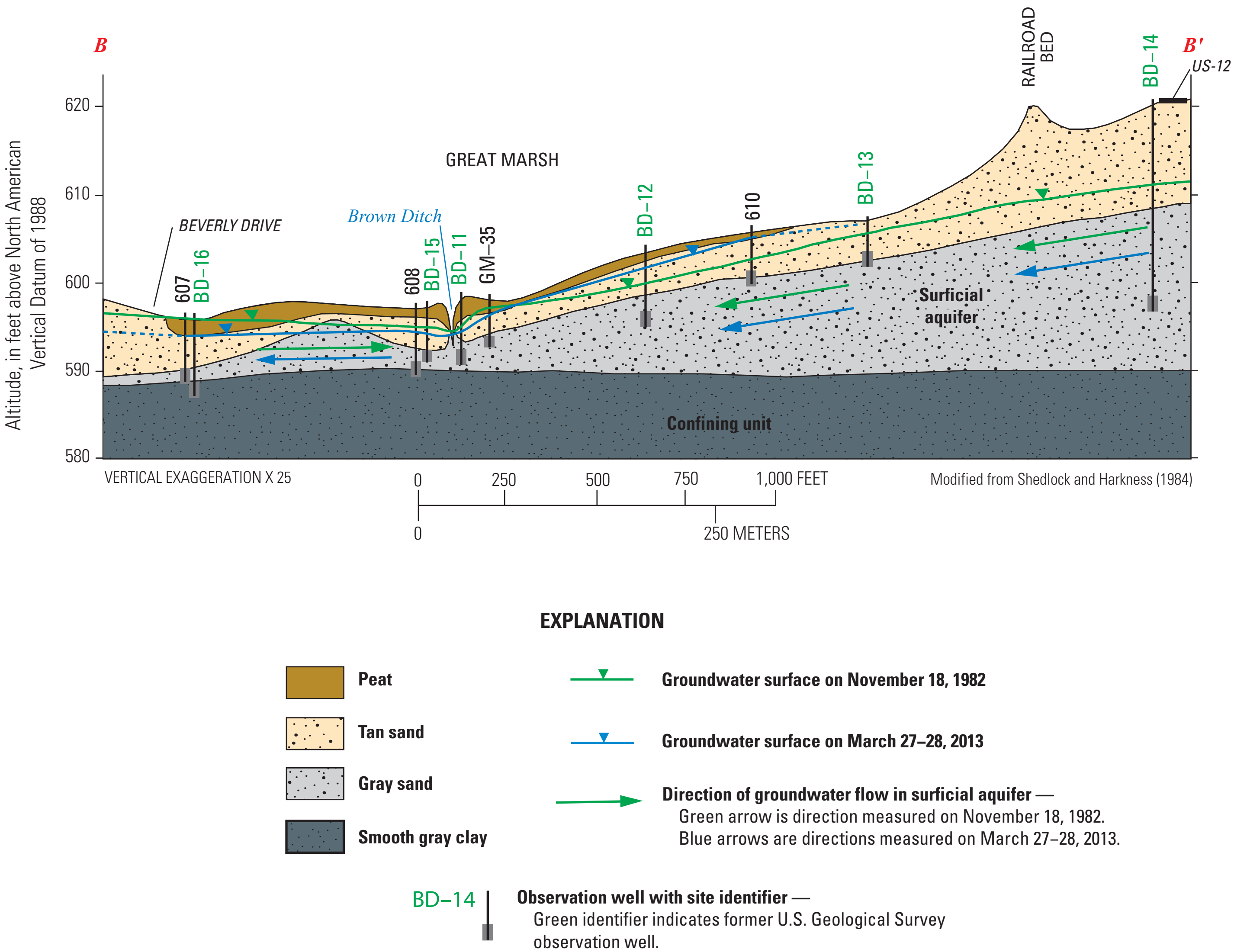
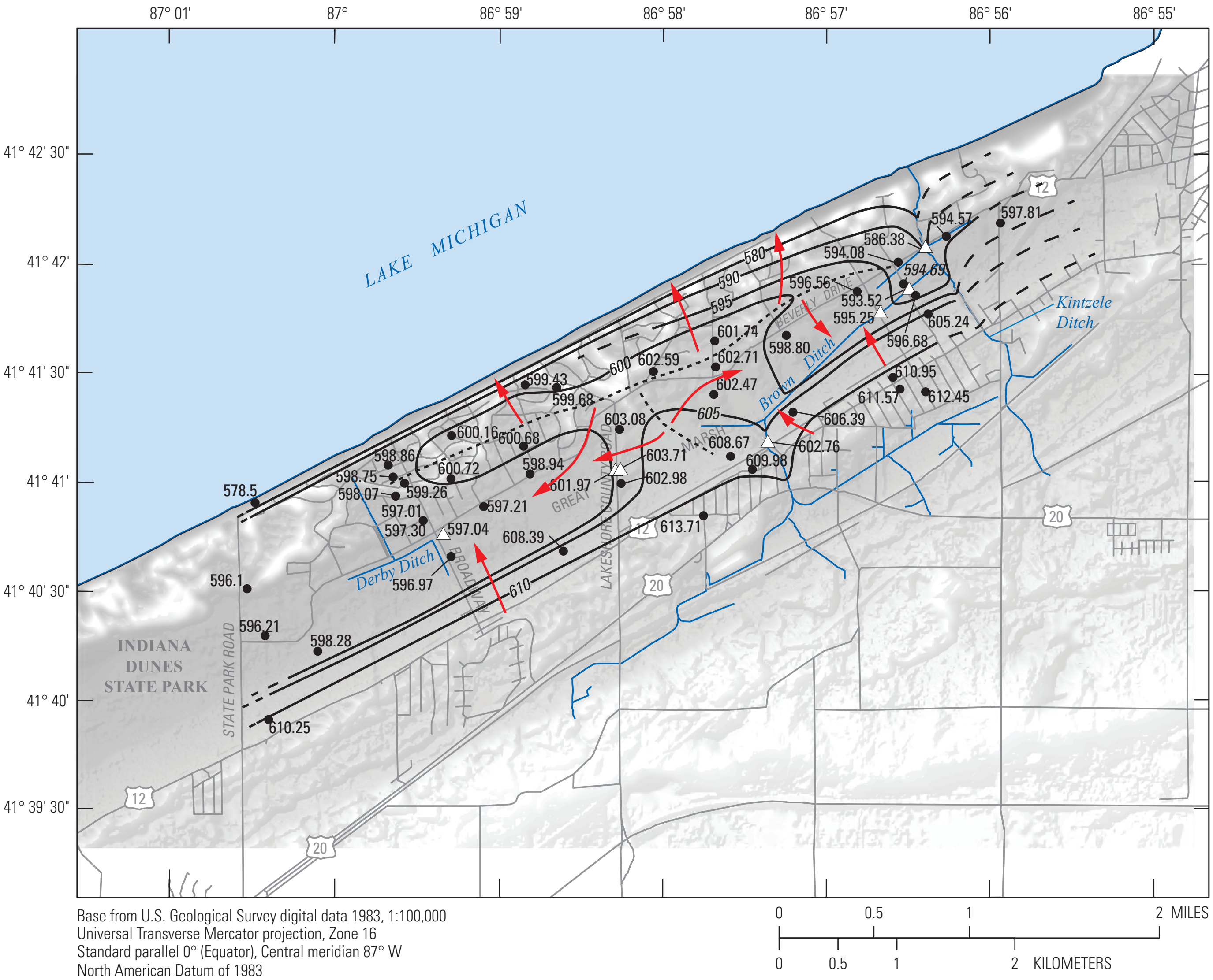



**Figure 14.** Hydrogeologic section and water-table altitude in November 1982 (in green) and March 2013 (in blue) in the surficial aquifer along Carolina Avenue, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana (modified from Shedlock and Harkness, 1984). (Location of section shown in fig. 5.)




**EXPLANATION**

598.28 ● **Observation well, with water-level altitude on March 27–28, 2013, in feet above North American Vertical Datum of 1988 (NAVD 88)**

597.04 △ **Surface-water-level monitoring site, with water-level altitude on March 27–28, 2013, in feet above NAVD 88**

— —*610*—— **Water-table contour**—Shows approximate altitude of the water table in the surficial aquifer system on March 27–28, 2013. Contour interval is in feet above NAVD 88. Contour interval variable. MDashed where approximately located

**Arrow indicating direction of groundwater flow inferred from water-table contours**

- - - - - - - - - - - - **Groundwater divide**—Approximate divide in surficial aquifer, March 27–28, 2013.

**Figure 15.** Altitude of the water table in the surficial aquifer measured on March 27–28, 2013, during wet-weather conditions, in the vicinity of Great Marsh, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana.

***A.*** **East-west transect of five wells and one surface-water monitoring site.**

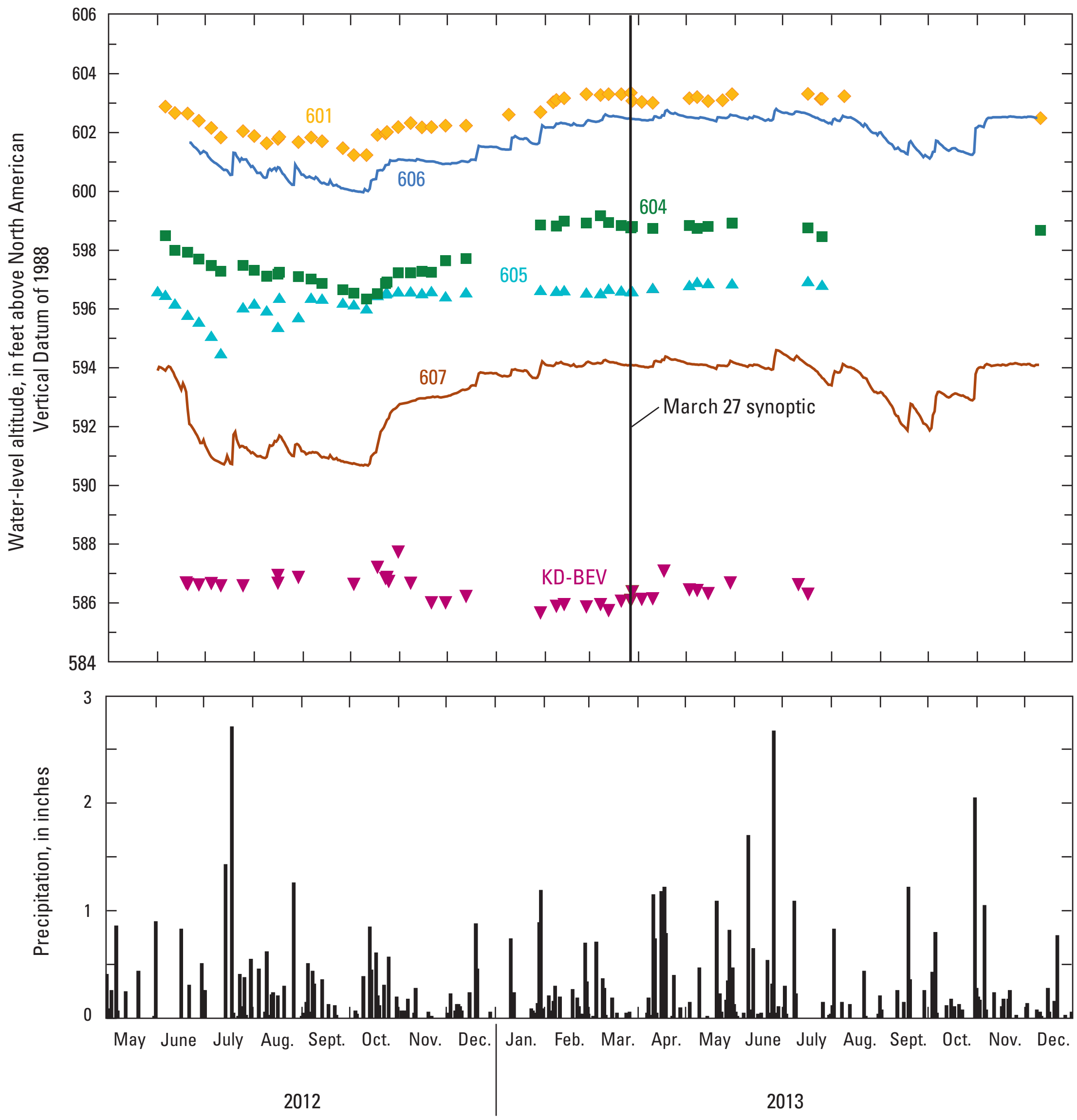



**Figure 16.** Hydrographs of continuous water-level altitude in 11 wells and discrete water-levels at 6 sites, May 2012–December 2013, near Great Marsh, Indiana Dunes National Lakeshore, Indiana. ***A*, East-west transect of five wells and one surface-water monitoring site.** *B*, North-south transect of six wells just east of Lakeshore County Road. *C*, North-south transect of six wells and one surface-water monitoring site. *D*, Subset of the sites shown on figure 16*B* of three wells and one surface-water monitoring site detailing gradient reversals. *E*, Subset of the sites shown on figure 16C of three wells detailing gradient reversals.

***B.* North-south transect of six wells just east of Lakeshore County Road.**

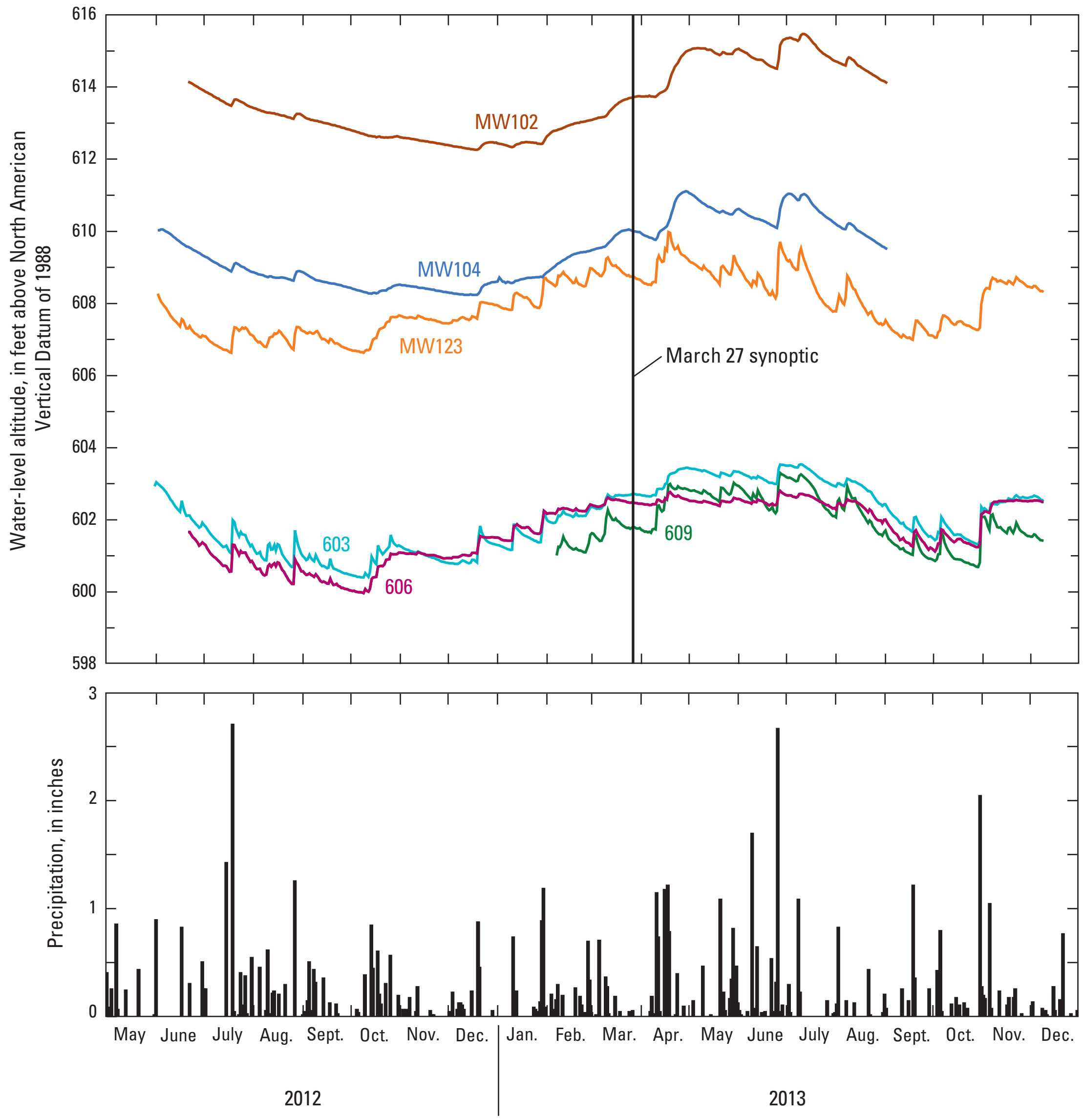



**Figure 16, continued.** Hydrographs of continuous water-level altitude in 11 wells and discrete water-levels at 6 sites, May 2012–December 2013, near Great Marsh, Indiana Dunes National Lakeshore, Indiana. *A*, East-west transect of five wells and one surface-water monitoring site. ***B*, North-south transect of six wells just east of Lakeshore County Road.** *C*, North-south transect of six wells and one surface-water monitoring site. *D*, Subset of the sites shown on figure 16*B* of three wells and one surface-water monitoring site detailing gradient reversals. *E*, Subset of the sites shown on figure 16C of three wells detailing gradient reversals.

***C.*** **North-south transect of six wells and one surface-water monitoring site.**

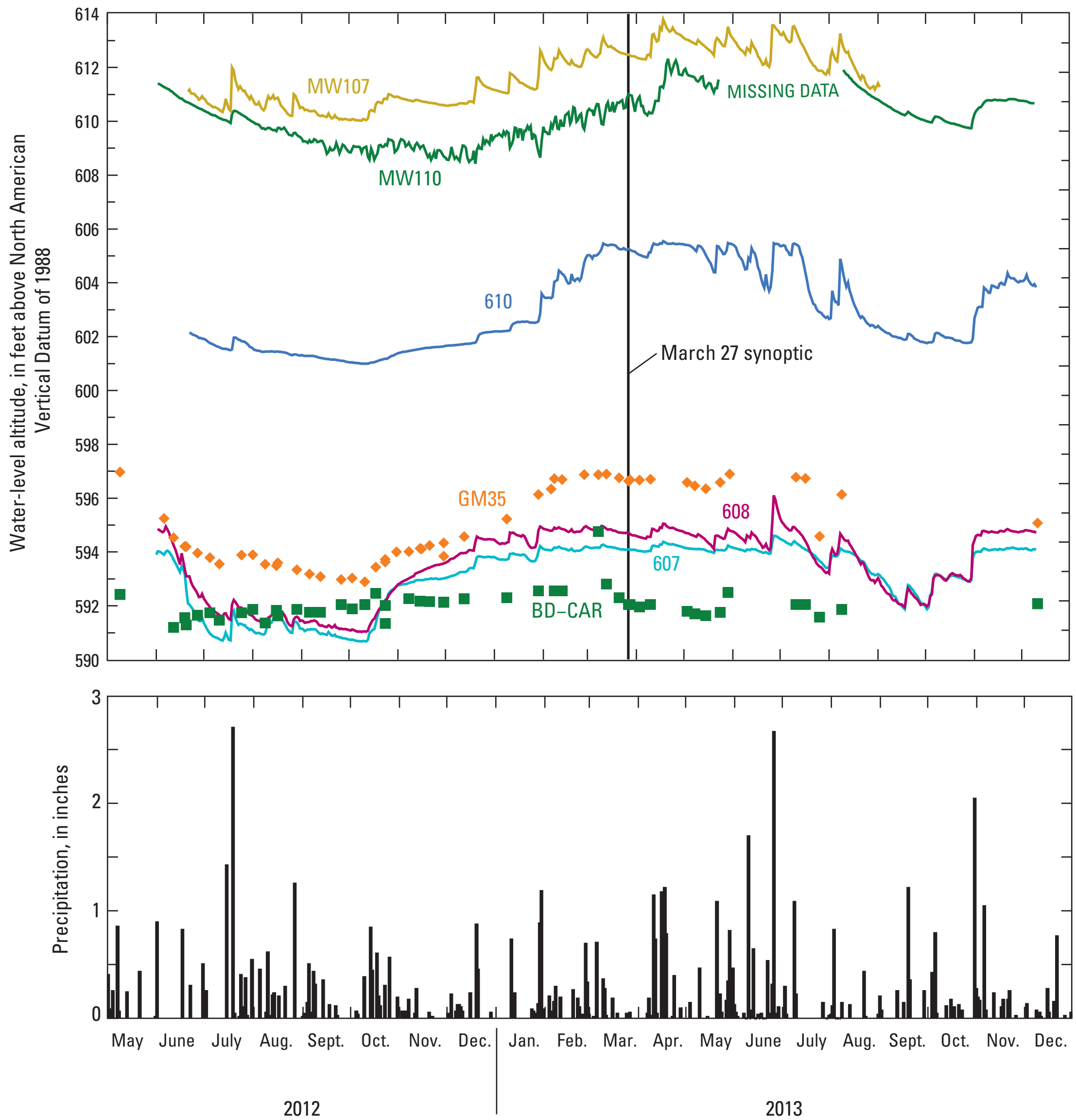



**Figure 16, continued.** Hydrographs of continuous water-level altitude in 11 wells and discrete water-levels at 6 sites, May 2012–December 2013, near Great Marsh, Indiana Dunes National Lakeshore, Indiana. *A*, East-west transect of five wells and one surface-water monitoring site. *B,* North-south transect of six wells just east of Lakeshore County Road. ***C*, North-south transect of six wells and one surface-water monitoring site.** D, Subset of the sites shown on figure 16*B* of three wells and one surface-water monitoring site detailing gradient reversals. *E*, Subset of the sites shown on figure 16C of three wells detailing gradient reversals.

***D.*** **Subset of the sites shown on figure 16*B* of three wells and one surface-water monitoring site detailing gradient reversals.**

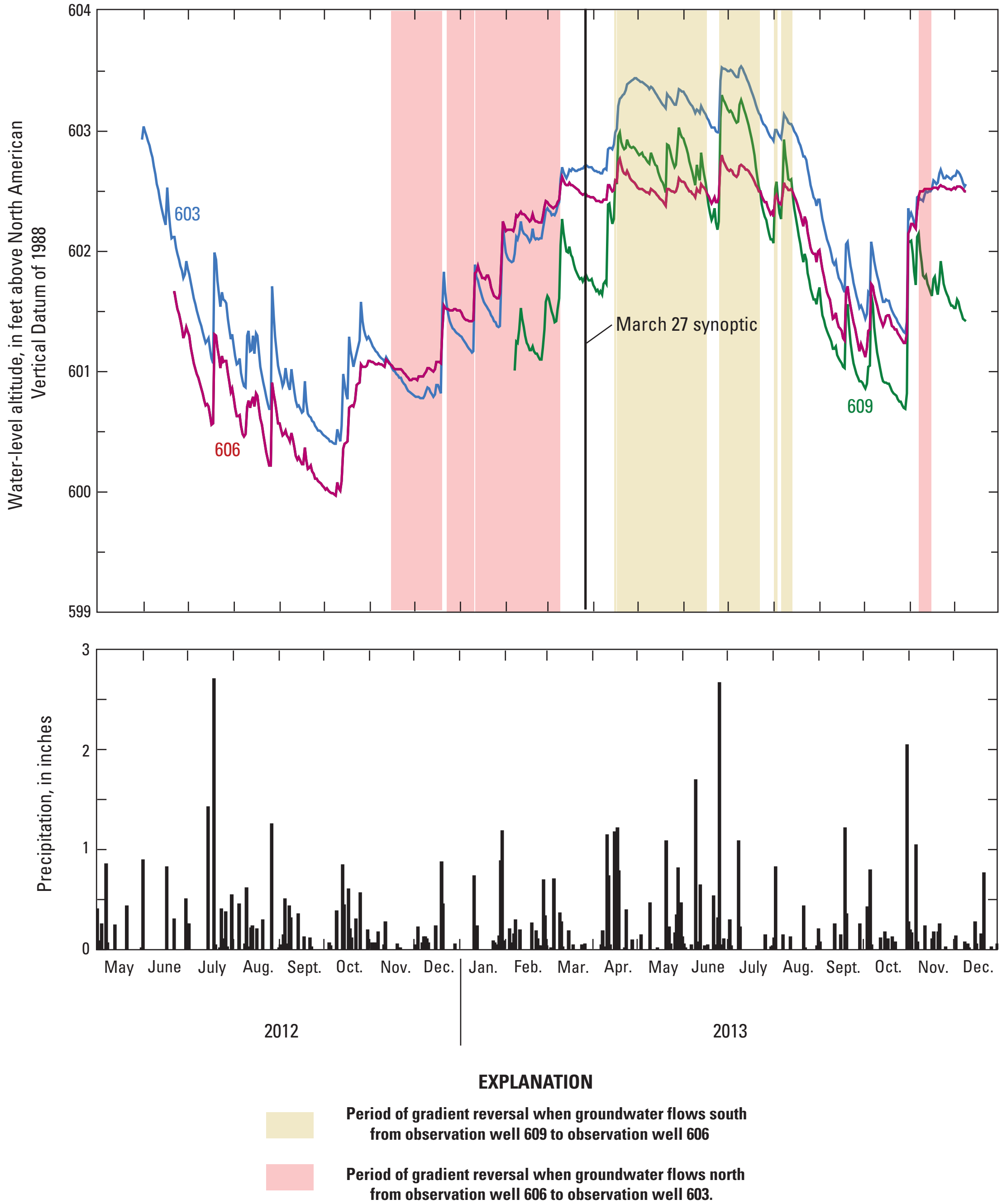
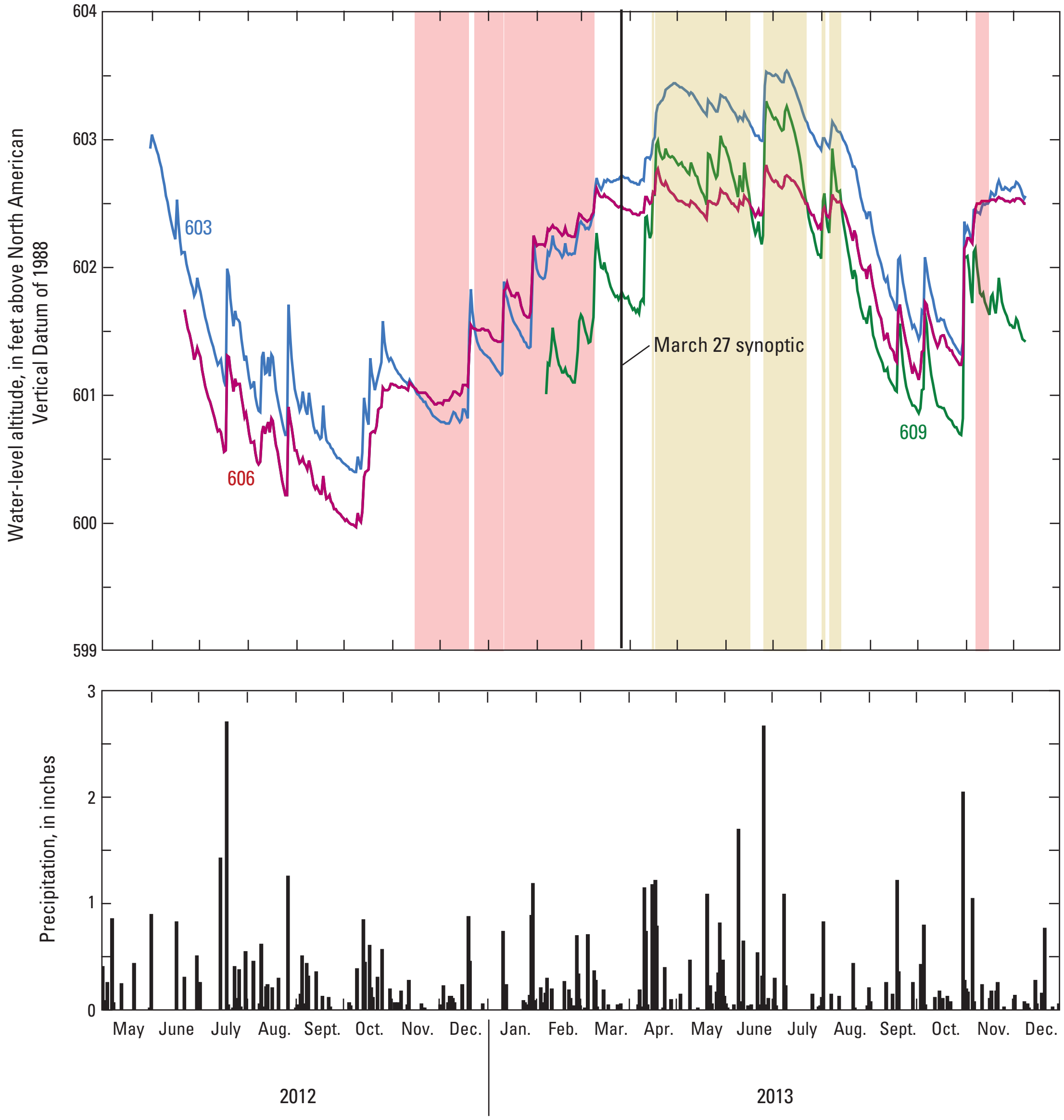



**Figure 16, continued.** Hydrographs of continuous water-level altitude in 11 wells and discrete water-levels at 6 sites, May 2012–December 2013, near Great Marsh, Indiana Dunes National Lakeshore, Indiana. *A,* East-west transect of five wells and one surface-water monitoring site. *B*, North-south transect of six wells just east of Lakeshore County Road. *C*, North-south transect of six wells and one surface-water monitoring site. ***D*, Subset of the sites shown on figure 16*B* of three wells and one surface-water monitoring site detailing gradient reversals.** *E*, Subset of the sites shown on figure 16C of three wells detailing gradient reversals.

***E.*** **Subset of the sites shown on figure 16*C* of three wells detailing gradient reversals.**




**EXPLANATION**

**Period of gradient reversal when groundwater flows south from observation well 609 to observation well 606**

**Period of gradient reversal when groundwater flows north from observation well 606 to observation well 603.**

**Figure 16, continued.** Hydrographs of continuous water-level altitude in 11 wells and discrete water-levels at 6 sites, May 2012–December 2013, near Great Marsh, Indiana Dunes National Lakeshore, Indiana. *A,* East-west transect of five wells and one surface-water monitoring site. *B*, North-south transect of six wells just east of Lakeshore County Road. *C*, North-south transect of six wells and one surface-water monitoring site. *D*, Subset of the sites shown on figure 16B of three wells and one surface-water monitoring site detailing gradient reversals. **E, Subset of the sites shown on figure 16C of three wells detailing gradient reversals.**

Continuous groundwater-level data indicated recharge to the surficial aquifer during January–March 2013 from melting and infiltration of the winter snowpack, precipitation, and the decrease in evapotranspiration during the winter months. Continuous and discrete groundwater-level data presented in figure 16 for May 2012–December 2013 show that water levels gradually increase from October 2012 through March 2013. The gradual increase is followed by a period of relatively stable water levels from mid-March 2012 through May–June 2013, followed by a decrease in water levels into the fall.

Continuous groundwater-level data compared with the annual growing season and land-surface elevation at the monitoring well for 12 specific sites located in Great Marsh indicate the presence and duration of a physical wetland condition (appendix 1) and can be used in interpreting biological data, verifying wetland class, and diagnosing potential stressors (U.S. Environmental Protection Agency, 2002). One of the requirements for an area to be designated a jurisdictional wetland is that the water table is within 1 ft of the land surface for 14 consecutive days during the annual growing season (U.S. Army Corps of Engineers, 2012). For each plot in appendix 1, the altitude of the land surface above NAVD 88 at the observation well is indicated by a horizontal green line. An altitude 1 ft lower than the land surface altitude is indicated by a red line and the area between is shaded grey. The annual growing season also is represented on the hydrographs as green shaded areas.

