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National Water-Quality Assessment of the Lake Erie-Lake St. Clair Basin, Michigan, Indiana, Ohio, Pennsylvania, and New York—Environmental and Hydrologic Setting

Water-Resources Investigations Report 97–4256

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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

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By
George D. Casey, Donna N. Myers, Dennis P. Finnegan, and
Michael E. Wieczorek

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U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief

Water Resources Division

U.S. Geological Survey

975 W. Third Avenue

Columbus OH 43212-3192

Copies of this report can be purchased from:

U.S. Geological Survey

Branch of Information Services

Box 25286

Denver, CO 80225

ACKNOWLEDGMENTS

TECHNICAL REVIEWERS OR ADVISORS

Gary L. Rowe, Supervisory Hydrologist, U.S. Geological Survey, Columbus, Ohio

James R. Nicholas, Supervisory Hydrologist, U.S. Geological Survey, Lansing, Mich.

David A. Eckhardt, Hydrologist, U.S. Geological Survey, Ithaca, N.Y.

Jeffrey DeShon, Aquatic Biologist, Ohio Environmental Protection Agency, Columbus, Ohio

Mark Bamberger, Geologist, Ohio Environmental Protection Agency, Columbus, Ohio

Ronald J. Veley, Information Officer, U.S. Geological Survey, Columbus, Ohio

Cynthia Nolan, Environmental Scientist, U.S. Environmental Protection Agency, Chicago, Ill.

Scott Painter, Head, Regional Studies Section, Environment Canada, Burlington, Ont., Canada

EDITORIAL, GRAPHICS, AND TEXT PREPARATION TEAM

Richard P. Frehs, Publications Graphics Specialist, U.S. Geological Survey, Columbus, Ohio

Betty B. Palscak, Technical Publications Editor, U.S. Geological Survey, Columbus, Ohio

Margery A. Tibbetts, Library Technician, U.S. Geological Survey, Columbus, Ohio

APPROVING OFFICIAL

Michael Eberle, Technical Publications Editor, U.S. Geological Survey, Columbus, Ohio

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Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
acre	0.4047	square hectometer (hectare)
pound (lb)	0.4536	kilogram
pound (lb)	2,205	metric ton
ton	0.9072	metric ton
acre foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	3.785	liter per minute
million gallons per day (Mgal/d)	3,785	cubic meter per day
mile per hour (mi/hr)	0.4470	meter per second

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

$$°C = (°F-32)/1.8$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the concentration of chemical constituents in solution as weight (milligrams or micrograms) of solute per unit volume (liter) of water. One-thousandth gram per liter is equivalent to one milligram per liter. One-millionth gram per liter is equivalent to one microgram per liter. For concentrations less than 7,000 mg/L, the numerical value is approximately the same as for concentrations in parts per million.

National Water-Quality Assessment of the Lake Erie-Lake St. Clair Basin, Michigan, Indiana, Ohio, Pennsylvania, and New York—Environmental and Hydrologic Setting

By George D. Casey, Donna N. Myers, Dennis P. FInnegan, and Michael E. Wieczorek

ABSTRACT

The Lake Erie-Lake St. Clair Basin covers approximately 22,300 mi^2 (square miles) in parts of Indiana, Michigan, Ohio, Pennsylvania, and New York. Situated in two major physiographic provinces, the Appalachian Plateaus and the Central Lowland, the basin includes varied topographic and geomorphic features that affect the hydrology. As of 1990, the basin was inhabited by approximately 10.4 million people.

Lake effect has a large influence on the temperature and precipitation of the basin, especially along the leeward southeast shore of Lake Erie. Mean annual precipitation generally increases from west to east, ranging from 31.8 inches at Detroit, Mich., to 43.8 inches at Erie, Pa.

The rocks that underlie the Lake Erie-Lake St. Clair Basin range in age from Cambrian through Pennsylvanian, but only Silurian through Pennsylvanian rocks are part of the shallow ground-water flow system. The position of the basin on the edge of the Michigan and Appalachian Basins is responsible for the large range in geologic time of the exposed rocks. Rock types range from shales, siltstones, and mudstones to coarse-grained sandstones and conglomerates. Carbonate rocks consisting of limestones, dolomites, and calcareous shales also underlie the basin. All the basin is overlain by Pleistocene deposits—till, fine-grained stratified sediments, and coarse-grained stratified sediments—most of Wisconsinan age. A system of buried river valleys filled with various lacustrine, alluvial, and coarse glacial deposits is present in the basin.

The soils of the Lake Erie-Lake St. Clair Basin consist of two dominant soil orders: Alfisols and Inceptisols. Four other soil orders in the basin (Mollisols, Histisols, Entisols, and Spodosols) are of minor significance, making up less than 8 percent of the total area.

The estimated water use for the Lake Erie-Lake St. Clair Basin for 1990 was 10,649 Mgal/d (million gallons per day). Power generation accounted for about 77 percent of total water withdrawals for the basin, whereas agriculture accounted for the least water-use withdrawals, at an estimated 38 Mgal/d. About 98 percent of the total water used in the basin was drawn from surface water; the remaining 2 percent was from ground water.

Agricultural and urban land are the predominant land covers in the basin. Agriculture makes up approximately 74.7 percent of the total basin area; urban land use accounts for 11.2 percent; forested areas constitute 10.5 percent; and water, wetlands, rangeland, and barren land constitute less than 4.0 percent.

The eight principal streams in the basin are the Clinton, Huron, and Raisin Rivers in Michigan, the Maumee, Sandusky, Cuyahoga, and Grand Rivers in Ohio, and Cattaraugus Creek in New York. The Maumee River, the largest stream in the basin, drains 6,609 mi^2 and discharges just under 24 percent of the streamflow from the basin into Lake Erie. Combined, the eight principal streams discharge approximately 54 percent of the surface water from the basin to the Lake Erie system per year. Average runoff increases from west to east in the basin.

The glacial and recent deposits comprise the unconsolidated aquifers and confining units within the basin. Yields of wells completed in tills range from 0 to 20 gal/min (gallon per minute), but yields generally are near the lower part of this range. Fine-grained stratified deposits can be expected to yield from 0 to 3 gal/min, and coarse-grained stratified deposits can yield 0.3 to 2,050 gal/min. Pennsylvanian sandstones can yield more than 25 gal/min, but they generally yield 10 to 25 gal/min. Mississippian sandstones in the basin generally yield 2 to 100 gal/min. The Mississippian and Devonian shales are considered to be confining units;

in places, they produce small quantities of water from fractures at or near the bedrock surface. Wells completed in the Devonian and Silurian carbonates yield 25 to 500 gal/min, but higher yields have been reported in several zones.

Most streamwater in the Lake Erie-Lake St. Clair Basin is moderately hard to very hard as a result of contact with carbonate-containing materials. The softest water is found in small streams in far northeastern Ohio and in western New York. The hardest water is found in streams in southeastern Michigan and certain streams in western New York, near Buffalo.

The amounts of nitrogen and phosphorus fertilizers, herbicides and insecticides, and sediment discharged to Lake Erie from its basin are higher than the amounts discharged from any other basin of the Great Lakes. Although trends in phosphorus concentrations over the combined period 1975–90 for the Raisin, Maumee, Sandusky, Cuyahoga, and Grand Rivers have been downward, trends in nitrate-N concentrations for the Raisin, Maumee, and Sandusky Rivers have been upward. Pesticides have been detected in streams draining row-cropped areas after application and runoff in the spring and early summer. Peak concentrations of atrazine can range from much less than 1.0 μg/L (microgram per liter) in samples collected during preapplication runoff to 35 μg/L or more in samples collected during postapplication runoff.

Most ground water in the Lake Erie-Lake St. Clair Basin is moderately hard to very hard as a result of contact with carbonate bedrock and surficial materials of similar origin. The softest ground water is found in relatively shallow, unconsolidated aquifers in western New York, and the hardest water is found in carbonate and sandstone aquifers of the basin. Although water contained in glacial deposits is typically lower in concentrations of dissolved solids and major ions than water contained in bedrock, ground water and surface water are both dominated by calcium, bicarbonate, and sulfate ions.

Concentrations of nitrate plus nitrite-N in ground water greater than or equal to 3 milligrams per liter have been detected in a small percentage of wells sampled in certain areas of the Lake Erie-Lake St. Clair Basin. Currently used pesticides have been detected, but only rarely, generally at concentrations less than 0.1 μg/L.

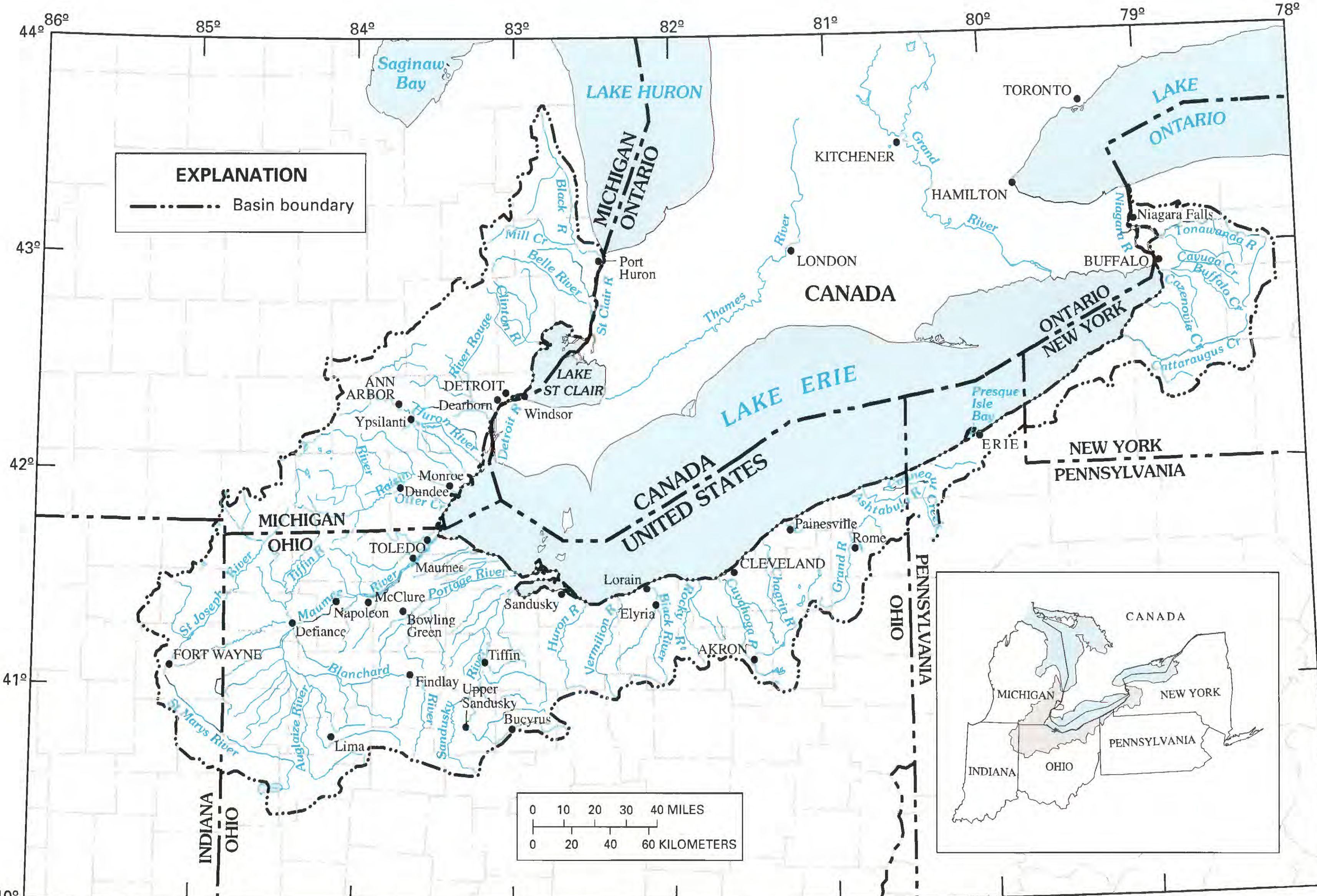
INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) initiated a full-scale program to assess water-quality conditions for a large part of the Nation's stream and aquifer systems. The long-term goals of the National Water-Quality Assessment (NAWQA) Program are to (1) describe the current quality of the Nation's surface- and ground-water resources, (2) determine whether any trends in the quality of the surface- and ground-water resources can be described, and (3) provide a better understanding of natural factors and human activities that affect the quality of the surface- and ground-water resources. The Lake Erie-Lake St. Clair Basin was selected as one of 59 of the Nation's important river basins and aquifer systems to be investigated under the NAWQA Program.

The Lake Erie-Lake St. Clair Basin covers approximately 22,300 mi^2 in northeastern Indiana, southeastern Michigan, northern Ohio, northwestern Pennsylvania, and western New York (fig. 1). The basin drains to Lake Erie, Lake St. Clair, and to the St. Clair and Detroit Rivers and eventually to the Niagara River at the outflow of Lake Erie (fig. 1). Principal tributaries within the basin are the Maumee River and its tributaries in Indiana, Michigan, and Ohio; the River Raisin in Michigan; the Sandusky, Cuyahoga, and Grand Rivers in Ohio; and Cattaraugus Creek in western New York.

The basin is inhabited by approximately 10.4 million people, with about 45 percent of the people residing in southeastern Michigan, 40 percent residing in Ohio, 6 percent residing in western New York, 3 percent residing in northeastern Indiana, and the remaining 2 percent residing in northwestern Pennsylvania (data from U.S. Geological Survey Aggregated Water Use Data Systems, 1990). The basin includes several major population centers: Detroit, Mich.; Cleveland, Toledo, and Akron, Ohio; Fort Wayne, Ind.; Erie, Pa.; and Buffalo, N.Y. The economy in the urban areas is mostly related to manufacturing, service, and trade industries. The economy of the remainder of the basin is reliant on row-crop agriculture and livestock production.

The purpose of this report is to describe the environmental and hydrologic setting of the Lake Erie-Lake St. Clair Basin and the factors that affect water quality. This report is the first in a series of NAWQA reports on the Lake Erie-Lake St. Clair Basin. The report is intended to be used as a general guide to the environmental setting of the basin and as preliminary



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Figure 1. Location of the Lake Erie-Lake St. Clair Basin.

information for subsequent in-depth topical reports on water quality and aquatic biology.

The report describes the climate, physiography, geologic setting and stratigraphy, structural geology, geologic history, soils, population, land use, water use, and water quality for selected chemical constituents, physical properties and characteristics, and aquatic biota and stream habitat in the basin. The environmental features described largely determine water-quality characteristics and the potential for future water-quality issues in the basin.

ENVIRONMENTAL SETTING

The environmental setting of the Lake Erie-Lake St. Clair Basin is described by data for climate, physiography, geologic setting and stratigraphy, soils, population, land use, and water use. These factors in combination shape the quality of streams and aquifers described in subsequent sections of the report.

Climate

The climate of the Lake Erie-Lake St. Clair Basin is influenced primarily by continental air masses and lake effect, owing to its location in the lower Great Lakes Basin. Air masses are characterized by regional climatic characteristics—temperature and humidity—that are characteristic of the areas where these air masses originate. The first of three air masses affecting climate is the Maritime Tropical air mass from the Gulf of Mexico. This warm, moist air mass usually moves northeast from the Gulf and delivers most of the precipitation to the basin. The second, a cool and dry air mass that originates in Canada, is called the Continental-Polar air mass. It brings cool, dry days in summer and arctic cold in winter. The third, the Maritime Polar air mass, arrives from the west. It originates as a moist air mass in the Pacific but loses most of its moisture by way of precipitation as it crosses the Rocky Mountains and the Great Plains. It eventually reaches the basin as a cool air mass. When high- and low-pressure cells of the colliding continental air masses meet, fronts are formed that usually give rise to storms (Bolsenga and Herdendorf, 1993).

Lake effect is especially influential in shaping climate along the leeward, southeastern shore of Lake Erie. Major characteristics of lake effect are enhanced precipitation, temperature moderation, and increased cloudiness and humidity over lake and nearshore land areas. Four properties lead to the lake effect: water transparency, evaporation, heat capacity, and water mixing. Water transparency of Lake Erie provides a medium for solar radiation to penetrate and be absorbed by water. Land surfaces are not penetrated to nearly the extent of water, so land heats and cools more quickly than water. Evaporation from the water surface releases heat, thus maintaining a cool surface temperature for the lake relative to the land nearby. With regard to heat capacity, more energy is required to heat a mass of water than to heat an equal mass of land to the same degree, so the lake stores heat. The final property is mixing; the lake flow is continuously mixing, increasing the efficiency of thermal conductance. The lake buffers temperature extremes, resulting in more moderate nearshore temperatures than are recorded in inland areas. Increased humidity, snow, and rain also characterize lake-effect areas (Bolsenga and Herdendorf, 1993).

Data gathered over a 30-year period (1961–90) show the following patterns of mean temperature (fig. 2). From west to east, mean annual temperatures range from 49.7°F in Fort Wayne, Ind., to 46.7°F in Buffalo, N.Y. (Midwest Climate Center, 1995). Seasonally, mean monthly temperatures for January and February range from 22.4 to 27.8°F in the basin, whereas those in July and August range from 69.0 to 73.8°F. On the average, temperatures in the basin exceed 90°F only about 10 to 15 days a year and dip below 0°F only a few days a year (National Oceanic and Atmospheric Administration, 1993 a–c)

Cloudiness and humidity are typical, especially in the spring, when they are responsible for retarding the flowering of fruit trees and protecting preemergent plants from a late-spring frost. The last killing frost of the season is usually in April, and the first frost is normally in October. The average growing season in the basin (the period in between the last and first frost kill of the season) lasts from 160 to 180 days. Moderate temperatures, caused by the lake effect, result in a relatively long growing season and have helped sustain vineyards and orchards near Lake Erie (National Oceanic and Atmospheric Administration, 1993 b–f).

Mean annual precipitation generally increases from the western end to the eastern end of the basin (fig. 3). For the period 1961–90, mean annual precipitation at Detroit, Mich., was 31.9 in., whereas at Erie, Pa., mean annual precipitation was 43.8 in. (Midwestern Climate Center, 1995). The months of highest pre-

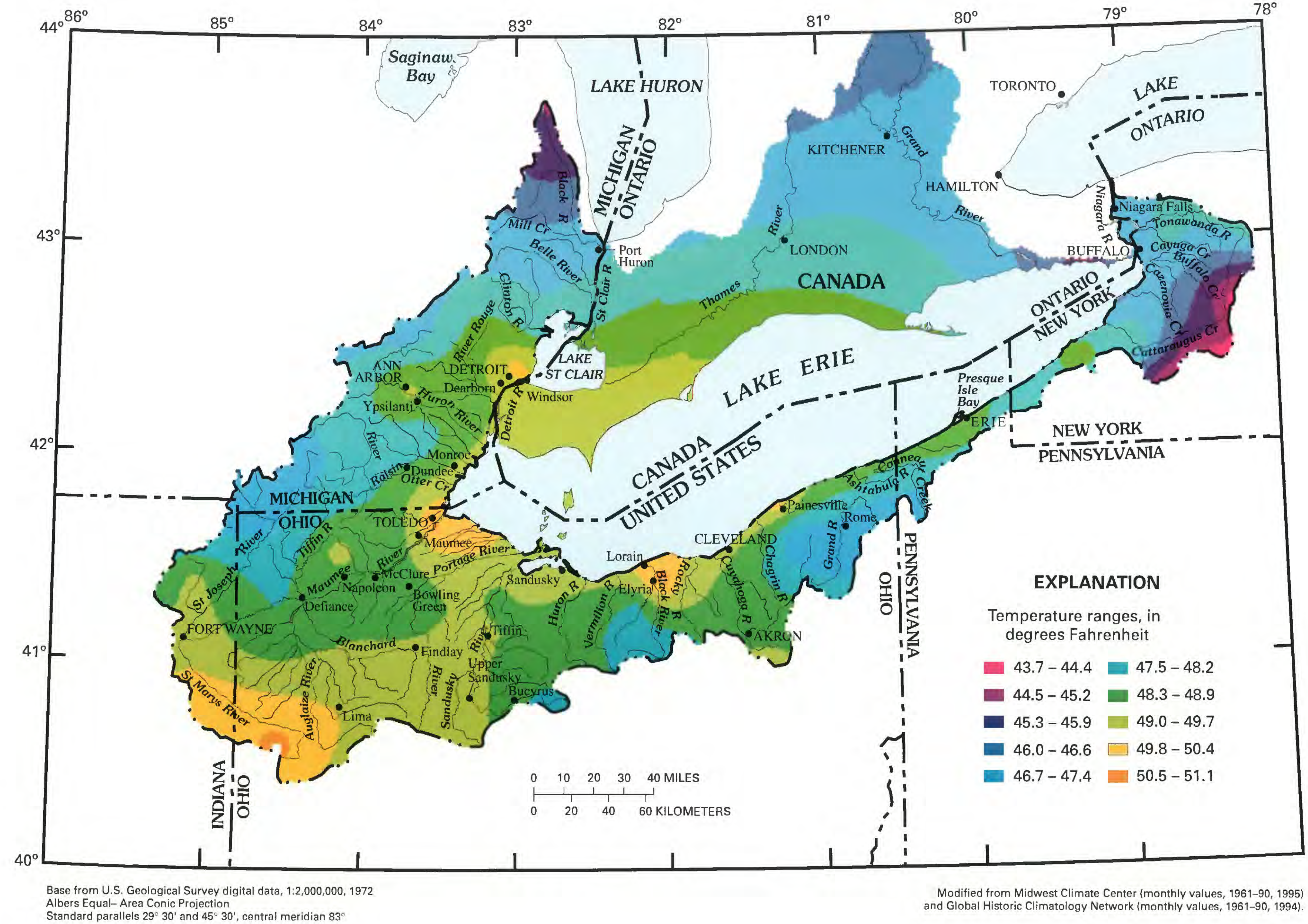


Figure 2. Mean annual air temperature ranges for the Lake Erie-Lake St. Clair Basin, based on 30-year annual values, 1961–90.

cipitation are May, June, and July, during which 3.0 to 3.9 in. of rain falls per month. The months of lowest of precipitation are January and February, during which the precipitation∞ ranges from 1.7 to 2.7 in. (National Oceanic and Atmospheric Administration, 1993 b, d).

Common occurrences in the basin are cold or warm fronts, which are usually associated with high winds. Weather fronts can cause damaging winds and thunderstorms and can occasionally spawn tornadoes. Tornadoes are more frequent at the western end of the basin than at the eastern end during the spring and summer. In northwestern Ohio, sustained wind velocity is 32 mi/h for an average of 23 days per year. Prevailing winds in the basin are out of the southwest. The weather changes constantly every few days with the passage of cold fronts and subsequent warming. The driest and calmest weather of the year tends to be in late summer and early fall (National Oceanic and Atmospheric Administration, 1993 a, c).

Winter storms bring various combinations of rain, freezing rain, sleet, and snow. Mean annual snowfall increases from west to east. From Cleveland, Ohio, to Buffalo, N.Y., snowfall is influenced by Lake Erie, and snow squalls are common until the lake freezes over (National Oceanic and Atmospheric Administration, 1993 a,b,d,g).

Potential evapotranspiration for the basin is fairly uniform. Average potential evapotranspiration ranges from 35.4 to 36.2 in. (Midwestern Climate Center, written commun., 1992).

Physiography

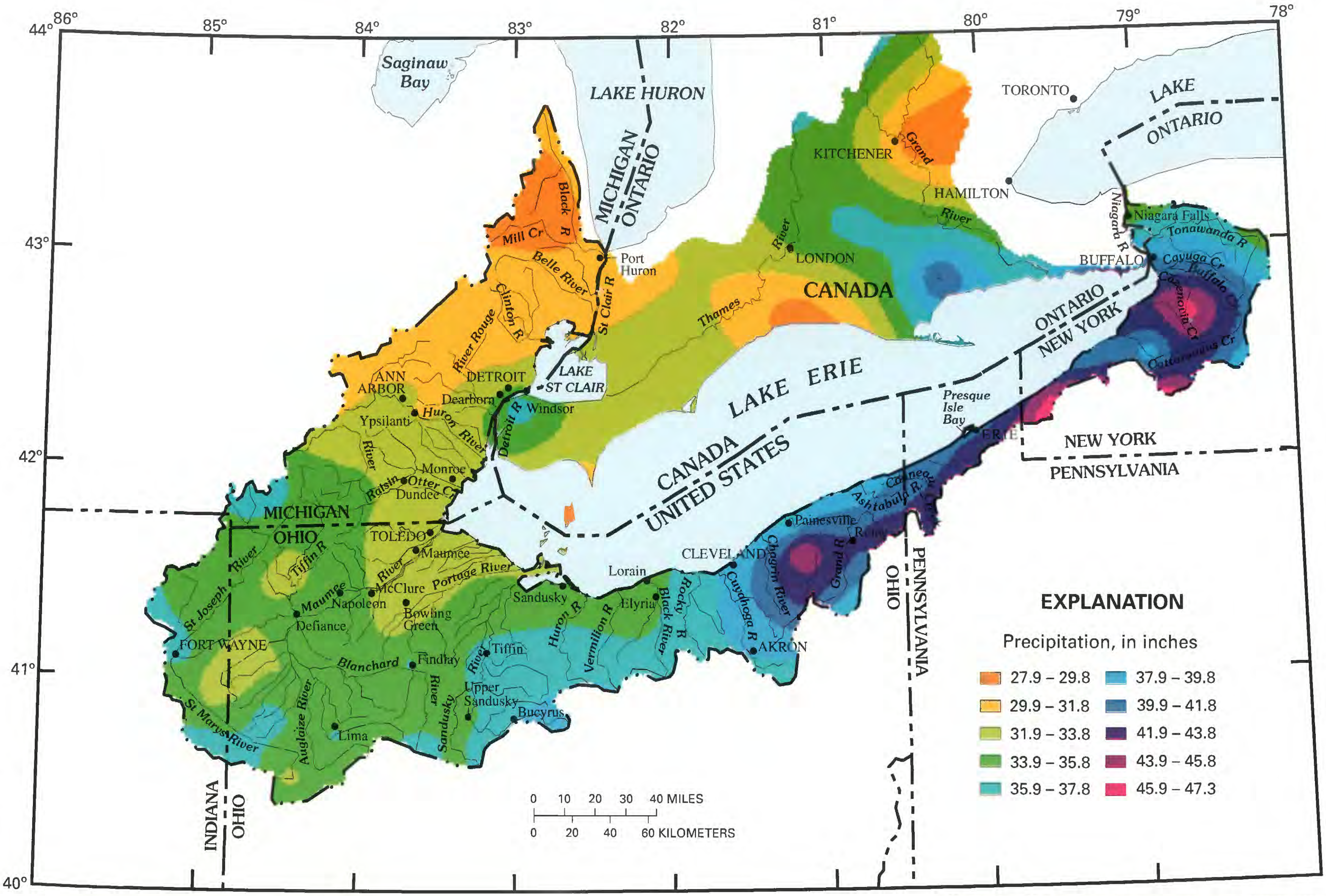
Central Lowland Province

The Central Lowland Province encompasses 585,000 mi^2 in all or part of 16 states. The physiography of this province is controlled by the major structural features, lithology of the rocks, and glacial history. The Lake Erie-Lake St. Clair Basin includes only a small part of the northeastern section of the Central Lowland Province. The total area of the basin contained within the Central Lowland Province is approximately 19,000 mi^2, or slightly greater than 3 percent of the total area of the province. The basin contains an approximately 280-mi-long segment of the eastern boundary between the Central Lowland and Appalachian Plateaus Provinces (fig. 4).

Within the basin are two distinct physiographic sections of the Central Lowland Province, the Eastern Lakes and the Till Plains (fig. 4) (Fenneman, 1938). The Eastern Lake Section of the Central Lowland Province makes up approximately 14,300 mi^2 or 63 percent of the Lake Erie-Lake St. Clair Basin, whereas the Till Plains Section makes up approximately 4,700 mi^2 or 21 percent of the basin (Fenneman, 1938).The Eastern Lake Section is distinguished from the Till Plains Section by depositional characteristics of the sediments. In the Eastern Lake Section, the landscape is dominated by recessional moraines and beach ridges, lacustrine plains, and outwash plains, some of which have been pitted and contain many small lakes or swamps. In the Till Plains Section, topographic expression is minimal, owing to the burial of the preglacial topography by ground moraine and terminal moraine and the filling of valleys with lacustrine, alluvial, and glacial deposits (Fenneman, 1938). The dividing line between the Eastern Lake Section and the Till Plains Section is placed at the point where the recessional moraines and beach ridges become more numerous and have more topographic expression at land surface. This broad, flat plain that borders Lake Erie is the result of deposition in the glacial lakes that formed during the retreat of the Wisconsinan ice sheet (Fenneman, 1938).

The maximum land-surface altitude in the basin within the Central Lowland Province is about 1,100 ft in western Ohio near the basin boundary. In southeastern Michigan, the highest land-surface altitude, about 1,040 ft, is north of Detroit. Land-surface altitudes decrease away from these areas toward Lake Erie, Lake St. Clair, the St. Clair River, and the Detroit River. The land-surface altitude along the shore of Lake Erie is less than 580 ft and along the shore of Lake St. Clair is less than 590 ft. Topography in the province ranges from nearly flat-lying land to rolling hills with low relief.

Within the basin, stream-drainage patterns are dendritic across most of the Central Lowland Province, owing to the consistent cover of surficial material (glacial and alluvial) deposited on the various bedrock units. Where the surficial materials thinly mantle the bedrock, the bedrock is generally a carbonate type. Low topographic relief combined with either thick surficial deposits or a homogeneous composition of the underlying bedrock creates conditions that form a dendritic drainage pattern.Where the Central Lowland Province is only a narrow strip along the shore of Lake Erie and near the edge of the Appalachian Plateaus province in northeastern Ohio and western New York, the drainage pattern is transitional from dendritic to



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
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Standard parallels 29° 30' and 45° 30', central meridian 83°

Modified from Midwest Climate Center (monthly values, 1961–90, 1995)
and Global Historical Climatology Network (monthly values, 1961–90, 1994)

Figure 3. Mean annual precipitation ranges for the Lake Erie-Lake St. Clair Basin, based on 30-year averages, 1961–90.

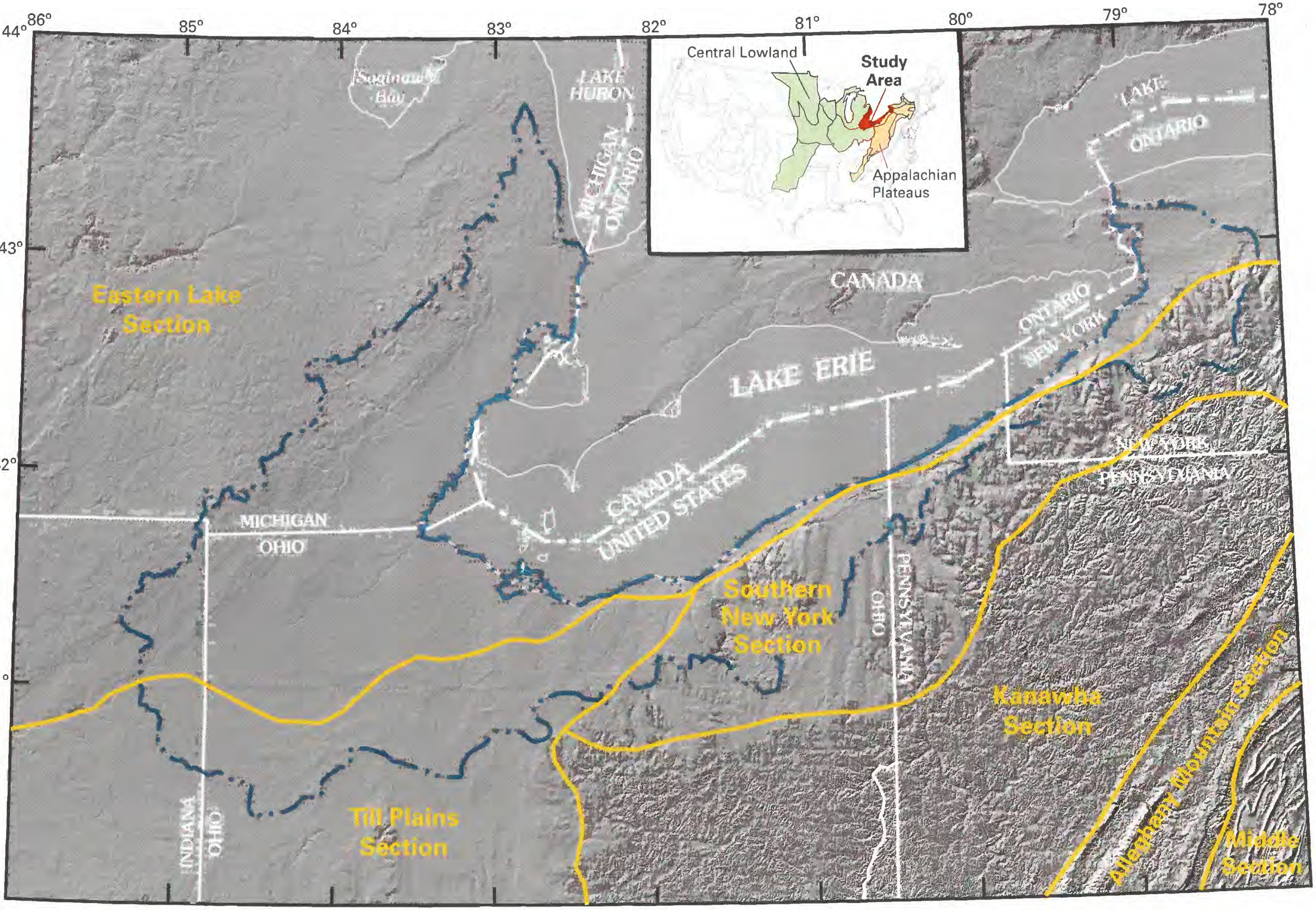


Figure 4. Physiographic subdivisions and digital elevation model of the Lake Erie-Lake St. Clair Basin.

parallel. This transition could be the result of the parallel outcrop of Devonian shales that rim Lake Erie in northeastern Ohio and western New York.

Appalachian Plateaus Province

The Appalachian Plateaus Province encompasses 113,400 mi^2 in parts of 10 states. The physiography of this province is controlled by uplift and erosion that has occurred during various mountain-building events that have affected the eastern margin of the North American Craton.

The Lake Erie-Lake St. Clair Basin intersects only a small part of the Appalachian Plateaus Province. The total area of the basin contained within the Appalachian Plateaus Province is approximately 3,700 mi^2 (fig. 4). Only one physiographic section of the Appalachian Plateaus Province, the Southern New York Section, is within the basin. The Southern New York Section, which is distinguished from the remainder of the Allegheny Plateau by the glacial modification of the topography, is described as a glaciated plateau of moderate relief (Fenneman, 1938).

The maximum land-surface altitude in the basin within the Appalachian Plateaus Province is about 2,200 ft, in the southeastern part of the basin (in New York) near the hydrologic boundary. The highest land-surface altitude in northeastern Ohio, north and east of Cuyahoga Falls, is about 1,300 ft. Land-surface altitudes decrease away from these areas toward Lake Erie to an altitude along the shore of Lake Erie that is less than 580 ft. Topography in the province ranges from low, rolling hills with moderate relief to steep-sided hills and deeply incised river valleys.

Within the basin, stream drainage patterns are transitional across the Appalachian Plateaus Province, owing to the variability of surficial material (glacial and alluvial) and thickness of the surficial material deposited on the different bedrock units. The composition of the bedrock ranges from easily erodible shale to more resistant sandstone. The variability of the surficial deposits and the varied composition of the underlying bedrock create conditions that form a dendritic drainage pattern that changes to parallel and trellis drainage patterns. This drainage-pattern transition could be the result of the parallel outcrop of Devonian shales that rim Lake Erie in northeastern Ohio, northwestern Pennsylvania, and western New York.

Geologic Setting and Stratigraphy

The uppermost bedrock units in the Lake Erie-Lake St. Clair Basin range in age from Ordovician through Pennsylvanian (fig. 5). The basin has been divided into six separate geographic areas where similar time-stratigraphic units are present (Patchen and others, 1985; Shaver, 1985). The basin is on the edge of the Michigan and Appalachian Basins, and this position is responsible for the large range in geologic time of the exposed rocks. The time-stratigraphic units that are exposed at the bedrock surface in northeastern Indiana and northwestern Ohio are deeply buried by younger sedimentary rocks in northeastern Ohio, northwestern Pennsylvania, and southwestern New York (fig. 5 and fig. 6). This is due to the deposition of sediments in the Appalachian Basin, which buried the older rocks, and the subsequent uplift and erosion that occurred along the Cincinnati Arch, which exposed the older rocks along the crests of the arch (fig. 5).

This configuration of time-stratigraphic units makes it difficult to describe the rock types relative to age, location, and relevance to the shallow ground-water flow system. In some parts of the basin, a time-stratigraphic unit crops out at the bedrock surface and is part of the shallow ground-water flow system; elsewhere within the basin, the same time-stratigraphic unit is hundreds of feet below the bedrock surface and is not part of the shallow ground-water flow system. Thus, only the time-stratigraphic units that are part of the shallow ground-water flow system are described in this report.

