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Use of Isotopes to Identify Sources of Ground Water, Estimate Ground-Water-Flow Rates, and Assess Aquifer Vulnerability in the Calumet Region of Northwestern Indiana and Northeastern Illinois

Water-Resources Investigation Report 02-4213

Prepared in cooperation with the
U.S. Environmental Protection Agency

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

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By Robert T. Kay, E. Randall Bayless, and Robert A. Solak[1]

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Water-Resources Investigation Report 02-4213

Indianapolis, Indiana
2002

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[1] MACTEC Engineering and Consulting, Novi, Michigan

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

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Denver, CO 80225-0286

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Tables

Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
tritium unit (TU)	3.2	picocuries per liter (pCi/L)

Temperature, given in degrees Celsius (°C), can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = 1.8(°C) + 32$$

Vertical Datum: In this report, vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

δ (delta), as used in this report, refers to the stable isotope ratio $\delta x=[(R_x/R_{STD})-1]\ x1000$, where R_x and R_{STD} are the $^2H/^1H$ and $^{18}O/^{16}O$ values of the sample and reference standard. The value of δ is generally expressed in parts per thousand ($^o/_{oo}$, or per mil).

Per mil, as used in this report, is equivalent to parts per thousand.

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Abstract

Isotope data collected in the Calumet Region of northwestern Indiana and northeastern Illinois, one of the most heavily industrialized regions of the United States, indicated that water in the surficial Calumet aquifer is well mixed. The Calumet aquifer is recharged areally by precipitation and locally may be recharged by surface water. The residence time of ground water in the Calumet aquifer is approximately 5 to 15 years. Ground-water-flow rates through the Calumet aquifer are estimated to be 400 to 2,300 feet per year. The permeable deposits, shallow water table, lack of an overlying confining unit, and proximity to numerous contaminant sources indicate that the Calumet aquifer is vulnerable to contamination.

Isotopic data indicate that ground water in the confining unit underlying the Calumet aquifer is derived from a variety of sources that include Lake Michigan, modern precipitation, and discharge from the basal Silurian-Devonian bedrock aquifer. The source and apparent age of the water are variable and appear to be affected locally by various geologic and hydraulic factors. The vertical ground-water-flow rate through the unweathered part of the confining unit is about 0.20 feet per year and is about 6.3 feet per year through the weathered part. The data indicate the weathered part of the confining unit may be more vulnerable to contamination than the unweathered confining unit.

Ground water in the basal Silurian-Devonian aquifer is derived from Lake Michigan, glacial-age water, and modern precipitation. Post-1952 recharge has occurred in the vicinity of Stony Island, Ill. Ground-water recharge of the Silurian-Devonian aquifer may be occurring near Calumet Harbor. The Silurian-Devonian aquifer is vulnerable to contamination where the confining unit is thin or absent or where the integrity of the confining unit has been compromised.

Introduction

The Calumet region of northwestern Indiana and northeastern Illinois is one of the most heavily industrialized areas of the United States (fig. 1). Current and historical industries include steel mills, petroleum refineries and tank farms, foundries, railroads, and chemical manufacturing (fig. 2). Two hazardous-waste incinerators, at least 11 sanitary landfills, numerous uncontrolled waste-disposal sites, and approximately 80 accidental-spill sites are in the region. Low-lying and moist-soil areas throughout the region have been filled with slag, municipal and industrial waste, dredging spoil, construction and demolition debris, fly ash, and natural materials (Kay and others, 1997). Chemicals from these and other sources have degraded surface- and ground-water quality in the region

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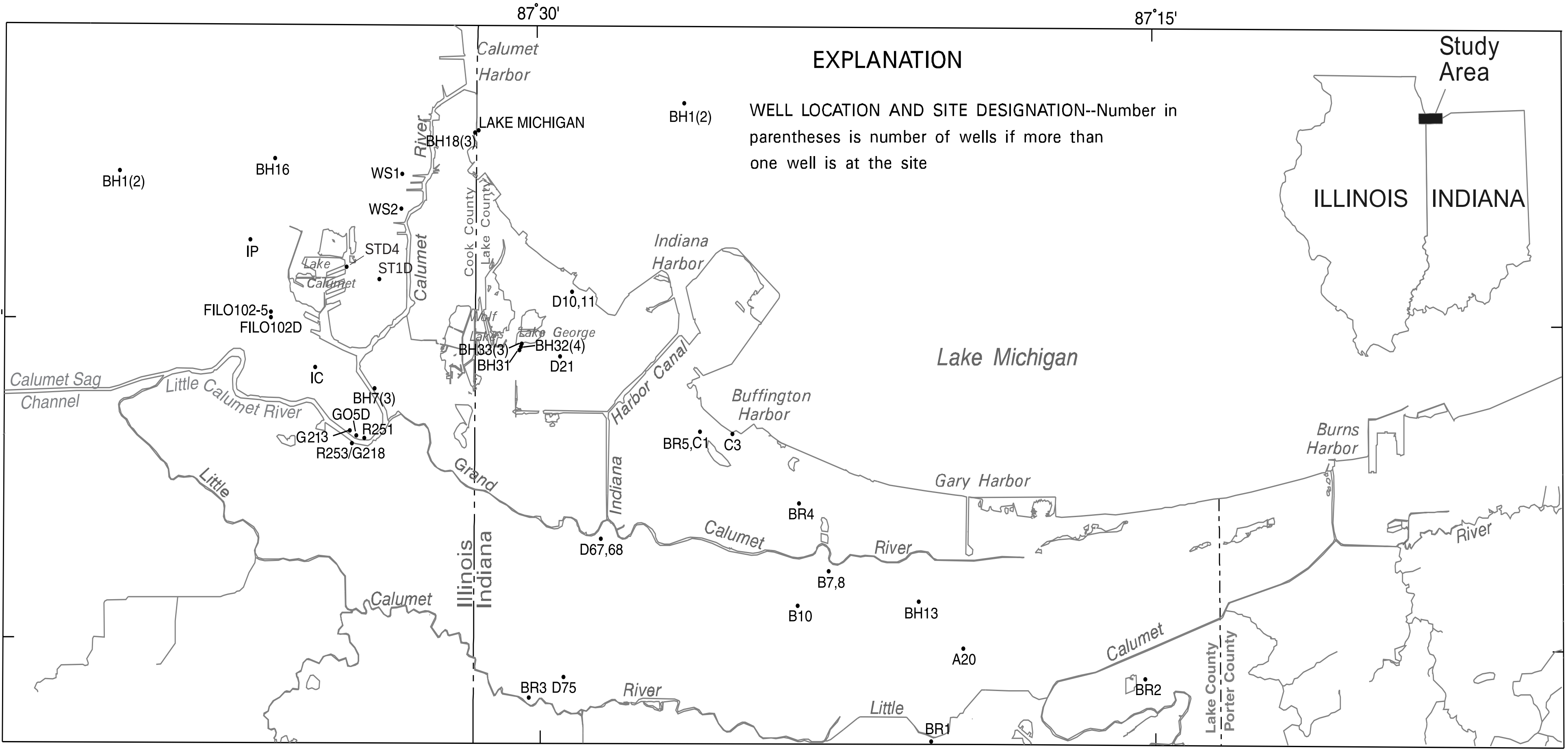
[1] MACTEC Engineering and Consultin, Novi, Michigan.



Base from U.S. Geological Survey digital data 1;24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

Geology modified from Kay and others (1996)

Figure 1. Location of study area and sampling locations, Calumet region of northwestern Indiana and northeastern Illinois.

(U.S. Department of Health, Education and Welfare, 1965; and HydroQual, Inc., 1985; Fenelon and Watson, 1993; Duwelius and others, 1996). Because of the presence of wetlands, the proximity to Lake Michigan, the vulnerability of aquifers that supply water for much of the region, and the existence of many facilities that are subject to environmental regulation, there is a need to understand the sources of water and vulnerability of various geologic units to contamination and to assess the potential for remediation.

To characterize ground-water recharge and flow rates as well as aquifer vulnerability in northwestern Indiana and northeastern Illinois, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), collected water samples from an areally distributed network of ground-water wells and one surface-water sampling site. Water samples were analyzed for concentrations of tritium (^3H) and helium (^3He) and isotopic abundances of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$). The data were used to assess the relative age of water in Lake Michigan and the hydrogeologic units in the area, the sources of water in the hydrogeologic units in the area, the interconnection between the various hydrogeologic units, and the factors affecting vulnerability of the hydrogeologic units to contamination. The insight gained as the result of this investigation can be used to assess the migration rates and directions of anthropogenic compounds in ground water and the effectiveness of ground-water remediation efforts.

Purpose and Scope

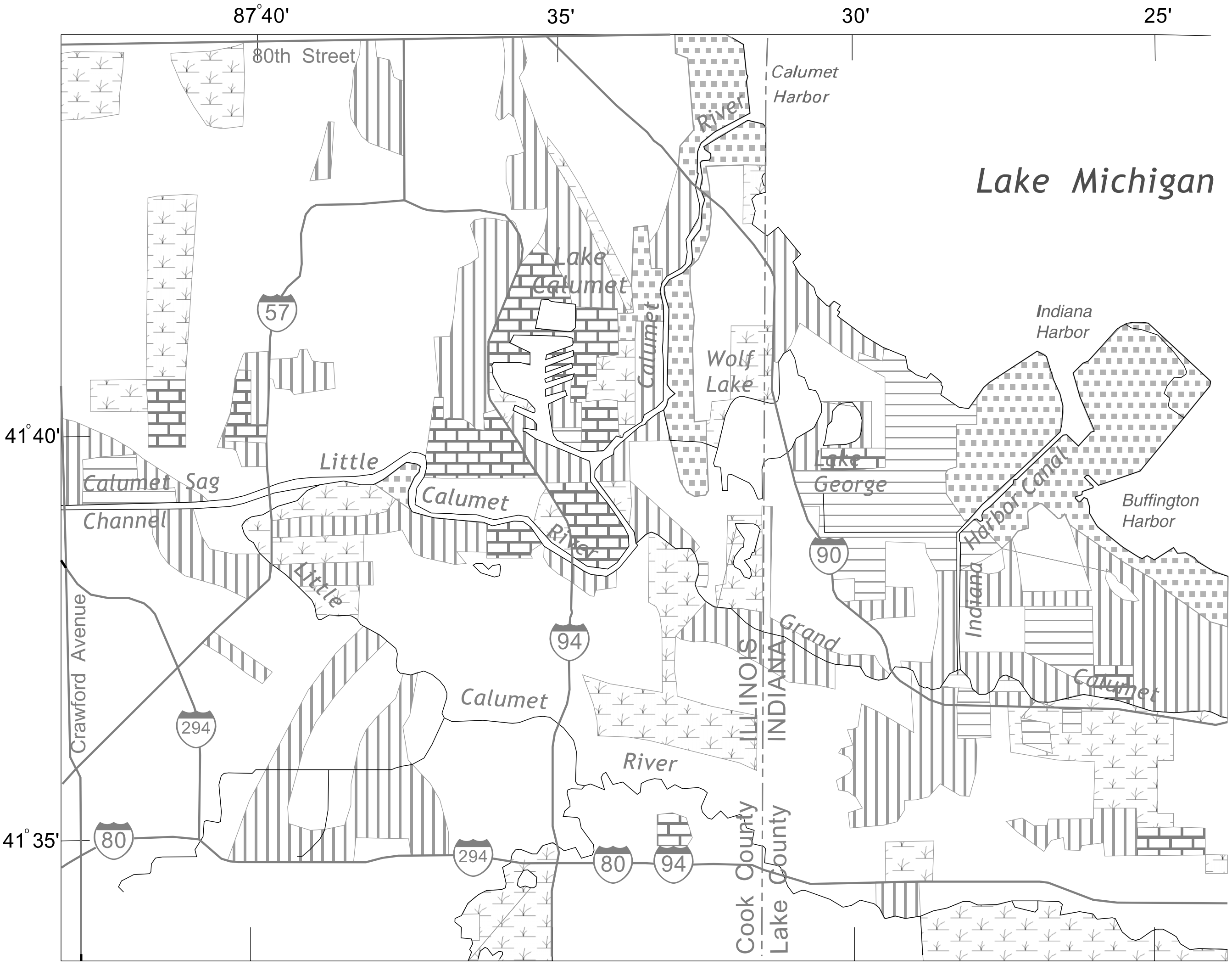
This report describes the results of an investigation designed to characterize ground-water recharge and flow rates and vulnerability of the aquifers to contamination in a heavily industrialized area of northwestern Indiana and northeastern Illinois. Water samples were collected from a well network distributed across northwestern Indiana and northeastern Illinois. Samples were collected from 26 wells during July 1997 and from 21 different wells and Lake Michigan between January 2000 and April 2001. Thirty-six of the sampled wells were screened in unconsolidated deposits and 16 were finished in bedrock. Samples were analyzed for concentrations of tritium and helium and isotopic abundances of oxygen and hydrogen. Absolute and relative ages of ground water, computed from sample results, were used to address project objectives.

Acknowledgments

The authors thank the many state and local agencies and corporations that provided the information and (or) access to the data-collection sites that made this study possible.

ARCADIS Geraghty & Miller,
  Langhorne, Inc., Chicago, Ill.
BP (formerly Amoco), Whiting, Ind.
Bethlehem Steel Corp.,
  Burns Harbor, Ind.
Canonie Environmental Services
  Corporation, Porter, Ind.
E.I. duPont deNemours and
  Company, East Chicago, Ind.
Illinois Department of Natural
  Resources, State Water Survey
Indiana Department of Environmental
  Management
Indiana Department of Natural
  Resources, Division of Water
Indiana Department of Transportation
Indiana Geological Survey
Ispat Inland Inc., (formerly Inland
  Steel Co.), East Chicago, Ind.
LTV Corporation, East Chicago, Ind.
National Steel Corporation,
  Midwest Operations, Portage, Ind.
Navistar International Corporation,
  Chicago, Ill.
Northern Indiana Public Service
  Company (NIPSCO),
  Merrillville, Ind.
USX Corporation (formerly United
  States Steel LLC), Gary, Ind.
Waste Management of Illinois, Inc.,
  CID Facility, Calumet City, Ill.

The authors also thank Fredrick A. Micke and Douglas Yeskis of the U.S. Environmental Protection Agency for their assistance with the investigation.

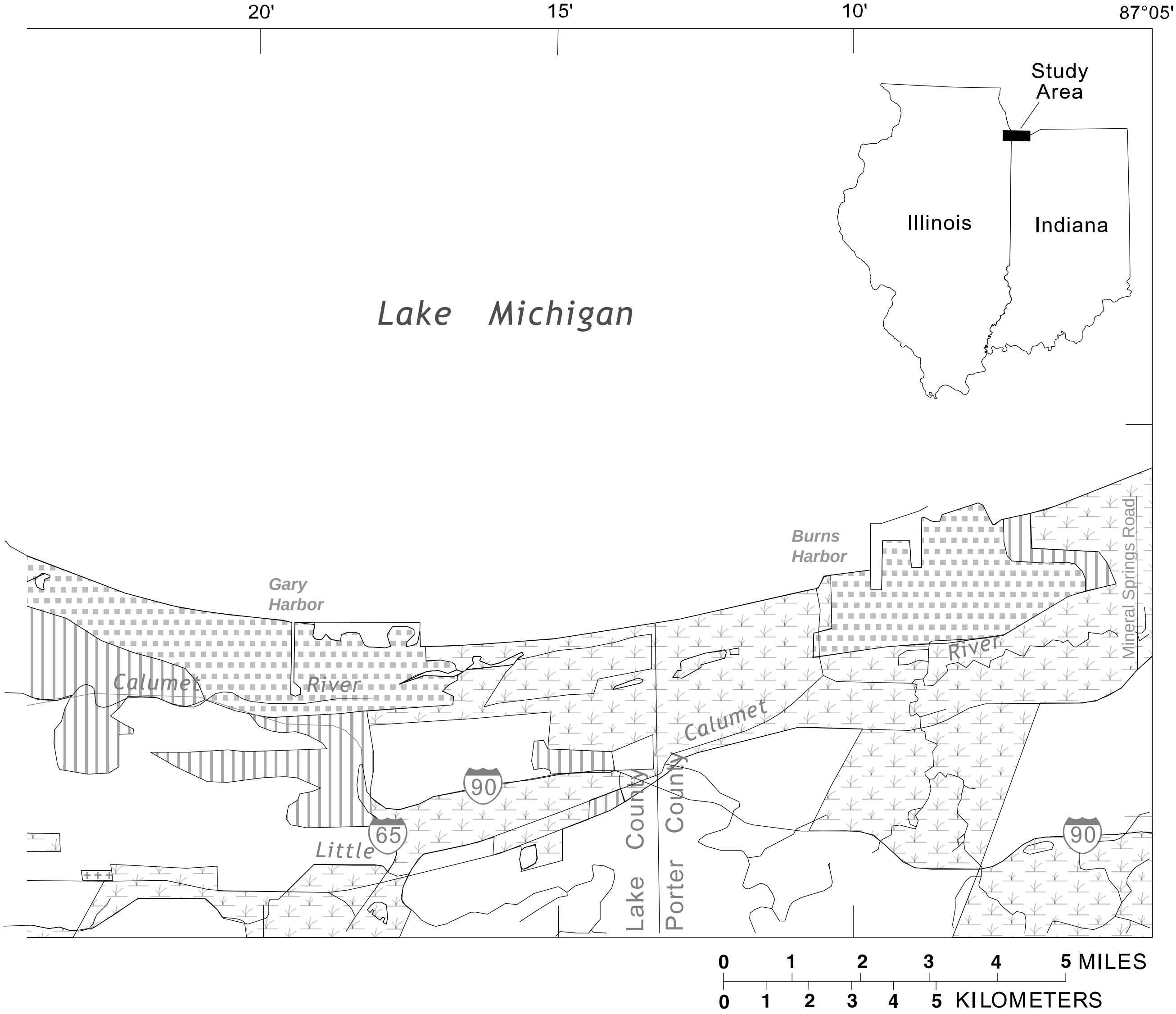


Base from U.S. Geological Survey digital data 1;100,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

▦	STEEL INDUSTRY	☐	RESIDENTIAL OR OPEN WATER
▥	INDUSTRY-Other than steel or petrochemical	▩	WASTE TREATMENT OR DISPOSAL
▤	PETROCHEMICAL INDUSTRY	▨	NATURAL

Figure 2. Land use, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)


20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Gary Harbor
Burns Harbor
Calumet River
Calumet River
Little
Mineral Springs Road
90
65
90
Lake County
Porter County
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Description of the Study Area

The study area is in northwestern Indiana and northeastern Illinois and includes parts of Lake and Porter Counties, Indiana, and Cook County, Illinois. The study area is approximately bounded by the southern limit of the Little Calumet River and Interstates 80/94 and 294 to the south, Crawford Avenue to the west, Mineral Springs Road to the east, and 80th Street and Lake Michigan to the north.

Physiography

The study area is in the Eastern Lake Section of the Central Lowland physiographic province defined by Fenneman (1938). The Indiana part of the study area is in the Calumet Lacustrine Plain subdivision of the Northern Moraine and Lake Region (Malott, 1922; Schneider, 1966). The Calumet Lacustrine Plain extends westward into the Illinois part of the study area where it is called the Chicago Lake Plain subsection of the Great Lakes Section of the Central Lowland physiographic province (Leighton and others, 1948).

The study area generally has a low relief surface and is largely covered by rivers, lakes, and poorly drained swampy wetlands. Topographically elevated features including dunes, beach ridges, hummocky moraine deposits, and bedrock mounds break up this flat surface. The Tolleston Beach Ridge rises more than 30 ft above the surrounding area and trends east-west through the study area (fig. 3). Hundreds of smaller, sandy, beach ridges and dunes with heights of 5 to 10 ft above the surrounding wetlands are present north of the Tolleston Beach Ridge which separates the Little Calumet and Grand Calumet Rivers in the central part of the study area. These ridges and dunes roughly parallel the shoreline of Lake Michigan. In addition to the dunes and beach ridges, Blue Island and Stony Island rise above the lowlands. The Calumet Sag Channel is in a glacial sluiceway, or outwash channel, between the Tolleston Beach Ridge and Blue Island.

Climate

The climate in the study area is classified as temperate continental, with a mean annual temperature of about 10^{o}C and a mean annual precipitation of 35.7 in. (National Oceanic and Atmospheric Administration, 1982). More than half of the average annual precipitation falls from April 1 through August 31. Although large variations in precipitation and temperature may occur in any year, summers generally are hot and humid and the winters are cold. Lake Michigan has a moderating local effect on temperature.

The National Oceanic and Atmospheric Administration (NOAA) maintained two weather stations in the study area—one at the Gary, Ind., Regional Airport and the other at the Indiana Dunes National Lakeshore. From 1951 to 1980, the mean monthly temperature at these stations varied from about –5^{o}C in January to about 23^{o}C in July, and the mean monthly precipitation varied from 1.5 in. in February to 4.0 in. in June. Precipitation at the Indiana Dunes National Lakeshore was slightly higher than at Gary (National Oceanic and Atmospheric Administration, 1982).

An estimated 70 percent of the average annual precipitation in this area is returned to the atmosphere by evapotranspiration (Mades, 1987). Based on that information, the average annual precipitation available for recharge to ground water is no greater than 10.7 in. More than three-quarters of all evapotranspiration occurs during the growing season (U.S. Geological Survey, 1970). During the growing season, evapotranspiration normally exceeds precipitation by about 1 to 2 in. and depletes available soil moisture. During the nongrowing season, precipitation generally exceeds evapotranspiration by about 11 in., replenishes soil moisture, and recharges ground water. The mean annual evaporation from Lake Michigan is 29.5 in., or about 83 percent of the average annual precipitation.

Land Use

Land use in the study area is primarily residential and industrial. Large tracts of open water, natural land, and land for the processing and disposal of wastes also are present. Much of the land along Lake Michigan and the Calumet River is or was used for steel production. Land used by the petrochemical industry for tank farms and petroleum refining is south and west of the steel mills in Indiana and at scattered locations along the Grand Calumet River, the Calumet Sag Channel, and Lake Calumet in Illinois. A variety of other industries including automobile assembly, scrap processing, and chemical manufacturing are in the study area. Several large sanitary landfills, wastewater-treatment plants, and unregulated waste-disposal sites also are present.

Hydrogeologic Setting

The geology and hydrology of the study area have been described by a number of investigators (Bretz, 1939, 1955; Rosenshein and Hunn, 1968; Willman, 1971; Hartke and others, 1975; Watson and others, 1989; Cravens and Zahn, 1990; Kay and others, 1996; Kay and others, 1997). Their descriptions include lithologic and hydrologic data and form the basis for the following discussion of the hydrogeologic setting.

The geologic deposits of concern to this investigation are bedrock units of the Silurian and Devonian Periods and unconsolidated deposits of the Quaternary Period. The stratigraphic nomenclature used in this report is from the Illinois State Geological Survey (Willman and Frye, 1970; Willman and others, 1975) and the Indiana Geological Survey (Shaver and others, 1970, 1986; Brown and Thompson, 1995).

Unconsolidated Geology

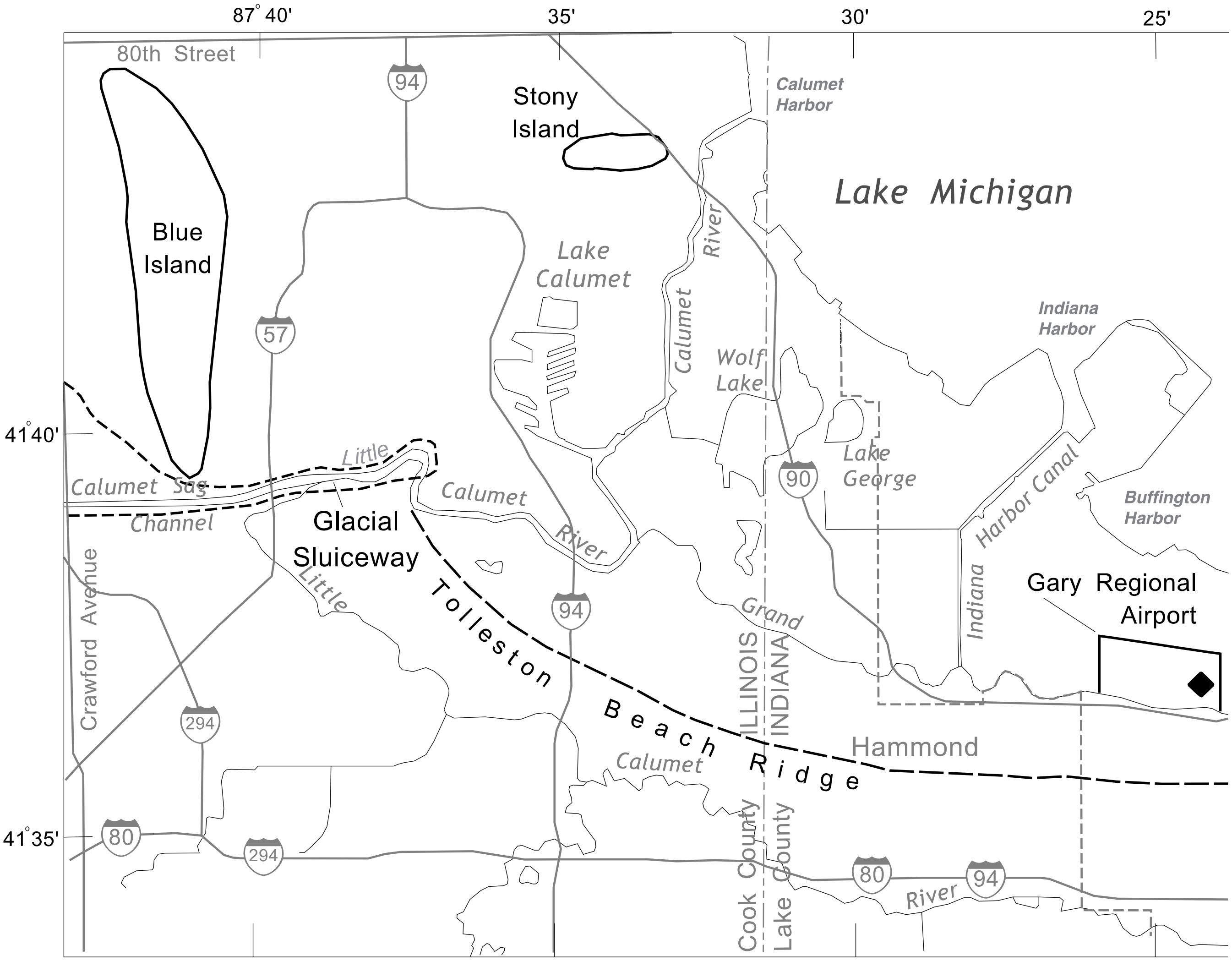
Most unconsolidated sediments in the study area originally were the result of continental glaciation or were lake-bottom and near-shore deposits of historic Lake Michigan (Willman, 1971; Hartke and others, 1975). Glacial and lacustrine processes resulted in the deposition of three types of materials: fluvial and eolian sand, lacustrine silt and clay, and glacial till (fig. 4). The thickness of unconsolidated sediments in the study area ranges from less than 1 ft in the vicinity of Thornton Quarry to more than 200 ft east of Burns Harbor (figs. 5 and 6).

