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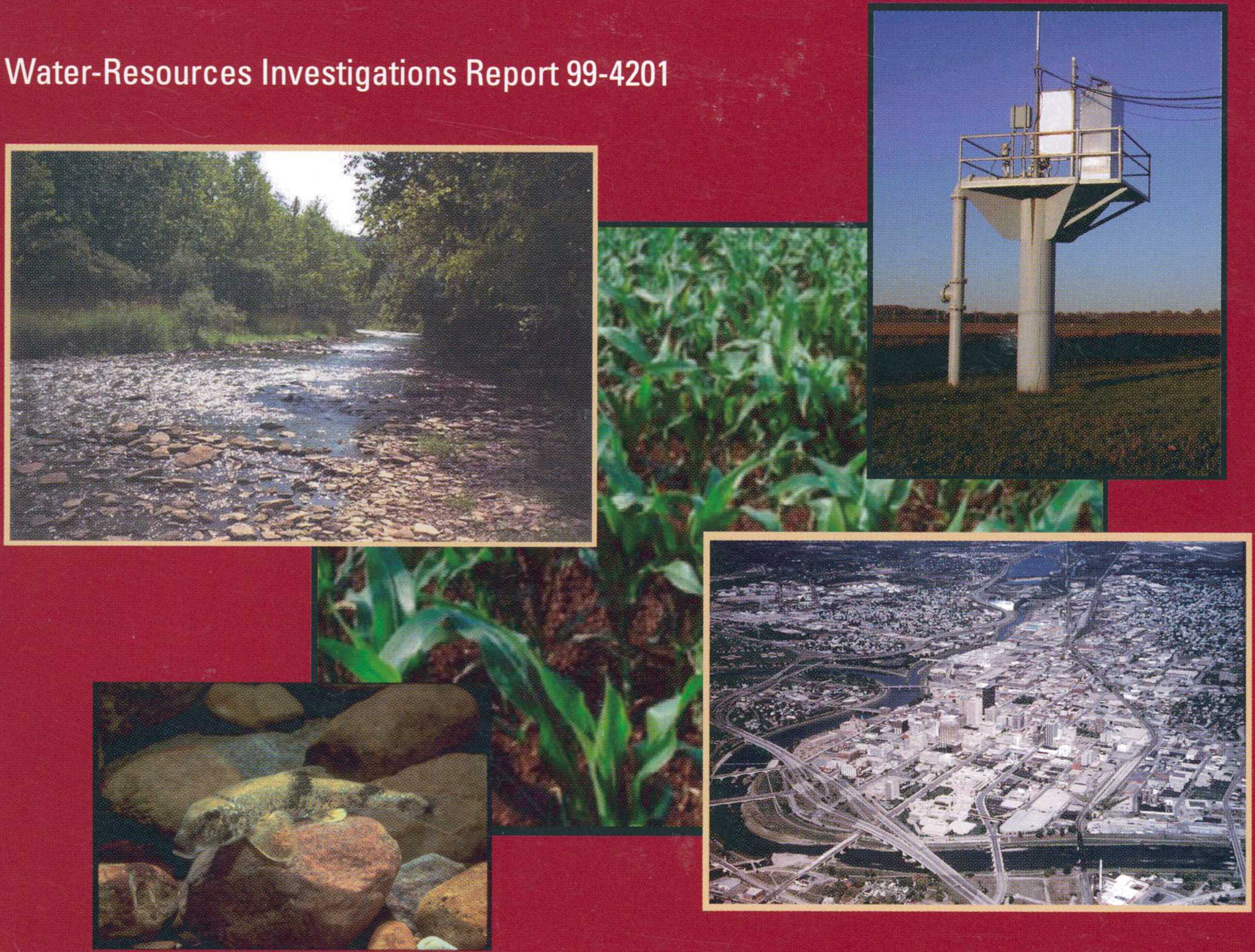
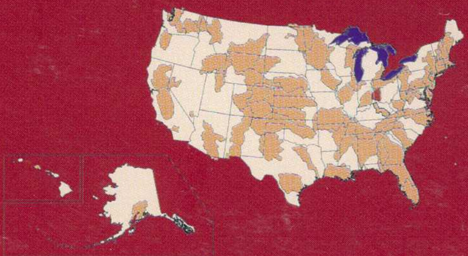
National Water-Quality Assessment Program