The major structural features that affected the deposition within the Lake Erie-Lake St. Clair Basin are the Michigan and Appalachian Basins and the Cincinnati, Findlay, and Algonquin Arches. The crests of the arches form a southwest-northeast trend in northwestern Ohio and southeastern Ontario. In southeastern Ontario and southeastern Michigan, between the Findlay and Algonquin Arches, is a structural low called the Chatham Sag (fig. 5). Tectonic events during the Paleozoic and Mesozoic Eras influenced the deposition of the sedimentary rocks that underlie the Lake Erie-Lake St. Clair Basin. Mountain-building events east of the Appalachian Basin provided a source area for large amounts of sediments that were deposited in the Appalachian Basin and west of the basin. The tectonic forces were also responsible for the development and positioning of the basins and arches on the craton. As the basins were subsiding and (or) the arches were being uplifted, the effect would change the relative water

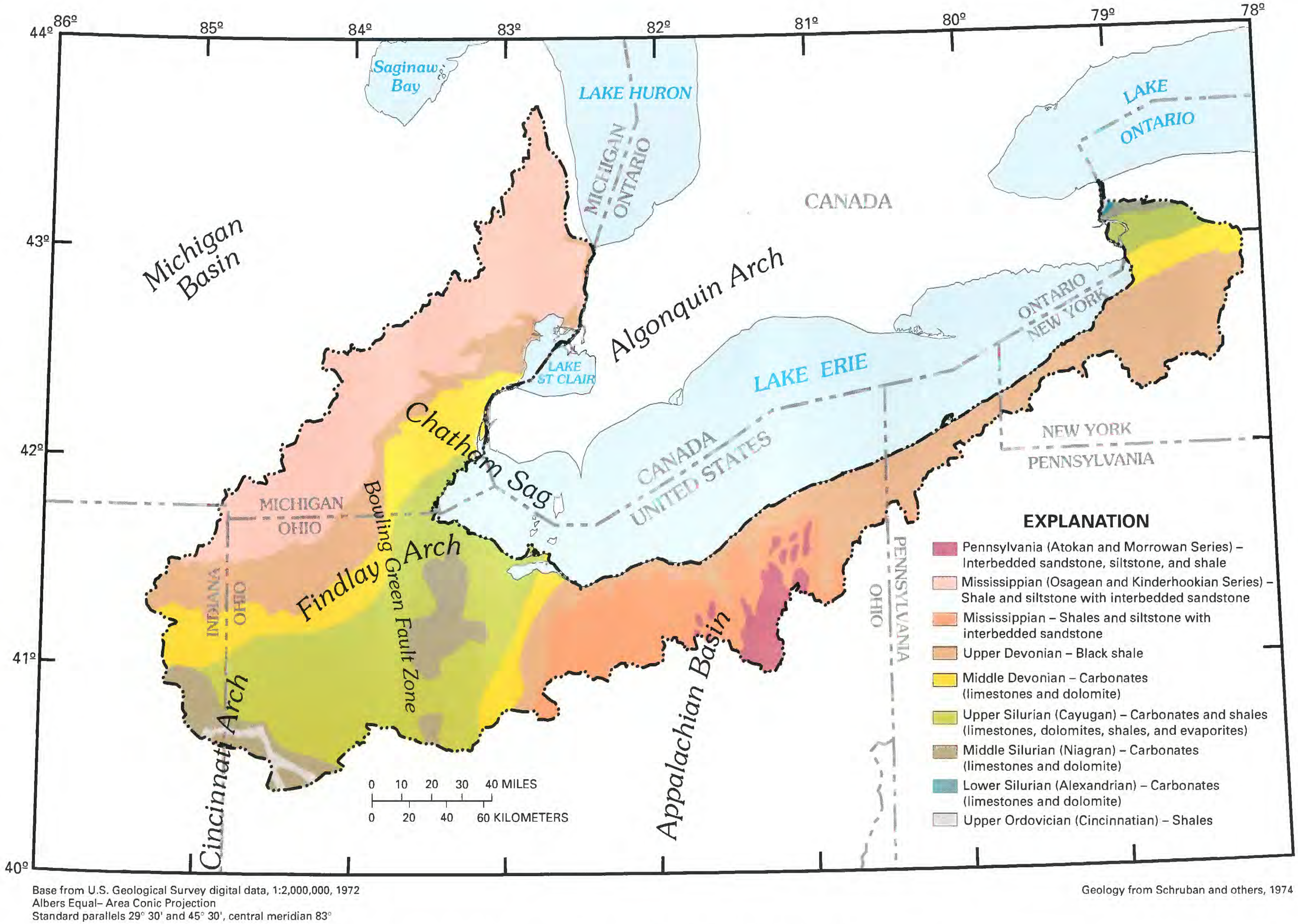


Figure 5. Generalized bedrock geology and major structural features of the Lake Erie-Lake St. Clair Basin.

depth, currents, salinity, and sedimentary depositional environments in the intercratonic seas that covered this section of the craton. (Droste and Shaver, 1983; Qunilan and Beaumont, 1984; Beaumont and others, 1988).

Silurian Rocks

The Silurian rocks in northeastern Indiana that are part of the shallow ground-water flow system can be grouped into Salamonie Dolomite and the Salina Group (fig. 6). In southeastern Michigan, the Silurian rocks that are part of the shallow ground-water flow system are the Salina Group and the Bass Islands Group. The stratigraphic units in northwestern Ohio and southeastern Michigan have been subdivided more than those in Indiana. In northwestern Ohio, the Silurian rocks that are part of the shallow ground water flow system are the Lockport Dolomite and its equivalent units, the Salina Group and the Bass Islands Group (fig. 6). The Silurian rocks in northeastern Ohio and northwestern Pennsylvania are deeply buried and not part of the shallow ground-water flow system. In western New York, the Silurian rocks that are part of the shallow ground-water flow system are the Lockport Group and the Salina Group.

In Indiana, the Salamonie Dolomite consists of two distinct lithologies. The basal part generally is a fine-grained, impure, argillaceous limestone, dolomitic limestone, and shale (Shaver and others, 1986). The upper part of the Salamonie Dolomite is generally a uniform dolomite with a coarse-grained, bioclastic, vuggy texture (Shaver and others, 1986). In Ohio, the correlative of the upper part of the Salamonie Dolomite is the lower and middle part of the Lockport Dolomite.

The Lockport Dolomite conformably overlies the Rochester Shale equivalent and is conformably overlain, with minor local unconformities near reef-bank facies (Shaver, 1991), by the Salina Group where the Salina has not been eroded from above the Lockport Dolomite. The Lockport Dolomite interval contains three distinct units: a microcrystalline to coarsely crystalline dolomite; a microcrystalline to finely crystalline dolomite; and a fossiliferous, predominantly coarsely crystalline, vuggy dolomite (Janssens, 1977).

Droste and Shaver (1976) described the Salamonie Dolomite as a laterally extensive, blanketlike deposit of carbonate rocks that covered all of what is now Indiana before the multiple post-Silurian periods of erosion. This description can be extended to the correlative Lockport Dolomite of Ohio. The pre-Devonian erosion resulted in the removal of not only the Salamonie and the Lockport Dolomites but also the Silurian strata below these units south of the basin.

In western New York, the Lockport Group conformably overlies the Clinton Group and consists of several distinct lithologies. The basal section is a shaly dolomite, overlain by a crinoidal limestone; fine-grained, massive to thick-bedded dolomite; fine-grained dolomite; and a coarse- to medium-grained, sucrosic dolomite (Johnston, 1964; La Sala, 1968).

Within the basin, the Salina Group conformably and unconformably overlies the Salamonie Dolomite and the Lockport Dolomite. The unconformities are considered to be minor local unconformities near the reef-bank facies (Shaver, 1991). The upper contact of the Salina Group where the Bass Islands Group or Dolomite either was not deposited or was eroded is a regionally extensive unconformity. The overlying Devonian rocks, where present, range in age from Early to Middle Devonian (Droste and Shaver, 1982; Hull, 1990).

In Indiana, the Salina Group includes a diverse assemblage of dominantly carbonate rocks that range from fine-grained argillaceous rocks to a pure carbonate mud. The Salina Group also includes a coarse-grained, bioclastic, vuggy and fossiliferous facies that comprises reef-framework rocks (Shaver and others, 1986). The dolomites that compose the lower half of the Salina Group consist of a micritic to fine-grained, partly laminated dolomite and a granular, vuggy dolomite (Shaver and others, 1986).

The upper half of the Salina Group in Indiana contains several lithologies that grade into one another (Shaver and others, 1986). The lithologies of these rocks include dense to fine-grained, calcareous, silty dolomite; dolomitic, silty limestone; fine-grained limestone; dolomitic limestone; and dolomite. Also included are micritic to fine-grained, thinly laminated limestone; granular, vuggy dolomite; and carbonate mudstones that are contained within the bank, reef, reef-detrital, and biohermal deposits.

The upper part of the Salina Group has been subjected to post-Cayugan, pre-Middle Devonian subaerial exposure and erosion. This is apparent where the uppermost part of the Salina Group is exposed within quarries. At several locations in Indiana where the Cayugan carbonate rocks have not been removed by erosion, paleokarst features are evident. The paleokarst features consist of caves, grykes (solution-widened fissures), solution-widened bedding joints, and fractures derived from the settling of reef-flank deposits (Shaver, 1989). The paleokarst features are filled with a quartz sand, a shaly material, breakdown that consists of the local host rock, and what appear to be pisolites. As evidence of the age of these features in relation to the overlying sediment, Shaver (1989) described a calcareous shaly material that fills a cave containing Devonian conodonts.

In southeastern Michigan, the Salina Group consists of dolomites, shaly dolomites, shales, and evaporite deposits. The carbonate rocks in the Salina Group are primarily coarsely crystalline to dense dolomites with an occasional limestone. The evaporite deposits are primarily anhydrite and gypsum in the southern section of southeastern Michigan, whereas salts (halite, sylvite) dominate in the northern section of southeastern Michigan (Mozola, 1969, 1970). The clastics are fine-grained shales and dolomitic shales. The upper half of the Salina group consists of interbedded shale, carbonate, evaporite lithology, and the lower third of the Salina Group is mostly carbonates.

In Ohio, the Salina Group consists of a diverse assemblage of carbonate and evaporate deposits. This group ranges from an argillaceous microcrystalline dolomite to saccharoidal, medium-grained dolomite and bedded evaporate deposits (Janssens, 1977).

In northwestern Ohio, the Salina Group contains lithologies that also vary with the location. In the western half of northwestern Ohio, the Salina Group contains the following dominant lithologies: (1) a stromatolitic dolomite, (2) a partly argillaceous, silty, microcrystalline dolomite that contains some shale, (3) a microcrystalline dolomite that is partly laminated, argillaceous, and pelletal and that locally contains secondarily deposited gypsum (Janssens, 1977), and (4) a karsted Salina facies that contains mud cracks and a secondary filling of caverns with what is believed to be Devonian sediments (G. E. Larsen, Ohio Geological Survey, oral commun., 1992). The Salina Group is a petroliferous unit downdip in the Michigan and Appalachian Basins. Along the crests of the Cincinnati and Findlay Arches, where the overlying impermeable units that function as a stratigraphic trap have been removed, the Salina group has many reported occurrences of tar or asphalt deposits in cores on file with the Ohio State Geological Survey. This could be the remaining evidence of petroleum that was once contained in the Salina Group updip from the Michigan and Appalachian Basins.

A facies change has been noted within the Salina Group of northwestern Ohio east of the Bowling Green Fault Zone, where it contains dolomite, bedded anhydrite, very argillaceous dolomite, and shale. Janssens (1977, p. 23) described it as "an important updip facies of the salt-bearing Salina rocks of eastern Ohio." This facies change in northwestern Ohio could be the result of several periods of movement along the Bowling Green Fault Zone and their effect on depositional environments, coupled with subsidence in the Michigan Basin during this depositional episode (Onasch and Kahle, 1991).

In western New York, the Salina Group is a sequence of dolostone, shales, and evaporites (Isachsen and others, 1991). The basal section of the Salina Group in western New York is a shale with dolomite layers, anhydrite, and minor salt beds. This is overlain by a dolomitic shale to a shale that contains dolomite, limestone, anhydrite, and salt layers. The uppermost section of the Salina Group consists of dolomite and dolomitic limestone that contain interbedded shales (La Sala, 1968; Rickard, 1969; Isachsen and others, 1991).

In northwestern Ohio and southeastern Michigan, the Salina Group is conformably overlain by the Bass Islands Group (fig. 6) where the Bass Islands Group can be recognized. The Bass Islands Group is a dolomite that contains traces of chert and anhydrite (Mozola, 1969; Mozola, 1970; Janssens, 1977). In southeastern Michigan, some shales, dolomitic shales, and layers of anhydrite and gypsum are contained in the basal section of this unit (Mozola, 1969, 1970).

Devonian Rocks

The Devonian carbonate rocks in northeastern Indiana can be grouped into two major stratigraphic units, the Detroit River and Traverse Formations, which together compose the Muscatatuck Group (fig. 6). The stratigraphic units in Ohio and southern Michigan have been more subdivided than those in Indiana. In Ohio and southern Michigan, the Devonian carbonate rocks are the Bois Blanc Formation, the Sylvania Sandstone, the Detroit River Group or Formation, the Columbus Limestone, the Delaware Limestone or the Dundee Limestone, and the Traverse Formation. In western New York, the Devonian carbonate rocks are the Bois Blanc Limestone, the Onondaga Limestone, and the Hamilton Group (fig. 6).

The Antrim Shale and the Ellsworth Shale are the upper Middle Devonian and Upper Devonian shales in northeastern Indiana, southeastern Michigan, and northwestern Ohio north of the Findlay Arch. South and east of the Findlay Arch in northwestern and northeastern Ohio, the equivalent lithologic units are the Olentangy and Ohio Shale and the lowest part of the Bedford Shale (fig. 6). In northwestern Pennsylvania only the uppermost Devonian units are considered to be within the shallow ground-water flow system. These units are the Conneaut Group and the Conewango Group (fig. 6). The Genesee, Sonyea, West Falls, Canadaway, Conneaut, and Conewango Groups are the upper Middle Devonian and Upper Devonian shales in Western New York (fig. 6).

After the post-Cayugan, pre-Middle Devonian erosional event, the Great Lakes Region was again a site of carbonate and evaporite deposition. The controlling tectonic forces of this depositional event were the Acadian Orogeny and a major subsidence episode in the Michigan and Illinois Basins (Droste and Shaver, 1983; Beaumont and others, 1988). The late Niagaran and Cayugan Fort Wayne Bank also is thought to have played a large role in the deposition of the Middle Devonian carbonate rocks, which, as a resistant carbonate reef-bank facies, may have functioned as a barrier or a sill during the early deposition of the Detroit River Group or the Detroit River Formation of the Muscatatuck Group (Doheny and others, 1975). Some investigators (Doheny and others, 1975; Briggs and others, 1978) have proposed that the Fort Wayne Bank was a continuous feature that extended from northwestern Indiana to northwestern Ohio. The Fort Wayne Bank, in conjunction with another carbonate bank in southern Michigan (proposed by Briggs, 1959), formed a restricted evaporite basin in northern Indiana, northwestern Ohio, and southern Michigan (Mesolella and others, 1974).

The only Lower Devonian rocks in the basin that are within the shallow ground-water flow system are the Bois Blanc Formation of southeastern Michigan and the Bois Blanc Limestone of Western New York. In southeastern Michigan, the Bois Blanc Formation is a chert-rich dolomite that is dense to finely crystalline (Mozola, 1969, 1970).The Bois Blanc Formation unconformably overlies the Bass Islands Group and is conformably overlain by the Detroit River Group or the Sylvania Sandstone. The Bois Blanc Limestone is a thin limestone unit that occurs sporadically in western New York. The Bois Blanc Limestone unconformably overlies the Salina Group and is unconformably overlain by the Onondaga Limestone (Isachsen and others, 1991).

In northeastern Indiana, southeastern Michigan, and northwestern Ohio, the Detroit River Formation or Group was deposited during late Early Devonian and Middle Devonian time. This stratigraphic unit unconformably overlies rocks of the Salina Group. In northeastern Indiana, the Detroit River Formation is unconformably overlain by the Traverse Formation. In northwestern Ohio, the Detroit River Formation is conformably overlain by a thin section of the Columbus Limestone. The Detroit River Formation or Group was described by Janssens (1970) and Shaver and others (1986) as having several distinct facies. The basal unit consists of a sandy dolomicrite that grades to a fine to medium sandstone cemented with dolomite and containing thin lenses of dolomicrite; this basal unit grades upward into a fine-grained, laminated dolomite, dolomicrite, and dolosiltite that contains anhydrite and gypsum nodules (Janssens, 1970; Shaver and others, 1986). The Detroit River Formation or Group is a petroliferous unit downdip in the Michigan and Appalachian Basins. Along the crests of the Cincinnati and Findlay Arches, a strong petroleum odor is noticeable in freshly broken samples from the Detroit River Formation or Group (R.W. Shaver, oral commun., 1989).

The Muscatatuck Group unconformably overlies the Salina Group, and the Antrim Shale contact with the Muscatatuck Group generally is unconformable, but, in places, is conformable (fig. 6) (Shaver and others, 1986). In northern Indiana, the Muscatatuck Group is divided into the Detroit River and Traverse Formations (Shaver and others, 1986). Several carbonate lithologies are dominant in the Muscatatuck Group. The lowest part consists of a sandy, fine-grained, quartz-rich dolomite or a dolomitic quartz sandstone overlain by a granular, vuggy dolomite. These basal units are overlain by shaly to pure, granular limestone and dense, lithographic to fine-grained, typically laminated dolomites and dolomitic limestones (Becker, 1974; Shaver and others, 1986). Certain coarsely granular and fibrous anhydrite and gypsum deposits within the Muscatatuck Group correspond to the Detroit River Formation in northern Indiana (Becker, 1974; Shaver and others, 1986).

In southeastern Michigan, the Detroit River Group has a laterally equivalent unit that also is considered to be the basal unit of the Detroit River Group. The Sylvania Sandstone either lies conformably on the Bois Blanc Formation or, where the Bois Blanc Formation is absent, lies unconformably on the Bass Islands Group. The Sylvania Sandstone is a fine- to medium-grained sandstone that exhibits crossbedding. The Detroit River Group is conformably overlain by the Dundee Limestone and is conformably underlain by the Bois Blanc Formation. The Detroit River Group is a dolomite that is finely crystalline to granular (Mozola, 1969, 1970).

In northwestern Ohio, the Detroit River Group is conformably overlain by a thin section of the Columbus Limestone (Shaver, 1985). The Columbus Limestone consists of a basal highly crystalline and porous dolomite or dolomitic limestone overlain by a massive, fossiliferous limestone that locally contains some chert (Westgate, 1926; Stout, 1941; Hall and Alkire, 1956). The Columbus Limestone is unconformably overlain by the Dundee and the Delaware Limestones (fig. 6), which are laterally equivalent. The Dundee Limestone is a saccharoidal, sandy, fine- to medium-crystalline dolomitic limestone or dolomite that contains nodular chert (Janssens, 1970). The Delaware Limestone is a fine-grained, argillaceous and fossiliferous limestone (Janssens, 1968). The Delaware and the Dundee Limestones are unconformably overlain by the Traverse Formation (fig. 6).

In northwestern Ohio, the Delaware Limestone unconformably overlies the Columbus Limestone and is unconformably overlain by the Olentangy Shale (Shaver, 1985; Hull, 1990; Larsen, 1991). The Olentangy Shale is the basal part of the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system in central and western Ohio. The Delaware Limestone consists of a thinly bedded limestone that contains nodules of chert and thin layers of shale. This basal section grades into an argillaceous limestone, which contains beds of chert, and a massive limestone unit (Hall and Alkire, 1956; Dow, 1962; Janssens, 1968).

In western New York, the equivalent of the Detroit River Formation or Group and the Columbus Limestone is the Onondaga Limestone. The Onondaga Limestone is unconformably underlain in places by the Bois Blanc Formation and conformably overlain by the Hamilton Group (Isachsen and others, 1991). The basal section of the Onondaga Limestone is a coarse-grained, crinoidal limestone overlain by a cherty limestone, and the upper section is a limestone (La Sala, 1968).

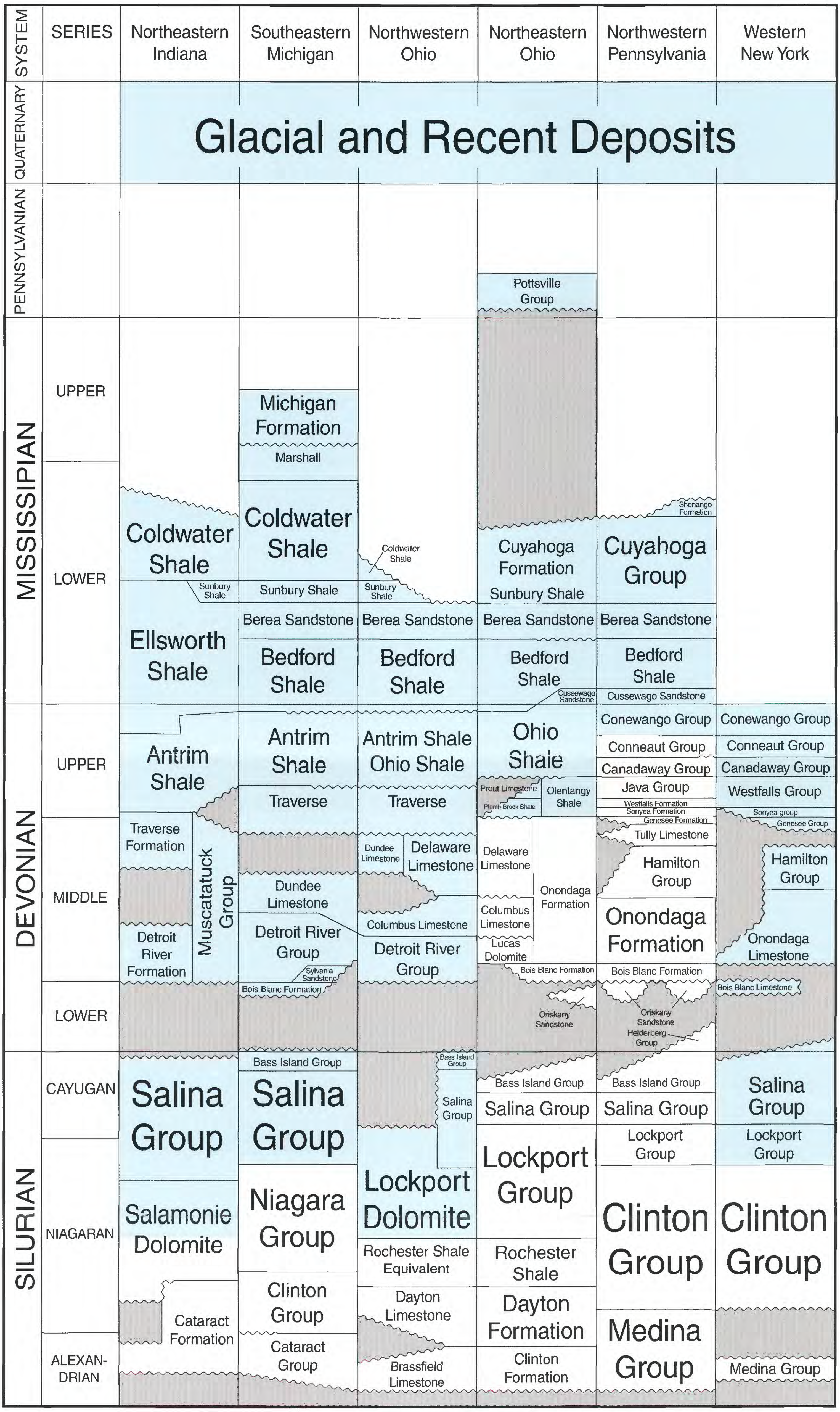
The Traverse Formation in northeastern Indiana is lithologically similar to the strata of the same name in Ohio. In Indiana, the Traverse Formation contains the following distinct lithologies: (1) a basal dense, micritic, fossiliferous limestone, (2) a highly fossiliferous, lithographic and sublithographic limestone that grades into a fossiliferous calcareous shale and an argillaceous limestone from northwestern to northeastern Indiana, and (3) a cherty, dense to medium-grained dolomite that overlies both of these units (Shaver and others, 1986). The Traverse Formation unconformably overlies the Detroit River Formation. The Traverse Formation overlies progressively younger parts of the Detroit River Formation updip from the Michigan Basin onto the Wabash Platform (Shaver and others, 1986). The Traverse Formation is overlain conformably and unconformably by the Antrim Shale (Shaver and others, 1986).

In southeastern Michigan, the Traverse Group consists of variable amounts of shales, limestones, and dolomites. The ratios of the carbonates to the shales can change greatly from one location to another in southeastern Michigan. The shales can contain thin carbonate lenses. The limestone and dolomite can exhibit thin or massive bedding and can contain some chert lenses (Mozola, 1969, 1970).

The Traverse Formation in northwestern Ohio contains two major lithologies. The basal part of the Traverse is an fine- to coarse-grained, argillaceous and fossiliferous limestone interbedded with calcareous shale. The upper part consists of a dense to medium-crystalline dolomite that contains lenticular and nodular chert and minor interbedded shaly dolomite and shale (Janssens, 1970). The Traverse Formation unconformably overlies the Delaware and the Dundee Limestones and is unconformably overlain by the Antrim or Ohio Shale (Janssens, 1970; Hull, 1990; Larsen, 1991).

In western New York, the Hamilton Group is equivalent to the Delaware and Dundee Limestones and the Traverse Formation. The upper part of the Hamilton Group is equivalent to the Olentangy Shale and the Plum Brook Shale and the Prout Limestone (fig. 6). The Hamilton Group is a predominantly shale sequence with minor limestone and sandstone layers. The Hamilton Group lies conformably on the Onondaga Limestone and is unconformably overlain by the Genesee Group (Isachsen and others, 1991). The basal section of the Hamilton Group is a black shale that is overlain by thin limestone, which in turn is overlain by a fissile shale with several calcarious beds or thin limestone layers (La Sala, 1968).

During late Middle Devonian and Late Devonian time, the Acadian Orogeny resulted in the formation of the Catskill Delta complex, which spread from the



EXPLANATION

Unconformity

Stratigraphic unit in the shallow ground-water flow system (well yields and relations of aquifers and confining units given in Table 11)

Nomenclature is primarily that of Patchen and others (1984) and Shaver (1984), with the following exceptions: Silurian units in northeastern Ohio modified from Hull (1990); Upper Devonian units in northwestern Pennsylvania modified from Schiner and Gallaher (1979). Nomenclature may vary from that of the U.S. Geological Survey.

Figure 6. Geologic and hydrologic units in the Lake Erie-Lake St. Clair Basin.

northeastern Appalachian Basin south along the trend of the basin and west onto contiguous sections of the craton. The Acadian Mountains were uplifted along the eastern margin of the craton and were a source area for the sediments that were shed into the Appalachian Basin (Ettensohn and Barron, 1981). The Catskill Delta complex had a widespread distribution that ranged from the source area near the cratonic margin, across the Appalachian Basin onto the Cincinnati, Findlay, and Algonquin Arches, and into the east- and north-central midcontinent area of Indiana, Illinois, and eastern Iowa (Ettensohn and Barron, 1981; Devera and Hasenmueller, 1991).

In northeastern Ohio, the Olentangy Shale unconformably overlies the Delaware Limestone and is unconformably overlain by the Ohio Shale (Hoover, 1960; Larsen, 1991). The Olentangy Shale is equivalent to the Plum Brook Shale and the Prout Limestone (Hoover, 1960). The Olentangy Shale is a shale with black, fissile shale beds in the upper part of the unit; these black shale beds are more numerous in southwestern Ohio. The Plum Brook Shale is a soft, fossiliferous shale with bands of argillaceous limestone, and the Prout Limestone is a hard, siliceous limestone (Hoover, 1960).

In northeastern Indiana, the Antrim Shale paraconformably overlies the Traverse Formation (Muscatatuck Group) and is laterally equivalent with parts of the Ellsworth Shale (fig. 6) (Shaver and others, 1986; Gutschick and Sandberg, 1991). The Antrim Shale was described by Lineback (1970) as a mostly brownish-black shale that includes a greenish-gray shale in the basal section of the unit.

The Antrim or the Ohio Shale in southeastern Michigan and northwestern Ohio unconformably overlies the Traverse Formation and is conformably and unconformably overlain by the Bedford Shale; it is buried by glacial sediments where it crops out at the bedrock surface (fig. 6) (Shaver, 1985; Hull, 1990; Larsen, 1991). The Antrim Shale was described by Janssens (1970) as a fissile shale in which the basal 30 ft is interbedded with minor dolomitic layers.

The Ohio Shale in northeastern Ohio unconformably overlies the Olentangy Shale or the Plum Brook Shale and the Prout Limestone. The Ohio Shale is a fissile shale that contains some argillaceous layers, thin sheets of micaceous sandstone, and pyrite (Hoover, 1960). The Ohio Shale and its equivalents constitute a carbon-rich or petroliferous shale sequence that has been a producer of moderate quantities of natural gas (Janssens and de Witt, 1976). The Ohio Shale in northeastern Ohio is equivalent to the Antrim or Ohio Shale in northeastern Indiana and northwestern Ohio, north of the Findlay Arch (Shaver, 1985).

In northwestern Pennsylvania within the basin, Upper Devonian rocks are the oldest time-stratigraphic units in the shallow ground-water flow system. These units are the Conneaut Group and the Conewango Group. The Conneaut Group is a shale interbedded with siltstone and shaly fine-grained sandstone. The Conneaut Group conformably and unconformably overlies the Canadaway Group and is conformably overlain by the Conewango Group. The Conewango Group consists primarily of interbedded shale and siltstone with layers of thin, very fine grained sandstone. The upper section of the Conewango Group is a shale (Schiner and Gallaher, 1979; Richards and others, 1987)

In western New York, the equivalents of the Ohio or the Antrim Shale are the Genesee, the Sonyea, the West Falls, the Canadaway, and the Conneaut Groups (Isachsen and others, 1991). The Genesee Group is a shale with limestone beds at its base. The Sonyea Group is a shale. The West Falls Group is a shale and siltstone that is petroliferous in the lower part. The Canadaway Group is a shale and siltstone that contains many calcareous concretions in the lower half of the unit and grades from a shale to siltstone in the upper half of the unit. The Conneaut Group is a shale, siltstone, and fine-grained sandstone (La Sala, 1968).

Devonian and Mississippian Rocks

In northeastern Indiana, the Ellsworth Shale conformably overlies the Antrim Shale. In northern Indiana, the Ellsworth Shale is laterally equivalent to the Sunbury Shale and is conformably overlain by the Coldwater Shale (Shaver and others, 1986). The Ellsworth Shale crops out at the bedrock surface in northeastern Indiana, where it is covered by glacial deposits. The Ellsworth Shale is described as consisting of alternating beds of gray-green shale and brownish-black shale in the lower part and grayish-green shale in the upper part (Hasenmueller and Woodard, 1981).

In southeastern Michigan, the Bedford Shale conformably overlies the Antrim Shale and is conformably overlain by the Berea Sandstone. The Bedford Shale is a limy or sandy shale. It also can contain a micaceous sandstone and a shaly dolomite. The Bedford Shale is a subcrop beneath glacial drift and is not exposed at land surface in the basin (Mozola, 1969).

North of the Findlay Arch in northwestern Ohio, the Bedford Shale is a soft to hard siliceous shale (J.M. King, 1977). South and east of the Findlay Arch in northwestern and northeastern Ohio, the Bedford Shale grades from a soft, clay-rich shale in the lower part of the formation to a siltstone containing silty shale layers in the upper part of the formation. In easternmost Ohio, the basal section of the Bedford Shale is in a facies relation with a poorly cemented, medium- to coarse-grained quartz sandstone. This basal section is the westernmost extension of the Cussewago Sandstone. In northeastern Ohio, the Cussewago Sandstone conformably overlies the Ohio Shale and is conformably overlain by the Bedford Shale (Winslow and White, 1966; Rau, 1969; Hull, 1990). The Bedford Shale conformably overlies the Antrim or the Ohio Shale and is conformably and unconformably overlain by the Berea Sandstone (Hoover, 1960).

Mississippian Rocks

In northwestern Pennsylvania, the Cussewago Sandstone is a sandstone that can be divided into a lower and upper section. The lower section of the Cussewago Sandstone is a fine- to coarse-grained, dominantly massive sandstone. This section may contain very coarse sand or pebbles of quartz or chert near its base. The lower section of the Cussewago Sandstone is poorly cemented and, in places, the massive sandstone exhibits steep-angle crossbedding. The upper section of the Cussewago Sandstone is a very fine to fine-grained, thin-bedded, micaceous sandstone that contains interbedded shales and siltstones. The Cussewago Sandstone conformably overlies the Conewango Group and is conformably overlain by the Bedford Shale (Schiner and Gallaher, 1979; Richards and others, 1987). The Bedford Shale is a thinly bedded, silty shale that in places is a siltstone to a very fine grained sandstone. The Bedford Shale is conformably overlain by the Berea Sandstone and conformably overlies the Cussewago Sandstone (Schiner and Gallaher, 1979).

In southeastern Michigan and north of the Findlay Arch in northwestern Ohio, the Berea Sandstone is a fine-grained sandstone and shale. The Berea Sandstone conformably overlies the Bedford Shale and is conformably overlain by the Sunbury Shale. The Berea Sandstone is the lateral equivalent of the upper section of the Ellsworth Shale in northeastern Indiana (Mozola, 1969; Shaver, 1984; Harrell and others, 1991).

The Berea Sandstone in northeastern Ohio can have three separate sections. The basal section is a crossbedded, coarse-grained, well-indurated sandstone. The middle section is a massive, medium- to coarse-grained sandstone. The upper section of the Berea Sandstone is a fine-grained sandstone that contains shale stringers and partings. The Berea Sandstone is conformably and unconformably underlain by the Bedford Shale and conformably overlain by the Sunbury Shale (Winslow and others, 1953).

In northwestern Pennsylvania, the Berea Sandstone is a silty, fine-grained sandstone that can be very difficult to distinguish from the underlying Bedford Shale. The Berea Sandstone in northwestern Pennsylvania is a finer grained facies of the Berea Sandstone northeastern Ohio. The Berea Sandstone is conformably underlain by the Bedford Shale and conformably overlain by the Cuyahoga Group (Schiner and Gallaher, 1979; Richards and others, 1987).

In northern Indiana and northwestern most Ohio, the Sunbury Shale conformably overlies and is laterally equivalent to the Ellsworth Shale (Shaver and others, 1986) (fig. 6). The Sunbury Shale is conformably overlain by the Coldwater Shale (Shaver and others, 1986) (fig. 6). Hasenmueller and Woodard (1981) describe the Sunbury Shale as a brownish-black, carbonaceous shale.

The Sunbury Shale in southeastern Michigan is a well-cemented shale that can contain traces of dolomite. The Sunbury Shale is conformably underlain by the Berea Sandstone and conformably overlain by the Coldwater Shale (Mozola, 1969).

In northeastern Ohio, the Sunbury Shale is a bituminous shale that grades into a siltstone that pinches out near the Ohio-Pennsylvania State line (Rau, 1969). The Sunbury Shale is conformably underlain by the Berea Sandstone and conformably overlain by the Cuyahoga Formation (Hull, 1990).

The Coldwater Shale in northern Indiana conformably overlies the Ellsworth and Sunbury Shales. The Coldwater Shale crops out at the bedrock surface in northern Indiana, where it is deeply buried by glacial deposits (Johnson and Keller, 1972). Shaver and others (1986) describe the Coldwater Shale as a silty shale.

In southeastern Michigan and northwesternmost Ohio, the Coldwater Shale is primarily a shale in the basal section; the upper section includes some fossiliferous shale that can contain lenses or thin beds of sandstone dolomite or siltstone. The Coldwater Shale conformably overlies the Sunbury Shale and is conformably overlain by the Marshall Sandstone (Mozola, 1969; Cohee, 1979).

In northeastern Ohio, the Cuyahoga Formation is the time equivalent of the Coldwater Shale in northern Indiana and southeastern Michigan. The Cuyahoga Formation is composed of interbedded shales and thin sandstones and a uniform soft, fissile shale. This formation can be subdivided into three sections: a basal section consisting of a fissile shale; a middle section consisting of interbedded shale and limy, fine sandstone; and an upper section consisting of sandstone beds (Winslow and others, 1953; Winslow and White, 1966). The Cuyahoga Formation is unconformably overlain by the Pottsville Group or by Quaternary deposits, and it conformably overlies the Sunbury Shale (Winslow and others, 1953; Winslow and White, 1966; Hull, 1990).

The Cuyahoga Group in northwestern Pennsylvania is the time equivalent of both the Sunbury Shale and the Cuyahoga Formation of northeastern Ohio. Schiner and Gallaher (1979) describe the Cuyahoga Group as a unit that could be considered a single formation consisting primarily of shale and containing widespread lenses of sandstone in the middle of the unit. The basal section is an argillaceous to silty, fissile shale that contains thin beds of fine-grained sandstone to siltstone. The middle section consists of a thinly bedded, fine-grained sandstone separated by beds of siltstone and shale, and it may contain limestone near the base. The upper section of the group is a micaceous siltstone and silty shale with some lenses of fine-grained sandstone (Schiner and Gallaher, 1979). The Cuyahoga Group conformably overlies the Berea Sandstone and is conformably overlain by the Shenango Formation; where the Shenango Formation has been eroded, the Cuyahoga Group is unconformably overlain by the Quaternary deposits (Schiner and Gallaher, 1979).

Where the Shenango Formation has not been eroded in northwestern Pennsylvania, it contains two dominant lithologies. The basal section consists of a well-cemented, very fine to medium-grained sandstone that is intertongued with shale and siltstone. The upper section of the Shenango Formation is a shale interbedded with thin layers of siltstone to very fine sandstone; thin, silty limestones; and thin layers of siderite concretions. The Shenango Formation conformably overlies the Cuyahoga Group and, within the basin in northwestern Pennsylvania, is unconformably overlain by the Quaternary and Holocene deposits (Schiner and Gallaher, 1979)

In southeastern Michigan, the Marshall Sandstone consists of sandstone interbedded with limestone, dolomite, siltstone, and shale. The basal section of the Marshall Sandstone is a fine- to medium-grained sandstone that contains abundant micas in its lower half. The middle section of the Marshall Sandstone consists of a shale and carbonate sequence. The upper section of the Marshall Sandstone consists of a fine- to medium-grained sandstone (Westjohn and Weaver, 1994). The Marshall Sandstone conformably overlies the Coldwater Shale and is unconformably overlain by the Michigan Formation (Michigan Geological Survey, 1964).

The Michigan Formation is an interbedded sequence of shale, limestone, dolostone, gypsum or anhydrite, siltstone, and sandstone. The individual beds that compose this formation are generally less than 10 ft thick (Westjohn and Weaver, 1994). The Michigan Formation unconformably overlies the Marshall Sandstone and is conformably overlain by the Bayport Limestone (Michigan Geological Survey, 1964).

Pennsylvanian Rocks

In northeastern Ohio, the Pottsville Group is principally a sandstone unit with a few discontinuous shale lenses and two shale units that contain thin coals, underclays, and limestones. The basal section of the Pottsville Group is a coarse- to medium-grained, pure quartz sandstone conformably overlain by a sandy, gray-black shale with thin coal seams. This section can contain poorly cemented lenses or channel fillings of coarse, pebbly conglomerate. The next stratigraphically younger section is a coarse- to medium-grained sandstone that unconformably overlies the previously described sandy shale. This sandstone is moderately cemented to well cemented; it can be massive or it can contain crossbedding and channel-fill deposits. Within the section, the sandstone is separated by a distinct shale break. Overlying this sandstone section is a silty to carbonaceous shale that is interbedded with coarse- to medium-grained sandstones, thin coal seams, underclays, and thin limestones. The shale unconformably underlies the uppermost section of the Pottsville Group. The uppermost section of the Pottsville Group ranges from a well-sorted quartz sandstone to a poorly sorted, medium- to fine-grained sandstone. This uppermost section commonly contains shale lenses and can locally be a shale (Winslow and White, 1966; Sedam, 1973).