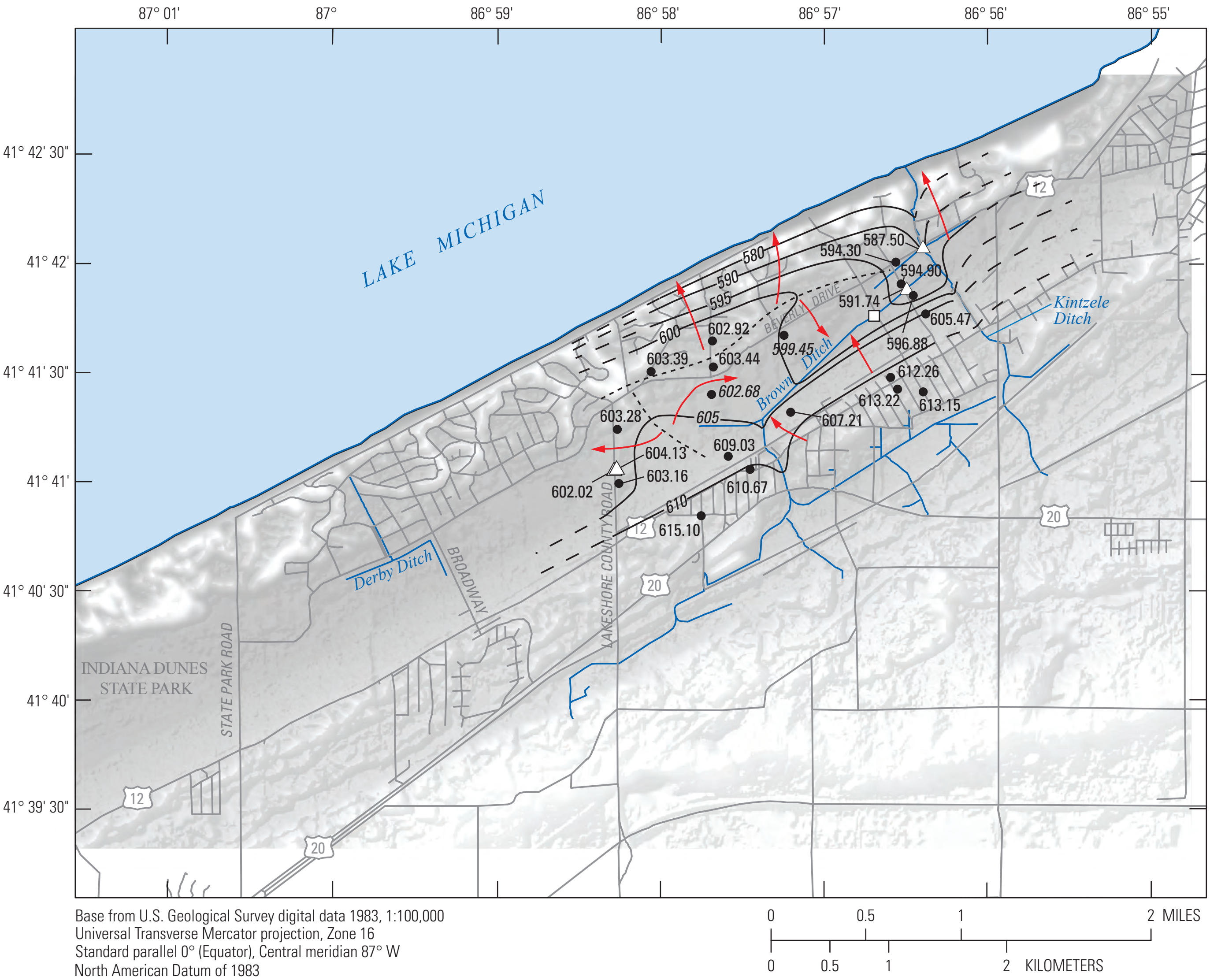
At the beginning of the study in May 2012, observation well sites 601, 602, 603, 604, 606, 607, 608, and GM-35 had water levels within 1 ft of the land surface altitude, but levels decreased below the 1 ft threshold by July 2012 due to increased transpiration from vegetation and lack of prolonged significant precipitation in the area during the months of April, May, and June (figs. 11 and 12). In contrast, water levels in monitoring well 605 maintained altitudes within 1 ft of the land surface. Near the end of the 2012 growing season, water levels at all 12 sites rebounded to near the land surface due to increased precipitation, decreased evapotranspiration in October, and the construction of beaver dams and debris jams located in Great Marsh and Brown Ditch.

Prior to the beginning of the growing season in April 2013, water levels at 11 of the 12 sites were above or within 1 ft of the land surface with the only exception being well 609, which is located in an interdunal wetland north of Great Marsh. Water-levels at all 12 sites continue to be within 1 ft of the land surface until August 2013 due to lower than normal precipitation in July and August 2013 (fig. 11). Water levels increase near the end of the growing season in November due to increased precipitation in October and November 2013 and the decrease in transpiration associated with the end of the growing season.

## April 2014 Levels and Flow

Hydrologic conditions were measured again on April 29, 2014, in response to the installation of a large beaver dam in Brown Ditch just upstream of Central Avenue (figs. 17 and 18). The hydrologic conditions observed were generally similar to the conditions observed during March 2013. Major groundwater divides coincided with dune ridges that parallel Lake Michigan to the north and south of Great Marsh in Beverly Shores and Town of Pines, respectively. A secondary groundwater divide trended northwest-southeast just east of Lakeshore County Road. Groundwater on the east side of this secondary divide flows toward Brown and Kintzele Ditches and ultimately toward Lake Michigan.


**Figure 17.** Photographs showing *A,* a beaver dam located at U.S. Geological Survey (USGS) streamgage 04095154 in Brown Ditch on the upstream side of Central Avenue, and *B*, a beaver dam in relation to the staff gage located at USGS streamgage 04095154. The comparison was used to estimate the altitude of the top of the beaver dam from the known elevation of the staff gage.




**EXPLANATION**

□ **Location of beaver dam in Brown Ditch**

598.28 ● **Observation well, with water-level altitude on April 29, 2014, in feet above North American Vertical Datum of 1988 (NAVD 88)**

597.04 △ **Surface-water-level monitoring site, with water-level altitude on April 29, 2014, in feet above NAVD 88**

— —610—— **Water-table contour**—Shows approximate altitude of the water table in the surficial aquifer system on April 29, 2014. Contour interval is in feet above NAVD 88. Contour interval variable. Dashed where approximately located

← **Arrow indicating direction of groundwater flow inferred from water-table contours**

- - - - - - - - - **Groundwater divide**—Approximate divide in surficial aquifer, April 29, 2014.

**Figure 18.** Altitude of the water table in the surficial aquifer measured on April 29, 2014,during wet-weather conditions in the vicinity of Great Marsh, Indiana Dunes National Lakeshore, near Beverly Shores, Indiana.

## Groundwater/Surface-Water Interaction

Several studies describe groundwater flowing from areas of recharge in dune-beach complexes downgradient and discharging into ditches and ponded areas in the interdunal wetlands (Doss, 1993; Shedlock and others, 1994; Winter, 1999; Lampe and Bayless, 2013). Water levels measured during March 2013 indicate groundwater highs beneath higher elevation dune ridges south of US-12 near Town of Pines and north of Great Marsh beneath Beverly Shores (fig. 15). Groundwater-flow paths indicate that groundwater moves from these areas of groundwater highs to areas of lower elevation and lower groundwater altitudes like those in Great Marsh. The discrete record water-level data collected at monitoring well 605 (fig. 8; appendix 1) indicate that during the dry months (July–October 2012) water-level altitudes remained high, while water levels decreased in nearby monitoring wells 604 and 607. This may be due to the presence of beaver dams in Brown Ditch and their effect on increasing water levels in the wetland to the north, or it may indicate the effect of groundwater discharging to Great Marsh near well 605.

Continuous water-level data collections at sites 603, 606, and 609 during November 2012–November 2013 (fig. 16*A*) may show the effects of the transient change in the water table along the margins of wetlands. In early November 2013, directions of groundwater flow are south from well 603 to well 606 and Great Marsh. The direction of groundwater flow reverses north in late November due to falling water levels in well 603. This condition continues through the relatively dry winter months until March 2013 when the groundwater-flow direction returns south once again when water levels in well 603 rise above those of well 606. This condition continues until early November 2013 when water levels in well 606 rise above those of well 603 and groundwater-flow directions reverse again and flow north for a short period of time. The period of groundwater-flow reversal from November 2012 to March 2013 coincide with a period of relatively low precipitation.

Shedlock and others (1994) describe similar conditions along a north-south trending transect of observation wells near the western margin of the current study area. Continuous water-level data were collected from the wells installed in the upgradient dunes and along the margins of Great Marsh. Gradient reversals and transient water-table mounds were observed in wells along the margin of Great Mash following precipitation events that sometimes persisted for several days (Shedlock and others, 1994, fig. 16). Subtle gradient reversals also were observed at the margins of smaller wetlands in dune-beach complexes that usually followed significant rainfall.

Similarly, climate effects on the configuration of the water table in areas near the margins of surface-water bodies were simulated by Winter (1983). Winter found that the effects of recharge were focused initially in areas where the unsaturated zone was thinnest, raising the water table more rapidly than areas where the unsaturated zone was thicker. Over time, the water table rises progressively more in areas with thicker unsaturated zones. Groundwater-flow gradients can steepen and change direction during this process due to this highly dynamic water-table distribution creating transient water-table mounds in the areas near surface-water bodies. As conditions dry, and the effects of recharge dissipate, transient water-table mounds recess and groundwater-flow directions shift back to the original direction.

## Surface-Water Flow

Streamflow was continuously measured at USGS streamgages for the length of the project (1) where Derby Ditch enters a culvert just upstream of Lake Michigan (04095100), (2) where Brown Ditch is crossed by Central Avenue (04095154), and (3) where Kintzele Ditch is crossed by Beverly Drive (04095158) (table 3). Discrete discharge measurements were made for previous projects in the study area on July 16, 1982, at three locations on Brown Ditch and one location on Kintzele Ditch downstream of the confluence of Brown and Kintzele Ditches (table 6). Discharge measurements were made for this study on March 27–28, 2013, at two sites on Brown Ditch, two sites on Kintzele Ditch, and four sites on Derby Ditch (table 6).

On July 16th, 1982, during a relatively dry portion of the year when 2 of the previous 3 months received below average precipitation, discharge in Brown Ditch just upstream of Great Marsh (BD-TRAIL; fig. 10) was 0.89 cubic foot per second ($ft^3/s$), increased to 1.06 $ft^3/s$ at a site approximately 1 mi downstream (BD-CENT), and ultimately was measured at 1.41 $ft^3/s$ at a site another 1,000 ft further downstream (BD-CAR). Discharge in Kintzele Ditch downstream from the confluence of Brown Ditch (KD-BEV) was measured as 4.38 $ft^3/s$.

Discharge was measured in locations of Brown, Kintzele, and Derby Ditches on March 27–28, 2013, during a period of relatively wet conditions (table 6). Discharge in Brown Ditch measured just upstream of Great Marsh (BD-TRAIL) was 1.78 $ft^3/s$ and increased to 3.13 $ft^3/s$ at a site approximately 1.2 mi further downstream (BD-CAR). Discharge in Kintzele Ditch measured just upstream of Great Marsh (KD-TRAIL) was 3.66 $ft^3/s$ and increased to 7.39 $ft^3/s$ at the location of USGS streamgage 04095158 just downstream of Great Marsh. Discharge in Derby Ditch measured just downstream of Great Marsh was 3.56 $ft^3/s$, decreased to 3.44 $ft^3/s$ at a site approximately 900 ft downstream, decreased further to 3.22 $ft^3/s$ at the location of USGS streamgage 04095100 just upstream of where Derby Ditch enters a culvert under Fairwater Avenue, and increased to 3.91 $ft^3/s$ just upstream of where Derby Ditch discharges to Lake Michigan (DD-LAKE). The increase in discharge between USGS streamgage 04095100 and DD-LAKE is mostly due to the addition of water from tile drains from areas within Beverly Shores to Derby Ditch within the culvert (Egler and others, 2013).

Groundwater seepage to Brown Ditch was calculated from both sets of discharge measurements. Estimated groundwater seepage to Brown Ditch was calculated by dividing the difference between the furthest upstream and downstream

**Table 6.** Discrete discharge measurements from streams and ditches in the study area.

[USGS, U.S. Geological Survey; ft3/s, cubic feet per second; —, not applicable]

| USGS station-identification number | Site name | Water body | Date | Measured discharge ($ft^3/s$) | Instrument reported percent error (percent) | Change from upstream station (percent) |
|---|---|---|---|---|---|---|
| | | | 1982 | | | |
| 414110086572201 | BD-TRAIL | Brown Ditch | 7/16/1982 | 0.89 | 5 | — |
| 414146086563901 | BD-CENT | Brown Ditch | 7/16/1982 | 1.06 | 8 | 19.10 |
| 414153086562901 | BD-CAR | Brown Ditch | 7/16/1982 | 1.41 | 5 | 58.43 |
| 414204086562401 | KD-BEV | Kintzele Ditch | 7/16/1982 | 4.38 | 5 | — |
| | | | 2013 | | | |
| 414110086572201 | BD-TRAIL | Brown Ditch | 3/27/2013 | 1.78 | 10 | — |
| 414153086562901 | BD-CAR | Brown Ditch | 3/27/2013 | 3.13 | 2.2 | 76.12 |
| 414149086560800 | KD-TRAIL | Kintzele Ditch | 3/27/2013 | 3.66 | 1.9 | — |
| 04095158 | — | Kintzele Ditch | 3/27/2013 | 7.39 | 5 | 101.73 |
| 414038086593901 | DD-MARSH | Derby Ditch | 3/28/2013 | 3.56 | 3.7 | — |
| 414050086594701 | DD-DUNE | Derby Ditch | 3/28/2013 | 3.44 | 4.5 | -3.39 |
| 04095100 | — | Derby Ditch | 3/28/2013 | 3.22 | 6.8 | -9.67 |
| 414107086592800 | DD-LAKE | Derby Ditch | 3/28/2013 | 3.91 | 2.5 | — |

discharge measurements by the length of the stream channel between the measurement sites. This value was then multiplied by the total stream reach length to give an estimated groundwater seepage. Two sets of calculations were made using low- and high-end estimates of discharge measurement error to produce a range of estimate values. Seepage is estimated as 1.11–1.42 $ft^3/s$ along Brown Ditch between sites BD-TRAIL and BD-CAR on July 16, 1982, and 1.26–1.46 $ft^3/s$ on March 27, 2013, between the same two sites.

The percent of surface-water flow contributing to Kintzele Ditch from Brown Ditch can be estimated by dividing the measured discharge from the site just upstream of the confluence of Brown Ditch and Kintzele Ditch (BD-CAR) from the discharge measured in Kintzele Ditch just downstream of Great Marsh (KD-BEV). In July 1982, Brown Ditch was estimated to contribute approximately 32 percent of the total flow in Kintzele Ditch. In March 2013, Brown Ditch was estimated to contribute approximately 42 percent of the total flow in Kintzele Ditch. The 10 percent increase in total flow from 1982 to 2013 may be due to the difference in observed climate conditions in the study area.

Groundwater seepage to Kintzele Ditch was calculated from only the 2013 set of discharge measurements due to the unavailability of a discharge measurement at site KD-TRAIL in July 1982. The groundwater seepage rate to Kintzele Ditch was calculated by subtracting the measured flow from Brown Ditch at BD-CAR from the difference between the furthest upstream and downstream discharge measurements (KD-TRAIL and 04095158). Two sets of calculations were made using low- and high-end estimates of discharge-measurement error to produce a range of estimate values. The seepage rate is estimated to be from −0.07 to 1.13 $ft^3/s$, where negative values indicate seepage from the ditch to the aquifer. The mean value (0.53 $ft^3/s$ ) was then divided by the length of the stream channel between the upstream and downstream Kintzele Ditch measurement sites to determine the approximate gain per stream foot of $2.65 \times 10^{-4}$ $ft^3/s$. This value is similar to the calculated gain per stream foot estimated for Brown Ditch in both 1982 and 2013.

The 2013 set of discharge measurements in Derby Ditch were used to calculate the volume of water that Derby Ditch contributed to the surficial aquifer between measurement sites. The difference in discharge between sites DD-MARSH and 04095100 was divided by the length of the stream channel between the two sites to determine the approximate loss per stream foot. Two sets of calculations were made using low- and high-end estimates of discharge measurement error to produce a range of estimate values. The range in stream loss between DD-MARSH and 04095100 was −0.26 to −0.42 $ft^3/s$. The difference in the measured discharge between sites 04095100 and DD-LAKE (0.58–0.81 $ft^3/s$) represents the volume of water contributed from the Beverly Shores tile drain to the flow of Derby Ditch.

Continuous surface-water discharge and surface-water elevation was measured at USGS streamgages on Brown, Kintzele, and Derby Ditches (fig. 10). Continuous daily discharge data collected for Derby and Kintzele Ditches from May 2012 to December 2013 is provided in figure 19. Monthly mean discharge for Kintzele Ditch for June 2012–September 2013 is available in table 7.

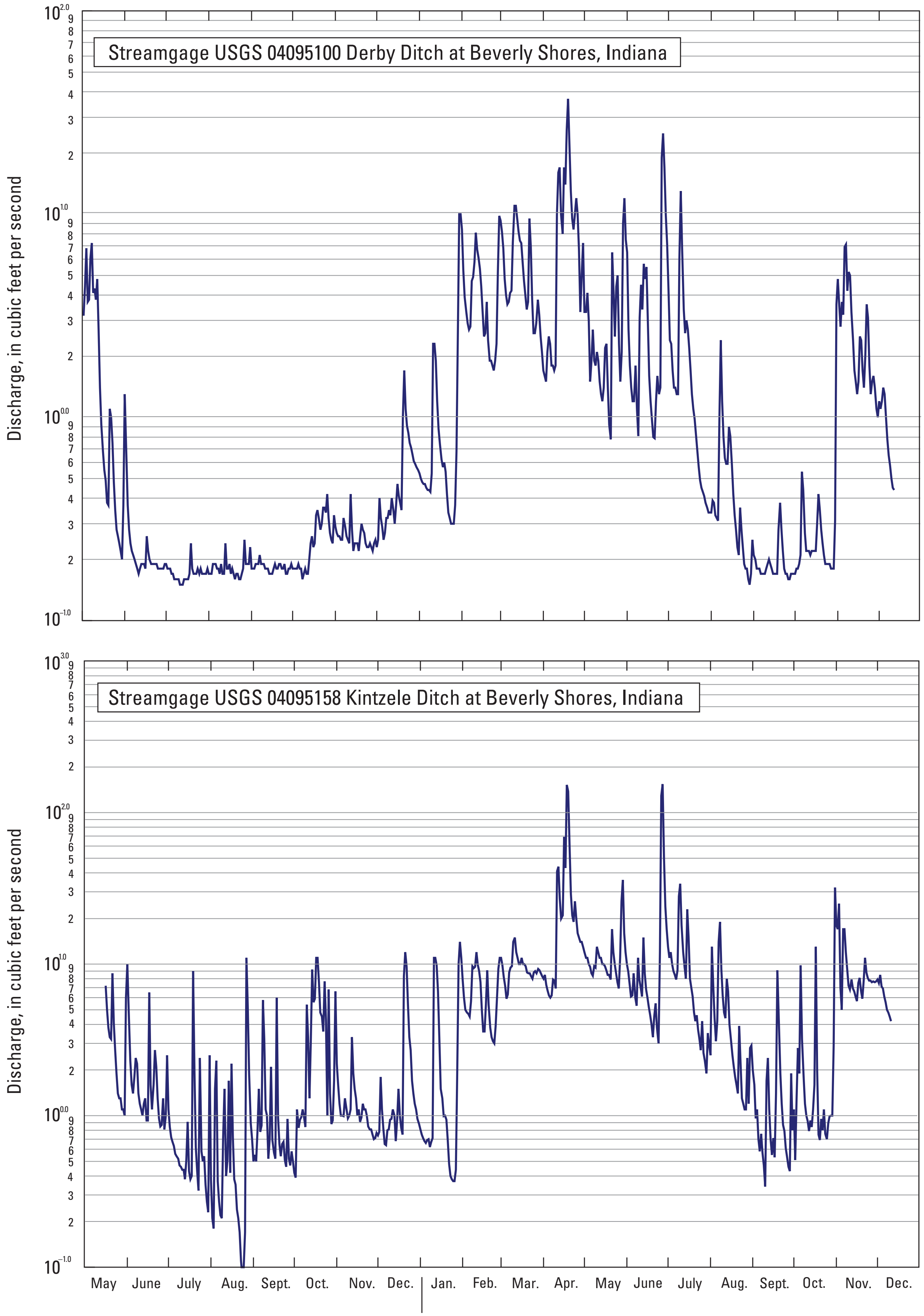



**Figure 19.** Daily value discharge data for May 2012–December 2013 from two streamgages. A, U.S. Geological Survey (USGS) 04095100, Derby Ditch at Beverly Shores, Indiana. B, USGS 04095158, Kintzele Ditch at Beverly Shores, Indiana.

The monthly mean discharge statistics presented in table 7 indicate that during the period of record, streamflow in Kintzele Ditch was lowest in July 2012 (0.97 $ft^3/s$), and highest during April 2013 (29.20 $ft^3/s$). In Derby Ditch, streamflow also was lowest in July 2012 (0.17 $ft^3/s$), and highest during April 2013 (9.36 $ft^3/s$).

The calculation of discharge at a continuously recording streamgage site relies on a stable control structure through which the water can flow and be measured. Continuous discharge could not be calculated from data collected at USGS streamgage 04095154 on Brown Ditch due to the repeated construction and removal of beaver dams at the gage site creating continuously changing control and backwater conditions. However, the percentage of water Brown Ditch contributes to total flow in Kintzele Ditch was estimated by comparing the hydrographs of the two sites during the typically dryer fall and winter seasons, and the typically wetter spring and summer seasons (Rantz and others, 1982). Flow from Brown Ditch is estimated to be approximately 40–50 percent of the total flow in Kintzele Ditch during the typically dryer fall and winter season, and approximately 6–8 percent during the wetter spring and summer season.

**Table 7.** Monthly mean discharge for U.S. Geological Survey station numbers 04095100, Derby Ditch at Beverly Shores, Indiana; and 04095158, Kintzele Ditch at Beverly Shores, Indiana.

[USGS, U.S. Geological Survey; ft3/s, cubic feet per second; —, not applicable]

| Month | Monthly mean discharge at USGS station number 04095158 ($ft^3/s$) | | Monthly mean discharge at USGS station number 04095100 ($ft^3/s$) | |
|---|---|---|---|---|
| | Year | | Year | |
| | 2012 | 2013 | 2012 | 2013 |
| January | — | 3.04 | — | 1.36 |
| February | — | 6.48 | — | 4.16 |
| March | — | 9.47 | — | 5.54 |
| April | — | 29.20 | — | 9.36 |
| May | — | 11.70 | — | 3.15 |
| June | 2.03 | 18.30 | 0.26 | 4.58 |
| July | 0.97 | 9.35 | 0.17 | 2.13 |
| August | 1.14 | 4.62 | 0.18 | 0.49 |
| September | 1.17 | 1.36 | 0.18 | 0.20 |
| October | 3.72 | — | 0.25 | — |
| November | 1.17 | — | 0.26 | — |
| December | 2.14 | — | 0.53 | — |

## Hydrologic Modeling Parameters From Previous Studies

Results from several hydrologic investigations in or near the modeled area and the INDU yielded information about local hydrogeology, groundwater, surface-water levels, and flows that affected the design of this study (table 8). These studies relate to the study area because of similarities in hydrogeologic setting and climatic conditions. Some characteristics of the groundwater model developed for this study are based on conceptual elements and hydrologic properties determined or derived by these previous investigations.

Shedlock and Harkness (1984) used numerical simulations to examine the potential obstruction of surface-water flow in Brown Ditch and to compute the effects of ditch dredging on the water table. The study was prompted by groundwater flooding in basements in a nearby residential area during the spring season and a desire to generally lower the water table. Simulated water-table declines in response to simulated ditch dredging ranged from 0.2 to 2.0 ft depending on the ditch configuration.

Lampe and Bayless (2013) used numerical simulations to examine the effects of urban development and ditching on groundwater and surface-water interaction in and around the Long Lake watershed in the INDU west unit, approximately 8 mi west of the Brown Ditch watershed. The study was prompted by groundwater flooding in basements in a nearby residential area and by the proposed closing of the discharge of US-12 ditch, a major drainage ditch in the watershed. Simulated modifications to the control structure for US-12 ditch resulted in decreases in the discharge of US-12 ditch by up to 61 percent.

Marie (1976) examined a 3.36-square mile ($mi^2$) area about 6 mi west of the Brown Ditch watershed that was considered for dewatering as part of the construction of a power-generation facility. Numerical simulations of that groundwater-flow system indicated that an extensive cone of depression would be created by sustained pumping and that interdunal ponds about 0.15 mi away on INDU property could become dry.

Meyer and Tucci (1979) examined the effects of seepage to the surficial aquifer from fly-ash settling ponds and construction-related dewatering on groundwater levels in the Cowles Unit at the INDU, approximately 5 mi west of the Brown Ditch watershed. The study area was similar to that described in Marie (1976). Results of numerical simulations of steady-state conditions characteristic of those in October 1976 indicated that observed groundwater-level rises in the park (as much as 10 ft) were likely a result of water seeping from nearby fly-ash settling ponds; seepage of as much as 2 million gallons per day (Mgal/d) was estimated by the simulation. The same groundwater-flow model was used to explore the hydrology at a proposed construction site. The construction site was surrounded by a slurry wall and was being dewatered to facilitate construction. Results of the simulations indicated that water levels were being lowered at INDU, outside of the

**Table 8. Hydrologic parameters used or estimated from field measurements in previous studies in northwestern Indiana.**

[in/yr, inches per year; ft/d, feet per day; $ft^3/s$, cubic feet per second; <, less than]

| Reference | Precipitation (in/yr) | Groundwater recharge (in/yr) | Groundwater recharge (in/yr) | Storage coefficient | Vertical hydraulic conductivity of surficial aquifer (ft/d) | Hydraulic conductivity of streambed (ft/d | Hydraulic conductivity of confining unit (ft/d) | Vertical hydraulic conductivity of confining unit (ft/d) | Hydraulic conductivity of carbonate bedrock (ft/d) | Hydraulic conductivity value used to simulate open water (ft/d) | Porosity of surficial aquifer | Leakage rate of sewer (ft3/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Estimated hydraulic parameter values used in simulations in and around the study area | | | | | | | | | | | | |
| Marie (1976) | 37 | 8.4–9.2 | | | | | | | | | | |
| Meyer and Tucci (1979) | | 0–9 | 167 | 0.0002 | 16.7 | | | $6.7\times10^{-3}$ | | $8.6\times10^{8}$ | 0.3 | |
| Shedlock and Harkness (1984) | | | 50 | | | | | | | | | |
| Fenelon and Watson (1993) | 35 | 2–17 | <1–180 | | 3–4 | 1 | 0.0003–0.0006 | 0.0002–0.0030 | 0.01–70 | | 0.4 | 15–50 |
| Lampe and Bayless (2013) | | 5.6–7.9 | 21.34 | | 3 | 17.6 | | | | 7,000 | | |
| Measured hydraulic parameter values in and around the study area | | | | | | | | | | | | |
| Rosenshein and Hunn (1968) | | 13 | | 0.003–0.12 | | | | | | | | |
| Kay and others (1996) | | | 0.65–360 | | | | | | | | | |

slurry containment, by groundwater seepage through or under the wall. Notably, field data indicated that groundwater flow was generally in the vertical direction from below. Gillies and Lapham (1980) reconfigured the numerical model by Meyer and Tucci (1979) in response to updated data and a new configuration of hypothetical water withdrawals from the aquifer. The water levels simulated by Gillies and Lapham (1980) did not substantially differ from those documented in Meyer and Tucci (1979).

Kay and others (1996) used slug-test results from wells completed in the surficial sand aquifer to describe the hydrogeology and determine the horizontal hydraulic conductivity ($K_h$) of the surficial aquifer near the Grand Calumet River and the Indiana Harbor Canal, approximately 20 mi west of the Brown Ditch watershed. Values of $K_h$ ranged from 0.65 to 360 feet per day (ft/d), with most values ranging from 2.1 to 30 ft/d. These slug-test-derived values also were in fair agreement with $K_h$ estimated from nearby specific-capacity tests, which ranged from 8.0 to 130 ft/d and had a mean value of 60 ft/d. The mean $K_h$ computed from specific-capacity-test data is about double the values calculated from the slug-test data. Differences in the values can relate to differences in the method of analysis, the volume of aquifer tested, and the location of testing.

Fenelon and Watson (1993) examined the hydrology near the Grand Calumet River and the Indiana Harbor Canal, approximately 20 mi west of the area examined in this investigation, using measured field data and numerical simulations. A contour map of water-level altitudes indicated a groundwater divide that paralleled the shoreline and separated groundwater flowing south to the Grand Calumet River from that flowing north to Lake Michigan. Results of the numerical simulations indicated that groundwater discharged about 15 $ft^3/s$ to leaky sewers, 10 $ft^3/s$ to the Grand Calumet River, 4 $ft^3/s$ to Lake Michigan, and 0 to 10 $ft^3/s$ to the underlying bedrock. Groundwater leakage into the sewers varied from 15 to 50 $ft^3/s$, but these estimates were based on generalized locations of sewer lines and their elevations relative to the water table. Fenelon and Watson (1993) stated,

> The recharge rate of the Calumet aquifer is virtually unknown; values of 4 to 23 in/yr were used by investigators in several modeling studies of the aquifer. Estimating recharge rates in a given area is complicated by urban and industrial development, which increases surface-water runoff and lowers recharge rates.

Precipitation and recharge rates mentioned in Fenelon and Watson (1993) include a precipitation rate of 35 in/yr (National Oceanic and Atmospheric Administration, 1986–87) and recharge rates of 13 in/yr (Rosenshein and Hunn, 1968) and 4–23 in/yr (Meyer and Tucci, 1979; Warzyn Engineering, Inc. 1987; Watson and others, 1989) depending on land use. In Fenelon and Watson (1993), the recharge was varied from 2 to 17 in/yr depending on land use. Shedlock and others (1994) indicated that the bedrock in the eastern part of their study area probably discharges some water up through the clay unit.

# Simulation of Groundwater Flow

A groundwater model was used to simulate the groundwater-flow system in the vicinity of Great Marsh, INDU to establish a better understanding of the effects that proposed drainage modifications can have on the hydrologic system in the area. The simulations were intended to help the NPS and other local stakeholders manage and protect the resources within the study area. A specific objective in developing the model was to understand the interaction of water levels in Great Marsh and Brown Ditch with groundwater levels in nearby areas. Since the model published by Shedlock and Harkness (1984) adequately simulated surface water/groundwater interactions in the vicinity of Brown Ditch, it was recreated as a starting point for simulations in this study. This section describes

- the reconstruction of the model originally published by Shedlock and Harkness (1984) including a comparison of the reconstructed model results with those of Shedlock and Harkness,
- the conceptual model of the hydrogeology used to guide modifications made to the reconstructed model and the simplifying assumptions made in the design of the modified model,
- discretization in the modified model of the groundwater-flow system, boundary conditions, stresses, and hydraulic properties,
- calibration of the modified model to measured conditions,
- the sensitivity of the model results to model input,
- the presentation of results from the modified model in the form of simulated water-table contours and flow paths,
- the results of scenarios that illustrate the effects of different drainage modifications and climatic conditions on the hydrology near Great Marsh, and
- the limitations and qualifications associated with the results.

The groundwater-flow system was modeled by using the MODFLOW-NWT computer code for simulating groundwater flow of uniform density (Niswonger and others, 2011). MODFLOW-NWT is a Newton-Raphson formulation for MODFLOW-2005 created to improve solution of unconfined aquifers stand-alone program intended to solve computational problems involving nonlinear parts of the unconfined groundwater-flow equation used in the model and to enable cells in simulated unconfined parts of the groundwater-flow system to dry and rewet as the computer calculations converge to a solution, which is a common occurrence when trying to simulate wetland conditions (Niswonger and others, 2011).

## Simplifying Assumptions of the Conceptual Model

Several simplifying assumptions were used to develop the groundwater model. The following assumptions were made to represent the geometry, hydraulic properties, and other characteristics of the groundwater-flow system under the study area:

1. The geologic deposits of the surficial aquifer are generalized as an unconfined sand aquifer.
2. Horizontal and vertical hydraulic conductivity within the surficial aquifer are assumed to be uniform throughout the model except in northern areas beneath the Holocene Dune-Beach Complex and the Tolleston Dune-Beach Complex that join north of Great Marsh (fig. 5), where Buszka and others (2011) describe an organic muck deposit extending an unknown distance and depth beneath the northern dune ridge. Thompson (1987) describes that the same northern margin of Great Marsh Basin is difficult to define due to sediments of the Tolleston complex overlying the sediments of Great Marsh.
3. The surficial aquifer in the model is underlain by a confining unit made up of till and glacial-lacustrine clay and silt. The surficial aquifer is assumed to be considerably more permeable than the underlying confining unit. Flow rates are determined by the thickness and vertical hydraulic conductivity of the confining unit and by the water-level difference between the surficial sand aquifer and the basal sand aquifer.
4. The thickness of all simulated streambeds is assumed to be 1 ft. The calibrated value of vertical hydraulic conductivity of the streambed is based on this 1 ft streambed thickness.
5. The groundwater-flow system is assumed to be in dynamic equilibrium. Dynamic equilibrium is defined as a water-level fluctuation above and below a long-term mean water level. The starting water levels are assumed to be at steady-state and not in any long-term rise or fall.
6. A third-party high resolution light detection and ranging (lidar) dataset was used to represent the land surface of the groundwater-flow model. Lidar does not penetrate areas of open water. Land-surface elevations of the dataset in areas known to be inundated were field verified during data collection and were evaluated to be accurate. The elevations are assumed to be accurate throughout the simulation extent, but some inconsistencies within the groundwater-flow model and the evaluation of the simulated water-table altitudes may occur in areas that were inundated during lidar data collection.

## Reconstruction of the Original Groundwater-Flow Model

The original groundwater-flow simulations published by Shedlock and Harkness (1984) were conducted using the two-dimensional finite-difference model of Trescott and others (1976). This model was a precursor to MODFLOW, which is the USGS current three-dimensional finite-difference groundwater-simulation software package. MODFLOW was first published in 1984 and has been updated periodically with major releases. All of the simulations discussed in this report were completed using MODFLOW-NWT (Niswonger and others, 2011). The original model was reconstructed using MODFLOW-NWT by a university student under supervision of USGS staff. Techniques and a description of the methods used were provided by the student in the form of a report and are cited in this report as a written communication (Jesse Wright, Indiana University-Purdue University Indianapolis, written commun., 2012).

The original model grid contained 21 rows and 32 columns and was 1 layer thick (Shedlock and Harkness, 1984, fig. 10). All rows were 500 ft wide and columns were of varying size. In the western portion of the grid, cells were 1,000 ft wide while columns in the eastern portion of the grid were 500 ft wide. There was a transition zone of three columns between the eastern and western portions where the where the cell widths were 600 and 800 ft. The total width (west to east) of the model grid was 22,500 ft, while the total height (north to south) of the model grid was 10,500 ft.

Elevation values were assigned to the top of the reconstructed model cells using contours from USGS topographic maps (Jesse Wright, Indiana University-Purdue University Indianapolis, written commun., 2012). Little information is available regarding the bottom-surface elevation of the original model. A bottom of aquifer elevation was interpolated using driller's logs from wells pictured in the original report figures and data from 27 additional driller's logs from the IDNR Water Well Record Database. This bottom of aquifer surface was assigned to the reconstructed model cells.