Sand and sand-and-gravel deposits of the Parkland Sand, the Dolton and Carmi Members, and an unnamed glacial sluiceway generally occur at or near land surface and overlie fine-grained deposits in the area east of Lake Calumet. The thickness of these deposits generally increases from west to east, ranging from less than 1 ft in most of the study area west of Lake Calumet to about 100 ft at the Indiana Dunes National Lakeshore (fig. 5).

The Parkland Sand has been described as a well-sorted, medium-grained sand that was blown from the glacial outwash and beach deposits into dunes and sheet-like deposits around the dunes (Willman, 1971). The Parkland Sand is found along the Tolleston Beach Ridge and the western flank of Blue Island and at the Indiana Dunes National Lakeshore. The Parkland Sand is equivalent to the dune facies of the Atherton Formation in Indiana (Shaver and others, 1970). The Parkland Sand (Atherton Formation) forms the upper part of the surficial Calumet aquifer.

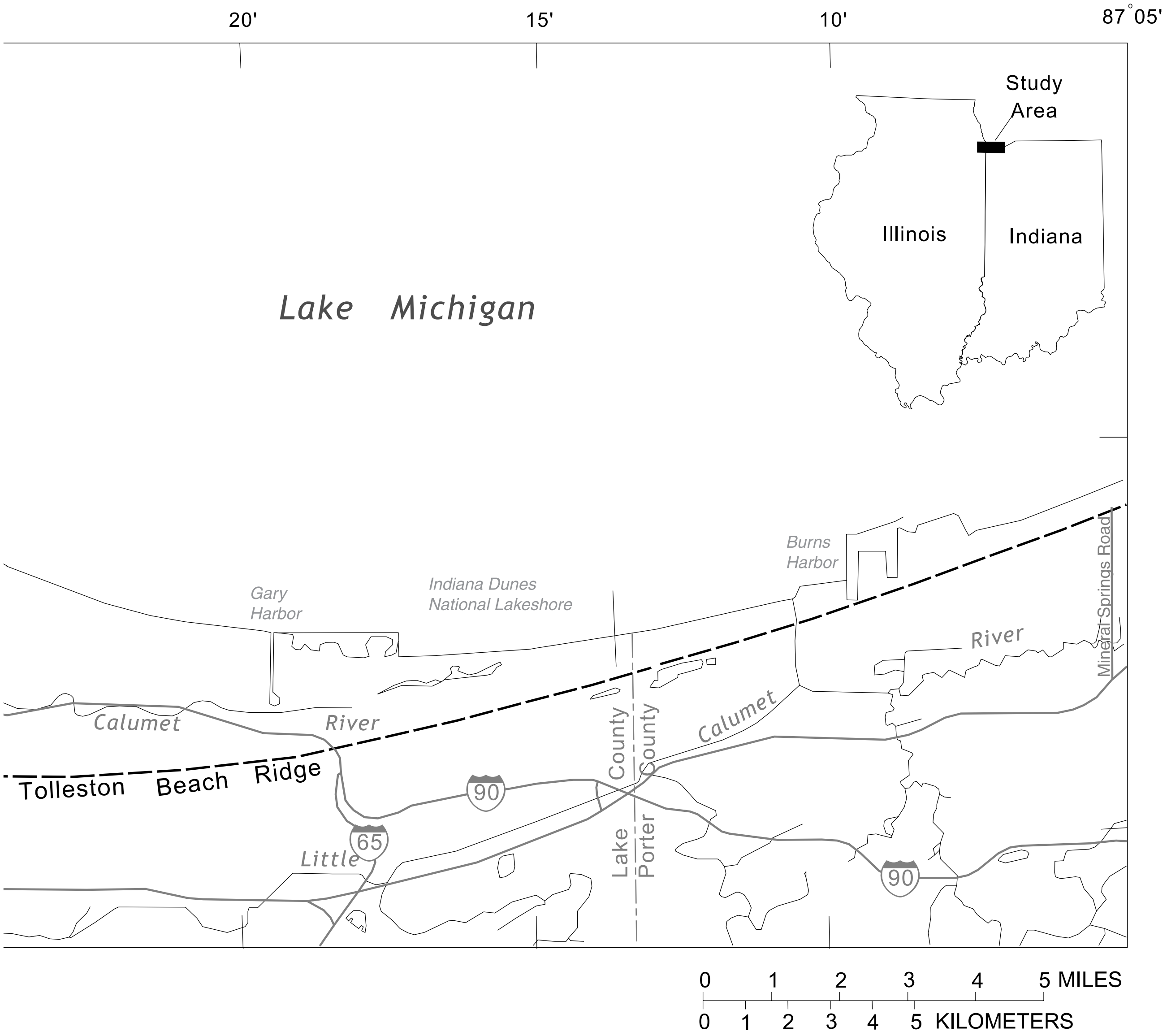
A glacial sluiceway, eroded into and—in some areas—through surficial till deposits along the Calumet Sag Channel, contains fluvial sand-and-gravel deposits overlain by muck and silt (fig. 4). The maximum thickness of these sands and gravels is about 25 ft (fig. 5). Glacial outwash deposits of sand and gravel also are found along the path of the Little Calumet River in parts of Indiana. In Indiana, outwash and sluiceway deposits are part of the Martinsville Formation described by Shaver and others (1970).

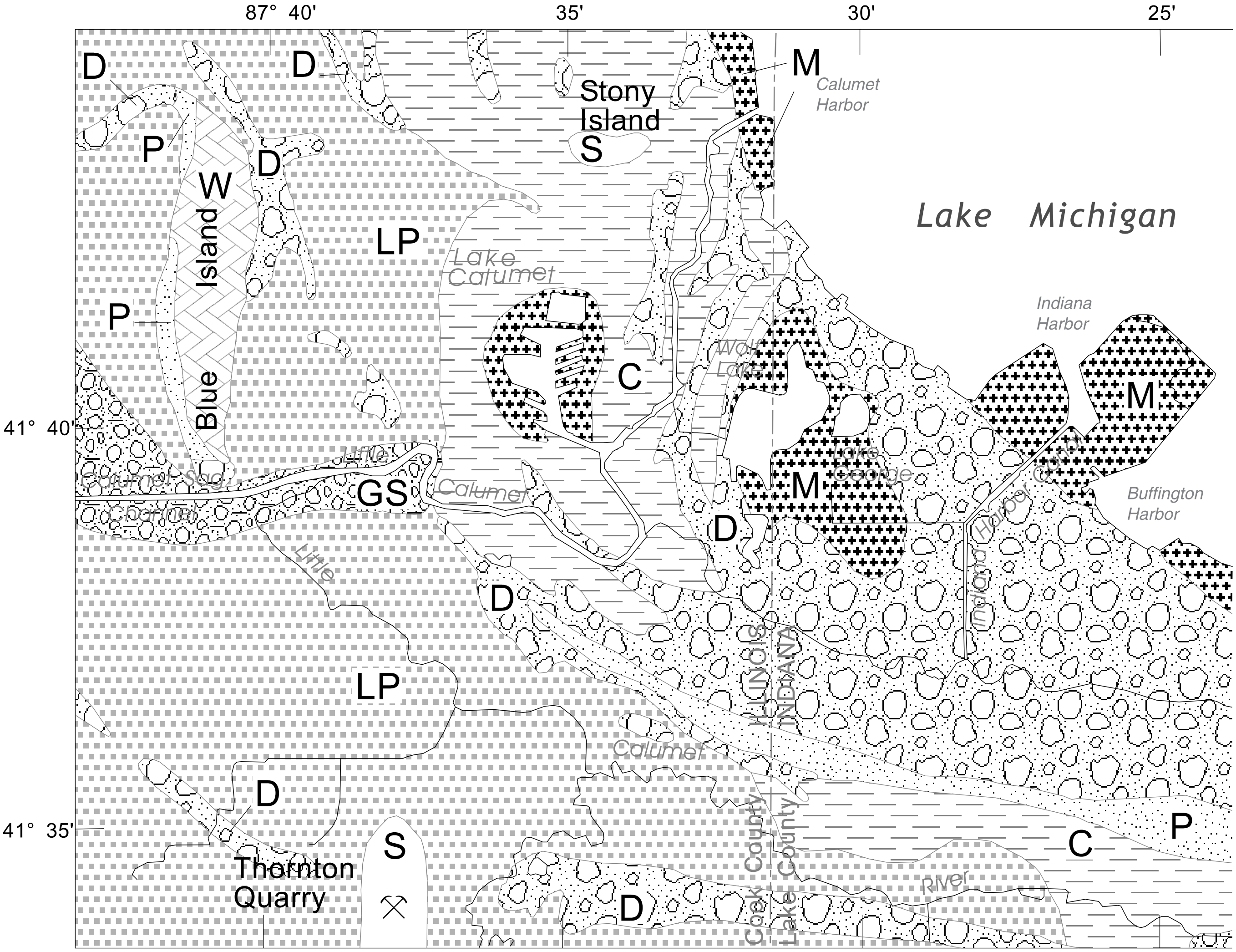
The Equality Formation is subdivided into the Dolton and Carmi Members. The Dolton Member is equivalent to the beach and shoreline deposits of the Atherton Formation (Schneider and Keller, 1970; Willman, 1971). The Dolton Member is predominantly sand but contains thin, discontinuous beds of muck and peat as well as pebbly sand and gravel. The sands consist of shore and shallow-water lake deposits and commonly are found in ridges that define the former locations of spits and beaches. The Dolton Member is at the land surface



Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

Figure 3. Location of important topographic features, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)


20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Burns Harbor
Gary Harbor
Indiana Dunes National Lakeshore
Mineral Springs Road
River
Calumet
River
Calumet
Tolleston Beach Ridge
County
County
Lake
Porter
90
65
Little
90
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS



Base from U.S. Geological Survey digital data 1; 24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

RECENT

M MADE AND MODIFIED LAND-Artificial fill and land substantially modified by the removal of unconsolidated deposits. Many small areas not mapped

WISCONSINAN AND RECENT

GS MUCK OR SILT OVER SAND AND GRAVEL-Outwash sand and gravel overlain in places by thin lacustrine, paludal or alluvial deposits of peat, muck, or clay. Martinsville Formation over outwash facies of Atherton Formation in Indiana, glacial sluiceway in Illinois

P SAND AND SOME SILT-Dune deposits. Dune facies of Atherton Formation in Indiana, Parkland Sand in Illinois

D SAND AND GRAVEL-Beach and shoreline deposits in bars, spits, and beaches. Some dune sand. Atherton Formation in Indiana, Dolton Member in Illinois

C CLAY AND SILT-Lacustrine deposits. Lacustrine facies of Atherton Formation in Indiana, Carmi Member in Illinois

WISCONSINAN

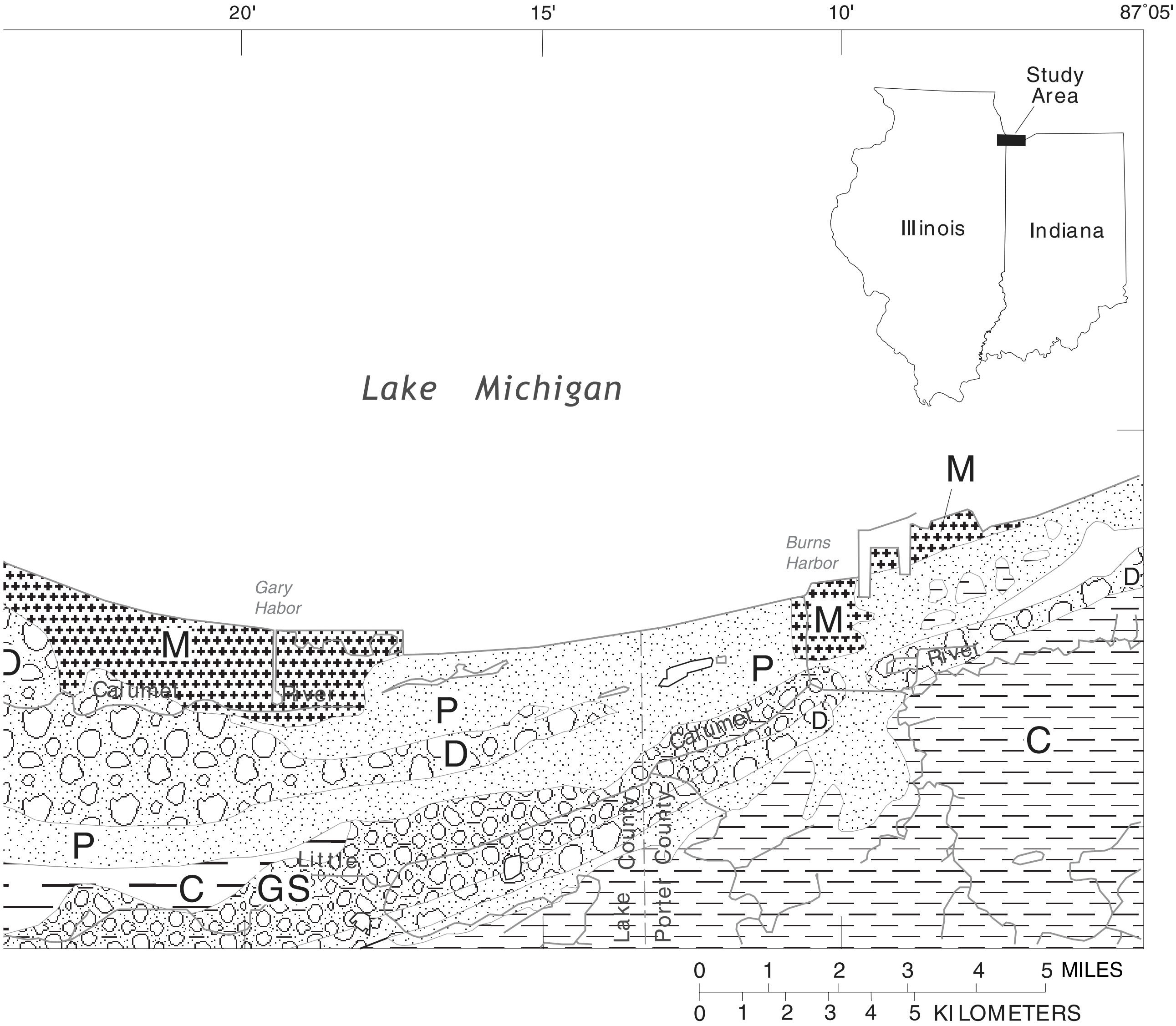
W TILL-End moraine deposit. Lagro Formation in Indiana, Wadsworth Till in Illinois

LP TILL-Wave-scoured lake-bottom till. Lagro Formation in Indiana, Wadsworth Till in Illinois

SILURIAN

S DOLOMITE-Marine deposit. Niagaran Series

Figure 4. Surficial geology, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)


20'
15'
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Study Area
Illinois
Indiana
Lake Michigan
M
Burns Harbor
Gary Habor
M
M
P
P
D
D
D
D
Calumet
River
Calumet
River
C
P
Little
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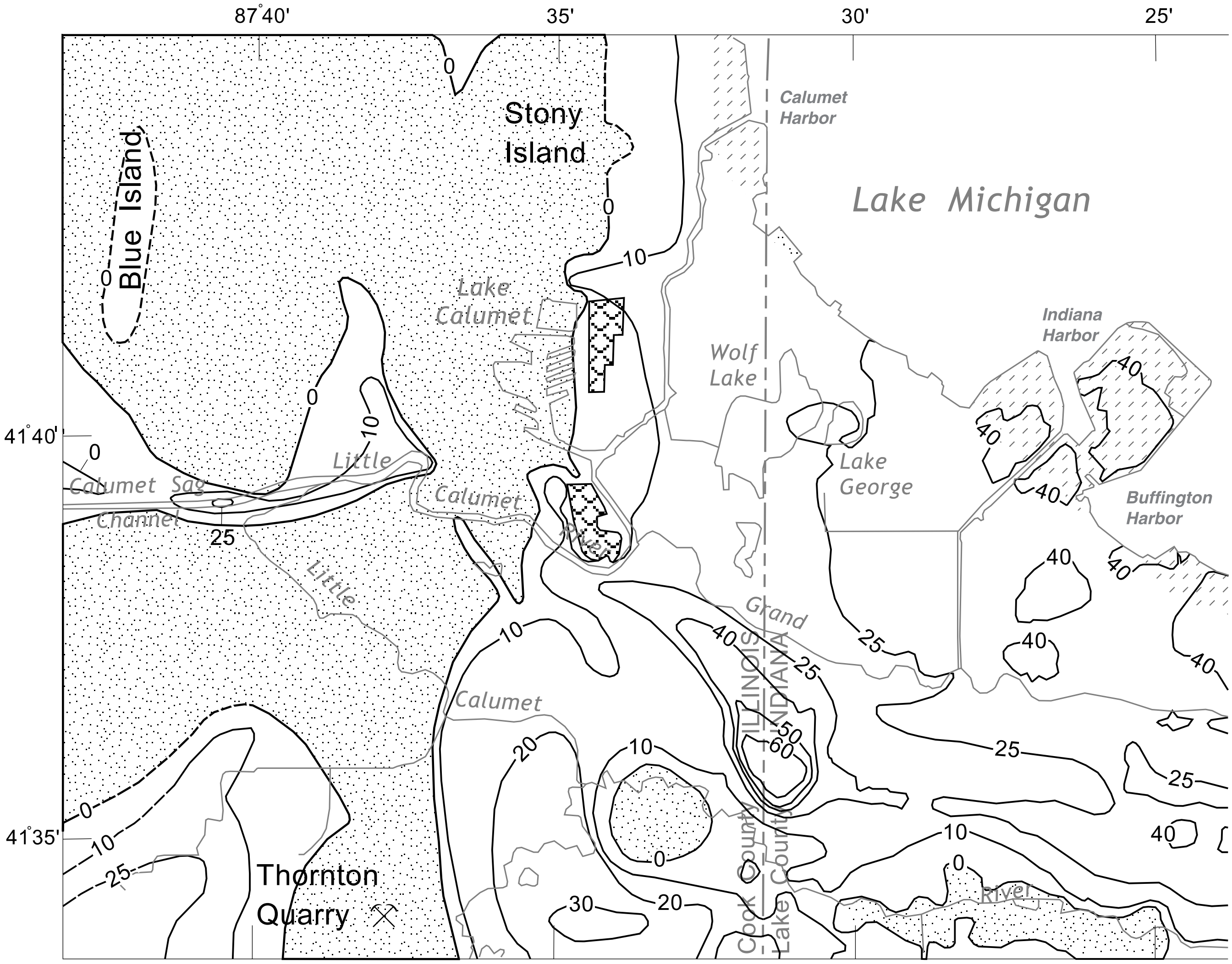
GS
Lake County
Porter County
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS



Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

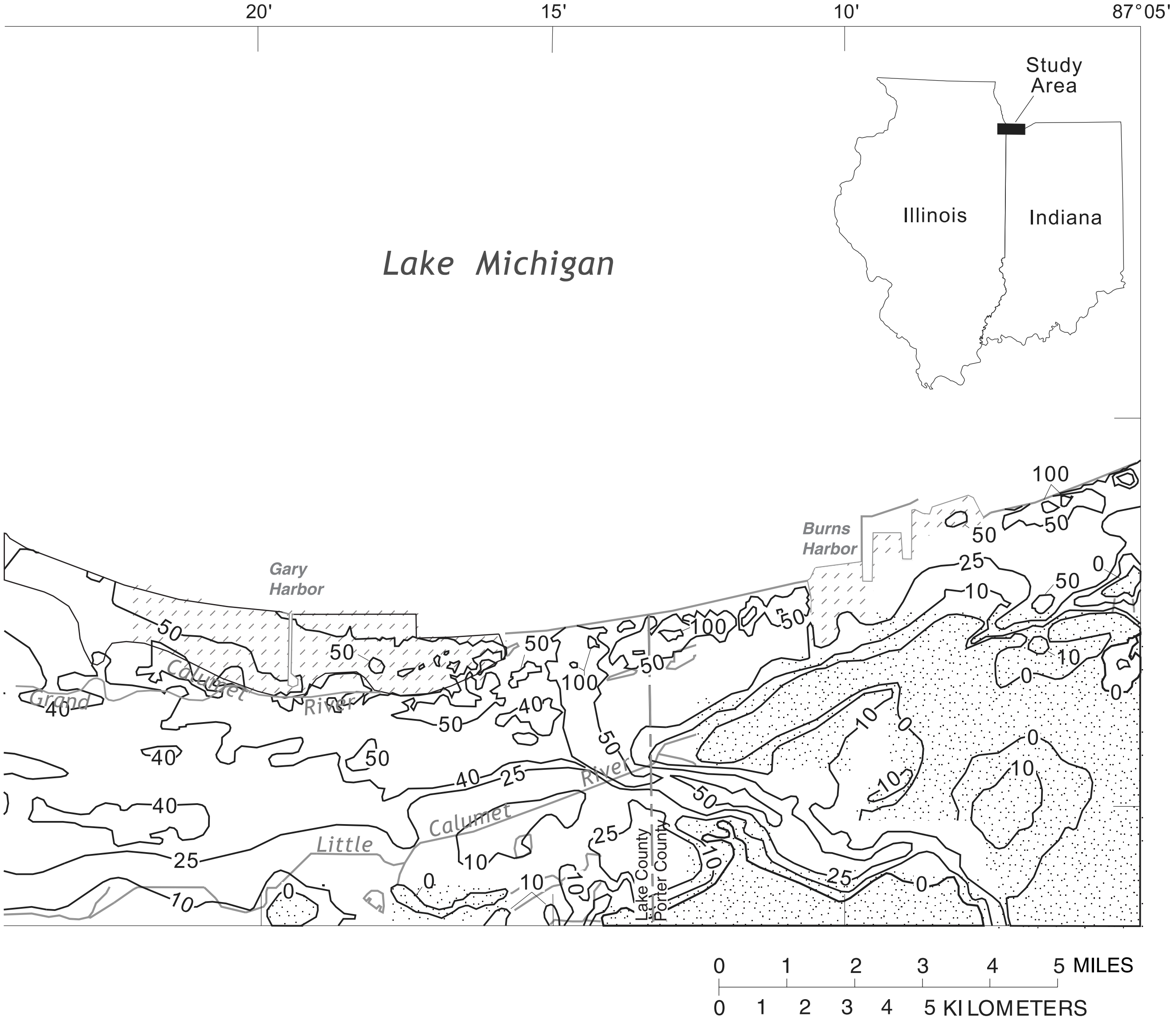
░ SAND ABSENT WITHIN 20 FEET OF LAND SURFACE

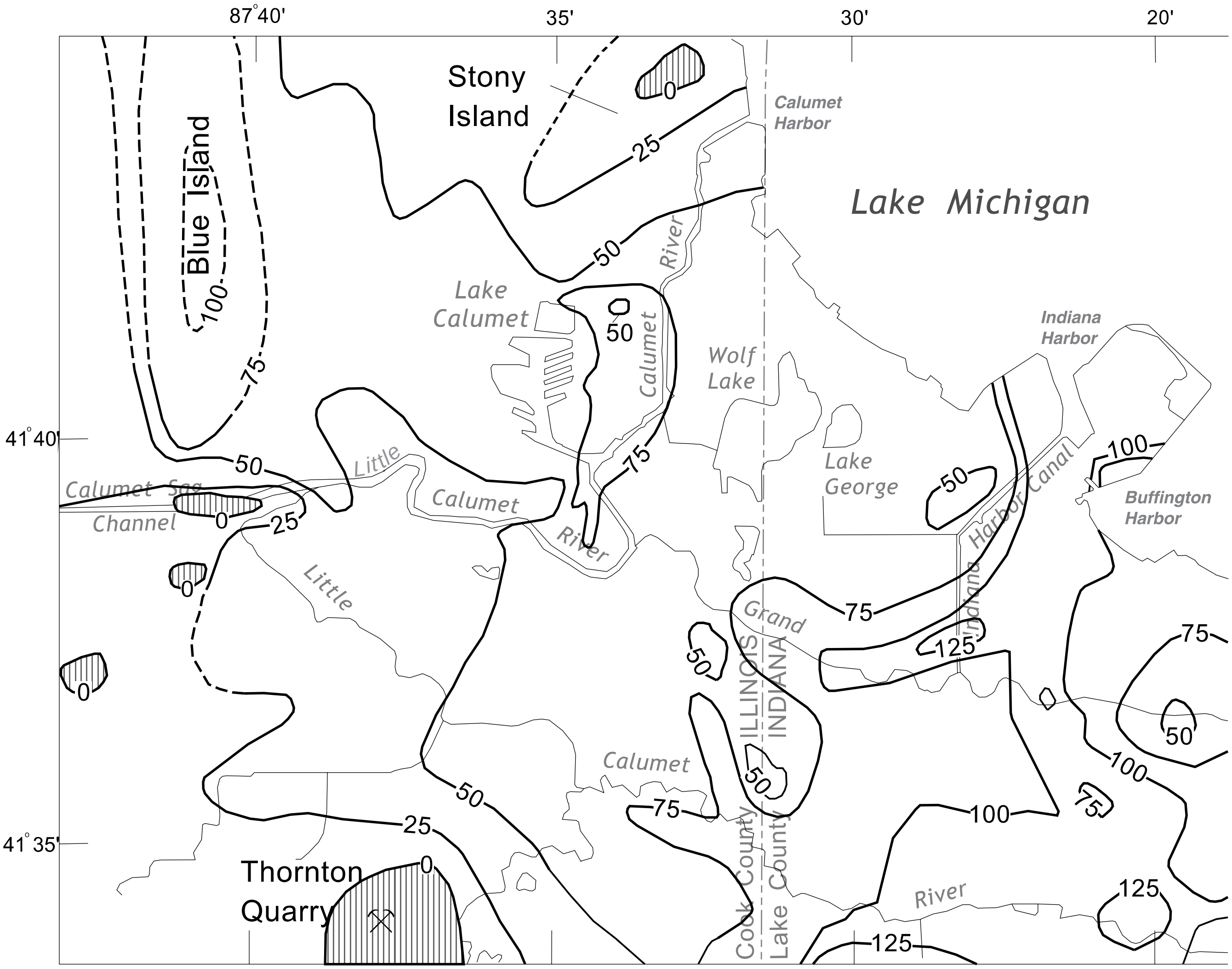
▨ SAND INTERSPERSED WITH FILL

▩ SAND ORIGINALLY PRESENT BUT REMOVED BY QUARRYING

—25— LINE OF EQUAL THICKNESS-Shows thickness of sand deposits where the top is within 20 feet of the land surface. Dashed where approximate. Interval, in feet, is variable

Figure 5. Thickness of the Calumet aquifer, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)


20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Gary Harbor
Burns Harbor
Grand Calumet River
Little Calumet River
Lake County
Porter County
100
50
40
25
10
0
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS



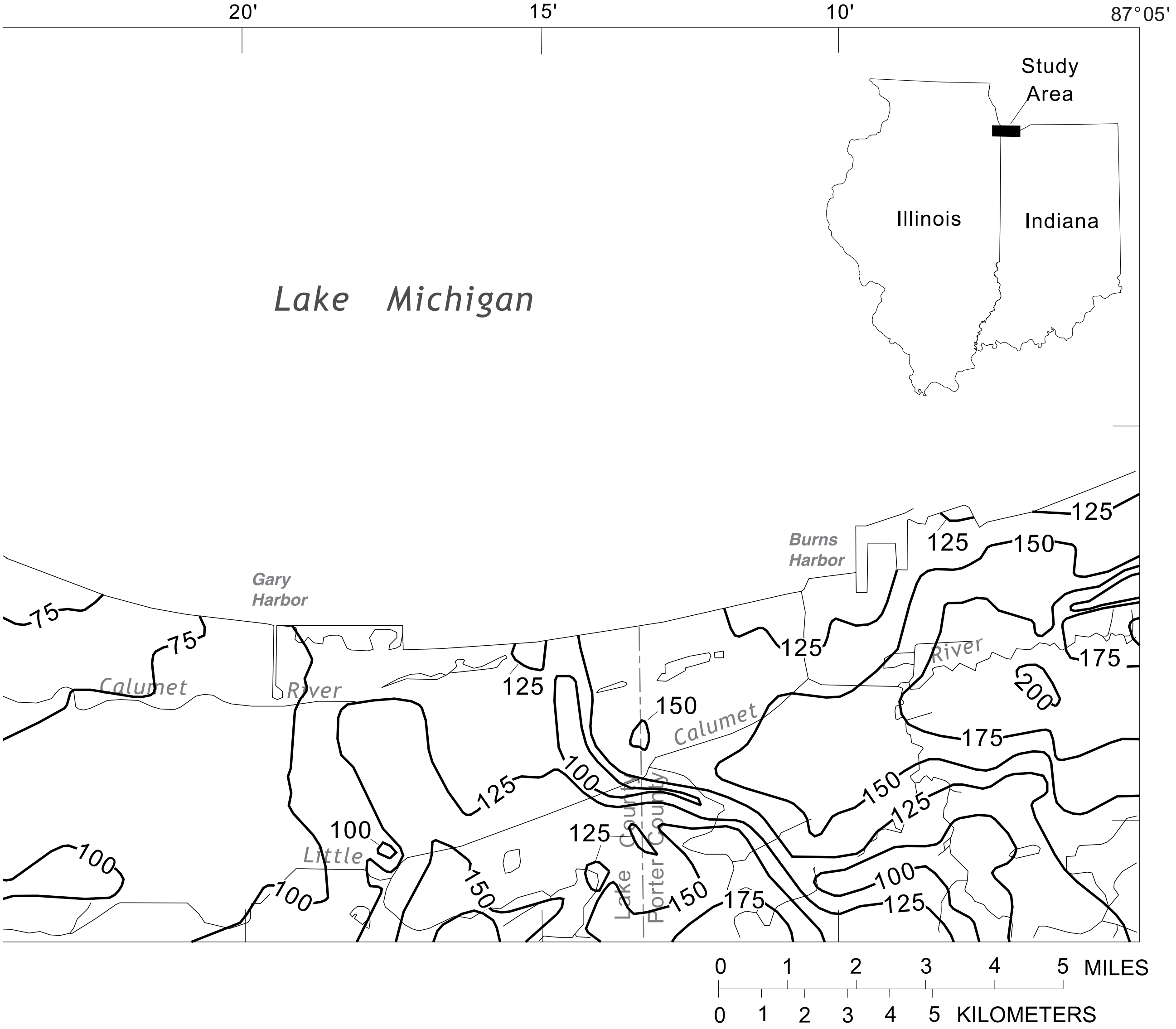
Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

▥ SILT AND CLAY ABSENT

—50— LINE OF EQUAL THICKNESS
Shows thickness of silt and clay deposits. Dashed where approximate. Interval 25 feet

Figure 6. Thickness of the confining unit, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)



20'
15'
10'
87°05'
Lake Michigan
Study Area
Illinois
Indiana
Gary Harbor
Burns Harbor
Calumet River
Little Calumet River
Lake County
Porter County
75
100
125
150
175
200
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

in most of the area east of the Calumet River and at sporadic locations west of Lake Calumet. The Dolton Member underlies the Carmi Member between the Illinois/Indiana State line and the eastern shore of Lake Calumet and along parts of the Little Calumet River. Together, the Parkland Sand and the Dolton member of the Equality Formation (equal to the Atherton of Indiana), combine to form the Calumet aquifer.

The Carmi Member consists of finely bedded or laminated lake deposits of silt and clay with localized peat beds and is the surficial deposit in much of the area around Lake Calumet and parts of the Little Calumet River. The Carmi Member underlies the Dolton Member near the confluence of the Calumet, Grand Calumet, and Little Calumet Rivers (Woodward-Clyde Consultants, 1984) and most of the Indiana part of the study area (Watson and others, 1989). The Carmi Member is equivalent to the lacustrine facies of the Atherton Formation (Schneider and Keller, 1970; Willman, 1971).

The Wadsworth Till Member overlies the Equality Formation (Shaver and others, 1970; Willman, 1971) and is comprised primarily of gray clayey till. The till is very hard and tends to become denser and more consolidated with depth. The Wadsworth Till Member is part of the Wedron Formation in Illinois (Willman, 1971) and composes part of the Lagro Formation in Indiana (Shaver and others, 1970). The Wadsworth Till Member is present at land surface at Blue Island and east of the Calumet Lagoons. Throughout most of the study area, the Wadsworth Till periodically was submerged and reworked by wave action (Willman, 1971; Watson and others, 1989).

Throughout much of the study area, lenticular bodies of poorly sorted gravel, sand, and silt overlie the bedrock. These deposits informally are known as the Lemont Drift in Illinois (Cravens and Zahn, 1990). The exact age of these deposits is unknown, but they appear to have been eroded and weathered before being covered by sediments during subsequent glacial advances.

The Lemont Drift, Wadsworth Till Member, and Carmi Member (where not underlain by sand) constitute a continuous unit of fine-grained unconsolidated material overlying the bedrock in almost all of the study area. These fine-grained deposits are absent in small areas northeast of Stony Island and west of the Little Calumet River in Illinois, but they are more than 150 ft thick beneath much of the eastern part of the study area (fig. 6). In the western part of the study area, the Lemont Drift and the Wadsworth Till Member constitute most of the fine-grained material, with the Carmi Member typically being less than 15 ft thick (Land and Lakes Co., 1988). In those parts of the study area where fine-grained deposits are within about 10 ft of the land surface, the upper part of the unit typically is weathered. An extensive network of vertical fractures, macropores, soil joints, and root channels characterizes the weathered zone (Ecology and Environment, Inc., 1990). The size and number of the weathering features decrease with depth, and these features appear to be absent below about 30 ft (Ecology and Environment, Inc., 1990).

The unconsolidated deposits in the study area have been altered extensively by anthropogenic activities. Substantial volumes of unconsolidated geologic material have been removed during quarrying, tunneling, and excavating for buildings and landfills. In addition, the surficial geology also has been modified by the deposition of large amounts of fill including slag, dredging spoil, construction and demolition debris, and municipal wastes. These activities have combined to disrupt the spatial continuity of the unconsolidated deposits, particularly near the land surface, modifying the surface topography (Kay and others, 1997) and disrupting the shallow hydrologic system.

Bedrock Geology

The bedrock that underlies unconsolidated deposits in the study area is from the Silurian and Devonian Periods (fig. 7). The bedrock units comprise primarily dolomite, limestone, and shale. The strata are essentially horizontal, except in the northeastern part of the study area where the bedrock strata dip slightly toward the northeast.

The Upper Devonian Antrim Shale is the youngest bedrock unit and is at the bedrock surface in the Porter County, Ind., part of the study area. The Antrim Shale consists of brown to black, noncalcareous shale with gray calcareous shale or limestone in the lower part of the formation, and it paraconformably overlies the Traverse Formation (Shaver and others, 1986).

The lower to middle Devonian deposits include the Detroit River and Traverse Formations. These units unconformably overlie the Niagaran Series in the eastern part of the study area. The Traverse Formation unconformably overlies the Detroit River Formation. The Traverse Formation consists of brown to gray, fine- to coarse-grained limestone to dolomitic limestone (Shaver and others, 1986). The Detroit River Formation varies from a light-colored, fine-grained, sandy dolomite near the base of the formation to a gray to dark-brown dolomite and limestone with thin to massive beds of gypsum and anhydrite in the upper part of the formation (Shaver and others, 1986). Both formations thicken toward the northeast.

The oldest bedrock strata of concern to this investigation are Silurian carbonates (dolomites and limestones) of the Niagaran Series. The Niagaran carbonates are up to 300 ft thick in the study area and are present at the bedrock surface in Illinois and western Indiana. These deposits are known as the Wabash Formation in Indiana (Shaver and others, 1986) and the Racine Dolomite in Illinois (Willman, 1971).

Large reef structures present at the land surface at Stony Island and Thornton Quarry characterize the Niagaran carbonates. The reefs are made up of a vuggy dolomite with traces of argillaceous material and sand. Away from the reefs, the Niagaran deposits consist of dense, cherty, argillaceous dolomite and limestone with local lenses of green shale.

The Niagaran carbonates contain an irregularly distributed network of vertical fractures with a major trend at N. 47 W. and a minor trend at about N. 57 E. (Zeizel and others, 1962). Fractures generally are more abundant near the rock surface, where the rock is more weathered, and decrease in number with depth as the rock becomes more competent (Suter and others, 1959). The reef deposits tend to have fewer fractures than the inter-reef deposits.

In addition to fractures, vertical faults have been identified in the bedrock in Illinois (fig. 7). Faulting has offset the bedrock strata as much as 30 ft, but displacement does not extend upward into the unconsolidated deposits (Keifer and Associates, 1976). The extent of faulting in Indiana is unknown.

The relief of the bedrock surface varies by more than 175 ft in the study area (fig. 8). Bedrock highs are present at Stony Island and Thornton Quarry. Bedrock lows are present near Burns Harbor, Gary Harbor, and the Indiana Harbor Canal. Bedrock highs at Stony Island and Thornton Quarry are attributed to the greater erosion resistance of the reef deposits in these areas (Bretz, 1939). The bedrock valleys may mark the paths of pre-glacial-age drainage systems (Bretz, 1939).

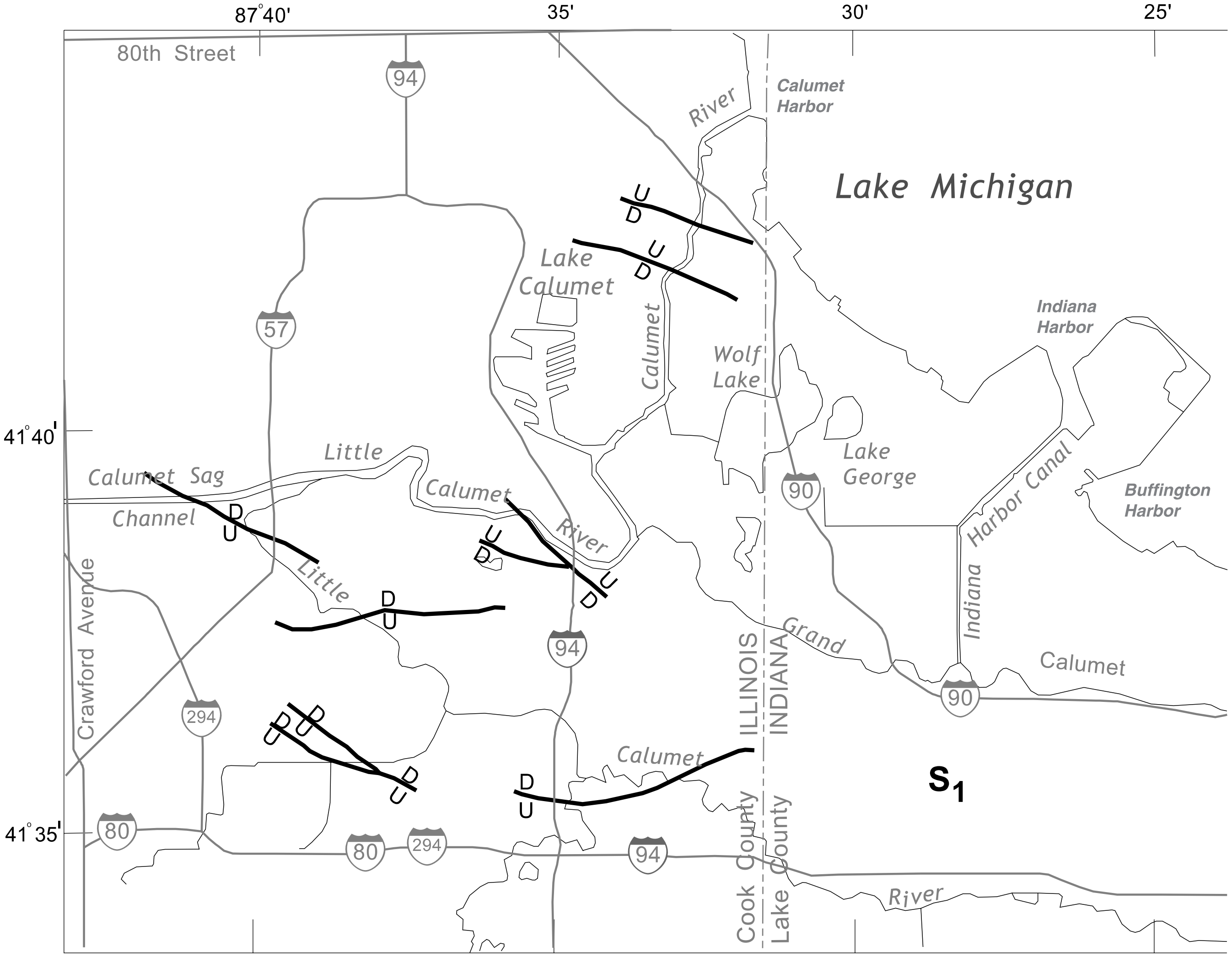
The bedrock deposits have been altered extensively by anthropogenic activities in the western part of the study area. Substantial volumes of bedrock material have been removed during quarrying and tunneling. These activities have combined to disrupt the continuity of the bedrock geologic deposits and to modify the hydrology in the bedrock aquifer (Kay and others, 1996).

Ground Water

The hydrogeologic units of concern to this investigation are the surficial Calumet aquifer, the underlying confining unit, and the basal Silurian-Devonian aquifer.

Calumet Aquifer

Surficial sands and permeable fill deposits compose the Calumet aquifer (Hartke and others, 1975). The Calumet aquifer is under water-table conditions; it is continuous throughout most of the area east of Lake Calumet but is present only at scattered locations west of Lake Calumet. The thickness of the Calumet aquifer increases from west to east in the study area, with a maximum



Base from U.S. Geological Survey digital data 1; 24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

DEVONIAN

D_2 ANTRIM SHALE-Brown to black and gray shale with limestone in lower part

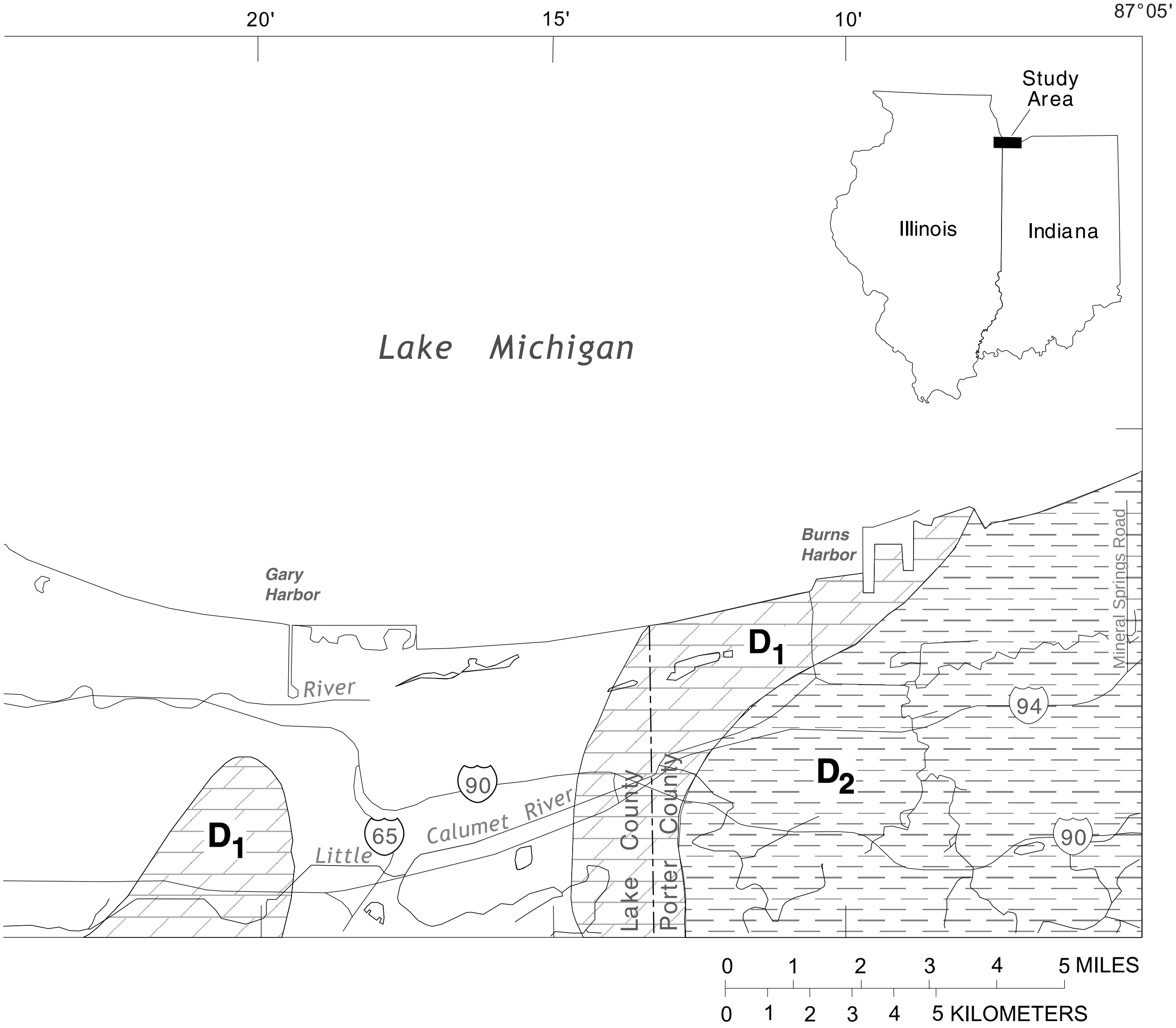
D_1 TRAVERSE AND DETROIT RIVER FORMATIONS-Predominately limestone and dolomite

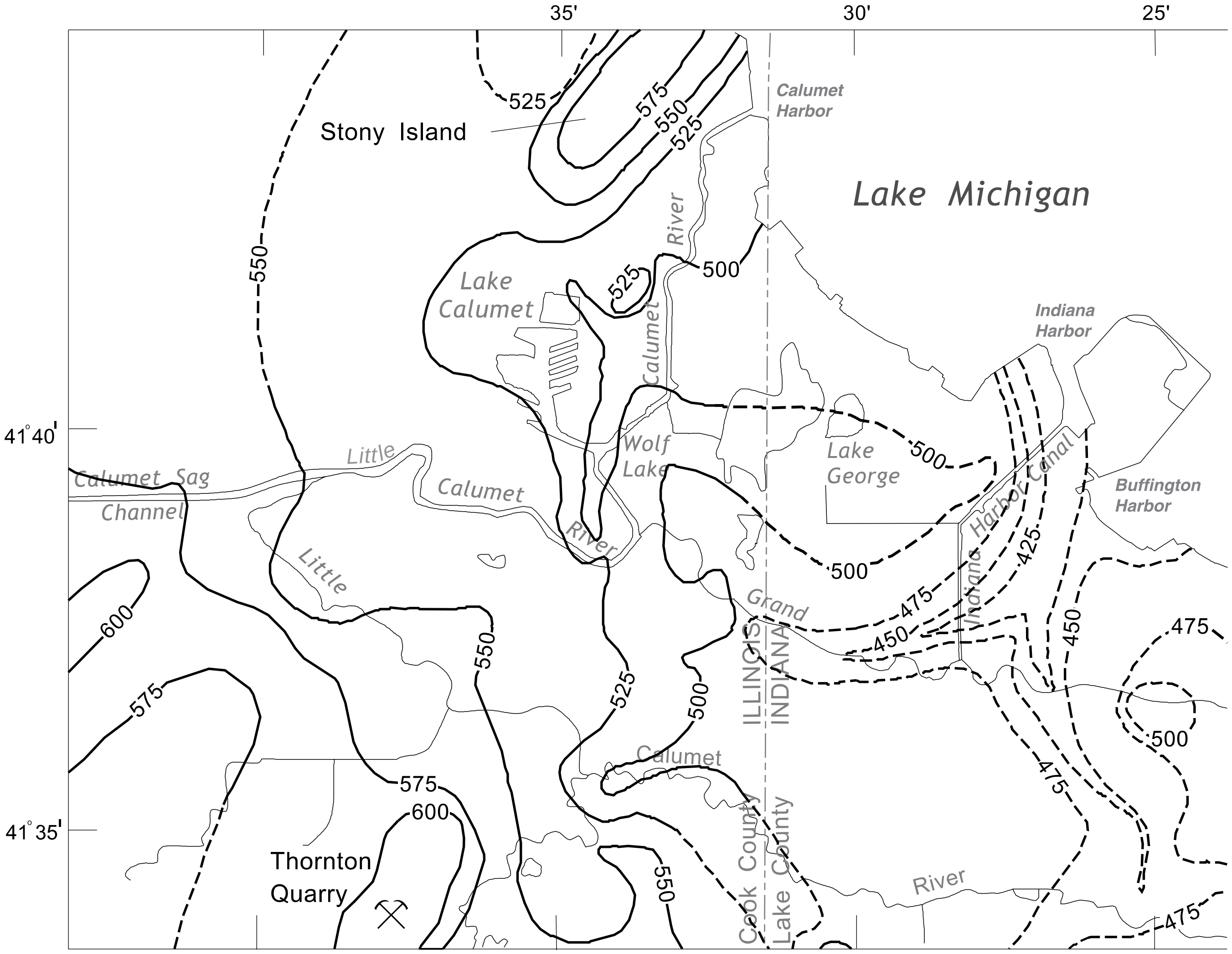
SILURIAN

S_1 NIAGARAN SERIES-Predominately dolomite

U/D FAULT-Approximately located. U indicates upthrown side. D indicates downthrown side. No fault data available for Indiana

Figure 7. Bedrock geology, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)


20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Burns Harbor
Gary Harbor
D1
D1
D2
River
Calumet River
Little
90
65
94
90
Lake County
Porter County
Mineral Springs Road
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

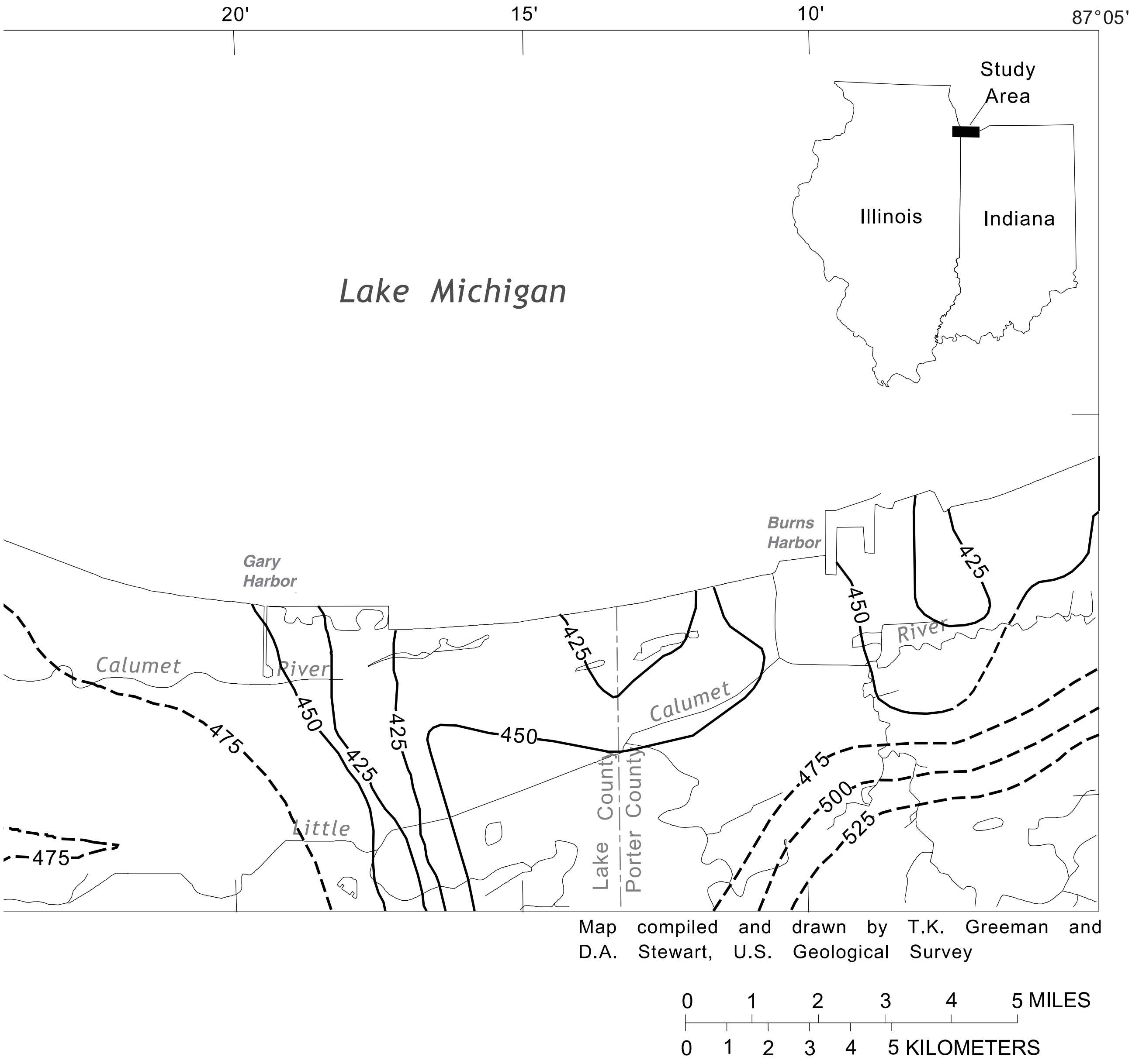


Base from U.S. Geological Survey digital data 1; 24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

– – 450 – – BEDROCK-SURFACE CONTOUR
Shows altitude of bedrock surface.
Dashed where approximate.
Contour interval 25 feet.
Datum NGVD of 1929

Figure 8. Elevation of bedrock surface, Calumet region of northwestern Indiana and northeastern Illinois. (Modified from Kay and others, 1996.)