Quaternary deposits

All of the basin is overlain by Pleistocene deposits (fig. 7). Most are of Wisconsinan age and represent three major stages of the Wisconsinan glaciation (early, middle, and late). Advances by the late Wisconsinan Laurentide Ice Sheet removed evidence of earlier glaciations in most places by eroding the surficial materials and incorporating earlier deposits with those transported by the glacier. In many places, the ice sheets overrode and deposited sediments on top of older deposits (Mickelson and others, 1983). The resulting landforms are a composite of unconsolidated deposits from multiple glacial advances and retreats.

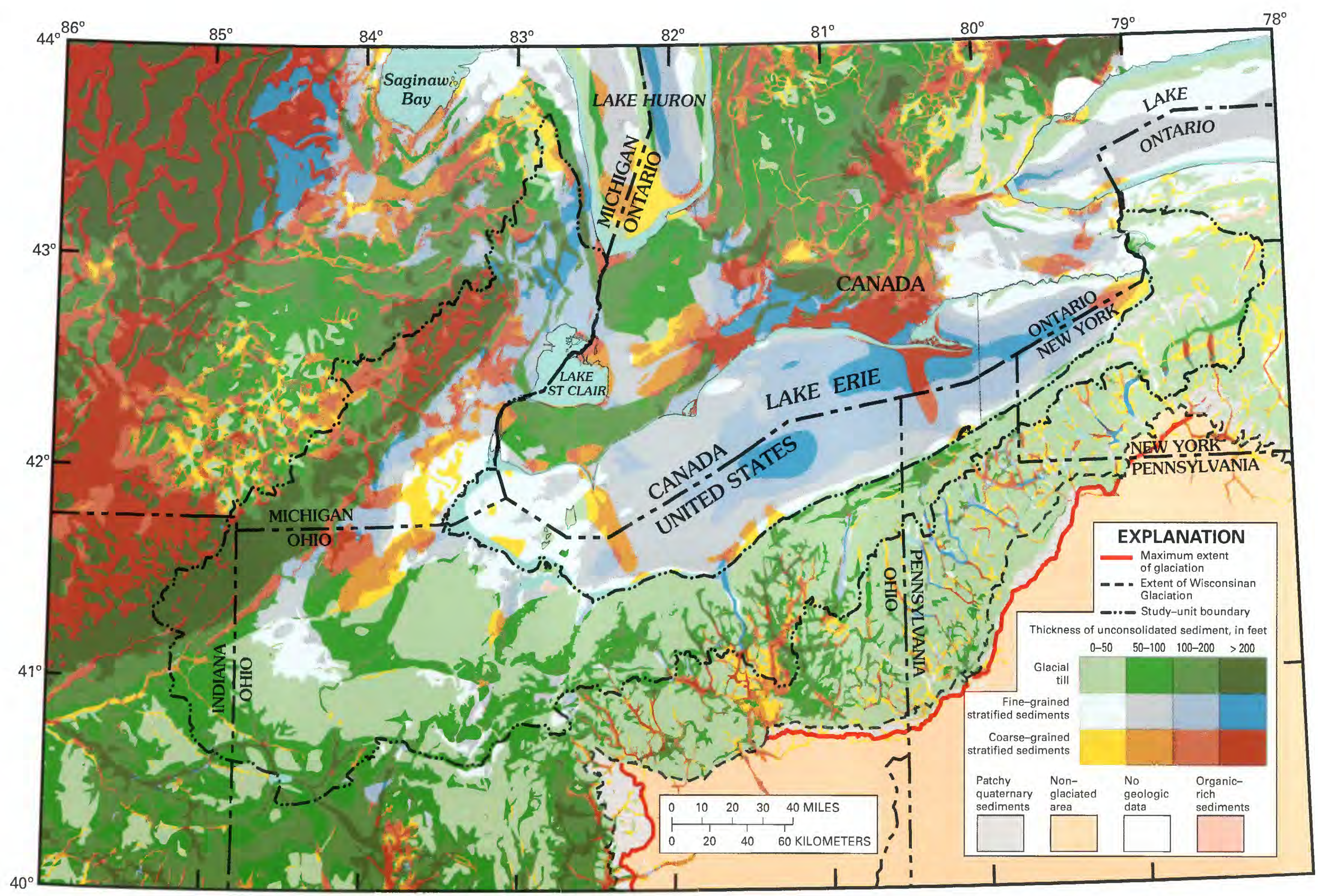
Till, the most widespread surficial material in the Lake Erie-Lake St. Clair Basin, consists of material deposited in contact with glacial ice. Soller (1992, p. 5) describes till as "a poorly sorted and generally unstratified deposit composed of particles ranging in size from clay to large boulders." The composition of till in the glacial deposits depends on glacial flowpaths and local geology. Most of the mineral composition of a till is representative of local bedrock (Strobel and Faure, 1987). Many of the till units in the study area are clay rich because of the composition of the bedrock (the Devonian and Mississippian shales) and its low resistance to glacial erosion. The Wisconsinan glacial deposits have a till composition that is determined by the inclusion of earlier glacial and interstadial material during the final ice advance. The direction of flow determined from erosional and depositional features indicates that ice advances during the late Wisconsinan time crossed the Lake Erie and Lake Ontario Basins and other interstadial lakes (Whillans, 1985). The Lake Erie and Lake Ontario Basins and the interstadial lakes provided clay-rich lacustrine sediments that have been included in the upper Wisconsinan tills. This flow of ice across lakes is probably responsible for much of the clay component in some of the tills (Whillans, 1985; Prudic, 1986).

As glaciers melt during a recession or a still-stand, sediments are released from the glacial ice and are generally deposited in flowing water. These stratified sediments are found in several settings that include glaciolacustrine, glaciofluvial, and outwash plains (Soller, 1992). Two types of stratified sediments, determined by grain size, make up the remainder of the major glacial sediments (fig. 7).

Coarse-grained stratified sediments consist of sand and gravel deposited as glacial outwash on alluvial plains and deltas, and as fluvial, glaciofluvial, and deltaic deposits in valleys. In many valleys, thick, coarse-grained stratified sediments underlie thin Holocene alluvium. Some holocene alluvium is also included in the coarse-grained stratified sediments because it has been derived from reworked glacial sediments, but it can be silty or clay rich (Soller, 1992).

Fine-grained stratified sediments consist of clay, silt, very fine sand, and small amounts of interbedded coarser sediment. These sediments were deposited in slow-moving or stagnant water, in a distal position relative to the melting ice front. Along the edge of Lake Erie and Lake Ontario, Holocene mud overlies fine-grained, stratified, glacial-lake-derived sediments. On these ancient lake plains, clay-rich till has been winnowed by lake waters or has incorporated an older lake deposit (Soller, 1993). As the glacial ice receded from the western end of the Lake Erie Basin, the meltwater was contained within the postglacial topography at an elevation of about 800 ft above sea level and the margin of the receding glacier. During this time, all drainage from the ancient lake is postulated to have flowed through an outlet near Fort Wayne, Ind., and across Indiana in the Wabash River. In this lake and succeeding lakes, fine-grained stratified sediments were deposited.

A system of buried river valleys filled with various lacustrine, alluvial, and glacial deposits is present in the Lake Erie-Lake St. Clair Basin beneath the St. Marys, Auglaize, Cuyahoga, and Grand Rivers and Cattaraugus Creek (fig. 7). These buried river valleys have been referred to by several names based on location and origin. These valleys were formed as a result of the continental glaciations during the Pleistocene Epoch, although there is evidence that preglacial river systems followed similar courses (Fullerton, 1986; Goldthwait, 1991). As the ice margin retreated northward, sediment-laden rivers incised the bedrock of northern Ohio and eastern Indiana, altering the preglacial valleys and later depositing valley-fill material (Gray, 1991). In the glacially altered valley near the mouth of the Cuyahoga River, the stratified deposits exceed 600 ft in thickness (Soller, 1993). There is also evidence of smaller buried valleys cut in glacial till in northeastern Ohio (fig. 7). These buried valleys have been formed by several mechanisms, one of which seems to have been cutting by streams in interglacial or interstadial times and simultaneous filling with coarse-



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Data from Soller, David R., 1993, 1994, and in press, U.S. Geological Survey Miscellaneous Investigations Series Map I–1970–A,–B,–C,–D

Figure 7. Limit of Wisconsinan glaciation, major surficial-deposit types, and thickness of unconsolidated materials in the Lake Erie-Lake St. Clair Basin.

grained deposits. Another proposed mechanism is cutting by meltwater streams and subsequent filling by an ice readvance (Norris and White, 1961).

Soils

The soils of the Lake Erie-Lake St. Clair Basin consists of two dominant soil orders, Alfisols and Inceptisols, at about 74 percent and 18 percent of the total basin area, respectively. The four other soil orders in the basin (Mollisols, Histisols, Entisols, and Spodosols) are of minor significance, making up less than 8 percent of the total area. The soils of the basin are relatively young because of the recent glacial history. Four major glaciations affected the basin, the last (Wisconsinan glaciation) ending roughly 12,000 years ago. During the Wisconsinan glaciation, former glacial deposits mixed with new deposits, resulting in young, clayey soils that are deep in some areas. The soils in the basin are derived from predominantly lacustrine deposits and ground moraines that are unsorted, unconsolidated materials. Most of the soils of the basin are naturally fertile because of their high clay content, seasonal wetness, and low permeability (Ohio Department of Natural Resources, 1987). In much of the basin, the flat to gently rolling topography helps to retain nutrients so that they are not leached out of the soils.

The most common soil order in the basin is the Alfisols, which are characterized by clay accumulation in the B horizon and relatively high base saturation values. Base saturation is defined as the sum of exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), expressed as a percentage of the cation-exchange capacity (CEC) at pH 7.0 or 8.2. The CEC of a soil is the amount of negative charge per unit weight of soil that is neutralized by easily replaceable cations and is proportional to the amount of clay and organic matter in the soil (Hausebillier, 1985, p. 148–154). Alfisols in the Lake Erie-Lake St. Clair Basin have low amounts of organic material; therefore, they owe their CEC values to clay minerals derived from weathered and reworked glacial deposits. Because glacial deposits in the basin were derived from glacial erosion of underlying calcareous shales and carbonate bedrock (particularly in southeastern Michigan and northwestern Ohio), the resulting soils are rich in calcium and magnesium, have pH's near 7.0, and consequently have high base saturation values. As a result, Alfisols in the basin are very fertile

Table 1. Major soil associations in the Lake Erie-Lake St. Clair Basin
[From Boul and others, 1989]

Soil orders	Great groups	Properties	Percentage of basin[1]
Alfisols: High clay accumulation, high base saturation, neutral to slightly acidic pH	Ochraqualfs	Wet soils with less organic matter than described by the soil order	44.2
	Hapludalfs	Soils formed under humid conditions, with indiscriminate characteristics (misc. category)	23.6
	Fragiaqualfs	Wet soils with a fragipan (a restrictive zone)	3.4
Inceptisols: Weakly developed young soils, low clay content, low moisture, low base saturation	Haplaquepts	Wet soils with less organic matter than described by the soil order	12.3
	Dystrochrepts	Low organic matter with indiscriminate characteristics	5.0
Mollisols: Deep, dark, fertile topsoils, exceptional soil structure, poor natural drainage	Argiaquolls	Wet soils for most of the year, composed mostly of sand	2.8
Entisols: Little or no evidence of development of soil structure	Udipsamments	Wet soils with a horizon of illuvial clay	2.0

[1]Two smaller soil orders and nine smaller great groups make up the rest of the basin.

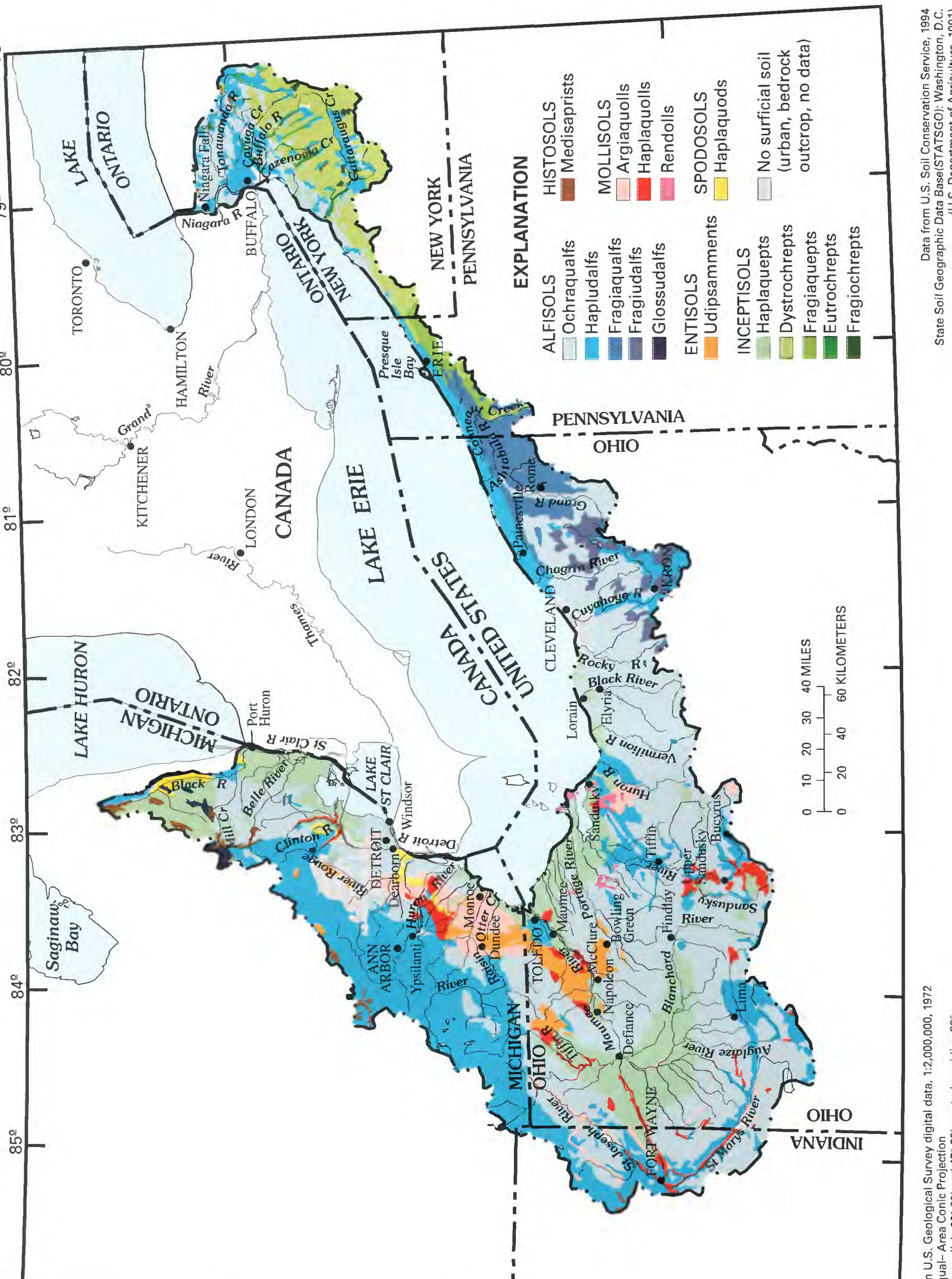


Figure 8. Distribution of soil orders and great groups in the Lake Erie-Lake St. Clair Basin.

and can sustain intensive agriculture without a need for extensive lime amendments.

The 6 soil orders in the basin are subdivided into 16 associations, called great groups, 4 of which make up 85 percent of the total area (table 1). The Ochraqualfs soil association (fig. 8) is the dominant great group, making up 44 percent of the basin area. The Ochraqualfs association is an Alfisol group that is nearly level to undulating. Ochraqualfs soils are poorly drained and are slightly acidic to neutral (University of Wisconsin, 1950). These soils are naturally fertile, with low permeability and a high clay content. Prior to the widespread settlement of northwestern Ohio in the 1870's, these poorly drained Ochraqualfs soils comprised an area known as the Black Swamp. Artificial drainage was necessary for agriculture to take place on the flat topography, where ponds commonly form when these soils became saturated (Ohio Department of Natural Resources, 1987). The use of artificial drainage techniques transformed the Ochraqualfs soils of the Black Swamp into productive cropland.

The Hapludalf soil association (fig. 8) is an Alfisol that covers about 24 percent of the basin. The Hapludalfs are associated with a nearly level to rolling landscape. The soils are moderately well drained to poorly drained. Hapludalfs are grayish-brown, medium acid, silty loams that have very dark brown or black, neutral, clay loam surfaces. The permeability of the clay or silty clay subsoils is very low. These soils developed from calcareous clay loam or silty clay loam (University of Wisconsin, 1950). They are moderately productive when liming, fertilization, and erosion-control practices are used. Within the Hapludalf soil association, small sections of dark-colored, poorly drained organic soils (Histisols) are present in the associated depressions or bogs (kettles). Also occurring within the Hapludalf soil association is a sandy soil (Entisols). This Entisol is mixed with the Hapludalfs along the western edge of ancient Lake Erie. It was developed from lacustrine clay and till deposits. These sandy soils have low natural fertility, low moisture-holding capacities, and a tendency to be eroded by wind. Artificial drainage is needed for poorly drained (Hapludalf) soils that lie beneath variable thicknesses of sandy overburden (University of Wisconsin, 1950).

The next most common soil order in the basin is the Inceptisols, which are weakly developed, young soils derived from highly resistant parent material; they contain little organic matter. The parent material of Inceptisols in the basin is shale and sandstone. The resistant parent material slows weathering and limits the amount of clay produced (Boul and others, 1989). A low clay content in the soil leads to low moisture-holding capacity and a low base saturation, which results in low fertility. The Inceptisols in the basin represent about 18 percent coverage of the total area.

The Haplaquepts is an Inceptisol that covers 12 percent of the basin (fig. 8). This soil association is formed in nearly level to undulating topography. Haplaquepts are poorly to moderately drained soils with black and dark-grayish-brown, neutral clay loam and loam surfaces. Haplaquepts developed from calcareous loam and clay loam till. A few sandy beach ridges are also present within this association (University of Wisconsin, 1950). Inceptisols that are seasonally wet and have an organic subsurface horizon that is mottled or gray in color; they are normally used for woodland pastures and hay. Inceptisols generally have either a light-colored or a black surface horizon. (U.S. Geological Survey, 1967).

The Dystrochrepts is an Inceptisol that covers roughly 5 percent of the basin. It is found mostly in New York, in the Cattaraugus Creek Basin on the Appalachian Plateaus. The soil is one of six suborders of the Inceptisols called Ochrepts, which refers to the soil association as having low organic-matter content (Boul and others, 1989). The prefix "dystr" in this great group means miscellaneous; this association does not fit the criteria of the other great groups in the suborder.

Mollisols and Entisols together make up only about 7 percent of the basin, 5 and 2 percent respectively. Generally, Mollisols are formed under steppe and prairie conditions that lead to the development of deep, dark, relatively fertile topsoil with exceptional soil structure for agriculture (Boul and others, 1989). However, some Mollisols, like those in the basin, form under woodland conditions that lead to poor natural drainage and (or) a high base saturation (Boul and others, 1989). Entisols are soils that show little or no evidence of development of soil features, such as soil structure, but nevertheless can support life (Boul and others, 1989). The Entisols in the basin were formed from ancient Lake Erie deposits laid down by longshore currents that also formed old sandy beach ridges when lake levels of ancient Lake Erie were higher than those of the present-day lake.

The two remaining soil orders, Histisols and Spodosols, combined make up barely 1 percent of the basin. Histisols are an organic soil, and the Spodosols have subsoil accumulation of organic matter and clay.

The accumulation in the subsoil of Spodosols is due to an upper soil horizon that is prone to leaching.

Population

In 1990, the population of the Lake Erie-Lake St. Clair Basin was approximately 10.4 million people. About 340,000 people resided in Indiana, 4.64 million in Michigan, 3.93 million in Ohio, 235,000 in Pennsylvania, and 1.25 million in New York (U.S. Geological Survey, 1995a). Large urban areas in the basin are common: 38 cities in the basin had a population that exceeded 20,000 people in 1990 (American Map Corporation, 1993). The metropolitan areas of Detroit, Mich., Cleveland, Ohio, and Buffalo, N.Y., represent roughly 62 percent of the population in the basin (fig. 9).

The population of cities with greater than 100,000 people generally decreased between the 1980 and 1990 censuses (table 2). Major population declines occurred in Detroit, Cleveland, and Buffalo; overall, the three cities registered a 12.9-percent reduction in population. Other cities whose population decreased between 1980 and 1990 were Toledo and Akron, Ohio, Erie, Pa., and Livonia and Warren, Mich. (Livonia and Warren are suburbs of Detroit.) Cities in the basin where population increased were Ann Arbor and Sterling Heights, Mich., and Fort Wayne, Ind. (U.S. Department of Commerce, Bureau of the Census, 1993, table 2).

Land use

Land use is the "most important representation of the human element of the environmental framework" (Hitt, 1994b). Land use implies human activity, which in turn implies an influence on the quality of water. For example, land use classified as agricultural implies the use of fertilizers and pesticides as a part of the associated human activity. Likewise, land use defined as industrial implies the potential for release of contaminants and by-products as a part of the associated human activity.

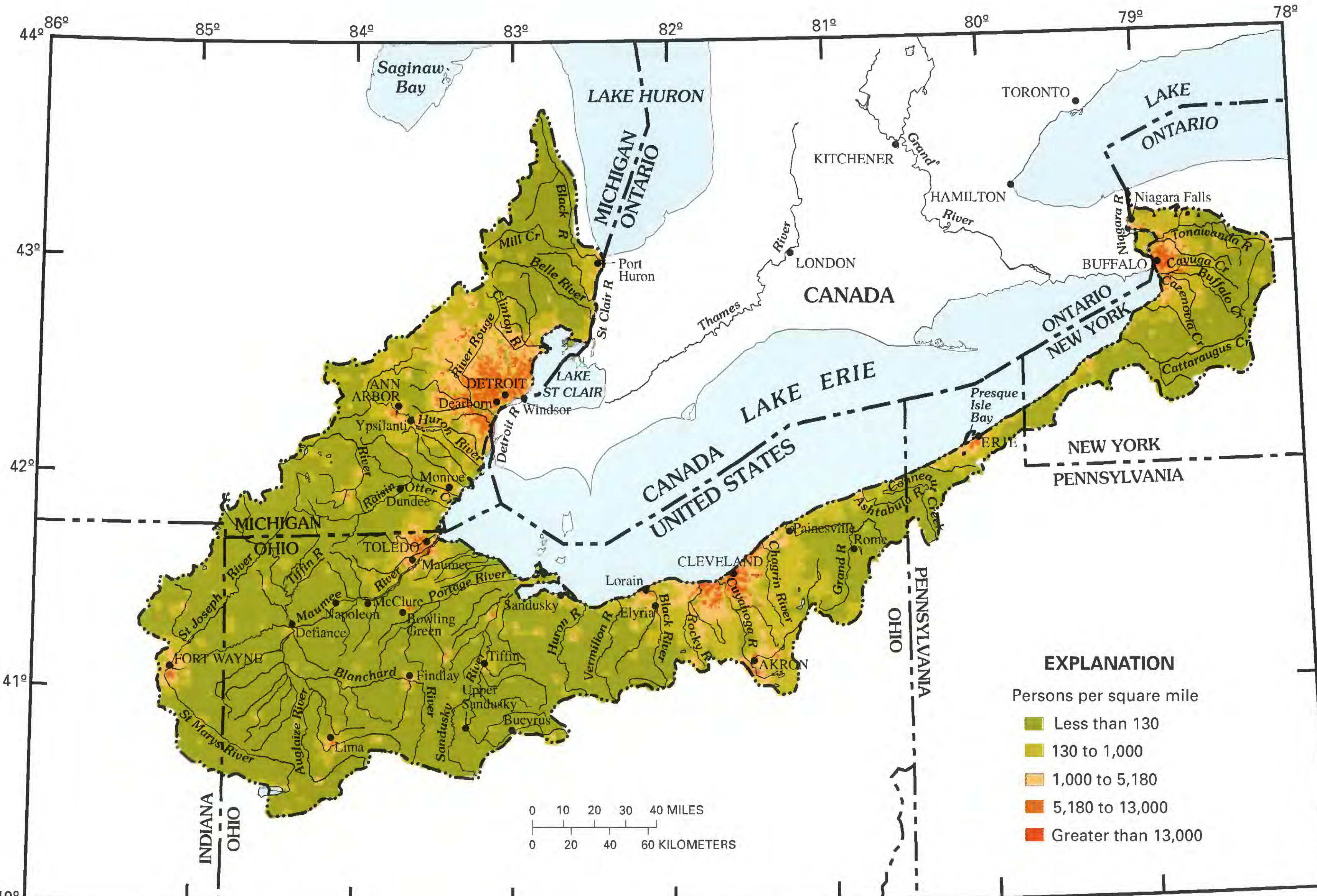
Because a nationwide data base on recent land use and land cover does not exist, information was derived from various sources. The only national data base is the USGS land use and land cover digital data set from 1:250,000- and 1:100,000-scale maps (U.S. Geological Survey, 1990). Although the data base is limited because source materials are somewhat outdated and the resolutions are coarse, it can be used to illustrate general patterns of land use and to establish a baseline for assessing change since the 1970's. This land-use data set was the foundation for a refined land-use classification scheme for the basin, in which 1990 population census data were used to redefine urban residential land use. Agricultural census data from 1987 were used to help describe the types of agricultural activity in the basin. The USEPA Toxic Release Inventory (TRI) and the National Pollution Discharge and Elimination System (NPDES) data sets were used to help describe other point sources of pollutant emissions associated with land use that may affect water quality in the basin.

The USGS land-use and land-cover data set is coded by use of the Anderson classification system (Anderson and others, 1976). The Anderson system is a hierarchical system of classes that range from 9 general classes (level I) to 37 more specific characterizations (level II). The data are stored in a digital format

Table 2. Population and percentage change in population of metropolitan areas with 100,000 people or more in the Lake Erie-Lake St. Clair Basin, 1980-90

Metropolitan area	Population (in thousands)		Percent change
	1980[1]	1990[1]	
Akron, Ohio	237	223	-5.9
Ann Arbor, Mich.	108	110	1.8
Buffalo, N.Y.	358	328	-8.4
Cleveland, Ohio	574	506	-11.8
Detroit, Mich.	1,203	1,028	-14.5
Erie, Pa.	119	109	-8.4
Fort Wayne, Ind.	172	173	.6
Livonia, Mich.	105	101	-3.8
Sterling Heights, Mich.	109	118	7.6
Toledo, Ohio	355	333	-6.2
Warren, Mich.	161	145	-9.9

[1]Source: U.S. Department of Commerce, Bureau of the Census, 1993.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal–Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Population distribution modified from U.S. Department of Commerce, Bureau of the Census, 1993, and U.S. Geological Survey Geographic Information Retrieval Analysis System land-use data, 1991

Figure 9. Population density in the Lake Erie-Lake St. Clair Basin, 1990.

called Geographical Information Retrieval System, or GIRAS (Mitchell and others, 1977), which was converted to a more usable vector format (polygon coverage) for the Lake Erie-Lake St. Clair Basin. Data for the basin consist of thirteen 1:250,000-scale quadrangles that were merged into one data set. The level I and level II land-use categories pertaining to the basin are listed in table 3.

Agricultural and urban land uses are the principal anthropogenic land uses in the basin (fig. 10). Agriculture makes up 74.8 percent of the total basin area, with croplands and pasture as the predominant types (74.6 percent) and orchards, groves, and vineyards making up the remainder (0.1 percent). Urban land use accounts for 11.2 percent of the basin area, with residential (6.7 percent) predominating and commercial (1.5 percent), transportation (0.9 percent), industrial (0.8 percent) and other mixed urban land (1.3 percent) making up the remainder. Forested areas constitute 10.5 percent of the basin area, whereas water, wetlands, and barren land constitute less than 4.0 percent of the basin area (fig. 10).

Land use in the basin, particularly agriculture, is affected by the physiography and climate. To help describe the various types of agricultural practices, county data from the 1987 Census of Agriculture (U.S. Department of Commerce, Bureau of the Census, 1990) were used to develop information on the distribution and percentage of total agricultural acres used for row crops, orchard and vineyards, rangeland, and other agricultural uses.

The county-by-county analysis shows that row-crop agriculture is more common in the flat, fertile Central Lowland Province of southeastern Michigan, northeastern Indiana, and northwestern Ohio than in the hilly Appalachian Plateaus Province of northeastern Ohio, northwestern Pennsylvania, and western New York. Table 4 shows the distribution of crop type by location in the basin (Gilliom and Thelin, 1997). In the northeastern part of Michigan, between Saginaw Bay and Lake Huron, a greater percentage of the total crop is wheat because the climate is cooler and drier than in most other places in the basin. Elsewhere, crops in the Central Lowland are predominantly corn and soybeans.

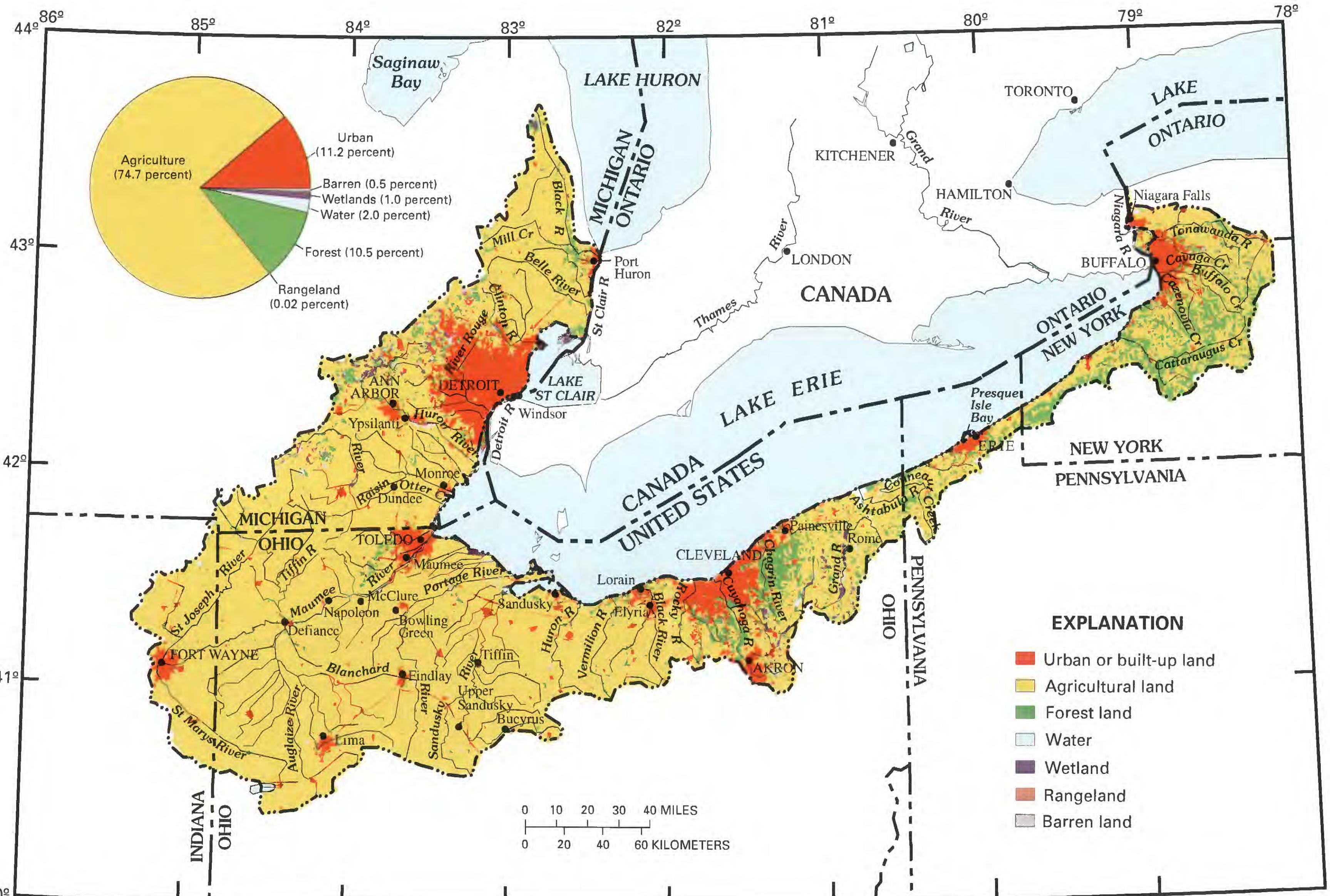
Coastal areas along Lake Erie are dominated by vineyards and orchards, owing to the lake-affected climate. Summers are cool and dry, and winters are moderate in temperature and wet.

In the Appalachian Plateaus, pasture and forage crops (corn and alfalfa) are the main crops. These crops are grown for silage because the hilly terrain is more

Table 3. U.S. Geological Survey land use and land cover classification system

[From Anderson and others, 1976]

Level I	Level II
1 Urban or built-up land	11 Residential
	12 Commercial and services
	13 Industrial
	14 Transportation, communications, and utilities
	15 Industrial and commercial complexes
	16 Mixed urban or built-up land
	17 Other urban or built-up land
2 Agricultural land	21 Cropland and pasture
	22 Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
	23 Confined feeding operations
	24 Other agricultural land
3 Rangeland	32 Shrub and brush rangeland
4 Forest land	41 Deciduous forest
	42 Evergreen forest
	43 Mixed forest
5 Water	51 Streams and canals
	52 Lakes
	53 Reservoirs
	54 Bays and estuaries
6 Wetland	61 Forested wetland
	62 Nonforested wetland
7 Barren land	72 Beaches
	75 Strip mines, quarries, and gravel pits
	76 Transitional areas



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Land use from U.S. Geological Survey Geographic Information Retrieval System data, 1990, scale 1:250,000

Figure 10. Distribution and percentages of Anderson level I land used classifications in the Lake Erie-Lake St. Clair Basin.

conducive to pasture and dairy farming than to row cropping.

Urban land use also has been heavily influenced by physiography. The major urban centers in the basin are near Lake Erie or Lake St. Clair and their connecting channels, not only because of the industrial and public need for freshwater but also for transportation and power-generation purposes. Land-use categories from Anderson and others (1976) were overlain with a digital county coverage (U.S. Department of Commerce, Bureau of the Census, 1990) to derive total area of urban land use by county. According to the classification system of Anderson and others (1976), level I urban areas consist of categories for residential, commercial, industrial, and other built-up land. Urban land use accounted for 64.8 percent of the land area in Cuyahoga County, Ohio, making it the most urbanized county. Wayne County, Mich., ranks second, at 55.5 percent, and Summit County, Ohio, ranks third at 36.7 percent urban (Anderson and others, 1976).

In the Lake Erie-Lake St. Clair Basin, residential land use accounted for 6.7 percent of the total land area. Most of this area borders Lake Erie and major waterways and includes the cities of Detroit, Mich.; Cleveland, Toledo, and Akron, Ohio; Fort Wayne, Ind.; and Buffalo N.Y. Cuyahoga County, Ohio, has the greatest percentage of area devoted to residential land use (41.5 percent). Wayne and Oakland Counties, Mich., rank second and third, with 35.8 percent and 25 percent residential land, respectively. Summit County, Ohio, ranks fourth with 23 percent residential land.

Industrial areas include a wide array of land uses from light to heavy manufacturing, chemical production, and oil refining. Wayne County, Mich., has the greatest percentage of area devoted to industry (5.9 percent). Cuyahoga and Lucas Counties, Ohio, rank second and third, with 4.0 percent and 2.7 percent industrial land, respectively. Macomb County, Mich., ranks fourth with 2.6 percent industrial land.

Commercial land uses are predominantly for the sale of products and services (Anderson and others, 1976). Cuyahoga County, Ohio, has the greatest percentage of area devoted to commercial services (7.4 percent). Wayne County, Mich., and Lorain County, Ohio, rank second and third, with 5.8 percent and 4.5 percent commercial land use, respectively (Anderson and others, 1976).

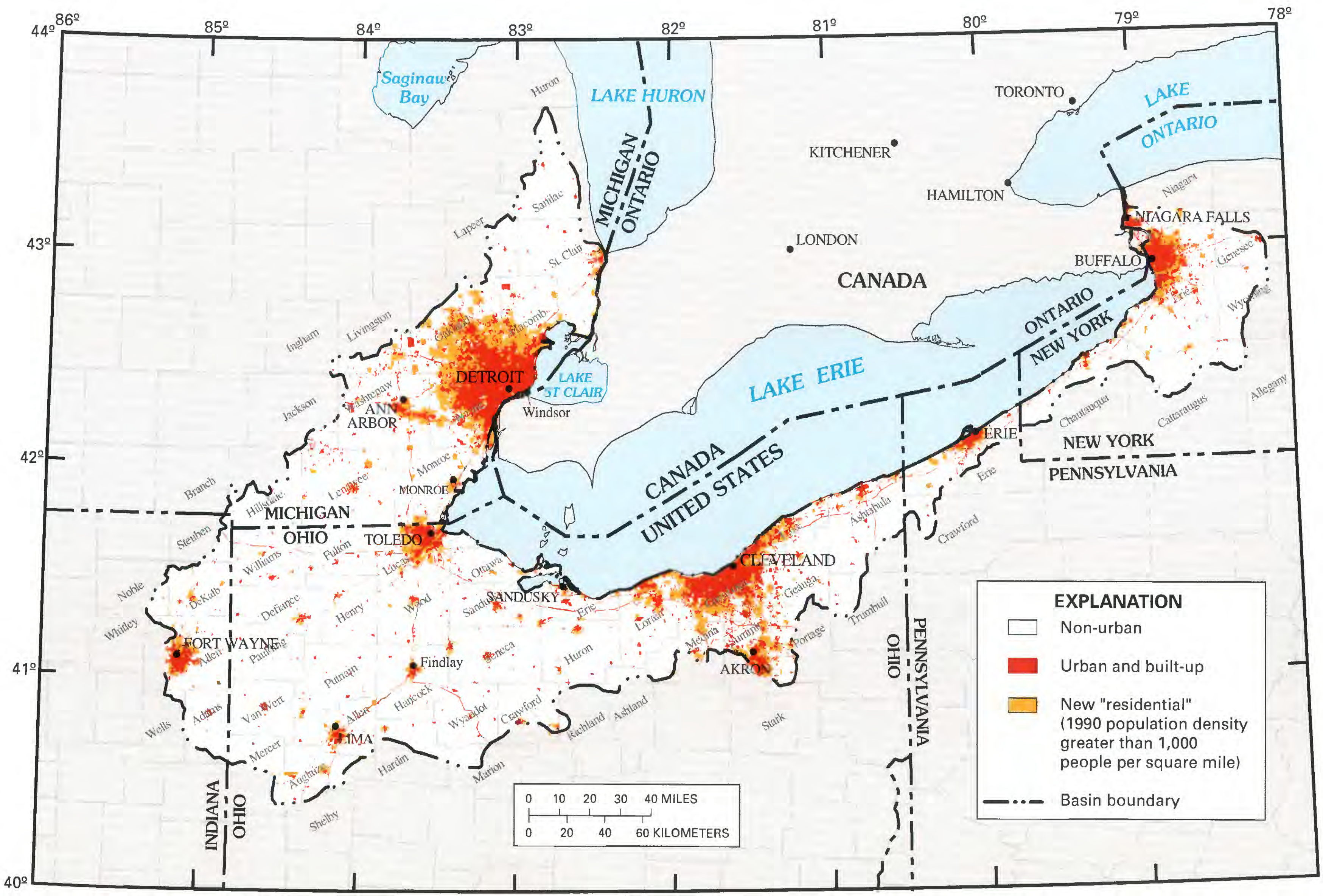
Increases in urban land use in the basin over the period 1970–90 have been evaluated by the use of GIS techniques (Hitt, 1994b). These techniques involved overlaying U.S. Bureau of the Census 1990 population-density data at the block-group level over 1970's digital land-use data from 1:250,000- and 1:100,000-scale maps (Hitt, 1994b). For this analysis, any area having a population density of 1,000 per mi^2 or greater is reclassified as "urban" land (fig. 11).