The surficial aquifer was assumed to be homogeneous and isotropic and was assigned a uniform $K_h$ value of 50 ft/d, following the methods described by Shedlock and Harkness (1984). The $K_h$ value of the cells along the south, east, and west borders of the reconstructed model grid was specified as zero to simulate no-flow boundaries. Ditches in the model area were simulated using constant head cells with water-surface elevations assigned using interpolations supplied in the original report figures for Brown Ditch (figs. 4, 10, and 11, Shedlock and Harkness, 1984) and unpublished data for Kintzele and Derby Ditches collected by the USGS at the time of the report and stored with the National Archives and Records Administration by the original report authors.

### Results of the Reconstructed Model

The original model documentation by Shedlock and Harkness (1984) only reports results from a dredging experiment where the original model is altered to show the effects of deepening the upstream east branch of Brown Ditch. Similar alterations were made to the reconstructed model to compare the results to those presented in the original model report.

The simulated drawdown using the reconstructed MODFLOW-NWT model differs mostly on the southern side of the model south of Brown Ditch and Town of Pines (fig. 20). Contours for the reconstructed simulation closely resemble those reported by Shedlock and Harkness (1984) in the areas beneath and to the north of Town of Pines. Differences to the south may be due to differences in the bottom elevation of the model grid cells used by the original model and those in the reconstructed model. The simulation output from the reconstructed model is very similar to the original Shedlock and Harkness (1984) model and indicates that the reconstructed model adequately recreates the original model.

## Modification of the Original Groundwater-Flow Model to Incorporate Current Conditions

In order to more accurately simulate the conditions of the study area, a modified groundwater-flow model was developed by making the following modifications to the reconstructed model. These modifications take advantage of more current technology and expanded features of the MODFLOW-NWT software package, as well as incorporating additional and more current hydrologic and elevation conditions:

- A finer discretization of the same model area,
- Addition of two model layers to simulate ponded surface water (layer 1) and vertical flow paths within the surficial aquifer (layer 3),
- Implementation of the drain package to simulate the effects of surface-water levels in Derby, Brown, and Kintzele Ditches on the groundwater system,
- Addition of parameters to simulate spatial differences in the hydraulic conductivity distribution within the modeled area,
- Addition of spatial recharge of varying amounts to account for the effects of precipitation, evaporation, land use, topographic characteristics, and discharge of groundwater from the surficial aquifer through a local flowing well,
- Inclusion of a finer resolution land-surface elevation dataset derived from the lidar data,
- Inclusion of groundwater- and surface-water level observations and surface-water discharge observations from the study area from March 2013, a relatively wet hydrologic condition, as calibration targets to examine the specific effects of the condition on the surrounding land uses and to assist with sensitivity analysis and estimation of aquifer parameters.

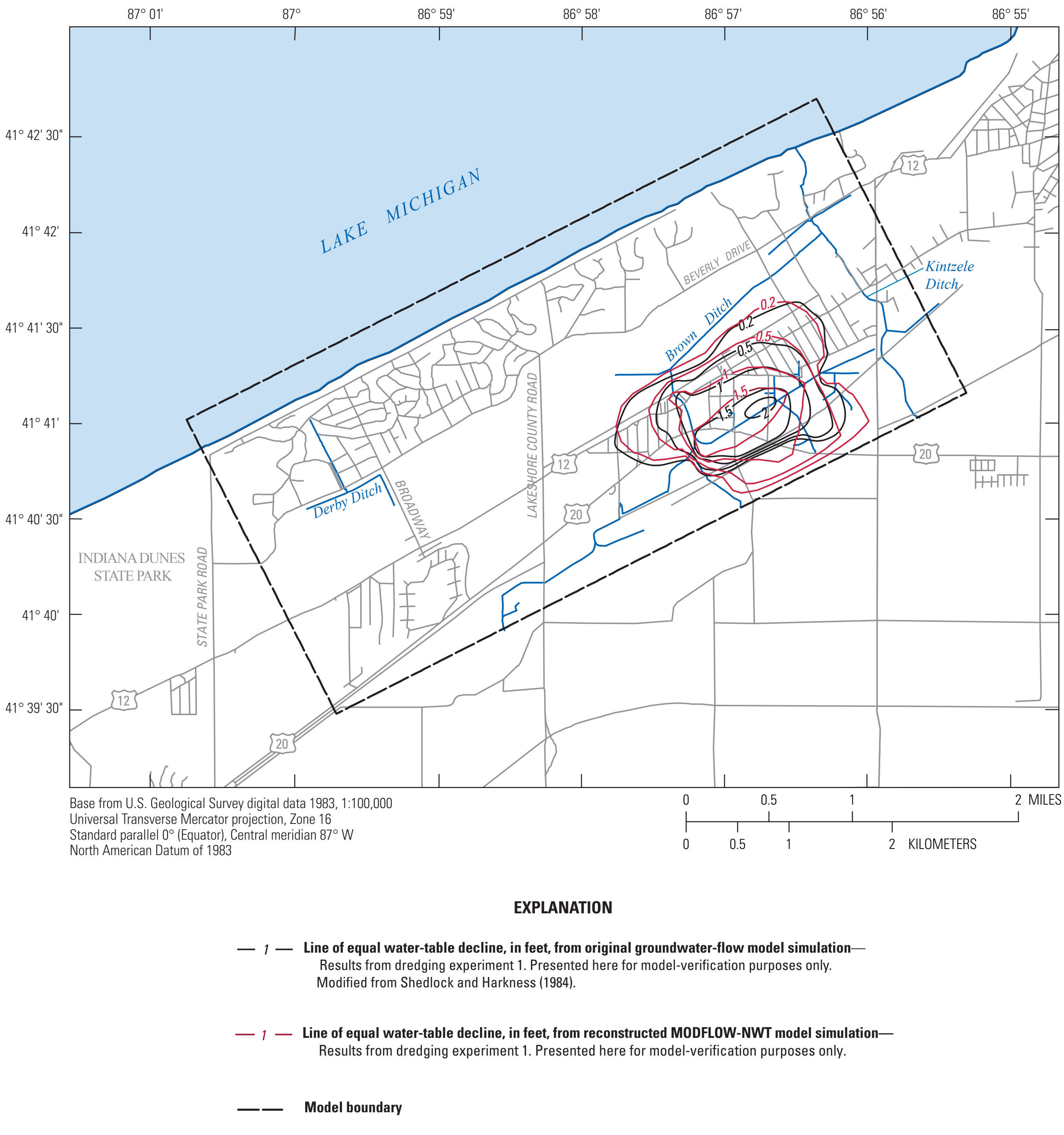



**Figure 20.** Comparison of the results of the dredging experiment using the original model published by Shedlock and Harkness (1984) to the results of a similar experiment using the reconstructed MODFLOW-NWT model (in red).

## Spatial Discretization

The modified groundwater-flow model is based on a rectangular block-centered finite-difference grid network that extends approximately 4.25 mi in length and 2.0 mi in width (fig. 21). The active grid generally extends to natural boundaries: Lake Michigan on the north, Brown Ditch on the south, and Kintzele Ditch to the east. Kintzele and Brown Ditches were observed to be perennial streams during the length of this study. Areas outside of these boundaries are represented by inactive cells and are not simulated by the groundwater model. The western and southwestern model boundary is defined approximately along a flow line and sufficiently to the west so as to not affect simulated flow patterns near the eastern portions of Great Marsh. The model grid contains 105 rows, 225 columns, and 3 layers for a total of 70,875 cells. All model cells measure 100 × 100 ft in horizontal dimension.

Groundwater flow is simulated by three model layers that represent surface water of the model area and the surficial aquifer (fig. 22). Layer 1 represents open-water areas of the model including Great Marsh, and is allowed to be wet in response to the simulated conditions of the model (for example, areas of layer 1 can become wet or dry in response to changes in recharge or other model parameters). Layers 2 and 3 represent the surficial aquifer. Layers 1 and 2 were simulated as potentially confined or unconfined, and layer 3 is simulated as confined. The bottom of layer 1 represents the land surface of the model area. Lidar data in the form of land-surface contours with a 1-ft interval made available by the Porter County surveyor's office was used to compile the land-surface layer within the model (Kevin Breitzke, Porter County Surveyor, written commun., 2013). Surveyed elevations of the bottoms of Derby, Brown, and Kintzele Ditches were used in combination with interpolation techniques to assign land-surface elevation values to cells in the model area that represent these ditches. The bottom of layer 3 represents the top of a till and glacial-lacustrine clay and silt confining unit found throughout the study area (Shedlock and others, 1994). Layer 2 is three-quarters the total simulated thickness of the surficial aquifer. Layer 3 is one-quarter the total simulated thickness of the surficial aquifer.

## Boundary Conditions

A total of 587 drain cells (McDonald and Harbaugh, 1988) were used in layer 2 to represent the ditches shown in figure 23. Drain cells receive groundwater discharge but do not recharge the groundwater system whenever the water table falls below the bottom of the drain. A streambed hydraulic conductivity of 3.0 ft/d was chosen for the ditches because both streambeds were observed to contain sand, peat, muck, and organic material and is similar to values used in previous investigations (Lampe and Bayless, 2013). Bottom elevations for all of the stream and drain cells were based on field measurements made at data-collection sites along the channel and interpolated between. While sump pumps are present in residential neighborhood areas in the model area, sump withdrawals were not simulated in the model due to their relatively small localized impact on the water table.

Boundary conditions in the groundwater model were selected so that the type and location of the boundary would have minimal effect on simulated flow in the modeled area. A constant-flux boundary was used at the top of the model to represent recharge as a spatially variable, fixed value for each cell. A head-dependent-flux boundary was used at the bottom of the model to simulate exchange of vertical flow through the silt and clay confining unit separating the surficial aquifer from the confined basal sand and bedrock aquifer. As inferred from available water levels from the pre-existing USGS monitoring wells installed in the basal sand aquifer (table 2), the flow direction is upward from the basal sand aquifer into the surficial aquifer in the modeled area. No new water-level data were collected from these sites as part of this project. Flow rates are determined by the thickness and vertical hydraulic conductivity ($K_v$) of the silt and clay unit and by the water-level difference between the surficial aquifer and the confined basal sand aquifer. A $K_v$ value of $1.0 \times 10^{-4}$ ft/d was used, which was similar to that used by Lampe and Bayless (2013). A no-flow boundary condition was used on the west side of the model where groundwater flow is assumed to be parallel to the boundary, as shown in Shedlock and others (1994, fig. 14). Kintzele Ditch and upstream reaches of Brown Ditch are assumed to be a hydrologic boundary to the flow system of the model. A head-dependent flux boundary (consisting of drain cells) was placed along the southern and eastern boundaries of the model along these ditches. The bottom elevation of the drain cell values were based on the measured elevation of the bottom of the ditch. A constant-head boundary was placed along the northern edge of the model to represent Lake Michigan, and a value of 576.87 ft NAVD 88 as recorded from the NOAA monitoring site at Calumet Harbor, Illinois, for the period of data collection within the study area.

Initial water levels for all model layers were set at an altitude of 10 ft above the land-surface elevation (top of layer 2), which ensured that all model cells would contain water at the beginning of the simulation. The depths to groundwater generally ranged less than 20 ft throughout the modeled area; therefore, simulated water levels did not need to change substantially to final values during the first simulation.

The sensitivity of the model to features of the model design, such as boundary conditions or the extent of the model grid, was tested by enlarging the active model grid area to the full horizontal extent of the reconstructed model area with no applied boundary conditions and comparing those results with the results of the calibrated modified groundwater-flow simulation. The simulation with the larger active model area produced water levels in two areas that were 1 ft or more higher than the original model results: areas south of US-12 in the western portion of the active model area, and a small area in Town of Pines in the southeast portion of the active model area near upstream portions of Brown and Kintzele Ditches. Both of these areas are located in portions of the model where

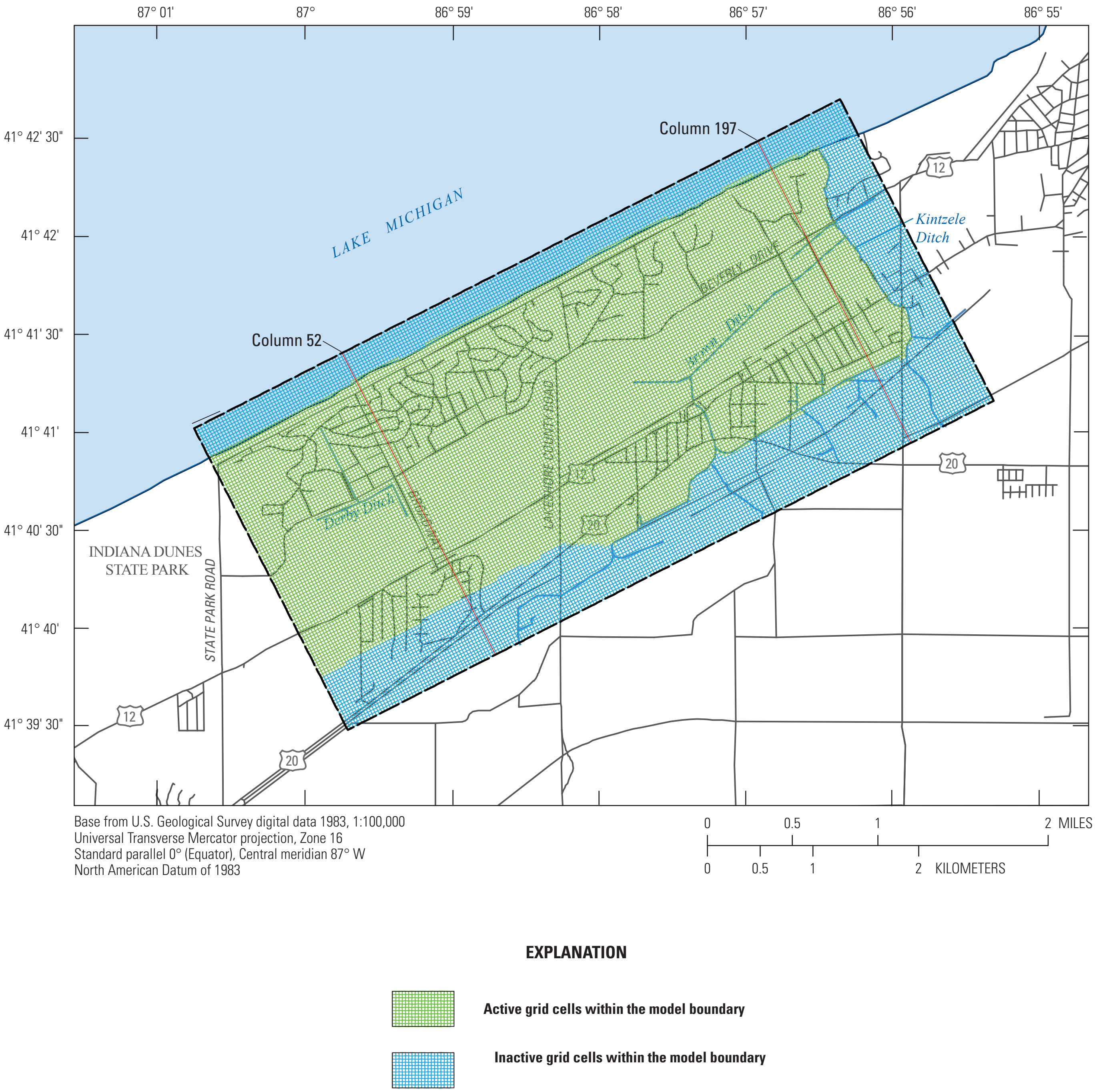



**Figure 21.** Model grid used in the simulation of groundwater flow in the vicinity of Great Marsh, near Beverly Shores, Indiana.

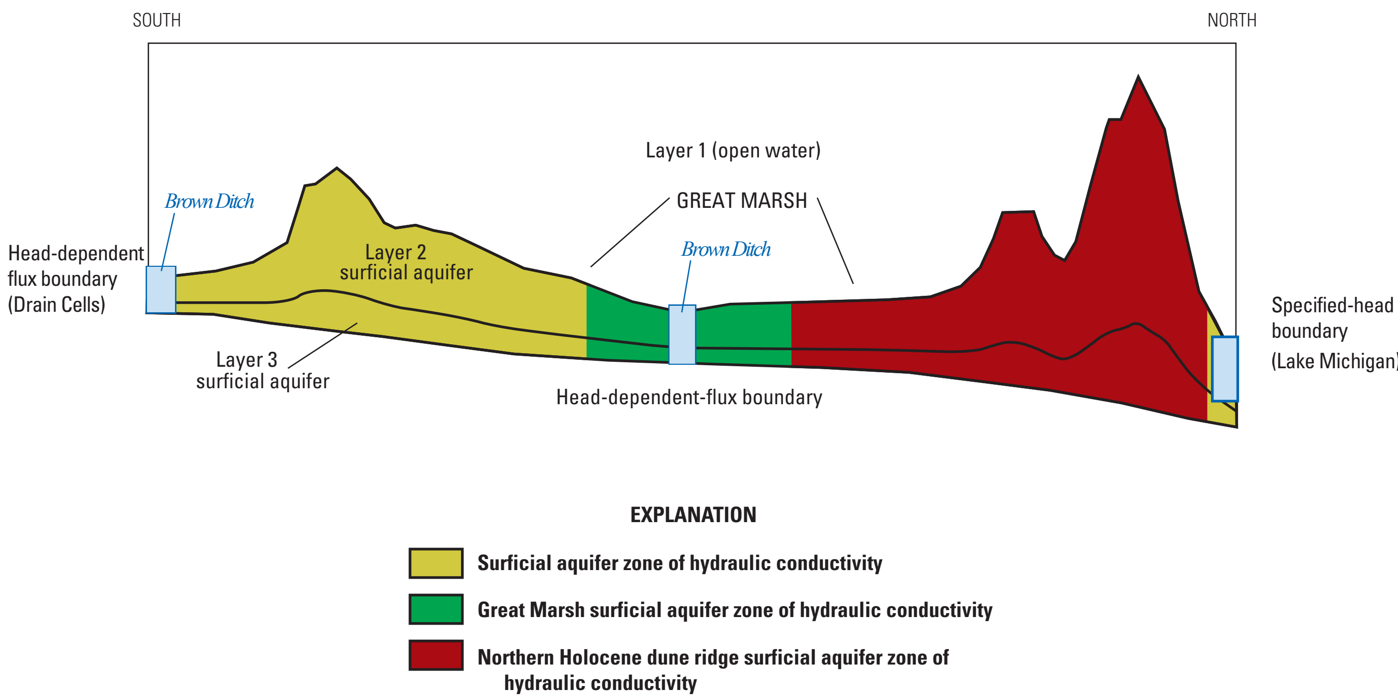



**Figure 22.** Layering design for the model in the vicinity of Great Marsh, near Beverly Shores, Indiana.

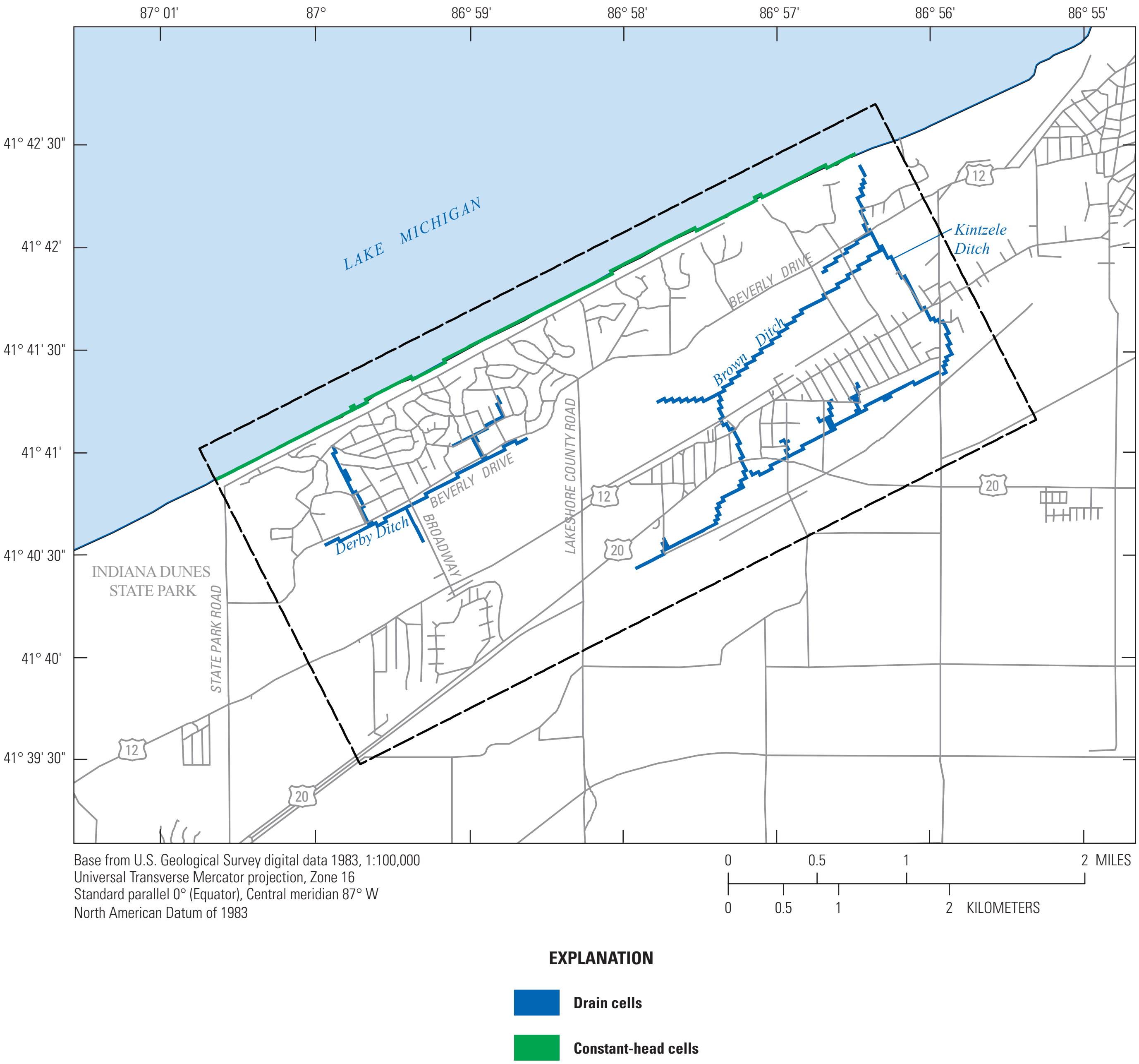



**Figure 23.** Boundary conditions and drain cells used in the simulation of groundwater flow in the study area.

boundary conditions are not well defined. Water levels in the vicinity of Brown Ditch, Great Marsh, and the residential area along US-12 east of Lakeshore County Road were altered by less than 0.03 ft.

The model presented in this report is a modification of a previously published model and was constrained to the extent of the original model. The sensitivity of the results of the simulation to the boundary conditions of the model are presented in this report as a guide that future users of the model can use to determine the suitability of the model for future investigations.

## Hydraulic Properties

Initial values for the $K_h$ were based on previous reported values (table 8) and on other published values for similar materials (Freeze and Cherry, 1979; Fetter, 1994). The $K_h$ of the surficial aquifer in layers 2 and 3, except for areas beneath the northern Holocene dune ridge, was based on aquifer-test information from previous studies reported by Kay and others (1996, p. 30) and from groundwater-flow model results by Lampe and Bayless (2013). According to Kay and others (1996), values of $K_h$ commonly range from 2 to 30 ft/d. Lampe and Bayless (2013) reported initial and final model calibrated values for the $K_h$ of the surficial aquifer as 30 and 21.34 ft/d, respectively. The upper-end value (30 ft/d) was chosen as the initial value on the basis of observed aquifer sediment characteristics in the study area. Areas of the northern Holocene dune ridge where other studies have reported localized finer grained deposits at depth were simulated with lower $K_h$ of 15 ft/d for both layers 2 and 3 than the rest of the surficial aquifer (Buszka and others, 2011; Thompson, 1987; fig. 24).

Portions of the model representing wetland areas were initially assigned a $K_h$ and $K_v$ value of 20 ft/d based on the organic rich nature of the sediments and their probable resistance to flow. Following the work of Lampe and Bayless (2013), the $K_h$ of open water in layer 1 was initially set at 10,000 ft/d to represent the low resistance of flow through open water.

## Recharge

Initial values of recharge rate were based on previous reported values used in groundwater-flow models for similar environments in northern and northwestern Indiana, such as those of as Meyer and Tucci (1979), Arihood and Cohen (1998), Duwelius and others (2001), and Lampe and Bayless (2013). Four initial individual recharge rates were assigned to areas of the model representing wetlands, the town of Beverly Shores, Town of Pines, and other undeveloped areas including some areas of low-density development (fig. 25). Recharge was applied to the top of the model.

A recharge value applied to a single model cell in the western portion of the model just south of Beverly Drive was used to simulate the discharge of a flowing well that penetrates the underlying confined aquifer system (fig. 25). A value of 533 in/yr was assigned to the cell, which simulates the discharge of approximately 9,100 gallons per day (gal/d) of water to the land surface as measured on September 3, 2013. Discharge from the well for the purposes of this study is assumed to be relatively constant and the measurement made on September 3, 2013 to be representative for the period of investigation.

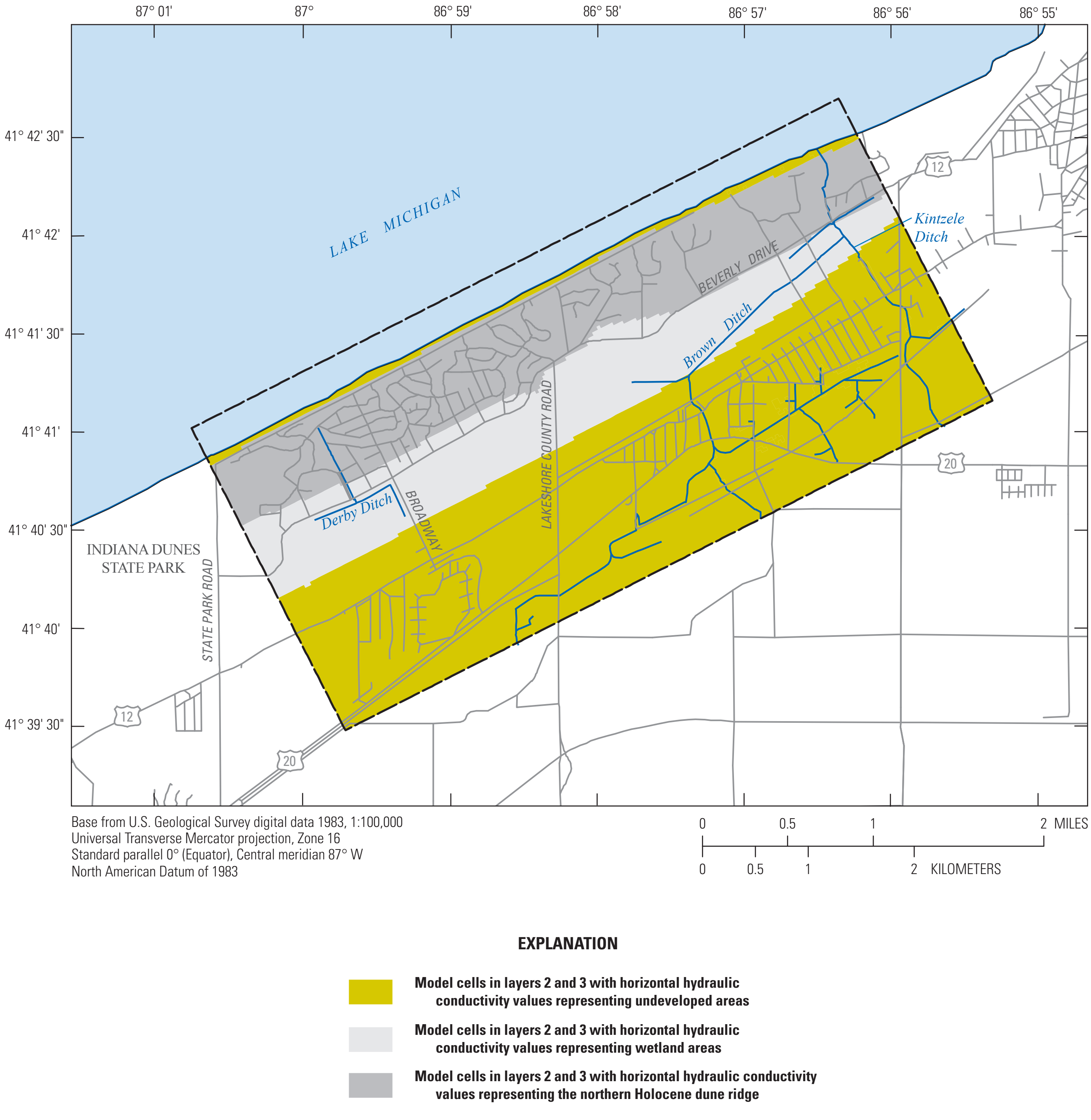



**Figure 24.** Hydraulic conductivity distribution within model area of layers 2 and 3.

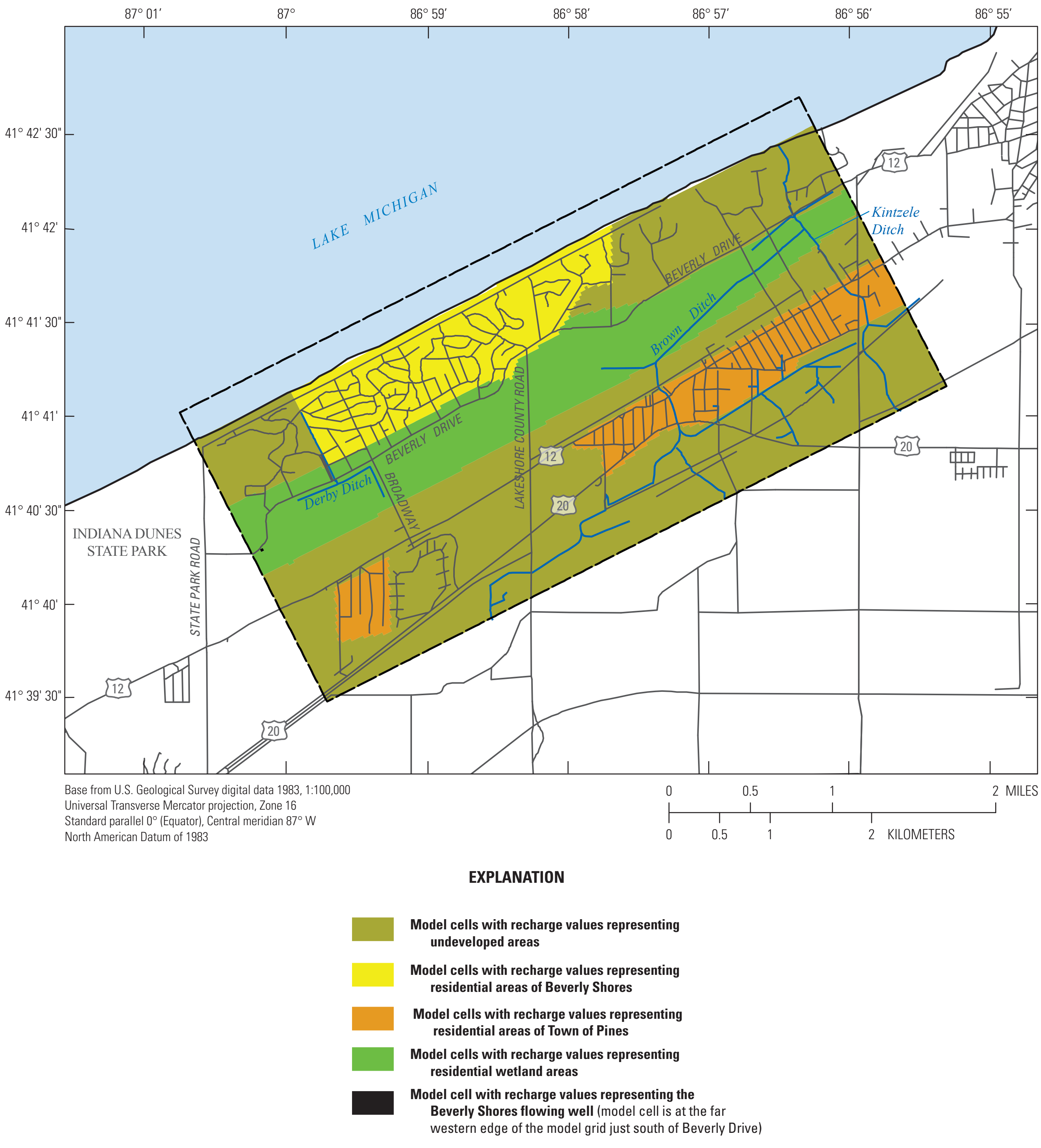



**Figure 25.** Location of recharge zones in the town of Beverly Shores, Town of Pines, and other undeveloped and wetland areas of the groundwater-flow model; and point representing the discharge of water from the Beverly Shores flowing well.

## Model Calibration

Calibration is the process of adjusting the model input variables, also called parameters, to minimize the errors or differences between simulated and observed hydraulic heads and flows. In this report, the term "head" is used interchangeably with water-level altitude (Lohman and others, 1972). Many of the model parameters were automatically adjusted during parameter estimation. During calibration of the modified groundwater-flow model, parameters were adjusted manually at first and then by use of automatic parameter-estimation techniques to match hydraulic heads from observation wells and streamflow fluxes. ("Streamflow flux" in this case is the increase in discharge along a reach attributed to groundwater inflow).