Environmental Setting and Effects on Water Quality in the Great and Little Miami River Basins, Ohio and Indiana

Water-Resources Investigations Report 99-4201





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Municipal supply well near Fairfield, Ohio
(Photograph by Rhett Moore, U.S. Geological Survey)

East Fork Little Miami River, downstream from Harsha Lake Dam near Mt. Holly, Ohio
(Photograph by Dave Reutter, U.S. Geological Survey)

Northern hog sucker (*Hypentelium nigricans*)
(Photograph by Alvin E. Staffan, Ohio Department of Natural Resources)

Confluence of Mad and Great Miami Rivers at Dayton, Ohio
(Photograph by Joel Kane, Joel Kane Aerial Photography, Dayton, Ohio)

Corn field
(Photograph from U.S. Department of Agriculture Online Photography Center accessed on October 5, 1999, at URL: http://www.usda.gov/oc/photo/opchomea.htm)

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By Linda M. Debrewer, Gary L. Rowe, David C. Reutter, Rhett C. Moore, Julie A. Hambrook, and Nancy T. Baker

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Water-Resources Investigations Report 99-4201

Columbus, Ohio

2000

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<URL: http://wwwrvares.er.usgs.gov/nawqa/nawqa-home.html>

Foreword

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for specific contamination problems; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional- and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the U.S. Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of more than 50 of the Nation's most important river basins and aquifer systems, which are referred to as Study Units. These Study Units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within these Study Units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the Study Units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

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Multiply	By	To obtain
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day[1] (ft^2/d)	0.0929	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
people per square mile ($people/mi^2$)	0.3861	people per square kilometer
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
pound per day (lb/d)	0.4536	kilogram per day
pound per acre (lb/acre)	1.121	kilogram per hectare
gallon per minute (gal/min)	3.785	liter per minute
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

[1]Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Air temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8 \times °C + 32$$

Conversion Factors, Vertical Datum, Water-Quality Units, and Abbreviations—Continued

Vertical datum: 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 the United States and Canada, formerly called Sea Level Datum of 1929.

Water year: In U.S. Geological Survey reports, water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 1990, is called the "1990 water year."

Water-quality units used in this report: Chemical concentrations, atmospheric chemical loads, 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 per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Chemical loads are given in milligrams per square meter (mg/m^2), a unit that expresses the weight (milligrams) of a chemical constituent per unit area (square meter).

The following abbreviations are used in this report:

Abbreviation	Description
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
GIRAS	Geographic Information Retrieval and Analysis System
IDEM	Indiana Department of Environmental Management
MCD	Miami Conservancy District
NASQAN	National Stream Quality Accounting Network
NAWQA	National Water-Quality Assessment
NPDES	National Pollutant Discharge Elimination System
ORSANCO	Ohio River Valley Water Sanitation Commission
PCS	Permit Compliance System
RCRA	Resource Conservation and Recovery Act
STATSGO	State Soil Geographic Data Base
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
MCL	Maximum Contaminant Level
AMCL	Alternative Maximum Contaminant Level
SMCL	Secondary Maximum Contaminant Level
pH	Negative log (base-10) of the hydrogen ion activity, in moles per liter
7Q10	The average streamflow for 7 consecutive days below which streamflow recedes on average once every 10 years
Kg/ha	kilograms per hectare
pCi/L	picocuries per liter

Environmental Setting and Effects on Water Quality in the Great and Little Miami River Basins, Ohio and Indiana

By Linda M. Debrewer, Gary L. Rowe, David C. Reutter, Rhett C. Moore, Julie A. Hambrook, *and* Nancy T. Baker