Map compiled and drawn by T.K. Greeman and D.A. Stewart, U.S. Geological Survey thickness of about 70 ft along the Lake Michigan shoreline near the Grand Calumet Lagoons. In the extreme eastern part of the study area, a confining unit is present between the upper and lower parts of the aquifer.

The Calumet aquifer is recharged by direct infiltration of precipitation and is the primary pathway for lateral ground-water flow in the unconsolidated deposits (Watson and others, 1989; Cravens and Zahn, 1990; Fenelon and Watson, 1993; Greeman, 1995). Water in the Calumet aquifer generally flows from topographic highs toward topographic lows (fig. 9) (Fenelon and Watson, 1993; Greeman, 1995; Kay and others, 1996) and from higher water-table elevations to lower elevations. Local changes in this pattern are a result of perturbations in natural ground-water flow, including ground-water recharge from landfill leachate and ponded water; ground-water discharge to sewer lines and ditches; and pumping centers at quarries, underpasses, and ground-water remediation sites. Horizontal ground-water velocities in the Calumet aquifer have been estimated at 3.6 to 120 ft/yr (Kay and others, 1996).

The depth to the water table in the Calumet aquifer ranges from near land surface along the shoreline of Lake Michigan to more than 100 ft beneath dunes along the lake shore in the eastern part of the study area. The depth to water in the Calumet aquifer in most of the study area is less than 15 ft (Greeman, 1995; Kay and others, 1996).

Natural discharge from the Calumet aquifer primarily is to the rivers, lakes, and wetlands in the study area. Evapotranspiration also constitutes a major portion of the total discharge during spring and summer (Rosenshein and Hunn, 1968; Greeman, 1995). Water from the Calumet aquifer also discharges to the underlying confining unit in most of the study area. In addition to natural discharge, a substantial volume of water from the Calumet aquifer discharges to sewers and storm drains (Fenelon and Watson, 1993).

No clear pattern is evident in the direction of vertical flow within the Calumet aquifer. Downward flow is indicated by ground-water levels measured south of Burns Harbor; on the peninsula east of Indiana Harbor; and between the Grand Calumet River, the Indiana Harbor Canal, Gary Harbor, and Lake Michigan (fig. 10). Upward flow is indicated along parts of the ground-water divide at the Tolleston Beach Ridge between the Grand Calumet and Little Calumet Rivers and near Lake Michigan. Horizontal flow is indicated in most of the area near Wolf Lake. Flow within the Calumet aquifer in the area between Lake George, Lake Michigan, and the Indiana Harbor Canal is directed upward, downward, or horizontally. Vertical flow in the Calumet aquifer appears to be affected primarily by pumping and drainage to sewers (Fenelon and Watson, 1993).

Confining Unit

The Antrim Shale, glacial till, lacustrine silt and clay deposits, and low-permeability fill deposits compose the confining unit. The water table is in the confining unit in most of the area west of Lake Calumet where the Calumet aquifer is absent. The confining unit is more than 200 ft thick in Porter County and is thin (less than 20 ft thick) or absent near Stony Island, Thornton Quarry, and in isolated areas south of Blue Island. Except for small areas northeast of Stony Island and south of Blue Island, the confining unit underlies the Calumet aquifer and restricts flow between the Calumet aquifer and the underlying Silurian-Devonian aquifer (Kay and others, 1996). In those parts of the study area where the fine-grained deposits are within 10 ft of the land surface, the upper part of the confining unit is more weathered and is more permeable than at depth. Rosenshein (1963, p. 22) estimated the average vertical hydraulic conductivity of the confining unit in Lake County at 4.0×10^{-4} ft/d.

The water-table configuration in the confining unit generally is a subdued reflection of surface topography. Ground water generally flows from topographic highs to topographic lows, typically from topographic ridges to the surface-water bodies (Kay and others, 1996). Local changes in this pattern result primarily from enhanced recharge to ground water beneath landfills and surface-water impoundments.

The confining unit is recharged by ground-water flow from the Calumet aquifer and infiltration from precipitation where the Calumet aquifer is absent. Discharge from the confining unit primarily is to the underlying Silurian-Devonian aquifer, with some discharge to the rivers, lakes, and wetlands in the study area. In the shallow part of the confining unit where the Calumet aquifer is absent, evapotranspiration constitutes a major part of the discharge during spring and summer (Rosenshein and Hunn, 1968). The depth of the water table in the confining unit is typically about 15 ft but ranges from near land surface around Lake Calumet to about 27 ft near some of the landfills (Kay and others, 1996).

The vertical distribution of water levels in the study area indicates the potential for flow from the water table or the base of the Calumet aquifer down into the confining unit in most of the study area (Kay and others, 1996). Vertical flow through the weathered and unweathered parts of the confining unit is greater than the horizontal flow. The horizontal ground-water velocity at the water table in the confining unit was calculated to range from 0.16 to 0.37 ft/yr (Kay and others, 1996). The vertical ground-water velocity through the weathered and unweathered parts of the confining unit is estimated to be 13.9 and 0.55 ft/yr, respectively (Kay and others, 1996).

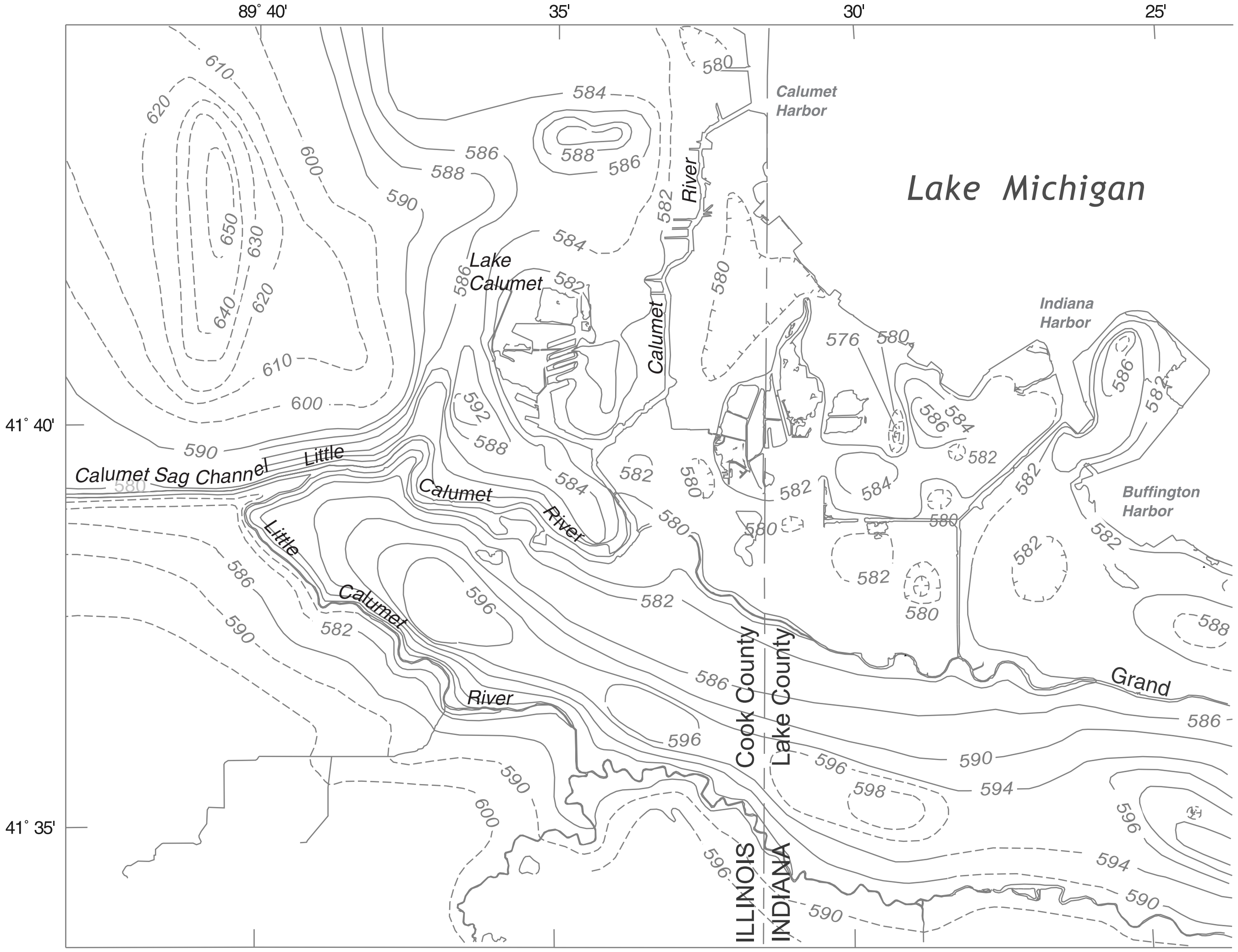
Silurian-Devonian Aquifer

The Silurian-Devonian aquifer is composed of dolomite and limestone strata that underlie the confining unit in most of the study area. The Silurian-Devonian aquifer is unconfined at Stony Island and Thornton Quarry. In small areas northeast of Stony Island and south of Blue Island, the confining unit is absent and the Silurian-Devonian aquifer is in direct hydraulic connection with the Calumet aquifer. In the rest of the study area, the Silurian-Devonian aquifer is semi-confined. Movement of ground water within the Silurian-Devonian aquifer is primarily through an interconnected network of joints, fissures, faults, bedding-plane openings, and solution cavities in the bedrock.

Prior to industrial and urban development of the study area, which began about 1870, water levels in the Silurian-Devonian aquifer are thought to have been substantially higher than at present; discharge from the Silurian-Devonian aquifer appears to have been to Lake Michigan through the confining unit and the Calumet aquifer. Pumping from the Silurian-Devonian aquifer for industrial supply and dewatering of deep tunnels in the study area has lowered water levels in the aquifer substantially (Rosenshein, 1963; Watson and others, 1989; Cravens and Zahn, 1990; Fenelon and Watson, 1993; Kay and others, 1996), particularly in the vicinity of Lake Calumet. By the early 1980s, the Silurian-Devonian aquifer had been abandoned as a source for industrial water supply, but dewatering of deep tunnels continues. Recharge to the Silurian-Devonian aquifer from the confining unit may be a recent (within the past 100 years) phenomena, resulting from overdrafts of the Silurian-Devonian aquifer (Rosenshein, 1963).

Water-level measurements in the Silurian-Devonian aquifer made in 1992 indicate the potentiometric surface is highest at the bedrock high near Stony Island and in the southeastern part of the study area (fig. 11). The potentiometric highs are separated by a depression centered near the confluence of the Little Calumet and Grand Calumet Rivers. This depression appears to be centered at a drop shaft open to the aquifer that has been used to dewater the formation. The depression in the potentiometric surface around Thornton Quarry is attributed to excavation and pumping at the quarry. The average linear ground-water velocity through the uppermost 20 ft of the Silurian-Devonian aquifer is calculated to range from 5.1 to 10.6 ft/yr (Kay and others, 1996).

In areas where a confining unit overlies the Silurian-Devonian aquifer, water-level data indicate the potential for ground water to flow from the Calumet aquifer and the confining unit into the Silurian-Devonian aquifer (Kay and others, 1996). Where the confining unit is absent, recharge is from the Calumet aquifer or direct infiltration from precipitation.

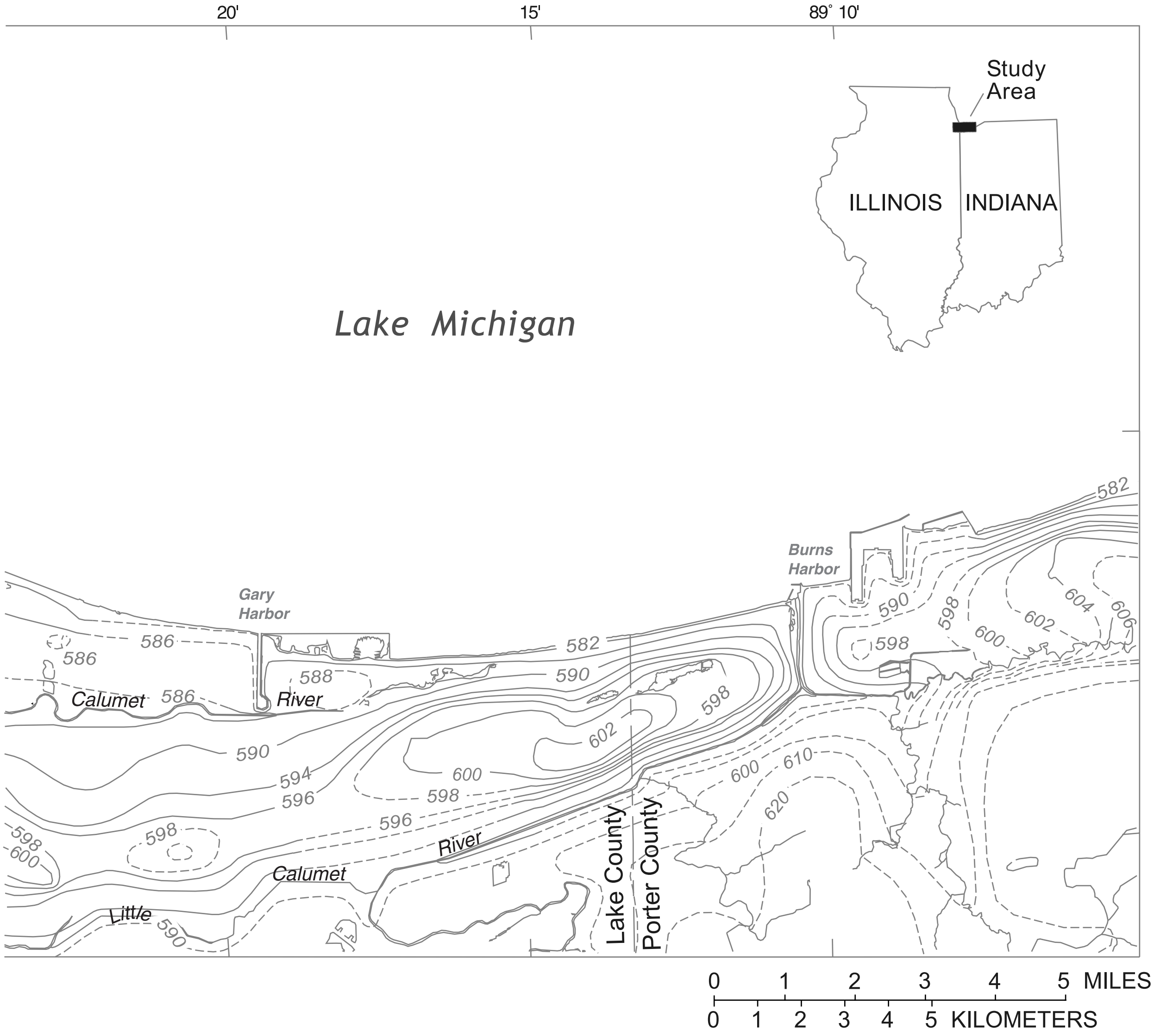


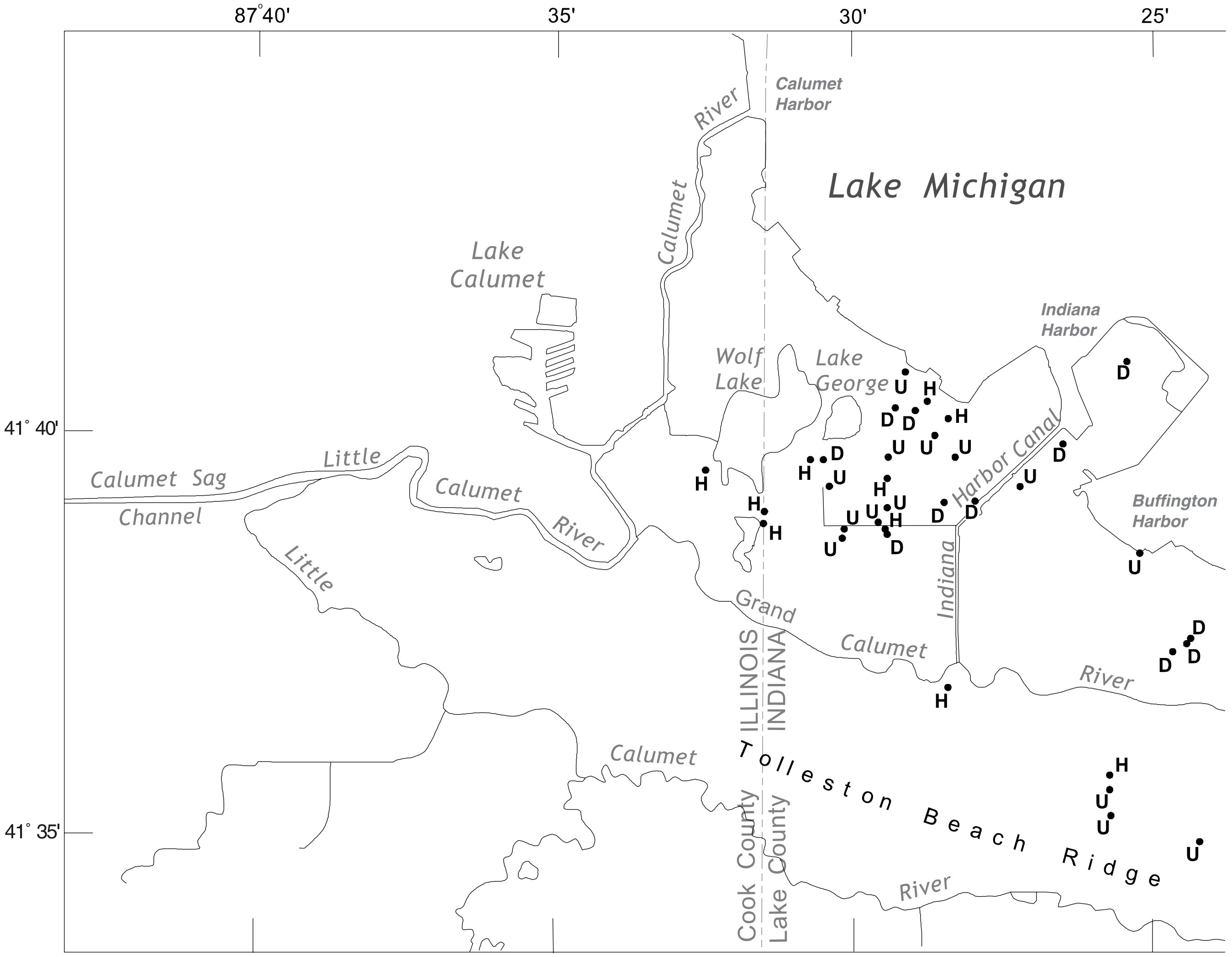
Base from U.S. Geological Survey digital data, 1:100,000, 1991
Albers Equal-Area projection
Standard parallels 33° and 45°, and central meridian -89°00'

EXPLANATION

——606– – – WATER-TABLE CONTOUR-Shows altitude of water table. Dashed where approximate. Contour interval variable. Datum NGVD of 1929

Figure 9. Water-table configuration, Calumet region of northwestern Indiana and northeastern Illinois, June 23-25, 1992. (Modified from Kay and others, 1996.)


20'
15'
89° 10'
Study Area
ILLINOIS
INDIANA
Lake Michigan
Gary Harbor
Burns Harbor
582
586
588
590
594
596
598
600
602
604
606
610
620
Calumet
River
Little
Lake County
Porter County
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

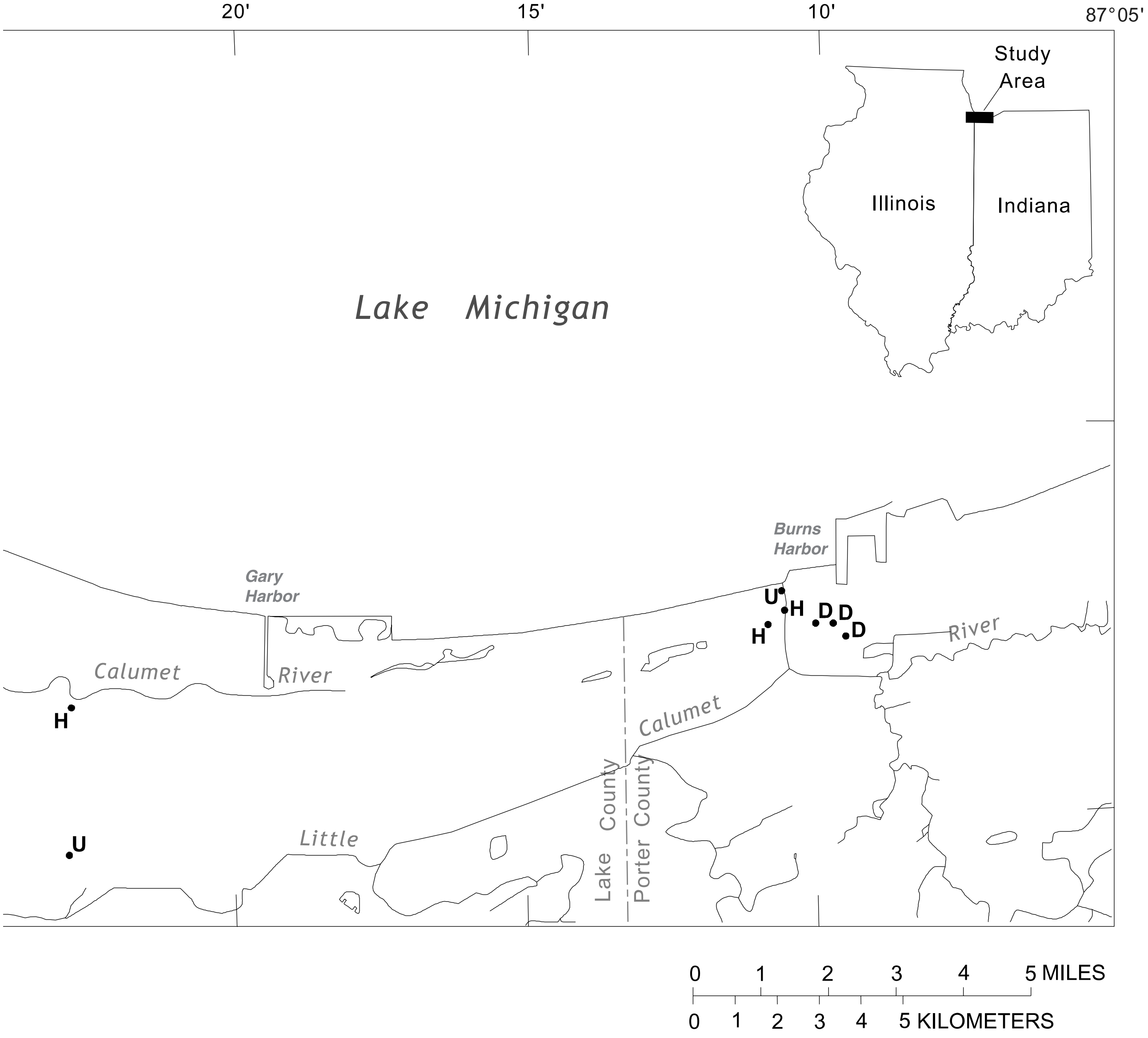


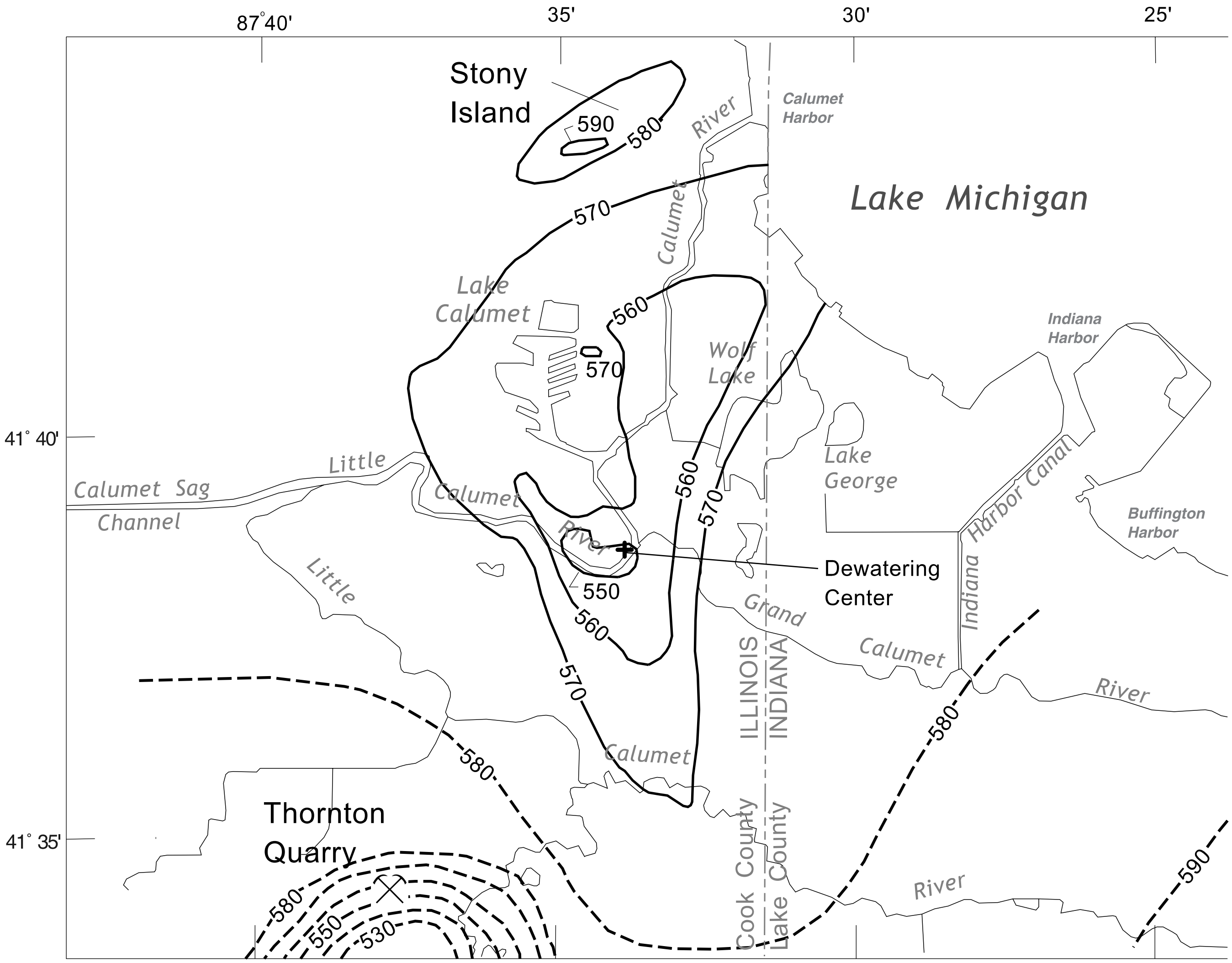
Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

• U VERTICAL HYDRAULIC GRADIENTS IN CALUMET AQUIFER-
- U, denotes upward gradient
- D, denotes downward gradient
- H, denotes vertical gradient absent

Figure 10. Direction of vertical hydraulic gradients within the Calumet aquifer, Calumet region of northwestern Indiana and northeastern Illinois, June 23-25, 1992. (Modified from Kay and others, 1996.)