Parameter estimation in MODFLOW-NWT was accomplished with the UCODE_2005 program (Harbaugh, 2005; Poeter and others, 2005), which uses a nonlinear least-squares regression method to aid in estimating parameters that represent hydrologic properties and to further evaluate the model. The parameters estimated during calibration represent the hydrologic properties distributed as constant values over broad areas or parameter zones, as well as over extended linear features such as ditches. Calibrated parameter values are not necessarily expected to equal or agree with specific values of field tests within a given zone of aquifer or stream reach because parameters represent hydraulic conditions over broad areas.

Parameter-estimation techniques were used to estimate values of hydrologic properties for the groundwater-flow simulations; some of those values were then adjusted manually to the final parameter values used in the model. This method is explained in great detail in Hill (1998) and Hill and Tiedeman (2007). The regression method is a more efficient and objective process compared to trial-and-error calibration because all parameter values are adjusted automatically and concurrently to obtain the best possible fit between observed and simulated values. The numerical difference between observed and simulated values is called a residual. During the parameter-estimation process, parameter values are estimated by minimizing the sum of the squared weighted residuals, called the objective function. Parameter estimation was manually constrained by the authors so that parameter values used for the groundwater simulations would be within a range of values expected for the environmental conditions existing in the study area. In some cases, parameter estimation resulted in the final reported value; but in others, a slight manual trial-and-error adjustment of the estimated parameter value resulted in new values that achieved lower total root mean square error (RMSE) values for both head and flow observations. If manual adjustment of a parameter from the estimated value did not achieve lower RMSE values, the original parameter estimated value was adopted and is reported herein as the final value. The model was considered calibrated once the overall fit of the groundwater-flow model was near 1 ft (a further discussion is available in the "Model Fit to Observations" section).

### Model Parameters

In the model, grid cells assumed to have similar hydrologic properties were grouped together as a parameter zone and assigned a single parameter value that was adjusted during the calibration process. In all, 14 parameters were used in the final model design. Names of the parameters used in the model, the model component that each parameter represents, and associated values are listed in table 9.

The sensitivity of simulated water levels to changes in model parameters was measured to evaluate which parameters could be estimated by means of automated parameter-estimation techniques. The sensitivity of hydraulic heads with respect to various model parameters was calculated by using the sensitivity equation method (Hill and others, 2000). Composite scaled sensitivities (CSS) and significant correlations between parameters were calculated for each parameter (table 9). CSS values aid in determining whether there is adequate information in the calibration data to estimate a particular parameter; generally, parameters that are highly correlated with other estimated parameters cannot themselves be estimated. CSS values less than approximately 0.01 times the largest CSS of the parameters indicate that the regression may not be able to estimate the parameter (Hill, 1998, p. 38; Hill and Tiedeman, 2007, p. 50).

### Observations and Observation Weights

The observations used for model calibration consisted of 36 water-level measurements and 3 streamflow gain/loss measurement made in March 2013 (table 10). Of the 36 water-level measurements, 30 were made in groundwater-monitoring wells and 6 were made using surface-water level sites. Most of the water-level measurements were in the vicinity of Great Marsh and Brown Ditch on March 27–28, 2013. Streamflow gain and loss targets were derived from multiple discrete discharge measurements made in Brown, Kintzele, and Derby Ditches on the same day as groundwater- and surface-water level measurements (table 6).

Water-level and streamflow gain/loss observations were weighted before they were used in model calibration to reduce the influence of observations that were less accurate and to increase the influence of observations that were more accurate. Residuals of water-level observations are reported in units of feet, and residuals of streamflow are reported in units of cubic feet per second. The weighting process produces "weighted residuals" (a measure of the difference between an observation and its corresponding simulated value) that have the same measurement units, whether the residual is for water levels or streamflow gain/loss. Model calibration that uses water-level and streamflow gain/loss residuals in the same measurement units allows both types of residuals to be included in the sum of squared errors that the automated parameter-estimation process attempts to minimize.

**Table 9.** Final parameter values and parameter composite-scaled sensitivities used in the modified model simulations.

| Parameter | Parameter description | Parameter type | Parameter derived by means of parameter estimation | Correlations with other parameters | Parameter value | CSS |
|---|---|---|---|---|---|---|
| kdrn1 | Vertical hydraulic conductivity of the streambed for the ditch along US-12 | Drain | Yes | NC | 3.115 ft/d | 18.34 |
| kow | Horizontal hydraulic conductivity assigned to the cells of layer one used to simulate areas of the open water of East Long Lake and West Long Lake | Horizontal hydraulic conductivity | No | NC | 10,000 ft/d | 11.60 |
| ks | Horizontal hydraulic conductivity of the surficial sand aquifer | Horizontal hydraulic conductivity | Yes | PineRech, SandRech, MarshRech, kwet, Bev-ShoresR | 17.73 ft/d | 150.64 |
| kBevS | Horizontal hydraulic conductivity of the surficial sand aquifer of northern dune ridge | Horizontal hydraulic conductivity | — | BevShoresR, SandRech, kwet, MarshRech | 14.34 ft/d | 266.06 |
| kwet | Horizontal hydraulic conductivity of the surficial aquifer of Great Marsh | Horizontal hydraulic conductivity | — | SandRech, MarshRech, BevShoresR | 17.82 ft/d | 30.62 |
| kvow | Vertical hydraulic conductivity assigned to the cells of layer 1 used to simulate areas of the open water of East Long Lake and West Long Lake | Vertical hydraulic conductivity | No | NC | 10,000 ft/d | 0.28 |
| kvs | Vertical hydraulic conductivity of the surficial sand aquifer | Vertical hydraulic conductivity | No | NC | 5 ft/d | 1.58 |
| kvBevS | Vertical hydraulic conductivity of the surficial sand aquifer of northern dune ridge | Vertical hydraulic conductivity | — | NC | 3.0 ft/d | 0.48 |
| kvwet | Vertical hydraulic conductivity of the surficial sand aquifer of Great Marsh | Vertical hydraulic conductivity | — | NC | 10 ft/d | 2.01 |
| SandRech | Recharge rate to the surficial sand aquifer in non-urban and non-wetland areas | Recharge | Yes | MarshRech | 14.66 in/yr | 170.71 |
| BevShoresR | Recharge rate to the surficial sand aquifer in urban areas | Recharge | Yes | SandRech, MarshRech | 21.97 in/yr | 294.26 |
| MarshRech | Recharge rate to the surficial sand aquifer in wetland areas | Recharge | Yes | NC | −6.91 in/yr | 139.46 |
| PineRech | Recharge rate to the surficial sand aquifer in Town of Pines | Recharge | Yes | MarshRech, SandRech | 11.70 ft/d | 99.62 |
| flowingWel | Recharge values used to simulate flow from the flowing well in Beverly Shores | Recharge | No | NC | 533 ft/d | 0.28 |

**Table 10.** Measured (observed) and model-calculated (simulated) water levels and discharge measurements used as observations and model residuals for the modified groundwater model.

[NAVD 88, North American Vertical Datum of 1988]

| Observation name | Site type | Date | Observed value | Simulated value | Residual |
|---|---|---|---|---|---|
| Water level, in feet above NAVD 88 | | | | | |
| 213G | Groundwater | March 2013 | 596.97 | 597.34 | −0.37 |
| SG-1 | Surface water | March 2013 | 597.04 | 595.30 | 1.74 |
| GM-27 | Groundwater | March 2013 | 608.39 | 608.09 | 0.30 |
| 559B | Groundwater | March 2013 | 597.01 | 597.37 | −0.36 |
| MW102 | Groundwater | March 2013 | 613.71 | 614.34 | −0.63 |
| GM-25 | Groundwater | March 2013 | 597.21 | 596.37 | 0.84 |
| 511 | Groundwater | March 2013 | 598.07 | 597.19 | 0.88 |
| 212G | Groundwater | March 2013 | 578.50 | 578.79 | −0.29 |
| MW120 | Groundwater | March 2013 | 602.98 | 604.24 | −1.26 |
| 555 | Groundwater | March 2013 | 599.26 | 597.86 | 1.40 |
| 560 | Groundwater | March 2013 | 600.72 | 601.72 | −1.00 |
| 554 | Groundwater | March 2013 | 598.94 | 597.78 | 1.16 |
| MW104 | Groundwater | March 2013 | 609.98 | 608.84 | 1.14 |
| C601E | Surface water | March 2013 | 603.71 | 603.95 | −0.24 |
| MW123 | Groundwater | March 2013 | 608.67 | 608.03 | 0.64 |
| 553 | Groundwater | March 2013 | 600.68 | 599.79 | 0.89 |
| BD-TRAIL | Surface water | March 2013 | 602.76 | 603.10 | −0.34 |
| 601 | Groundwater | March 2013 | 603.08 | 602.92 | 0.16 |
| GM-31 | Groundwater | March 2013 | 606.39 | 605.39 | 1.00 |
| 606 | Groundwater | March 2013 | 602.47 | 601.68 | 0.79 |
| MW107 | Groundwater | March 2013 | 612.45 | 612.68 | −0.23 |
| MW106 | Groundwater | March 2013 | 611.57 | 612.06 | −0.49 |
| 552 | Groundwater | March 2013 | 599.68 | 599.84 | −0.16 |
| MW110 | Groundwater | March 2013 | 610.95 | 611.39 | −0.44 |
| 602 | Groundwater | March 2013 | 602.59 | 603.64 | −1.05 |
| 603 | Groundwater | March 2013 | 602.71 | 602.05 | 0.66 |
| 609 | Groundwater | March 2013 | 601.74 | 603.68 | −1.94 |
| 604 | Groundwater | March 2013 | 598.80 | 600.07 | −1.27 |
| 610 | Groundwater | March 2013 | 605.24 | 604.80 | 0.44 |
| BD-CENT | Surface water | March 2013 | 595.25 | 596.51 | −1.26 |
| GM-35 | Groundwater | March 2013 | 596.68 | 595.37 | 1.31 |
| 605 | Groundwater | March 2013 | 596.56 | 597.58 | −1.02 |
| BD-CAR | Surface water | March 2013 | 592.05 | 593.47 | −1.42 |
| 608 | Groundwater | March 2013 | 594.69 | 593.52 | 1.17 |
| 607 | Groundwater | March 2013 | 594.08 | 593.80 | 0.28 |
| KD-BEV | Surface water | March 2013 | 586.38 | 585.86 | 0.52 |
| Discharge, in cubic feet per second | | | | | |
| Brown Ditch | Surface water | March 2013 | −4.5 | -0.79 | −3.71 |
| Derby Ditch | Surface water | March 2013 | −3.5 | -1.06 | −2.44 |
| Kintzele Ditch | Surface water | March 2013 | −2 | -0.27 | −1.83 |

Weights on observation data account for measurement error associated with the accuracy of the sampling device, method of determining land-surface elevation, effects of recent water withdrawals in the vicinity of the observation, uncertainties in the depths of screened intervals of groundwater wells, and other factors. In theory, weights on the observations used in the regression procedure can be calculated from estimates of the variance or standard deviation of measurement error (Hill, 1998, p. 45–47). The weights are proportional to 1 divided by the variance of the measurement errors for the observation. To estimate these variances, the UCODE_2005 program applies statistics on measurement error from which the variances of the observation errors are calculated. The standard deviation of the measurement error was used as the statistic to estimate the weights for water-level observations, and the coefficient of variation was used for the streamflow gain/loss measurements. The calculations of the statistics are described in Hill (1998, p. 46–47).

Weights for the water-level observations were based on the assumption that 95 percent of the measurements were within the measurement error, which was considered to be 0.01 ft. Statistical theory for normally distributed populations states that for the 95-percent confidence interval, the measurement error should be 1.96 times the standard deviation of the measurement error (Cooley and Naff, 1990, p. 44). The standard deviation of the measurement error is, therefore, equal to 0.0153 (0.01 divided by 1.96); the standard deviation of the measurement error is used as an input to UCODE_2005 for calculating water-level weights. The weights for the streamflow observations in Brown, Kintzele and Derby Ditches were calculated by using an estimated coefficient of variation value of 0.2; this assumes a standard deviation of 20 percent of the measurement made at the site.

## Simulation Results

This section provides the final calibrated values for model parameters for the modified groundwater-flow model, indicates how the model simulates observed values of water level and streamflow with its calibrated parameter values, and presents a simulation of the groundwater-flow system as represented by the model.

### Calibrated Parameter Values

The calibrated values for all parameters are listed in table 9. The final parameter value for the hydraulic conductivity of the surficial sand aquifer (ks) was 17.73 ft/d, whereas the value of the parameter that represents the hydraulic conductivity of the less permeable aquifer material beneath the northern Holocene dune ridge (kBevS) was 14.34 ft/d. The final parameter value that represents the recharge to the aquifer system in the undeveloped areas of the model domain (SandRech) is 14.66 in/yr; the recharge to the aquifer system in the developed areas of the town of Beverly Shores (BevShoresR) and Town of Pines (PineRech) are 21.97 and 11.70 in/yr, respectively; and the recharge to the aquifer system in wetland areas of the model domain (MarshRech) is −6.91 in/yr. The negative recharge value simulates evaporation from the ponded areas of Great Marsh. Lampe and Bayless (2013) also simulated wetland areas with lower recharge values than those of the surrounding surficial aquifer in a similar setting.

### Model Fit to Observations

The calibrated groundwater-flow model accurately simulated water levels and streamflow gain/loss in the actual flow system during low-flow conditions, as measured by a correlation coefficient of nearly 1.0 between weighted observations of water levels and streamflow gain/loss and weighted simulated equivalents computed by the model. The model fit between field-observed values and model-simulated values is an indication of how well the model simulates the observed conditions of the groundwater-flow system. Model fit is measured in multiple ways, including correlation coefficients of weighted simulated values with weighted observed hydrologic measurements. Residuals, in this case, are the difference between the observed conditions in March 2013 and the model-simulated values. Ideally, model values should be close to observed values such that when weighted observations are plotted against weighted simulated values, the points should fall close to a line with slope equal to 1 and intercept of 0. The correlation coefficient between weighted observations and weighted simulated equivalents reflects how close the points plot along the line. A value greater than 0.90 is desirable, and the model calibration to the dry-weather data resulted in a value of nearly 1.00. A plot of both unweighted simulated values with unweighted observed values and weighted simulated values with weighted observed values is shown in figures 26*A* and 26*B*.

The calibrated groundwater-flow model also met two other criteria that are required of valid models. The weighted residuals or difference of weighted simulated water levels and streamflow gain/loss and their weighted observed values were determined to plot along a straight line with a correlation coefficient of nearly 1, close to the desired 1:1 relation. Two types of weighted-residual plots that illustrate these model characteristics are shown in figure 26. In figure 26*C*, the weighted residuals are plotted according to their position in an assumed normal distribution. If the weighted residuals are normally distributed, then they should plot along a straight line. The statistic that measures the linearity of the plot, as well as the independence of one residual from another, is called the correlation between ordered weighted residuals and normal order statistics. This correlation coefficient also should be near 1, and the value associated with the calibration is 0.980; the weighted residuals plot generally along a straight line. In figure 26*D*, weighted residuals are plotted with their simulated values. Ideally, the weighted residuals should be evenly distributed around 0 (no difference between weighted simulated and weighted residual values,) and the size of the

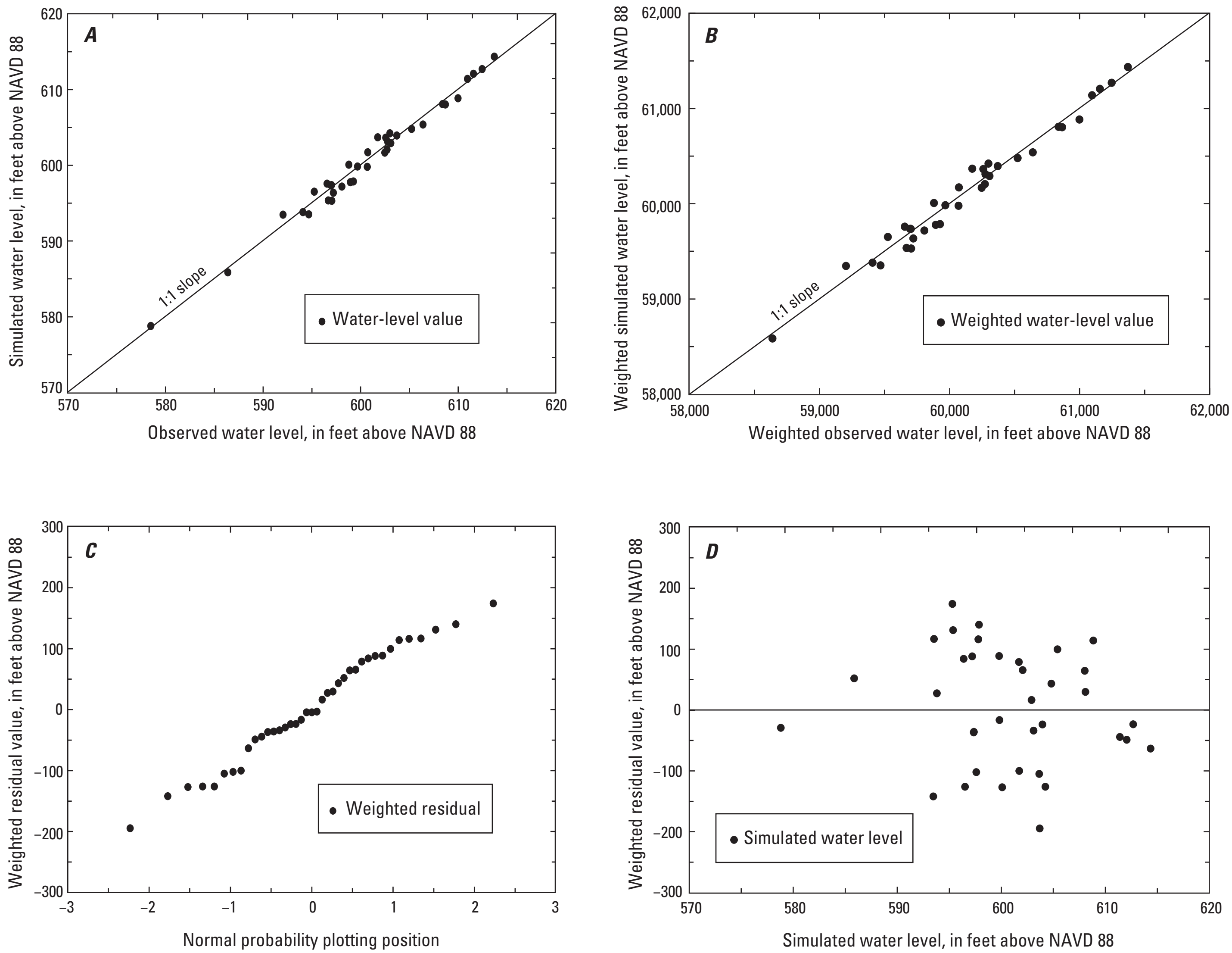



**Figure 26.** Graphical analysis of model fit. *A*, Simulated and observed water levels. *B*, Weighted simulated and weighted observed water levels. *C*, Normal probability plot of weighted residuals. *D*, Weighted residuals and simulated water levels.

weighted residuals should not relate to the magnitude of the simulated values (for example, large residuals should not be associated with lower simulated values). These requirements are generally satisfied.

To display the more important error associated with the simulated water levels, the axes on the residual plots on figures 26C and 26D were chosen to show only the weighted residuals that represent water levels. The residual plots do not show the residual associated with measured streamflow gain/loss because the streamflow gain/loss residual plots near the origin of the axis, whereas the water-level residuals plot farther from the origin. Showing all residuals on figures 26*C* and 26*D* would result in clumped data points, and details of the distribution of the water-level residuals would be obscured. The streamflow gain/loss residuals plotted above the 1:1 line for the figure 26*C* plot and near the zero line for the figure 26*D* plot indicating the simulation is underpredicting the groundwater discharge to the ditches within the study area.

Small overpredictions and underpredictions of water levels by the model are relatively scattered in their geographic distribution across the model area (fig. 27). Unweighted residuals can be analyzed by their areal distribution, range, and magnitude; unweighted water-level residuals are the actual difference between measured and simulated water levels with no weighting factor applied. The unweighted water-level residuals for March 2013 are shown in figure 27 for the modified model simulation to depict the mixed nature of positive and negative residuals in different parts of the model area, which is characteristic of an adequately calibrated model. The largest residual values are in areas of greatest relief in the northern dune ridge near Beverly Shores or along areas of steep banks near ditches where the model grid cell size may impact the simulated values due to large variations in topography being averaged within a single model cell. Residuals west of Lakeshore County Road in Great Marsh are mostly positive, while residuals on the east side are a mixture of positive and negative values. These results indicate that the model is simulating observed water-level conditions adequately in the area of greatest interest surrounding Brown Ditch.

Simulated water levels and streamflow gain/loss data are very similar to the observed data, as indicated by several statistics that compare them. Computed statistics based on the unweighted water-level residuals are presented in table 11. The range of unweighted water-level residuals can be expressed by their standard deviation, and the standard deviation of the residuals for the calibration is 0.94 ft. Almost 60 percent of the residuals are within 1 standard deviation of the mean residual, and all but one are within 2 standard deviations. The magnitude of water-level residuals can be represented by the mean absolute error, or the mean of the magnitudes of the water-level residuals, which is 0.81 ft. The relative accuracy of the model calibration can be measured by the percent mean absolute error, which is the mean absolute error divided by the overall range in water levels. The percent mean absolute error for the model was 2.27 percent.

Simulated residuals of groundwater loss to the ditches in the study area indicate that the model underpredicts the amount of groundwater that is discharged to the ditches. The simulated loss of groundwater to Brown Ditch was 0.79 $ft^3/s$, while the observed estimate based on discharge measurements was 4.5 $ft^3/s$. The simulated loss of groundwater to Derby Ditch was 1.06 $ft^3/s$, while the observed estimate based on discharge measurements was 3.5 $ft^3/s$. The simulated loss of groundwater to Kintzele Ditch was 0.27 $ft^3/s$, while the observed estimate based on discharge measurements was 2.1 $ft^3/s$. Efforts to decrease the streamflow residuals through automated parameter-estimation techniques resulted in the increase in water-level residuals with little to no improvement to streamflow residuals. This may indicate the error associated with the calculation of the gain/loss observations is greater than originally believed.

Weighted residuals were used to determine that the overall fit of the groundwater-flow model was within 1 ft. Weighted residuals can be used to determine a measure of model fit for water levels and streamflow gain/loss that includes error in the measurement of the observations. The weighted residuals are used to calculate the standard error of the regression. The standard error of the regression for the model is dimensionless, so it is multiplied by the standard deviation of water-level measurement error to obtain a measure of overall model fit for water levels. The standard error for the model for the dry-weather simulation is 111.90, and the standard deviation of measurement error for water levels is 0.01; therefore, the overall model fit is ± 1.12 (dimensionless).

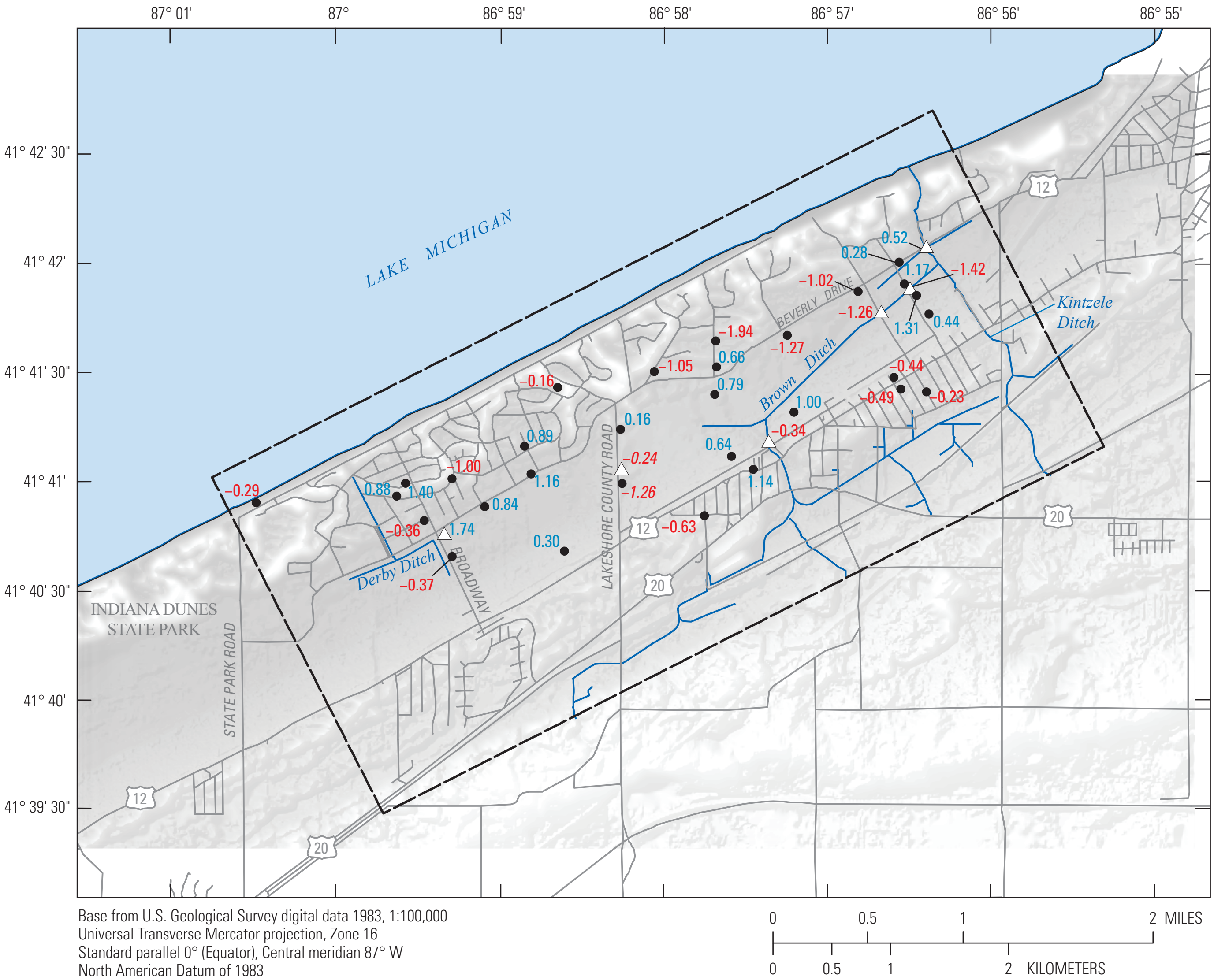
## Simulated Water Budget

The resulting calibrated model can be quantified and analyzed by an overall water budget and by a budget for individual parts of the flow system. Table 12 lists the overall budget for the modified model simulation. The influx of water into the model comes predominantly from aerial recharge values assigned during the calibration process across the extent of the model to simulate precipitation and simulated infiltration from the filtration pond. To a lesser extent, water also enters the model from the confined aquifer below across the head-dependent basal boundary. A large portion of the discharge from the model goes to Lake Michigan (40 percent), but even more discharge enters Brown, Kintzele, and Derby Ditches (44 percent). A smaller portion (16 percent) of the discharge from the model goes to evaporation (negative recharge) simulated in the model.

The budget between the model and four areas of the model (fig. 28)—Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, Town of Pines, and Beverly Shores—was analyzed, and the results are shown in table 13. Nearly 100 percent of all water entering the area simulating Town of Pines is from recharge. Of all the water simulated to enter the eastern and western portions of Great Marsh, nearly 20 and 18 percent, respectively, flows from Town of Pines to the western and eastern portions of Great Marsh. Less than 1 percent of the water from Great Marsh flows south to the aquifer beneath Town of Pines.

Nearly 3 and 8 percent, respectively, of all water entering the eastern and western portions of Great Marsh flows from the aquifer beneath Beverly Shores. Less than 1 percent flows from Great Marsh south to the aquifer beneath Beverly Shores. Nearly 71 percent of all groundwater leaving the Beverly Shores simulated area flows into Lake Michigan.

Approximately 70 percent of the water from both simulated areas of Great Marsh is lost to evapotranspiration while approximately 28 to 25 percent, respectively, of recharge eventually discharges to ditches for the western and eastern Great Marsh. Nearly 10 times more water (0.1 versus 0.005 $ft^3/s$) flows from east to west beneath Lakeshore County Road between the two simulated Great Marsh areas than flows from west to east.




**EXPLANATION**

−0.34 ● **Location of an observation well with a positive (blue) or negative (red) residual**—At these locations, positive values indicate the groundwater-flow model underestimated the water level in the observation well. Negative values indicate the groundwater-flow model overestimated the water level in the observation well.

1.74 △ **Location of a surface-water elevation monitoring site with a positive (blue) or negative (red) residual**—At these locations, positive values indicate the groundwater-flow model underestimated the water level at the site. Negative values indicate the groundwater-flow model overestimated the water level at the site.

— — — **Model boundary**

**Figure 27.** Difference between observed and simulated water levels for the modified groundwater-flow model of the Great Marsh area near Indiana Dunes National Lakeshore, Indiana.

**Table 11.** Computed statistics based on the water-level and gain/loss residuals for the modified groundwater-flow model.

[ft, feet; ft$^3$/s, cubic feet per second]

| Type of residual | Statistics based on unweighted model residuals | | | | | | |
|---|---|---|---|---|---|---|---|
| | Minimum residual (ft) | Mean residual (ft) | Maximum residual (ft) | Standard deviation of the residuals (ft) | Bias (ft) | Mean absolute error (ft) | Percent mean absolute error |
| Water level | –1.94 | 0.04 | 1.73 | 0.94 | 1.52 | 0.81 | 2.27 |

| Type of residual | Drainage feature name | Observed (ft$^3$/s) | Simulated (ft$^3$/s) | Residual (ft$^3$/s) |
|---|---|---|---|---|
| Streamflow | Brown Ditch | –4.5 | –0.79 | –3.71 |
| Streamflow | Derby Ditch | –3.5 | –1.06 | –2.44 |
| Streamflow | Kintzele Ditch | –2.1 | –0.27 | –1.83 |

**Table 12.** Water budget associated with the modified groundwater-flow model.

[ft$^3$/s, cubic feet per second; >, greater than]

| Inflow to model | Inflow rate (ft$^3$/s) and percent of total | | Outflow from model | Outflow rate (ft$^3$/s) and percent of total | |
|---|---|---|---|---|---|
| Lake Michigan (constant-head boundaries) | 0 | 0.00 | Lake Michigan (constant-head boundaries) | 1.94 | 40.08 |
| | | | Leakage into Brown Ditch, Kintzele Ditch, and Derby Ditch (model drains) | 2.12 | 43.8 |
| Confined aquifer (head-dependent boundary | 4.29 × 10-6 | >1 | Confined aquifer (head-dependent boundary) | 1.14 × 10-8 | |
| Precipitation (recharge) | 4.84 | 100.00 | Evaporation (recharge) | 0.77 | >1 |
| **Total inflow** | **4.84** | | **Total outflow** | **4.84** | **15.91** |

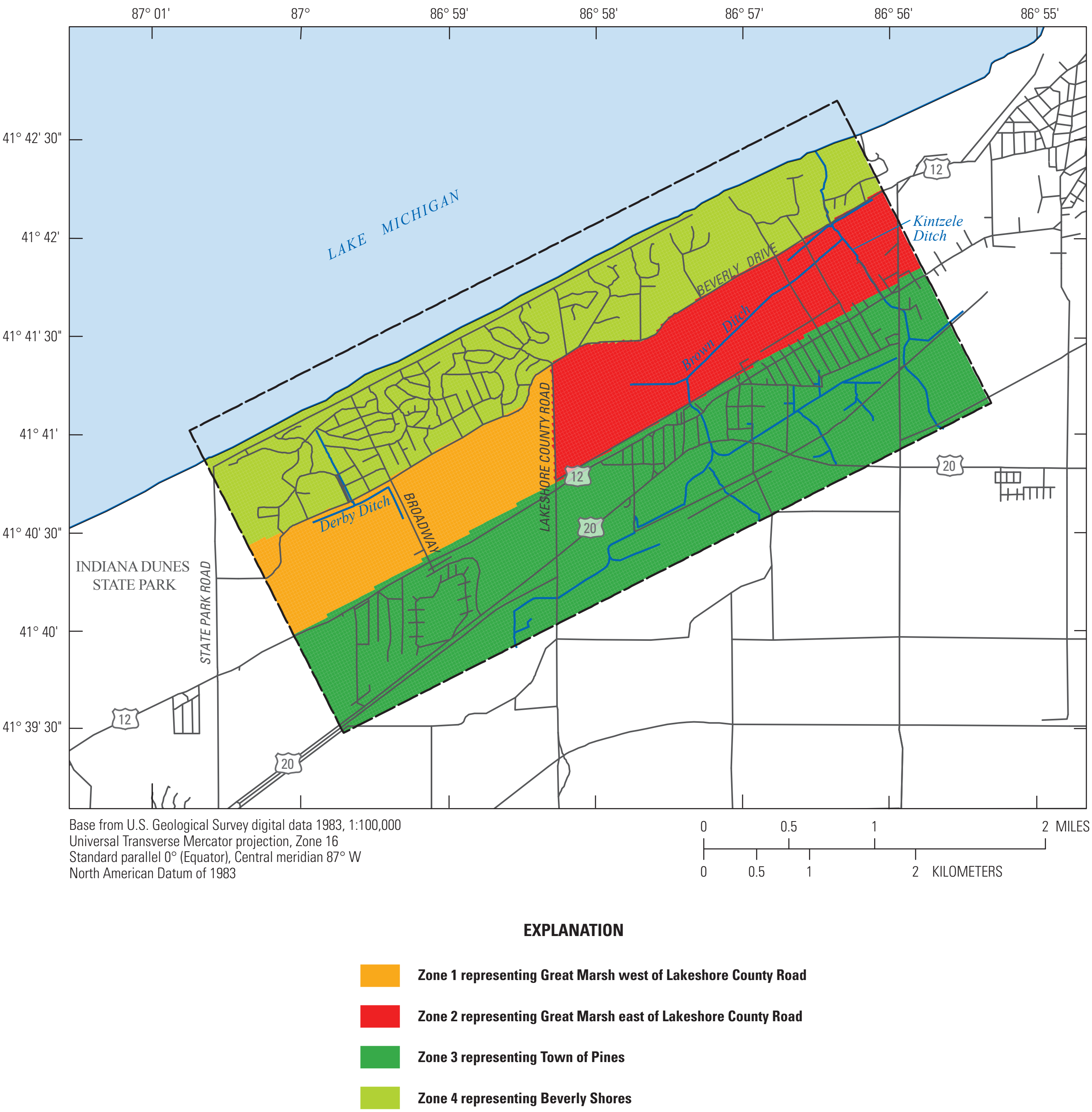



**Figure 28.** Zones representing Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, the town of Beverly Shores, and Town of Pines used in the estimates of individual water budgets and groundwater-flow interactions with the modified groundwater-flow model of the Great Marsh area near Indiana Dunes National Lakeshore, Indiana.