Abstract

The Great and Little Miami River Basins drain approximately 7,354 square miles in southwestern Ohio and southeastern Indiana and are included in the more than 50 major river basins and aquifer systems selected for water-quality assessment as part of the U.S. Geological Survey's National Water-Quality Assessment Program. Principal streams include the Great and Little Miami Rivers in Ohio and the Whitewater River in Indiana. The Great and Little Miami River Basins are almost entirely within the Till Plains section of the Central Lowland physiographic province and have a humid continental climate, characterized by well-defined summer and winter seasons. With the exception of a few areas near the Ohio River, Pleistocene glacial deposits, which are predominantly till, overlie lower Paleozoic limestone, dolomite, and shale bedrock. The principal aquifer is a complex buried-valley system of sand and gravel aquifers capable of supporting sustained well yields exceeding 1,000 gallons per minute. Designated by the U.S. Environmental Protection Agency as a sole-source aquifer, the Buried-Valley Aquifer System is the principal source of drinking water for 1.6 million people in the basins and is the dominant source of water for southwestern Ohio. Water use in the Great and Little Miami River Basins averaged 745 million gallons per day in 1995. Of this amount, 48 percent was supplied by surface water (including the Ohio River) and 52 percent was supplied by ground water.

Land-use and waste-management practices influence the quality of water found in streams and aquifers in the Great and Little Miami River Basins. Land use is approximately 79 percent agriculture, 13 percent urban (residential, industrial, and commercial), and 7 percent forest. An estimated 2.8 million people live in the Great and Little Miami River Basins; major urban areas include Cincinnati and Dayton, Ohio. Fertilizers and pesticides associated with agricultural activity, discharges from municipal and industrial wastewater-treatment and thermoelectric plants, urban runoff, and disposal of solid and hazardous wastes contribute contaminants to surface water and ground water throughout the study area.

Surface water and ground water in the Great and Little Miami River Basins are classified as very hard, calcium-magnesium-bicarbonate waters. The major-ion composition and hardness of surface water and ground water reflect extensive contact with the carbonate-rich soils, glacial sediments, and limestone or dolomite bedrock. Dieldrin, endrin, endosulfan II, and lindane are the most commonly reported organochlorine pesticides in streams draining the Great and Little Miami River Basins. Peak concentrations of the herbicides atrazine and metolachlor in streams commonly are associated with post-application runoff events. Nitrate concentrations in surface water average 3 to 4 mg/L (milligrams per liter) in the larger streams and also show strong seasonal variations related to application periods and runoff events.

Ambient iron concentrations in ground water pumped from aquifers in the Great and Little Miami River Basins often exceed the U.S. Environmental Protection Agency Secondary Maximum Contaminant Level (300 micrograms per liter). Chloride concentrations are below aesthetic drinking-water guidelines (250 mg/L), except in ground water pumped from low-yielding Ordovician shale; chloride concentrations in sodium-chloride-rich ground water pumped from the shale bedrock can exceed 1,000 mg/L. Some of the highest average nitrate concentrations in ground water in Ohio and Indiana are found in wells completed in the buried-valley aquifer; these concentrations typically are found in those parts of the sand and gravel aquifer that are not overlain by clay-rich till. Atrazine was the most commonly detected herbicide in private wells. Concentrations of volatile organic compounds in ground water generally were below Federal drinking-water standards, except near areas of known or suspected contamination.

Evaluation of fish and macroinvertebrate community performance in streams and rivers draining the Great and Little Miami River Basins indicates that most streams meet basic aquatic-life-use criteria set by the Ohio Environmental Protection Agency for warmwater habitat. Stream reaches whose biological community performance meet aquatic-life-use criteria defined for exceptional warmwater habitat are found in Twin Creek, the Upper Great Miami River, the Little Miami River, and the Whitewater River Basins. Other streams have exhibited significant improvements in biological community performance (and water quality) that are attributed primarily to reduced pollutant loadings from wastewater-treatment plants upgraded since 1972.

Four hydrogeomorphic regions were delineated in the Great and Little Miami River Basins based on distinct and relatively homogeneous natural characteristics. Primary features used to delineate the hydrogeomorphic regions include bedrock geology, surficial geology, physiography, hydrology, soil types, and vegetation. These four regions—Till Plains, Drift Plains/Unglaciated, Interlobate, and Fluvial—are used in the Great and Little Miami River Basins study to assess the influence of natural features of the environmental setting on surface- and ground-water quality.