20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Burns Harbor
Gary Harbor
Calumet River
Calumet
Little
River
Lake County
Porter County
U
H
D
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

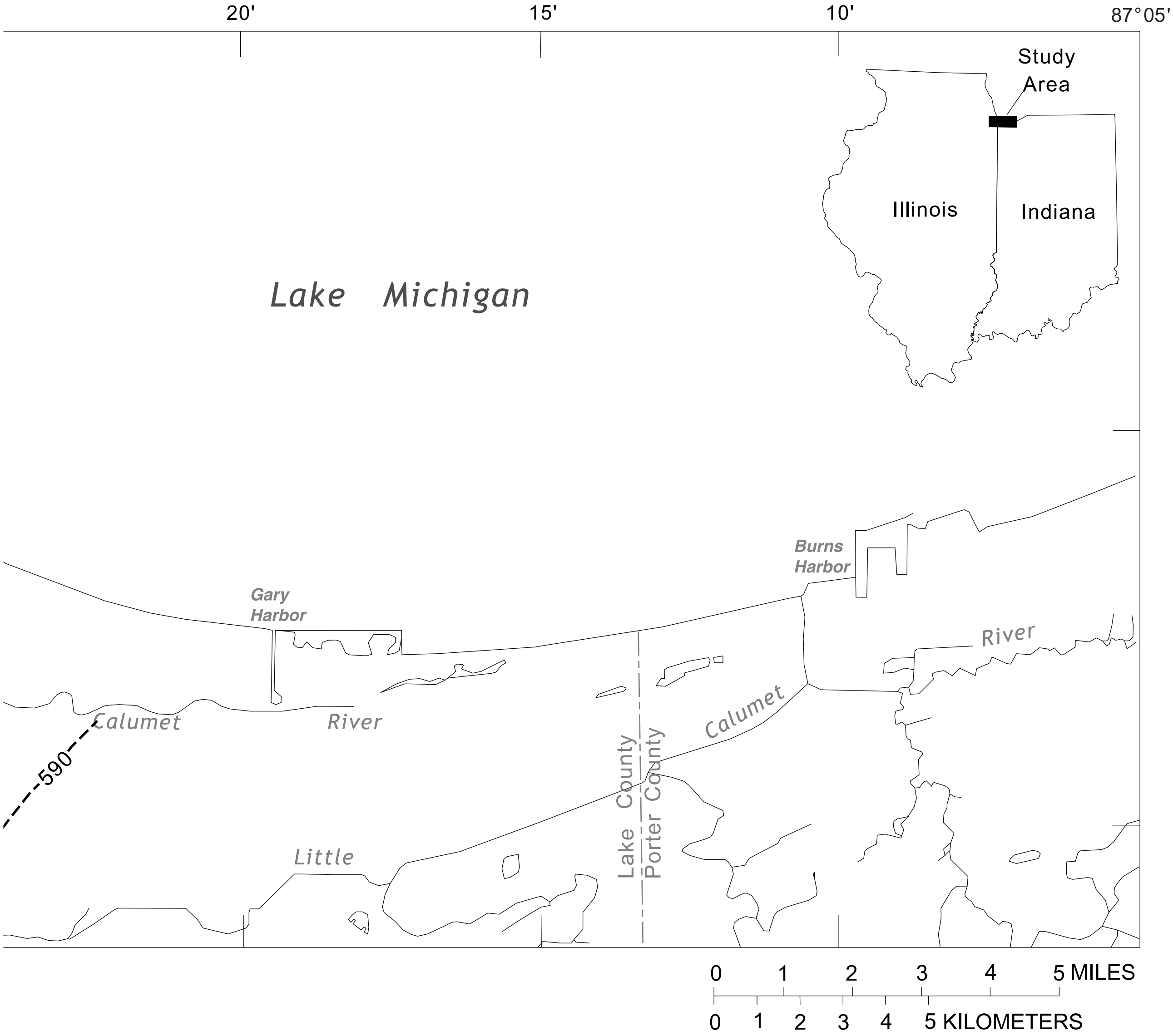


Base from U.S. Geological Survey digital data 1; 24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

—550— POTENTIOMETRIC CONTOUR-Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximate. Contour interval 10 feet. Datum NGVD of 1929

Figure 11. Potentiometric surface of the Silurian-Devonian aquifer, Calumet region of northwestern Indiana and northeastern Illinois, June 23-25,1992. (Modified from Kay and others, 1996.)



20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Burns Harbor
Gary Harbor
Calumet River
Calumet River
Little
590
Lake County
Porter County
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Some ground water may discharge from the Silurian-Devonian aquifer to Lake Michigan through the confining unit and the Calumet aquifer in the eastern half of the study area (Watson and others, 1989). Water levels in the Silurian-Devonian aquifer, however, are lower than levels in Lake Michigan in most of the area between the Indiana Harbor Canal and Stony Island, indicating the potential for water to flow from the lake into the aquifer.

Surface Water

The Grand Calumet, Little Calumet, and Calumet Rivers are the principal drainages in the study area (fig. 12). Surface-water flow in most of the Grand Calumet and part of the Little Calumet Rivers is to Lake Michigan through the Indiana Harbor Canal and Burns Harbor, respectively. Surface-water flow in a western part of the Grand Calumet River (2 mi east of the Illinois/Indiana State line) and the western part of the Little Calumet River (4 to 5 mi east of the Illinois/Indiana State line), however, is west to the Calumet Sag Channel in Illinois. Surface-water flow of the Calumet River is spatially and temporally variable, often being toward Lake Calumet south of the confluence with Squaw Creek and toward Lake Michigan north of the confluence. A decline in the level of Lake Michigan by as little as 0.5 ft can produce a hydraulic gradient capable of shifting the surface-water-drainage divide in the Little Calumet and Grand Calumet Rivers to the west and reversing flow in the Calumet River (U.S. Department of Health, Education and Welfare, 1965, p. 60; Greeman, 1995). Conversely, a rise in lake level could increase the amount of flow from Lake Michigan into the Calumet River and Lake Calumet and shift the flow divides on the Grand Calumet and Little Calumet Rivers to the east.

Surface-water gradients on the Calumet and Grand Calumet Rivers and the Indiana Harbor Canal averaged less than 0.5 ft/mi in June 1992 (Kay and others, 1996). Surface-water gradients on the Little Calumet River averaged 0.7 ft/mi in June 1992 (Kay and others, 1996). The low hydraulic gradients on the rivers indicate sluggish flow. The flow of the Grand Calumet River primarily is derived from industrial and wastewater discharge (HydroQual, 1985). Because Lake Michigan is the primary source of potable water in the study area, virtually all wastewater discharge (and therefore most of the water in the Grand Calumet River) ultimately is derived from Lake Michigan.

With the exception of Lake Michigan, the lakes in the study area partially or completely are isolated from the surface-water-flow system. Water is delivered to Lake Calumet through manmade drainage channels, storm sewers, recharge from ground water, and flow from and to the Calumet River. Water originally pumped from Lake Michigan is discharged to Wolf Lake by industries along the northern arm of the lake. Squaw Creek, a shallow, manmade drainage ditch connects Wolf Lake to the Calumet River. Therefore, most of the water in Wolf Lake and Squaw Creek ultimately is derived from Lake Michigan. Wolf Lake, Lake George, and the smaller lakes scattered throughout the region are either in topographic depressions between dune and beach ridge deposits or in pits created by mining of sand and clay.

Surface-Water and Ground-Water Interactions

Interactions between surface water and ground water in the study area are complex. Shallow ground-water flow typically is toward the major surface-water bodies, indicating the potential for ground-water discharge to surface water in most of the region. Observation of ground-water levels in wells paired with surface-water gages, however, indicates the potential for frequent periodic reversals of surface-water/ground-water flow along some river reaches in the study area (Greeman, 1995) and at Lake Michigan near Calumet Harbor. Precipitation, variations in the quantity of industrial and wastewater discharge to the rivers, evapotranspiration, and fluctuations in the stage of Lake Michigan affect the timing and location of the flow reversals.

Interpretation of the interaction between surface water and ground water also is complicated by the presence of sheet piles driven through the Calumet aquifer along much of shorelines of Lake

Michigan and Lake Calumet, the Calumet River, the Calumet Sag Channel, and the Indiana Harbor Canal. The sheet piles form a barrier to the flow of surface water and ground water, forcing water to move under the wall or through cracks, holes, and joints in the sheet piles. Surface-water/ground-water flow across the sheet piles is probably small, compared to flow between the Calumet aquifer and surface-water bodies where pilings are absent.

Recharge of ground water from the Calumet aquifer accounts for approximately 10 percent of the water in the Grand Calumet River (Fenelon and Watson, 1993). Water in the confining unit has the potential to discharge to surface water in most of the study area where the confining unit is at or near the land surface (Kay and others, 1996). Calculations indicate, however, that recharge from the confining unit accounts for less than 1 percent of the flow in the rivers in the study area.

Study Methods

Water samples were collected from 26 wells during July 1997 and 21 different wells during January–February 2000 and April 2001. In addition, one sample was collected from Lake Michigan near the Illinois/Indiana State line, south of Calumet Harbor in January 2000 (table 1).

Sampling Methods

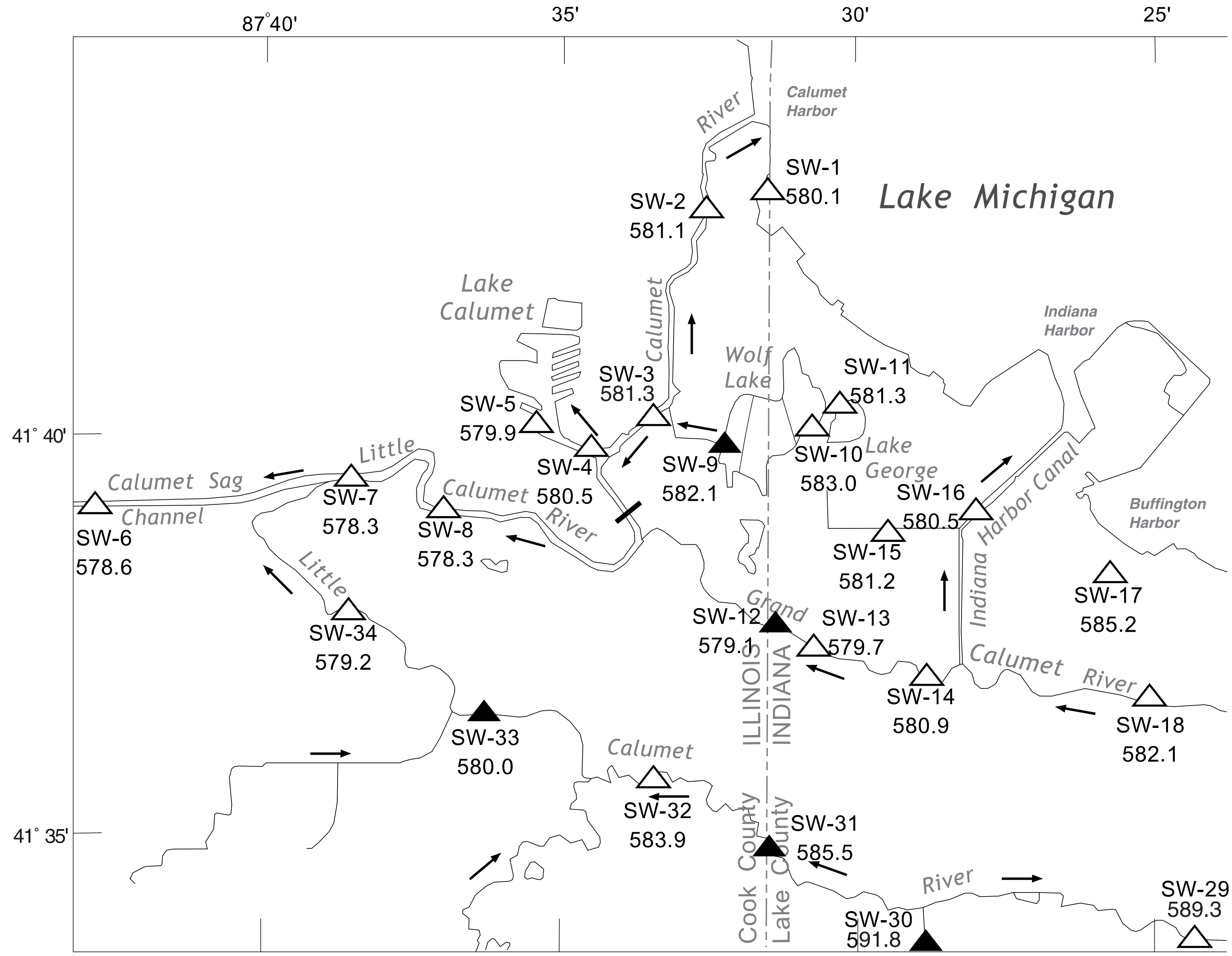
All samples from wells open to the Calumet aquifer and the Silurian-Devonian aquifer were collected with submersible sampling pumps after at least three well volumes were purged from the well. The temperature, pH, specific conductance, redox potential, and dissolved-oxygen concentration of the purge water were measured to ensure parameter stabilization prior to sample collection. Wells open to the confining unit could not sustain discharge and were sampled with low-flow submersible sampling pumps. The low-flow submersible pumps were lowered into the screened interval of the well and the sample was collected after the volume of water in the discharge line was purged at least twice. Samples were collected and stored in accordance with standard USGS procedures (Wilde and others, 1999).

Samples for determination of tritium (^{3}H), oxygen ($^{18}O/^{16}O$), hydrogen ($^{2}H/^{1}H$), and tritiogenic helium (^{3}He) initially were collected throughout the study area during July 1997. The samples from Illinois, however, were damaged during shipping and were re-collected during January and February 2000. Additional samples were collected in Illinois during April 2001. Additional samples for the analysis of ^{3}H, $^{18}O/^{16}O$, and $^{2}H/^{1}H$ were collected in Indiana during February 2001.

Ground-water samples collected in Indiana in July 1997 were submitted to the National Risk Management Laboratory of the U.S. Environmental Protection Agency in Cincinnati, Ohio, in July 1998 for analysis. (There is no holding time for these samples.) All other samples were analyzed by the USGS National Water Quality Laboratory in Denver, Colo. The analysis included samples collected in Illinois in January and February 2000 and submitted for analysis in March 2000, samples collected in Illinois in April 2001 and submitted for analysis in May 2001, and samples collected in Indiana during February 2001 and submitted for analysis in February 2001. Ground-water samples for ^{3}He analysis were submitted to the Lamont-Doherty Earth Observatory at Columbia University in December 2000.

Laboratory Methods

All Indiana samples and the Illinois samples from wells open to the Calumet aquifer or the water table in the confining unit were analyzed based on USGS schedule 460, with a detection limit of 1.8 tritium units (TU). Tritium samples from Illinois wells open to the Silurian-Devonian aquifer and the lower part of the confining unit were analyzed using USGS schedule 624, with a detection limit of 0.78 TU. The $^{2}H/^{1}H$ and $^{18}O/^{16}O$ analyses were performed using USGS schedule 1142, and the ^{3}He analyses were performed using USGS schedule 1033.



Base from U.S. Geological Survey digital data 1; 24,000,1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

← DIRECTION OF SURFACE-WATER FLOW

SW-15 581.2 △ SURFACE-WATER-LEVEL MEASUREMENT SITE AND DESIGNATION-Number is water-level altitude, in feet. Datum NGVD 1929

SW-31 585.5 ▲ CONTINUOUS MONITORING SITE AND DESIGNATION-Number is water-level altitude, in feet. Datum NGVD 1929

Figure 12. Direction of surface-water flow, Calumet region of northwestern Indiana and northeastern Illinois, June 23-25, 1992. (Modified from Kay and others, 1996.)

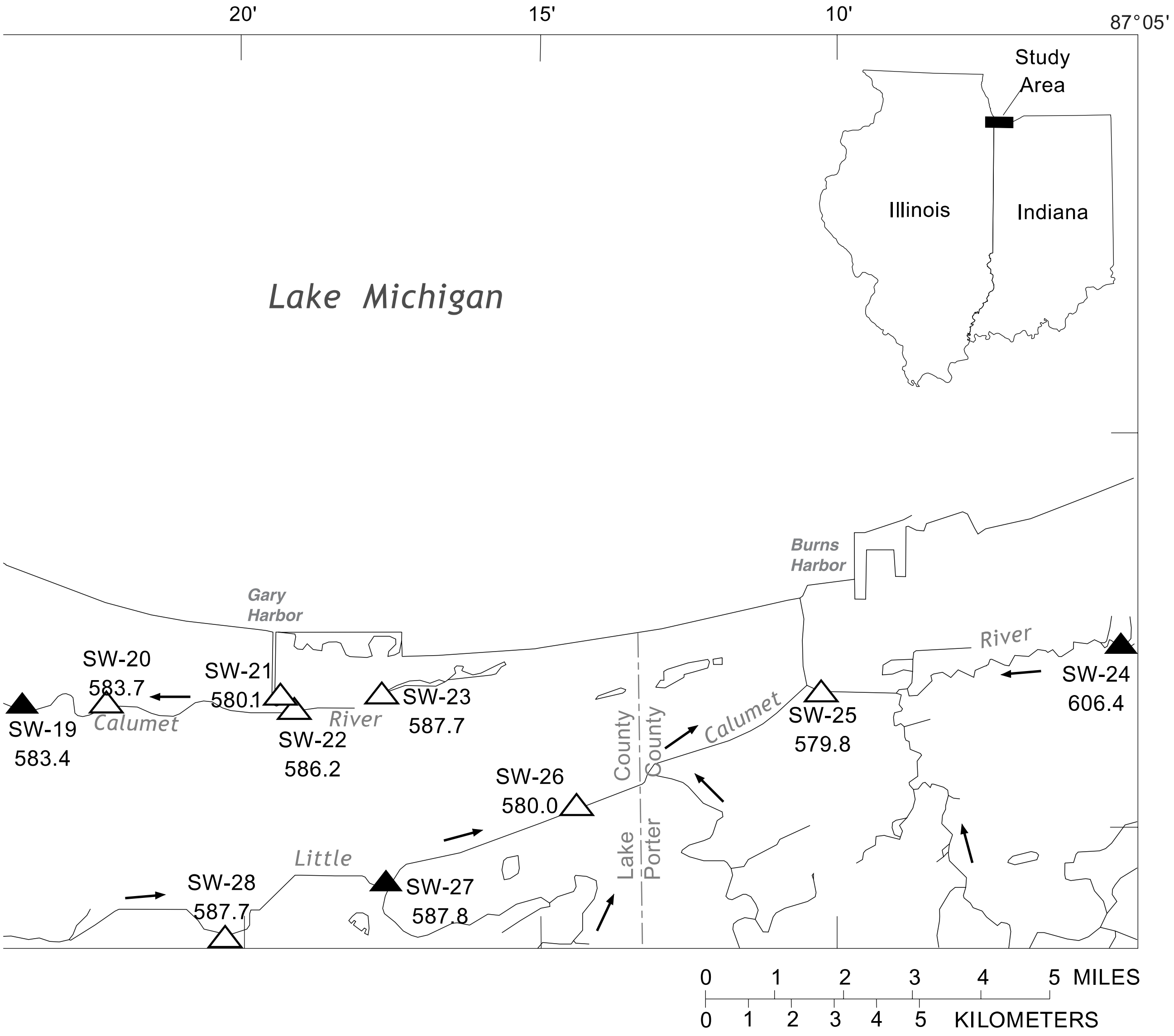

20'
15'
10'
87°05'
Study Area
Illinois
Indiana
Lake Michigan
Gary Harbor
Burns Harbor
SW-19
583.4
SW-20
583.7
SW-21
580.1
SW-22
586.2
SW-23
587.7
Calumet
River
SW-24
606.4
SW-25
579.8
SW-26
580.0
SW-27
587.8
SW-28
587.7
Little
Calumet
River
Lake County
Porter County
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Table 1. Well descriptions for sampled sites in northwestern Indiana and northeastern Illinois

[DUP, quality-assurance replicate sample; NA, not applicable; CA, Calumet aquifer; MCU, mid-depth confining unit; WTCA, water table; CA, Calumet aquifer; SD, Silurian-Devonian bedrock aquifer; SW, surface water; SL, slag]

Well name	Date of sample collection	Latitude/ longitude	U.S. Geological Survey site-identification number	Land-surface altitude (NGVD of 1929)	Well open interval (feet below land surface)	Hydrologic unit
A20	7/09/1997	413503/871935	413503087193501	614	21 -24	CA
B7	7/15/1997	413617/872252	413617087225202	595	8 -11	CA
B8	7/15/1997	413617/872252	413617087225201	595	32 -37	CA
B8 (DUP)	7/15/1997	413617/872252	413617087225201	595	32 -37	CA
B10	7/09/1997	413544/872337	413544087233700	606	17 -20	CA
BH1D	1/18/2000	414238/874011	414238087401102	667	75 -90	MCU
BH1S	1/18/2000	414238/874011	414238087401101	667	5 -15	WTCA
BH7D	1/18/2000	413910/873358	413910087335803	587	69 -79	SD
BH7I	1/18/2000	413910/873358	413910087335802	587	19 -29	MCU
BH7S	1/18/2000	413910/873358	413910087335801	587	7 -17	WTCA
BH13	7/09/1997	413548/872040	413548087204001	603	9 -19	CA
BH16D	1/10/2000	414250/873624	414250087362402	599	68 -78	SD
BH18D	1/18/2000	414316/873131	414316087313103	595	58 -68	SD
BH18D (DUP)	1/18/2000	414316/873131	414316087313103	595	58 -68	SD
BH18I	1/18/2000	414316/873131	414316087313102	594	35 -45	MCU
BH18S	1/18/2000	414315/873131	414315087313101	594	8 -18	WTCA
BH31	7/16/1997	413947/873025	413947087302501	598	15 -28	SL&CA
BH32D	7/16/1997	413949/873019	413949087301901	597	36 -38.5	CA
BH32D (DUP)	7/16/1997	413949/873019	413949087301901	597	36 -38.5	CA
BH32I	7/16/1997	413949/873019	413949087301902	597	27.5-30	CA
BH32S	7/14/1997	413949/873019	413949087301903	597	21 -23.5	CA
BH32SL	7/14/1997	413949/873019	413949087301904	597	17.5- 2	SL
BH33I	7/16/1997	413951/873019	413951087301901	585	13.5- 1	CA
BH33S	7/16/1997	413951/873019	413951087301902	585	7.5-10	CA
BH33SL	7/16/1997	413951/873019	413951087301903	585	2.5- 5	SL

Table 1. Well descriptions for sampled sites in northwestern Indiana and northeastern Illinois—Continued

Well name	Date of sample collection	Latitude/ longitude	U.S. Geological Survey site-identification number	Land-surface altitude (NGVD of 1929)	Well open interval (feet below land surface)	Hydrologic unit
BR1	7/10/1997	413328/872023	413328087202301	595	145	SD
BR2	2/07/2001	413437/871506	413437087150601	600	147	SD
BR3	7/11/1997	413419/873017	413419087301701	595	140	SD
BR4	20/7/2001	413716/872326	413716087232601	595	147	SD
BR5	2/08/2001	413732/872558	413732087255801	587	156	SD
C1	7/17/1997	413830/872600	413830087260000	586	4.5- 9.5	CA
C3	7/17/1997	413828/872513	413828087251301	595	23 - 28	CA
D10	7/18/1997	414043/872908	414043087290802	588	27.5- 32.5	CA
D11	7/18/1997	414043/872908	414043087290801	588	22 - 27	CA
D21	7/17/1997	413941/872926	413941087292600	584	18 - 23	CA
D67	7/10/1997	413647/872852	413647087285202	588	4 - 7	CA
D68	7/10/1997	413647/872852	413647087285201	588	18 - 23	CA
D68 (DUP)	7/10/1997	413647/872852	413647087285201	588	18 - 23	CA
D75	7/10/1997	413435/872919	413435087291901	600	5 - 8	CA
FILO102-5	1/18/2000	414023/873634	414023087363402	593	73 - 83	SD
FILO102D	1/18/2000	414021/873634	414021087363402	600	80 - 90	SD
GO5D	1/17/2000	413829/873423	413829087342301	592	83 - 93	SD
G213	1/17/2000	413834/873433	413834087343301	593	10 - 19	SD
G218	1/17/2000	413823/873429	413823087342903	585	66 - 75	SD
IC	1/10/2000	413929/873522	413929087352201	590	53 - 58	SD
IC (DUP)	1/10/2000	413511/873522	413511087352201	590	53 - 58	SD
IP	1/10/2000	414132/873659	414132087365901	591	72 - 77	SD
R251	1/17/2000	413824/873411	413824087341101	589	35 - 45	MCU
R253	1/17/2000	413823/873429	413823087342902	586	32 - 42	MCU
ST1D	4/04/2001	414106/873355	414106087335502	588	98 -115	SD
ST4D	4/04/2001	414104/873431	414104087343102	590	80 -103	SD
WS1	2/16/2000	414238/873320	414238087332002	588	20 - 25	MCU
WS2	2/16/2000	414158/873316	414158087331601	588	4 - 15	WTCA
Lake Michigan[1]	1/18/2000	414315/873130	414315087313001	582	NA	SW

[1] Lake Michigan site sampled from the lake surface.

Quality Assurance

Duplicate samples were collected from five wells to help verify the reproducibility of the sampling techniques. Tritium concentrations were identical in duplicate samples. The $\delta^{18}O$ values varied by less than 0.3 per mil (0.003 percent) between samples. The $\delta^{2}H$ values varied by less than 5 per mil (0.05 percent). Replicate estimates of ground-water age at a single well site, based on $^{3}H/^{3}He$ measurements, were 9.90 and 9.95 years.

Distribution of Isotopes in Ground Water

The structure of an atom is defined by the number of protons (which defines the element) and the number of neutrons (which defines the isotope of the element). The sum of the protons and the neutrons for a given element is its atomic weight.

Oxygen and Deuterium

Most oxygen molecules have 8 protons and 8 neutrons, for an atomic weight of 16 (^{16}O). About 0.20 percent of oxygen atoms have 10 neutrons, for an atomic weight of 18 (^{18}O) (Freeze and Cherry, 1979). Hydrogen (^{1}H) has one proton in its nucleus. About 0.016 percent of hydrogen atoms are in the form of deuterium (^{2}H), which has a proton and a neutron in its nucleus (Freeze and Cherry, 1979). The ^{16}O, ^{18}O, ^{1}H, and ^{2}H isotopes are the main isotopes that make up the water molecule. These isotopes of oxygen and hydrogen are stable and do not disintegrate by radioactive decay.

Stable isotopes of oxygen and hydrogen in the water molecule are measured as the ratio of the two most abundant isotopes of a given element, $^{2}H/^{1}H$ and $^{18}O/^{16}O$, relative to a reference standard. These ratios are expressed in delta units (δ) as parts per thousand (per mil, written as $^{o}/_{oo}$). The general expression for stable isotope notation is

$$\delta x = [(R_x/R_{\mathbf{STD}})\text{-}1] \times 1000,$$

where R_x and $R_{\mathbf{STD}}$ are the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ of the sample and reference standard, respectively.