Although population decreased in the Detroit Mich., and in the Cleveland and Akron, Ohio, metropolitan areas, total urban and built-up land in their respective counties increased (table 2 and fig. 11). Results of this analysis show that the three counties in Michigan with the largest increase in urban area are Macomb County (21.2 percent increase), Oakland County (14.3-percent increase), and Wayne County (12.7-percent increase). Summit County, Ohio (7.6-percent increase), ranked fourth.

Point sources of contaminants may be associated with agricultural, commercial, industrial, or residential land uses in the basin. The numbers and types of point

Table 4. Crop types expressed as percentage of total acres in agricultural production in the Lake Erie-Lake St. Clair Basin
[Data from Gilliom and Thelin, 1997]

Location in the basin	Crop type	Range of total acres in agricultural production, by crop type (percent)
Thumb of Michigan	Alfalfa	9.8–25.2
	Corn	33.3–45.3
	Soybeans	6.4–34.8
	Wheat	3.0–4.7
Southeastern Michigan, northeastern Indiana, northwestern and central Ohio	Alfalfa	0.9–22.9
	Corn	20.3–57.2
	Soybeans	4.7–58.3
	Wheat	4.8–16.2
Northeastern Ohio, northwestern Pennsylvania	Alfalfa	15.5–31.9
	Corn	34.0–47.2
	Soybeans	0–7.2
	Wheat	1.7–9.5
Western New York	Alfalfa	19.5–46.0
	Corn	37.9–48.8
	Soybeans	0–5.0
	Wheat	0–8.1



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Land use modified from U.S. Department of Commerce, U.S. Bureau of the Census, 1993, and U.S. Geological Survey Geographic Information Retrieval System land-use data, 1991

Figure 11. Population density as an indicator of 1990 urban land use in the Lake Erie-Lake St. Clair Basin.

sources of contaminants discharged to surface waters in the basin were estimated for 1993 by use of the USEPA Pollution Control System (PCS) data base, which contains locations and ancillary data for all National Pollutant Discharge and Elimination System (NPDES) permits in the Nation. For the Lake Erie-Lake St. Clair Basin, a total of 1,515 NPDES permits (fig. 12) are listed. Most of these point sources are in urban areas. In all, 108 point sources are listed as major discharges in the basin. Major discharges are those that generally release 1 Mgal/d or more of treated wastewater.

Other contaminant sources are tracked and documented in the Toxics Release Inventory (TRI) data base compiled by the USEPA. TRI is mandated by Section 313 of the Emergency Planning and Community Right-To-Know Act (EPCRA) of 1986. The law ensures that citizens are provided information about possible harmful chemicals in their communities, in part so that response to chemical accidents can be planned. TRI facilities are those facilities that process 25,000 lb or more of listed toxic chemicals per year.

A total of 2,438 TRI sites are in the basin (U.S. Environmental Protection Agency, written commun., 1993; fig. 12). More than 300 toxic chemicals and 20 chemical categories are subject to reporting in the inventory. These chemicals vary in form and in toxicity. Facilities must report estimated releases to the water, air, land, or underground storage. These reports document releases of chemicals but are not intended to document the potential of exposure of the public.

According to the USEPA, in 1993 there were 30 sites in the basin on the National Priority List (NPL) of abandoned toxic-waste sites (U.S. Environmental Protection Agency, 1995). The NPL contains sites that are considered by USEPA to pose a potential risk to life, property, or human health in the local area. There is at least one NPL site in each state within the basin and in 15 of the 65 counties. The counties with the most sites are Niagara County, N.Y., with six, followed by Ashtabula County, Ohio, and Macomb County, Mich., with four each, followed by Oakland County, Mich., with three, and Livingston and Wayne Counties, Mich., and Erie County, Pa., with two each.

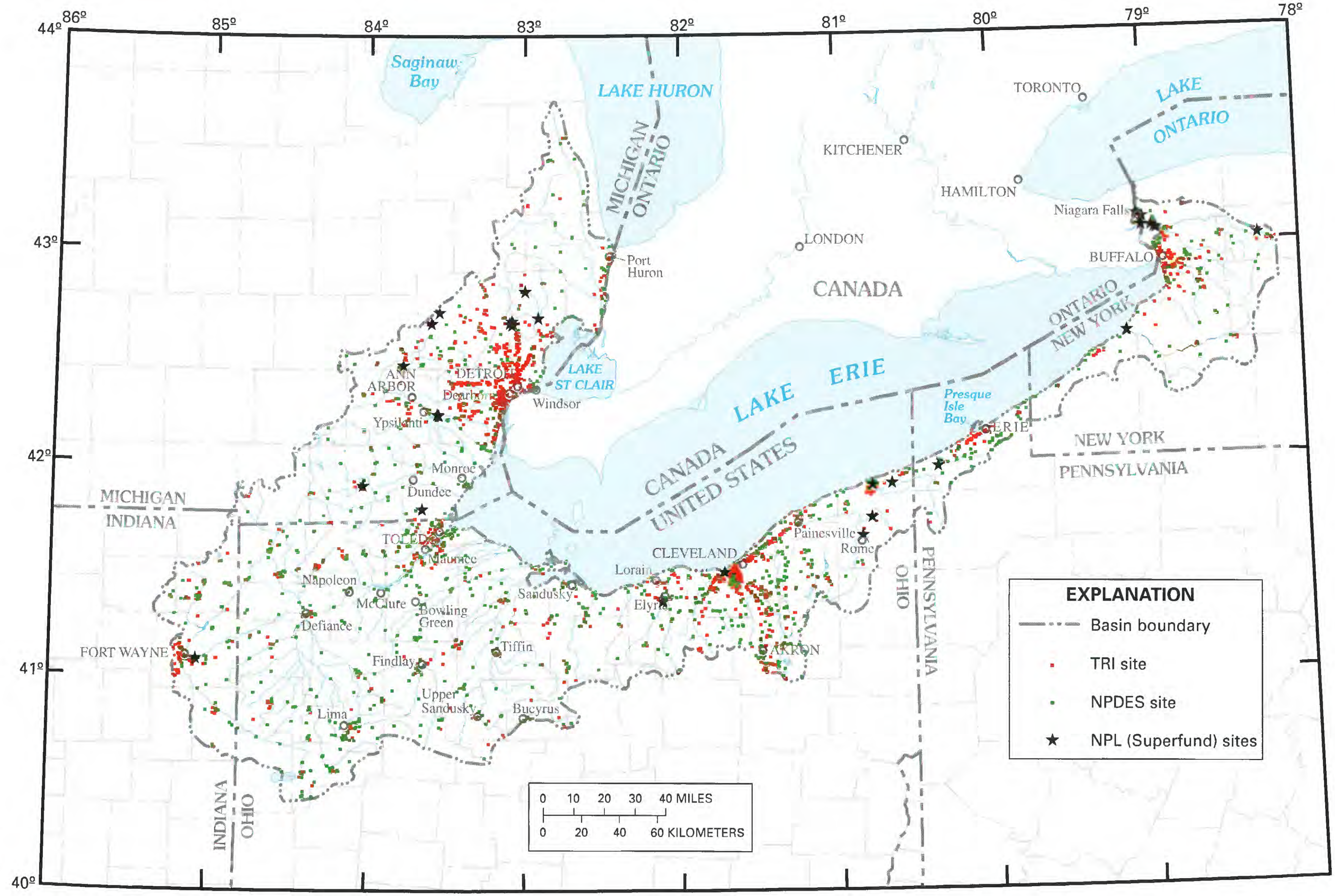
Land use and land cover in the Lake Erie-Lake St. Clair basin is a mosaic of varied land uses. The basin's environment is greatly influenced by anthropogenic land uses, mainly agricultural and urban. These activities, as well as the many point sources of contaminants, can greatly affect water quality. Very little land area in the basin is unaffected by some sort of human activity.

Water Use

Estimated water-use information for the Lake Erie-Lake St. Clair basin was obtained from data collected and stored in the Aggregated Water-Use Data Systems (AWUDS) maintained by the USGS (1995a). In 1950, the USGS began publishing water-use data on a national level every 5 years. Since 1985, AWUDS has been the standard source for USGS estimated water-use data. Water-supply categories are public, domestic, industrial, power generation, and agriculture. Data can be retrieved from AWUDS within political boundaries (counties within each state) or hydrologic boundaries (watersheds identified as hydrologic units labeled by Hydrologic Unit Codes). For the purpose of this report, the first four digits of eight-digit Hydrologic Unit Codes were used for 1990 water-use estimates within the Lake Erie-Lake St. Clair Basin (fig. 13). The first two numbers indicate the region (in this case, 04 is the Great Lakes), and the next two numbers (09 through 12) indicate the subregion.

The estimated water-use total for all uses in the Lake Erie-Lake St. Clair Basin in 1990 was 10,649 Mgal/d (table 5), the equivalent of 32,687 acre-ft/d. Of the five categories listed in table 5, power generation accounted for the greatest water use, about 77 percent of the total water withdrawals. Power-generation facilities withdrew an estimated 8,193 Mgal/d, 99 percent of which was from surface water; fossil-fuel power-plants accounted for more than 98 percent of the water used by power generators in the basin in 1990. Agriculture accounted for the smallest water withdrawals by category, an estimated 38 Mgal/d. Hydrologic unit 0409, which includes Detroit, withdrew the greatest amount of freshwater, an estimated 3,953 Mgal/d, whereas hydrologic unit 0412, which includes Buffalo, withdrew the least amount of freshwater, an estimated 1,632 Mgal/d (table 6).

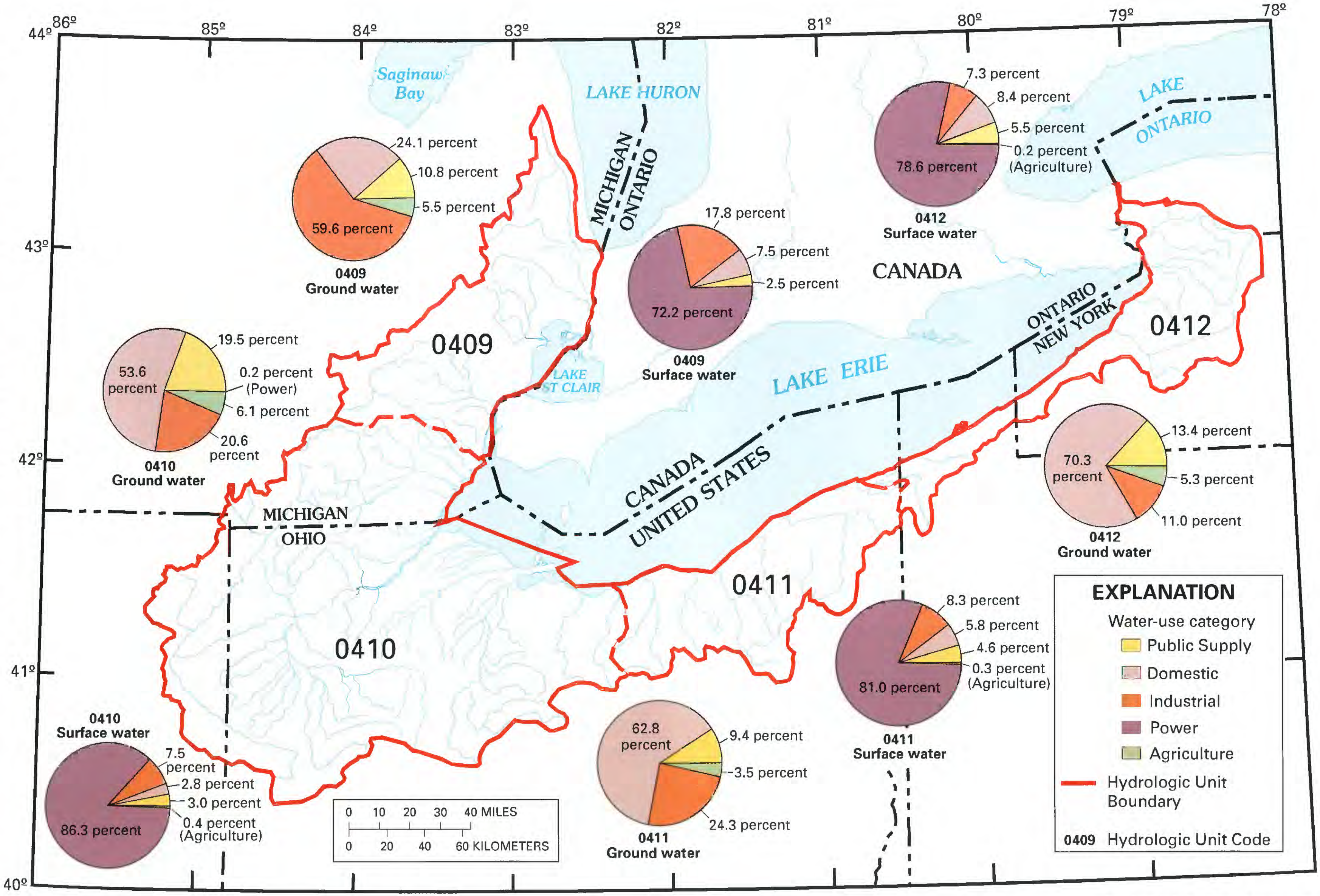
Percentages of water use for both ground water and surface water among the hydrologic units are similar for the various categories (fig. 13). An exception is the industrial category; the percentage of industrial surface-water withdrawals in hydrologic unit 0409 is at least 10 percent higher than that of any other hydrologic unit, and for ground-water withdrawals, the percentage is at least double that of any other hydrologic unit. This difference may be explained by the high con-



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Modified from U.S. Geological Survey NPDES Facility File, 1993, and from USEPA TRI location data, 1995, and from U.S. Environment Protection Agency NPL data, 1993

Figure 12. Location of 1993 toxic release inventory (TRI) sites, 1993 National Pollutant Discharge and Elimination System (NPDES) sites, and 1993 National Priority List (NPL) sites in the Lake Erie-Lake St. Clair Basin.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Data from U.S. Geological Survey, 1995a

Figure 13. Percentages of ground-water and surface-water withdrawals within categories by hydrologic unit code in the Lake Erie-Lake St. Clair Basin.

centration of industry in the Detroit, Mich., area that depends on a ready supply of freshwater. Domestic ground-water withdrawals increase from west to east relative to the total ground-water withdrawals.

About 98 percent of the total water used in the basin was withdrawn from surface water, and the remaining 2 percent came from ground-water sources. If large surface-water withdrawals associated with power generation and industrial uses are removed from the total water-use budget, ground water accounts for roughly 15 percent of the remaining water used for agriculture, domestic use, and public supply. Among these categories, ground-water withdrawals represent nearly 33 percent of agricultural supply, 15 percent of domestic supply, and 8 percent of public supply.

Table 5. Total water use and percentages of the total, by surface water and ground water in the Lake Erie-Lake St. Clair Basin
[Data from U.S. Geological Survey, 1995a; Mgal/d, million gallons per day]

Category of supply	Total water use (Mgal/d)	Ground water		Surface water	
		Withdrawal (Mgal/d)	Percent of total	Withdrawal (Mgal/d)	Percent of total
Public	406.04	33.31	8.2	372.73	91.8
Domestic	743.86	110.09	14.8	633.77	85.2
Industrial	1,268.23	72.19	5.7	1,196.04	94.3
Power generation	8,192.81	.28	.0	8,192.53	100.0
Agricultural (livestock/irrigation)	38.63	12.41	32.1	26.22	67.9
Total	10,649.57	228.28	2.2	10,421.29	97.8

Table 6. Contributions to total water use by hydrologic unit in the Lake Erie-Lake St. Clair Basin, 1990
[Water use in million gallons per day. Data from U.S. Geological Survey, 1995a]

Hydrologic unit (major city in unit)	Total water use	Percent of total
0409 (Detroit)	3,953.0	37.1
0410 (Toledo)	2,600.3	24.5
0411 (Cleveland)	2,464.1	23.1
0412 (Buffalo)	1,632.1	15.3

In addition to offstream water use for power generation, instream water use in the Lake Erie-Lake St. Clair Basin directly affects the social and economic welfare of the basin. The basin contains more then 300 recreational areas and more than 90,000 acres of inland water. Recreational instream water use, such as fishing during the spring walleye run in the Maumee and Sandusky Rivers, enhances local economies. Navigable channels connect vital shipping lanes from the upper Great Lakes to Lake Ontario as part of the St. Lawrence Seaway. Thirteen major shipping ports in the basin import and export commodities to and from world markets.

HYDROLOGIC SETTING

The Lake Erie-Lake St. Clair Basin is one of the world's largest freshwater-resource regions. Lake Erie is the 11th largest freshwater lake in the world. About 78.5 percent of the water supplied to Lake Erie comes from the upper Great Lakes by way of the St. Clair and Detroit Rivers. The inland streams of the Lake Erie-Lake St. Clair Basin contribute about 10.5 percent of the water supplied to Lake Erie, the remaining 11.0 percent being supplied by precipitation to the lake surface (U.S. Environmental Protection Agency and Government of Canada, 1995) and ground-water discharge to the lake (Eberts and Lesney, in press). All rivers in the basin drain either to Lake Erie, to Lake St. Clair, or to the connecting channels, the St. Clair, Detroit, and Niagara Rivers (fig. 14). Local and regional ground-water systems drain to streams and eventually to Lake Erie or the connecting channels. Modern rivers and unconsolidated-aquifer systems in the Lake Erie Basin are relatively young compared to those in adjacent basins

Table 7. Water budget for the Lake Erie-Lake St. Clair Basin

[Inflow and outflow totals dif fer slightly because of computations from independent data sets]

Basin inflow (average annual values)	Acre-feet (x10^6)	Inches
Precipitation		
Indiana	2.46	35.9
Michigan	10.10	33.5
Ohio	24.90	36.8
Pennsylvania	.67	38.3
New York	2.59	37.2
Total	40.72	35.9

Basin outflow (average annual values)	Acre-feet (x10^6)	Inches
Runoff from streamflow		
Michigan	2.90	9.6
Ohio and Indiana	9.74	13.0
Pennsylvania	.36	20.6
New York	1.53	22.0
Evaporation from lake surfaces		
Indiana	0.01	0.1
Michigan	.15	.6
Ohio	.12	.2
Pennsylvania	<.01	<.1
New York	<.01	<.1
Evapotranspiration		
Indiana	1.63	23.9
Michigan	7.13	23.6
Ohio	16.00	23.5
Pennsylvania	.40	23.0
New York	1.60	23.0
Total	41.59	36.5

draining to the Mississippi River. The recent surface and ground-water systems in the basin began to form about 12,500 B.P., near the end of the last glacial period.

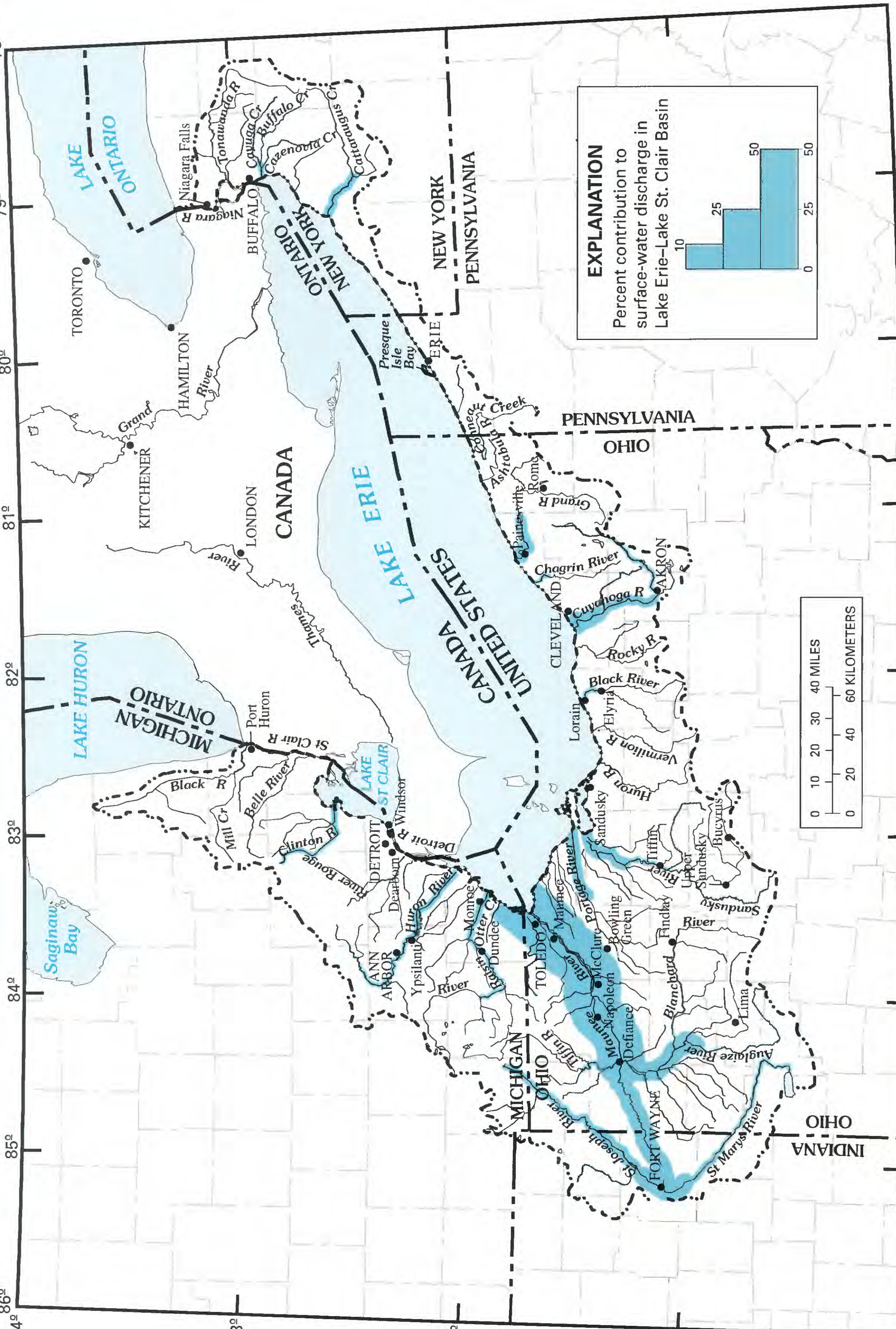
The Lake Erie-Lake St. Clair Basin is in the humid Upper Midwest, where precipitation exceeds water loss from evapotranspiration by about one-third annually (table 7). The major input of freshwater to the basin, excluding that which arrives from the upper Great Lakes, is from precipitation. There are a few small interbasin water transfers, but they are negligible inputs in comparison to rain and snow. Direct ground-water discharge to the lake is thought to be a relatively minor component of the water budget of the Lake Erie Basin. Studies by Eberts and Lesney (in press) have shown that direct discharge of ground water to Lake Erie is very small, probably less than 1 percent of the ground-water budget of regional flow in the Silurian and Devonian carbonate aquifer. Ground-water discharge to streams can comprise as much as 30 to 50 percent of the total streamflow on an annual basis for certain streams.

Evapotranspiration is the largest water-loss factor in the basin and is proportionally more important in Michigan and northwestern Ohio than in northeastern Ohio, Pennsylvania, and western New York (table 7). Conversely, runoff and streamflow play a larger role in water loss than does evapotranspiration in northeastern Ohio, Pennsylvania, and western New York (table 7).

Streams

Streams in the Lake Erie-Lake St. Clair Basin are tributaries to Lake Erie, Lake St. Clair and the connecting channels, the St. Clair, Detroit, and Niagara Rivers. The Lake Erie-Lake St. Clair Basin contains one relatively large stream, the Maumee River, and many smaller streams (fig. 14). Selected hydrologic characteristics of streams are listed in table 8. Drainage areas indicated in table 8 represent the drainage area at the gage, which, for direct tributaries to the Great Lakes, is slightly less than the total drainage area of the stream basin.

The Maumee River discharges just under 24 percent of the streamflow from tributary streams into western Lake Erie through Maumee Bay at Toledo, Ohio



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal- Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Blumer and others, 1995, Hornlein and others, 1994
Lescinsky and others, 1993, Shindel and others, 1995
and Stewart and others, 1993

Figure 14. Surface-water discharge of the Lake Erie-Lake St. Clair Basin tributaries, as a percentage of total tributary surface-water discharge.

(fig. 14). No other stream contributes more than 10 percent of the total streamflow from the basin (table 8; fig. 14). Eight of the largest streams— Clinton and Huron Rivers; River Raisin; Maumee, Sandusky, Cuyahoga, and Grand Rivers; and Cattaraugus Creek— discharge approximately 54 percent of the surface water from the basin to the Lake Erie system annually.

Streams Tributary to the St. Clair River, Lake St. Clair, and the Detroit River

The Black River drains 746 mi^2 and the Belle River drains 210 mi^2 in the northeastern part of the lower peninsula of Michigan (fig. 14; table 8), the coolest and driest part of the basin. These two rivers are tributary to the St. Clair River and drain areas underlain by Mississippian sandstones interbedded with shale and till, fine-grained stratified sediment, and coarse-grained stratified sediment in equal proportions. Land use is almost entirely row crops of corn, dry beans, wheat, soybeans, and alfalfa (fig. 10). The largest city in the area is Port Huron, at the mouth of the Black River and near the source of the St. Clair River and outflow of Lake Huron. Water supply for the area is provided by the Detroit Metropolitan Water Supply and is drawn from the St. Clair River. The quantity and quality (in terms of mineral content) of inland rivers in this area make them insufficient for domestic supply (Rheaume, 1991).

The Clinton River drains 767 mi^2 in an area of Mississippian sandstone and shale bedrock overlain by deposits of coarse-grained stratified sediment and till ranging from 100 to more than 250 ft in thickness. The Clinton River is tributary to Lake St. Clair. Land use in the Clinton River Basin is almost completely urban (fig. 10). Petrochemical and automobile-related manufacturing are important local industries. The Clinton River is not used for water supply because concentrations of dissolved solids are higher than recommended for domestic purposes (Rheaume, 1991). Cities and outlying areas in St. Clair, Macomb, Oakland, and Wayne Counties obtain about 16 Mgal/d of ground water from glacial aquifers. The majority of public supply is provided by the Detroit Metropolitan Area water-supply system, which withdraws water from the St. Clair and Detroit Rivers (Rheaume, 1991).

The River Rouge drains 455 mi^2 in an area underlain by Devonian shale and limestone overlain by deposits that are predominantly fine-grained stratified sediment that range from 0 to 50 ft in thickness. The River Rouge is tributary to the Detroit River (fig. 14; table 8). Land use in the basin is almost completely urban (fig. 10). The Main Branch of the River Rouge is formed by the confluence of the Upper, Middle, and Lower Branches near Dearborn, Mich. Automotive manufacturing and steel making are the major industries in the River Rouge Basin. Like the Clinton River, the River Rouge is not used for water supply because high concentrations of dissolved solids make it relatively more expensive to treat to make suitable for public supply than water from the St. Clair and Detroit Rivers (Rheaume, 1991).

Streams tributary to Lake Erie

The Huron River drains an area of 924 mi^2, which is underlain by Mississippian sandstone interbedded with shale. The bedrock is overlain by coarse-grained deposits and till of glacial origin, ranging from 100 to more than 250 ft in thickness. The Huron River drains Ann Arbor and Ypsilanti, Mich., and discharges to the western basin of Lake Erie. The western basin of Lake Erie is defined as the area of the lake from the mouth of the Detroit River to Sandusky, Ohio. Ann Arbor and Ypsilanti are primarily residential and commercial urban areas (fig. 10), although automobile-related manufacturing is the main industry in Ypsilanti. The city of Ann Arbor withdraws water from the Huron River for supply, although about 16 Mgal/d is also obtained from well fields that tap glacial deposits (Rheaume, 1991).

The River Raisin drains 1,043 mi^2 and discharges to the western basin of Lake Erie (fig. 14; table 8). It is underlain by three types of bedrock—Mississippian sandstone interbedded with shale, Devonian shale, and Devonian and Silurian limestones and dolomites—and all three types of glacial sediments, which range from 0 to 400 ft in thickness. Land use is mainly in row crops of corn, soybeans, and alfalfa (fig. 10). A major urban area is Monroe, Mich., where automobile manufacturing is a primary industry. The River Raisin is the water supply for Dundee, Mich. (Rheaume, 1991), and the South Branch of the River Raisin is the water supply for Adrian, Mich. The city of Monroe, Mich., obtains its public supply from Lake Erie.

The Maumee River drains the largest area in the basin, 6,609 mi^2, in parts of Indiana, Michigan, and Ohio. The Maumee River is formed by the confluence of the St. Joseph and St. Marys Rivers at Fort Wayne, Ind. The Maumee River flows northeast and discharges at Toledo, Ohio, into the western basin of Lake Erie. The Maumee River is underlain by areas of Silurian and Devonian limestone and dolomite, Devonian and Mississippian sandstone interbedded with shale, and Devonian and Mississippian shales; these bedrock units are overlain predominantly by till ranging in thickness from 0 to more than 400 ft. Land use is mostly row crops of corn, soybeans, and wheat. Several large urban areas—Fort Wayne, Ind., and Toledo, Lima, and Findlay, Ohio—are in the basin (fig. 10). Petrochemical refining, glass, chemical, automotive, and automotive-related manufacturing are the largest industries. The area from Findlay through Lima was once an area of intensive oil production, thus explaining the presence of refineries in Toledo, Lima, and Findlay (Wickstrom and Gray, 1994). The Maumee River is the source of water for several towns and cities in the basin, among which are Napoleon, Defiance, Bowling Green, McClure, and Maumee, Ohio.

The four largest tributaries to the Maumee River, in descending order, are the Auglaize, St. Joseph, St. Marys, and Tiffin Rivers (fig. 14; table 8). The St. Joseph River, which drains 1,086 mi^2, is underlain by Devonian and Mississippian shales and sandstones interbedded with shale. The glacial materials are predominantly till, and they can range in thickness from about 100 to 400 ft in areas of end moraines and ground moraines. The St. Joseph River is the water supply for Fort Wayne, Ind. The St. Marys River drains 839 mi^2, and the Auglaize River drains 2,435 mi^2; both are underlain by Silurian and Devonian limestone and dolomite and thin, clayey and silty till ranging from 0 to 150 ft in thickness. The upper Auglaize River flows over a rolling till plain, whereas the lower part flows over the flat lake plain. The streamflow of the Auglaize River is diverted into the Bressler upground reservoir for public and industrial supply. The mean annual streamflow of the Auglaize River is the second highest in the Lake Erie-Lake St. Clair Basin (table 8). The Auglaize River joins the Maumee River at Defiance, Ohio.

The Sandusky River, the fifth largest stream in the basin (fig. 14; table 8), drains 1,420 mi^2 to the western basin of Lake Erie at Sandusky, Ohio. Like the Auglaize River, the Sandusky River is underlain by Silurian and Devonian limestone and dolomite and Devonian shale; the overlying thin, silty to clayey till ranges in thickness from 0 to 150 ft in areas characterized by gently rolling till plains in the upper and middle reaches and flatter lake plains in the lower reaches. Land use in the Sandusky River Basin is primarily row crops of corn, soybeans, and wheat (fig. 10). The Sandusky River is the source of public supply for Upper Sandusky, Tiffin, and Fremont, Ohio.

The Huron, Vermilion, Black, and Rocky Rivers are underlain by Devonian and Mississippian shale. Bedrock is overlain by till ranging from 0 to 150 ft in thickness. The Huron River drains 405 mi^2, the Vermilion River drains 268 mi^2, and the Black River drains 470 mi^2 (fig. 14; table 8). The easternmost of the above four rivers, the Rocky River, drains 293 mi^2 and is split by the boundary of the Central Lowland and Appalachian Plateaus Provinces such that about half the drainage lies in each. These streams drain to the central basin of Lake Erie (defined as the area from Sandusky, Ohio, to Erie, Pa.). Land use in the Vermilion and Huron River Basins is predominantly row crops, whereas land use in the Black and Rocky River Basins is predominantly urban (fig. 10). Major urban areas are Lorain, Elyria, and part of Cleveland, Ohio. Steel, chemical, and automotive manufacturing are the primary industries. However, many of these industries have undergone dramatic changes such as cutbacks in production, shifts in the types of manufacturing, or closure since the mid-1970's. The Vermilion, Huron, and Black Rivers serve as public supplies for small communities inland from Lake Erie.

The Cuyahoga, Chagrin, and Grand Rivers are tributary to the central basin of Lake Erie. The Cuyahoga River is the third largest stream in the Lake Erie-Lake St. Clair Basin by mean annual streamflow (fig. 14; table 8). The Cuyahoga River drains 809 mi^2 underlain by predominantly Mississippian and Pennsylvanian sandstone and shale, some Mississippian and Devonian shale, and till and coarse-grained stratified sediment. Land use is predominantly urban. A small percentage of land use in the uppermost part of the basin is in pasture and forage crops (fig. 10). Cleveland, Ohio (at the mouth of the Cuyahoga River), and Akron, Ohio (at the midpoint), are the major urban areas. The Cuyahoga River is the source of the water supply for Akron. The River is impounded into three water-supply reservoirs upstream from Akron. The Cuyahoga Valley National Recreation Area straddles the river valley between Akron and Cleveland.

The Chagrin River, which drains 264 mi^2, is similar to the Cuyahoga River in geologic setting. The Chagrin River drains the residential and rural areas east of Cleveland, Ohio. The Grand River drains a 705-mi^2 area underlain by Mississippian and Devonian shale, till, and fine-grained stratified sediments (table 8). Land use is predominantly pasture and forage crops in

Table 8. Hydrologic characteristics of selected streams in the Lake Erie-Lake St. Clair Basin

[mi^2, square miles; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; in., inches; streamflow is mean annual streamflow for period of record; runoff is mean annual runoff. Numbers in parentheses for tributaries are included in total for receiving streams. Drainage areas indicated in table represent the drainage area at the gage, which, for direct tributaries to the Great Lakes, is slightly less than the total drainage area]

River name and gaging-station location	Drainage area at gage (total) (mi^2)	Streamflow of tributary (ft^3/s)	Unit runoff ($ft^3/s/mi^2$)	Percent of total basin streamflow
Michigan[1]				
Black River near Jeddo, Mich.	464	299	0.64	1.41
Mill Creek near Avoca, Mich.	169	93.8	.61	.44
Belle River at Memphis, Mich.	151	91.6	.55	.43
Clinton River at Mt. Clemens, Mich.	734	551	.75	2.60
River Rouge at Detroit, Mich.	187	121	.65	.57
Lower River Rouge at Inkster, Mich.	(83)	(53.6)	(.65)	(.25)
Middle River Rouge near Garden City, Mich.	(100)	(74.1)	(.74)	(.35)
Huron River at Ypsilanti, Mich.	807	611	.76	2.88
River Raisin near Monroe, Mich.	1,042	736	.71	3.47
Otter Creek at La Salle, Mich.	51	46.1	.90	.22
Ungaged streams in Michigan	1,916	1,533	.80	7.23
Michigan total				19.27
Indiana[2] **and Ohio**[3,4]				
Ottawa River at Toledo University, Toledo, Ohio	150	130	.87	0.61
Maumee River at Waterville, Ohio	6,330	4,990	.78	23.50
Auglaize River near Defiance, Ohio	(2,318)	(1,765)	(.75)	(8.33)
St. Josephs River near Fort Wayne, Ind.	(1,060)	(1,066)	(1.01)	(5.03)
St. Marys River near Fort Wayne, Ind.	(762)	(603)	(.81)	(2.85)
Tiffin River at Stryker, Ohio	(410)	(333)	(.81)	(1.57)
Portage River at Woodville, Ohio	428	332	.78	1.57
Sandusky River near Fremont, Ohio	1,251	1,018	.81	4.80
Huron River at Milan, Ohio	371	307	.83	1.45
Vermilion River near Vermilion, Ohio	262	210	.93	.99
Black River at Elyria, Ohio	396	336	.85	1.59
Rocky River near Berea, Ohio	267	279	1.04	1.32
Cuyahoga River at Cleveland, Ohio	788	1,536	1.53	7.25
Chagrin River at Willoughby, Ohio	246	338	1.37	1.59

Table 8. Hydrologic characteristics of selected streams in the Lake Erie-Lake St. Clair Basin—Continued

[mi^2, square miles; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; in., inches; streamflow is mean annual streamflow for period of record; runoff is mean annual runoff. Numbers in parentheses for tributaries are included in total for receiving streams. Drainage areas indicated in table represent the drainage area at the gage, which, for direct tributaries to the Great Lakes, is slightly less than the total drainage area

River name and gaging-station location	Drainage area at gage (total) (mi^2)	Streamflow of tributary (ft^3/s)	Unit runoff ($ft^3/s/mi^2$)	Percent of total basin streamflow
Grand River near Painesville, Ohio	685	1,050	1.52	4.95
Ungaged streams in Ohio	2,889	3120	1.08	14.72
Ohio and Indiana total				64.39
	Pennsylvania[5]			
Conneaut Creek at Conneaut, Ohio	273	273	1.00	1.29
Raccoon Creek near W. Springfield, Pa.	2.5	3.43	1.37	.02
Brandy Run near Girard, Pa.	4.5	7.18	1.60	.03
Ungaged streams in Pennsylvania	324	557	1.72	2.63
Pennsylvania total				3.97
	New York[6]			
Cattaraugus Creek at Gowanda, N.Y.	436	743	1.70	3.51
Buffalo River at Buffalo, N.Y. (not gaged)	374	571	1.53	2.69
Buffalo Creek at Gardenville, N.Y.	(142)	(204)	1.44	(.96)
Cayuga Creek near Lancaster, N.Y.	(96.4)	(134)	1.39	(.63)
Cazenovia Creek at Ebenezer, N.Y.	(135)	(233)	1.73	(1.10)
Tonawanda Creek at Rapids, N.Y.	349	400	1.15	1.89
Ungaged streams in New York	494	908	1.83	4.28
New York total				12.37

[1]Blumer and others, 1995. [2]Stewart and others, 1993. [3]Shindel and others, 1981. [4]Shindel and others, 1995. [5]Lescinski and others, 1994. [6]Hornlein and others, 1994.

the uplands and orchards and vineyards near the lake (fig. 10). The major urban area is Painesville, Ohio, at the mouth of the Grand River at Lake Erie. The Chagrin and Grand Rivers are warmwater habitats that contain diverse bivalve and warmwater fish communities. Both rivers are seasonal habitats for Great Lakes salmonids such as steelhead. An impoundment on a tributary to the Grand River is the water supply for Rome, Ohio.