Introduction

In 1991, the U.S. Geological Survey (USGS) began the National Water-Quality Assessment (NAWQA) Program. The NAWQA Program is designed to describe water-quality conditions for a large, representative part of the Nation's surface- and ground-water resources; define long-term trends in water quality; and identify the natural and human factors that affect observed water-quality conditions and trends (Hirsch and others, 1988). The goal of the NAWQA Program is to provide water-quality information to policy makers and resource managers at the Federal, state, and local level so they can better prioritize and manage water resources in diverse hydrologic and land-use settings. Results of the NAWQA studies also can be used to consider the effects of key natural processes and human activities on water quality when management strategies and policies designed to restore and protect the Nation's waters are being developed.

The NAWQA Program focuses on water quality in more than 50 major river basins and aquifer systems that range in size from about 1,200 to about 48,000 mi^2 (square miles). Investigations in these basins, referred to as "Study Units," use a nationally consistent scientific approach and standardized methods. Together, the Study Units represent about 60 percent of the population served by public water systems and about 50 percent of the total land area of the conterminous United States (Gilliom and others, 1995). The consistent design of the NAWQA Program allows investigations of local conditions and trends within individual study areas, while also providing the basis to make comparisons among individual Study Units. The comparisons demonstrate that water-quality patterns are related to the environmental setting (chemical use, land use, climate, geology, topography, soils) and thereby improve our understanding of how and why water quality varies regionally and nationally.

The Great and Little Miami River Basins make up one of the NAWQA Study Units where NAWQA activities began in 1997. The Great and Little Miami River Basins (referred to as the "study area" in the remainder of this report), encompass 7,354 mi^2 in southwestern Ohio (80 percent) and southeastern Indiana (20 percent) (fig. 1). Principal streams are the Great and Little Miami Rivers in Ohio and the Whitewater River in Indiana; all major streams drain south-southwest into the Ohio River. Estimated population in the study area was about 2.8 million in 1995. Most land in the study area is devoted to agricultural activities, primarily row-crop production of corn, soybeans, and wheat. Urban land use concentrated along the heavily industrialized Dayton-Cincinnati corridor affects water quality in the study area. The study area contains one of the most productive glacial aquifer systems in the Nation; the Buried-Valley Aquifer System (BVAS) is the principal source of drinking water for nearly 1.6 million people. The study area also contains many streams classified as being in full or partial attainment of exceptional warmwater habitat criteria, including nearly the entire length of the main stem Little Miami River (a designated State of Ohio and National Scenic River), the Stillwater River (a State of Ohio Scenic River), the Upper Great Miami River and its tributaries in Ohio, and the Whitewater River in Indiana.

The study area contains important agricultural and urban land-use settings that are characteristic of the midwestern United States. Major water-quality issues being addressed by water suppliers and water-resource managers include the following:

- contamination of the sole-source sand and gravel aquifer by synthetic organic chemicals, trace elements, and radionuclides;
- degradation of surface-water and ground-water quality by urban and agricultural sources of nutrients and pesticides;
- determination of the relative contributions of point and nonpoint sources to contaminant loads in streams and rivers;
- the effect of rapid urbanization on water quality, stream habitat, and aquatic biota;
- assessment of the role of surface-water/shallow ground-water interactions on ground-water quality;
- the effect of land use and combined-sewer overflows on the distribution and occurrence of waterborne pathogens in streams and shallow ground water; and
- the effect of dams and impoundments on fish and benthic-invertebrate communities.

Purpose and Scope

This report describes the environmental setting of the Great and Little Miami River Basins study area and the various factors that may affect current and future water-quality conditions. The scope of this report is limited to a description of the major natural (physiography, geology, soils, climate, and hydrology) and human (population, land and water use, and waste-disposal practices) components of the environmental setting and some examples of their effect on water quality in the study area. A detailed evaluation of how natural and human components of the environmental setting affect water-quality conditions and trends is beyond the scope of this report. This report also describes how various components of the environmental setting were used to prioritize watershed and aquifer settings that will be targeted for planned NAWQA surface-water, ecological, and ground-water-quality studies. The report is intended as a reference document for subsequent, topical NAWQA reports addressing specific water-quality issues in the study area and for synthesis reports that will integrate results from NAWQA investigations across the Nation.