The reference standard ($R_{\mathbf{STD}}$) for oxygen and hydrogen isotopes is Standard Mean Ocean Water (Freeze and Cherry, 1979). For example, an oxygen sample with an $\delta^{18}O$ value of –50 $^{o}/_{oo}$ is depleted in ^{18}O by 5 percent or 50 $^{o}/_{oo}$ relative to the standard.

The difference in the mass of oxygen and hydrogen isotopes in water results in distinct partitioning of the isotopes (fractionation) as a result of evaporation, condensation, freezing, melting, or chemical and biological reactions. For example, $\delta^{2}H$ and $\delta^{18}O$ values in precipitation are isotopically lighter in areas with lower mean annual temperature. Strong seasonal variations are expected at any given location (Dansgaard, 1964). Average annual values of $\delta^{2}H$ and $\delta^{18}O$ in precipitation, however, show little variation at any one location.

The International Atomic Energy Agency monitored the oxygen and hydrogen isotopic composition of precipitation at Chicago's Midway Airport from January 1962 through October 1979; the data are accessible through the World Wide Web at:

ftp://ftp.iaea.org

Midway Airport is approximately 10 mi northwest of Lake Calumet. The isotopic composition of precipitation in the study area is assumed to be identical to that of Midway. The $\delta^{2}H$ and $\delta^{18}O$ in precipitation at Midway Airport are lowest in January (mean values of –13.5 and –95.3 $^{o}/_{oo}$, respectively), when air temperatures are coolest, and highest in July (–2.4 and –17.2 $^{o}/_{oo}$, respectively), when air temperatures are warmest (fig. 13). The values of $\delta^{2}H$ and $\delta^{18}O$ in precipitation show a significant (R^2 [root mean square] of 0.80 or greater) direct correlation with the average monthly air temperature. During 1962 through 1978, the $\delta^{18}O$ values for the precipitation samples at Midway Airport ranged from 2.5 to –22.6 $^{o}/_{oo}$, and the $\delta^{2}H$ values ranged from 4.9 to –165.3 $^{o}/_{oo}$. The weighted mean $\delta^{18}O$ value for all precipitation was –6.9 $^{o}/_{oo}$, and the weighted mean $\delta^{2}H$ value was –43 $^{o}/_{oo}$ (Harvey, 2001). Plotting values of $\delta^{2}H$ with $\delta^{18}O$ in precipitation at Midway Airport (fig. 14) shows a significant (R^2 value of 0.96) direct covariance in the hydrogen and oxygen

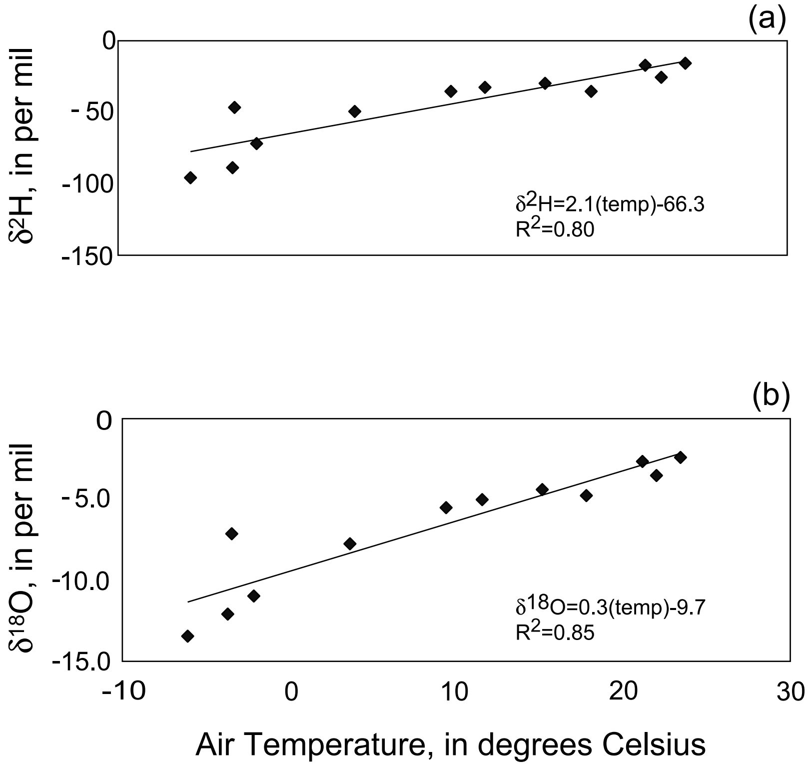


Figure 13. The hydrogen (a) and oxygen (b) isotopic composition of precipitation relative to monthly air temperature at Midway Airport, Chicago, Ill., 1962-1979.

isotopic composition of precipitation in the study area, described by the equation

$$\delta^2H = 6.9\delta^{18}O + 0.08\ ^{o}/_{oo}.$$

This equation describes the local meteoric water line (LMWL) and provides a reference with which the isotopic composition of the ground water in the region can be evaluated.

In shallow ground-water systems with temperatures less than 50^{o}C, such as are present in the study area, the isotopic compositions of δ^2H and $\delta^{18}O$ in water are not affected by water/rock interactions (Perry and others, 1982), and these stable isotopes can be used as natural tracers. Differences in the isotopic composition of ground water and precipitation, therefore, can be used to detect differences in the source water.

Plotting values of δ^2H with $\delta^{18}O$ for ground water and Lake Michigan samples shows that most of the samples plot near the LMWL (fig. 15). The δ^2H and $\delta^{18}O$ values for Lake Michigan at Calumet Harbor (–43.2 and –5.7 $^{o}/_{oo}$, respectively) are similar to the values of –45 $^{o}/_{oo}$ for δ^2H and –5.9 $^{o}/_{oo}$ for $\delta^{18}O$ reported by Machavaram and Krishnamurthy (1995) from southeastern Lake Michigan. These values also are similar to the weighted mean value in precipitation measured at Midway Airport.

The δ^2H values in samples from wells open to the water table ranged from –41.9 to –71.3 $^{o}/_{oo}$ (table 2, fig. 16). The $\delta^{18}O$ values in samples from wells open to the water table ranged from –5.4 to –11.6 $^{o}/_{oo}$. The geometric mean of the δ^2H (–48.1 $^{o}/_{oo}$) and $\delta^{18}O$ (–7.0 $^{o}/_{oo}$) values in the samples from wells open to the water table in the western part of the study area are substantially heavier than the geometric mean of the δ^2H (–66.9 $^o/_{oo}$) and δ^{18}O (–9.9 $^o/_{oo}$) values in the samples from the water-table wells in the eastern part.

The δ^2H values in samples from wells open to the middle or the base of the Calumet aquifer (all wells open to the middle or the base of the Calumet aquifer are west of Wolf Lake and designated as Hydrologic unit "CA" in table 1) ranged from –63.4 to –76.3 $^o/_{oo}$ (table 2, fig. 16). The δ^{18}O values in samples from wells open to the middle or the base of the Calumet aquifer ranged from –9.0 to –9.7 $^o/_{oo}$ (fig. 16). The geometric means of δ^2H and δ^{18}O for samples open to the middle and base of the aquifer were –66.3 $^o/_{oo}$ and –9.4 $^o/_{oo}$, respectively.

The geometric mean of the δ^2H and δ^{18}O values in the samples from wells open to the water table in the Calumet aquifer in the eastern part of the study area are nearly identical to the geometric mean of the δ^2H and δ^{18}O values in the samples from wells open to the middle and the base of the Calumet aquifer in the eastern part of the study area (fig. 16).

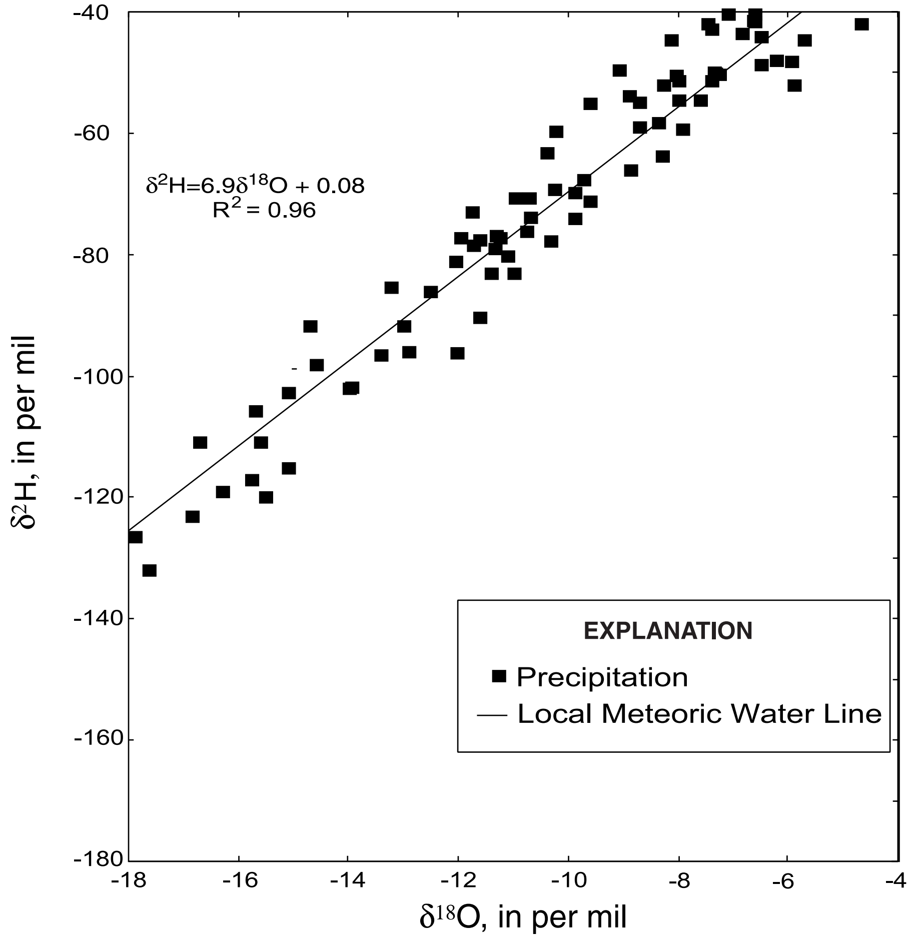


Figure 14. Isotopic composition of precipitation at Midway Airport, Chicago, Ill., 1962-1979.

A transect of nested wells at the Bairstow landfill were selected for the measurement of δ^2H and $\delta^{18}O$ values. The Bairstow site is part of a former steel-slag landfill near the central part of the study area. With one exception, the isotopic measurements occurred within a limited range of values (–65.3 to –71.3 $^{o}/_{oo}$ δ^2H and –8.4 to –10.2 $^{o}/_{oo}$ $\delta^{18}O$) (fig. 17). The δ^2H at one site (BH32S) was –76.3 $^{o}/_{oo}$.

All wells open to the middle or the base of the confining unit are in the western part of the study area. The δ^2H values in samples from wells open to the middle or the base of the confining unit ranged from –43.9 to –74.2 $^{o}/_{oo}$ (fig. 18). Values of $\delta^{18}O$ in samples from wells open to the middle or the base of the confining unit ranged from –5.7 to –12.2 $^{o}/_{oo}$. Values of δ^2H and $\delta^{18}O$ in these samples show a range along the meteoric water line.

Values of δ^2H and $\delta^{18}O$ in ground water from the confining unit (fig. 15) show a covariance in the hydrogen and oxygen isotopic composition described by the equation

$$\delta^2H = 6.95\delta^{18}O + 0.009\ ^{o}/_{oo}.$$

The equation is similar to that of the LMWL.

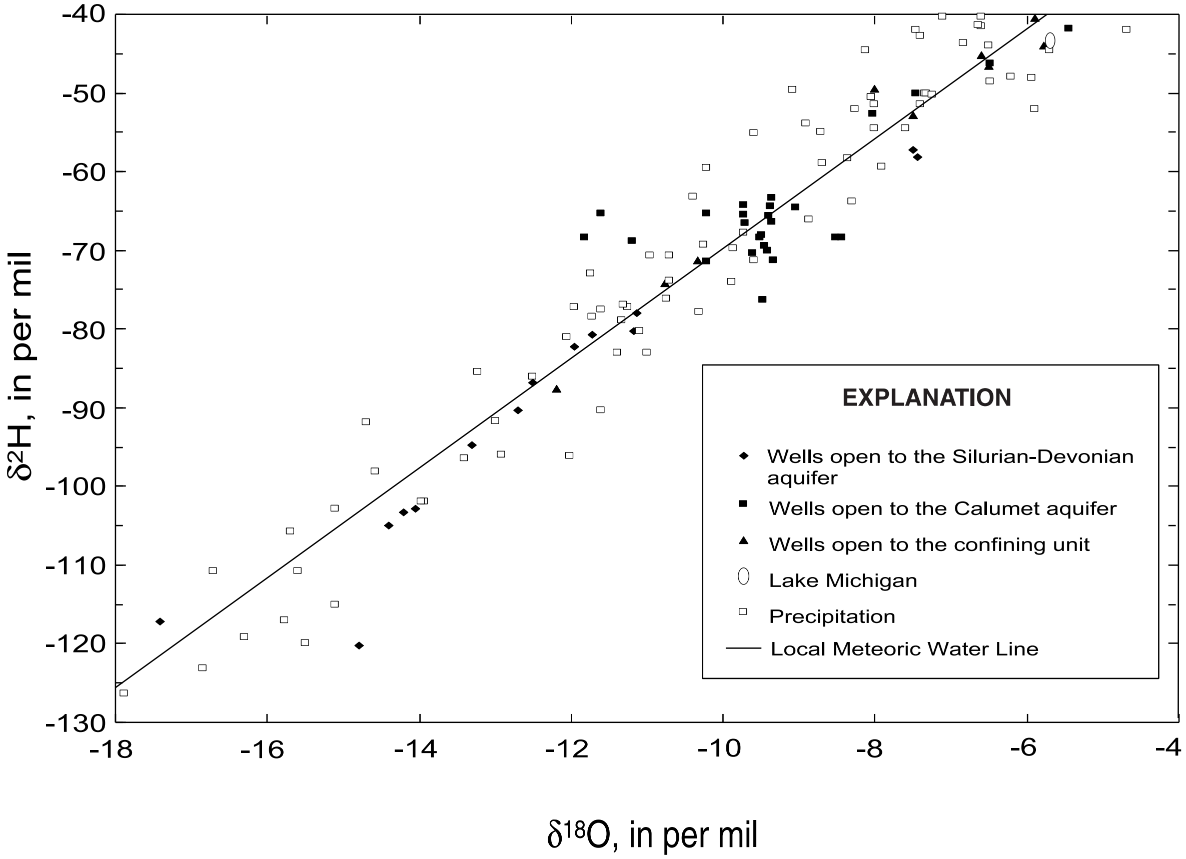
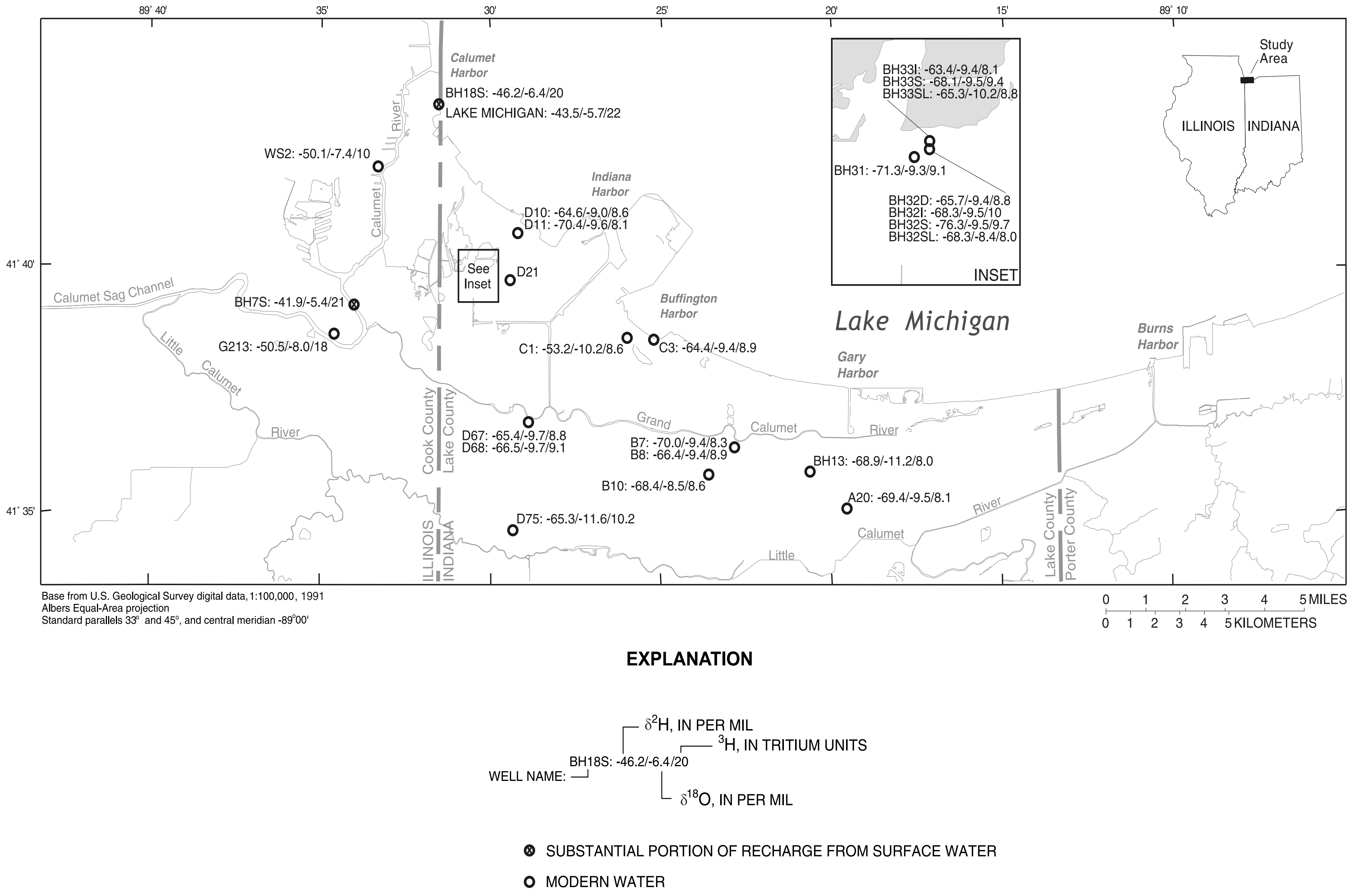


Figure 15. Isotopic composition of ground water, precipitation, and lake water, Calumet region of northwestern Indiana and northeastern Illinois, July 1997–February 2001.



Base from U.S. Geological Survey digital data, 1:100,000, 1991
Albers Equal-Area projection
Standard parallels 33° and 45°, and central meridian -89°00'

Figure 16. The del deuterium (δ^2H), del oxygen-18 (δ^{18}O), and tritium (^{3}H) values in water samples from the Calumet aquifer, Calumet region of northwestern Indiana and northeastern Illinois, July 1997–February 2001.

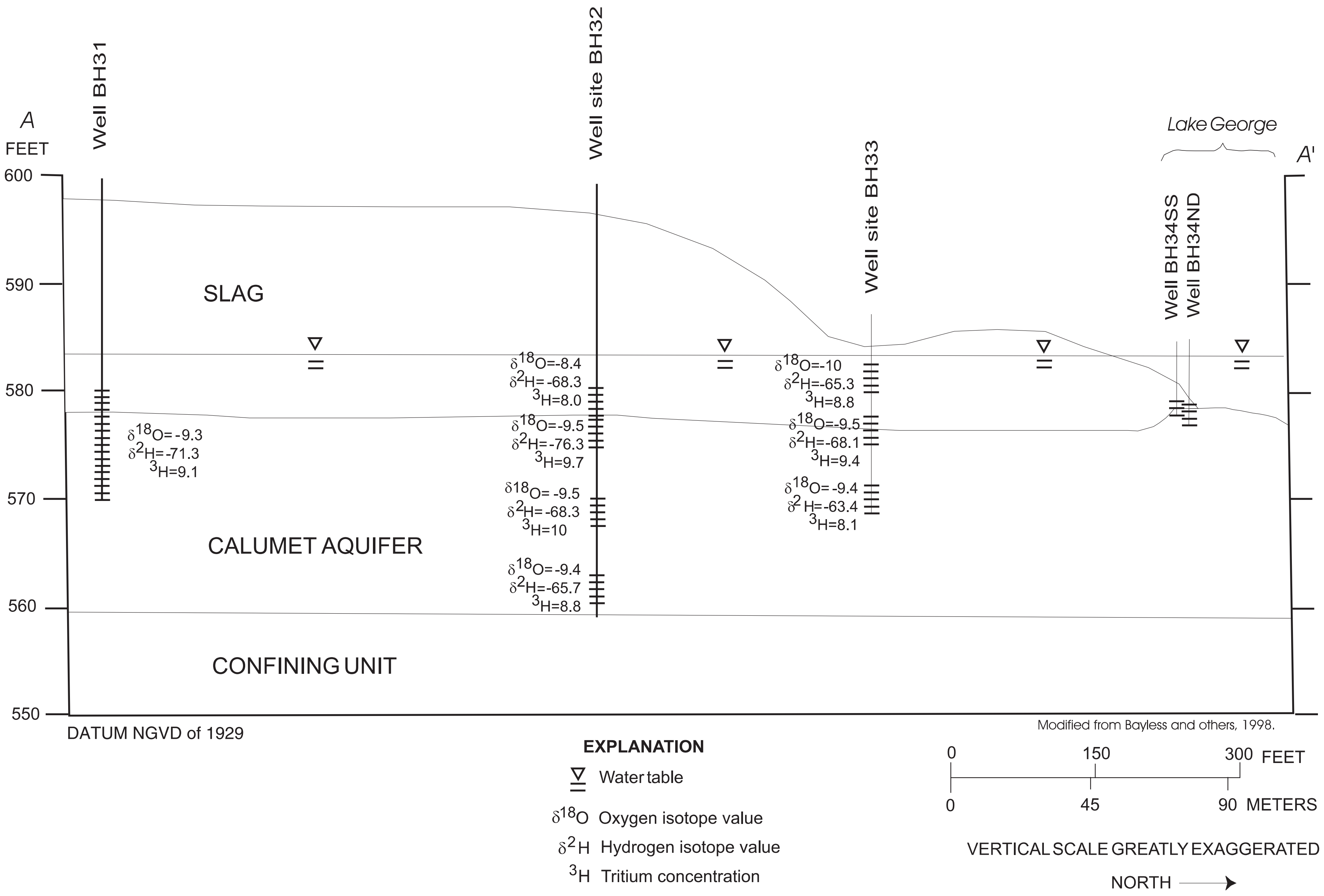
Table 2. Isotope data for sites in the study area, northwestern Indiana and northeastern Illinois

[δ, del notation; ^{2}H, hydrogen-2; ^{18}O, oxygen-18; ^{3}H, hydrogen-3; ^{3}He, helium-3; per mil, parts per thousand; --, no data; <, less than; DUP, quality-assurance replicate sample; U, unsuccessful attempt to measure ground-water age]

Well name	^{3}H (tritium units)	δ^{2}H (per mil)	δ^{18}O (per mil)	^{3}H/^{3}He age (years at date of sample collection)	^{3}H/^{3}He age error (years)
A20	8.1	-69.4	-9.5	7.16	0.39
B7	8.3	-70.0	-9.4	1.71	.45
B8	8.9	-66.4	-9.4	6.71	.32
B8 (DUP)	8.9	-67.5	-9.6	5.96	.31
B10	8.6	-68.4	-8.5	3.59	.39
BH1D	10	-49.5	-8.0	U	--
BH1S	13	-52.7	-8.0	--	--
BH7D	<.78	-103	-14.2	--	--
BH7I	8.9	-45.2	-6.6	U	--
BH7S	21	-41.9	-5.4	--	--
BH13	8.0	-68.9	-11	6.20	.33
BH16D	4.0	-90.3	-12	--	--
BH18D	<.78	-58.1	-7.4	--	--
BH18D (DUP)	<.78	-57.3	-7.5	--	--
BH18I	.90	-43.9	-5.7	U	--
BH18S	20	-46.2	-6.4	--	--
BH31	9.1	-71.3	-9.3	--	--
BH32D	8.8	-65.7	-9.4	--	--
BH32D (DUP)	8.8	-70.2	-9.4	--	--
BH32I	10	-68.3	-9.5	--	--
BH32S	9.7	-76.3	-9.5	--	--
BH32SL	8.0	-68.3	-8.4	--	--
BH33I	8.1	-63.4	-9.4	--	--
BH33S	9.4	-68.1	-9.5	--	--
BH33SL	8.8	-65.3	-10	--	--

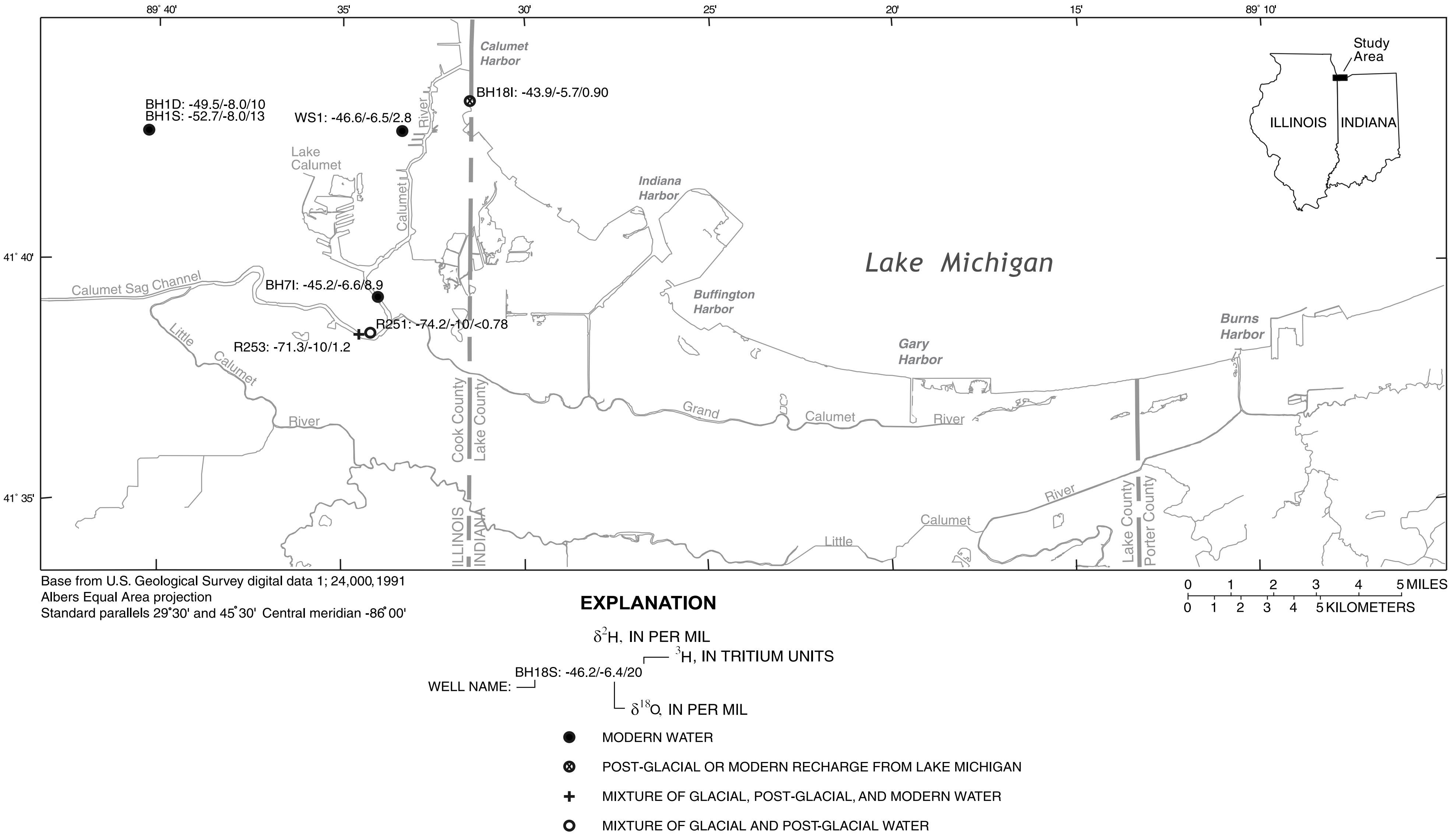
Table 2. Isotope data for sites in the study area, northwestern Indiana and northeastern Illinois—Continued

Well name	^3H (tritium units)	δ^2H (per mil)	$\delta^{18}O$ (per mil)	$^3H/^3He$ age (years at date of sample collection)	$^3H/^3He$ age error (years)
BR1	1.5	-120	-14	--	--
BR2	.19	-102	-14	--	--
BR3	1.4	-117	-17	--	--
BR4	.78	-150	-20	--	--
BR5	.31	-140	-19	--	--
C1	8.6	-53.2	-10	U	U
C3	8.9	-64.4	-9.4	15.89	.22
D10	8.6	-64.6	-9.0	--	--
D11	8.1	-70.4	-9.6	U	--
D21	9.4	-64.2	-9.7	U	U
D67	8.8	-65.4	-9.7	U	U
D68	9.1	-66.5	-9.7	9.95	.29
D68 (DUP)	--	--	--	9.90	.30
D75	10	-65.3	-11	U	--
FILO102-5	2.0	-82.2	-11	--	--
FILO102D	<.78	-80.8	-11	--	--
GO5D	1.3	-86.8	-12	--	--
G213	18	-50.5	-8.0	--	--
G218	<.78	-105	-14	--	--
IC	<.78	-80.2	-11	--	--
IC (DUP)	<.78	-78.0	-11	--	--
IP	<.78	-94.7	-13	--	--
R251	<.78	-74.2	-10	--	--
R253	1.2	-71.3	-10	--	--
ST1D	4.2	-99.0	-13	--	--
ST4D	6.9	-63.6	-9.5	--	--
WS1	2.8	-46.6	-6.5	--	--
WS2	10	-50.1	-7.4	--	--
Lake Michigan	22	-43.5	-5.7	--	--



Modified from Bayless and others, 1998.