The Ashtabula River drains 137 mi^2 and Conneaut Creek drains 189 mi^2, both in extreme northeastern Ohio and northwestern Pennsylvania (fig. 14; table 8). The two streams are underlain by Devonian shale that is mantled by a thin till. Land use is predominantly pasture and forage crops (fig. 10). Ashtabula, Ohio, the major urban area, is at the mouth of the Ashtabula River near Lake Erie. Major industries in Ashtabula are industrial-chemical production. Although Erie, Pa., is near these streams, it is drained by several small streams that are direct tributaries to Lake Erie.

Cattaraugus Creek drains a 552 mi^2 area to the eastern basin of Lake Erie (fig. 14; table 8) and is the principal stream tributary to the eastern basin of Lake Erie (the area from Erie, Pa., to the outflow at the Niagara River near Buffalo, N.Y.) The Cattaraugus Creek Basin is underlain by Devonian shale and thin till in the uplands; but in the valleys, coarse-grained stratified drift and alluvium fill buried valleys cut into the Devonian shale. Cattaraugus Creek and adjacent creeks provide seasonal habitats for Great Lakes salmonids. The Cattaraugus Creek Basin is in the coolest and wettest part of the Lake Erie-Lake St. Clair Basin.

Streams tributary to the Niagara River

Streams tributary to the Niagara River are in the easternmost part of the Central Lowland province; however, their headwaters form in the Appalachian Plateaus Province. These streams drain areas of Silurian and Devonian limestone and Devonian shale overlain by till ranging in thickness from 0 to 100 ft. The Buffalo River is a tributary to Lake Erie and is a relatively short stream formed by the confluence of Buffalo, Cayuga, and Cazenovia Creeks (fig. 14). Buffalo Creek drains 144 mi^2, Cayuga Creek drains 96.4 mi^2, and Cazenovia Creek drains 135 mi^2 (table 8). Tonawanda Creek is in the easternmost part of the basin and drains 352 mi^2 to the Niagara River. Land use in the Buffalo River and Tonawanda Creek Basins is predominantly urban; Buffalo and Niagara Falls, N.Y., are the major cities (fig. 10). Petrochemical, steel, industrial-chemical, and agricultural-chemical production are the major industries.

Hydrologic characteristics

The streams of the Lake Erie-Lake St. Clair Basin receive most of their flow from precipitation. Very little water is transferred into or out of the basin. Two small but noteworthy interbasin transfers are at Grand Lake St. Marys, an impoundment of the St. Marys River in northwestern Ohio, and at Summit Lake, an impoundment of the Little Cuyahoga River in northeastern Ohio. At these two locations, water is transferred between the Lake Erie and Ohio River Basins through the old Ohio Canal system. At Tonawanda Creek, near Buffalo, N.Y., water is transferred out of the Lake Erie Basin and into the Lake Ontario Basin by diversion into the Erie Barge Canal.

Unit runoff is a normalized value for stream runoff that is weighted by the area of the contributing drainage basin and expressed in cubic feet per second per square mile. Unit runoff increases from west to east in the Lake Erie-Lake St. Clair Basin. Unit runoff from subbasins of equal size is nearly three times less in the western part of the basin than in the eastern part. For example, unit runoff in the Black River in Michigan is 0.64 $ft^3/s/mi^2$ compared to 1.70 $ft^3/s/mi^2$ in the Cattaraugus Creek in New York. Unit runoff typically decreases as drainage-area size increases (table 8). Unit runoff values for streams tributary to the Maumee River, such as the St. Joseph, St. Marys, and Tiffin Rivers, are higher than the unit runoff values for the Maumee River. Unit runoff from the Auglaize River, the largest tributary to the Maumee River, is similar to that of the main stem at Waterville, Ohio (table 8).

Runoff, expressed as inches of water discharged from a drainage basin per unit area, increases from west to east in the Lake Erie-Lake St. Clair Basin (fig. 15). This gradient in runoff is attributable to climate (temperature and precipitation patterns), soils, and topographic relief. Runoff (in inches) in streams of the Lake Erie-Lake St. Clair Basin is about 30 to 50 percent of precipitation (table 7).

Streamflow at many streams in the basin is highest during February, March, and April and lowest during September and October (fig. 16). For example, the highest mean monthly streamflows for the period 1964–93 for the Maumee River at Waterville, Ohio, were in February, March, and April, whereas the lowest streamflows were in August, September, and October. The highest mean monthly streamflows for the same period for the Cattaraugus Creek at Gowanda, N.Y., were in March and April, and the lowest were in August and September.

Variations in mean annual streamflow in the Lake Erie-Lake St. Clair Basin can differ by a factor of 2 to 10 between dry and wet years (fig. 17). For example, mean annual streamflow of the Clinton River at Mt. Clemens, Mich. (in the driest part of the basin), ranged from a low of 230 ft^3/s in 1964 to a high of 929 ft^3/s in 1974. Similarly, mean annual streamflow of the Maumee River at Waterville, Ohio (the largest stream in the basin), ranged from a low of 849 ft^3/s in 1931 to a high of 8,286 ft^3/s in 1950. For Cattaraugus Creek at Gowanda, N.Y., in the coolest and wettest part of the basin, mean annual streamflow ranged from 536 ft^3/s in 1949 to 1,030 ft^3/s in 1977.

Floods and Droughts

Floods are a natural part of the hydrology of a stream; they transport nutrients and sediments to flood plains, recharge ground water to unconsolidated and bedrock aquifers, and determine the dimensions, form, and meander of the stream channel and the width and other physical features of the flood plain. Flood-control structures in the Lake Erie-Lake St. Clair Basin are uncommon because the topography of the area is generally flat to gently rolling and provides few places for the construction of dams. Major floods have been recorded in almost all areas of the basin since the beginning of record keeping, about 90 years ago.

Floods can be local to regional and generally have a duration that ranges from hours to several days. Floods in the basin are intensified by rain falling on frozen or saturated ground or by rapid snowmelt. Hurricanes have been responsible for some severe floods in the basin. The single largest regional flood in the basin took place in March 1913 (table 9). The Ohio part of the basin was hardest hit, but flooding also reached record levels in Indiana. The recurrence interval was 25 to greater than 100 years. Other important floods are those of 1904, 1947, 1968, and 1982 in southeastern Michigan; floods of 1959, 1978, and 1982 in northeastern Indiana, floods of 1959, 1969, and 1982 in Ohio; and the flood of June 1972 in northern Pennsylvania and western New York, a result of Hurricane Agnes (table 9).

Droughts, unlike floods, take weeks to develop and generally affect larger areas (table 9). Like floods, droughts can have a profound effect on the hydrologic system; droughts can alter ground-water levels and decrease the amount of water available for supply and wildlife. The most regional and longest droughts in the Lake Erie-Lake St. Clair Basin, as in much of the Midwest, occurred during 1931–36 and 1939–42. Other droughts were more severe over shorter periods and in smaller areas, such as the drought 1952–57 in Michigan, Indiana, and Ohio. Droughts of shorter duration occurred during the mid-1970's and again in the late 1980's in Michigan, Indiana, and Ohio.

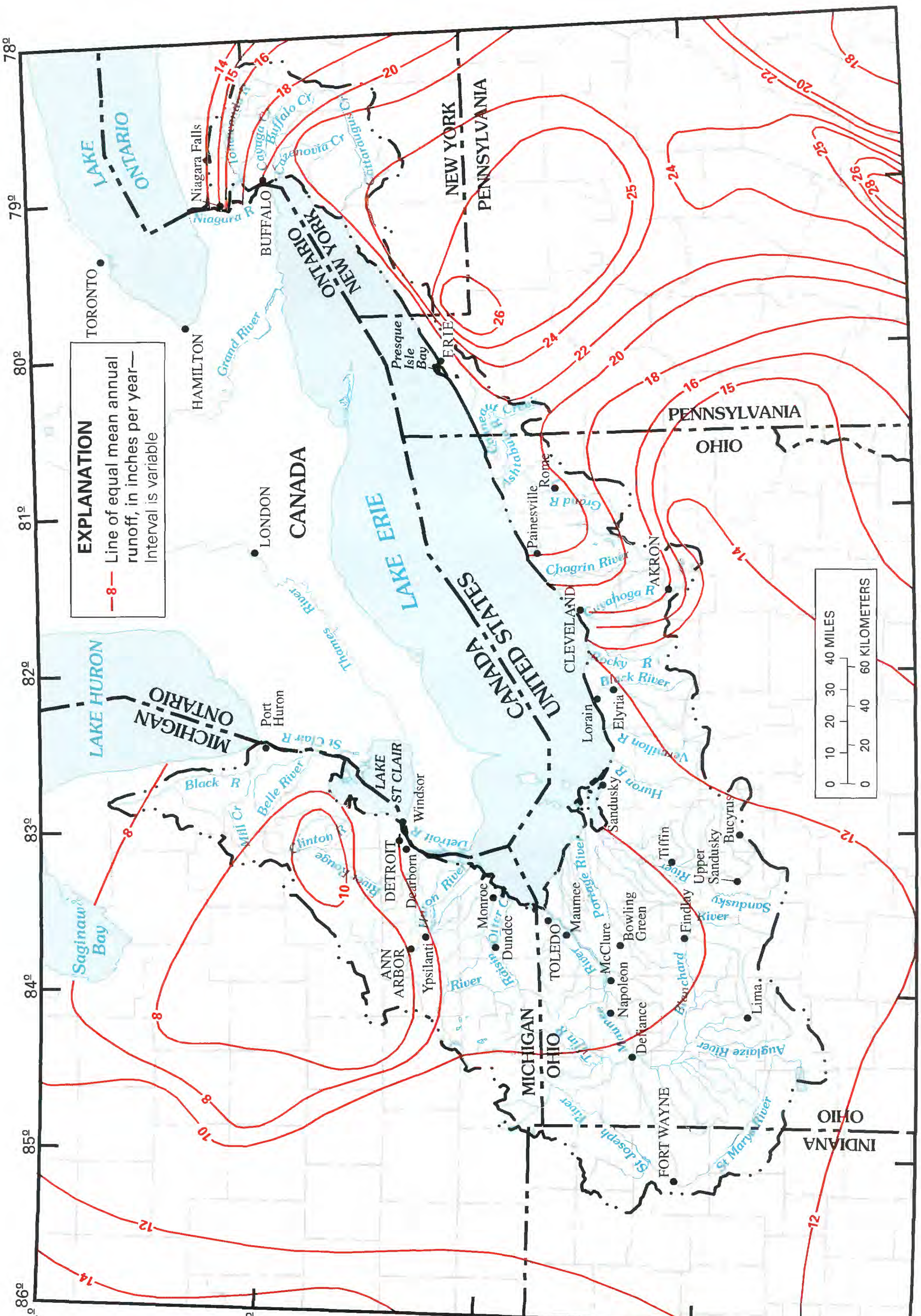
Lakes, Reservoirs, and Wetlands

The Lake Erie-Lake St. Clair Basin contains 19 surface-water impoundments greater than 5,000 acres (Ruddy and Hitt, 1990; table 10). The primary uses of these reservoirs are water supply, recreation, and hydroelectric power generation. The Huron River in Michigan is impounded to form five reservoirs, more reservoirs than on any other stream in the basin. A number of natural lakes and reservoirs smaller than 5,000 surface acres are scattered across the basin. Small areas with natural lakes of glacial origin are in northeastern Indiana in De Kalb County; in southeastern Michigan in Hillsdale, Livingston, Oakland, Macomb, and Washtenaw Counties (Miller and Thompson, 1970); in northwestern Ohio in Williams County; and in northeastern Ohio in Geauga, Portage, and Summit Counties. Shorelines of these lakes are typically lined with seasonal and permanent residences. Eutrophication is a major water-quality problem for most lakes and reservoirs in the basin as a result of agricultural and residential land uses and associated fertilizer and other types of nutrient runoff.

The Lake Erie-Lake St. Clair Basin was once the location of extensive coastal and inland wetlands. These wetlands were predominantly in the Central Lowland Province, Eastern Lake Plain Section (Fenneman and Johnson, 1946), and could be found in virtually all the land draining to the St. Clair River, Lake St. Clair, the Detroit River, and Lake Erie (Robbins and others, 1994). The Nature Conservancy (1994) has identified unique wetland systems supporting biological diversity in the Great Lakes Basin. These systems are the Coastal Shore System, Coastal Marsh System, and the Inland Wetland System. Of these systems, coastal marshes and coastal shores were found to sustain the greatest numbers and diversity of species important in terms of wetland biodiversity (The Nature Conservancy, 1994).

Existing coastal wetlands serve as important areas for fish reproduction (Herdendorf, 1987), bird migration (Herdendorf and Herdendorf, 1986), and habitats for specialized wetland plant species (Marshall, 1977; Marshall and Stuckey, 1974; Herdendorf and others, 1981). The decline of lake plants in Put-In-Bay harbor, western Lake Erie, has been documented by Stuckey (1978). Special wetland habitats in the Lake Erie Basin are areas of sand beaches and dunes, interdunal wetlands, and cobble and bedrock shores. Fish and wildlife resources and community ecology have been described for such areas by Herdendorf (1987) and Herdendorf and others (1981). An environmental sensitivity index has been developed for Lake Erie coastal areas (Herdendorf and Fay, 1988). These areas bear the brunt of storms and protect the coastal wetlands systems from the fluctuating Lake Erie water levels, waves, and seiches.

Most of the nearshore areas in Monroe, Wayne, Macomb, and St. Clair Counties, Mich., were once coastal wetlands but have since been converted to urban and marina uses. The St. Clair River Delta Wetlands, one third of which is in Michigan and two-thirds of which is in Ontario, is the largest river delta in the Great Lakes and the largest wetland in the basin. At one time, the St. Clair River delta was much more extensive, but much of it has been drained for agriculture and urban development. The remaining wetlands are now



Lines of equal mean annual runoff modified from Gebert and others, 1987, scale 1:17,000,000

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic Projection
Standard parallels 29° 30' and 45° 30', central meridian 83°

Figure 15. Mean annual runoff in the Lake Erie-Lake St. Clair Basin, 1951–80.

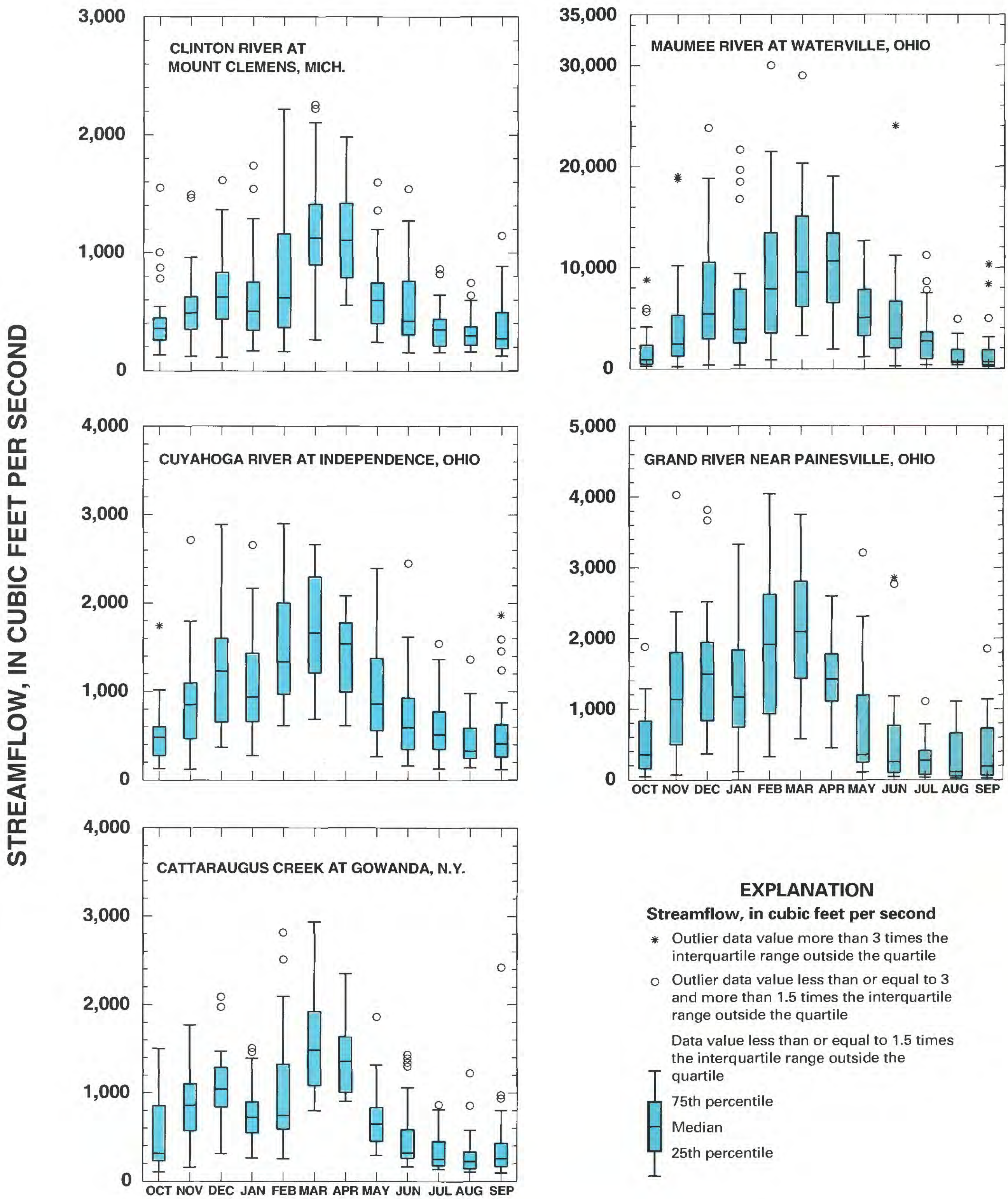


Figure 16. Seasonal distribution of streamflow for selected streams in the Lake Erie-Lake St. Clair Basin, 1964–93.

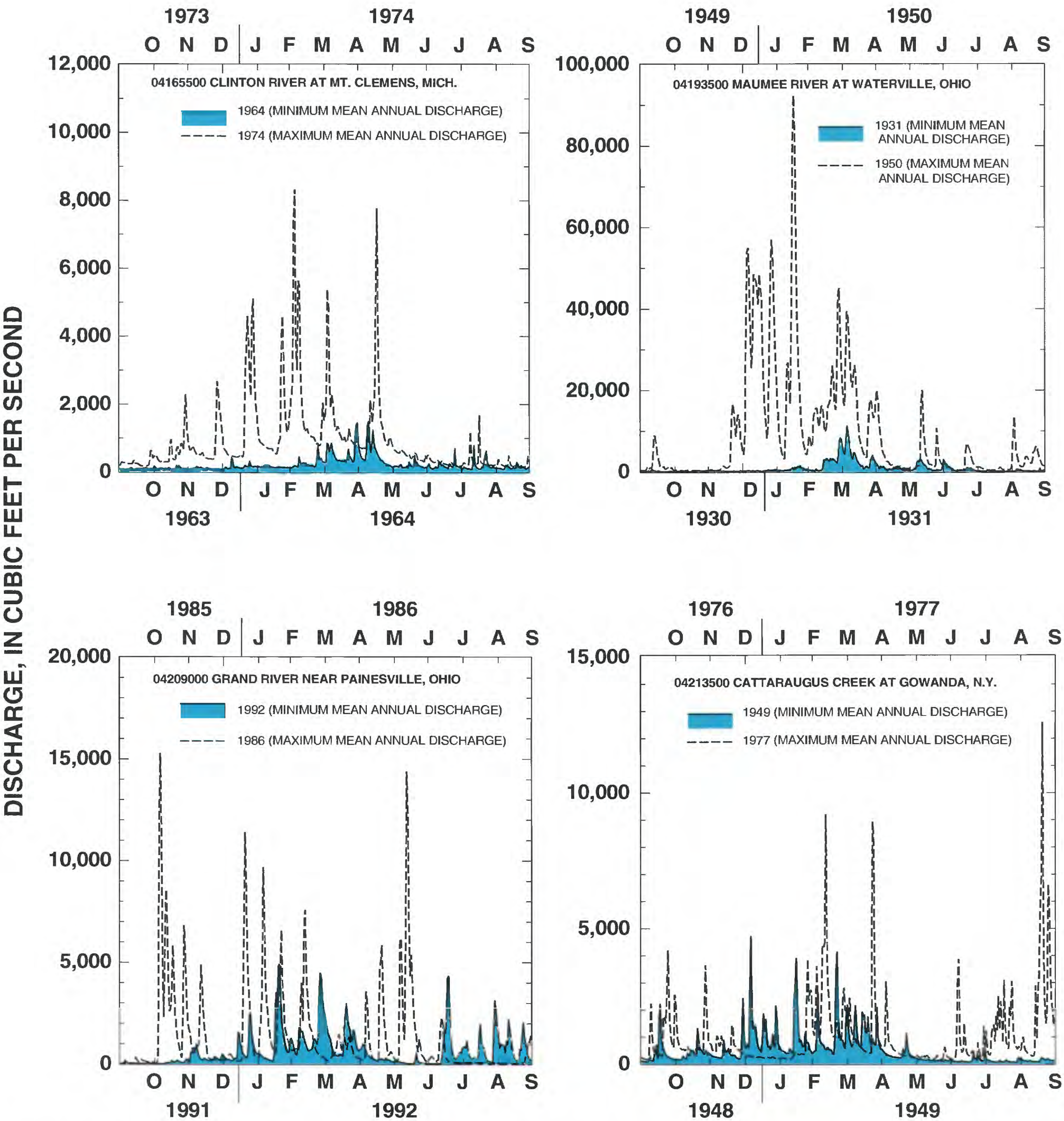


Figure 17. Daily mean streamflows for selected streams in the Lake Erie-Lake St. Clair Basin for water years with the highest and lowest mean annual streamflow.

protected. These wetlands support 12 unique habitats that vary with depth along deltaic distributary channels, storm deposits, and bays (Robbins and others, 1994). Descriptions of the Michigan part of the St. Clair River Delta Wetlands are given in Edsall and others (1988).

The largest wetland in the basin historically was the Black Swamp, a forested wetland one-third the size of the original Everglades. The Black Swamp originally covered an area of about 1,500 mi^2, was 30 to 40 mi wide, and extended 120 mi from Lake Erie at Toledo, Ohio, to Fort Wayne, Ind. In its original range, the Black Swamp was contained within the southern limit of Lake Maumee, a glacial lake that existed about 12,000 years B.P.

Many settlers came to farm the rich soils of northwestern Ohio in the decades after the War of 1812 but were impeded by the Black Swamp. Logging in the 1850's and 1860's began to remove original swamp forest, and the cleared land was ready for agricultural development. During the 1870's, farmers began to dig canals and ditches through their fields to improve drainage (Campbell, 1995). By 1870, the Black Swamp was half cleared of trees. By 1900, most of the Black Swamp was cleared and drained. Before drainage, the waters were reported to be clear; with drainage, the "springs and streams that had once run drinkably clear either disappeared or choked on runoff from ploughed fields and eroded banks" (Campbell, 1995, p. 107). Wetland plant species such as wild rice, which formerly grew in Maumee and Sandusky Bays, were lost, as the needed sunlight failed to penetrate the waters. Today, more than 90 percent of the original wetlands in the Lake Erie-Lake St. Clair Basin have been drained for predominantly agricultural uses (The Nature Conservancy, 1994; Lafferty, 1979). Some of the unique forested wetlands of the Black Swamp are preserved at Ottawa National Wildlife Refuge, east of Toledo, Ohio.

Several smaller coastal marshes line the southwestern shore of Lake Erie from the mouth of the Detroit River to Sandusky, Ohio. These are the Point Mouillee Marshes, near Rockwood, Mich.; Metzger Marsh and Cedar Point National Wildlife Refuges near Toledo, Ohio; Ottawa National Wildlife Refuge and Magee Marsh, west of Sandusky, Ohio; Winous Point Marsh on Sandusky Bay; and Old Woman's Creek National Estuarine Research Reserve west of Cleveland, Ohio. Relatively fewer coastal marshes are along the northeastern shore of the lake. Mentor Marsh in northeastern Ohio and Presque Ilse-Erie City Wetland Complex near Erie, Pa., are important coastal wetlands (Lafferty, 1979; Robbins and others, 1994).

There has been an almost complete loss of coastal wetlands in the Lake Erie Basin in western New York. At one time, much of the land from Buffalo south to Lackawanna, N.Y., was a cattail marsh that formed on the delta of the Buffalo River where it drained into Lake Erie (Robbins and others, 1994). Most of this wetland has been filled for other purposes. The 75-acre Tifft Farm Nature Preserve has been established to protect the remaining habitats: open-water ponds; wet, grassy meadows; thick, bushy, wet areas called shrub carrs; and forested wetlands.

Table 9. Chronology of major floods and droughts in the Lake Erie-Lake St. Clair Basin, 1904-94

[Data from Paulson and others, 1991; recurrence interval is the average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts]

Flood or drought	Date	Area affected	Recurrence interval (years)	Remarks
			Michigan	
Flood	Mar. 24–27, 1904	River Raisin and Huron River Basins	25 to >100	Rain on snowpack and frozen soils. Damage, $2 million; 1 death.
Drought	1930–37	Statewide (Michigan)	50 to 70	Most severe in State's history. In 1930, precipitation 9 inches less than normal.
Drought	1939–42	Lower Peninsula	15 to > 50	Alternating periods of normal and less than normal precipitation. Crop damage in 1941.
Flood	Apr. 4–11, 1947	Clinton River and River Rouge Basin	25 to 100	Most damaging since 1904. Result of thunderstorms and snowmelt.
Drought	1952–56	Statewide (Michigan)	5 to 25	Temperatures greater than normal for 4 years. In 1953, precipitation 9 inches less than normal.
Drought	1960–67	Statewide (Michigan)	40 to 65	Second longest of record. Precipitation least since 1931.
Flood	June 25–27, 1968	Clinton, Huron, and River Raisin Basins	10 to 100	Worst since 1947. Several dams breached. Overland flooding, sewer backup, and basement flooding of about 4,000 structures. Lives lost, 4; damage, $11.5 million.
Drought	1976–80	Statewide (Michigan)	10 to 20	Eased in 1979 in northern Lower Peninsula.
Flood	Mar. 14–24, 1982	River Raisin Basin	10 to > 100	Severe in multistate area. Two counties declared disaster areas. Lives lost, 1.
Drought	1986–89	Statewide (Michigan)	Unknown	New streamflow minimums at many sites. Continued in northern Lower Peninsula in 1989.
			Indiana	
Flood	Mar. 1913	Statewide (Indiana)	25 to >100	Worst in Indiana history. Multistate flood. Lives lost, at least 90; damage, $15 million.
Drought	Mar. 1930–Aug. 1931	Statewide (Indiana)	10 to 20	Began decade of low-flow conditions. Streamflow generally less than 7-day, 10-year value in central and northern Indiana.
Drought	June 1933–Sept. 1936	Statewide (Indiana)	25 to 60	Streamflow less than 7 day, 10-year value in central and northern Indiana.
Drought	May 1939–Jan. 1942	Statewide (Indiana)	20 to 60	Central Indiana severely affected. Most streamflows less than 7-day, 10-year value.
Drought	Apr. 1952–Mar. 1957	Statewide (Indiana)	10 to 60	Streamflow less than 7-day, 10-year value. Broken in northern Indiana in Oct. 1954 by floods.

Table 9. Chronology of major floods and droughts in the Lake Erie-Lake St. Clair Basin, 1904-94—Continued

[Data from Paulson and others, 1991; recurrence interval is the average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts]

Flood or drought	Date	Area affected	Recurrence interval (years)	Remarks
Flood	Jan.–Feb. 1959	Maumee River	5 to > 50	Caused by runoff from rainfall on frozen ground during two storms. Ice jams on larger rivers. Lives lost, 3.
Drought	Apr. 1962–Nov. 1966	Statewide (Indiana)	20 to 60	Streamflow less than 7-day, 10-year value. Floods occurred in 1963 and 1964 in central and southern Indiana.
Flood	Mar. 1978	Maumee River	5 to > 50	Rainfall and melting snow from the "Blizzard of 1978." Extensive damage in Fort Wayne. Damage, $11 million.
Flood	Mar. 1982	St. Joseph and Maumee River Basins	5 to > 100	Rapid melting of dense snowpack and rainfall. Damage in Fort Wayne, $51 million.
Drought	1986–1988	Statewide (Indiana)	Unknown	Affected agriculture, water supply, and electric-power generation.
			Ohio	
Flood	Mar. 24–Apr. 8, 1913	Statewide (Ohio)	50 to > 100	Largest of record in Ohio. Multistate, caused by intense rain. Deaths, 467; damage, $143 million.
Drought	1930–36	Statewide (Ohio)	20 to 70	Regional, with serious water shortages; loss of gross farm income estimated at $58 million during 1930.
Drought	1939–46	Statewide (Ohio)	15 to 60	Serious water shortages.
Drought	1952–57	Statewide (Ohio)	10 to 60	Regional; more severe in southwestern Ohio than drought of 1930–36.
Flood	Jan. 21–24, 1959	Wide band extending from southwestern to northeastern Ohio	2 to > 100	Intense rain on frozen, snow-covered ground. Deaths, 16; damage, $101 million.
Drought	1959–68	Statewide (Ohio)	10 to 60	Most severe in east-central and northwestern Ohio.
Flood	July 4–8, 1969	Huron River and Black Rivers	25 to >100	Most intense and widespread summer thunderstorms recorded in Ohio. Deaths, 41; damage, $66 million.
Drought	1975–77	Auglaize River	5 to 15	Mild; interrupted period of greater than average streamflow (1968–87).
Flood	June 13–15, 1981	Blanchard River	25 to > 100	Locally intense rain on saturated ground; 25 percent of Findlay flooded, 55 percent of Ottawa flooded. Damage, $35 million.
Drought	1988	Statewide (Ohio)	Unknown	Short but severe. Rapid declines in streamflow, ground-water levels, and reservoir levels. Mandatory water-use restrictions instituted in many municipalities.

Table 9. Chronology of major floods and droughts in the Lake Erie-Lake St. Clair Basin, 1904-94—Continued

[Data from Paulson and others, 1991; recurrence interval is the average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts]

Flood or drought	Date	Area affected	Recurrence interval (years)	Remarks
			Pennsylvania	
Drought	1930–34	Statewide and regional	>25	Serious water shortage.
Drought	1939–42	Statewide and regional	10 to > 50	Severe water shortage within entire region.
Drought	1961–67	Statewide and regional	10 to >50	Northeastern United States drought. Critical water shortage throughout entire region.
Flood	June 20–25, 1972	Statewide (Pennsylvania)	50 to >100	Hurricane Agnes. Most destructive natural disaster in Pennsylvania in terms of property damage and area affected. Entire state declared a disaster area. Deaths, 48; damage $2.1 billion, or about two-thirds of the total damage caused by Hurricane Agnes.
			New York	
Drought	1919–26	Western and central New York	10 to >25	Allegheny River Basin most affected.
Drought	1930–35	Statewide (New York)	10 to >25	Regional.
Drought	1939–42	Statewide (New York)	10 to >25	Regional.
Drought	1960–68	Statewide (New York)	35–80	Regional; serious water shortages. New York's most severe drought.
Flood	June 20–25, 1972	Western and central New York	25 to >100	Hurricane Agnes. Deaths, 24; damage, $703 million.

Table 10. Reservoirs in the Lake Erie-Lake St. Clair Basin with a normal capacity of at least 5,000 acre-feet or a maximum capacity of at least 25,000 acre-feet

[Data from Ruddy and Hitt, 1990; C, flood control; H, hydroelectric; O, other; R, recreation; S, water supply; —, no data]

Name of reservoir (name of impounded stream)	Hydrologic unit	Latitude/ longitude	Capacity (acre-feet)		Surface area (acres)	Drainage area (acres)	Year com-pleted	Use
			Normal	Maximum				
Michigan								
Barton Pond (Huron River)	04090005	42° 18' 30"/ 83° 45' 12"	6,362	7,298	302	308	1920	RSCH
Belleville Lake (Huron River)	04090005	41° 12' 54'/ 83° 26' 48"	17,780	25,225	1,280	825	1920	RCH
Ford Lake (Huron River)	04090005	42° 12' 18"/ 83° 33' 30"	28,867	31,729	917	87	1932	HRCS
Kent Lake (Huron River)	04090005	42° 30' 48"/ 83° 40' 30"	9,600	12,000	1,000	148	1946	R
Lake Columbia (Goose Creek)	04100002	42° 05' 00"/ 84° 19' 30"	56,000	73,000	800	—	1961	R
Lake Hudson (Bean Creek)	04100006	41° 49' 30"/ 84° 15' 42"	5,368	8,917	—	—	1972	R
Oxbow Lake (Huron River)	04090005	42° 38' 24'/ 83° 28' 54"	6,900	8,300	270	—	1964	R
Stony Creek Lake (Stony Creek)	04090003	42° 43' 00"/ 83° 05' 24"	5,000	7,750	608	68	1961	R
Ohio								
Bressler Upground Res-ervoir (Auglaize River)	04100007	40° 44' 12"/ 84° 14' 00"	12,634	15.074	582	—	1969	SR
Defiance Reservoir (Auglaize River)	04100007	43° 14' 18"/ 84° 24' 00"	10,800	15,000	1,240	2,329	1913	HR
Ferguson Upground Reservoir (Lost Creek)	04100007	40° 44' 18"/ 84° 02' 36"	6,900	8,209	309	<1	1958	SR
Findlay Upground Reservoir (Blanchard River)	04100008	41° 00' 36"/ 83° 34' 18"	16,368	19,478	600	—	1971	SR
Killdeer Upground Reservoir (Tymochtee Creek)	04100011	40° 42' 00"/ 83° 22' 48"	6,674	7,700	253	<1	1972	RS
La Due Reservoir (Bridge Creek)	04110002	41° 24' 24"/ 81° 11' 12"	18,100	41,300	1,500	28	1961	SR
Lake Rockwell (Cuyahoga River)	04110002	41° 11' 00"/ 81° 19' 54"	8,172	18,250	769	207	1915	SR
Mogadore Reservoir (Little Cuyahoga River)	04110002	41° 03' 30"/ 81° 22' 48"	7,000	21,000	900	14	1938	RSC
Roaming Rock Shores Lake (Rock Creek)	04110004	41° 39' 18"/ 80° 50' 24"	6,091	10,594	460	74	1967	SR

Table 10. Reservoirs in the Lake Erie-Lake St. Clair Basin with a normal capacity of at least 5,000 acre-feet or a maximum capacity of at least 25,000 acre-feet—Continued

[Data from Ruddy and Hitt, 1990; C, flood control; H, hydroelectric; O, other; R, recreation; S, water supply; —, no data]

Name of reservoir (name of impounded stream)	Hydrologic unit	Latitude/ longitude	Capacity (acre-feet)		Surface area (acres)	Drainage area (acres)	Year com- pleted	Use
			Normal	Maximum				
Willard City Reservoir (West Branch Huron River)	04100012	41° 03' 24"/ 82° 39' 54"	7,087	7,628	212	—	1971	SOR
			New York					
Lewiston Lake (Niagara River)	04120104	43° 08' 36"/ 79° 01' 18"	60,000	60,000	—	—	1960	H

Aquifers

Ground water in the Lake Erie-Lake St. Clair Basin can be obtained from wells that derive their water supply from glacial deposits and bedrock aquifers. The aquifers that are composed of glacial deposits are the uppermost, the most widespread, the most extensively used, and the most easily accessible within the basin. Aquifers are present at the bedrock surface but also extend into the subsurface and can yield substantial quantities of water in a much larger area than the bedrock outcrop. Summary information on aquifers and confining units is listed for the Lake Erie-Lake St. Clair Basin in table 11 with regard to rock or sediment type, range of reported well yields, and hydrogeologic-unit classification. In the paragraphs that follow, aquifers and confining units are described generally in order of increasing depth, starting with unconsolidated glacial deposits.

Quaternary Deposits

Three major classifications of glacial deposits are found in the Lake Erie-Lake St. Clair Basin: till, fine-grained stratified sediments, and coarse-grained stratified sediments. Till is the primary glacial material within the basin (Soller, 1993; Soller, in press). Hydraulic conductivities of tills range from 10^{-4} to 3 ft/d, and yields of wells completed in tills range from 0 to 20 gal/min (Schiner and Gallaher, 1979; Prudic, 1986; Stephenson and others, 1988). Wells that produce sufficient quantities of water from tills generally intersect thin layers or lenses of sand and gravel that are present at some locations. Till aquifers such as those described are found in the St. Joseph River Basin in northeastern Indiana and northwestern Ohio.