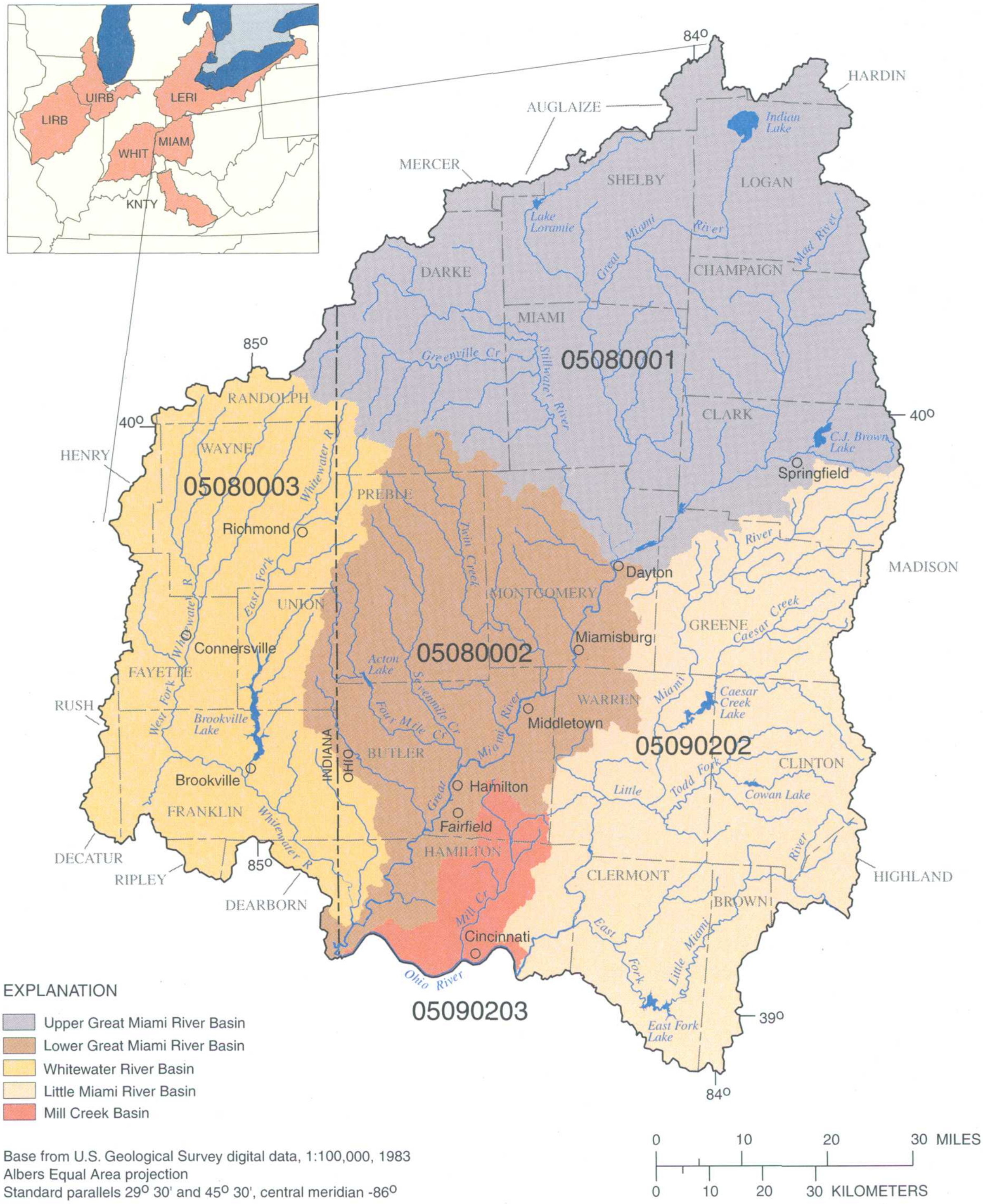


Figure 1. Location of the Great and Little Miami River Basins and eight-digit hydrologic units. Inset shows relation of study area (MIAM) to nearby NAWQA Study Units: Kentucky River Basin (KNTY), Lake Erie–Lake St. Clair Basin (LERI), Lower Illinois River Basin (LIRB), Upper Illinois River Basin (UIRB), and White River Basin (WHIT).