**Table 13.** Water budgets for four zones of the groundwater-flow model simulating Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, the town of Beverly Shores, and Town of Pines.

[$ft^3/s$, cubic feet per second; —, not applicable]

| | West Great Marsh Zone 1 | East Great Marsh Zone 2 | Town of Pines Zone 3 | Beverly Shores Zone 4 |
|---|---|---|---|---|
| | **Water moving into cells Rate, in $ft^3/s$ (percent of total flow)** | | | |
| **From Recharge Zone 0** | 2.194 (74.35%) | 1.09 (73.96%) | 1.77 (99.83%) | 2.69 (99.01%) |
| **From West Great Marsh Zone 1** | — | 0.005 (0.34%) | 0.00 (0.00%) | 0.02 (0.74%) |
| **From East Great Marsh Zone 2** | 0.1 (3.32%) | — | 0.002 (0.11%) | 0.007 (0.26%) |
| **From Town of Pines Zone 3** | 0.58 (19.52%) | 0.26 (17.72%) | — | — |
| **From Beverly Shores Zone 4** | 0.084 (2.85%) | 0.12 (7.91%) | — | — |
| **Total ($ft^3/s$)** | 2.95 | 1.47 | 1.78 | 2.72 |
| | **Water moving out of cells Rate, in $ft^3/s$ (percent of total flow)** | | | |
| **To Lake Michigan** | — | — | — | 1.94 (71.41%) |
| **To ditches** | 0.83 (28.06%) | 0.36 (24.81%) | 0.61 (34.52%) | 0.31 (11.55%) |
| **To Recharge Zone 0** | 2.1 (71.06%) | 1.00 (67.96%) | 0.33 (18.41%) | 0.26 (9.64%) |
| **To West Great Marsh Zone 1** | — | 0.1 (6.68%) | 0.58 (32.43%) | 0.58 (32.43%) |
| **To East Great Marsh Zone 2** | 0.005 (0.17%) | — | 0.26 (14.64%) | 0.12 (4.27%) |
| **To Town of Pines Zone 3** | 0.00 (0.00%) | 0.002 (0.14%) | — | — |
| **To Beverly Shores Zone 4** | 0.02 (0.68%) | 0.007 (0.48%) | — | — |
| **Total ($ft^3/s$)** | 2.95 | 1.47 | 1.78 | 2.72 |

## Simulated Water Levels and Groundwater-Flow Paths

The results of the calibrated, modified groundwater-flow model indicate that the dune ridges beneath Town of Pines and to a lesser extent beneath Beverly Shores are a major source of recharge to the surficial aquifer and Great Marsh under the conditions observed during March 2013. The groundwater-flow system can be illustrated by water-level contours from which direction of flow can be inferred. Simulated water-level contours are presented in figure 29 for the modified groundwater-flow model. The major simulated flow paths are north from the dune ridges beneath Town of Pines toward Great Marsh and Brown Ditch. To a lesser extent, groundwater in the simulation flows south from the dune ridge beneath Beverly Shores to Great Marsh and Brown Ditch. Groundwater also is simulated to flow north from areas beneath Beverly Shores and discharges to Lake Michigan.

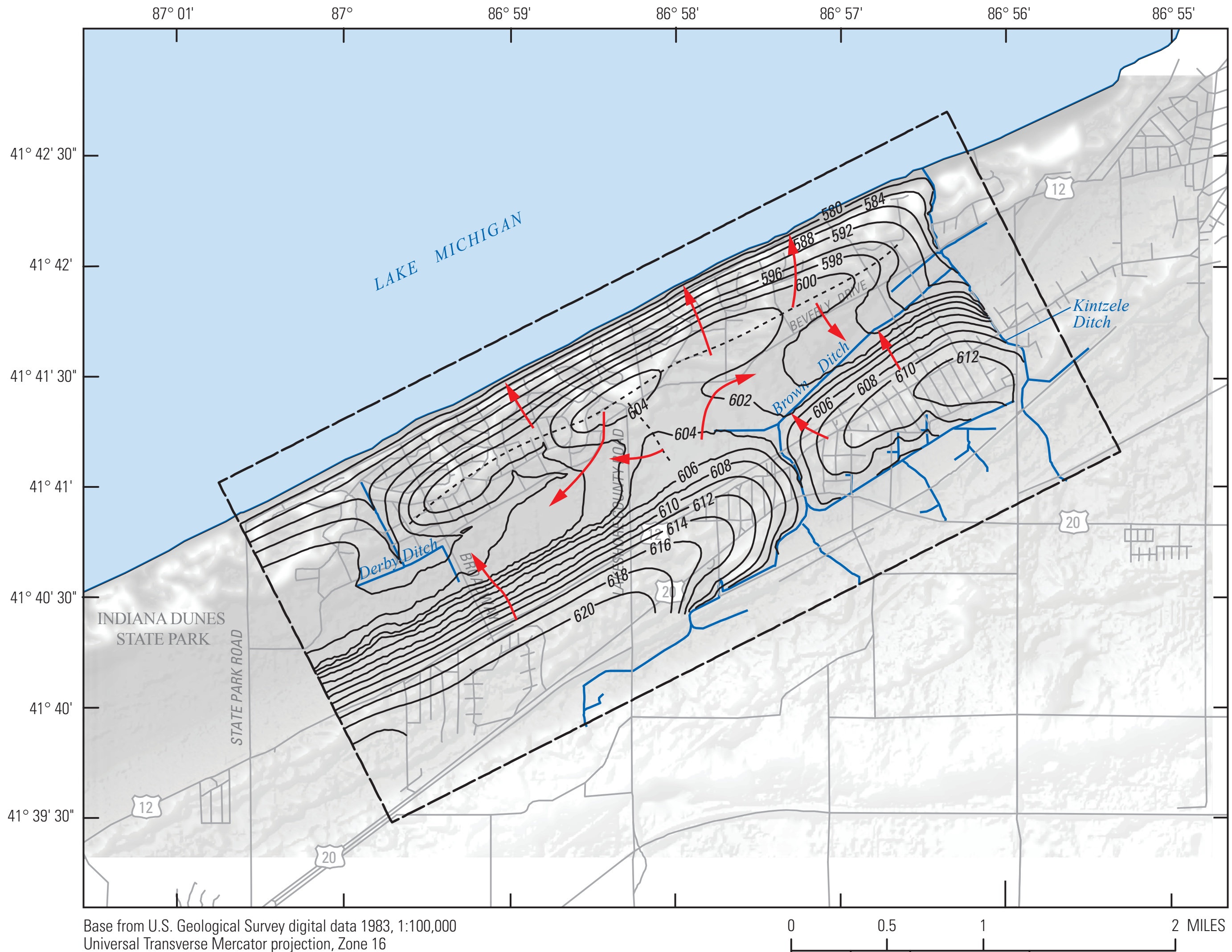
A predominant groundwater divide in the calibrated simulation runs east from Derby Ditch parallel to the dune ridge beneath Beverly Shores to Kintzele Ditch in the eastern portion of the modeled area. A secondary groundwater divide in the calibrated simulation runs southeast from approximately the intersection of Beverly Drive and Lakeshore County Road and terminates near the southern boundary of Great Marsh. Groundwater is simulated to flow east of this minor divide toward Brown Ditch and west to Derby Ditch. Groundwater discharges to Brown Ditch in the calibrated simulation where it cuts through the dune ridge beneath Town of Pines and is intercepted by the ditch as it flows north from Town of Pines toward Great Marsh on the eastern side of the modeled area. Groundwater discharges to Derby Ditch where it cuts through the dune ridge beneath Beverly Shores. Groundwater also discharges to Derby Ditch as the ditch flows north from Town of Pines toward Great Marsh on the western side of the modeled area.

Groundwater-flow paths, which are perpendicular to the water-level contours, provide useful information about the source, distribution, and discharge of groundwater. Backward tracking flow paths were generated in nodes[3] representing Brown Ditch, Kintzele Ditch, Derby Ditch, and the Lake Michigan shoreline using MODPATH (Pollock, 2012); results are shown in figure 30. MODPATH, a particle-tracking post-processing package for MODFLOW, computes paths for imaginary particles of water moving through the simulated groundwater system. To create backward tracking flow paths, the model, for each node specified, calculates a starting point for groundwater that ultimately ends up at the specified node. This allows for the calculation of the areas contributing flow to features of interest. For example, by specifying each node assigned to simulate the Lake Michigan shoreline, an area can be delineated that includes all flow paths that directly supply water to the Lake. The resulting flow paths in the calibrated simulation generally extend north and south from each feature, just as would be interpreted from the contours in figure 29, but additional details in flow can be seen. The area contributing water to Brown Ditch in the calibrated simulation is predominantly from the south, but some flow seemingly is captured that enters the ditch from the north. Capture zones for Brown and Kintzele Ditches overlap in the area southwest of their confluence; this is likely due to deeper flow paths discharging into one ditch while shallower flow paths discharge into the other. The majority of groundwater in the area west of Lakeshore County Road beneath Great Marsh flows into Derby Ditch.

In figure 31, the vertical distribution of the flow lines just discussed is shown at two north-south cross sections, one along model column 52 beneath Derby Ditch just east of Broadway (fig. 31*A*) and the other along column 197 beneath Brown Ditch (fig. 31*B*) (column locations shown in fig. 21). Both sets of flow lines show the same pattern of mostly downward-directed vertical flow near groundwater divides and mostly horizontal flow away from the divides.

Results from the calibrated simulation indicate that the majority of groundwater flowing from the south in the western portion of the modeled area flows into the zones that represent Great Marsh before entering Derby Ditch. The majority of groundwater flowing from the south in the eastern portion of the modeled area discharges to Brown Ditch. In figure 31*A*, flow from a large area to the south of US-12 and Great Marsh and in the western portion of the study area flows north beneath US-12 where some of the flow enters Great Marsh, and the rest flows further north and discharges to Derby Ditch. A smaller amount of flow from the northern dune ridge flows south and discharges to Derby Ditch. In figure 31*B*, flow from a large area to the south of US-12 and Great Marsh and in the eastern portion of the study area flows beneath US-12. A small portion enters Great Marsh while the remaining flow continues north and discharges to Brown Ditch. Flow originating from the northern dune ridge flows south and enters Great Marsh north of Brown Ditch. In both figures 31*A* and 31*B*, flow from the north side of the northern dune ridge flows north to Lake Michigan.

[3] A node is the point within a model cell at which head is calculated.




Base from U.S. Geological Survey digital data 1983, 1:100,000
Universal Transverse Mercator projection, Zone 16
Standard parallel 0° (Equator), Central meridian 87° W
North American Datum of 1983

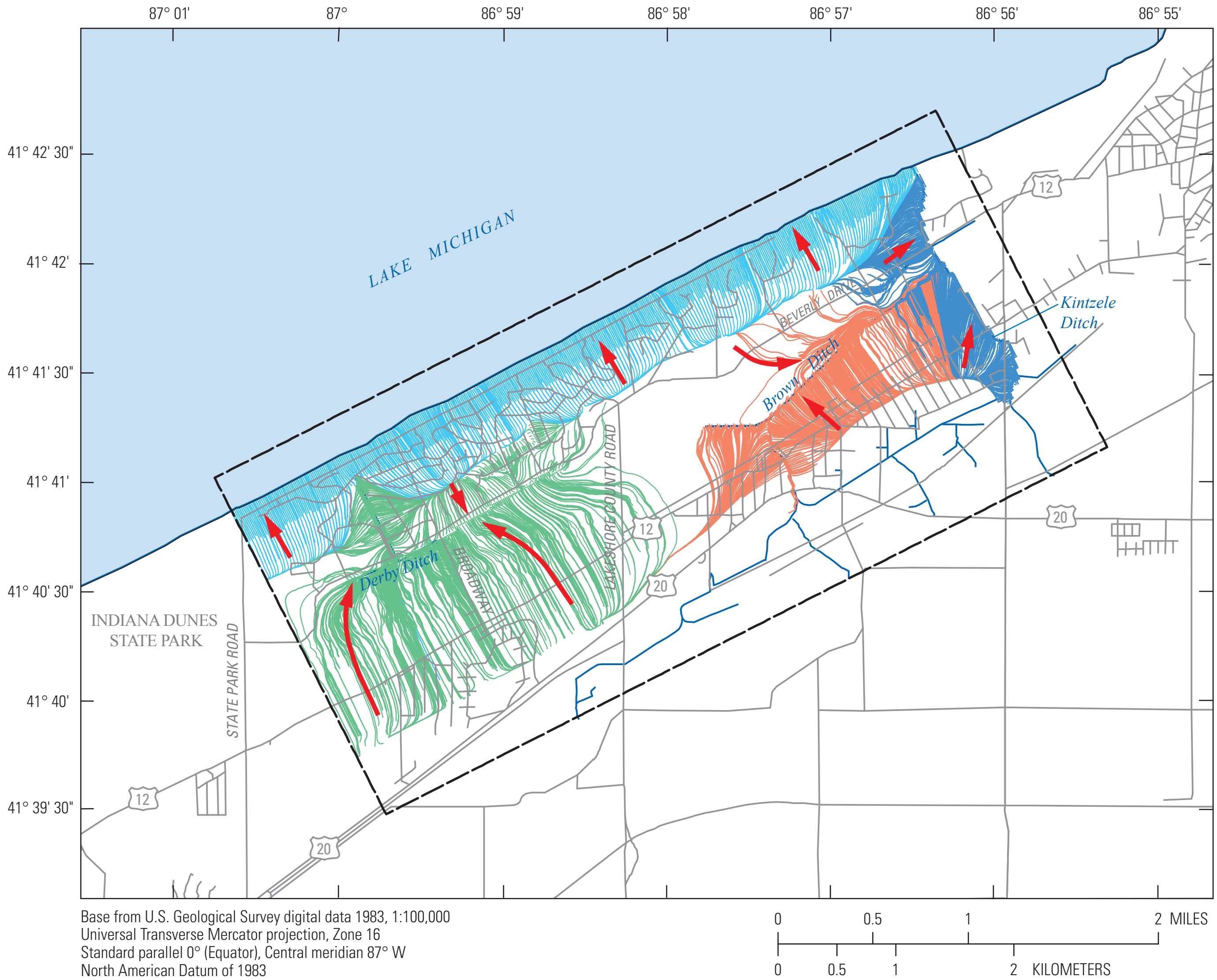
**EXPLANATION**

610 — **Simulated water-table contour**—Shows the altitude of the water table in feet above North American Vertical Datum of 1988 simulated by the groundwater-flow model in the surficial aquifer. Contour interval variable.

**Arrow indicating direction of groundwater flow inferred from simulated water-table contours**

**Groundwater divide**—Approximate simulated divide in surficial aquifer, March 27–28, 2013

**Figure 29.** Simulated water-table contours from the modified groundwater-flow model of the Great Marsh area near Indiana Dunes National Lakeshore, Indiana.




**EXPLANATION**

- Horizontal groundwater-flow path within the surficial aquifer terminating in Derby Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Brown Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Kintzele Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Lake Michigan.
- Model boundary
- Arrow indicating general direction of groundwater flow simulated by the modified groundwater-flow model.

**Figure 30.** Flow lines representing simulated groundwater-flow paths in the surficial aquifer under steady-state conditions, March 2013, near Indiana Dunes National Lakeshore, Indiana. (Arrows represent general directions of simulated groundwater flow)

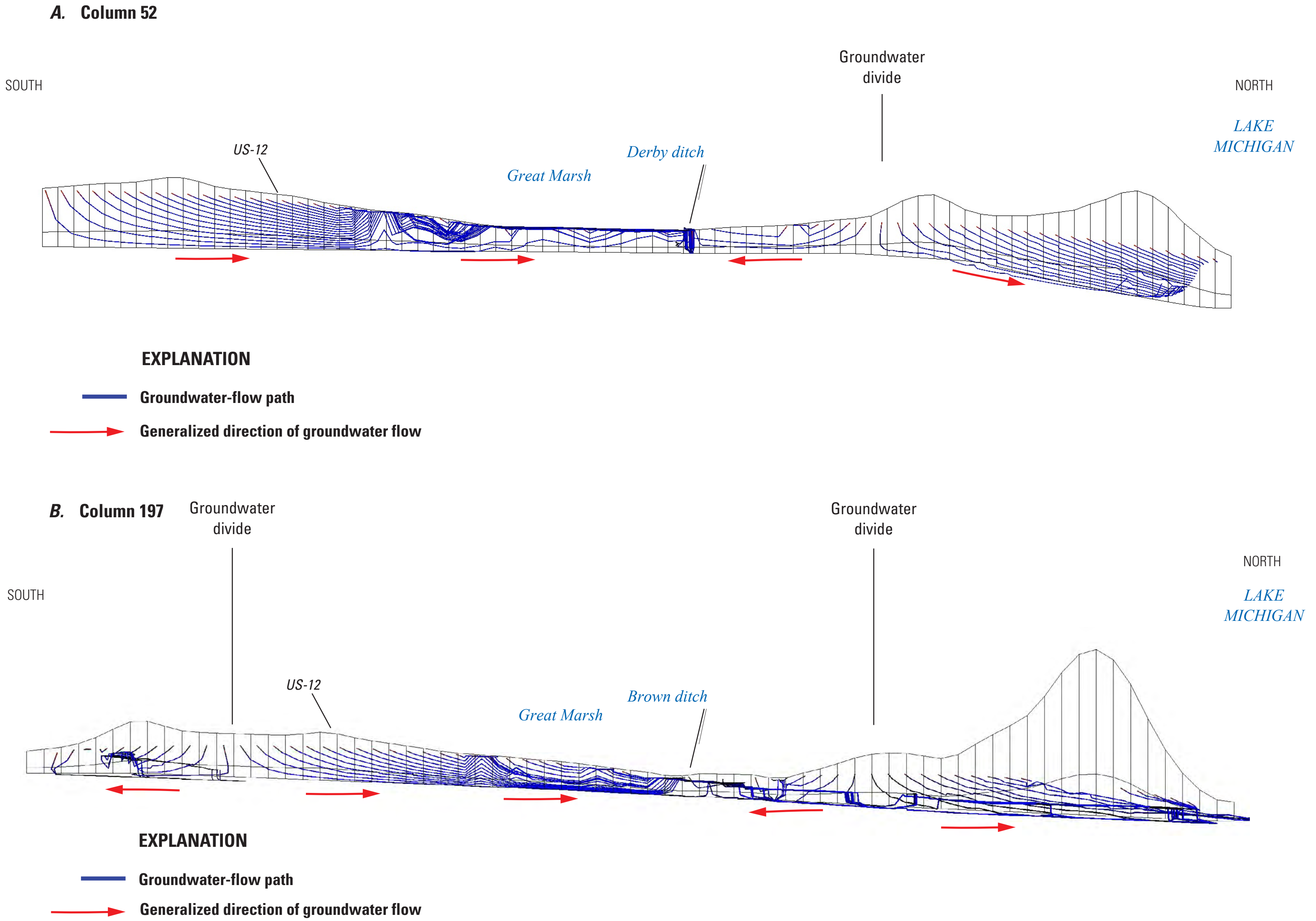



**Figure 31.** Vertical flow paths simulated with the modified groundwater-flow model. *A.*, Flow paths along column 52 and through Derby Ditch. *B.*, Flow paths along column 197 and through Brown Ditch. (Column locations are shown in fig. 21.)

## Simulated Inundated Areas

Inundated areas (areas where the water table is simulated to be above the land surface) and areas where the water table is simulated to be within 7 ft of the land surface (the estimated altitude of typical basements or other below grade structures) are displayed in figure 32. The display of the simulated inundated areas helps describe the differences in the simulated position of the water table in relation to the land surface in the modeled area between the simulated March 2013 condition and other simulated scenarios. Inundated areas were calculated by using the altitude of the simulated, steady-state water table and the lidar-based, land-surface elevation dataset. The digital land-surface altitude was subtracted from the water-table altitude to calculate the depth of the water table above the land surface. At the point where the water table rises above land surface, surface runoff should be generated. Because of this, the actual area where water levels rise above ground surface may be smaller than the area shown in figure 32, even though the amount of surface runoff is estimated to be small because of the high permeability of the materials at land surface. Imprecision in land-surface altitude in some of the areas represented also adds to the uncertainty of the estimated area of inundation for parts of the model.

Water levels in most areas north of Beverly Drive and south of US-12 are simulated to be below the land surface with exceptions being smaller wetland cells just west of the intersection of Lakeshore County Road and Beverly Drive, smaller interdunal wetlands north of Beverly Drive and Brown Ditch in the eastern portion of the modeled area, and areas near the upstream portions of Brown Ditch in the southeast portion of the study area. Ponded water is simulated extensively in the area of Great Marsh north of US-12 and south of Beverly Drive throughout the study area although the ponded area is smaller to the east of Lakeshore County Road. In the eastern portion of the modeled area, water levels are simulated to be within 7 ft of the land surface directly north of US-12 in the area of Town of Pines and within 3 ft north of those areas and closer to Great Marsh. In the western portion of the modeled area, water levels are simulated to be within 7 ft of the land surface directly south of US-12, and within 3 ft of the land surface north of US-12.

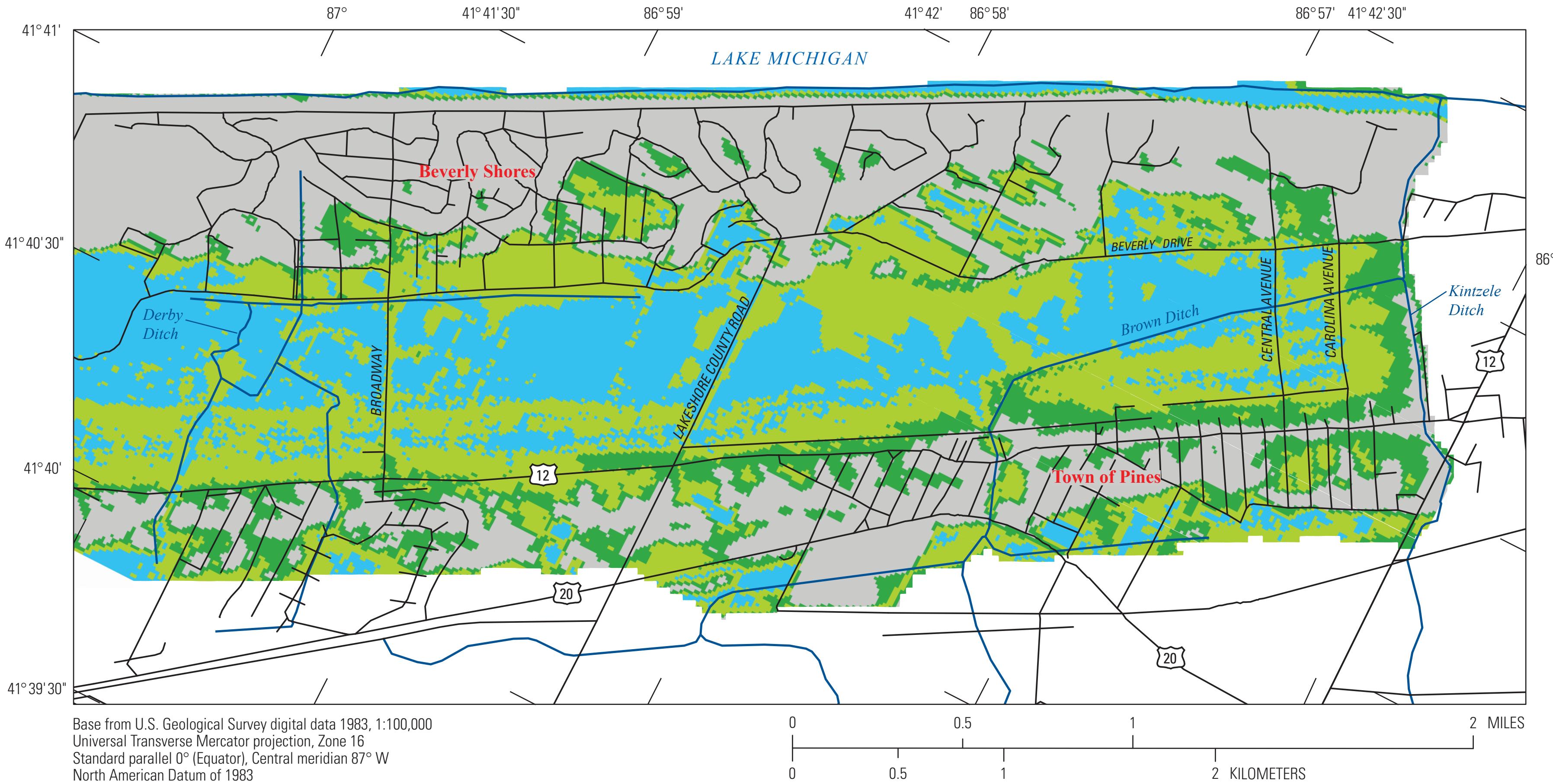
## Sensitivity Analysis

The purpose of a sensitivity analysis is to determine the parameters that are more important to water levels and streamflow gain/loss predictions within the model (Hill and Tiedeman, 2007). If certain parameters substantially affect simulated water levels, then these parameters are important to accurate model predictions. The process of automated parameter estimation provides three types of sensitivity-related data: dimensionless scaled sensitivity, 1-percent scaled sensitivities, and composite scaled sensitivities (Hill, 1998, p.14–16; Hill and Tiedeman, 2007, p. 46–56).

The three types of sensitivity data reflect the degree of change in water levels for a given change in a parameter value. The dimensionless scaled sensitivity numbers can be used to compare the importance of different observations to the estimation of each of the parameters, a comparison that is useful during calibration. One-percent scaled sensitivities measure the variation in sensitivity of observations to a parameter throughout the model. One-percent scaled sensitivities are calculated for each node of the model, and the sensitivities can be mapped. The areas of larger sensitivity for a parameter are good locations for obtaining additional observations to improve the estimate of the parameter. The CSS measure the sensitivity of model output to variations in a given model parameter on the basis of the available set of observations. Larger values of CSS associated with a specific parameter mean that the available observations are more useful in estimating those parameters.

The CSS values for the calibrated model parameters are listed in table 9. A high CSS value indicates that the observations used in the model provide enough information to estimate a particular parameter, and the parameter can therefore be estimated by automated methods. Hydraulic conductivity of the surficial aquifer and of the northern dune ridge surficial aquifer (ks and kBevS, respectively), parameters for recharge rates to the aquifer for areas with undeveloped (non-wetland/non-urban) wetland, the town of Beverly Shores, and Town of Pines (SandRech, MarshRech, BevShoresR, and PinesRech) are the major parameters controlling water-level elevations. All these parameters have relatively high CSS values, indicating that sufficient observations were available to estimate those parameters. If the major parameters are adequately estimated, then the simulated water-level surfaces have a higher probability of reflecting actual conditions. For these parameters, the parameter-estimation process was used to calculate an initial parameter that was then finalized by using manual techniques, including trial-and-error adjustment of the estimated parameter value. If the adjustment of any parameter achieved lower total RMSE values for both head and flow observations, the adjusted parameter value was assigned as the final value.

Significant correlations between parameters also are listed in table 9. The parameter representing the hydraulic conductivity of the ks is correlated to parameters for recharge rates to the aquifer for areas with undeveloped (non-wetland/non-urban), wetland, and areas representing Beverly Shores and Town of Pines as well as the hydraulic conductivity of the wetland areas (SandRech, MarshRech, BevShoresR, PinesRech, and kwet). Although the use of parameter-estimation techniques are not recommended on parameters that are correlated with each other, these techniques were used on these parameters to assist in model calibration. Once final parameter values were determined, the parameter-estimation process was repeated with different starting values for these parameters, which resulted in values equal to the previously determined final parameter values.




**EXPLANATION**

**Water-table position in the March 2013 simulation:**

- The water table is above the land surface
- The water table is between 0 and 3 feet below land surface
- The water table is between 3 and 7 feet below land surface
- The water table is greater than 7 feet below land surface

**Figure 32.** Simulated water-table position within areas near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana, March 2013.

# Model Simulations of Hydrologic Modifications and Climatic Effects on the Brown Ditch Watershed

In addition to the groundwater-flow model of the March 2013 hydraulic condition, several other scenarios were run with the groundwater-flow model to simulate the effects of various drainage modifications and climatic conditions on the simulated hydrology in the modeled area. These scenarios were simulated by using the groundwater-flow model calibrated to the March 2013 hydraulic condition because it most represents the current conditions of the study area.

Simulated drainage modifications and engineering controls included the following:

1. *Including a beaver dam in Brown Ditch present in April 2014.* The simulated conditions of this scenario would decrease amounts of flow through the ditch and increase water levels in the areas upstream of the beaver dam located on the upstream side of Central Avenue. Results of the simulation are compared to data collected on April 29, 2014, while the beaver dam was present.

2. *Decreasing the discharge from Brown Ditch by simulating proposed control structures within the channel of the ditch.* This was simulated by increasing the elevation of the drain cells that represent Brown Ditch, effectively increasing the amount of water allowed to pool behind proposed control structures within the channel of the ditch. Proposed control structures are pool-riffle type structures where the elevation of a spillway is a significantly higher elevation (approximately 3–4 ft) than the ditch upstream of the structure causing water to pool on the upstream side. Locations of the proposed control structures were estimated by INDU staff.

Two climate-related conditions were simulated:

1. *An increase in the water level of Lake Michigan, represented by setting the value of the northern boundary condition of the groundwater-flow model equal to the extreme high level of 583.86 ft NAVD 88 recorded on May 31, 1998, at the NOAA Lake Michigan monitoring site at Calumet Harbor, Ill. (period of record March 12, 1905, through September 8, 2011; National Oceanic and Atmospheric Administration, 2011).* The conditions of this scenario would simulate the effects of higher Lake Michigan water levels on the water table within the study area using the March 2013 groundwater-flow model.

2. *A decrease in the water level of Lake Michigan, represented by setting the value of the northern boundary condition of the groundwater-flow model equal to the extreme low level of 575.14 ft above NAVD 88 recorded on December 23, 2007, at the NOAA Lake Michigan monitoring site at Calumet Harbor, Ill. (period of record March 12, 1905, through September 8, 2011; National Oceanic and Atmospheric Administration, 2011).* The conditions of this scenario would simulate the effects of lower Lake Michigan water levels on the water table within the study area using the March 2013 groundwater-flow model.

Results of these simulated scenarios are presented and compared to the results of other scenarios and the results of the March 2013 groundwater-flow model. Figures are presented that display (1) areas where the water table is simulated to be at or above the land surface, (2) areas where the water table is within 3 to 7 ft of the land surface, and (3) comparisons of the simulated water table from the various scenarios with the water table from the groundwater-flow model calibrated to the March 2013 hydraulic condition, or another modeled scenario.

## Simulated Inclusion of Beaver Dam to Brown Ditch at Central Avenue

The scenario including the Beaver Dam located at Central Avenue in April 2014 used the calibrated March 2013 model and simulated an increased extent of inundated area in Great Marsh and increased discharge to Brown Ditch. From May 2012 to October 2013, NPS staff attempted to keep Brown Ditch clear of debris and beaver dams to assist in the collection of streamflow data at the USGS streamgage locations (fig. 10). Despite their best efforts and as previously discussed, the data collected at the gaging station on Brown Ditch at Central Avenue (USGS 04095154) were frequently affected by beaver dams. Following October 2013, the beaver dam at Central Avenue was not removed to provide data to estimate the effects on groundwater and surface-water levels of a permanent control structure at the site. Water levels in select wells were measured on April 29, 2014, to estimate the effects of the beaver dam on the water level in Great Marsh (fig. 17, table 5). The beaver dam remained in place until June 2014 when it was removed due to concerns for the stability of the Central Avenue roadbed.

The groundwater-flow model built to simulate the March 2013 hydraulic condition was adjusted in two ways to simulate the April 2014 observed conditions:

1. Recharge parameter values were increased from the original values to represent increased precipitation.

2. The elevations of the bottom of the drain cells that represent Brown Ditch were adjusted to account for the location and estimated altitude of a beaver dam in the ditch on the upstream side of Central Avenue at the location of USGS streamgage 04095154 (fig. 10).

## Adjustment of Parameter Values to Hydrologic Conditions

Parameters that simulate groundwater recharge in wetland (MarshRech), non-wetland/non-urban areas (SandRech), Beverly Shores (BevShoresR), and Town of Pines (PineRech) were adjusted by using a combination of parameter estimation and manual adjustment from the original values used in the March 2013 simulation (table 14) in order to simulate the observed April 2014 conditions. The value of the parameter representing wetland recharge (MarshRech) increased 4.18 in/yr (0.35 inch per month [in/month]), from −6.91 to −2.72 in/yr. The value of the parameter representing recharge in non-urban and wetland areas (SandRech) increased 0.5 in/yr (0.04 in/month), from 14.66 to 15.16. The parameter value representing recharge in Beverly Shores decreased 6.44 in/yr (0.54 in/month), from 21.97 to 15.53, whereas the parameter representing recharge in the developed areas of Town of Pines increased by 5.07 in/yr (0.42 in/month), from 11.70 to 16.77.