The next most common glacial sediments are fine-grained stratified sediments, which include bedded clay, silt, and very fine sand; for these sediments hydraulic conductivities range from 10^{-6} to 10^{-3} ft/d, and well yields range from 0 to 3 gal/min (La Sala, 1968; Crowell, 1979; Schiner and Gallaher 1979; Hartzell, 1980; Stephenson and others, 1988). Again, some wells that are completed in fine-grained stratified sediments may intersect thin layers or lenses of sand and gravel and may produce an adequate supply of water at some locations.

The least common glacial sediments are the coarse-grained stratified sediments, which include sand, gravel, alluvium, and some silt and clay (Soller, 1993; Soller, in press). For these sediments, hydraulic conductivities range from 10^{-2} to 300 ft/d, and well yields range from 0.3 to 2,050 gal/min (La Sala, 1968; Schiner and Gallaher, 1979; Stephenson and others, 1988). Ground-water flow in the coarse-grained stratified sediments is through intergranular openings that can be limited in size by the presence of clay, silt, and very fine sand. Examples of the aquifers in the Lake Erie-Lake St. Clair Basin are in the end-moraine areas of southeastern Michigan.

Hydrologic data for glacial deposits considered to be aquifers in the Midwestern Basins and Arches Regional Aquifer-System Analysis study area (western Ohio, eastern Indiana, and southeastern Michigan) were compiled by Joseph and Eberts (1994). Transmissivities reported for all glacial deposits, as determined from aquifer tests, range from 1.5 to 69,700 ft^2/d (Joseph and Eberts,1994). Where the Devonian and Mississippian shales and siltstones have been eroded, the overlying glacial sediments can confine the Silurian and Devonian carbonate-rock aquifer; in some areas,

Table 11. Aquifers and confining units within the Lake Erie-Lake St. Clair Basin

[gal/min, gallons per minute; D, meager yields but sufficient for domestic supply if no other aquifer is available; NR, no reported yields. Reference numbers in parentheses in the yield column refer to the footnotes at end of table]

Unit	Rock or sediment type	Range of reported well yield (gal/min)	Hydrogeologic classification
Unconsolidated sediments	Till	0-20 ([15 12 20])	Aquifer and confining unit
	Fine-grained sediment	0-3 ([9 3 15 8 21])	Aquifer and confining unit
	Coarse-grained sediment	0.3-2,050 ([9 16 21])	Aquifer
Pottsville Group	Sandstone	10-25 ([18])	Aquifer
Michigan Formation	Interbedded shale and sandstone	NR ([12 24])	Confining unit
Marshall Sandstone	Sandstone	900-1,000 ([12 24])	Aquifer
Coldwater and Sunbury Shales	Shale	D ([12 24])	Confining unit
Shenango Formation	Interbedded sandstone, siltstone, and shale	2-80 ([16])	Aquifer
Cuyahoga Formation	Interbedded shale and sandstone	3-10 ([26 27])	Aquifer
Cuyahoga Group	Shale, siltstone, and lenses of sandstone	5-62 ([15])	Aquifer
Sunbury Shale	Shale	NR ([12 24])	Confining unit
Berea Sandstone:			
Southeastern Michigan	Sandstone and shale	D ([4 10 11 12])	Aquifer and confining unit
Northwestern Ohio	Sandstone and shale	NR ([2])	Aquifer
Northeastern Ohio	Sandstone	1-100 ([14])	Aquifer
Northwestern Pennsylvania	Silty sandstone	1-50 ([15 16])	Aquifer
Ellsworth, Bedford, Antrim, and Ohio Shales and Conewango, Conneaut, Canadaway, West Falls, Sonyea, and Genesee Groups	Shale and siltstone	0-2;D ([27 9 4 10 11 23 18 7 1 12])	Confining unit
Cussewago Sandstone	Sandstone	1-200 ([14 16])	Aquifer
Silurian and Devonian carbonates	Limestone, dolomite, and evaporites	25-500 ([9 18 5 6])	Aquifer

[1] Bailey and Imbrigiotta (1982).
[2] Coen (1989).
[3] Crowell (1979).
[4] Fleck (1980).
[5] Hallfrisch (1986a).
[6] Hallfrisch (1986b).
[7] Hartke and others (1980).
[8] Hartzell (1980).
[9] La Sala (1968).
[10] Mozola (1969).
[11] Mozola (1970).
[12] Olcott (1992).
[13] Prudic (1986).
[14] Rau (1969).
[15] Richards and others (1987).
[16] Schiner and Gallaher (1979).
[17] Schmidt (1954).
[18] Sedam (1973).
[19] Schmidt (1980).
[20] Smith and Schmidt (1953).
[21] Stephenson and others (1988).
[22] Walker (1953).
[23] Walker and Schmidt (1953).
[24] Westjohn and Weaver (1994).
[25] Westjohn and others (1990).
[26] Winslow and White (1966).
[27] Winslow and others (1953).

however, the Silurian and Devonian carbonate-rock aquifer is unconfined (S.M. Eberts, U.S. Geological Survey, written commun., 1992).

As can be inferred from the preceding discussion, the glacial deposits in the Lake Erie-Lake St. Clair Basin are heterogeneous mixtures of sediments. This relatively nonuniform configuration of sediments that have a wide range of hydraulic properties (as compared to specific consolidated rock units) makes the description of regional ground-water flow directions impossible. Only in specific areas where a high degree certainty about the configuration and composition of these sediments is known can accurate predictions of the direction ground-water flow be made. In general, however, regional to subregional ground-water flow is from topographically high areas toward topographically low areas that contain streams, rivers, and lakes or ponds.

A system of buried river valleys filled with various lacustrine, alluvial, and glacial deposits is present in the Lake Erie-Lake St. Clair Basin (fig. 7). These buried river valleys have several types of aquifer configuration, depending on location and origin. In areas where the buried-valley aquifers consist of lenses of coarse-grained material that are buried by less permeable, fine-grained materials and till, reported well yields range from less than 1 to 35 gal/min (Winslow and White, 1966; La Sala, 1968). Well yields have been reported to be as large as 1,000 gal/min from coarse-grained materials at a depth of 100 to 125 ft below land surface in the Cuyahoga River Valley (Winslow and White, 1966; Ford, 1987; Totten, 1988). In the Tonawanda Creek Valley, coarse-grained material reportedly extends to a depth of 70 ft below land surface and is capable of yielding 1,000 to 1,400 gal/min (La Sala, 1968). These large well yields are related not only to the nature of the material but also to the amount of water that can recharge the unconsolidated aquifer from precipitation, infiltration, and flow of ground water from the surrounding bedrock.

In some areas within the buried river valleys, the glacial sediments consist principally of fine-grained deposits and till. Yields in these areas are generally less than 10 gal/min, and many boreholes fail to penetrate materials coarse enough for the development of a domestic source of supply (Winslow and White, 1966).

Bedrock units considered in the remainder of this section are described as aquifers, confining units, or both. Because the compilation is on a regional scale, the hydrogeologic classifications are only generalized indicators of potential yield. The hydraulic properties of these aquifers and confining units are given in greater detail in the following paragraphs, in order of west to east within each major time-stratigraphic division.

Pennsylvanian Units

Hydrologic data for the Pottsville Group in northeastern Ohio were compiled by Sedam (1973). Transmissivities reported for the Pottsville Group, as determined from specific-capacity data derived from drillers' logs, range from 160 to 610 ft^2/d. Wells completed in the Pottsville Group in northeastern Ohio generally yield 10 to 25 gal/min, but yields exceed 25 gal/min in some locations. In areas where yields exceed 25 gal/min, poor cementation may increase the effective porosity, and secondary openings (such as joints and fractures or the primary pore spaces between sand grains) may be enlarged by solution. Elsewhere, the Pottsville Group yields less than 10 gal/min, probably where shale lenses are interbedded with the sandstone or primary porosity has been reduced by increased cementation within the sandstone (Sedam, 1973).

Generalized regional ground-water flow in the Pottsville Group was described by Eberts (1991) to be from areas of high water levels, located generally in a topographically high position, to areas of low water levels in topographically lower valleys. The general direction of ground-water flow is radially away from the topographic highs and into the glacial deposits in the valleys (Eberts, 1991).

Mississippian Units

The Michigan Formation in southeastern Michigan is described as a confining unit by Olcott (1992) and by Westjohn and Weaver (1994). The determination that the Michigan Formation is a confining unit is based on evidence from the oil and natural gas industry in Michigan. In the central part of the Michigan Basin, the Michigan Formation functions as a stratigraphic trap for reservoirs of natural gas in the underlying Marshall Sandstone. Small quantities of water for domestic use may be developed from fractures at or near the bedrock surface.

The Marshall Sandstone in southeastern Michigan is described as an aquifer unit by Olcott (1992) and by Westjohn and Weaver (1994). Transmissivities of the Marshall Sandstone determined from aquifer tests range from 2,700 to 29,000 ft^2/d. The highest transmissivities are found within or close to the subcrop of the aquifer, where it contains the largest and most abundant fractures and bedding-plane partings. Well yields in the subcrop area of the aquifer range from 900 to 1,000 gal/min (Olcott, 1992). The Marshall aquifer is primarily confined or semiconfined, but it is unconfined locally where it is exposed at the bedrock surface and the overlying glacial deposits are not fine grained.

The Coldwater and Sunbury Shales in northeastern Indiana and southeastern Michigan are described as a confining unit by Olcott (1992) and Casey (in press c). Hydrologic data for the Mississippian shales and siltstones are not known to have been published. Westjohn and others (1990) made porosity and hydraulic conductivity measurements on cores obtained from the base of the Marshall Sandstone. They concluded that vertical and horizontal hydraulic conductivities were two to three orders of magnitude less than those of the overlying permeable sandstone: "Shales that form the bulk of the Coldwater confining unit are assumed to have lower hydraulic conductivities than the micaceous sandstone/siltstones at the base of the Marshall aquifer * * * " (Westjohn and Weaver, 1994; p. 24). In places, small quantities of water for domestic use can be developed from fractures at or near the bedrock surface.

The Shenango Formation in northwestern Pennsylvania was described by Schiner and Gallaher (1979) as an aquifer unit that will generally produce water of sufficient quantity and quality for domestic and some commercial use. They reported that yields of wells completed in the Shenango Formation range from 2 to 80 gal/min and that the median yield is 20 gal/min (Schiner and Gallaher, 1979). The most important controls for yields from Shenango Formation in northwestern Pennsylvania are the amount of fracturing, the lithology, and the composition of the overlying glacial materials.

The Cuyahoga Formation in northeastern Ohio is divided into three lithologic units, but the water-bearing characteristics of these units are similar (Winslow and White, 1966). Wells in the Cuyahoga Formation yield from 3 to 10 gal/min and are generally used for domestic purposes. The Cuyahoga Formation is not as productive an aquifer as the underlying Berea Sandstone; for that reason, many wells are drilled through the Cuyahoga Formation and are completed in the Berea Sandstone. Ground-water flow in the Cuyahoga Formation is controlled by secondary permeability due to fractures, bedding-plane partings, and openings along unconformity surfaces within the formation (Winslow and others, 1953).

The Cuyahoga Group in northwestern Pennsylvania is described by Richards and others (1987) as an aquifer unit that will generally produce water of sufficient quantity and quality for domestic and some commercial use. They reported that yields of wells completed in the Cuyahoga Group range from 5 to 62 gal/min and that the median yield is 13.5 gal/min. In places where a more sandy-shale or a sandstone facies is at or near the bedrock surface, the aquifer is more productive than where a siltstone or a shale facies is near the bedrock surface (Richards and others, 1987).

The Sunbury Shale in northeastern Ohio is considered to be a confining unit. Hydrologic data for the Sunbury Shale are not known to have been published. In places, small quantities of water for domestic use can be developed from fractures at or near the bedrock surface.

The Berea Sandstone in southeastern Michigan has been called an aquifer by Mozola (1969; 1970) and Fleck (1980); however, Olcott (1992) calls the Berea Sandstone part of a regional confining unit. The discrepant opinions among these authors may be due to the scale at which the Berea Sandstone was studied. Mozola and Fleck analyzed data at the county level, whereas Olcott analyzed data at a regional scale. Locally, small quantities of water for domestic use may be developed from intergranular porosity or from bedding-plane partings and fractures at or near the bedrock surface. Hydrologic data for the Berea Sandstone in southwestern Michigan are not known to have been published.

The Berea Sandstone in northwestern Ohio is deeply buried by glacial sediments in many places, so it is generally not used as a ground-water source (Coen, 1989). Hydrologic data for the Berea Sandstone in northwestern Ohio are not known to have been published. Locally, where the Berea Sandstone is at or near the bedrock surface, small quantities of water for domestic use can be developed from intergranular porosity or from bedding-plane partings and fractures.

In northeastern Ohio, the Berea Sandstone is a productive aquifer. Rau (1969) reported that the yield of wells completed in the Berea Sandstone averages about 18 gal/min and ranges from 1 to 100 gal/min. This large range in well yields can be a result of the thickness and the porosity of the Berea Sandstone and the permeability of the overlying material. Where the Berea Sandstone is as much as 150 ft thick and overlain by saturated permeable glacial materials, well yields generally range from 25 to 50 gal/min and can be as high as 100 gal/min. In areas where the Berea Sandstone is thin or has reduced porosity or where the overlying bedrock or glacial materials are poorly permeable, well yields range from 1 to 10 gal/min. Average transmissivities for the Berea Sandstone range from 140 to 900 ft^2/d (Rau, 1969).

The Berea Sandstone in northwestern Pennsylvania is described by Schiner and Gallaher (1979) and Richards and others (1987) as an aquifer unit that will generally produce water of sufficient quantity and quality for domestic and some commercial use. They reported that yields of wells completed in the Berea Sandstone range from 1 to 50 gal/min and that median yield is 8 gal/min. Here, the Berea Sandstone is finer grained than in northeastern Ohio, so ground-water flow is primarily through fractures and bedding-plane partings (Richards and others, 1987).

Lower Mississippian and Upper Devonian Units

In northeastern Indiana, southeastern Michigan, northwestern Ohio, northeastern Ohio, and western New York, the remaining Lower Mississippian and Upper Devonian shales and siltstones are described as confining units or unproductive aquifers (Winslow and others, 1953; La Sala, 1968; Mozola, 1969, 1970; Fleck, 1980; Olcott, 1992; Casey, in press c). These lithologic units include the Ellsworth Shale, the Bedford Shale, the Antrim Shale, the Ohio Shale, and the Conewango, Conneaut, Canadaway, West Falls, Sonyea, and Genesee Groups. Hydrologic data for the Devonian and Mississippian shales and siltstones are sparse, but some vertical and horizontal hydraulic conductivities have been determined from analysis of cores collected from the Devonian shales in Ohio. Horizontal and vertical matrix permeabilities determined for cores from two wells drilled into the Ohio Shale ranged from 10^{-5} to 10^{-7} ft/d (unpublished data maintained in the files of the U.S. Geological Survey, Columbus, Ohio) and are similar to those reported for shales by Heath (1983). In Ohio and Indiana, the Devonian and Mississippian shales and siltstones have been described as having a very low effective porosity (Bailey and Imbrigiotta, 1982; Coen, 1989). Yields of water wells completed in the Devonian and Mississippian shales and siltstones typically are low (less than 2 gal/min), and dry holes are common (Smith and Schmidt, 1953; Walker and Schmidt, 1953; Walker, 1953; Schmidt, 1954; La Sala, 1968; Hartke and others, 1980; Bailey and Imbrigiotta, 1982).

In easternmost northeastern Ohio and northwestern Pennsylvania, the Cussewago Sandstone (the basal Mississippian section) is a productive aquifer (Rau, 1969; Schiner and Gallaher, 1979). Yields from the Cussewago Sandstone in northeastern Ohio generally range from 1 to 100 gal/min and are 200 gal/min in places; average yield is 26 gal/min (Rau, 1969). Low yields can be expected in areas where the Cussewago Sandstone is thin and only partially saturated, well cemented, or overlain by a moderate amount of shale or poorly permeable glacial materials. High yields from the Cussewago Sandstone are found in areas where the aquifer is composed of thick channel sand deposits or is overlain by permeable glacial materials (Rau, 1969).

In northwestern Pennsylvania, yields from the Cussewago Sandstone range from less than 1 to 130 gal/min, and the median yield is 20 gal/min. High yields from the Cussewago Sandstone are found in areas where the unit is thick, poorly cemented, and overlain by permeable glacial deposits. Low yields can be expected in areas where the aquifer is thin, well cemented, and overlain by till or more than about 200 ft of shale (Schiner and Gallaher, 1979).

Devonian and Silurian Units

The units underlying the Lower Mississippian and Upper Devonian shales and siltstones constitute a regionally extensive carbonate-rock aquifer. The permeability of a carbonate rock is the result of primary openings that form when the carbonate sediment is deposited or precipitated and secondary openings that form after the sediment has been lithified. The carbonate rocks that form the Silurian and Devonian carbonate-rock aquifer have been affected by many processes that control the ability of the various geologic units to transmit water. These processes include cementation, recrystallization, micritization, solution, dolomitization, uplifting, faulting, unloading, and weathering (Brahana and others, 1988). Many of these processes can either increase or decrease the ability of carbonate rocks to transmit water.

In the Silurian and Devonian carbonate-rock aquifer in the Lake Erie-Lake St. Clair Basin, certain facies have a porous and vuggy texture (noted in the section "Geologic Setting and Stratigraphy"). This texture can be the result of various diagenetic processes that can increase the porosity and permeability of the carbonate-rock aquifer in the facies that has been subjected to diagenesis. Throughout the carbonate-rock aquifer, rocks that have this porous and vuggy texture can be laterally equivalent to dense rocks that do not have this texture. These relations are present throughout the carbonate-rock aquifer. At a regional scale, the areas of diagenetically controlled increases or decreases in permeability are not mappable.

The flow and storage of ground water in the carbonate-rock aquifer is primarily within those zones of rock that contain openings along joints, fractures, and bedding planes (secondary permeability). Some of these openings have been enlarged by dissolution as ground water flowed through them. The magnitude and degree of interconnection between these openings determine the ability of the rock to transmit and yield water. The matrix of the carbonate rocks also contains water that contributes to the ground-water flow system (primary and secondary permeability), but this water is assumed to be insignificant when compared to the quantities of water that move through the joints, fractures, and bedding planes (Arihood, 1994). Results of a series of aquifer tests in northwestern Indiana (outside of the basin but within the same lithologic units being studied by the Lake Erie-Lake St. Clair NAWQA) showed that "almost all of the transmissivity is derived from horizontal fracturing; however, only a few fractures present in the carbonate are transmissive" (Arihood, 1994).

The upper zone of the Silurian and Devonian carbonate-rock aquifer (the strata at or near the bedrock surface regardless of the lithologic unit) generally contains more fractures and solution-enlarged openings than do deeply buried zones. This prevalence of fractures and solution-enlarged openings is a result of weathering of the bedrock, unloading (removal of overlying material), and dissolution of the carbonate rock by ground-water flow. At depths greater than 250 to 300 ft below land surface, however, these fractures generally are considered incapable of transmitting water because (1) the weight of the overlying strata limits the unloading-related fracturing and (2) the secondary mineralization of the fractures limits the size of the openings between the fracture walls. Some investigators (Beaumont and others, 1988) have suggested that a thick sequence of sedimentary rock was deposited on top of the carbonate-rock aquifer and was removed from the study area by weathering and erosion. The removal of the overlying strata, coupled with the multiple glacial advances and retreats in the Great Lakes Region, allowed the unloading-related joints to form preferentially at preexisting points of weakness in the Silurian and Devonian carbonate rocks (Kappel and Tepper, 1994).

Some zones within the carbonate-rock aquifer below the upper fractured zone are more transmissive than the rest of the carbonate-rock aquifer. The "Newburg Zone," a zone in eastern Ohio named by the oil and gas industry, was documented by Norris and Fidler (1971). This zone is in the carbonate strata overlying the Lockport Dolomite in the lower part of the Salina Group (Norris and Fidler, 1971). The Newburg Zone is not contiguous within the study area, and other permeable zones at about the same depth have been noted in a broader stratigraphic section than that described by Norris and Fidler (1971). Strobel and Bugliosi (1991) proposed that the Newburg Zone could be the result of multiple, diachronous processes. Because of the lack of evidence that this zone is laterally extensive, it is probably not regionally important as a water-bearing zone, but it could be significant locally.

In western New York, the lower section of the Salina Group is an interbedded limestone, dolomite, and shale that contains significant amounts of gypsum. These gypsum zones have been dissolved by ground-water flow in areas where this unit is near the bedrock surface. These solution-widened water-bearing zones are present at various depths and stratigraphic locations within the Salina Group. These water-bearing zones can be continuous over several miles, but data on exact extent of these zones are not available (La Sala, 1968).

The carbonate rocks at and above a regionally extensive erosional surface (the Silurian-Devonian unconformity) can yield continuously large quantities of water from seeps within quarries and outcrops (Shaver, 1989). This feature has been eroded in the southwestern and northeastern part of the basin, where older rocks crop out; however, the unconformity and a zone above the unconformity appear to be a less resistant path for ground-water flow than zones either above or below it. A clastic-rich zone contained within the lower part of the Middle Devonian Detroit River Formation directly above the unconformity (described in the section "Geologic Setting and Stratigraphy") transmits ground water effectively. The underlying Silurian rock is a massive carbonate rock, whereas the rock from within the clastic-rich zone is a fine-grained sandstone and sandy dolomite that is overlain by alternating units of argillaceous to pure bioclastic, vuggy, nonfossiliferous dolomite (Shaver, 1989). Additionally, when exposed in a quarry face, surficial iron staining of carbonate rocks below this zone indicates that water moves preferentially within this zone as a result of the change in hydrologic character between the overlying Devonian carbonate rock and the underlying Silurian carbonate rock. This staining results from the flow of ground water out of the more transmissive zone and down the quarry face below.

Faulting of carbonate rocks can affect ground-water flow in various ways. It can increase an aquifer's ability to transmit water by fracturing the rock, thereby increasing the ground-water flow and the dissolution of the carbonate rock, consequently enlarging the original fractures. Faulting also can restrict ground-water flow where a poorly permeable unit is displaced along the fault and comes in contact with a more permeable unit.

The Bowling Green Fault Zone has been studied with respect to its hydrologic effects. VanWagner (1988) described the variation of specific capacity (which was termed "transmissivity factor") across sections of the fault zone. VanWagner (1988) noted that the largest specific capacities were found along fracture trends but that some unproductive wells were within several hundred feet of wells with large specific capacities. This example demonstrates that hydrologic characteristics can differ widely over short distances within a feature such as the Bowling Green Fault Zone.

In Ohio, rock units within the Silurian and Devonian carbonate-rock aquifer have been displaced by faults within the Bowling Green Fault Zone (fig. 5), although regional ground-water flow does not seem to be affected by this displacement. Multiple faults have been mapped within this fault zone (VanWagner, 1988), which extends from northwestern Ohio along the western edge of the Appalachian Basin into southeastern Michigan. Movement along this feature may have occurred during early Paleozoic time but could have occurred as recently as Mesozoic or possibly Cenozoic time (Onasch and Kahle, 1991). Vertical displacement along the Bowling Green Fault Zone ranges from 90 to 300 ft (VanWagner, 1988).

Transmissivities for the carbonate-rock aquifer, determined from aquifer tests, range from 70 to 28,000 ft^2/d, and storage coefficients range from 0.00001 to 0.01 (Joseph and Eberts, 1994). Well yields in the Silurian and Devonian carbonate-rock aquifer generally range from 25 to 500 gal/min, but yields are locally higher in specific units (La Sala, 1968; Schmidt, 1980; Hallfrisch, 1986a,b).

Regional ground-water flow directions in the Silurian and Devonian carbonate rock aquifer are from a potentiometric high that is located south and west of the Lake Erie-Lake St. Clair Basin toward the perennial streams and Lake Erie. Local ground-water flow directions may differ because of the presence of fractures and solution openings in the carbonate aquifer (Eberts and Lesney, in press).

Water Quality

Quality of streams and stream sediments in the Lake Erie-Lake St. Clair Basin has been assessed in great detail at certain locations for contaminants associated with dissolved-oxygen depletion and nutrient enrichment, trace-element and toxic-substance contamination, and sedimentation. In contrast, water quality in aquifers in the Lake Erie-Lake St. Clair Basin has been investigated in only a few comprehensive and regional studies. Discussions of water quality in the subsequent sections of this report are based on summaries of published, comprehensive reports.

Stream Quality

As early as 1951, statewide and regional water-quality assessments were conducted chiefly by the U.S. Geological Survey and the Federal Water Pollution Control Administration. By the 1970's, statewide and regional studies by Federal agencies were often done in cooperation with state resource-management and public-health agencies such as the Ohio Department of Natural Resources (ODNR), Ohio Department of Health (ODH), Ohio Environmental Protection Agency (OEPA), Michigan Department of Natural Resources (MDNR), Michigan Department of Health, Indiana Department of Natural Resources (IDNR), and New York State Department of Environmental Conservation (NYSDEC). During the mid-1970's to early 1980's, water-quality programs were carried out by state pollution-control agencies, health departments, and the USEPA. Such programs were and are still driven by legislation such as the Clean Water Act and the Safe Drinking Water Act. The USGS National Stream Quality Accounting Network program (NASQAN) was among the earliest national stream-quality monitoring programs; eight NASQAN sites in the Lake Erie-Lake St. Clair Basin were sampled during 1975–95. The outcome of these monitoring activities is a substantial and diverse amount of water-quality and associated data that have been reported on for the Lake Erie-Lake St. Clair Basin as a whole.

Fixed-site, fixed-frequency monitoring is currently done by Michigan Department of Environmental

Quality (MDEQ), IDEM, OEPA, USGS, Heidelberg College Water Quality Laboratory, Pennsylvania Department of Environmental Regulation, and NYSDEC. These above-mentioned state agencies monitored stream quality at 58 fixed-site, fixed-frequency sampling locations in the basin in 1994.

Among the measurements and analyses obtained from monitoring activities at these fixed sites are water temperature, pH, alkalinity, turbidity, specific conductance, and concentrations of dissolved oxygen, organic and inorganic ammonia-N, nitrate plus nitrite-N, total and dissolved phosphorus, oxygen-demanding substances determined as biochemical and chemical oxygen demand, trace elements, phenolic compounds, dissolved and suspended solids, suspended sediment, currently used pesticides, and total and dissolved organic carbon. Recent monitoring activities have focused more on characterizing concentrations of contaminants in streamwater, so much less recent data is available on the concentration of naturally occurring substances such as major ions.

Certain streams are investigated intensively at 3- to 10-year intervals by state agencies to determine their chemical and biological quality and to assess attainment of the goals of the Clean Water Act. MDEQ, OEPA, and NYSDEC collect streambed samples for determination of trace elements and synthetic organic substances and also conduct ecological-assessment studies of fish, aquatic macroinvertebrate, and habitat quality. Fish-contaminant data are collected by state environmental regulatory agencies and the U. S. Fish and Wildlife Service for status and trend analysis and for evaluation the suitability of edible fillets for human consumption.

Substantial progress has been made in the Lake Erie Basin to control and mitigate point-source contamination and improve water quality. Most water-quality assessment programs of the Federal and state governments have focused on assessment of concentrations and discharges of oxygen-demanding wastes, nutrients, trace elements, and trace organic substances and the effects of these contaminants on aquatic invertebrates and fish. This focus on assessment of contaminant issues is driven by the fact that these are the most frequently cited causes of partial attainment or nonattainment of the goals of the Clean Water Act for streams in the Lake Erie-Lake St. Clair Basin (Ohio Environmental Protection Agency, 1990, 1995; Michigan Department of Natural Resources, 1992b; Bode and others, 1993).

Regional water-quality initiatives are an outgrowth of public concern about water quality. Among these initiatives are the Great Lakes Water Quality Agreement of 1978 (GLWQA) between the United States and Canada and its revisions (1987). The GLWQA was a product of the International Joint Commission (IJC). Impairments to the uses of water resources from toxic substances, pathogens, and other adverse environmental conditions have been identified in 43 Areas of Concern (AOC's) by the IJC. Remedial Action Plans to clean up these areas have been prepared and in some cases have been partly implemented. Eleven AOC's are in the basin and include certain areas of the Clinton, Rouge, Raisin, Maumee, Black, Cuyahoga, Ashtabula, and Buffalo Rivers. In addition, there are AOC's in the St. Clair River, Detroit River, Presque Isle Bay, and Niagara River. Another outcome of the GLWQA was the formation of Lakewide Management Plans (LaMP's). The goals of the Lake Erie Lakewide Management Plan are to restore and protect the open waters of Lake Erie.

Major Ion Composition of Streams

The major-ion composition of most streams in the Lake Erie-Lake St. Clair Basin consists mostly of calcium, bicarbonate, and sulfate. To a lesser degree and in certain streams, sodium and chloride ions can be codominant with calcium, bicarbonate and sulfate ions.

The properties and concentrations of major ions in streamwater affect its use for public and domestic supply. Elevated concentrations of calcium, chloride, iron, manganese, sulfate, and dissolved solids can cause undesirable taste, odor, deposits, and stains on materials and certain unpleasant side effects from consumption. Hardness of water, expressed as the concentrations of calcium carbonate (milligrams per liter as $CaCO_3$), and concentrations of dissolved solids are commonly measured to characterize suitability for domestic supply. Qualitative terms used in this report to describe hardness ranges are given in table 12.

For domestic uses, water whose hardness is less than 100 mg/L and whose concentrations of dissolved solids and sulfate are less than 500 mg/L is considered acceptable (Hem, 1985; U.S. Environmental Protection Agency, 1994).

Most streams in the Lake Erie-Lake St. Clair Basin contain water that is moderately hard to very hard because of dissolution of limestone, dolomite, calcareous shale, and calcareous glacial and alluvial materials that dominate the surficial and bedrock geology and aquifer materials of the basin. The lowest hardness reported for streams in the basin ranges from slightly less than 60 mg/L as $CaCO_3$ (soft) to 100 mg/L as $CaCO_3$ (moderately hard) in the Ashtabula River and Conneaut Creek in northeastern Ohio and in Cattaraugus Creek and nearby smaller streams in western New York. Concentrations of dissolved solids in streams with relatively low hardness are typically less than 500 mg/L (table 13). Such areas of soft to moderately hard water and relatively low concentrations of dissolved solids are underlain by thin till and the Upper Devonian and Lower Mississippian shale bedrock. The highest hardness (greater than 300 mg/L as $CaCO_3$) and highest concentrations of dissolved solids (greater than 500 mg/L) are found in streams that drain areas underlain by a thin layer of glacial material and the Antrim Shale, such as the Clinton and Belle Rivers in southeastern Michigan, and streams underlain by Devonian and Silurian limestones and dolomites, such as the River Raisin (table 13). Streamwater near Buffalo, N.Y., which is underlain by the Salina Group, the Onondaga Limestone, and the Hamilton Group, also is very hard.

Detailed and broad-scale studies of the major-ion chemistry of streams tributary to the St. Clair River, Lake St. Clair, the Detroit River, and western Lake Erie have been reported on by Wood (1970), Cummings (1983), Rheaume (1991), Holtschlag (1987), Blumer (1993), Smith and others (1993), and Michigan Department of Natural Resources (1992a, b). The Black, Clinton, Huron, and Raisin Rivers contain water that is principally of the calcium-bicarbonate type. Concentrations of major anions (table 13) and hardness are reported to be inversely related to streamflow for the Black, Clinton, Huron, and Raisin Rivers (Michigan Department of Natural Resources, 1992a). Concentrations of chloride reported for the Clinton River were the highest of 21 sites reported in Michigan (Michigan Department of Natural Resources, 1992b). Ground water in the Coldwater Shale, Berea Sandstone, Bedford Shale, and Antrim Shale, which underlie the lower and middle reaches of the Black, Belle, Clinton, Rouge, Huron, and Raisin Rivers, can contain elevated concentrations of sodium (100–10,000 mg/L) and chloride (250–15,000 mg/L) (Mozola, 1970, p. 21; Rheaume, 1991, p. 44). Ground-water discharge from these formations and deposits is a likely source of the elevated concentrations of chloride in the Clinton River, which are frequently attributed solely to deicing chemicals. Chloride concentrations in the Huron River were the third highest of the 21 sites reported in Michigan (Michigan Department of Natural Resources, 1992b).

Concentrations of major ions have been published for streams tributary to the Lake Erie Basin in Ohio (Youngquist, 1953; Childress and Koltun, 1993; Smith and others, 1993). Youngquist (1953) reported that streams of the Lake Erie Basin in Ohio are of the calcium-bicarbonate and calcium-bicarbonate-sulfate type. In general, concentrations of major ions and dissolved solids in streams tributary to Lake Erie in Ohio are similar to or lower than those in Michigan. Within the Ohio part of the basin, chloride concentrations on average are slightly higher in the Portage, Cuyahoga, and Ashtabula Rivers than in the Maumee, Sandusky, and Grand Rivers. The highest sulfate concentrations in the basin are in the Raisin, Maumee, and Sandusky Rivers and are contributed by the evaporites contained within Silurian and Devonian limestone and dolomite underlying these streams.

Major-ion concentrations are reported for Cattaraugus Creek (table 13). Historical water-quality data for streams in western New York are reported in Archer and others (1968), Archer and La Sala (1968), Frimpter (1973), and Rogers (1993). Archer and others (1968) reported a gradient of increasing concentration from west to east for major ions in streamwater in western New York and an inverse relation between streamflow and major-ion concentrations. Concentrations of most major ions and hardness are lowest in Cattaraugus Creek compared to other similar-sized streams in the Lake Erie-Lake St. Clair Basin. Concentrations of most major ions and hardness in the main stem of the Buffalo River were intermediate when compared to other streams in the Lake Erie-Lake St. Clair Basin. Water from streams in the Buffalo Creek Basin were reported

Table 12. Hardness ranges and descriptions for natural waters

[From Hem (1985); $CaCO_3$, calcium carbonate]

Hardness Range (milligrams per liter of $CaCO_3$)	Description
0–60	Soft
61–120	Moderately hard
121–180	Hard
>180	Very hard

Table 13. Concentrations of chloride, sulfate, and dissolved solids in selected streams of the Lake Erie-Lake St. Clair Basin

[mg/L, milligrams per liter; ND, no data; NR, not reported]

	Black River	Clinton River	River Raisin	Maumee River		Sandusky River		Cuyahoga River		Grand River	Cattaraugus Creek
Period of record	1991	1980–89	1975–89	1980–89	1982–91	1980–89	1983–91	1980–89	1983–91	1980–91	1980–89
Reference	([1])	([2 3 4])	([2 3 4])	([4 5])	([6])	([4 5])	([6])	([4 5])	([6])	([3 5])	([7])
Chloride (mg/L)											
Median or quartiles	21–91	91–190	27–60	NR	28.7	NR	28	NR	94.8	<10–79	11–21
Sulfate (mg/L)											
Quartiles	40–120	28–89	44–180	80–100	ND	100–200	ND	60–90	ND	26–60	25–35
Dissolved solids (mg/L)											
Quartiles	300–500	250–650	300–750	100–500	ND	380–600	ND	400–530	ND	150–800	190–220

[1]Michigan Department of Natural Resources, 1992a. [2]Blumer, 1993. [3]Cummings, 1983. [4]Smith and others, 1993. [5]Childress and Koltun, 1993. [6]Baker, 1993. [7]Rogers, 1993.

to be moderately hard to very hard, in the range of 60 to 190 mg/L as $CaCO_3$.

Concentrations of most major ions in Tonawanda Creek were highest among streams in the Lake Erie-Lake St. Clair Basin in New York (Archer and others, 1968). Streamwater in the Tonawanda Creek Basin is very hard, ranging from 190 to 490 mg/L as $CaCO_3$ (Archer and others, 1968). The higher concentrations of major ions in Tonawanda Creek relative to Cattaraugus Creek and the Buffalo River may be the result ground-water discharge from of the Salina Group, which underlies lower Tonawanda Creek, and urbanization in Buffalo, N.Y.

Effects from Urban Runoff and Incompletely Treated Wastewater

Owing to the large population of the basin and incomplete treatment of domestic and municipal wastewater in some areas, nutrient enrichment and oxygen depletion of streams by point sources are among the most often cited water-quality problems (Michigan Department of Natural Resources, 1992a; Bode and others, 1993; Ohio Environmental Protection Agency, 1995). Nitrogen can be present in domestic wastewater and receiving streams in the form of ammonia-N, ammonia plus organic-N, and nitrate plus nitrite-N. Phosphorus can be present in streamwater either in the particulate or the dissolved form. Much of the point-source contribution of nitrogen historically entered surface water as reduced forms—ammonia-N or ammonia plus organic-N. When ammonia-nitrogen-containing wastes are discharged to streams along with other types of incompletely treated wastes, oxygen is consumed during decomposition.

Much has been done to reduce the oxygen-demanding discharges of ammonia and carbon compounds through advanced wastewater treatment, during which the nitrification process is enhanced and ammonia is converted to nitrate. More than $20 billion was spent in Ohio alone during 1980–94 in wastewater-treatment-plant construction and improvements to remediate the problem of oxygen depletion (Ohio Environmental Protection Agency, 1995). Increasingly, conversion of ammonia compounds to nitrate plus nitrite-N compounds has resulted in uptrends in nitrate concentrations in some streams in the Nation (Puckett, 1995). However, no uptrends in nitrate plus nitrite-N had been documented in urban streams in the Lake Erie-Lake St. Clair Basin as of the early 1990's (Richards and Baker, 1993; Smith and others, 1993).

Enrichment with phosphorus has long been the major water-quality concern for Lake Erie, and much has been done to reduce point-source discharges of phosphorus to the lake. Algal blooms and loss of oxygen in the hypolimnion of Lake Erie in the summer are undesirable characteristics of phosphorus enrichment and contributed to the notion that Lake Erie was dead (Herdendorf, 1986). Efforts to model the response of Lake Erie to phosphorus reductions resulted in a prediction that if phosphorus discharges were limited to 11,000 metric tons per year, then as much as 90 percent of the hypolimnion in the central basin of Lake Erie would remain oxygenated all year. Based on this assumption, a discharge limit of 11,000 metric tons (12,125 tons) of phosphorus from all sources was set as the annual target load by the IJC in the GLWQA (International Joint Commission, 1994).

The Lake Erie Basin receives the largest volume of treated wastewater of any of the other Great Lakes and from 2 to 20 times more phosphorus from point sources. Most of the point-source contribution of phosphorus is from major municipal dischargers in Detroit, Mich., and Cleveland and Toledo, Ohio (Dolan, 1993). (A major discharge is defined by USEPA as one that is discharging 1 Mgal/d or more or has an effect on receiving water quality that is of concern.) To help achieve the target phosphorus load for Lake Erie, these discharges are treated to contain less than 1.0 mg/L of total phosphorus. This treatment standard is prescribed by the IJC in Annex 3 of the Great Lakes Water Quality Agreement of 1978 (International Joint Commission, 1994).