Acknowledgments

The authors wish to acknowledge the significant contributions of the many Federal, state, and local agencies that provided information and data vital to this report. We thank the Ohio Department of Natural Resources, Division of Water and Division of Geological Survey; Ohio Environmental Protection Agency; Indiana Department of Natural Resources; Indiana Department of Environmental Management; Indiana Geological Survey; Purdue University Cooperative Extension; Indiana and Ohio Agricultural Statistics Services; Midwestern Climate Center; Miami Conservancy District; Miami Valley Regional Planning Commission; Ohio-Kentucky-Indiana Regional Council of Governments; U.S. Environmental Protection Agency; U.S. Bureau of the Census; Shelby County (Ohio) Soil and Water Conservation District; Darke, Shelby, and Miami County Extensions (Ohio); and Wayne and Union County Extensions (Indiana).

Environmental Setting

Natural and human factors affect the physical, chemical, and biological quality of surface and ground water in the study area. These factors, which collectively constitute the environmental setting, also will influence short- and long-term trends in water quality. Ambient water quality and the richness and diversity of aquatic ecosystems will be affected by natural factors such as climate, physiography, geology, soil, and ecology. More significant effects, such as degraded water quality or impaired biotic response, may be caused by human factors related to land use, water use, or waste-disposal activities. Significant nonpoint sources of contamination include (1) agricultural activities resulting in sediment loss as well as pesticide and nutrient runoff and (2) urban development resulting in removal of riparian vegetation and increased urban runoff. Point sources of contamination include industrial and wastewater discharges of toxic substances, pathogens, and nutrients. Table 1 summarizes important causes and sources of water-quality degradation and aquatic-ecosystem impairment related to human activities in the study area. Subsequent sections describe the natural and human factors that constitute the environmental setting and how they affect the quality of streams and aquifers.

Climate

Hydrologic cycles of streams and aquifers are controlled by seasonal variations in precipitation, runoff, and evapotranspiration. Climatic factors, including temperature and humidity, influence rates of physical and chemical weathering of rocks and soils; constituents from the breakdown of these media are carried into streams and lakes by runoff and into ground water through infiltration. Temperature determines growing seasons and governs evapotranspiration. Precipitation, carrying airborne contaminants, influences water chemistry.

The study area has a temperate continental climate characterized by well-defined winter and summer seasons that are accompanied by large annual temperature variations. Seasonal temperature variations reflect the dominance of polar continental air masses in the fall and winter and tropical maritime air masses in the late spring, summer, and early fall. The main sources of moisture are tropical maritime air masses from the Gulf of Mexico and the western Atlantic Ocean. Additional moisture is derived from local and upwind sources, including water recycled through the land-vegetation-air interface. The area experiences frequent cyclonic disturbances caused by tropical air masses moving northeast from the Gulf of Mexico. These storms interact with arctic air masses moving south and can transport considerable amounts of moisture (Indiana Department of Natural Resources, 1988; U.S. Geological Survey, 1991). In the spring and summer, most precipitation is associated with thunderstorms produced by daytime convection or passing cold fronts. Because the spatial distribution of rainfall is influenced by relative proximity to the humid tropical maritime air masses, mean annual precipitation increases from north to south (fig. 2).

Table 1. Cause and source of impairment to surface- and ground-water quality and aquatic ecosystems in the Great and Little Miami River Basins, Ohio and Indiana

[Modified from Ohio Environmental Protection Agency, 1997a]