The increased recharge rates for the areas of the model simulating Town of Pines and non-urban and wetland areas may be related to above average amounts of precipitation in January and February 2014 (fig. 33). The decreased recharge in Beverly Shores may be related to increased evapotranspiration and the lack of artificial recharge caused by septic return flow to the aquifer during a relatively cold time of year, and the effects of using parameter-estimation techniques when no observations were active in the area representing Beverly Shores recharge.

**Table 14.** Model parameters with the original values and the adjusted values used to match the April 2014 simulation.

[ft/d, feet per day; in/yr, inches per year; —, not applicable]

| Parameter | Parameter description | Parameter type | March 2013 calibration | Parameter derived by means of parameter estimation for April 2014 simulation | April 2014 simulation |
|---|---|---|---|---|---|
| | | | Final parameter value | | Final parameter value |
| kdrn1 | Vertical hydraulic conductivity of the streambed for the ditch along US-12 | Drain | 3.12 ft/d | — | No change |
| kow | Hydraulic conductivity assigned to the cells of layer one used to simulate areas of the open water of East Long Lake and West Long Lake | Hydraulic conductivity | 10,000 ft/d | — | No change |
| ks | Hydraulic conductivity of the surficial sand aquifer | Hydraulic conductivity | 17.73 ft/d | — | No change |
| kBevS | Hydraulic conductivity of the surficial sand aquifer of northern dune ridge | Hydraulic conductivity | 14.34 ft/d | — | No change |
| kwet | Hydraulic conductivity of the surficial aquifer of Great Marsh | Hydraulic conductivity | 17.82 ft/d | — | No change |
| kvow | Vertical hydraulic conductivity assigned to the cells of layer 1 used to simulate areas of the open water of East Long Lake and West Long Lake | Vertical hydraulic conductivity | 10,000 ft/d | — | No change |
| kvs | Vertical hydraulic conductivity of the surficial sand aquifer | Vertical hydraulic conductivity | 5 ft/d | — | No change |
| kvBevS | Vertical hydraulic conductivity of the surficial sand aquifer of northern dune ridge | Vertical hydraulic conductivity | 3.0 ft/d | — | No change |
| kvwet | Vertical hydraulic conductivity of the surficial sand aquifer of Great Marsh | Vertical hydraulic conductivity | 10 ft/d | — | No change |
| SandRech | Recharge rate to the surficial sand aquifer in non-urban and non-wetland areas | Recharge | 14.66 in/yr | Yes | 15.16 in/yr |
| BevShoresR | Recharge rate to the surficial sand aquifer in urban areas | Recharge | 21.97 in/yr | Yes | 15.53 in/yr |
| MarshRech | Recharge rate to the surficial sand aquifer in wetland areas | Recharge | –6.91 in/yr | Yes | –2.72 in/yr |
| PineRech | Recharge rate to the surficial sand aquifer in Town of Pines | Recharge | 11.70 ft/d | Yes | 16.77 ft/d |
| flowingWel | Recharge values used to simulate flow from the flowing well in Beverly Shores | Recharge | 533 ft/d | — | No change |

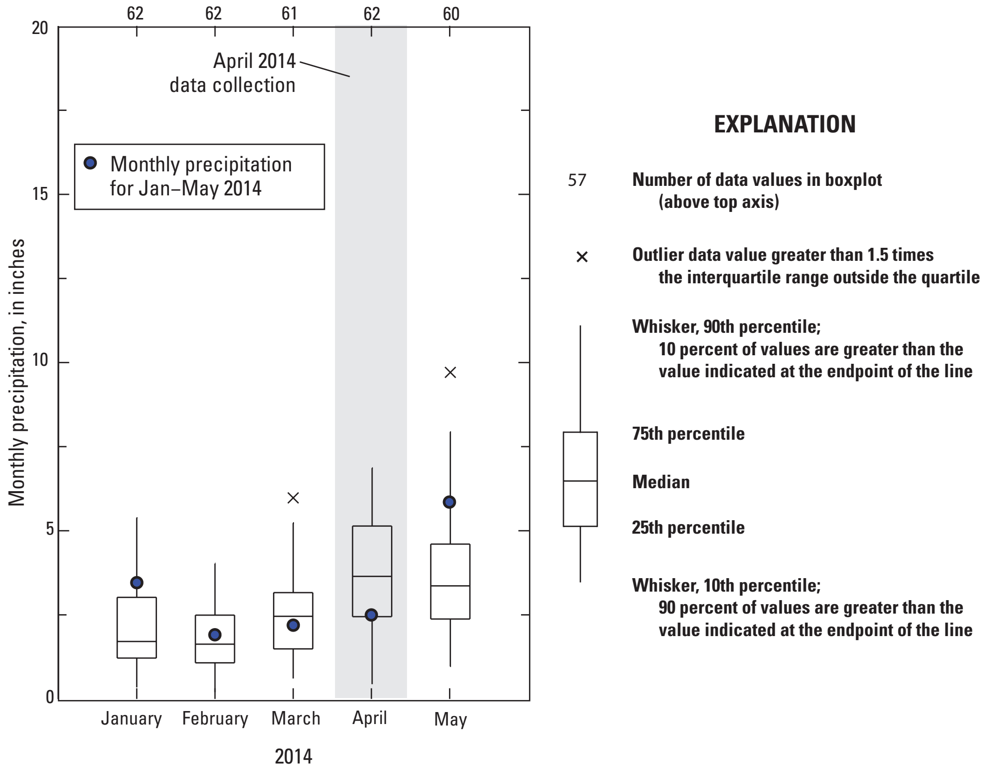



**Figure 33.** Box-and-whisker plots of monthly precipitation statistics for the combined records from the weather stations at Ogden Dunes (1951–89) and Indiana Dunes National Lakeshore, northwestern Indiana (1989–2013), and precipitation during January–May 2014. (Station locations are shown in fig. 1.)

To estimate the elevation of the top of the beaver dam, a photo was taken at the approximate level of the pooled water-level surface, and the elevation of the control was estimated by using the staff gage at the streamgage as a reference point (fig. 17*B*). The elevation value of 599.0 ft above NAVD 88 was estimated to be ± 0.5 ft of the actual value. The beaver dam was simulated by adjusting the bottom elevation of drain cells that represent Brown Ditch to the estimated elevation of the top of the beaver dam. Although there is a water-surface slope from upstream to downstream behind the dam, it was assumed that the change in elevation was insignificant over the short distance that was affected by the dam. This adjustment limits the amount of water available to pool in the cell to the altitude of the downstream dam. Any water that would potentially pool above this altitude will flow downstream.

## Observations

The observations used for model calibration consisted of 19 water-level measurements made on April 29, 2014 (table 15). Most water-level observations were in the vicinity of Great Marsh east of Lakeshore County Road and Town of Pines. The same techniques for weighting the observations from the calibrated March 2013 model were used for the April 2014 simulation.

## Model Fit to Observations

The unweighted water-level residuals are shown in figure 34 for the April 2014 simulation. The mix of positive and negative residuals in different parts of the model area is a characteristic of an adequately calibrated model. Computed statistics based on the unweighted water-level residuals are presented in table 16. The range of unweighted water-level residuals can be expressed by their standard deviation, which is 0.67 ft. Sixty-three percent of the residuals are within 1 standard deviation of the mean residual, and 100 percent are within 2 standard deviations. The magnitude of water-level residuals can be represented by the mean absolute error, which is 0.51 ft. The relative accuracy of the model calibration can be measured by the percent mean absolute error, which is the mean absolute error divided by the overall range in water levels. The percent mean absolute error for the model is 2.46 percent. No flow observations were made in April 2014.

Because this is a scenario simulating a modified hydrologic condition based on the calibrated March 2013 model, a weighted residual analysis was deemed unnecessary. Unweighted residuals of observations collected in April 2014 were used in the adjustment of recharge parameters and to calculate statistics that are presented in table 16. On the basis of higher, but relatively similar unweighted residual statistics such as the percent mean absolute error (2.27 percent for March 2013, 2.46 percent for April 2014), the simulation adequately represents the observed conditions.

**Table 15.** Measured and model-calculated water levels and discharge measurements and modeled residuals for the April 2014 simulation.

[NAVD 88, North American Vertical Datum of 1988]

| Observation name | Site type | Date | Observed value | Simulated value | Residual |
|---|---|---|---|---|---|
| Water level, in feet above NAVD 88 | | | | | |
| MW102 | Groundwater | April 2014 | 615.10 | 615.41 | −0.32 |
| MW120 | Groundwater | April 2014 | 603.16 | 604.30 | −1.14 |
| MW104 | Groundwater | April 2014 | 610.67 | 609.81 | 0.86 |
| C601E | Surface water | April 2014 | 604.13 | 604.07 | 0.06 |
| MW123 | Groundwater | April 2014 | 609.03 | 608.45 | 0.58 |
| 601 | Groundwater | April 2014 | 603.28 | 603.28 | 0.00 |
| GM-31 | Groundwater | April 2014 | 607.21 | 605.89 | 1.32 |
| 606 | Groundwater | April 2014 | 602.68 | 602.64 | 0.04 |
| MW107 | Groundwater | April 2014 | 613.15 | 614.00 | −0.85 |
| MW106 | Groundwater | April 2014 | 613.22 | 613.29 | −0.07 |
| MW110 | Groundwater | April 2014 | 612.26 | 612.37 | −0.11 |
| 602 | Groundwater | April 2014 | 603.39 | 603.21 | 0.18 |
| 603 | Groundwater | April 2014 | 603.44 | 602.96 | 0.48 |
| 609 | Groundwater | April 2014 | 602.92 | 603.79 | −0.87 |
| 604 | Groundwater | April 2014 | 599.45 | 600.43 | −0.98 |
| 610 | Groundwater | April 2014 | 605.47 | 605.17 | 0.30 |
| GM-35 | Groundwater | April 2014 | 596.88 | 595.93 | 0.95 |
| 608 | Groundwater | April 2014 | 594.90 | 595.34 | −0.44 |
| 607 | Groundwater | April 2014 | 594.30 | 594.54 | −0.24 |

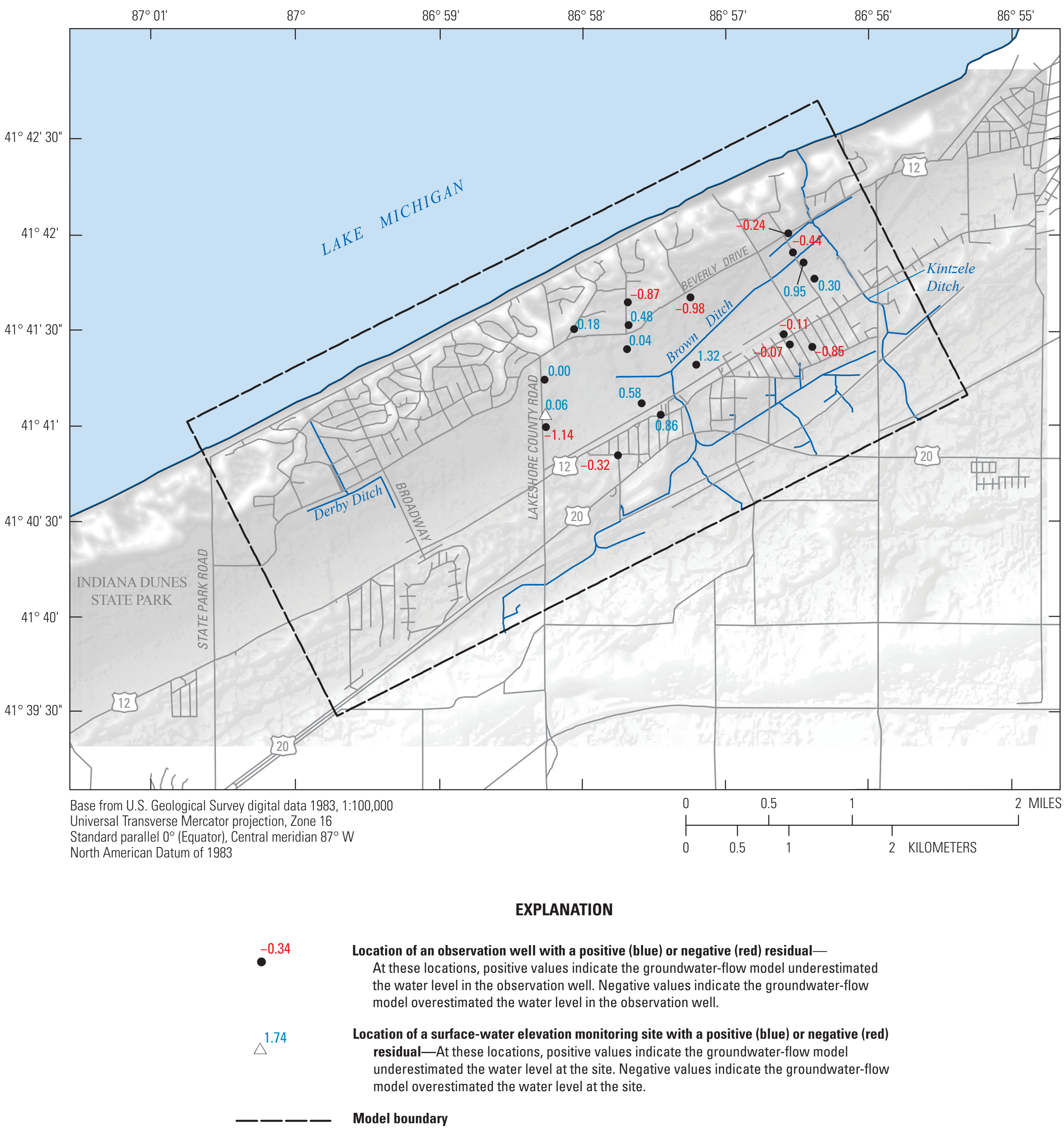



**Figure 34.** Difference between observed and simulated water levels for the April 2014 simulation of the Great Marsh area near Indiana Dunes National Lakeshore, Indiana.

**Table 16.** Computed statistics based on the unweighted water-level residuals for the April 2014 hydrologic condition.

[ft, feet]

| Type of residual | Statistics based on unweighted model residuals | | | | | | |
|---|---|---|---|---|---|---|---|
| | Minimum residual (ft) | Mean residual (ft) | Maximum residual (ft) | Standard deviation of the residuals (ft) | Bias (ft) | Mean absolute error | Percent mean absolute error |
| Water level | −1.14 | −0.01 | 1.32 | 0.67 | −0.24 | 0.51 | 2.46 |

## Simulated Water Budget

The results of the calibrated model can be quantified and analyzed by an overall water budget and by a budget for individual parts of the flow system. Table 17 lists the overall budget for the model simulating the conditions of April 2014. A large proportion of the discharge from the model (57 percent) goes to Brown, Kintzele, and Derby Ditches rather than to Lake Michigan representing an increase of 0.58 $ft^3/s$ over the results from the March 2013 calibrated model. Nearly 7 percent of the discharge from the model is simulated as evaporation, which is approximately 0.46 $ft^3/s$ less than the results from the March 2013 calibrated model.

The water budget between the model and four areas of the model (fig. 28)—the Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, Town of Pines, and Beverly Shores—for the April 2014 simulation was analyzed, and the results are shown in table 18. The total amount of water entering the zones representing the western and eastern portions of Great Marsh, and Town of Pines increased by 0.37, 0.26, and 0.35 $ft^3/s$, respectively. Despite the increases, there is still approximately zero simulated groundwater flow from Great Marsh to Town of Pines. The volume of water simulated to be entering the zone representing Beverly Shores decreased by 0.43 $ft^3/s$ in the April 2014 simulation. These simulated water-budget differences can be attributed to increased simulated recharge in Great Marsh and Town of Pines and decreased recharge in Beverly Shores in the April 2014 simulation.

**Table 17.** Water budget associated with the groundwater-flow model simulating the April 2014 hydrologic condition.

[$ft^3/s$, cubic feet per second; >, greater than]

| Inflow to model | Inflow rate ($ft^3/s$) and percent of total | | Outflow from model | Outflow rate ($ft^3/s$) and percent of total | |
|---|---|---|---|---|---|
| Lake Michigan (constant-head boundaries) | $9.40 \times 10^{-9}$ | 0.00 | Lake Michigan (constant-head boundaries) | 1.71 | 36.31 |
| | | | Leakage into Brown Ditch, Kintzele Ditch, and Derby Ditch (model drains) | 2.7 | 57.32 |
| Confined aquifer (head-dependent boundary) | $4.28 \times 10^{-6}$ | >1 | Confined aquifer (head-dependent boundary) | $2.70 \times 10^{-8}$ | >1 |
| Precipitation (recharge) | 4.71 | 100 | Evaporation (recharge) | 0.31 | 6.58 |
| **Total inflow** | **4.71** | | **Total outflow** | **4.71** | |

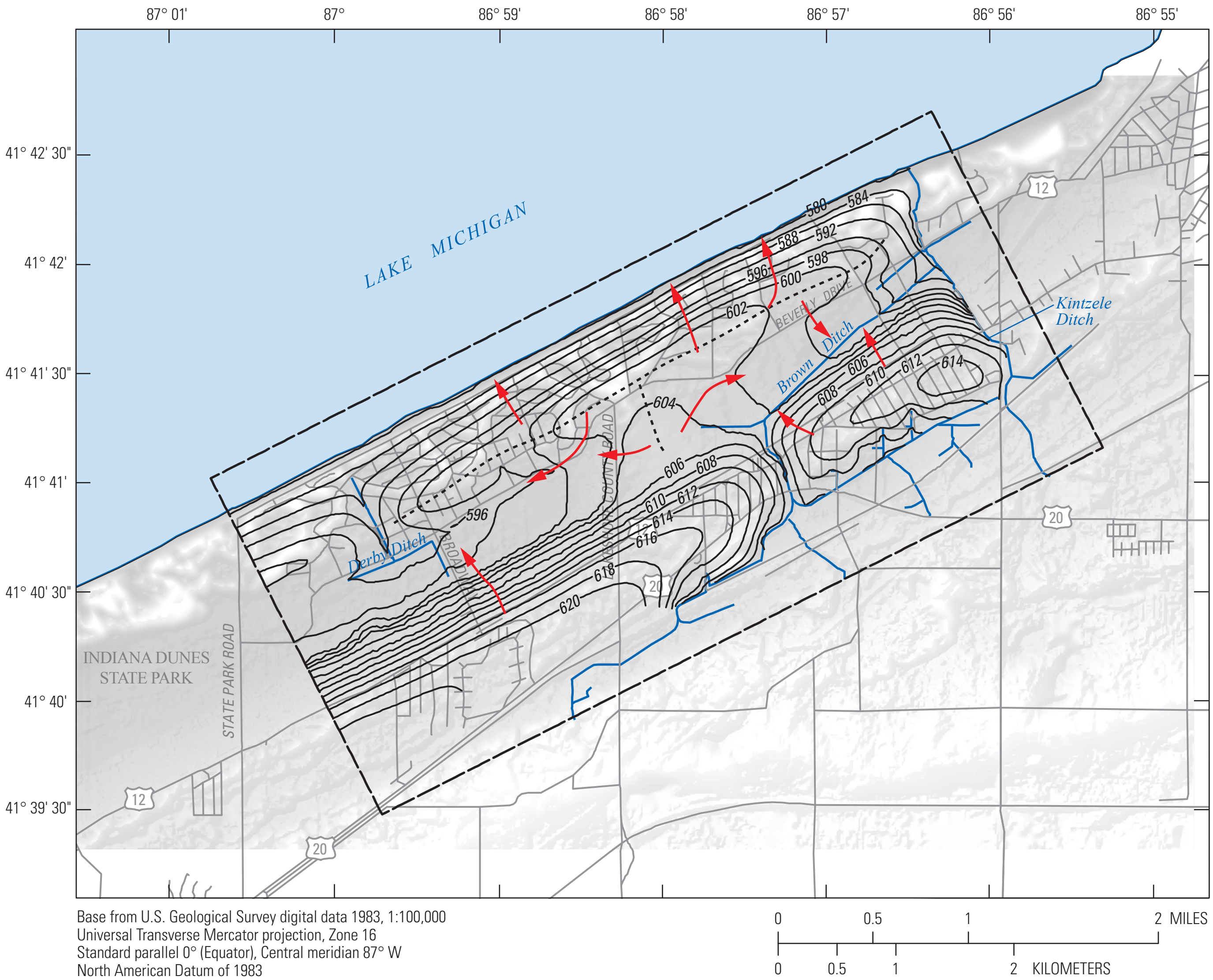
**Table 18.** Water budgets for four zones of the groundwater-flow model simulating Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, the town of Beverly Shores, and Town of Pines.

[ft$^3$/s, cubic feet per second; —, not applicable]

| | West Great Marsh Zone 1 | East Great Marsh Zone 2 | Town of Pines Zone 3 | Beverly Shores Zone 4 |
|---|---|---|---|---|
| | Water moving into cells Rate, in ft$^3$/s (percent of total flow) | | | |
| **From West Great Marsh Zone 1** | — | 0.003 (0.17%) | 0 (0.00%) | 0.02 (0.87%) |
| **From East Great Marsh Zone 2** | 0.11 (3.31%) | — | 0.002 (0.09%) | 0.01 (0.44%) |
| **From Town of Pines Zone 3** | 0.63 (18.98%) | 0.32 (18.50%) | — | — |
| **Total (ft$^3$/s)** | 3.32 | 1.73 | 2.13 | 2.29 |
| | Water moving out of cells Rate, in ft$^3$/s (percent of total flow) | | | |
| **To ditches** | 1.08 (32.53%) | 0.59 (34.10%) | 0.77 (36.15%) | 0.26 (11.35%) |
| **To West Great Marsh Zone 1** | — | 0.11 (6.36%) | 0.63 (29.58%) | 0.06 (2.62%) |
| **To Town of Pines Zone 3** | 0 (0.00%) | 0.002 (0.12%) | — | — |
| **Total (ft$^3$/s)** | 3.32 | 1.73 | 2.13 | 2.29 |

## Simulated Water Levels and Groundwater-Flow Paths

The results of the April 2014 groundwater-flow model show that the impacts from the beaver dam in Brown Ditch on the upstream side of Central Avenue impact water levels in Great Marsh. Simulated water-level contours for the April 2014 simulation are shown in figure 35. As in the March 2013 simulated conditions, the major groundwater divides are beneath the dune ridge beneath Beverly Shores and the dune ridge beneath Town of Pines. The major simulated flow paths are north from the dune ridges beneath Town of Pines toward Great Marsh, and Brown Ditch. To a lesser extent, groundwater is simulated to flow south from the dune ridge beneath Beverly Shores to Great Marsh and Brown Ditch. Another groundwater divide runs northwest-southeast from approximately the intersection of Beverly Drive and Lakeshore County Road and terminates near the southern boundary of Great Marsh; this divide has shifted slightly eastward as a result of the modifications to create the April 2014 model. Simulated changes due to the inclusion of the beaver dam in Brown Ditch include the shifting of the 602-, 600-, 598-, and 596-ft water-table contours to the east indicating that the water-table gradient is higher in the eastern portion of Great Marsh between the minor northwest-southeast trending minor water-table divide and Central Avenue than the condition simulated by the modified model (fig. 29).




**EXPLANATION**

— 610 — **Simulated water-table contour**—Shows the altitude of the water table in feet above North American Vertical Datum of 1988 simulated by the groundwater-flow model in the surficial aquifer. Contour interval variable.

**Arrow indicating direction of groundwater flow inferred from simulated water-table contours**

- - - - **Groundwater divide**—Approximate simulated divide in surficial aquifer, April 29, 2014

**Figure 35.** Simulated water-table contours from the April 2014 simulation. (Compare to fig. 29.)

Backward tracking flow paths were generated for the April 2014 simulation in nodes representing the Lake Michigan shoreline, Derby Ditch, Kintzele Ditch, and the segment of Brown Ditch north of US-20 using MODPATH (Pollock, 2012); results are shown in figure 36. Flow paths were similar to those for the March 2013 simulation, extending north and south from the groundwater divides to Lake Michigan and the ditches. The inclusion of the beaver dam in Brown Ditch on the upstream side of Central Avenue has altered the groundwater-flow paths in the eastern portion of Great Marsh from those presented for the March 2013 simulation (fig. 30). Longer flow paths now travel beneath Brown Ditch from areas just west of the mouth of Brown Ditch into Great Marsh and terminate near the confluence of Brown and Kintzele Ditches. Longer flow paths now travel from upstream portions of Brown Ditch and terminate into Kintzele Ditch. The distributions of flow paths flowing to Lake Michigan and Derby Ditch do not deviate from those presented for the March 2013 simulation.

### Simulated Inundated Areas

Areas where the water table is simulated to be at or above the land surface are displayed in figure 37. Inundated areas were calculated by using the altitude of the simulated, steady-state water table in April 2014 and the lidar-based land-surface elevation dataset. The digital land-surface altitude was subtracted from the water-table altitude to calculate the depth of the water table above the land surface. At the point where the water table rises above ground surface, surface runoff should be generated. Because of this, the actual area where water levels rise above land surface may be smaller than shown in figure 37, even though the amount of surface runoff is estimated to be small because of the high permeability of the materials at land surface. Imprecision in land-surface altitude in some of the areas represented also adds to the uncertainty of the estimated area of inundation for parts of the model.

The distribution of inundated areas shown in figure 37 (compare with fig. 32) displays the effects of the inclusion of the beaver dam in Brown Ditch just upstream of Central Avenue into the groundwater-flow model. The water table in most areas of Beverly Shores north of Great Marsh is simulated to be below the land surface except for some small locations north of Beverly Drive and east of Lakeshore County Road, which is consistent with areas estimated in the March 2013 simulation. Likewise, areas to the south of Great Marsh in and around Town of Pines are simulated to be below land surface except for some small areas near the southern boundary of the active model area near the upstream reaches of Brown Ditch. Areas estimated to have water above the land surface increase in size in Great Marsh east of Lakeshore County Road and south of Beverly Drive, which is likely due to the effects of including the beaver dam in Brown Ditch just upstream of Central Avenue within the simulation. The total area where the water table is above the land surface is much greater than the area from the March 2013 simulation.

## Simulated Inclusion of Pool-Riffle Control Structures in Brown Ditch

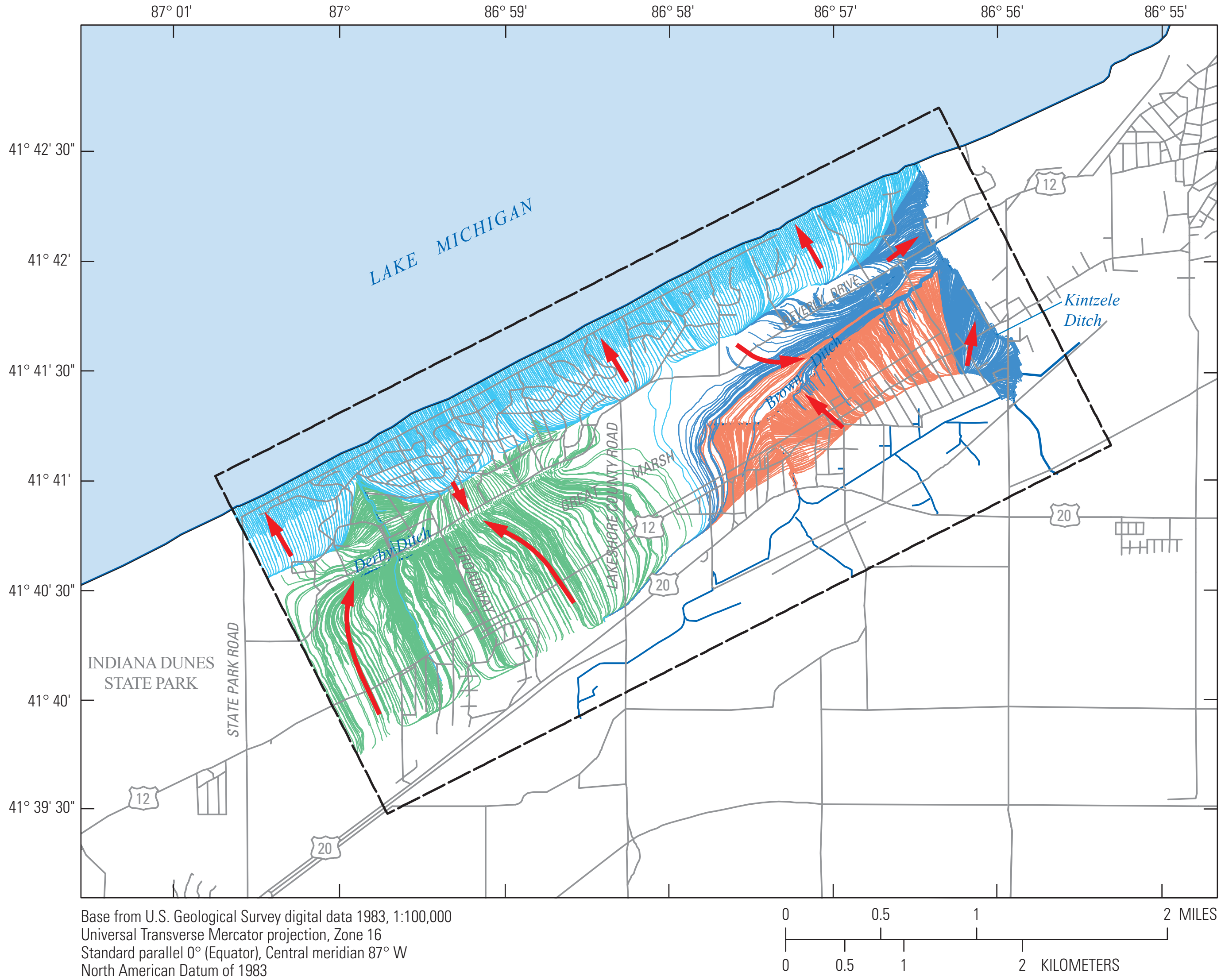
A simulated scenario with the March 2013 model in which six control structures were simulated resulted in enlarged areas simulated to be inundated by water in the March 2013 model. Great Marsh within the study area was historically described as covering an area of approximately 1,053 acres from Lakeshore County Road to its eastern terminus in Michigan City (Dan Mason, Indiana Dunes National Lakeshore, written commun., 2014). The NPS wishes to restore portions of Great Marsh within the study area by building pool-riffle type control structures within Brown and Kintzele Ditches, which will elevate the channel of the ditch to an altitude below which water will pool and saturate Great Marsh. In order to simulate the effects of these control structures, the calibrated March 2013 groundwater-flow simulation was modified by increasing the altitude of the bottom of Brown Ditch at locations were the NPS estimated the practice would be most beneficial. Overall, six control structures were included in the model, and their approximate locations and simulated control altitudes are presented in figure 38.

The control structures were simulated by increasing the altitude of the drain cells simulating the bottom of Brown Ditch within the model at the locations specified by the NPS. Increasing the control altitude for the drain cells simulates pooling of the surface water on the upstream side of the control. No other model parameters were altered from the March 2013 model during this simulation.

The inclusion of the six control structures enlarged areas simulated to be inundated by water in comparison to the March 2013 model, including areas just to the north of the entrance of Brown Ditch into Great Marsh, and areas north of the confluence of Brown and Kintzele Ditches (fig. 38; fig. 39, compare with fig. 32). There are no visible differences in the distribution of inundated area between the March 2013 simulation and the simulation that includes the six control structures in areas of Great Marsh directly northwest of the entrance of Brown Ditch into Great Marsh, areas west of Lakeshore County Road, or areas of Town of Pines south of Great Marsh.

The budget between the model and four areas of the model (fig. 28)—Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, Town of Pines, and Beverly Shores—for the March 2013 simulation that includes the six control structures in Brown Ditch was analyzed, and the results are shown in table 19. The total amount of water leaving the zones representing the eastern portions of Great Marsh, and Beverly Shores increased by 0.01 and 0.05 $ft^3/s$, respectively. These slight increases are most likely explained by the small increase in the amount of water discharging to ditches from both zones as well as by the increase in water leaving the model by evapotranspiration (recharge). The simulation did not produce or increase simulated discharge from Great Marsh to Beverly Shores or Town of Pines.

Groundwater- and surface-water monitoring sites simulated to have higher water levels in the March 2013 simulation that includes the six control structures in Brown Ditch than in the regular March 2013 simulation are shown in figure 40. Increases in water level range from 0.03 ft in monitoring well 602 to 2.39 ft in monitoring well 608.




**EXPLANATION**

- Horizontal groundwater-flow path within the surficial aquifer terminating in Derby Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Brown Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Kintzele Ditch.
- Horizontal groundwater-flow path within the surficial aquifer terminating in Lake Michigan.
- Model boundary
- Arrow indicating general direction of groundwater flow simulated by the modified groundwater-flow model.

**Figure 36.** Flow lines representing simulated groundwater-flow paths in the surficial aquifer under the steady-state hydraulic conditions of April 2014. (Arrows represent general directions of simulated groundwater flow.)