Phosphorus removal from wastewater resulted in about 82-percent decrease in amount of total phosphorus discharged from point sources from 1971–90 (Dolan, 1993). Point-source reductions in total phosphorus have resulted in a strong and significant downtrend in phosphorus concentration in the lake (Rathke and Edwards, 1985; Bertram, 1993). However, the problem of hypolimnetic oxygen depletion, while improved, has not been eliminated or reduced as much as was expected (Bertram, 1993). The less than expected declines in oxygen depletion have resulted in the development of other strategies to further decrease phosphorus discharges to the lake.

Dolan (1993) estimated that during 1986–90, point sources contributed from 17.8 to 32.5 percent of the total phosphorus discharged to Lake Erie and that nonpoint tributary sources discharged from 48.9 to 70.3 percent. The estimated atmospheric inputs of phosphorus during this period were a relatively small part of the total nonpoint source load, ranging from just 3.2 to 5.6 percent. Estimated inputs to Lake Erie from upstream sources of phosphorus in the Great Lakes Basin (measured at the outflow of Lake Huron) for the same period ranged from 8.4 to 13.8 percent of the total phosphorus load. Because most major wastewater treatment plants are in compliance with the 1-mg/L treatment standard, Dolan (1993) concluded that point-source contributions do not appear to determine whether the target of 11,000 metric tons per year is achieved. Rather, it is the more variable tributary nonpoint-source contribution that makes the difference in any given year.

Tributary loads are higher in wet years than in dry years. In wet years, the total annual amount of phosphorus discharged to Lake Erie from all sources commonly exceeds the target maximum of 11,000 metric tons. The focus of phosphorus control, therefore, is directed at reducing tributary discharges from nonpoint sources in urban and agricultural areas. For example, nearly all the states in the Lake Erie Basin have adopted bans on household detergents containing more than 0.5 percent phosphate by weight, resulting in further potential reductions in phosphorus from sources such as septic systems. Urban drainage management and control have been discussed as potential control measures for urban nonpoint sources of phosphorus (International Joint Commission, 1994).

Examples of nutrient enrichment in urban tributaries can be seen in comparisons of the Clinton River above and below Pontiac, Mich., and the Huron River above and below Ann Arbor, Mich., which show an increasing gradient from upstream to downstream sampling locations in median concentrations of total phosphorus and nitrate plus nitrite-N (Holtschlag, 1987; Michigan Department of Natural Resources, 1992b). Total phosphorus concentrations in the Clinton River increased from 0.02 mg/L upstream from Pontiac, Mich., to 0.09 mg/L downstream, and nitrate plus nitrite-N concentrations increased from 0.09 to 1.3 mg/L. For the Huron River upstream and downstream from Ann Arbor, Mich., nitrate plus nitrite-N increased from 0.26 to 0.84 mg/L, and total phosphorus increased from 0.02 to 0.06 mg/L (Michigan Department of Natural Resources, 1992b). The Huron River throughout its length is reported to be subject to moderate nutrient enrichment and turbidity (Michigan Department of Natural Resources, 1992b).

Aside from phosphorus and nitrogen enrichment, urban streams in the basin are affected by incompletely treated wastewater; that is, combined sewer and stormwater discharges. The effects of urban runoff are oxygen depletion and bacterial contamination. The Clinton, Rouge, Huron, and Raisin Rivers are subject to intermittent contamination with fecal bacteria (Michigan Department of Natural Resources, 1992a)

The Black River (Michigan) is affected by discharges from combined sewers near its mouth (Michigan Department of Natural Resources, 1992a). OEPA (1992a, b; 1993a) reported that public and industrial points sources and discharges from combined sewers have degraded certain areas of tributaries to the Maumee River (the Blanchard, Ottawa, and St. Marys Rivers). Public wastewater point sources and combined-sewer discharges, as well as siltation in the stream channel, have moderately degraded the fish community in the upper reaches of the Sandusky River (Ohio Environmental Protection Agency, 1991a).

The water quality in the main stem of the Black River (Ohio) has improved significantly since the mid-1980's owing to reduced discharges of incompletely treated domestic and industrial wastewaters and combined sewers (Ohio Environmental Protection Agency, 1994a,b). The upper reaches of the Black River continue to be influenced by the discharge of incompletely treated or untreated effluents from many small wastewater treatment plants, combined sewers, sanitary sewers, and unsewered areas (Ohio Environmental Protection Agency, 1994b). The main stem of the Rocky River is effluent dominated, and about 95 percent of the streamflow during critical low flow periods is composed of treated sewage effluent (Ohio Environmental Protection Agency, 1993c). OEPA (1993b) assessed 84.1 total stream miles of the Rocky River (Ohio) for chemical and biological quality in 1992; about 34 percent of the basin (21.4 stream miles) contained few species and reduced numbers of aquatic macroinvertebrates and fish.

In the early 1970's, the Cuyahoga River gained notoriety and national exposure as an example of water-quality degradation. The graphic photos and descriptions of the "burning river" have become part of its legacy, and this publicity reputedly hastened of the passage of the Water Pollution Control Act of 1972. Water quality of the Cuyahoga River near the mouth (tables 14–16) and the quality of fish, aquatic macroinvertebrate, and habitat are summarized for the Cuyahoga River Basin for the lower, middle, and upper main stem and selected tributaries (Ohio Environmental Protection Agency, 1994c). The lower main stem, which includes the navigation channel, has improved dramatically since the late 1960's but has shown only slight improvement since the early 1980's. Primary reason for current nonattainment of water-quality standards is failure to meet the dissolved-oxygen criteria as a result of a combination of factors including channelization and dredging to maintain navigation, discharges from point sources, combined sewers, sanitary-sewer overflows, and urban nonpoint sources. Failure to meet dissolved-oxygen criteria is a concern for fish passage from Lake Erie through the lower reaches of the River to upstream riverine habitats. Ammonia-N concentrations in the lower main stem of the Cuyahoga River have declined substantially because of improvements in treatment of wastewater (Ohio Environmental Protection Agency, 1994c). However, the major sources of nitrogen and phosphorus to the lower main stem are still point sources (Cuyahoga River Community Planning Organization, 1994).

The middle main stem of the Cuyahoga River, defined as a section from Akron downstream to Cleveland, is urban (fig. 10). A 23-mi segment of the middle main stem of the Cuyahoga River flows through the Cuyahoga Valley National Recreation Area (CVNRA), which is operated by the National Park Service. Discharges from combined sewers, sanitary sewers, point sources, and urban runoff were the primary sources of contaminants in the middle main stem. The middle main stem of the Cuyahoga River routinely meets chemical water-quality criteria for inorganic and organic contaminants and, except during periods of runoff, meets primary-contact recreation criteria for bacteria. Bacteriological sampling by various organizations (Ohio Environmental Protection Agency, 1994c; Francy and others, 1993; Childress, 1985) showed that elevated concentrations of fecal coliform bacteria and *E. coli* have been detected in the Cuyahoga River and are associated with runoff. Sources are discharges from combined sewers, sanitary sewers, and incompletely treated wastewater (Ohio Environmental Protection Agency, 1994c). Concentrations of fecal coliform and *E. coli* bacteria can range from 10,000 to more than 1,000,000 col/100 mL in the Cuyahoga River during runoff. Use of the river in the CVNRA for recreation is not advised during these periods.

Treated-wastewater sources of nutrients and oxygen-demanding wastes from small communities and agricultural nonpoint sources of sediment and nutrients are the main water-quality problems in the upper main stem of the Cuyahoga River, as well as in the middle and lower main stems. Only minor problems with fecal coliform bacteria were reported for the upper main stem of the Cuyahoga River.

The Chagrin River Basin was examined in detail in 1990 (Ohio Environmental Protection Agency, 1991b) to evaluate the effects of point and nonpoint sources on chemical quality, aquatic macroinvertebrate, fish, and stream habitat. Point sources of treated domestic sewage in the Chagrin River Basin are minimally affecting the water quality and biological populations in tributaries to the main stem. The chemical water quality and communities of aquatic macroinvertebrate and fish in the lower Grand River (Ohio Environmental Protection Agency, 1987) and Conneaut Creek (Ohio Environmental Protection Agency, 1992d) met aquatic life criteria except in the areas that are shipping channels or have undergone extensive marina development.

In New York, incompletely treated wastewater and nutrient enrichment were the primary water-quality issues most often described in water-quality studies of the Lake Erie Basin. Of the 23 river segments assessed during 1972–92 (Bode and others, 1993), 9 showed improvement in water quality and aquatic macroinvertebrate diversity and abundance, whereas 6 showed no change. No previous data were available for 5 stream segments. Of the 23 segments, 4 were rated nonimpacted by wastewater sources, 15 segments were rated as slightly impacted, and 4 segments were rated moderately impacted.

Bode and others (1993) documented improvements in water chemistry and aquatic macroinvertebrate species diversity and abundance for Cattaraugus Creek. Two sites in the Cattaraugus Creek Basin were evaluated in 1976 and again in 1987–88, one near the mouth and one farther upstream in the basin. Both were rated nonimpacted. Moderate to severe pollution from wastewater was eliminated, leading to an improvement in water quality that is referenced as one of 10 success stories in pollution control in the state of New York (Bode and others, 1993, p. 4). Three smaller streams in western New York that discharge directly to Lake Erie to the east and west of the Cattaraugus Creek Basin were rated slightly impacted as a result of treated wastewater discharges.

The water quality of the main stem of the Buffalo River was rated moderately impacted, and combined-sewer overflows were cited as a principal source of pollutants. Investigations of tributaries to the Buffalo River (Bode and others, 1993) showed sites ranging from nonimpacted to slightly impacted. The Buffalo River is designated an AOC because of the presence of oxygen-demanding wastes, trace elements, and soluble organic contaminants in the sediments. A report on a 1993 fish survey of the Buffalo River (Kozuchowski and others, 1994) states, "Water-quality improvements have led to the return of many fish species to the Buffalo River; however, some species present or common in other Lake Erie tributaries are not present or reproducing in the Buffalo River, possibly as a result of unsuitable habitat." Streams in the Tonawanda Creek Basin were given the poorest ratings compared to other streams in western New York; all were slightly to moderately impacted by treated wastewater and urban nonpoint-source runoff (Bode and others, 1993).

Effects from Agricultural Runoff

The chemicals used in greatest quantity in the Nation–fertilizers and pesticides–are used widely in the basin for agricultural purposes. Hydrologic factors such as precipitation, runoff, and infiltration play a key role in delivering agricultural contaminants to streams. Unlike urban streams, oxygen depletion is not characteristic of streams draining row-cropped agricultural basins unless there is runoff of animal and (or) human waste. However, because of the use of fertilizers and pesticides and the cultivation of large tracts of land, the presence of fertilizers, pesticides, and sediment in runoff is a water-quality concern in agricultural river basins. Streams draining agricultural basins, such as the River Raisin and Maumee and Sandusky Rivers, seem to contain higher concentrations of nitrate plus nitrite-N and total phosphorus than streams draining urban basins, such as the Clinton and Cuyahoga Rivers (fig. 18, table14). Likewise, streams draining basins in urban and row-crop land uses seem to contain higher concentrations of nitrate plus nitrite-N and total phosphorus than streams draining basins in pasture and forage or undeveloped land uses, such as the Grand River and Cattaraugus Creek (fig. 18).

The amounts of nitrogen and phosphorus fertilizers, herbicides, insecticides, and sediment discharged to Lake Erie from its basin are higher than in any other basin of the Great Lakes (Baker, 1993). Row-crop land use is reflected in observed concentrations of currently used herbicides such as atrazine, alachlor, and metolachlor and nutrients such as total phosphorus and nitrate plus nitrite-N during the "spring flush" in rivers. The spring flush is the first period or periods of runoff after application of agricultural chemicals (tables 14–16; Baker, 1993; Schribner and others, 1994).

During periods of runoff, nitrate-N concentrations can often approach, or for short periods exceed, the Maximum Contaminant Limit (MCL) of 10 mg/L in streams draining row-cropped areas in the Lake Erie-Lake St. Clair Basin. Elevated median and mean concentrations of nitrate plus nitrite-N (table 14) and maximum concentrations greater than 10 mg/L are reported for the Raisin, Maumee (fig. 18), Sandusky, and Huron Rivers. Consumption advisories are issued during these periods by water suppliers because concentrations of nitrate-N that exceed 10 mg/L can cause methemoglobinemia, an acute health problem that can occur in infants, fetuses, and the aged.

The concentrations of total phosphorus, nitrate plus nitrite-N, and suspended solids were positively related to streamflow in the Black and Raisin Rivers in Michigan and the Maumee and Sandusky Rivers in Ohio, indicating that nutrient concentrations increase during periods of runoff (Michigan Department of Natural Resources, 1992b; Richards and Baker, 1993). The annual discharge of suspended solids, total phosphorus, and nitrate plus nitrite-N for the Black River (Mich.) was second highest of seven sites investigated in Michigan in 1986–87 (Michigan Department of Natural Resources, 1992a). In the same study, concentrations of total phosphorus and nitrate plus nitrite-N were reported as relatively high in the River Raisin near Monroe, which was ranked fifth highest of 21 streams in Michigan.

The Maumee River is the single largest source of water, nutrients, pesticides, and suspended sediment to Lake Erie (Baker, 1993). By virtue of basin size, soil characteristics, and land use, the Maumee River tributaries such as the Auglaize, St. Joseph, and St. Marys Rivers are important sources of water, nutrients, pesticides, and suspended sediment to the main stem.

There has been a downtrend in phosphorus concentrations in the Raisin, Maumee, and Sandusky Rivers because of reductions in agricultural nonpoint sources (Richards and Baker, 1993). This downtrend may be a reflection of a reported 25-percent decline in phosphorus fertilizer sales in the Lake Erie Basin (Ohio Department of Agriculture, written commun., 1993; Richards and Baker, 1993). Agricultural management practices to reduce phosphorus such as conservation tillage, crop residue management, and vegetated buffer strips have been widely used in the Lake Erie Basin to

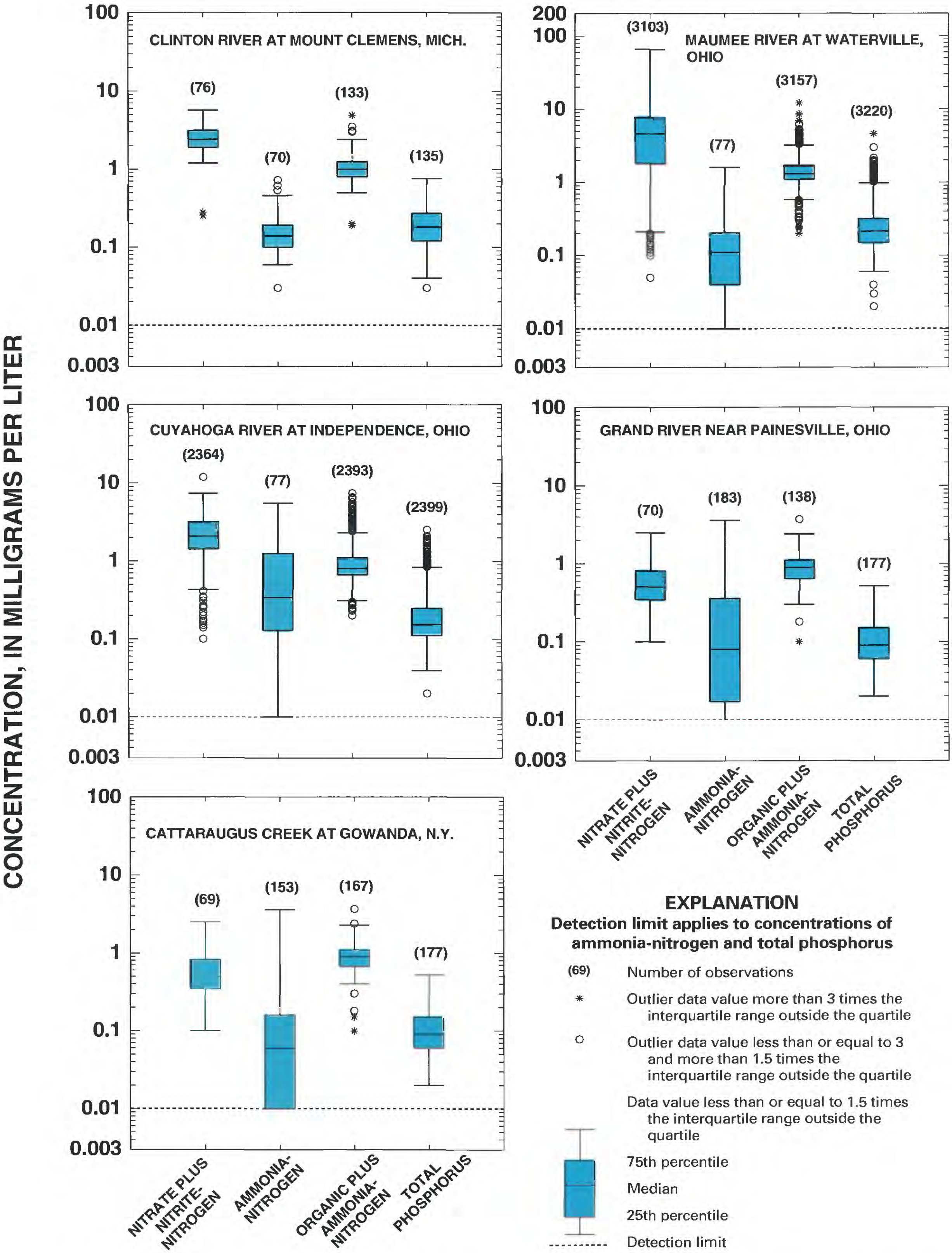


Figure 18. Concentrations of nitrate plus nitrite-N, organic plus ammonia-N, and total phosphorus for selected streams in the Lake Erie-Lake St. Clair Basin, 1976–94.

Table 14. Concentrations of total phosphorus and nitrate plus nitrite-N in selected streams of the Lake Erie-Lake St. Clair Basin

[mg/L, milligrams per liter]

	Clinton River	River Raisin		Maumee River		Sandusky River		Cuyahoga River		Grand River	Cattaraugus Creek
Period of record	1980–89	1975–89	1982–85	1980–89	1982–91	1980–89	1975–91	1980–89	1983–91	1980–91	1980–89
Reference	([1,2])	([1,2,3])	([4])	([2,5])	([6])	([2,5])	([4,6])	([2,5])	([4,6])	([2,5,7])	([2,8])
Total phosphorus (mg/L)											
Median or range of discharge-weighted means	0.13	0.07	0.15–0.26	0.20	0.39–0.45	0.10	0.35–0.46	0.17	0.39–0.53	0.05	0.02
Nitrate plus nitrite, as nitrogen (mg/L)											
Median or range of discharge-weighted means	2.00	3.00	1.54–4.23	5.50	3.99–6.03	5.40	3.59–5.74	2.0	1.83–1.99	0.33	1.0

[1] Blumer, 1993. [2]Smith and others, 1993. [3]Cummings, 1983. [4]Baker, 1988. [5]Childress and Koltun, 1993. [6]Baker, 1993. [7]Shindel and others, 1992. [8]Rogers, 1993.

reduce and control phosphorus concentrations in streams. Such practices are recommended by the IJC in order to achieve the target phosphorus load of 11,000 metric tons per year (International Joint Commission, 1994). State water-quality standards in the Lake Erie Basin also require that phosphorus concentrations in streams and lakes be limited to the extent necessary to prevent the nuisance growth of aquatic algae and weeds.

There has been an uptrend in nitrate plus nitrite-N concentrations for the Maumee and Sandusky Rivers (Rathke and Edwards, 1985; Richards and Baker, 1993; Smith and others, 1993). There has also been an uptrend in the amounts of nitrogen fertilizers applied to row crops in the basin (Richards and Baker, 1993). Manure is a major source of nutrients in runoff where farm animals are present in large numbers (Puckett, 1994), but the effects of this source have not been evaluated in the basin. The other major source of nitrogen is deposition of nitrate-N to the land surface from precipitation (Puckett, 1995). Concentrations of nitrate-N in rain range from about 0.01 to 2.00 mg/L across the region (Myers, 1991).

The herbicides commonly detected in tributary streams (Baker, 1988; 1993) and Lake Erie (Schottler and Eisenreich, 1994) are the same as those used in highest quantities in the basin on row crops. The herbicides currently used in greatest quantities, in terms of active ingredient applied per acre, are atrazine, alachlor, metolachlor, metribuzin, and cyanazine (Gianessi and Puffer, 1991). Currently used herbicides are detected in streams in similar agricultural settings in the Midwest (Schribner and others, 1993; 1994) and in precipitation (U.S. Geological Survey, 1995b). Concentrations of atrazine can range from less than 1.0 μg/L to as much as 35 μg/L in samples collected during postapplication runoff in the Raisin, Tiffin, Maumee, St. Joseph, Sandusky, Auglaize, and Huron Rivers (Baker, 1988; Schribner and others, 1993; City of Fort Wayne, written commun., 1996; table15). As stream-basin size decreases, peak herbicide concentrations can increase in postapplication runoff to as much as 200 to 250 μg/L in small tributaries to the Maumee and Sandusky Rivers (Baker and Richards, 1991).

Mean annual concentrations of atrazine approaching one-half to two-thirds the MCL of 3 μg/L have been consistently reported in the Raisin, Maumee and Sandusky Rivers (table 15). These rivers are source waters for public supplies. At the concentrations detected, atrazine does not cause acute illness in humans. The MCL for atrazine, unlike nitrate-N, is a chronic risk-based standard that, when exceeded, is predicted to result in a 1 in 1 million excess cancer risk from drinking an average of 2 liters of water per day containing an average concentration of 3 μg/L atrazine over a lifetime (70 years). Herbicide contamination of streams has led to the growing substitution of atrazine with more potent herbicides, such as acetochlor, that can be used in much smaller quantities. The concentrations of the atrazine substitutes have not been evaluated for the basin.

The types of herbicides used on pasture and forage crops, although similar to those used on row crops, are used in much lower quantities. Except for simazine, the difference in application amounts is reflected in lower concentrations of herbicides in the Cuyahoga and Grand Rivers compared to the Raisin, Maumee, and Sandusky Rivers. Baker (1988) reported that during postapplication periods of runoff, concentrations of herbicides in the Cuyahoga River, draining an urban area, were five to seven times lower than corresponding concentrations in streams draining row crops (table 15).

Similar information indicates that the insecticides used in highest quantities in the basin are oil-based organophosphate insecticides, carbaryl, chlorpyrifos, carbofuran, terbufos, and fonofos (Gianessi and Puffer, 1992a). Unlike herbicides, the mean and maximum concentrations of insecticides detected in stream samples in row-crop settings were similar to concentrations in streams draining urban or pasture and forage crop settings. Maximum concentrations of carbofuran ranged from less than 0.48 to 2.7 μg/L in the Maumee River and 0.88 to 2.0 μg/L in the Cuyahoga River during the period 1982-85 (Baker, 1988). Available data are insufficient to characterize the concentrations of lawn-care pesticides, such as 2,4-D, that are used in urban areas. Quantities of fungicides used in the most of the basin are small compared to other pesticides (Gianessi and Puffer, 1992b).

The Maumee River discharges more tons per year of suspended sediment than any other tributary in the Great Lakes Basin (Baker, 1993). The Sandusky River discharges the second greatest amount of sediment (tons per year) to Lake Erie. Data collected from the 1950's to the 1970's indicate that the Auglaize River, the largest tributary to the Maumee River, is a major source of suspended sediment (table16). The Cuyahoga River discharges the highest amount of sediment per unit area (tons per square mile per year)

(Baker, 1993). Historical data (Archer and La Sala, 1968) indicate that during runoff in the mid-1960's, concentrations of suspended sediment in Cattaraugus Creek ranged from 283 to more than 5,000 mg/L, far greater than that reported by Smith and others (1993). Large differences in reported estimates of the mean and range of suspended-sediment concentration can result when samples collected daily (Archer and La Sala, 1968) are compared to samples collected monthly or quarterly (Rogers, 1993; Smith and others, 1993). Samples collected more frequently are likely to provide the better estimate of actual concentrations.

The variability of suspended-sediment discharge can be large from year to year depending on precipitation and streamflow. In 1988, a relatively dry year, the amount of suspended sediment discharged from the Maumee River was about 14 percent of the amount discharged in 1993, a relatively wet year. This variability from year to year makes detection of trends in suspended-sediment discharge very difficult to discern. Hindall (1989) examined trends in suspended-sediment discharge and streamflow for the period 1950–87 for the Maumee River, for 1950–56 and 1978–87 for the Sandusky River, and for 1950–74 and 1976–84 for the Cuyahoga River. No discernible trends in suspended-sediment discharge were detected for any of the three streams.

Practices such as installation of tile drains have been implemented in extensive areas where drainage is moderate to very poor. In such areas, streams have also been dredged and straightened to improve drainage. Improving soil drainage in agricultural areas usually increases peak runoff rates (Fausey and others, 1995).. In nationwide rankings, Indiana, Ohio, and Michigan are 2nd, 4th, and 11th, respectively, in terms of acres of land drained for agriculture (Fausey and others, 1995).

Table 15. Concentrations of atrazine, alachlor, and metolachlor in selected streams of the Lake Erie-Lake St. Clair Basin

[All data except periods of record and references are concentrations in micrograms per liter; NR, not reported]

	River Raisin	Tiffin River		Maumee River		Sandusky River		Cuyahoga River
Atrazine								
Period of record	1982–91	1988–89	1982–91	1975–82 1984–91	1988–89	1982–91	1988–89	1982–91
Discharge-weighted mean	1.3	NR	NR	1.8	NR	1.7	NR	0.2
Maximum	12	16	35	21	7.0	25	1.7-5.9	6.8
Reference	([1])	([2])	([1])	([1,3])	([2])	([1])	([2])	([1])
Alachlor								
Period of record	1982–91	1982–91		1982–91		1982–91		1982–91
Discharge-weighted mean	0.8	0.80		0.80		0.60		0.03
Maximum	7.5	7.5		18		36		1.2
Reference	([1])	([1])		([1,3])		([1,3])		([1])
Metolachlor								
Discharge-weighted mean	0.40	0.40		1.1		1.5		0.03
Maximum	5.9	5.9		26		37		5.4
Reference	([1])	([1])		([1,3])		([1,3])		([1])

[1] Baker, 1993. [2] Schribner and others, 1993. [3] Baker, 1988.

Table 16. Characteristics of suspended-sediment concentrations, discharge, and yield in selected streams of the Lake Erie-Lake St. Clair Basin

[mg/L, milligrams per liter; ton/yr, tons per year; ton/mi^2/yr, tons per square mile per year; NR, not reported]

	Clinton River	River Raisin		Auglaize River	Maumee River		Sandusky River		Cuyahoga River		Grand River
Period of record	1974–80	1966–72 1978–80	1982–85	1946–70	1946–70 1988–94	1982–85	1946–70 1988–94	1982–85	1946–70 1988–94	1982–85	1946–70 1988–91
Mean or range of annual mean concentrations (mg/L)	42	42	49–91	216	244[a]	180–205	250[a]	144–283	266[a]	158–269	102[a]
Average sediment discharge or range of annual sediment discharges (ton/yr x 1,000)	NR	NR	47–88	373	275–1,940[b]	989–1,410	197–350[b]	118–433	99–431[b]	180–273	65–261[c]
Yield or range of annual yields (ton/mi^2/yr)	22	47–63	17–33	187	43–306[b]	156–223	75–431[b]	94–346	140–610[b]	231–386	95–381[c]
Reference	([1])	([1])	([2])	([3])	([3 4])	([2])	([3 4])	([2])	([3 4])	([2])	([3 4])

Notes on data:
[a]Corresponds to 1946–70 period of record.
[b]Corresponds to 1988–94 period of record.
[c]Corresponds to 1988–91 period of record.

References:
[1]Cummings, 1983.
[2]Baker, 1988.
[3]Anttila and Tobin, 1978.
[4] Shindel and others, 1991–95.

Within these row-crop areas, 30 to 50 percent of all land is artificially drained (Fausey and others, 1995). Relative to the effects of other agricultural practices, tile drains are thought to decrease the amount of sediment and phosphorus discharged to surface water and increase the amount of nitrates that infiltrate to ground water and subsequently discharge to base flow in streams.

Contamination of Streambed Sediments, Fish, and Wildlife with Organochlorine Compounds and Trace Elements

Bioaccumulative and persistent contaminants—organochlorine compounds and trace elements—have been targeted for virtual elimination in the Great Lakes Basin by the United States and Canada (U.S. Environmental Protection Agency, 1993; International Joint Commission, 1994). These two groups of contaminants are implicated in several water-quality issues related to the quality of fisheries for human consumption, the potential for disruption of normal endocrine function in wildlife and fish, and the problems associated with river-sediment contamination and remediation. The most contaminated sediments—those that have the potential to cause reproductive impairment, cancer, or deformities and abnormalities in fish and wildlife—are present in several AOC's and in other streams in the Lake Erie-Lake St. Clair Basin. The areas where bioaccumulation of organochlorine compounds have been found in fish at elevated concentrations are the Clinton River, River Rouge, Maumee River, Black River (Ohio), Cuyahoga River, Ashtabula River, Presque Isle Bay, and Buffalo River (U.S. Environmental Protection Agency and Government of Canada, 1995).

Because the use of polychlorinated biphenyls (PCB's) and most organochlorine pesticides has been discontinued in the United States, concentrations in fish and wildlife have declined by an order of magnitude from peak concentrations in the 1970's (U.S. Environmental Protection Agency and Government of Canada, 1995). However, the presence in game fish and wildlife populations of residues of these bioaccumulative, potentially endocrine-disruptive and carcinogenic substances is a water-quality issue in Lake Erie-Lake St. Clair Basin.

PCB's as a category of contaminants have been targeted for remedial actions in order to eliminate them from the environment and reduce their concentrations in fish and wildlife in the Lake Erie Basin. PCB's are still manufactured and used in certain parts of the world, are deposited from the atmosphere to the Great Lakes watershed by way of long-range transport, or are transported on suspended fluvial sediments to the lake by way of tributaries. Once in an aquatic system, organochlorine compounds like PCB's are biomagnified in the aquatic food web. Piscivorous fish and fish-eating birds have shown bioaccumulation of PCB's in the Lake Erie system. PCB's have been detected in gull eggs in colonies nesting on Lake Erie islands, areas adjacent to or in the Detroit and Niagara Rivers. For Lake Erie areas, a downtrend in PCB concentrations in gull eggs has been detected over time, and a west-to-east gradient has been found (U.S. Environmental Protection Agency and Government of Canada, 1995, p. 34).

Other fish-eating birds, such as eagles, have shown effects of bioaccumulations of organochlorine residues. Lower reproductive success has been observed for eagles nesting along the Great Lakes and Lake Erie compared to eagles nesting inland. Nest failures are more common among the older eagle pairs that were previously successful for the first 5 years of nesting than for younger eagles. Analyses have shown that unhatched eggs from coastal areas are more contaminated with PCB's than eggs collected at inland locations (Taylor, 1994).

Advice provided to fish eaters in the Lake Erie-Lake St. Clair Basin varies from state to state because of current scientific uncertainties regarding the toxicity of contaminated fish. Furthermore, the amounts of chemicals of concern in fish are not known to cause immediate illness. However, contaminated fish consumed regularly over time can affect the health of the consumer and even that of their children. Therefore, certain groups—women of child-bearing age who plan to have children, pregnant and nursing mothers, and children under 15—are advised to restrict their intake of fish caught in known areas of contamination from none to no more than one meal per week (Michigan Department of Natural Resources, 1994, p. 26–29; Ohio Department of Natural Resources, 1995; U.S. Environmental Protection Agency, 1997).

In Lake Erie and in several tributary streams, fish-consumption advisories are the result of contamination of fish with PCB's. Fish consumers are advised to restrict their consumption of certain species with regard to quantity, amount, and frequency of consumption. Consumption advisories for Lake Erie fish vary from state to state, but some examples of species for which advisories have been issued are carp, channel catfish, bullhead, walleye, freshwater drum, white bass, white perch, largemouth bass, steelhead, lake trout, lake whitefish, and coho salmon. In Ohio, restrictions range from a total ban on consumption of channel catfish in Maumee Bay to 12 meals per year for white perch, steelhead, coho salmon, chinook salmon, smallmouth and white bass; 6 meals per year for carp, channel catfish outside Maumee Bay, and lake trout; and 52 meals per year for walleye and freshwater drum. For the St. Clair River and the Detroit River, mercury and PCB's are a concern and consumption restrictions are in place for freshwater drum and carp.

In Michigan, all fish-consumption advisories for streams are the result of contamination of fish with PCB's. There are "no consumption advisories" for carp for certain areas of the Clinton River in Oakland County. There are "no consumption advisories" for northern pike, largemouth bass, smallmouth bass, catfish, carp, and white sucker in sections of the Middle Branch of the River Rouge and for carp and white sucker in the Lower Branch of the River Rouge in Wayne County. A fish-consumption advisory in the lower River Raisin in the AOC is a result of elevated concentrations of PCB's. Dredging and proper disposal of River Raisin sediments containing PCB's is expected to improve conditions. For the Ottawa River in Monroe County, Mich., there is a "no consumption advisory" for all species of fish because of contamination with PCB's.

Likewise, in Ohio, PCB's are the major contaminants listed in consumption advisories. All fish are restricted from consumption in the Ottawa River (Toledo, Ohio), in the lower Black River (Ohio), and in the lower Ashtabula River. For Summit Lake (Summit County, Ohio) there is a "no consumption advisory" for carp and channel catfish.

Certain organic compounds, such as polycyclic aromatic hydrocarbons (PAH's), inorganic compounds such as ammonia-N, and trace elements, are present in river sediments as a result of industrial activities or use in an urban area. These substances, when found in river sediments, are considered to be contaminants. Sediments sampled near the mouth of the Black River, Mich., in 1988 contained elevated levels of trace elements and detectable concentrations of PCB's that likely are the result of historical industrial discharges (Michigan Department of Natural Resources, 1992a). The water and sediments of the lower Clinton, Rouge, and Raisin Rivers are contaminated by trace elements, organochlorine compounds, and oil and grease (Michigan Department of Natural Resources, 1987; 1992a). Sediment contaminants in the Clinton, Rouge, and Raisin Rivers are thought to emanate in part from old leaking landfills (Michigan Department of Natural Resources, 1988; 1992a).

Impairment of water and sediment quality near the mouth of the Maumee River due to contamination from arsenic, cadmium, chromium, copper, lead, zinc, and PCB's has led to a designation of AOC. Contaminant sources are thought to be historical industrial discharges and the presence of many landfills, lagoons, and industrial sites along the banks of the lower Maumee River (Ohio Environmental Protection Agency, 1989). Arsenic-contaminated sediments were noted in samples collected from tributaries of the Maumee River in agricultural areas. This contamination is thought to be from residues of arsenate pesticides used on agricultural lands until the mid-1970's (Ohio Environmental Protection Agency, 1992a,b,c).

Sediment contamination with PAH's was documented in the upper reaches of the Sandusky River (Ohio Environmental Protection Agency, 1991a) and the Ottawa River (Allen County, Ohio; Ohio Environmental Protection Agency, 1992a). Fish taken from the degraded area of the Ottawa River exhibit a much higher than normal incidence of external deformities, lesions, and eroded fins.

The lower reaches of the Black River (Ohio) are designated an AOC, and waters and sediments are currently contaminated by oil and grease, trace elements, PCB's, and PAH's (Ohio Environmental Protection Agency, 1994b). Sediment contamination with PAH's has resulted in higher than normal frequencies of external tumors in certain fish species in the Black River (Ohio Environmental Protection Agency, 1994b; Baumann and others, 1987, 1990, 1991; Smith and others, 1994). Cleanup of contaminated sediments in the Black River has resulted in an improvement in fish health (Ohio Environmental Protection Agency, 1994b)

OEPA (1994c) reported that the major sources of trace elements to the lower main stem of the Cuyahoga River in the Cleveland area are now primarily urban nonpoint sources. Sediments in the lower main stem of the Cuyahoga River and Ashtabula River are contaminated with oxygen-demanding wastes, trace elements, and PCB's (Cuyahoga River Community Planning Organization, 1994; Ohio Environmental Protection Agency, 1994c).There has been a shift in the Cleveland and Akron area of the Cuyahoga River Basin from rubber and chemical manufacturing, coking, and petrochemical refining to other types of industrial and commercial manufacturing since the mid-1970's. Bed-sediment samples collected just above the mouth of the Chagrin River contained low levels of trace elements that were not a water-quality concern (Ohio Environmental Protection Agency, 1991b).

The Buffalo River is designated an AOC because of the presence of oxygen-demanding wastes, trace elements, and soluble organic contaminants in the sediments.

Aquatic Habitat Alteration and Disturbance

Chemical contamination is not the only factor contributing to water-resource degradation in the Lake Erie-Lake St. Clair Basin. Loss of habitat and habitat alteration from water-level management, conversion of forest and wetlands to agricultural and urban land uses, and recreational development along the Lake Erie shoreline have been the greatest threats to habitat and biodiversity in the Great Lakes and Lake Erie Basin (The Nature Conservancy, 1994). Other threats include proliferation of nonnative species, solid-waste disposal, fisheries management, and water withdrawals (The Nature Conservancy, 1994). Some of these threats are consistent with threats to global biodiversity that have been identified by the Office of Technology Assessment (1987). McNeely and others (1990) of the World Bank identified "habitat alteration, especially conversion to agriculture" as a primary threat to global biodiversity.

The special habitats that contain a diversity of aquatic and terrestrial species in the Lake Erie basin are a product of glacial history. These special areas are end moraines, till plains, lake plains, glacial-outwash areas (alluvial fans and alluvial plains), and beach ridges. These features were formed by glaciers that repeatedly advanced and receded 20,000 to 11,000 years ago. Ancient glacial meltwater streams and glacial lakes formed what is the present day Lake Erie Basin. Biological communities in the Lake Erie Basin are relatively young compared to those in the Mississippi River Basin, the former having been established about 4,000 to 5,000 years B.P., which is about the age of the modern Lake Erie (Robbins and others, 1994).

The greatest habitat alteration has occurred in the very poorly drained Eastern Lake Section of the Central Lowland Province. OEPA (1990) identified the Huron-Erie lake plains as being the area of Ohio most seriously affected by habitat alteration and sedimentation from agricultural land uses. The Black Swamp was almost entirely drained for agriculture and is now part of the Corn Belt. Likewise, about 90 percent of the wetlands in the Lake Erie Basin have been drained for urban and agricultural uses (The Nature Conservancy, 1994).