Figure 17. Hydrogen and oxygen isotopic composition (in per mil - 0/00) and tritium concentrations (in tritium units -TU) of ground water through a transect at Bairstow Landfill, Hammond, Ind., July 1997.



Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

Figure 18. The del deuterium (δ^2H), del oxygen-18 ($\delta^{18}O$), and tritium (^3H) values in water samples from the confining unit, Calumet region of northwestern Indiana and northeastern Illinois, July 1997–February 2001.

The δ^2H and $\delta^{18}O$ values in ground water from unconsolidated wells indicated a possible inverse relation with well depth (fig. 19). Isotopic values in wells in the eastern and central parts of the study area generally showed a slight decrease in δ^2H and $\delta^{18}O$ with depth. Isotopic values showed a greater decrease with increasing well depth for ground water in the western part of the study area.

The δ^2H values in samples from wells open to the top of the Silurian-Devonian aquifer ranged from –58.1 $^o/_{oo}$ near Lake Michigan at the Illinois/Indiana State line, to –150.4 $^o/_{oo}$ near Lake Michigan between Gary Harbor and Indiana Harbor (table 2, fig. 20). The $\delta^{18}O$ values ranged from –7.45 $^o/_{oo}$ to –20.06 $^o/_{oo}$ in the same wells, respectively. Values of δ^2H and $\delta^{18}O$ in ground-water samples from the Silurian-Devonian aquifer show a significant (R^2 value of 0.96) direct covariance described by the equation

$$\delta^2H = 7.32\delta^{18}O + 0.917.$$

Tritium

Tritium (^3H) is a radioactive form of the hydrogen atom that contains a proton and two neutrons and has a half-life of 12.3 years (Freeze and Cherry, 1979, p. 82). Tritium concentrations are measured by counting the rate of beta (electron) emissions associated with neutron decay and are expressed as absolute concentrations, using tritium units (TU). A tritium unit is the equivalent of 1 tritium atom for every 10^{18} atoms of hydrogen. For 1 liter of water, 1 TU is equivalent to 0.12 disintegrations per second.

Tritium is produced naturally by the bombardment of nitrogen in the atmosphere by cosmic radiation (Grosse and others, 1951). Atmospheric tritium and oxygen then combine to form water, which enters the ground-water system as precipitation. Although few measurements are available, it is estimated that the natural concentration of tritium in precipitation is between 5 and 20 TU (Kauffman and Libby, 1954).

Tritium also was created as a by-product of atmospheric testing of thermonuclear bombs from 1951 through 1980, particularly from 1951 through 1962 (Clark and Fritz, 1997). Tritium concentrations in precipitation have been measured monthly at a site in Ottawa, Canada, since 1952. Tritium concentrations at Ottawa varied on a monthly basis but showed a general increase from about 12 TU in early 1953 to about 6,000 TU in 1963 (Plummer and others, 1993). Tritium concentrations in precipitation at the Ottawa site have decreased since 1963. By about 1990, anthropogenic tritium had been removed from the atmosphere and tritium concentrations in precipitation had returned to near background levels.

Tritium concentrations in precipitation were measured at Midway Airport in Chicago from January 1962 through December 1979. Tritium concentrations at Midway Airport were greater than 700 TU for most of 1962 and reached a maximum of 3,572 TU in August 1963. Tritium concentrations in precipitation were less than 50 TU in 1979.

Changes in the amount of tritium in precipitation through time, radioactive decay, hydrodynamic dispersion, and mixing water of different ages in the subsurface typically preclude the use of this isotope for quantitatively estimating ground-water residence times. In many cases, qualitative observations may be the best use of tritium data (Clark and Fritz, 1997). The most accurate use of the data is to indicate pre- or post-1952 ground-water recharge. For a well-defined hydrologic system, analysis of the tritium-input function may provide sufficient information to make quantitative age estimates for ground water in the system. More-complex flow systems generally require more-complex models to quantitatively use the tritium data (Plummer and others, 1993). Time-sequence data and multi-depth samples also are required to accurately date ground-water horizons using tritium data. The $^3H/^3He$ method was developed to remove the ambiguity associated with tritium-age estimation.

To maximize the usefulness of the tritium data collected for this study, ground-water ages were estimated with general guidelines provided by Clark and Fritz (1997). The guidelines assume that a piston-flow model (Clark and Fritz, 1997) is applicable to the hydrologic system and, correlatively, no dispersion or mixing occurs (Plummer and others, 1993). For this study, the validity of

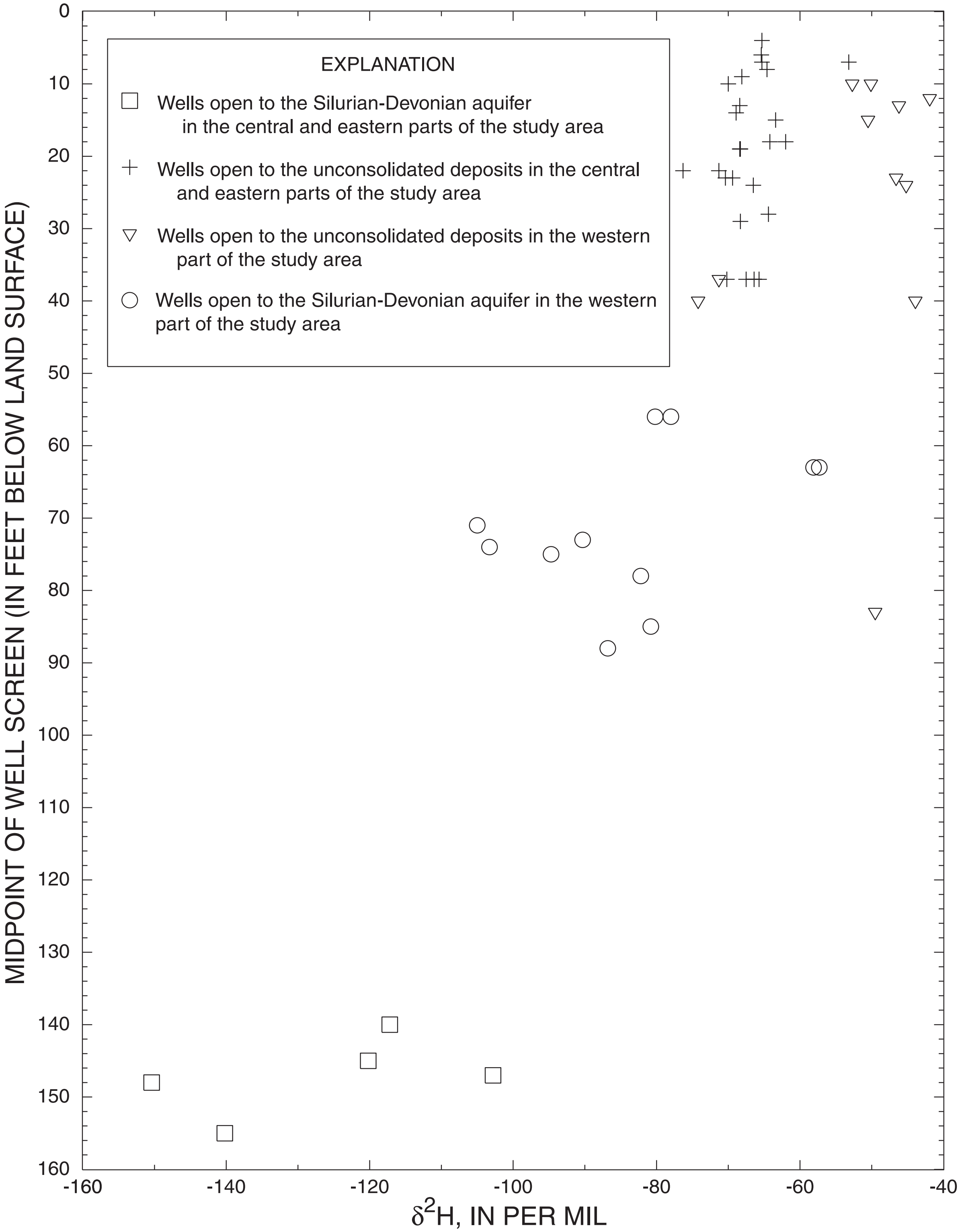
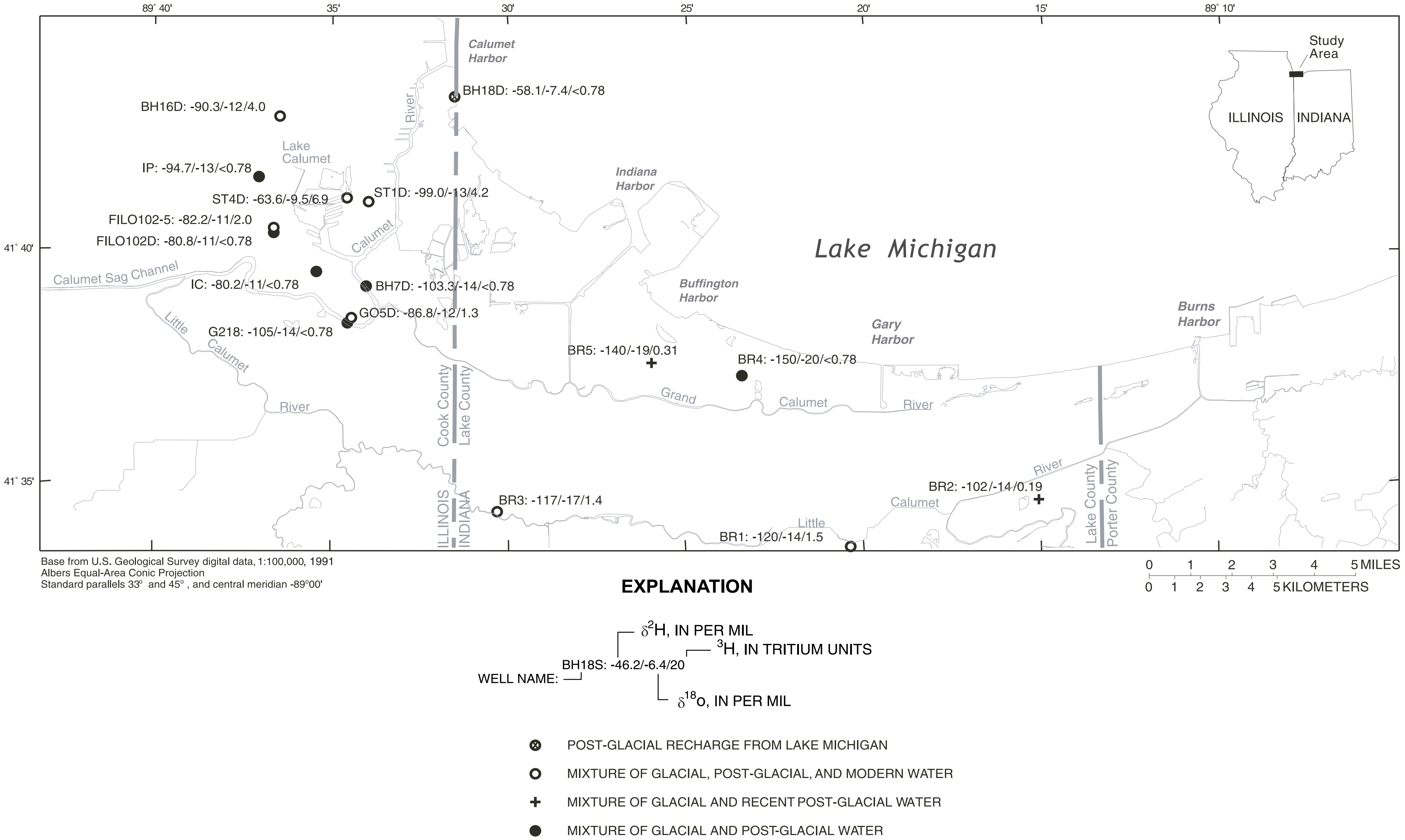


Figure 19. Hydrogen isotope composition and depth for samples from wells of the Calumet region in northwestern Indiana and northeastern Illinois, July 1997-February 2001.



Base from U.S. Geological Survey digital data, 1:100,000, 1991
Albers Equal-Area Conic Projection
Standard parallels 33° and 45°, and central meridian -89°00'

Figure 20. The del deuterium (δ^2H), del oxygen-18 ($\delta^{18}O$), and tritium (^3H) values in water samples from the Silurian-Devonian aquifer, Calumet region of northwestern Indiana and northeastern Illinois, July 1997–February 2001.

these assumptions varied across sites and between hydraulic units. Where tritium data are used to estimate ground-water age, the hydrologic setting also is described so that the appropriateness of the assumptions can be assessed.

The Clark and Fritz (1997) guidelines indicate that ground water underlying regions with continental climates containing less than 0.8 TU recharged the water table prior to 1952. Water with 0.8 to 4 TU may represent a mixture of water that contains components of recharge from before and after 1952. Tritium concentrations from about 5 to 15 TU may indicate recharge after about 1987. Tritium concentrations between about 16 and 30 TU are indicative of recharge since 1953 but cannot be used to provide a more specific time of recharge. Water with more than 30 TU probably is from recharge in the 1960s or 1970s, whereas water with more than 50 TU predominately is from recharge in the 1960s.

The highest tritium concentration (22 TU) measured during this study was in water from the surface of Lake Michigan near the Indiana/Illinois State line (table 2). Water from Lake Michigan is a composite from various water sources with a variety of ages.

Tritium concentrations in samples from wells open to the water table were 8.0 TU or greater in the study area. Tritium concentrations in wells open to the water table in the eastern part of the study area ranged from 8.0 to 10.2 TU (fig. 21) and may indicate ground water recharged since 1987. Tritium concentrations in wells open to the middle and deeper parts of the Calumet aquifer ranged from 8.1 to 10.3 TU (fig. 21), virtually identical to the range at water table for this area. Tritium concentrations in wells open to the water table in the western part of the study area ranged from 10 to 21 TU, indicating water with substantially varying ages (fig. 21).

Tritium concentrations in samples from wells open to the middle or base of the confining unit in the western part of the study area ranged from less than the detection limit to 10 TU (fig. 21). Tritium concentrations did not show a direct correlation with depth in the confining unit; however, tritium concentrations in wells screened below 40 ft are generally lower than tritium concentrations in wells screened above 40 ft.

Tritium concentrations in samples from wells open to the Silurian-Devonian aquifer ranged from less than the detection limit to 4.0 TU (fig. 21). Tritium concentrations in the Silurian-Devonian aquifer were 4 TU or greater in the three samples collected in the approximate area between Stony Island and the eastern part of Lake Calumet.

Helium

Radioactive decay of tritium produces the noble gas helium-3 (^{3}He). Determination of the ^{3}H/^{3}He ratio, therefore, can be used to estimate the apparent date when a sample of water entered the aquifer as recharge. Because these substances virtually are inert in ground water, unaffected by ground-water chemistry, and not derived from contamination from most of the typical anthropogenic sources, H^{3}/He^{3} dating can be applied to a wide range of hydrologic investigations (Schlosser and others, 1989; Aeschbach-Hertig and others, 1998; Ekwurzel and others, 1994; Solomon and others, 1995; Sheets and others, 1998; Stute and others, 1997; Dunkle-Shapiro and others, 1998). The ^{3}H/^{3}He method has been used to corroborate the results of other age-dating methods, such as chlorofluorocarbons (Ekwurzel and others, 1994; Szabo and others, 1996) and krypton 85 (^{85}Kr) (Ekwurzel and others, 1994). The ^{3}H/^{3}He method also has been used to provide information for site characterization (Solomon and others, 1995; Aeschbach-Hertig and others, 1998) and to assist with the calibration and interpretation of ground-water-flow models (Sheets and others, 1998; Szabo and others, 1996).

The ^{3}H/^{3}He method was used in an attempt to measure apparent age dates of water from the Calumet aquifer at 12 sites in Indiana and from the confining unit at 3 sites in Illinois. Analytical evidence indicated that data were unreliable at 5 of the 12 sites in Indiana and all of the sites in Illinois. Apparent ground-water ages at the eight remaining sites from the Calumet aquifer ranged from 1.71 to 15.9 years (fig. 22 and table 2). The median

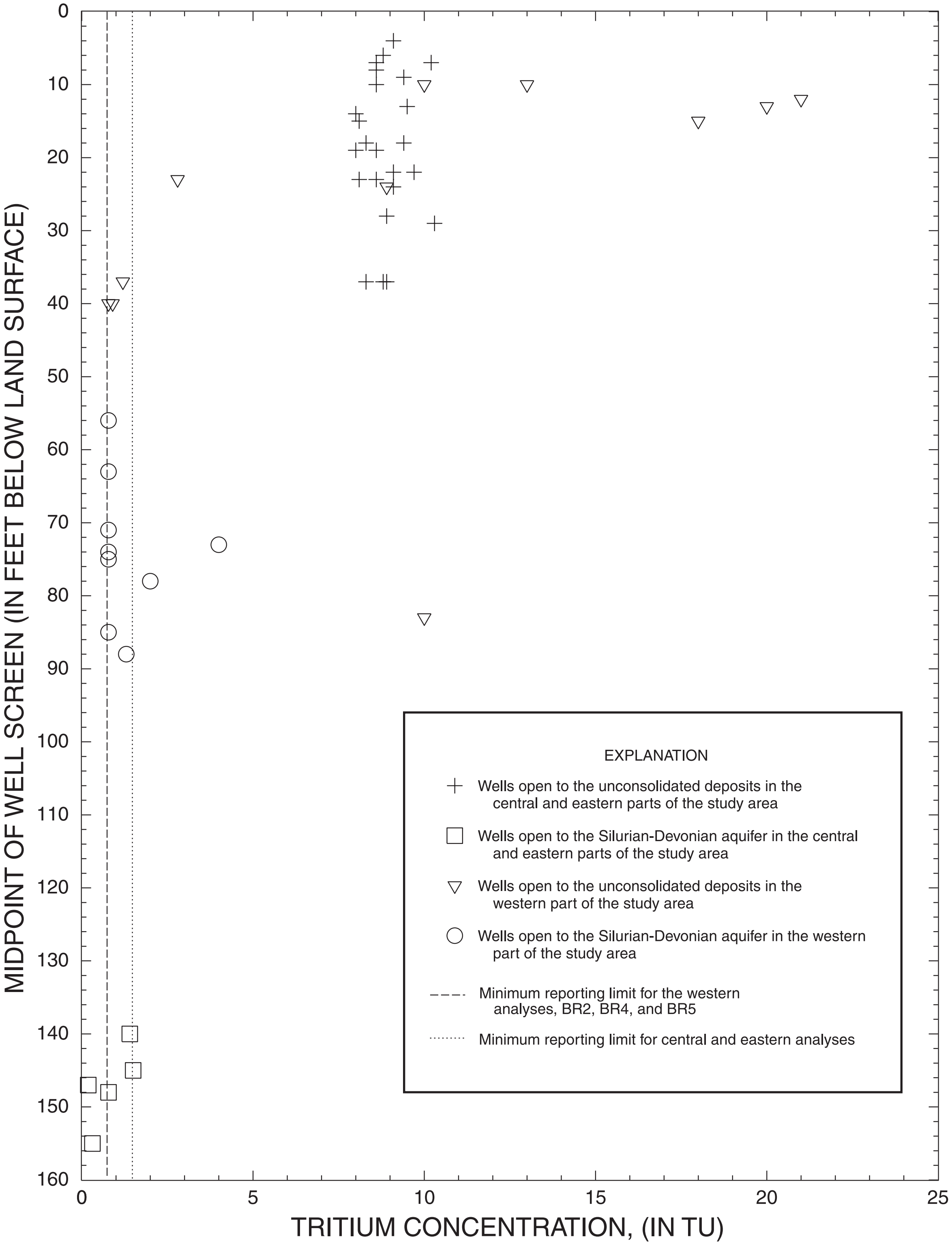


Figure 21. Tritium concentrations and depth for samples from wells of the Calumet region in northwestern Indiana and northeastern Illinois, July 1997–February 2001.

and mean ages were 6.00 and 6.71 years, respectively. The helium results are consistent with the interpretations made from the analysis of tritium concentrations.

Apparent ground-water ages in the Calumet aquifer between the Grand Calumet River and the Little Calumet River in Indiana vary from 1.71 years in water from a 9-ft well near the Grand Calumet River (B7) to 9.95 years at a 21-ft well near the Grand Calumet River (D68). Intermediate values are present at various points along the flowpath. Intermediate-age values were measured in water from wells B8 (6.71 years) and B10 (3.59 years); wells B7, B8, and B10 are along a possible ground-water flowpath. The apparent age of ground water in the Calumet aquifer in the one sample collected between the Grand Calumet River and Lake Michigan was 15.9 years in water from a depth of 26 ft near Lake Michigan.

The complex ground-water hydrology of the study area makes delineating a complete flowpath a difficult task. Fenelon and Watson (1993) identified leaky sewers, pump-and-treat systems, industrial discharges, and inflow from the bedrock aquifer as factors that made calibration of a numerical model impossible in the study area. Ground-water/surface-water interactions along the Lake Michigan shoreline, ship canals, streams, and ditches likely also cause perturbations to ground-water flowpaths. The flowpaths used to examine the $^3H/^3He$ ages were based on ground-water levels measured during June 1992 (Kay and others, 1996) and may be affected by seasonal changes and other factors discussed above.

Although water near discharge points in the Calumet aquifer tends to have a younger apparent age than water near the ground-water divides, there is no straightforward relation between apparent ground-water age and distance along the apparent flowpath. Various factors could explain this relation, including sparse data density, complicated flow systems, unidentified sources of tritium, and mixing of shallow and deep ground water. Data density would have to be increased throughout the study area to take full advantage of dating methods. Some of the wells sampled in the eastern part of the study area (such as A20-BH13-B8-B7 or B10-B8-B7) could be along a ground-water flowpath, but the well depths do not conform to a single ground-water flowpath. Wells must be located specifically along a probable flowpath to allow the examination of ground-water transport and water-quality evolution; the well network used for this data-collection effort was not designed to serve this purpose.

Recharge and Sources of Ground Water

The isotopic compositions of ground water in the hydrogeologic units of concern were examined to determine the recharge and sources of water to each unit. In so doing, some information was gleaned about the flowpath the ground water used to reach that destination.

Calumet Aquifer

The concentrations of tritium and helium and the oxygen and hydrogen isotopic composition indicate that water in the Calumet aquifer is derived from modern (post-1952) precipitation. The similarity of δ^2H and $\delta^{18}O$ and tritium values in water from wells screened at various intervals in the Calumet aquifer indicates a uniform source of water and a relatively rapid flow through the aquifer in the eastern part of the study area. Some of the variability in the isotopic composition in the aquifer may result from differences in the amount of recharge from Lake Michigan and other surface-water bodies, the seasonal timing of recharge from precipitation, flow rates, and flow patterns.

A transect of nested piezometers located immediately south of Lake George (fig. 17) illustrates the distribution of isotopes in the Calumet aquifer (figs. 16 and 17). Well BH31 and the BH32 and BH33 well clusters are open to various depths in the Calumet aquifer and are aligned along a single short flowpath near Lake George. Water samples from well clusters BH32 and BH33 have δ^2H values approximately –65 $^o/_{oo}$, with the exception of well BH32SL that has a δ^2H value of –76.3 $^o/_{oo}$. The $\delta^{18}O$ values in samples from the same wells are about –9.45 $^o/_{oo}$, with the exception of BH32S

(–8.4513 $^{o}/_{oo}$) and BH33S (–10.22 $^{o}/_{oo}$). Tritium concentrations similarly are uniform in water from the Lake George transect wells. The similarity of isotope values in ground water at the Lake George transect indicates that water in the Calumet aquifer is well mixed but that geologic heterogeneities (in combination with small fluctuations in the isotopic composition of recharge) may affect the measured isotope values.