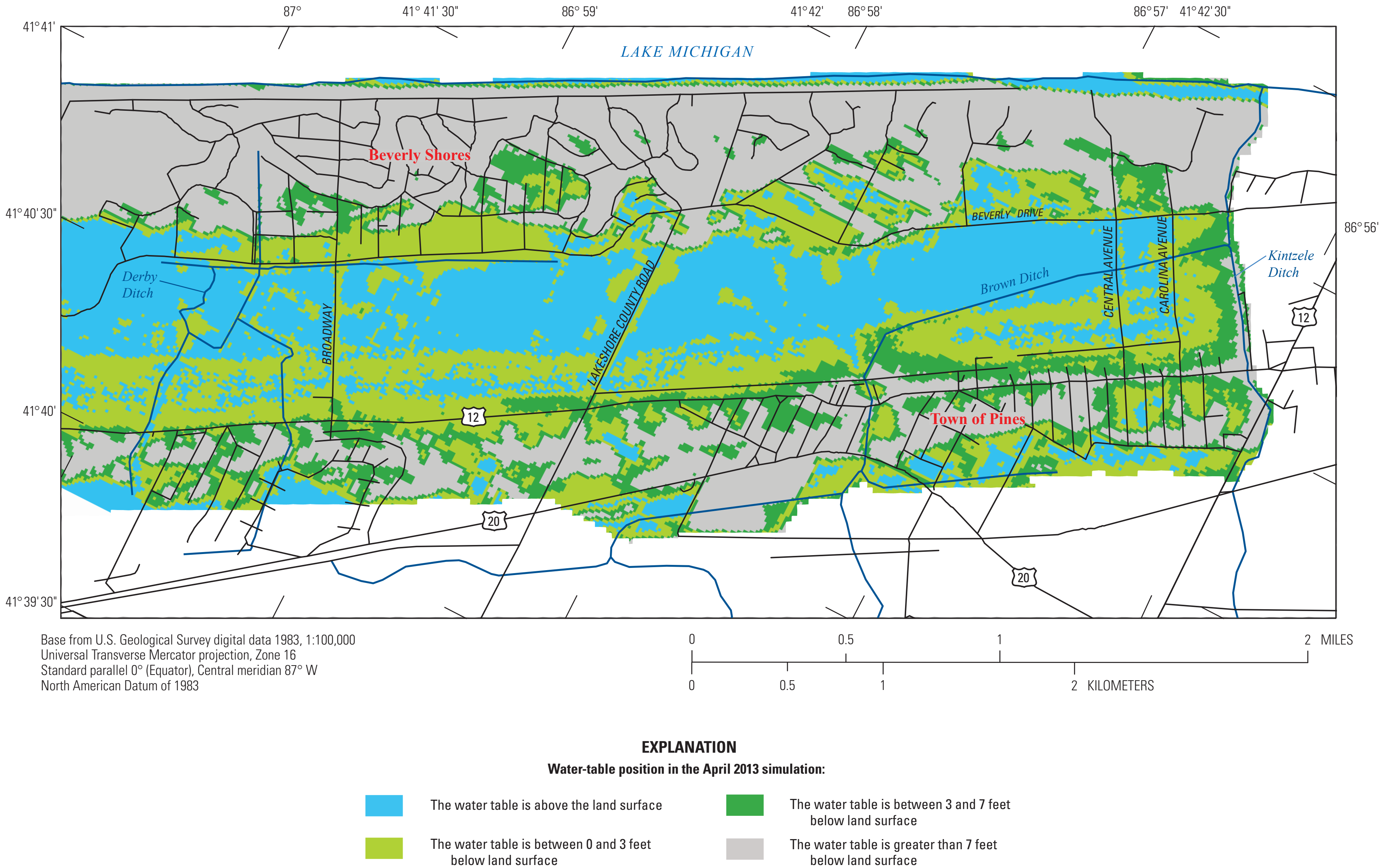



**Figure 37.** Simulated water-table position within areas near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana, April 2014. (Compare with fig. 32.)

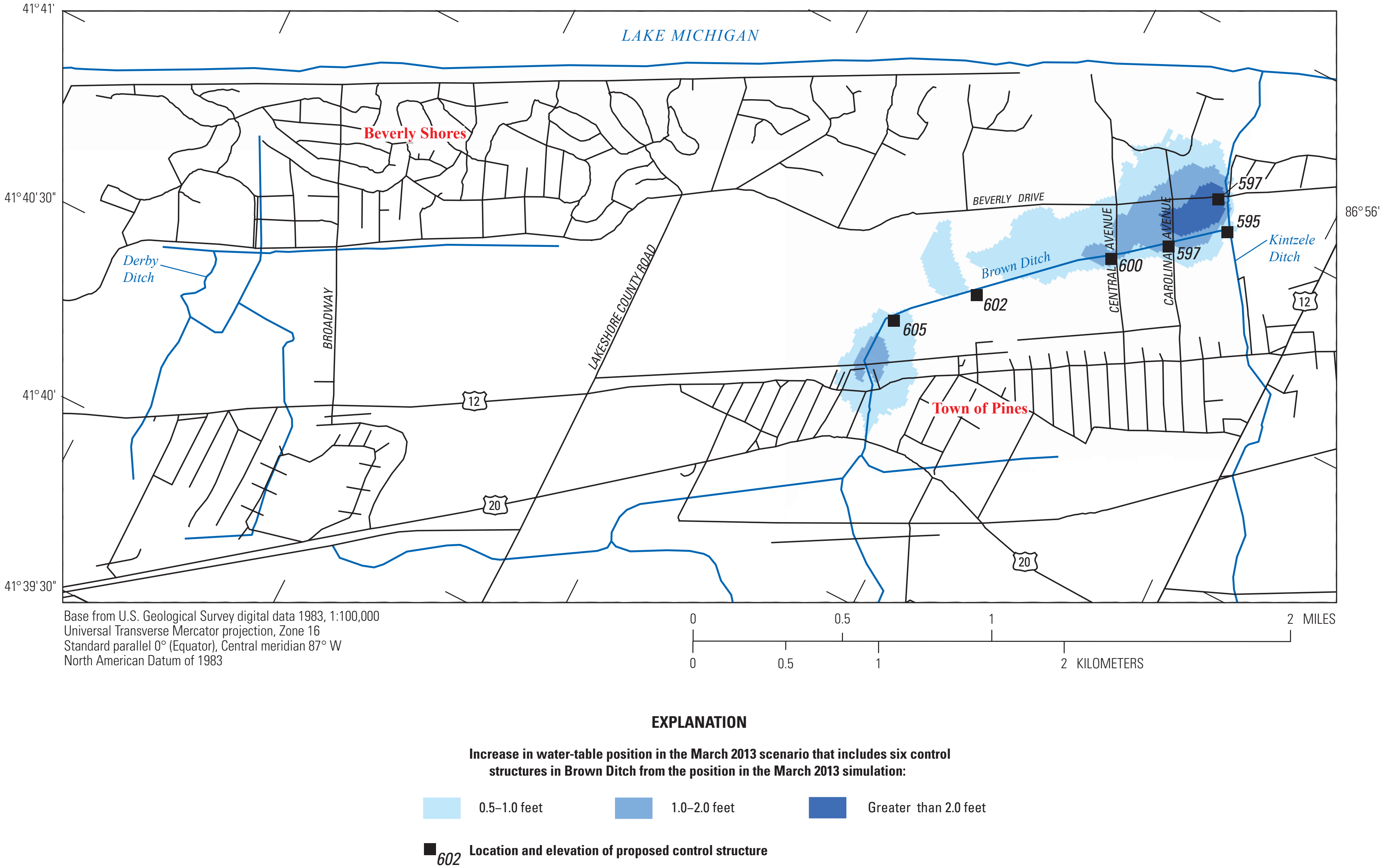



**Figure 38.** Approximate location of six simulated control structures and their simulated altitude in Brown Ditch, the difference in water-table position between the March 2013 simulation results, and a model scenario simulating the inclusion of six control structures in Brown Ditch during the March 2013 hydrologic condition near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana.

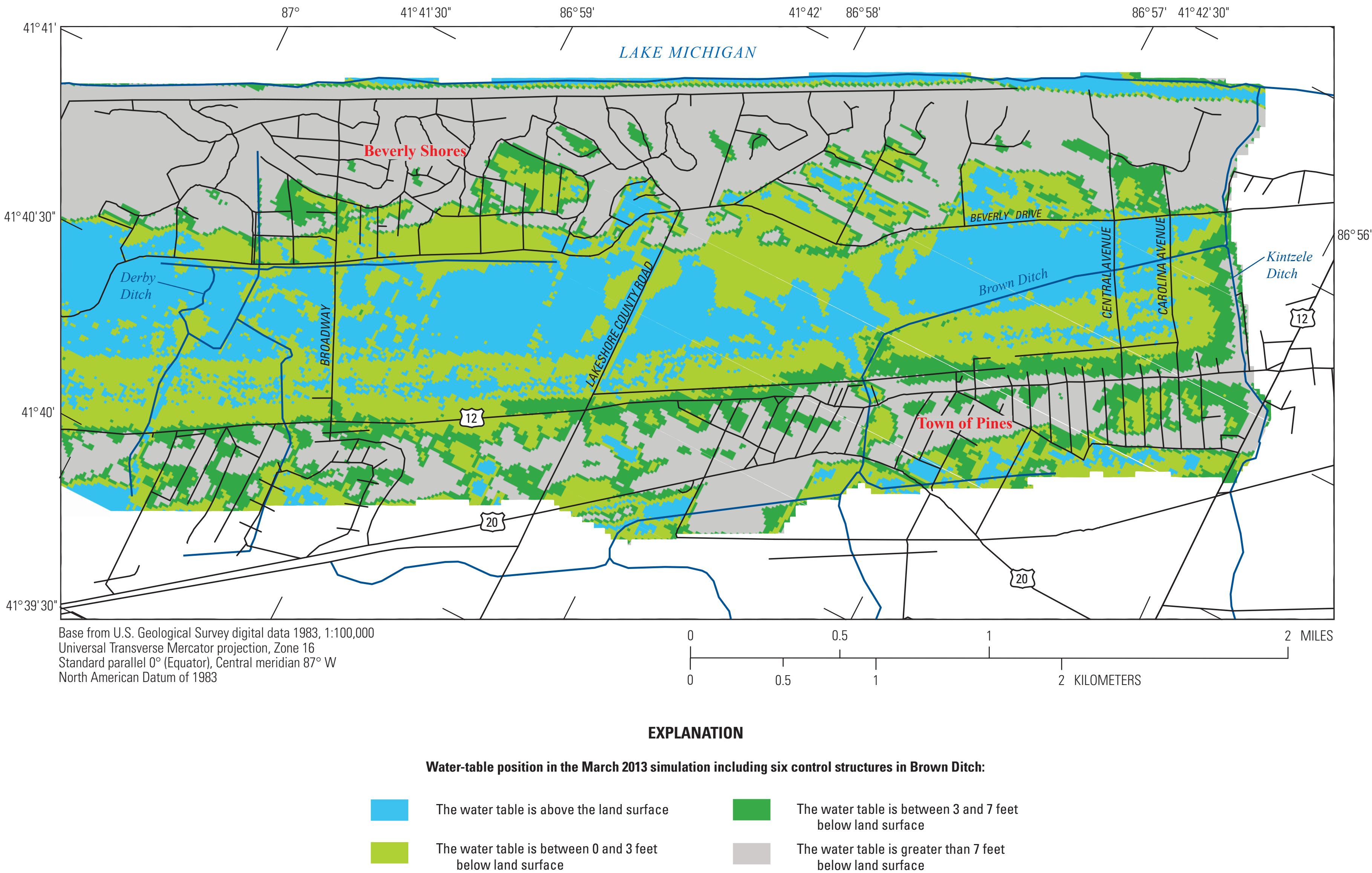
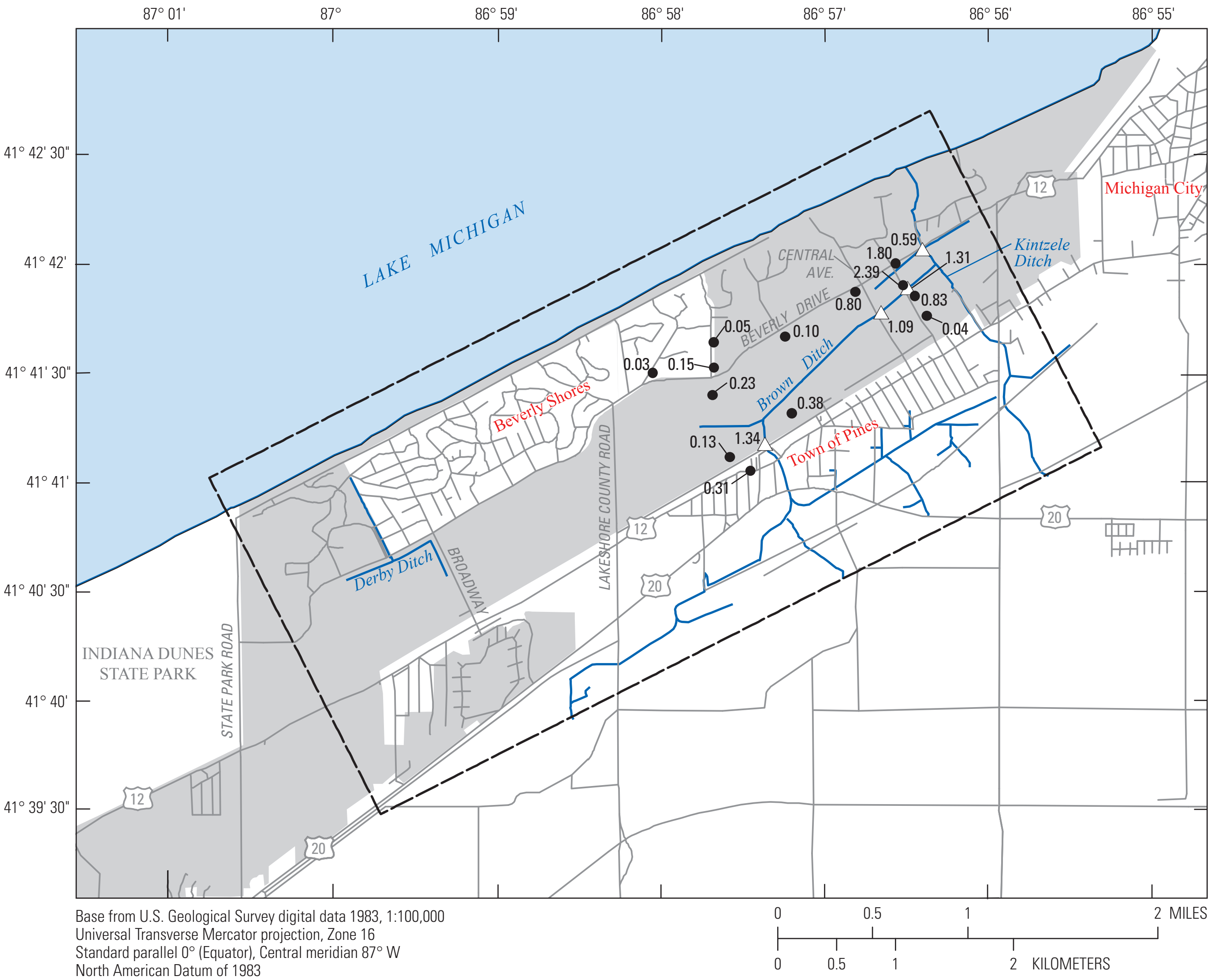



**Figure 39.** Water-table position resulting from a model scenario simulating the inclusion of six control structures in Brown Ditch during the March 2013 hydrologic condition near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana. (Compare with fig. 32.)

**Table 19.** Water budgets of four zones of the groundwater-flow model simulating Great Marsh west of Lakeshore County Road, Great Marsh east of Lakeshore County Road, the town of Beverly Shores, and Town of Pines using the simulation that includes six control structures in Brown Ditch.

[$ft^3/s$, cubic feet per second; —, not applicable]

| | West Great Marsh Zone 1 | East Great Marsh Zone 2 | Town of Pines Zone 3 | Beverly Shores Zone 4 |
|---|---|---|---|---|
| | **Water moving into cells Rate, in $ft^3/s$ (percent of total flow)** | | | |
| **From Recharge Zone 0** | 2.194 (74.37%) | 1.11 (75.00%) | 1.78 (100.00%) | 2.74 (98.92%) |
| **From West Great Marsh Zone 1** | — | 0.005 (0.34%) | 0.00 (0.00%) | 0.02 (0.72%) |
| **From East Great Marsh Zone 2** | 0.1 (3.39%) | — | 0.002 (0.11%) | 0.008 (0.29%) |
| **From Town of Pines Zone 3** | 0.58 (19.66%) | 0.26 (17.57%) | — | — |
| **From Beverly Shores Zone 4** | 0.084 (2.85%) | 0.1 (6.76%) | — | — |
| **Total (ft3/s)** | 2.95 | 1.48 | 1.78 | 2.77 |
| | **Water moving out of cells Rate, in $ft^3/s$ (percent of total flow** | | | |
| **To Lake Michigan** | — | — | — | 1.95 (70.40%) |
| **To ditches** | 0.83 (28.14%) | 0.32 (21.62%) | 0.6 (33.71%) | 0.37 (13.36%) |
| **To Recharge Zone 0** | 2.1 (71.19%) | 1.05 (70.95%) | 0.34 (19.10%) | 0.28 (10.11%) |
| **To West Great Marsh Zone 1** | — | 0.1 (6.76%) | 0.58 (32.58%) | 0.08 (2.89%) |
| **To East Great Marsh Zone 2** | 0.005 (0.17%) | — | 0.26 (14.61%) | 0.1 (3.61%) |
| **To Town of Pines Zone 3** | 0.00 (0.00%) | 0.02 (0.68%) | — | — |
| **To Beverly Shores Zone 4** | 0.02 (0.68%) | 0.008 (0.54%) | — | — |
| **Total (ft3/s)** | 2.95 | 1.48 | 1.78 | 2.77 |




Base from U.S. Geological Survey digital data 1983, 1:100,000
Universal Transverse Mercator projection, Zone 16
Standard parallel 0° (Equator), Central meridian 87° W
North American Datum of 1983

**EXPLANATION**

**Indiana Dunes National Lakeshore (INDU)**

**Model boundary**

0.13 **Location of an observation well with a water level in the simulation including six pool-riffle control structures greater than the simulation of the March 2013 hydrologic condition.**

1.34 **Location of a surface-water-level monitoring site with a water level in the simulation including six pool-riffle control structures greater than the simulation of the March 2013 hydrologic condition.**

**Figure 40.** Increases in water level at groundwater-monitoring wells and surface-water monitoring sites in the March 2013 simulation, which includes six control structures in Brown Ditch.

Conceptually, the inclusion of control structures within Brown Ditch increases the likelihood of water flowing from the ditch to the surrounding aquifer due to possibly higher water levels upstream of the control structures within the ditch than in the surrounding aquifer. Because the results of the March 2013 simulation that included six control structures in Brown Ditch did not produce results showing the expected increase in the water table in the area northwest of the point where Brown Ditch flows into Great Marsh near Beverly Drive, the conceptual model was reevaluated and simulations that use the MODFLOW River package (Harbaugh and others, 2000) to simulate the segment of Brown Ditch from its entrance into Great Marsh to its termination where it flows into Kintzele Ditch were completed. The MODFLOW River package differs from the Drain package used in the previous simulations by including the ability of the simulated river cells to contribute water back to the surrounding cells that simulate the aquifer when water levels in the ditch are simulated to be higher than those simulated in the surrounding aquifer.

The use of the MODFLOW River package in simulating Brown Ditch within Great Marsh produced larger areas simulated to be inundated by water in comparison to the March 2013 model that includes six control structures in Brown Ditch including areas just to the south of Beverly Drive and east of Lakeshore County Road and areas on either side of Carolina Avenue north of Brown Ditch (fig. 41; fig. 42, compare with fig. 38 and fig. 39). There are small increases in the distribution of inundated area south of Brown Ditch and north of US-12. The distribution of inundated areas of the simulations using the MODFLOW River package to simulate Brown Ditch within Great Marsh better represent the observed distribution during periods when the surficial aquifer is most saturated due to high precipitation or snowmelt.

## Simulated Increase in Level of Lake Michigan

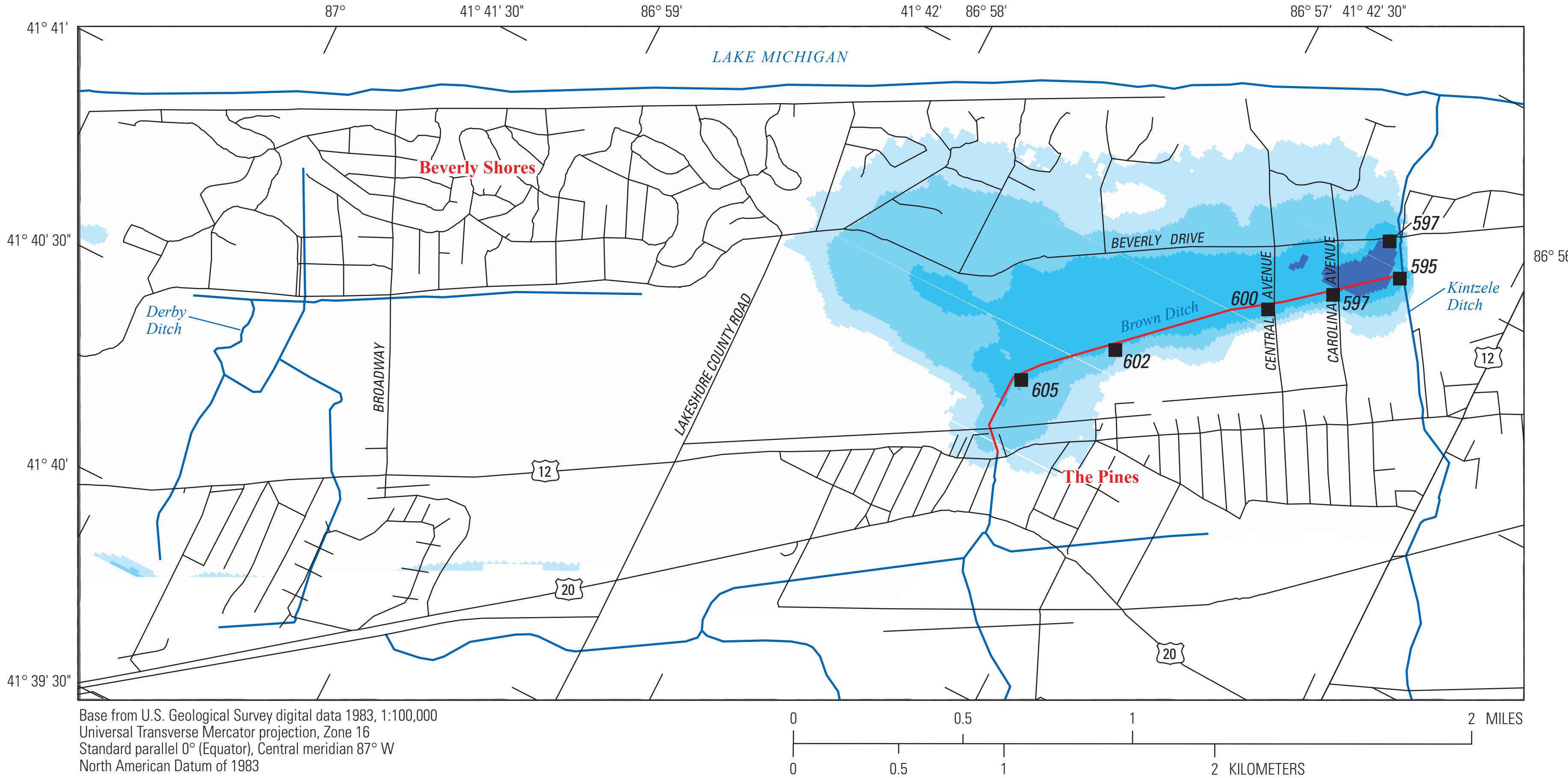
A scenario simulating the increase in the level of Lake Michigan was run with the calibrated March 2013 model to estimate the effects of increasing the water level of the major discharge point of the surficial aquifer and surface-water drainages on simulated hydrology in the modeled area. In order to perform the simulation, the constant-head boundary condition that represents Lake Michigan along the northern part of the model (fig. 23) was set equal to the extreme high level of 583.86 ft above NAVD 88 recorded on May 31, 1998, at the NOAA Lake Michigan monitoring site at Calumet Harbor, Ill. (period of record March 12, 1905, through September 8, 2011), an increase of 6.99 ft. No other parameter values or model input values were changed from those presented earlier in the report.

The simulated result of increasing the level of Lake Michigan was an increased area of inundated land relative to the March 2013 area (fig. 43; compare with fig. 32). Inundated areas of Great Marsh south of Beverly Shores enlarged on both sides of Lakeshore County Road with the greatest enlargement shown southeast of the intersection of Lakeshore County Road and Beverly Drive. In Beverly Shores, larger areas are simulated to be within 7 ft of the land surface likely in low lying interdunal areas. No significant changes in inundated area or areas of groundwater flooding resulted from the simulation in the area of Town of Pines.

## Simulated Decrease in Level of Lake Michigan

A scenario simulating the decrease in the level of Lake Michigan was run on the calibrated March 2013 model to estimate the effects on simulated hydrology in the modeled area. In order to perform the simulation, the constant-head boundary condition that represents Lake Michigan along the northern part of the model (fig. 23) was set equal to the extreme low level of 575.14 ft above NAVD 88 recorded on December 23, 2007, at the NOAA Lake Michigan monitoring site at Calumet Harbor, Ill. (period of record March 12, 1905, through September 8, 2011), a decrease of 1.73 ft. No other parameter values or model input values were changed from those presented earlier in the report.

The decrease of the level of Lake Michigan had little effect on the size of the area where the water table is simulated to be above land surface or the area where the water table reaches within 7 ft of the land surface (fig. 44; compare with fig. 32). The lack of changes in the study area can most likely be explained by the small difference between the value of Lake Michigan simulated in the March 2013 model and the extreme low value used in this simulation.




**EXPLANATION**

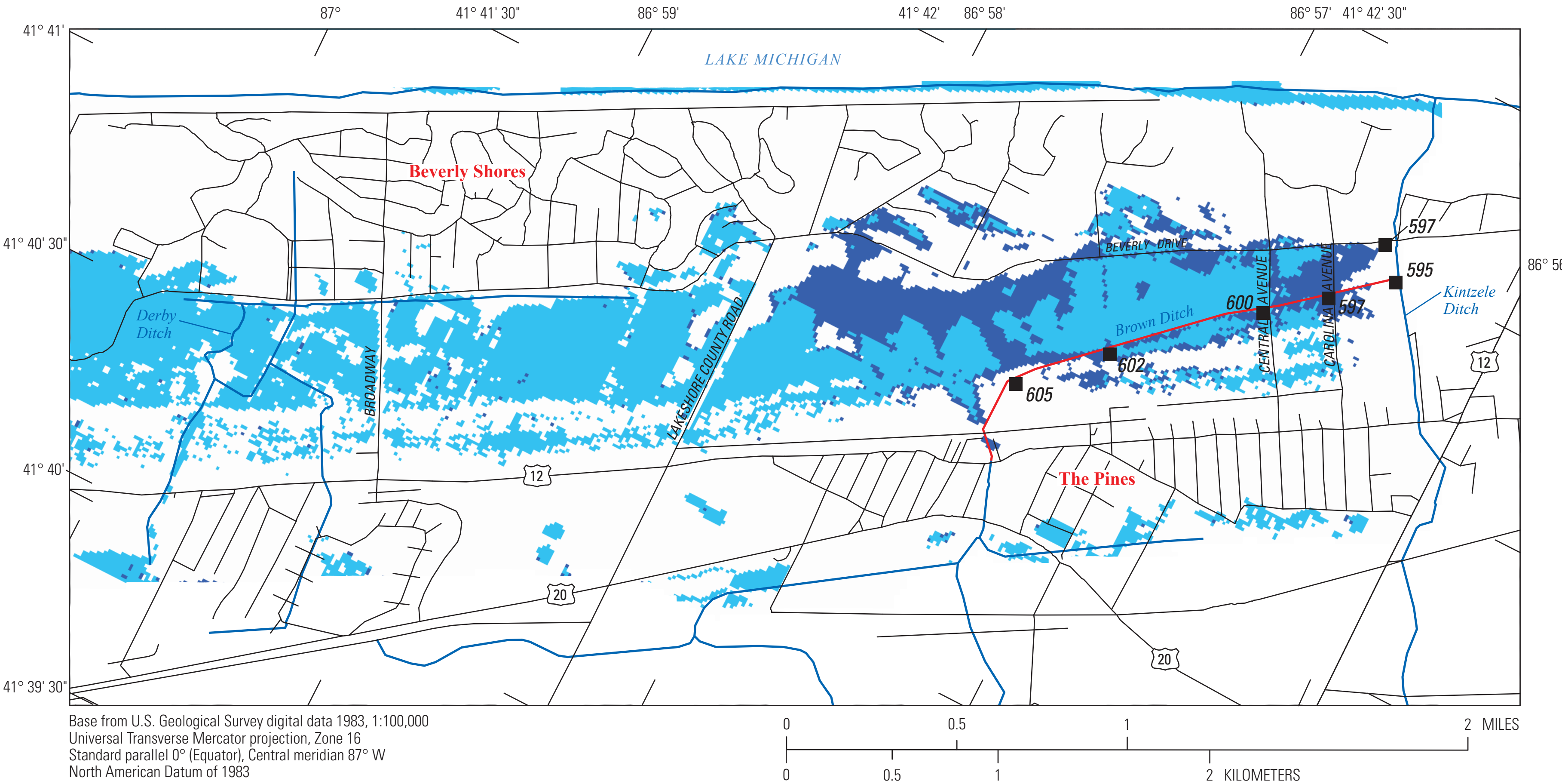
**Increase in water-table position in the March 2013 scenario that uses River cells instead of Drain cells and includes six control structures in Brown Ditch:**

0.5–1.0 feet
1.0–2.0 feet
2.0–3.0 feet
Greater than 3.0 feet

**Segment of Brown Ditch simulated using MODFLOW River cells instead of Drain cells**

602 **Location and elevation of proposed control structure**

**Figure 41.** Approximate location of six simulated control structures and their simulated altitude in Brown Ditch, the difference in water-table position between the March 2013 simulation results, and a model scenario simulating the inclusion of six control structures in Brown Ditch during the March 2013 hydrologic condition using MODFLOW River package to simulate Brown Ditch within Great Marsh near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana. (Compare with fig. 38.)




**EXPLANATION**

**Increase in water-table position in the March 2013 scenario that uses River cells instead of Drain cells and includes six control structures in Brown Ditch:**

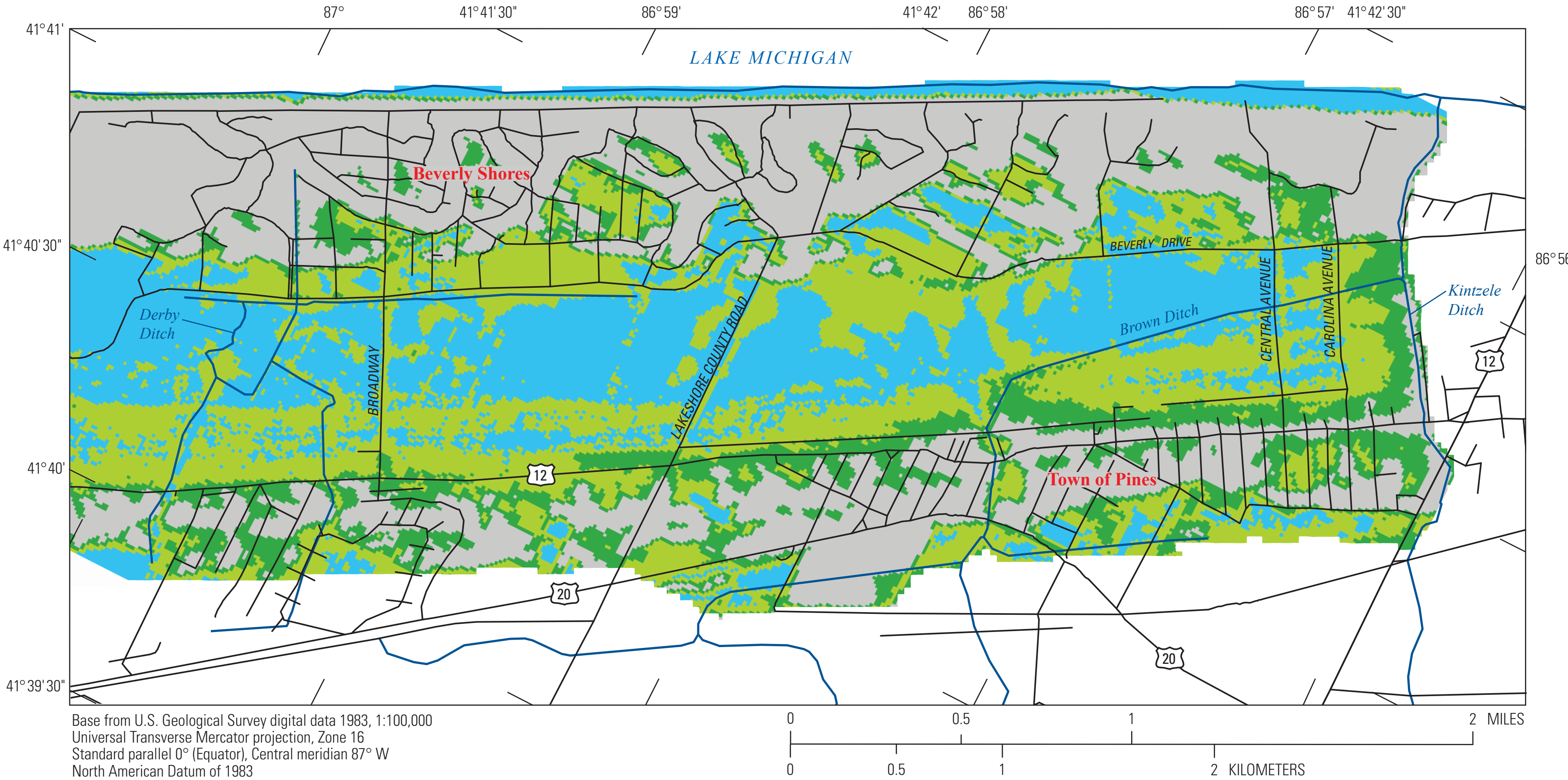
Locations where the water table is above the land surface in the March 2013 simulation

Additional locations where the water table is above the land surface with the inclusion of six control structures

**Segment of Brown Ditch simulated using MODFLOW River cells instead of Drain cells**

602 **Location and elevation of proposed control structure**

**Figure 42.** Inundated land surface areas resulting from a model scenario simulating the inclusion of six control structures in Brown Ditch during the March 2013 hydrologic condition using MODFLOW River package to simulate Brown Ditch within Great Marsh near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana. (Compare with fig. 39.)