OEPA (1995) has documented a 30 to 40-percent decline in fish species in Ohio since 1978. Many declining species of fish depend on clean stream substrates, perennial streamflow, intact riparian zones, pools, runs, and riffles. Those that are intolerant of siltation of stream habitats, such as the river chub, are among those species in sharpest decline. Stream channelization is a major problem throughout the basins of the Black and Belle Rivers in Michigan, and this practice severely limits habitat available to fish and other aquatic life (Michigan Department of Natural Resources, 1992a). Channelization and siltation were noted as serious limiting factors in fish-community composition and abundance in all the tributaries to the Maumee River investigated by OEPA (1992b,c; 1993a,b; 1994d). Elevated concentrations of suspended sediment and siltation of streambeds in the upper Black River Basin (Ohio) have resulted in loss of fish and aquatic macroinvertebrate species diversity and abundance (Ohio Environmental Protection Agency, 1994b).

The streams and connecting channels in the Lake Erie Basin support biodiversity of fish and freshwater mussel fauna, of which some are globally endangered. For example, Fish Creek, a till-plain stream and a tributary to the St. Joseph River in the Maumee River Basin contains several species of endangered fish and freshwater mussels. The Black, Clinton, Huron, and Raisin Rivers in Michigan and the St. Joseph, Maumee, Auglaize, Blanchard, Portage, upper Cuyahoga, Chagrin, and Grand Rivers in Ohio support native freshwater mussel populations. Extirpated, endangered, threatened, and special-concern fish species are listed in table 18, in the "Supplemental Data" section at the back of the report.

Various streams of the Lake Erie-Lake St. Clair Basin have been identified at the State level as wild, scenic, or recreational waters. In Michigan, the Huron River upstream from Ypsilanti, Mich., is designated as State Natural River. In Ohio, streams are designated State Resource Waters and (or) Wild or Scenic streams. Segments of the Maumee River, Sandusky River, upper Cuyahoga River, Chagrin River, and Grand River are designated State Scenic Rivers. Part of the Grand River is also designated a Wild River because of the low-intensity land use and intact riparian habitat.

The Chagrin River Basin contains isolated areas of coolwater and coldwater habitat (Ohio Environmental Protection Agency, 1991b). Species indicative of coolwater and coldwater streams that have been documented in the East Branch tributary to the Chagrin River are Northern crayfish (*Orconectes virilis*), Great Lakes crayfish (*O. propinquus*), 10 species of aquatic insects, brook trout (*Salvelinus fontinalis*), longnose dace (*Rhinicthyes cataractae*), and redside dace (*Clinostomus elongatus*). Among other threats to aquatic biodiversity in the Chagrin River basin, cool and coldwater habitats are at risk from urban development. Such development often leads to stream-channel alteration or removal of the trees (canopy) along the streambank. This in turn allows more sunlight to heat the stream than would occur under full canopy cover.

The Grand River Basin was examined in detail in 1985 (Ohio Environmental Protection Agency, 1987) to evaluate the effects of point and nonpoint sources on chemical quality, aquatic macroinvertebrates, fish, and stream habitat. In general, water quality, aquatic macroinvertebrate diversity and abundance, and fish diversity and abundance in the Grand River main stem were all rated as exceptional (Ohio Environmental Protection Agency, 1987). The Grand River contains the highest diversity of fish and freshwater mussels of any stream of its size in the Lake Erie-Lake St. Clair Basin. Water quality of the Grand River near the mouth is much improved over historical conditions because industrial waste lagoons near Painesville, Ohio, that contributed high concentrations of dissolved solids and chloride have been remediated (Ohio Environmental Protection Agency, 1987).

Proliferation of Nonnative Species

The introduction of nonnative animal and plant species to the Lake Erie-Lake St. Clair Basin is a growing water-quality and water-resources management problem. Species such as alewife (*Alosa pseudoharengus*), common carp (*Cyprinus carpio*), curly-leaf pondweed (*Potamogeton crispus*), eurasian watermilfoil (*Myriophyllum spicatum*), flowering rush (*Butomus umbellatus*), purple loosestrife (*Lythrum salicaria*), rusty crayfish (*Orconectes rusticus*), sea lamprey (*Petromyzon marinus*), rainbow smelt (*Osmerus mordax*), white perch (*Morone americana*), and zebra mussels (*Dreissena polymorpha*) have had highly visible effects that have resulted in a loss of diversity of native species (U.S. Fish and Wildlife Service, 1993; U.S. Environmental Protection Agency and Government of Canada, 1995). But overfishing, eutrophication, sedimentation, toxic contamination, and nonnative species in combination are the primary factors that have shaped the species composition and abundance of the fish in the Lake Erie-Lake St. Clair Basin. The changing fish-species composition in the Lake Erie Basin is described in Herdendorf (1983). Effects of exploitation, environmental changes, and new species on the fish habitats and resources of Lake Erie Basin was described by Hartman (1973).

The most notorious invader of recent years has been the zebra mussel. It is feared that invasions of Lake Erie and inland waters by zebra mussels may cause ecosystem-level changes and competition with economically and ecologically important fish and native mussel species. Zebra mussel removal from water intake pipes is a management concern for inland and coastal surface-water supplies. Continued introduction of nonnative species will likely change the aquatic ecosystems in ways that are unanticipated.

Ground-Water Quality

Ground-water-quality studies in the Lake Erie-Lake St. Clair Basin have been primarily of three types: investigations of ambient ground-water quality, water-supply quality, and contaminated-site monitoring and assessment. Water-quality data from supply wells typically are representative of ground water from several water-bearing zones, whereas water-quality data from monitor wells at ambient and contaminated sites typically are representative of single water-bearing zones.

MDNR, MDEQ, OEPA and county health departments in the basin monitor ground-water quality by sampling monitor and supply wells and comparing results to Maximum Contaminant Levels (MCL's). Regional-scale surveys of the quality of domestic supply wells in agricultural areas have been done by USGS (Kolpin and others, 1993; Risch, 1993; Kolpin and Goolsby, 1995), USEPA (1992), Heidelberg College Water Quality Laboratory (Baker and others, 1989), and the Michigan Department of Agriculture (Robert Pigg, Michigan Department of Agriculture, oral commun., 1995).

When a particular aquifer is the only readily available source of water supply, special emphasis can be given by the USEPA to communities who apply for the designation of a "sole-source aquifer." There are three sole-source aquifers in the Lake Erie-Lake St.

Clair Basin. In Ohio, two sole-source aquifers are the Catawba/Bass Island aquifer in Ottawa County (U.S. Environmental Protection Agency, 1987a) and the Allen County area-combined aquifer system (U.S. Environmental Protection Agency, 1992b); both are carbonate-bedrock aquifers. In New York, the Cattaraugus Creek Basin aquifer system, a valley-fill aquifer, is the third designated sole-source aquifer in the Lake Erie Basin (U.S. Environmental Protection Agency, 1987b).

Unconsolidated Aquifers

Most ground water in the unconsolidated quaternary deposits in the Indiana, Michigan, and Ohio is moderately hard to very hard, commonly exceeding 300 mg/L as $CaCO_3$ as a result of contact with glacial materials of calcareous origin (Olcott, 1992; Lloyd and Lyke, 1995). The softest water in ground-water supplies in the basin is found in relatively shallow, unconsolidated valley-fill aquifers in western New York (La Sala, 1968), and the hardest water is found in glacial aquifers in northwestern Ohio and southeastern Michigan (Cummings, 1989; Breen and Dumouchelle, 1991).

Major-ion and dissolved-solids concentrations of water contained in unconsolidated glacial and recent deposits is varied in the Lake Erie-Lake St. Clair Basin (table 17). The median dissolved-solids concentration for unconsolidated glacial deposits in Ohio and Indiana is reported as 500 mg/L, which is the Secondary Maximum Contaminant Level (SMCL) recommended by USEPA (Lloyd and Lyke, 1995). For the entire basin, median dissolved-solids concentrations for the unconsolidated aquifers range from 115 to 413 mg/L (table 17). Concentrations of iron are typically greater than 0.3 mg/L in these unconsolidated deposits (Olcott, 1992; Lloyd and Lyke, 1995). Water in unconsolidated deposits is predominantly of the calcium-magnesium-bicarbonate type (Cummings, 1989; Lloyd and Lyke, 1995). Cummings (1989) reported that Michigan ground waters in unconsolidated aquifers tend to be of the calcium-bicarbonate type and typically contain lower concentrations of dissolved substances than waters in bedrock aquifers (table 17). In Michigan, sulfate concentrations in unconsolidated aquifers are highest in undifferentiated glacial deposits and outwash (Cummings, 1989).

The unconsolidated aquifer in the far northeastern tip of Indiana consists of isolated sand and gravel lenses that are typically surrounded by silty clay and clay till. This aquifer is confined in most areas (Banaszak, 1986). Water in this till aquifer has median dissolved-solids concentration of 358 mg/L and is very hard, with a median hardness of 320 mg/L as $CaCO_3$ (Banaszak, 1986). Median chloride concentration in the till aquifer is low at 9 mg/L, whereas median iron concentration is relatively high at 1.9 mg/L. Water in this aquifer is typically anoxic and can contain traces of hydrogen sulfide because it is overlain by thick confining layers of till materials (Banaszak, 1986).

An important unconsolidated till aquifer is present in Williams County, Ohio (Coen, 1989). The water is predominantly of the calcium-magnesium-bicarbonate type and is hard, with a median hardness of 290 mg/L as $CaCO_3$. The water also is high in iron, with a median concentration of 1.4 mg/L, and it can contain traces of hydrogen sulfide (Coen, 1989). After an extensive survey of ground-water quality in northwestern Ohio, Breen and Dumouchelle (1991) reported that shallow wells in an unconfined, surficial sand aquifer underlying an urban area contained higher concentrations of dissolved solids, hardness, sodium, and chloride than waters from similar types of wells in undeveloped areas. Domestic-supply wells in undeveloped areas contained moderately hard water, with a median hardness concentration of 74 mg/L as $CaCO_3$, and low dissolved-solids concentrations, with a median of 89 mg/L. In contrast, water from wells in developed areas contained median concentrations of dissolved solids that were about four times higher than water from wells in undeveloped areas. Calcium, bicarbonate, and sulfate were the dominant ions in the wells in the unconfined, surficial sand aquifer in both land-use settings.

Waters from the unconsolidated aquifer systems in northeastern Ohio generally contain similar or somewhat higher concentrations of dissolved solids, chloride, and sulfate than water in the Upper Pennsylvanian sandstone aquifers from the same area (Lloyd and Lyke, 1995; table 17). Quality of water from wells in unconsolidated aquifers in Portage County, Ohio, was investigated in 1988 (Eberts, 1991). Water in the unconsolidated deposits ranged in type but was typically of the calcium-magnesium-bicarbonate type. A few wells in the unconsolidated aquifer produced water of the calcium-sodium-bicarbonate-chloride type. Median concentrations in samples from the unconsolidated aquifer were; calcium, 82 mg/L; magnesium, 22 mg/L; bicarbonate, 232 mg/L; sulfate, 74 mg/L; and chloride, 24 mg/L. The water was hard to very hard,

Table 17. Concentrations of major ions and dissolved solids in selected aquifers of the Lake Erie-Lake St. Clair Basin

[Data are median concentrations or ranges of median concentrations, in milligrams per liter]

Unconsolidated aquifers (sand, gravel, or till)				Carbonate aquifer		Sandstone aquifer
Southeastern Michigan[1 2]	Northwestern Ohio and northeastern Indiana[3 4 5]	Northeastern Ohio[3 6 7]	Western New York[7]	Southeastern Michigan[1 2 8]	Northwestern Ohio and northeastern Indiana[3 9]	Northeastern Ohio[3 10]
			Calcium			
25–57	67–80	82	55	57–400	110–120	54
			Magnesium			
5.6–18	31	22	11	36–120	49–50	17
			Bicarbonate			
100–200	297–544	232	255	NR	300–388	254
			Chloride			
1.1–4.9	9–12	10–31	14	9.4–10	8–16	4.1
			Sulfate			
7.8–12	23	36–76	23	150–1,200	176–290	108
			Dissolved solids			
115–249	358	322–413	296	207–2,430	617–738	407

[1]Cummings, 1989.
[2]Olcott, 1992.
[3]Lloyd and Lyke, 1995.
[4]Coen, 1989.
[5]Banaszak, 1986.
[6]Eberts, 1991.
[7]La Sala, 1968.
[8]Nicholas and others, 1996.
[9]Breen and Dumouchelle, 1991.
[10]Swisshelm and Lane, 1986.

with a median hardness of 300 mg/L as $CaCO_3$. Concentrations of major ions and hardness reported by Eberts (1991) are consistent with those reported for other unconsolidated aquifers in northeastern Ohio (Lloyd and Lyke, 1995).

Unconsolidated aquifers in western New York (La Sala, 1968) contain water that is a calcium-bicarbonate type and range widely in hardness, from 60 to 399 mg/L as $CaCO_3$ (moderately hard to very hard water). Concentrations of dissolved solids were reported to range from 103 to 536 mg/L and were acceptable in most cases for domestic supply. Concentrations of major ions in unconsolidated sand and gravel or till aquifers in western New York were varied and were reported to increase with depth in stratified glacial deposits (La Sala, 1968).

Bedrock Aquifers

The chemical quality of freshwater from the carbonate aquifers in western Ohio, northeastern Indiana, and southeastern Michigan is adequate or can be treated and made adequate for most purposes (Olcott, 1992; Lloyd and Lyke, 1995; table 17). The major-ion chemistry of carbonate aquifers of Silurian and Devonian limestone and dolomite in southeastern Michigan are highly varied (Nicholas and others, 1996). Most carbonate aquifers in southeastern Michigan contain water of a calcium-magnesium-bicarbonate type (Olcott, 1992) or a calcium-bicarbonate-sulfate type as in Monroe County, Mich. (Nicholas and others, 1996). Where the carbonate aquifer forms the bedrock surface and is overlain by the unconsolidated surficial aquifer, the carbonate aquifer contains water with dissolved-solids concentrations in the range of 200 to 500 mg/L (Olcott, 1992). The Dundee Limestone was reported to have the lowest dissolved-solids concentration of all carbonate aquifers in Michigan (Cummings, 1989). Downdip, at or near the contact of overlying bedrock, dissolved-solids concentrations increase to 1,000 mg/L in the carbonate aquifer of southeastern Michigan (Cummings, 1989; Olcott, 1992). Nicholas and others (1996) reported that dissolved-solids concentrations in the carbonate aquifer ranged from 207 to 2,430 mg/L in Monroe County, Mich. The carbonate aquifers may also contain elevated concentrations of strontium, the median concentration of which was 12.0 mg/L in the Bass Islands Dolomite in southeastern Michigan (Cummings, 1989, p. 47) and at least 10 mg/L in more than 75 percent of samples collected in Monroe County (Nicholas and others, 1996).

Breen and Dumouchelle (1991) reported median hardness for water from the carbonate aquifer in northwestern Ohio to be 540 mg/L as $CaCO_3$ and the 25th percentile to be 380 mg/L, indicating very hard water. Water in the carbonate aquifer is mostly of the calcium-magnesium-bicarbonate type in recharge areas and of the calcium-magnesium-sulfate type in discharge areas (Lloyd and Lyke, 1995). Median concentrations of calcium, magnesium, bicarbonate, and sulfate in the carbonate aquifer in northwestern Ohio were 120, 50, 300, and 290 mg/L, respectively. Concentrations of dissolved solids in 25 percent of all wells sampled in Seneca, Lucas, and Wood Counties and reported for the carbonate aquifer (Breen and Dumouchelle, 1991) were less than 500 mg/L and, as such, meet the USEPA's SMCL for domestic and public supply. Water samples collected from the carbonate aquifer that contained dissolved-solids concentrations between 500 and 1,000 mg/L were of the calcium-magnesium-bicarbonate or calcium-magnesium-sulfate type. In northwestern Ohio and southeastern Michigan, sulfate ion replaces bicarbonate ion as the dominant anion in waters from the carbonate aquifer whose concentrations of dissolved solids are greater than 1,000 mg/L (Breen and Dumouchelle, 1991; Nicholas and others, 1996). Water in the carbonate aquifer in northwestern Ohio, as in southeastern Michigan, was enriched with strontium, and the range of concentrations was reported to be from 12.0 to 15.0 mg/L (Breen and Dumouchelle, 1991).

Other important aquifers in the Lake Erie-Lake St. Clair Basin are Pennsylvanian sandstone aquifers in northeastern Ohio, which are contained within the Pottsville Formation (Eberts, 1991). In Ohio, calcium-magnesium-bicarbonate is the dominant type of water produced from the Pennsylvanian aquifers (Lloyd and Lyke, 1995). Concentrations of iron in these aquifers commonly exceed 0.3 mg/L (Lloyd and Lyke, 1995).

Studies of Ground-Water Contamination

The fine-textured till that mantles most of the Lake Erie-Lake St. Clair Basin is thought to be a semipermeable to impermeable barrier to contamination of underlying aquifer systems. Thickness of this protective layer is another factor that affects the vulnerability of aquifers to contamination from sources on the land surface. Consequently, alluvial and shallow unconfined, unconsolidated aquifers were found to be more vulnerable to contamination than underlying bedrock aquifers in Ohio (Baker and others, 1989) and in the midcontinental United States (Kolpin and others, 1993; Kolpin and Goolsby, 1995). In some cases, natural factors associated with the geochemistry and lithology of the aquifer materials, rather than human activities, make ground water unsuitable for domestic use. For example, ground water in Monroe County, Mich., contains traces of hydrogen sulfide, manganese, and iron that make it unsuitable for domestic uses without treatment (Nicholas and others, 1996).

The degree of chemical and microbiological contamination in the aquifers of the Lake Erie-Lake St. Clair Basin is thought to be of much smaller magnitude than corresponding contamination of streams for certain classes of contaminants such as fertilizers and currently used pesticides. However, once contaminated, ground water is difficult and costly to restore to beneficial use. In certain areas, ground water in the Lake Erie-Lake St. Clair Basin is contaminated by nitrates, bacteria, and volatile and semivolatile organic compounds (Michigan Department of Natural Resources, 1992b; Ohio Environmental Protection Agency, 1995).

Concentrations of nitrate plus nitrite-N in ground water greater than 3 mg/L are considered to be indicative of human activities, whereas concentrations greater than 10 mg/L are considered unsuitable in a domestic supply (Madison and Burnett, 1985; Baker and others, 1989; Kolpin and others, 1993). Concentrations of nitrate-N in ground water greater than or equal to 3 mg/L have been detected in a small percentage of total wells sampled, and only in certain areas of the Lake Erie-Lake St. Clair Basin. Kolpin and Goolsby (1995) reported on concentrations of nitrate plus nitrite-N in samples collected from water wells in a study of agricultural-chemical contamination in the midcontinent. Depending on location, from 0 to 19 percent of samples collected from water wells in row-cropped agricultural areas of the Lake Erie-Lake St. Clair Basin contained nitrate plus nitrite-N concentrations greater than or equal to 3 mg/L (Kolpin and Goolsby, 1995). In addition, contamination with nitrate plus nitrite-N was related to age of water, "very recent" recharged water having a higher number of detections of elevated nitrate plus nitrite-N than older water. Nitrate contamination was also more likely to be detected in oxygenated ground water than in anoxic ground water because nitrate is the dominant nitrogen species under oxidizing conditions (Kolpin and Goolsby, 1995).

In a statewide survey of Ohio water wells by Baker and others (1989), only Erie, Huron, and Lake Counties in the Lake Erie Basin were reported to have more than 20 percent of wells producing water with nitrate-N concentrations greater than 3 mg/L. Baker and others (1989) also noted that nitrate contamination in wells was more closely associated with shallow unconsolidated aquifers than with bedrock aquifers of Devonian and Silurian limestones and dolomites. Breen and Dumouchelle (1991) detected concentrations of nitrate plus nitrite-N in the carbonate aquifer of northwestern Ohio that were very low, less than 0.01 mg/L, in more than half of 143 wells sampled and no detections of nitrate plus nitrite-N in 63 of the 143 wells sampled.

Contamination of domestic supplies by total coliform bacteria affected more wells than any other form of contamination in Ohio (Swisshelm and Lane, 1986). In northwestern Ohio, 27 percent of domestic-supply wells and 8 percent of public-supply wells were reported to contain detectable levels of total coliform bacteria. In northeastern Ohio, 22 percent of domestic-supply wells and 6 percent of public-supply wells were reported to contain detectable levels of total coliform bacteria. The primary sources of total coliform bacteria in domestic-supply wells are thought to be septic systems (Swisshelm and Lane, 1986). Breen and Dumouchelle (1991) reported similar percentages of contaminated domestic-supply wells in northwestern Ohio.

Currently used pesticides have been rarely detected in water from domestic-supply wells and other ground-water sources in the Lake Erie-Lake St. Clair Basin. When detected, pesticide concentrations have been less than 0.1 μg/L in most cases. As with nitrate contamination, unconsolidated aquifers appear to be more vulnerable than underlying bedrock aquifers to contamination by currently used herbicides. Contamination also was related to age of water, young waters (younger than 1953 by tritium dating) containing higher concentrations of herbicides than older waters (Kolpin and Goolsby, 1995). Metabolites of herbicides were more often detected in domestic wells surveyed in the midcontinent study than the parent herbicides and were often present at higher concentrations (Kolpin and others, 1993). Simazine was most commonly detected pesticide in Ohio wells, comprising more than 60 percent of detections in the midcontinent study. In Indiana, dicamba was detected in two wells in unconsolidated deposits of till and outwash in Allen and De Kalb Counties examined as part of a 1988 USEPA study of pesticides in ground water.

IMPLICATIONS OF ENVIRONMENTAL AND HYDROLOGIC SETTING ON WATER QUALITY

Natural and human-related factors associated with the land, its uses, and the hydroclimatic system are driving forces in the determination of water quality and quantity. Water quality and quantity are determined by complex interrelationships between natural factors (climate, physiography, surficial and bedrock geology, geochemistry, and natural vegetation) and human activities (construction, paving, cultivating, fertilizer and pesticide use, and discharge of contaminants to water, air, land, and infiltration of contaminants to ground water).

The chemical concentrations, physical properties, and characteristics of streamwater vary with season, year, and streamflow. However, the relation between chemical concentration and streamflow can be positive, negative, or nonlinear, and can change with time and distance from natural and human-related sources depending on whether the constituent is conserved or degraded in the environment.

Likewise, chemical concentrations, physical properties, and characteristics of ground water can vary with season, year, water level and age, depth of the water table below the land surface, and transmissivity and geochemistry of the aquifer material. The geologic and geochemical settings of streams and aquifers in the basin are reflected in the dominance of calcium, magnesium, bicarbonate, and sulfate ions. Major-ion characteristics of ground water are similar throughout the basin, although concentrations are typically higher in ground water than in surface water (tables 12 and 17).

The contaminants of greatest concern in the Lake Erie-Lake St. Clair Basin have multiple sources, some of which are point sources and some of which are non-point sources. For example, the major sources of nutrient enrichment of streams in agricultural basins are nitrogen and phosphorus fertilizers. The major sources that contribute to nutrient enrichment of streams in urban basins are fertilizers and nitrogen-containing compounds in discharges of treated and incompletely treated wastewater. Many point sources of contaminants are largely along stream courses in the urban areas of the basin (fig. 13). However, what are conventionally thought of as primary agricultural areas also contain many wastewater and other point-source discharges and emissions (fig. 13). Major sources that contribute to contamination by trace-level compounds in fish, wildlife, and riverine sediments are residues of historical industrial production and use of PCB's, historical use of organochlorine pesticides, and long-range transport and atmospheric deposition from source areas outside the basin. Degradation of water quality in the basin is often exacerbated by natural factors such as atmospheric deposition, runoff, and transport characteristics of streams for suspended sediment and dissolved and suspended contaminants.

The large population of the basin and location of major urban areas at the shore of Lake Erie and along rivers are factors that lead to contamination of lakes and streams with bacteria and other microorganisms whose sources are domestic sewage, stormwater, and combined-sewer overflows. Bacterial contamination was identified as an impairment to human health and recreation at 7 of 11 AOC's. Bacterial water-quality standards for recreation are frequently exceeded during runoff in the Clinton, Rouge, Maumee, Black, and Cuyahoga Rivers and at Presque Isle Bay (International Joint Commission, 1994).

The chemicals used in greatest quantity in the Nation—fertilizers and pesticides—are used widely in the basin for agricultural purposes. Hydrologic factors such as precipitation, runoff, and infiltration play a key role in delivering agricultural contaminants to streams and aquifers. Unlike urban streams, oxygen depletion is not characteristic of streams draining row-cropped agricultural basins unless there is runoff of animal waste. However, because of the agricultural use of fertilizers and pesticides and the cultivation of large tracts of land, nutrient, pesticide, and sediment runoff are water-quality concerns.

Accelerated sediment runoff is a result of various land-disturbance activities in urban and agricultural settings. Erodibility of soils and bedrock, presence of natural vegetation or agricultural crops, and slope of the land determines the concentration and amount of sediment and chemical constituents transported by streams. Jones and others (1977) associated water quality with soil and type of surficial materials in three subbasins of the Maumee River. The fine-textured, clay-rich soils yielded the highest concentrations of sediment to streams. In general, the sediment eroded to streams in the Maumee River Basin is finer textured and more enriched with clays than that of the surface horizon of nearby soils (Rhoton and others, 1979). Streams such as the Clinton River and River Raisin drain areas composed of moderately well-drained soils with lower clay content than is typical of the Maumee, Sandusky, and Cuyahoga River Basins, which are areas composed of moderately poor to very poorly drained soils with higher clay content. The Clinton and Raisin Rivers yield a proportionately smaller amount of suspended sediment per square mile than the Maumee River and its tributaries and the Sandusky and Cuyahoga Rivers, which yield the largest amounts of suspended sediment in the basin (table 16). Erodible shale bedrock is another source of sediment in the Cuyahoga River Basin.

The unconsolidated and bedrock aquifers in the Lake Erie-Lake St. Clair Basin are vulnerable to both natural and human sources of contamination. Elevated concentrations of iron, manganese, and dissolved solids can be the result of the geochemical makeup of the aquifer matrix, the thickness and type of drift overlying the aquifer, and the past and current land-use practices above the aquifers.

Where aquifers in the Lake Erie-Lake St. Clair Basin are at or near the land surface, there is a potential for contamination from activities that occur on the surface. Two examples of this general model are glacial aquifers (generally, coarse-grained stratified drift) that are unconfined and shallow or exposed at land surface, and fractured bedrock aquifers that are overlain by 50 ft or less of permeable glacial material (fig. 7). This configuration of permeable materials at or near the land surface will greatly increase the likelihood of ground-water contamination. Such areas of potential vulnerability of ground water to contamination are located in unconsolidated and unconfined or semiconfined glacial aquifers in southeastern Michigan, northeastern Ohio, and western New York. Areas of potential vulnerability of ground water to contamination in bedrock aquifers are located in northwestern Ohio where till thinly mantles the fractured limestone and dolomite aquifers.

Several examples of the types of contamination that have affected these aquifers are application of nitrogen fertilizers, chloride contamination from development of oil and natural gas resources during the late 1800's and early 1900's, and, more recently, application of deicing chemicals. Another example is contamination by VOC's from practices related to the handling and disposal of cleaning solutions and other types of commercial and industrial solvents.

If the aquifer is buried by a less permeable unit (till or fine-grained stratified deposits), the less likely the aquifer is to be contaminated by surface activities. This appears to be the case in most of the basin (fig. 7). If the matrix of the aquifer contains minerals that can provide a source of ions in ground water, the quality of this water can be affected. Elevated concentrations of chloride, sulfate, iron, manganese, organic carbon, and dissolved solids have been detected in aquifers throughout the basin (table 17).

SUMMARY AND CONCLUSIONS

The Lake Erie-Lake St. Clair Basin is one of 59 stream and aquifer systems being studied or planned for study as part of the National Water-Quality Assessment (NAWQA) Program. The investigation of a study unit will include 6 years of intensive assessment activities followed by 4 years of low-level activities.

The Lake Erie-Lake St. Clair Basin has an area of approximately 22,300 mi^2 and includes parts of Indiana, Michigan, Ohio, Pennsylvania, and New York. Major water-quality issues in the basin include assessment of discharges of oxygen-demanding wastes, nutrients, trace elements, and trace organic substances. In certain streams in the basin, oxygen-demanding wastes, ammonia-N, and organic chemicals continue to be factors in nonattainment of water-quality standards for protection of aquatic life.

The basin has a temperate climate with mean annual precipitation generally increasing from west to east. The mean annual precipitation ranges from about 32 to 44 in., and the mean annual air temperature ranges from 47 to 50°F. Average potential evapotranspiration is fairly uniform throughout the basin, at 35 to 36 in/yr.

The Lake Erie-Lake St. Clair Basin includes parts of the Appalachian Plateaus and the Central Lowland Physiographic Provinces. These two major physiographic provinces include varied topographic and geomorphic features that affect the hydrology of the basin. Within the basin, altitudes range from 570 ft above sea level in the Eastern Lake Section of the Central Lowland Province to more than 1,300 ft above sea level in the Southern New York Section of the Appalachian Plateaus Province. Topography in the basin includes areas of nearly flat land; low, rolling hills with low relief; low, rolling hills with moderate relief; and steep-sided hills with deeply incised river valleys.

The sedimentary, glacial, and recent stratigraphic units that compose the shallow ground-water flow system in the basin range in age from Middle Silurian through Quaternary. These sedimentary rocks have been deformed by tectonic forces, and they have been eroded differentially by fluvial and glacial forces. The Silurian rocks consist primarily of carbonate rocks that include dolomite, limestone, shale, and variable amounts of evaporites. The Devonian rocks consist of both carbonates and shales that include limestone, shale, dolomite, and evaporites. Rocks of Mississippian age consist of shale, sandstone, and interbedded sandstone and shale. The Pennsylvanian rocks consist of sandstone, shale, and interbedded limestone and coal.

Alfisols and Inceptisols are the principal soil types in the basin; four other minor soil orders (Mollisols, Histisols, Entisols, and Spodosols) are of minor significance. These soils are mildly weathered because of their relatively young age as compared to soils in areas that have not been glaciated. These soils are generally poorly drained over most of the basin, with the exception of areas in the Appalachian Plateaus Province.

Population in the basin was approximately 10.4 million people in 1990. Detroit, Mich., Cleveland, Ohio, and Buffalo, N.Y., and surrounding metropolitan areas represent roughly 62 percent of the population in the basin. Detroit, Mich., is the largest city in the basin with a population of just over 1 million, not including the suburbs.

Land use in the basin is predominantly agricultural (75 percent in the mid-1970's). Row-crop farming prevails in northeastern Indiana and northwestern Ohio. Pasture and forage crops are the principal agricultural land use in northeastern Ohio, northwestern Pennsylvania, and western New york. Urban land use

(11 percent in the mid-1970's) and forested land cover (10 percent in the mid-1970's) account for approximately 21 percent of the land area in the basin. The remaining 4 percent of land in the basin is composed of water, wetlands, rangeland, and barren land.

Total water use averaged 10,649 Mgal/d in the basin in 1990. Approximately 98 percent was withdrawn from surface-water sources and 2 percent from ground-water sources. Power-generation facilities withdrew an estimated 8,193 Mgal/d in 1990, accounting for about 77 percent of total water withdrawals for the basin.

The eight principal streams are the Clinton, Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand Rivers, and Cattaraugus Creek. The Maumee River, the largest stream in the basin, drains 6,609 mi^2. Unit runoff ranges from 0.64 $ft^3/s/mi^2$ in the Black River in Michigan to 1.70 $ft^3/s/mi^2$ in Cattaraugus Creek in New York. Runoff increases from west to east in the basin.

The glacial and recent deposits comprise the unconsolidated aquifers and confining units within the basin. Yields of wells completed in tills range from 0 to 20 gal/min but are generally near the lower end of this range. Fine-grained stratified deposits can be expected to yield from 0 to 3 gal/min and coarse-grained stratified deposits from 0.3 to 2,050 gal/min. Pennsylvanian sandstones can yield more than 25 gal/min but generally yield from 10 to 25 gal/min. Mississippian sandstones in the basin can yield 2 to 100 gal/min, with a very few wells producing as much as 200 gal/min. The Mississippian and Devonian shales are considered to be a confining unit that can produce only small quantities of water from fractures at or near the bedrock surface. Wells completed in the Devonian and Silurian carbonates generally yield from 25 to 500 gal/min, but higher yields have been reported for several zones.

Most streams in the Lake Erie-Lake St. Clair Basin have moderately hard to very hard water as a result of contact with limestone and dolomite and surficial materials of shale, limestone, or dolomite origin. The lowest hardness concentrations (softest waters) are found in small streams in far northeastern Ohio, in the Grand and Ashtabula Rivers and Conneaut Creek, and in western New York in Cattaraugus Creek and smaller streams to the west. The highest hardness concentrations are found in streams in southeastern Michigan and near Buffalo, N.Y.

Surface-water quality in the Lake Erie-Lake St. Clair Basin has generally improved since the 1960's; however, the amounts of nitrogen and phosphorus fertilizers, herbicides and insecticides, and sediment discharged to Lake Erie from its basin are higher than in any other basin of the Great Lakes. Although trends in phosphorus concentrations for the Raisin, Maumee, Sandusky, Cuyahoga, and Grand Rivers and for point sources have been downward, trends in nitrate-N concentrations for the Raisin, Maumee, and Sandusky Rivers have been upward.

Pesticide concentrations are detected in streams draining row-cropped areas of the Lake Erie-Lake St. Clair Basin after application and runoff in the spring and early summer. Peak concentrations of atrazine can range from much less than 1.0 μg/L in samples collected during preapplication runoff to 35 μg/L or more in samples collected during postapplication runoff.

The Maumee River is the single largest source of sediment to Lake Erie and discharges more tons per year of suspended sediment than any other tributary in the Great Lakes Basin. The Sandusky River discharges the second greatest amount of sediment (tons per year) to Lake Erie.

Bacteriological sampling in urban watersheds indicates that elevated concentrations of fecal coliform bacteria and *E. coli* are associated with runoff; sources are discharges from combined sewers and sanitary sewers and bypasses of incompletely disinfected wastewater. An example has been the Cuyahoga River Basin, where concentrations of fecal coliform and *E. coli* bacteria are greatly elevated above recreational body-contact standards during runoff.

Most ground water in the Lake Erie-Lake St. Clair Basin is moderately hard to very hard, with concentrations ranging from 60 to 560 mg/L as $CaCO_3$. The lowest hardness concentrations (softest water) in ground-water supplies are found in relatively shallow, unconsolidated aquifers in western New York, and the highest hardness concentrations are found in carbonate and sandstone aquifers. Although water contained in glacial deposits is typically lower in dissolved solids and major ions than water contained in bedrock, ground water and surface water are both typically of the calcium-bicarbonate-sulfate type.

Concentrations of nitrate-N in ground water greater than or equal to 3 mg/L have been detected in a small percentage of wells sampled in certain areas of the Lake Erie-Lake St. Clair Basin. In ground-water samples from the Michigan, Indiana, and Ohio areas, 0 to 19 percent had nitrate plus nitrite-N concentrations greater than or equal to 3 mg/L. In addition, contamination with nitrate plus nitrite-N was related to age of water, recently recharged water having the higher number of detections of elevated nitrate plus nitrite-N. Currently used pesticides have been rarely detected in domestic-supply wells and other ground-water sources in the Lake Erie-Lake St. Clair Basin. In most cases, when detected, pesticide concentrations have been less than 0.1 µg/L.

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SUPPLEMENTAL DATA

Table 18. Fish species that are extinct, endangered, threatened, or of special concern in the Lake Erie-Lake St. Clair Basin[1]—Continued

	Extirpated	Endangered	Threatened	Special concern or interest
INDIANA	muskellunge *(Esox masquinongy)*	bluebreast darter *(Etheostoma camurum)*		eastern sand darter *(Ammocrypta pellucida)*
	harelip sucker *(Lagochila lacera)*	Tippecanoe darter *(Etheostoma tippecanoe)*		blue sucker *(Cycleptus elongatus)*
		variegate darter *(Etheostoma variatum)*		river redhorse *(Moxostoma carinatum)*
		gilt darter *(Percina evides)*		greater redhorse *(Moxostoma valenciennesi)*
MICHIGAN	Arctic grayling *(Thymallus arcticus)*	ironcolor shiner *(Notropis chalybaeus)*	redside dace *(Clinostomuselongatus)*	
		weed shiner *(Notropis texanus)*	creek chubsucker *(Erimyzon oblongus)*	
		northern madtom *(Noturus stigmosus)*	river redhorse *(Moxostoma carinatum)*	
		river darter *(Percina shumardi)*	silver shiner *(Notropis photogenis)*	
			pugnose minnow *(Opsopoeodus emiliae)*	
			southern redbelly dace *(Phoxinus erythrogaster)*	
			sauger *(Stizostedion canadense)*	
NEW YORK		eastern sand darter *(Ammocrypta pellucida)*		black redhorse *(Moxostoma duquesnei)*
		spoonhead sculpin *(Cottus ricei)*		long head darter *(Percina macrocephala)*
OHIO	pugnose shiner *(Notropis anogenus)*	pirate perch *(Aphredoderus sayanus)*	silver lampery *(Ichthyomyzon unicuspis)*	eastern sand darter *(Ammocrypta pellucida)*
	gilt darter *(Percina evides)*	longnose sucker *(Catostomus catostomus)*	river darter *(Percina shumardi)*	muskellunge *(Esox masquinongy)*

Table 18. Fish species that are extinct, endangered, threatened, or of special concern in the Lake Erie-Lake St. Clair Basin[1]—Continued

	Extirpated	Endangered	Threatened	Special concern or interest
OHIO—Continued		western banded killifish *(Fundulus diaphanus menona)*		Iowa darter *(Etheostoma exile)*
		northern brook lampery *(Ichthyomyzon fossor)*		river redhorse *(Moxostomacarinatum)*
		spotted gar *(Lepisosteus oculatus)*		brook trout *(Salvelinus fontinalis)*
		greater redhorse *(Moxostoma valenciennesi)*		lake troout *(Salvelinus namaycush)*
		popeye shiner *(Notropis ariommus)*		
		bigeye shiner *(Notropis boops)*		
		blacknose shiner *(Notropis heterolepis)*		
		blackchin shiner *(Notropis heterodon)*		
		northern madtom *(Noturus stigmosus)*		
		pugnose minnow *(Opsopoeodus emiliaes)*		
		channel darter *(Percina copelandi)*		

[1]Scientific names are consistent with Robins and others, 1991.

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