The isotopic data indicate that some parts of the Calumet aquifer may be affected by recharge from adjacent surface-water bodies in the western part of the study area. Wells BH7S and BH18S are within 50 ft of the Calumet River and Lake Michigan, respectively. The concentration of tritium and the δ^{2}H and δ^{18}O values in the ground-water samples from wells BH7S and BH18S are similar to that of Lake Michigan and are noticeably different from almost every other sample from the Calumet aquifer. These patterns indicate that ground water at wells BH18S and BH7S is comprised primarily of water recharged to the ground-water system from Lake Michigan and the Calumet River.

The isotopic composition of well G213 varies from that in the remainder of the study area. Well G213 is open to the Calumet aquifer and is in the western part of the study area near the confluence of the Calumet and Grand Calumet Rivers. The tritium concentration in well G213 is elevated, which is consistent with recharge from surface water in this area. The δ^{2}H and δ^{18}O values of water from this well, however, are isotopically lighter than those in the water from Lake Michigan. It is possible that the high tritium at this well is the result of leachate from a landfill in the vicinity. Landfill leachate often contains elevated concentrations of tritium (Hackley and others, 1999).

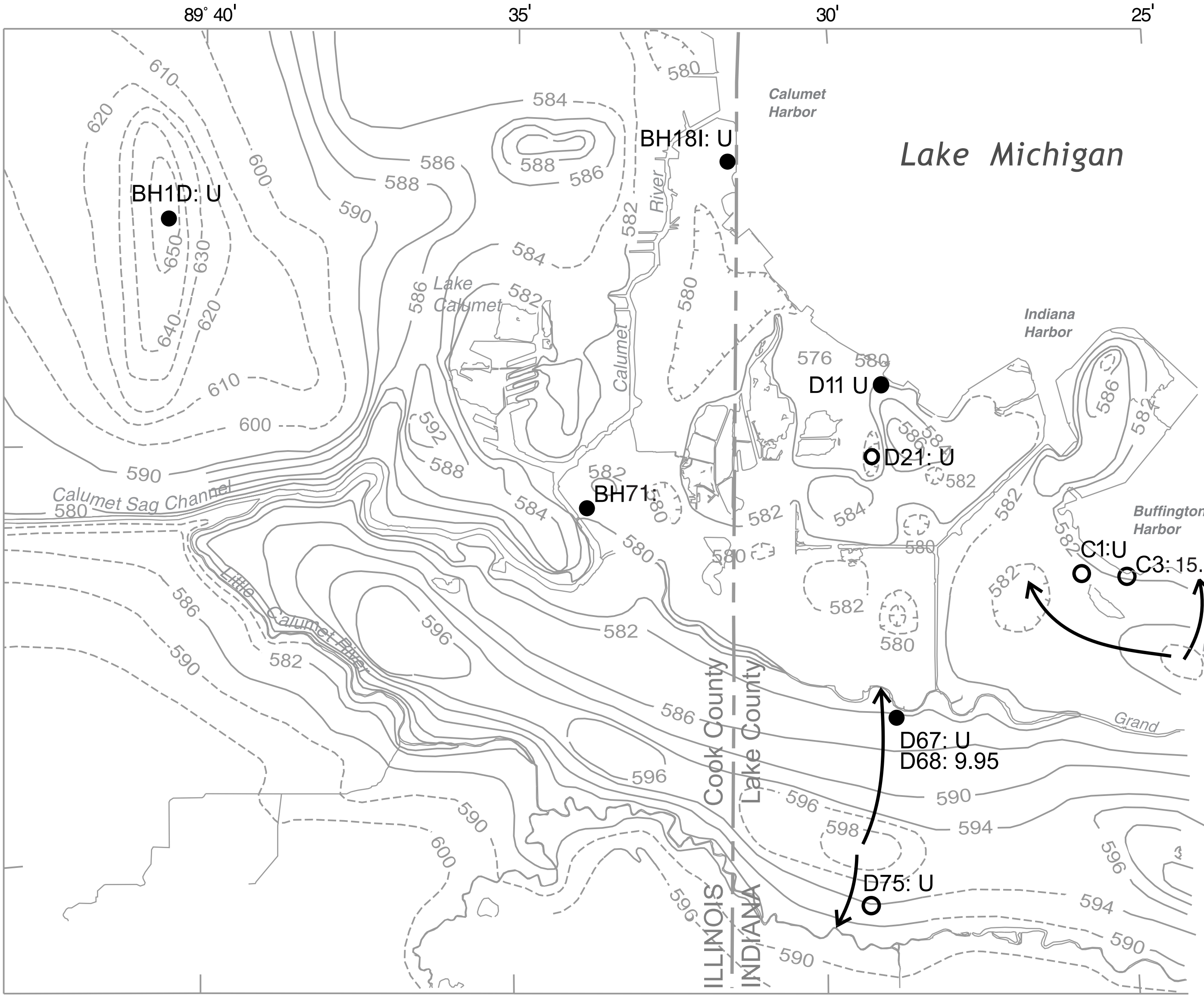
Analysis of the isotopic composition of well WS2 varies from that elsewhere in the study area. The tritium concentration in this well is consistent with values measured in the Calumet aquifer in the rest of the study area, but the δ^{2}H and δ^{18}O values are substantially heavier than elsewhere in the aquifer. The reason for these differences is not obvious.

Confining Unit

Potential sources of water to the confining unit include recharge from precipitation where the Calumet aquifer is absent, inflow from the Calumet aquifer and the Silurian-Devonian aquifer, and recharge from surface water. The concentration of tritium and the oxygen and hydrogen isotopic compositions indicate that water in the confining unit is derived from modern (post-1952) precipitation, pre-modern (before 1952 but less than 10,000 years before present) and perhaps “glacial-age” water from the Pleistocene Epoch (10,000 to 40,000 years before present). The variability of tritium concentrations and δ^{2}H and δ^{18}O values of water from wells screened at various depths in the confining unit indicates the potential for mixed sources of water and relatively slow rates of ground-water flow in the confining unit.

Most of the water in the confining unit contains more than 1 TU, which indicates the presence of modern water. With the exception of well BH1D, tritium concentrations in the confining unit decrease with increasing depth, indicating a decreasing percentage of modern water with depth in the confining unit. The sample from well R251 did not contain detectable tritium, indicating a pre-modern source of water.

The δ^{2}H and δ^{18}O values for water from well BH18I are virtually identical to the isotopic composition of the sample from Lake Michigan (table 2), indicating that the confining unit may be recharged locally by Lake Michigan. The presence of less than 1 (0.90) TU of tritium in the sample from well BH18I would indicate that the recharge from Lake Michigan of the confining unit occurred in 1952 or shortly thereafter. It seems probable that flow from Lake Michigan into the confining unit occurred sometime after 1952, given the fact that precipitation with elevated concentrations of tritium would require some time to accumulate in the lake. Recharge from Lake Michigan to the confining unit is likely a response to dewatering of the Silurian-Devonian aquifer and subsequent declines in the potentiometric surface in the confining unit.



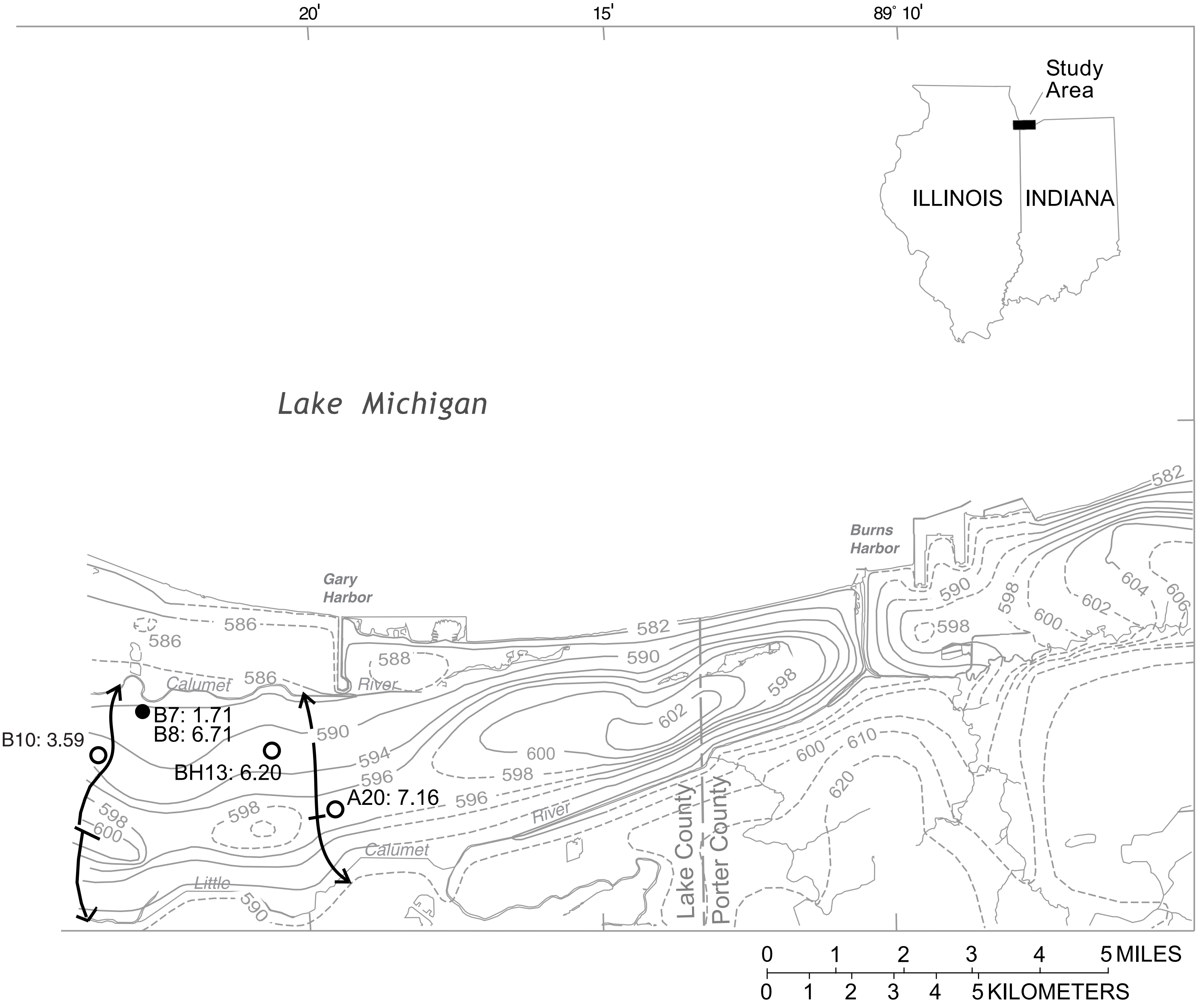
Base from U.S. Geological Survey digital data 1; 24,000, 1991
Albers Equal Area projection
Standard parallels 29°30' and 45°30' Central meridian -86°00'

EXPLANATION

—606- - - WATER-TABLE CONTOUR-Shows altitude of water table. Dashed where approximate. Contour interval variable. Datum NGVD of 1929

⟼ FLOW DIRECTION OF GROUND WATER

Figure 22. Apparent ground-water age in the Calumet aquifer, Calumet region of northwestern Indiana and northeastern Illinois, July 1997–February 2001.



B10: 3.59	WELL NAME: [^{3}H]/[^{3}He] AGE, IN YEARS
○	Single monitoring well
●	Paired monitoring wells
U	Age measurement was attempted but unsuccessful

The tritium concentration in ground water at well BH1D indicates that water has recharged the confining unit since 1987. Well BH1D is near a ground-water divide in the western part of the study area. A large component of vertical flow, common near ground-water divides, may explain the occurrence of relatively young ground water at depth in the confining unit at BH1D.

The $\delta^{2}H$ and $\delta^{18}O$ values in the middle and deeper parts of the confining unit generally are lighter than at the water table in the western part of the study area and show a clear tendency to decrease with depth. Samples collected from wells with a depth less than about 25 ft tend to have an isotopic composition similar to that of the water table in the western part of the study area and are likely to be completely modern water. Samples collected from wells deeper than 30 ft have $\delta^{2}H$ and $\delta^{18}O$ values that are substantially lighter than the values from water-table wells in the western part of the study area. These results are consistent with data from Hackley and others (1999), who examined $\delta^{2}H$ and $\delta^{18}O$ values at a cluster of wells in the northeastern part of Lake Calumet.

Tritium concentrations and $\delta^{2}H$ and $\delta^{18}O$ values indicate an increasing component of glacial-age water with depth in most of the confining unit. The confining unit may have received recharge primarily from the underlying Silurian-Devonian aquifer in the past. The prevailing flow direction, however, probably has been reversed by declining hydraulic heads in the Silurian-Devonian aquifer and the confining unit now is recharged primarily from precipitation, the Calumet aquifer, and surface water.

Silurian-Devonian Aquifer

Previous investigators examining $\delta^{2}H$ and $\delta^{18}O$ trends in the Cambrian-Ordovician aquifer system in north-central Illinois have attributed light $\delta^{2}H$ and $\delta^{18}O$ values found in the Chicago area to glacial-age recharge from the Pleistocene Epoch (Perry and others, 1982; Siegel and Mandle, 1984). In a study of Lake County Silurian-Devonian bedrock wells by Hasenmueller and others (2001), the $\delta^{2}H$ (–148 to –90 $^{o}/_{oo}$) and $\delta^{18}O$ (–19 to –12 $^{o}/_{oo}$) values were interpreted as indicating the presence of glacial-age water. The comparatively light $\delta^{2}H$ and $\delta^{18}O$ values that characterize much of the Silurian-Devonian bedrock aquifer in the study area probably reflect the presence of glacial-age water. Similarly light values were not observed in the Calumet aquifer or most of the confining unit.

In some wells open to the Silurian-Devonian aquifer, the aquifer appears to contain a large fraction of water with glacial-age origins. Water from wells BR4 (–150 $^{o}/_{oo}$ $\delta^{2}H$ and –20 $^{o}/_{oo}$ $\delta^{18}O$) and BR5 (–140 $^{o}/_{oo}$ $\delta^{2}H$ and –19 $^{o}/_{oo}$ $\delta^{18}O$) isotopically is depleted relative to other Silurian-Devonian wells in the network and probably contains a substantial amount of glacial-age recharge. Tritium values confirm that the water in the Silurian-Devonian aquifer beneath most of the study area was recharged prior to 1952.

In most wells open to the Silurian-Devonian aquifer, the $\delta^{2}H$ and $\delta^{18}O$ values of ground water generally are heavier than those measured in BR4 and BR5 and probably indicate a mixture of glacial-age water, post-glacial-age water, and modern recharge. The intermediate $\delta^{2}H$ and $\delta^{18}O$ values range from –80 to –105 $^{o}/_{oo}$ and from –11 to –14 $^{o}/_{oo}$, respectively, in the eastern and central part of the study area and from –102 to –120 $^{o}/_{oo}$ ($\delta^{2}H$) and –14.1 to –17.4 $^{o}/_{oo}$ ($\delta^{18}O$) in the western part. Data from this study indicate that samples from wells with intermediate $\delta^{2}H$ and $\delta^{18}O$ values most commonly occur where the confining unit is absent and may be related to leakage of stormwater runoff from the Water Reclamation District of Greater Chicago tunnel and reservoir project (TARP), improperly abandoned water-supply wells, natural mixing in response to hydraulic-head gradients, and landfill excavations into the Silurian-Devonian aquifer. Lake Michigan also may recharge the bedrock aquifer near Calumet Harbor.

The isotopic composition of bedrock well BH18D is similar to that of Lake Michigan and indicates that recharge to the bedrock through the confining unit may be occurring near this well. The absence of detectable concentrations of tritium in well BH18D indicates that the recharge is post-glacial but pre-modern.

The isotopic information indicates that some bedrock wells may contain a component of modern recharge. The presence of more than 1 TU of tritium and elevated values of δ^2H and δ^{18}O at wells BH16D, ST1D, ST4D, FILO102-5, and GO5D, for example, indicates the presence of primarily modern recharge. These wells are south (hydraulically downgradient) of Stony Island, and precipitation probably is directly recharging the aquifer where the confining unit is absent.

In addition to the presence of recharge from precipitation, intermediate δ^2H and δ^{18}O values and elevated tritium concentrations in the Silurian-Devonian aquifer at wells ST1D, ST4D, FILO102-5, and G05D may indicate facilitated transport through the confining unit. Well ST4D is near a landfill; the δ^2H and δ^{18}O values are –9.5 $^{o}/_{oo}$ and –63 $^{o}/_{oo}$, respectively, and the tritium concentration is 6.9 TU. The isotopic composition clearly indicates a modern component of ground water and may indicate enhanced recharge as a result of landfill excavation. Well ST1D is approximately 500 ft east of well ST4D and has similar isotopic characteristics. Bedrock well GO5D, near the Little Calumet River and a sanitary landfill, also shows a component of modern recharge. A nearby, improperly abandoned water-supply well may have affected the hydrology and isotopic values at well FILO102-5 (Ecology and Environment, Inc., 1990).

Some δ^2H and δ^{18}O values may indicate mixing of ground waters of various ages in response to flow along hydraulic-head gradients. The clustering of δ^2H data in plots of δ^2H with depth may indicate that ground water from some Silurian-Devonian wells in the western part of the study area is a mixture of water from shallower unconsolidated deposits and deeper, isolated bedrock aquifers like the Silurian-Devonian aquifer in the eastern and central part of the study area. Potentiometic data for the Silurian-Devonian aquifer may support the existence of an east-west flow component in some parts of the formation.

Hasenmueller and others (2001) also identified isotopic evidence that modern precipitation has mixed with glacial-age water in some parts of the bedrock aquifer. Ground water with isotopic signatures indicative of mixed Silurian-Devonian and Calumet aquifer ground water was identified near a regional ground-water divide in southern Lake County, Ind., farther to the east near Lake Michigan, and in areas with unconsolidated deposits that are underlain by the Antrim Shale (Hasenmueller and others, 2001).

Ground-Water-Flow Rates and Aquifer Vulnerability

The ground-water-isotope data were examined in the spatial context of the study area. In the classic model by Toth (1962), regional ground-water flowpaths in an aquifer system (without pumping or other human stresses) originate near a basin divide with a significant downward vertical component of flow. With distance from the divide, the vectors develop a dominantly horizontal component as water flows through the aquifer and beneath the basin. The flowpaths end with a substantial upward vertical component as ground water discharges to rivers, lakes, and wetlands. It should be expected, therefore, that the age of ground water in the Calumet aquifer generally increases with depth and distance along the flowpath.

Calumet Aquifer

Hydraulic and isotopic data indicate that water in the Calumet aquifer and at the water table in the confining unit is derived from precipitation that entered the ground-water system since 1987. The residence time for ground water in the Calumet aquifer probably is from 5 to 15 years, based on ^{3}H/^{3}He ages (5.27, 9.41, and 15.5 years) for samples collected from three wells near local discharge points. If the age of the ground water at the three wells near the surface-water bodies is divided by the distance from the ground-water divide to the well (2.3, 2.1, and 1.2 miles, respectively), ground-water velocity through the Calumet aquifer is estimated to be 1,200 and 2,300 ft/yr between the Tolleston Beach Ridge and the Grand Calumet River and 400 ft/yr in the area defined by the Indiana Harbor Canal, Lake Michigan, and Gary Harbor. These values are more than an order of magnitude greater than the ground-water velocities calculated from solution of the Darcy equation by Kay and others (1996).

The rapid ground-water-flow rates described above, the shallow water tables, the lack of an overlying confining unit, and the proximity to numerous sources of contamination, indicate that the Calumet aquifer is vulnerable to contamination. The relatively rapid ground-water-flow rates and short residence times in the aquifer, however, also demonstrate the potential for remediation in the event of aquifer contamination.

Confining Unit

Hydraulic and isotopic data indicate that water in the confining unit is derived from a variety of sources, including precipitation that has entered the aquifer since 1952, surface-water recharge, post-glacial and glacial-age water. At well BH7I, the confining unit is overlain by the Calumet aquifer, and tritium concentrations indicate that water in the confining unit is derived from (1) precipitation that recharged the aquifer since about 1987 and has not been subject to extensive dispersion or mixing, or (2) a mixture of ground waters in which at least one end member contains some post-1952 recharge. Elevated (above background) tritium concentrations in the overlying Calumet aquifer (BH7S), however, indicate recharge from the Calumet River. The ground-water-flow rate at BH7I was not calculated because the piston-flow assumption was not valid.

The confining unit also is overlain by the Calumet aquifer at well WS1 and is likely to be unweathered at this location. Tritium concentrations (2.8 TU) in water from the well indicate that water in the confining unit contains a component of post-1952 precipitation. Tritium concentrations in the Calumet aquifer near well WS1 indicate (1) water derived from either precipitation that recharged the aquifer since about 1952 and has not been subject to extensive dispersion or mixing, or (2) a mixture of ground water in which at least one end member contains some post-1952 recharge. The minimum vertical ground-water-flow rate for the unweathered part of the confining unit is estimated to be 0.28 ft/yr, assuming that water in well WS1 flowed through about 15 ft of the Calumet aquifer and 7 ft of the confining unit and that water in the Calumet aquifer and confining unit have maximum ages of 13 (1987 to 2000) and 48 years (1952 to 2000). This flow rate for the unweathered part of the confining unit is about one-half of the vertical velocity (0.55 ft/yr) estimated from hydraulic-head data and the Darcy equation by Kay and others (1996).

Isotopic data indicate that water from BH18I, which is open to the unweathered confining unit, contains a component of post-1952 recharge. Assuming piston flow, the water in well BH18I has flowed through approximately 30 ft of fill and 10 ft of the confining unit in no more than 48 years. Because of the high permeability of the fill deposits, it is assumed that the time required for ground water to flow through the fill deposits is negligible and the average vertical velocity through the confining unit is estimated at 0.21 ft/yr. This value is similar to the vertical velocity calculated for the confining unit at well WS1. The estimated vertical velocities indicate that the unweathered confining unit is only moderately vulnerable to contamination, provided the Calumet aquifer has not been removed completely or reduced substantially in thickness by quarrying or landfill excavations.

Well BH1D is near a ground-water divide and the Calumet aquifer is absent. Tritium data indicate that water from this well represents precipitation that recharged the aquifer since about 1987 and has not been subject to extensive dispersion or mixing or a mixture of ground waters in which at least one end member contains some post-1952 recharge. The hydrogeologic setting indicates a likelihood of substantial vertical flow through the confining unit. The approximate vertical ground-water-flow rate near well BH1D is 6.3 ft/yr, assuming an age of about 13 years (piston-flow conditions), uniform geology, and vertical ground-water flow. This velocity is about half the vertical velocity calculated for the upper part of the confining unit, based on hydraulic-head data and the Darcy equation (13.9 ft/yr); it exceeds the estimated vertical velocity through the lower unweathered part of the confining unit (0.55 ft/yr) by more than a factor of 10 (Kay and others, 1996). The flow velocity calculated with the isotope data may represent a composite of flow through weathered and unweathered parts of the confining unit in the vicinity of well BH1D, or the piston-flow assumption may not be applicable in this case. The computed flow rates indicate that the weathered part of the confining unit may be more vulnerable to contamination than the deeper unweathered part.

Isotopic data indicate that the lower, unweathered, part of confining unit near wells R251, R253, C6PI, and C6PD may contain a mixture of glacial-age water derived from upward flow under pre-development conditions and modern (post-1952) water. The mixing of ground waters with different apparent ages invalidates the piston-flow assumption. If post-1952 recharge is present at these wells, then it has flowed approximately 37 ft through the confining unit in no more than 48 years, for a minimum velocity of 0.77 ft/yr. This value is similar to the vertical velocity of 0.55 ft/yr calculated for the unweathered part of the confining unit from solution of the Darcy equation. Facilitated movement through the confining unit (landfill excavation, vertical fractures, and other features) may be indicated. Facilitated transport would increase the vulnerability of the confining unit to contamination.

Silurian-Devonian Aquifer

The hydraulic and isotopic data indicate that the hydrology of the Silurian-Devonian aquifer has been affected by historical and current withdrawals in the vicinity of Lake Calumet. The aquifer may be vulnerable to contamination where the overlying confining unit is thin or absent or where integrity of the confining unit has been compromised. The Silurian-Devonian aquifer appears to be substantially less vulnerable to contamination in the eastern and central parts of the study area than in the western part.

Summary and Conclusions

The area of northwestern Indiana and northeastern Illinois is one of the most heavily industrialized regions of the United States. To characterize ground-water recharge, flow rates, and aquifer vulnerability, the U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, collected water samples from 48 wells during July 1997 through April 2001. Samples were analyzed for ^{3}H, δ^{2}H, and δ^{18}O. The date of ground-water recharge of some samples was determined with the ^{3}H/^{3}He method.

Ground water in the study area is derived from modern and pre-modern precipitation, surface-water recharge, and glacial-age recharge residing in deeper aquifers. Isotopic values from the surficial Calumet aquifer in the eastern part of the study area fall within a limited range and indicate a well-mixed aquifer with active flow. Residence time of water in the Calumet aquifer in the eastern and central parts of the study area is approximately 5 to 15 years. Ground-water-flow rates are estimated at 400 to 2,300 ft/yr. Vulnerability of the Calumet aquifer to contamination is indicated by the data, but remediation may similarly be possible.

In the western part of the study area, the Calumet aquifer and weathered confining unit contain noticeably heavier isotopic values than those measured in shallow ground water in the east. The explanation for these differences may be attributed in part to recharge from Lake Michigan and its connected waterways.

In the western part of the study area, isotope values in wells open to the middle and base of the confining unit indicate multiple sources of water, including recharge from Lake Michigan near Calumet Harbor, modern precipitation near Blue Island, and glacial-age water in much of the surrounding area. The source and age of the water is affected by the presence or absence of the overlying Calumet aquifer, location along the ground-water flowpath, and natural and anthropogenic mechanisms that affect ground-water flow. Subject to the applicability of certain assumptions, the isotopic data indicate that the vertical ground-water flow in the confining unit ranges from 0.2 to 6 ft/yr.

The vulnerability of ground water in the confining unit to contaminants at land surface ranges from moderately vulnerable to invulnerable. The vulnerability of the confining unit to contamination is increased in areas where the unit is thin, absent, weathered, and affected by anthropogenic activities that include excavations and improperly abandoned wells. Remediation of contamination in the confining unit would be significantly more difficult than for the Calumet aquifer.

Isotopic values in ground water from wells open to the basal Silurian-Devonian aquifer indicate multiple sources of water in the aquifer, including recharge from Lake Michigan near the Calumet Harbor; modern precipitation near Stony Island; primarily glacial-age water near Lake Michigan in the eastern part of the study area; and a mixture of modern, pre-modern, and glacial-age water in the remainder of the study area. The source and age of the water is affected by the presence or absence of the overlying confining unit, location along the ground-water flowpath, pumping effects, and the presence of facilitated transport through the confining unit. The Silurian-Devonian aquifer is vulnerable to contamination in the western part of the study area, where the confining unit is thin or absent or where the integrity of the confining unit has been compromised. The Silurian-Devonian aquifer in the central and eastern part of the study area is less vulnerable to contamination.

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