**EXPLANATION**

**Water-table position in the March 2013 simulation with Lake Michigan at extreme high level:**

- The water table is above the land surface
- The water table is between 0 and 3 feet below land surface
- The water table is between 3 and 7 feet below land surface
- The water table is greater than 7 feet below land surface

**Figure 43.** Water-table position resulting from a model scenario simulating the water level of Lake Michigan at extreme high level and March 2013 conditions near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana. (Compare with fig. 32.)

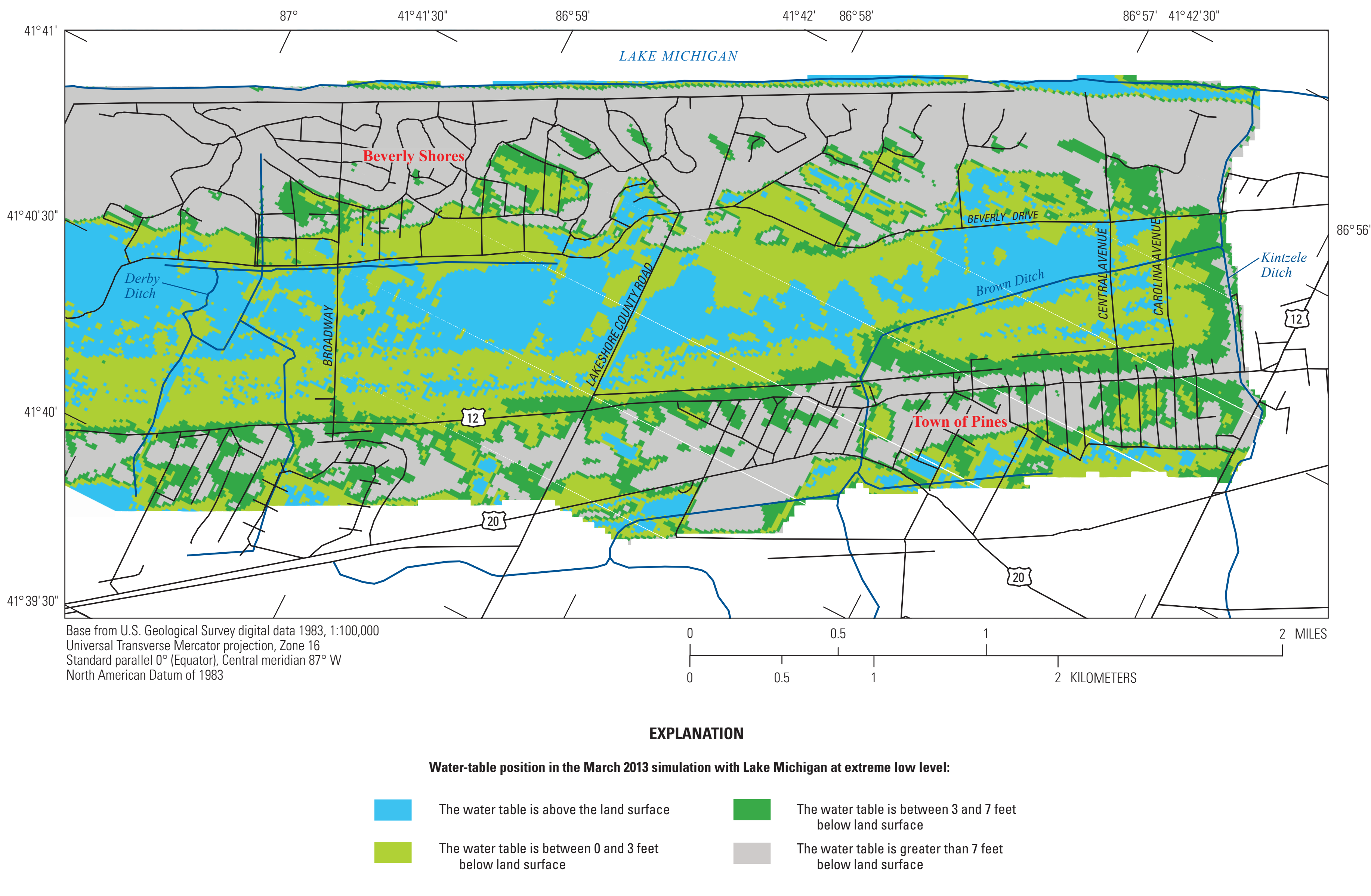



**Figure 44.** Water-table position resulting from a model scenario simulating the water level of Lake Michigan at extreme low level and March 2013 conditions near the town of Beverly Shores, Town of Pines, and within Great Marsh, Indiana Dunes National Lakeshore, Indiana. (Compare with fig. 32.)

## Model Limitations and Qualifications

Predictive simulations by the groundwater model should be evaluated and qualified on the basis of model reliability (Anderson and Woessner, 1992, p. 284). The reliability of the calibration is dependent upon the assumptions used in construction of the model and the adequacy (abundance, distribution, and accuracy) of the observations used in the calibration. The simplifying assumptions used in the development of this model were previously discussed. Although these assumptions were in some ways tested and described within this report, more data may be required to fully evaluate these and other assumptions. The following factors should be considered when evaluating this model and any predictive simulations that this model may produce:

1. The model presented in this report is a modification of a previously published model and was constrained to the extent of the original model. Testing of the sensitivity of the results of the simulation to the boundary conditions of the model resulted in the alteration of water levels throughout the study area and, in the vicinity of Brown Ditch, Great Marsh, and the residential area along US-12 east of Lakeshore County Road, changes of approximately ± 1 ft.

2. In order to simulate ponding of water on the land surface, the model was constructed with model layer 1 representing open water with horizontal and vertical hydraulic conductivity values of 10,000 ft/d. The accuracy of simulating volumes of open water in a model is directly related to the ability of using large values of hydraulic conductivity. The numerical solution of this groundwater-flow model became unstable with values greater than 10,000 ft/d. Although this value does not represent the ability of water to move without resistance, it is an adequate representation for this simulation. At the point where the water table rises above land surface, surface runoff should be generated. Because of this, the actual area where water levels rise above ground surface may be smaller than the area shown in the figures even though the amount of surface runoff is estimated to be small, owing to the high permeability of the materials at land surface.

3. Figures displaying inundated areas were calculated by using the altitude of the simulated, steady-state water table and lidar-based land-surface elevation contour datasets with an interval of 1 ft. Lidar-based elevations are accurate in areas of no ponded water. The dataset includes information on areas where ponded water was encountered. The displayed area of inundation could be less accurate in these areas. Uncertainty of the displayed area of inundation is made up of both the overall fit of the groundwater-flow model, errors associated with the discretization of the model areas into cells, and inaccuracies of the lidar-based land-surface altitudes.

4. The model is best used to simulate groundwater flow in the surficial aquifer surrounding Great Marsh because almost all of the observations used to calibrate the model are from the surficial sand aquifer simulated by layer 2. Fewer observations were used to calibrate the April 2014 simulation and almost all of those were east of Lakeshore County Road to simulate interactions between Great Marsh and Town of Pines due to the observed beaver dam. The simulated water-table configuration and groundwater-flow paths are considered to be more accurate near the areas surrounding Great Marsh than in areas with fewer observations.

5. Direct measures of recharge rates to the simulated deposits were not possible. Initial estimates of recharge were taken from investigations in similar areas with a similar makeup of materials. Automated parameter estimation and manual calibration techniques were used to derive final values for recharge for the groundwater-flow model.

6. The model was constructed by use of two layers to represent the surficial aquifer in the modeled area. Initial efforts were made to include additional model layers that would simulate the finer grained muck deposits in wetland areas and a leaky confining unit that may underlie parts of the modeled area. Investigations in similar areas have attempted to use model parameters to represent similar features but the model results were found to be insensitive to whether the features were or were not included during the model calibration process (Lampe and Bayless, 2013). Inclusion of these features was therefore not attempted by this investigation.

## Comparison of Results to Previous Investigations

The ability of Great Marsh to retain wetland conditions during relatively dry portions of the year is associated with the area being bounded by the Holocene and Calumet Dune Beach Complexes, each having water-table mounds that contribute recharge to the surficial aquifer. The configuration is similar to those of Shedlock and others (1994) in which areas of recharge were mapped in areas beneath the Holocene Dune Beach Complex and groundwater was interpreted to flow south from these areas to Great Marsh and other interdunal wetlands and north to Lake Michigan.

The water-table configuration differs from water-table configurations found by Lampe and Bayless (2013) in a similar investigation of a study area approximately 13 mi west. Significant differences were observed due to the absence of the northern Holocene dune ridge, which was removed by sand-mining operations. In that study, areas of recharge were simulated to occur beneath the Toleston Dune Beach Complex with groundwater-flow paths extending north through low lying areas and water-level altitudes diminishing onward to

Lake Michigan producing a transient wetland condition in the area between.

Winter (1999) proposes that the integrated knowledge of regional position within the groundwater-flow system and an understanding of the local geology and climate are necessary to understand areas of groundwater/surface-water interaction, and Doss (1993) illustrates the importance of considering the transient nature of interdunal wetlands by presenting the migration of groundwater divides due to not only topography, but also evapotranspiration, soil moisture, and recent recharge. Data collected during this study may show the effects of transient change in the water table along the margins of interdunal wetlands and the reversal of groundwater flow from Great Marsh during periods of relatively dry conditions. Future studies could focus on simulating transient conditions to help determine the impacts of prolonged dry conditions on the overall impacts of these different water cycle components on interdunal wetland environments like Great Marsh within INDU.

# Summary and Conclusions

A previously published steady-state groundwater-flow model by Shedlock and Harkness (1984) was reconstructed using MODFLOW-NWT. The results of the reconstructed model were verified by comparing the output to the figures published in the original report. Following model verification, the reconstructed model was modified to more accurately simulate the conditions of the study area. The modified groundwater-flow model—a steady-state, three-layer computer model consisting of 105 rows, 225 columns, and 3 layers—was calibrated to an observed hydrologic condition (March 2013) to simulate flow through the surficial aquifer and the interaction between hydrologic features in and around Great Marsh in the Indiana Dunes National Lakeshore near Beverly Shores and Town of Pines, Indiana. The top layer simulated water bodies by using a high hydraulic conductivity of 10,000 feet per day (ft/d), and the remaining two layers simulated the majority of the surficial aquifer.

Small observed differences between the water-level data collected during the March 2013 and the April 2014 hydraulic conditions include the pooling of surface water due to the effects of a beaver dam present in Brown Ditch just upstream of Central Avenue. Continuous groundwater-level data collected during May 2012–December 2013 indicate that the predominant groundwater-flow gradients vary during the course of the year (fig. 16). The comparison of annual growing season to the land-surface elevation at 12 site-specific monitoring wells indicates the presence and duration of a wetland condition in different areas of Great Marsh (appendix 1). At the beginning of the study in May of 2012, data collected at eight well sites were indicative of a wetland condition, but levels decreased by July 2012 due to increased transpiration from vegetation and lack of prolonged significant precipitation in the area during the months of April, May, and June (figs. 11 and 12). In contrast, data collected from one monitoring well (observation well 605) indicated the site maintained wetland condition throughout the 2012 growing season.

Continuous surface-water discharge and elevation was measured at one U.S. Geological Survey (USGS) streamgage location on Brown, Kintzele, and Derby Ditches (fig. 10). The mean monthly discharge statistics (table 7) indicate that during the period of record, streamflow in Kintzele Ditch was lowest during July 2012 (0.97 cubic foot per second [$ft^3/s$]) and highest during April 2013 (29.20 $ft^3/s$). In Derby Ditch, streamflow also was lowest during July 2012 (0.17 $ft^3/s$) and highest during April 2013 (9.36 $ft^3/s$). Continuous discharge could not be calculated from data collected at USGS streamgage 04095154 on Brown Ditch due to the repeated construction and removal of beaver dams at the gage site, which created continuously changing control and backwater conditions.

Nonlinear least-squares regression was used with automated parameter estimation to determine optimum parameter values for the model. The calibrated value of hydraulic conductivity for the sand was 17.73 ft/d, and recharge rates for the March 2013 model calibration varied from −6.91 inches per year (in/yr) for wetland areas representing evaporation to 21.97 in/yr for recharge in populated areas of Beverly Shores. The mean absolute error between simulated and measured water levels is 0.81 foot (ft), which translates into a relative error (based on water-level variation in the measured water levels) of 2.27 percent.

Noteworthy results from the March 2013 simulation include that nearly 100 percent of all water entering the area simulating Town of Pines is from recharge. Of all the water simulated to enter the eastern and western portions of Great Marsh, nearly 20 and 18 percent, respectively, flows from Town of Pines to the western and eastern portions of Great Marsh. The dune ridges beneath Town of Pines and to a lesser extent beneath Beverly Shores are a major source of recharge to the surficial aquifer and Great Marsh.

Particle tracking results from the March 2013 simulation indicate the area contributing water to Brown Ditch is predominantly to the south, but some flow is captured that enters the ditch from the north (fig. 30). Capture zones for Brown and Kintzele Ditches overlap in the area south-west of their confluence; this is likely due to deeper flow paths discharging into one ditch while shallower flow paths discharge into the other. The majority of the area west of Lakeshore County Road beneath Great Marsh flows into Derby Ditch.

An additional simulation was created by adjusting the calibrated March 2013 model to match surface-water and groundwater levels measured during April 2014 when a beaver dam in Brown Ditch altered the hydrologic conditions of the study area. Adjustments were made by (1) increasing recharge parameters from the calibration values to compensate for the increased amount of precipitation prior to data collection, and (2) manipulating the elevation of the bottom of the drain cells that represent Brown Ditch to account for the location and relative altitude of the beaver dams observed during data collection. The recharge values representing Town of Pines, wetland, and undeveloped areas of the model were increased by 5.07, 4.182, and 0.5 in/yr, respectively. The recharge value for the area representing Beverly Shores was decreased by 6.44 in/yr.

Noteworthy results from the April 2014 simulation include that despite increases in the amount of water entering Great Marsh, there is still zero simulated groundwater flow from Great Marsh to Town of Pines. This simulated difference in water budgets can be attributed to increased simulated recharge in Great Marsh and Town of Pines. Effects of the inclusion of the beaver dam included the enlargement of the simulated inundated area and the rising of the water table within Great Marsh due to the effects of ponding surface water upstream of the beaver dam (fig. 34).

Particle tracking results from the April 2014 simulation indicate changes in the area contributing water to Brown and Kintzele Ditches (fig. 36). Compared to the 2013 simulation, the April 2014 simulation produced longer flow paths now travel beneath Brown Ditch from areas just west of the entrance of Brown Ditch into Great Marsh and terminate near the confluence of Brown and Kintzele Ditches and from upstream portions of Brown Ditch that terminate into Kintzele Ditch.

The distribution of inundated areas in the April 2014 simulation show areas in Great Marsh east of Lakeshore County Road and south of Beverly Drive where areas estimated to have water above the land surface have increased in size (fig. 37). The total area where the water table is above the land surface is much greater than the area from the March 2013 simulation.

Three different scenarios were run in order to apply certain climatic conditions and engineering controls to the calibrated groundwater-flow model. The results of these scenarios will give the National Park Service, and other resource managers in the area an improved understanding of the hydrology in the vicinity of Great Marsh in order to understand the effects drainage alterations will make to the water levels of the water table in the surrounding residential areas.

Noteworthy results from the scenarios include the following:

1. In the scenario simulating the inclusion of six proposed pool-riffle control structures in Brown Ditch under the hydrologic conditions of March 2013, areas simulated to be inundated by water in the March 2013 model are much larger, including areas just to the north of the entrance of Brown Ditch into Great Marsh, and areas north of the confluence of Brown and Kintzele Ditches (fig. 38, fig. 39). Results of an additional simulation using the MODFLOW River package to characterize Brown Ditch within Great Marsh showed areas inundated by water were larger than those from the simulation using the MODFLOW Drain package only. The additional simulation better represented the observed distribution of open water during periods when the surficial aquifer is most saturated due to high precipitation or snowmelt (fig. 41, fig. 42).

2. For the scenario simulating the increase of the Lake Michigan water level to the historical high of May 31, 1998, inundated areas of Great Marsh south of Beverly Shores enlarged on both sides of Lakeshore County Road with the greatest enlargement shown southeast of the intersection of Lakeshore County Road and Beverly Drive (fig. 43).

3. For the scenario simulating the decrease of the Lake Michigan water level to the historical low of December 23, 2007, results show little change from the original March 2013 distribution (fig. 44).

The results of this study can be used by water-resource managers to understand how surrounding ditches affect water levels in and around Great Marsh. The groundwater model developed in this study can be applied in the future to answer questions about how alterations to the drainage system in the area will affect water levels in and around the study area. The modeling methods developed in this study provide a template for other studies of groundwater flow and groundwater/surface-water interactions within the shallow surficial aquifer in northern Indiana.

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# Appendix 1

Continuous and discrete water-level data collected at monitoring wells overlaid with land-surface elevation location; an elevation of 1 foot below land surface; and the growing season, May 2012 through December 2013. For each figure (plot) in appendix 1, the altitude of the land surface above North American Vertical Datum of 1988 at the monitoring well is indicated by a horizontal green line. An altitude 1 foot lower than the land surface altitude is indicated by a red line, and the area between is shaded grey. The annual growing season also is represented on the hydrographs as green shaded areas. Plots can be used to interpret the presence and duration of a wetland condition at the sites where data were collected. See figure 8 for monitoring-well locations and table 2 for monitoring-well characteristics.

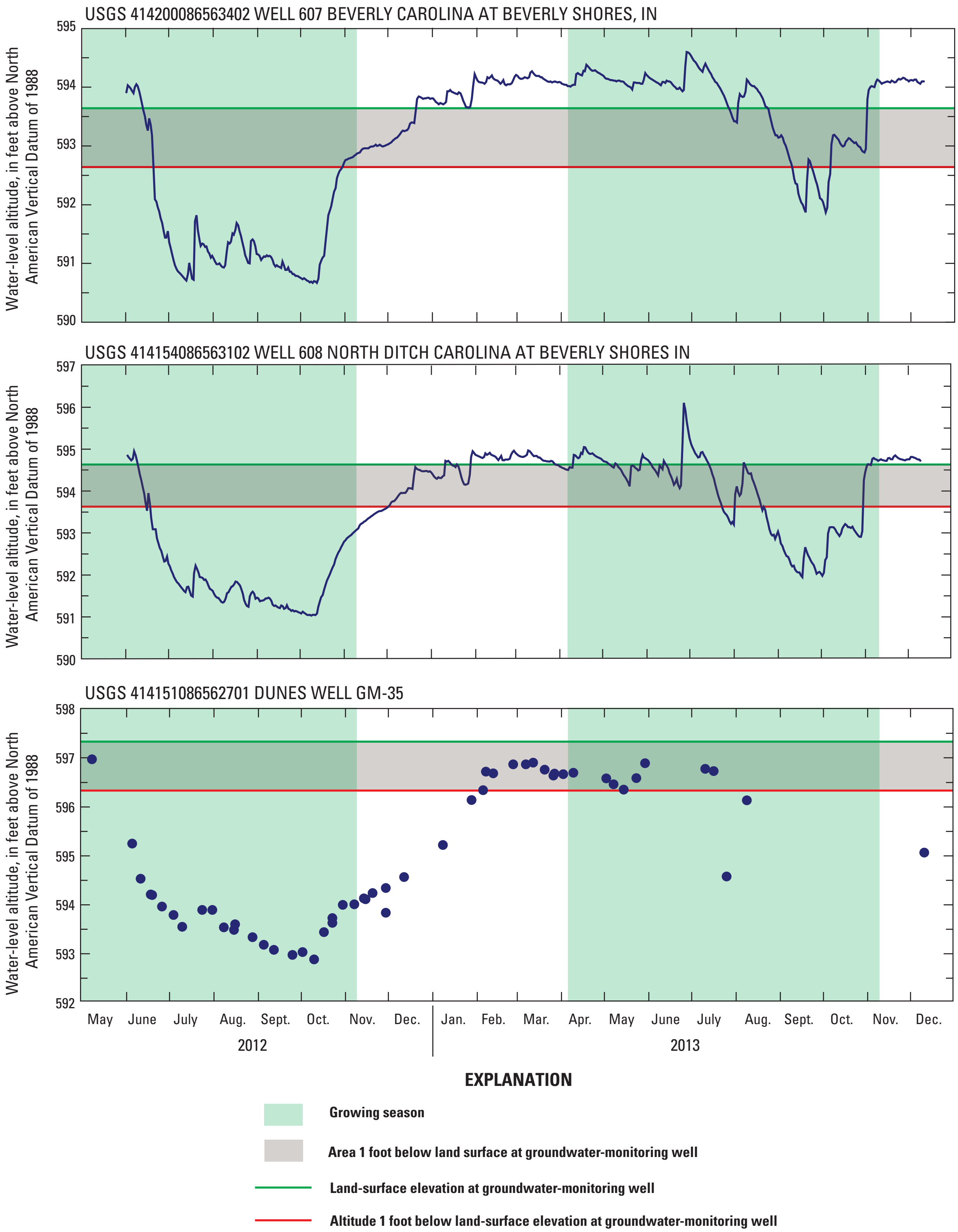


**Figure 1–1.** Graphs showing water-level data in comparison to land-surface elevation at U.S. Geological Survey (USGS) groundwater-monitoring wells 607, 608, and GM-35 near Indiana Dunes National Lakeshore, Indiana.

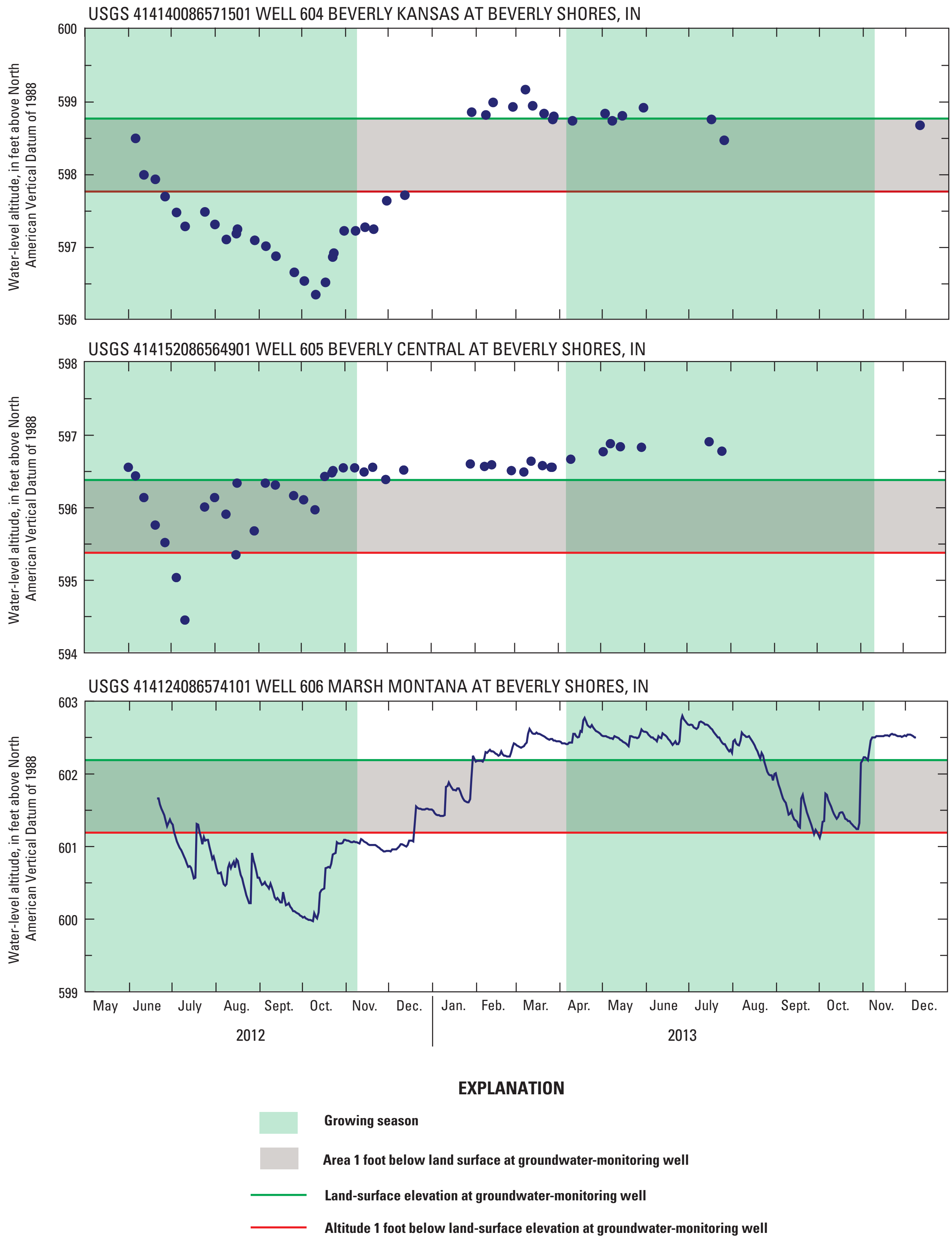


**Figure 1–2.** Graphs showing water-level data in comparison to land-surface elevation at U.S. Geological Survey (USGS) groundwater-monitoring wells 604, 605, and 606 near Indiana Dunes National Lakeshore, Indiana.

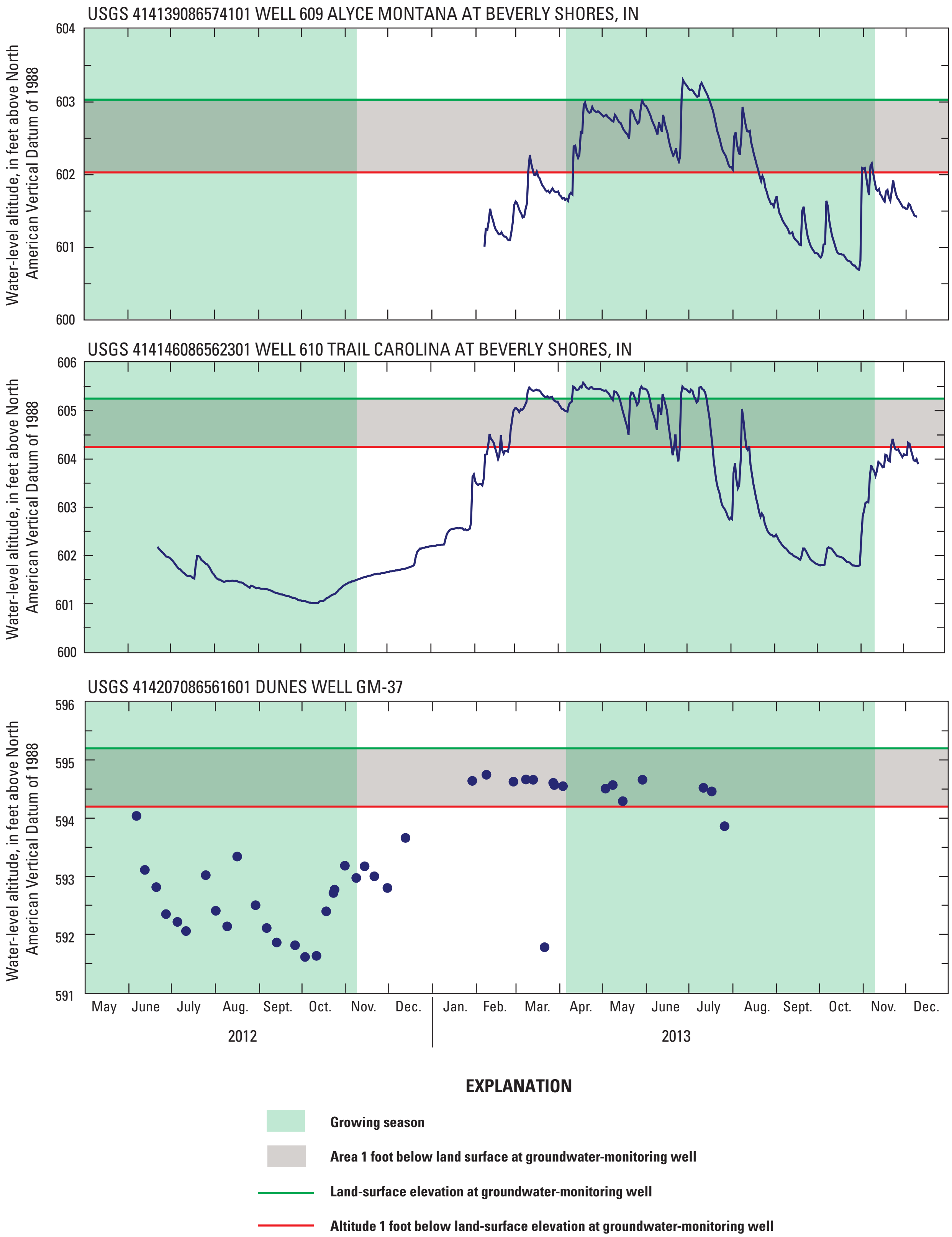


**Figure 1–3.** Graphs showing water-level data in comparison to land-surface elevation at U.S. Geological Survey (USGS) groundwater-monitoring wells 609, 610, and GM-37 near Indiana Dunes National Lakeshore, Indiana.

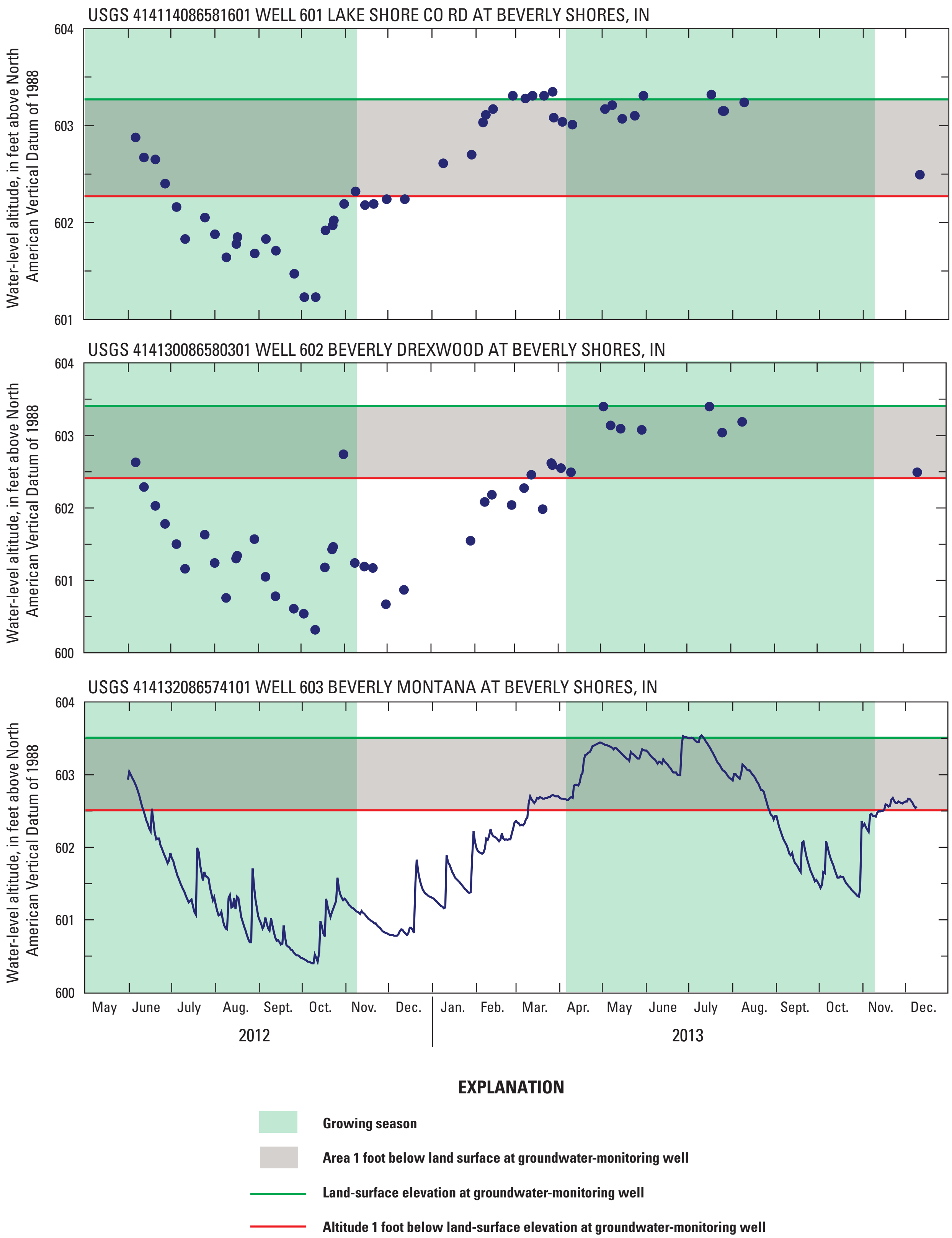


**Figure 1–4.** Graphs showing water-level data in comparison to land-surface elevation at U.S. Geological Survey (USGS) groundwater-monitoring wells 601, 602, and 603 near Indiana Dunes National Lakeshore, Indiana.

**Front cover background.** Photograph of Great Marsh west of Central Avenue and north of Brown Ditch, taken on June 11, 2013, by David C. Lampe.

**Front cover inset upper left.** Photograph of Brown Ditch near USGS Stream Gage Brown Ditch at Central Avenue (USGS 04095154), taken on April 29, 2014, by David C. Lampe.

**Front cover inset lower right.** Photograph of Brown Ditch west of Carolina Avenue, taken on June 11, 2013, by David C. Lampe.

**Back inner cover panorama.** Photograph of Beaver dam in Brown Ditch near USGS Stream Gage Brown Ditch at Central Avenue (USGS 04095154), taken on December 20, 2013, by David C. Lampe.

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