Cause	Source	Potential adverse effects
Sedimentation/siltation	Agricultural activities Mining operations Urban /residential development	1) Destroy fish habitat 2) Decrease recreational value of surface-water bodies 3) Increase wear on water-supply pumps and distribution systems 4) Increase treatment costs for water supplies 5) Allow adsorbed nutrients and toxic substances to enter aquatic food chains
Nutrient/organic enrichment (nitrogen, phosphorus, organic carbon)	Agricultural activities (erosion and runoff) Wastewater discharges Industrial discharges Septic-system leachate Animal wastes Decay of organic matter	1) Support growth of excessive algae and aquatic plants, leading to eutrophication 2) Reduce dissolved oxygen below aquatic-life-support levels 3) Affect health and diversity of fish and macroinvertebrate communities 4) Affect taste and odor of treated drinking water
Pathogens (bacteria, viruses)	Septic systems Animal wastes Agricultural activities Industrial activities Wastewater discharges	1) Transmit waterborne diseases to humans 2) Degrade public water supply 3) Limit recreational activities
Toxic substances (metals, organic compounds)	Urban runoff Wastewater treatment Industrial discharges Spills Underground-storage tanks	1) Dissolve in runoff or attach to sediment or organic material reaching surface waters 2) Infiltrate through soil to ground water 3) Enter the food chain 4) Degrade habitat and affect public water supplies
Pesticides	Agricultural activities Urban runoff	1) Dissolve in runoff or attach to sediment or organic material reaching surface waters 2) Infiltrate through soil to ground water 3) Enter the food chain 4) Degrade habitat and affect public water supplies
Thermal stress/sunlight	Industrial discharges Hydromodification	1) Elevate stream temperatures 2) Reduce dissolved oxygen and promote growth of nuisance algae

Table 1. Cause and source of impairment to surface- and ground-water quality and aquatic ecosystems in the Great and Little Miami River Basins, Ohio and Indiana—Continued

Cause	Source	Potential adverse effects
pH	Atmospheric deposition (wet and dry) Industrial discharges	1) Alter the reproduction and development patterns of fish and amphibians 2) Decrease microbial activity 3) Release toxic metals adsorbed to sediment 4) Accelerate deterioration of acid-sensitive building materials
Salinity (dissolved solids)	Urban runoff (road deicing) Oil extraction	1) Alter the taste of drinking water 2) Increase risks to human health and aquatic life 3) Degrade shallow ground-water quality
Habitat modification	Channelization Urban/residential development Change land use Remove riparian vegetation Dredging Streambank modification	1) Alter streamflow 2) Alter physical structure of aquatic and riparian ecosystems 3) Affect health and diversity of fish and macroinvertebrate communities
Refuse, litter, other debris	Urban runoff Industrial activities Urban/residential development	1) Clog fish-spawning areas 2) Reduce water clarity 3) Impede water-treatment-plant operations 4) Impair recreational uses

Precipitation and Temperature

Data gathered from 11 National Weather Service (NWS) stations over a 30-year period (1961–90) are used to characterize mean annual temperature and precipitation in the study area. The mean annual temperature ranges from 49° to 55°F (Fahrenheit). Mean monthly temperatures range from 68° to 77°F in the summer and from 26° to 33°F during the winter (fig. 2). On average, temperatures exceed 90°F about 19 days a year and drop below 0°F about 6 days a year (Midwestern Climate Center, 1997).

Mean annual precipitation is 39 in. (inches) in the study area. Precipitation ranges from less than 36 to more than 42 in., increasing towards the south (fig. 2). Annual extremes in the study area were recorded at the Greenville Water Plant in Darke County, Ohio, (22.15 in. in 1963) and at the Brookville NWS station in Franklin County, Ind. (63.73 in. in 1990). March through August tend to be the wettest months, averaging about 3.8 in. of rainfall per month; January and February tend to be the driest (fig. 2). Precipitation events during the fall and winter months tend to be longer and of mild intensity; convective storms during the spring and summer tend to be shorter and more intense. Mean annual snowfall ranges from 11 to 30 in. across the study area. Based on 30-year data collected in Cincinnati and Dayton, Ohio, the estimated evapotranspiration rate is 26.5 in. per year (Traci Hasse, Midwestern Climate Center, written commun., 1998).

Precipitation Quality

Natural and human factors contribute to the chemistry of precipitation. Atmospheric depositional processes are subdivided into "wet" and "dry" deposition. In wet deposition, contaminants are dissolved in or are adsorbed onto rain, snow, sleet, dew, or hail. Wet deposition and its entrained contaminants then are deposited onto the land surface or water bodies. In dry deposition, pollutants are removed from the atmosphere by adsorption onto dust particles. Although dry deposition is believed to be a larger contributor of pollutants than is wet deposition, little dry-deposition data are available. Major constituents measured in wet-deposition samples include acidity (pH), calcium, magnesium, potassium, sodium, chloride, ammonium, nitrate, and sulfate.

Trends in the quality of atmospheric deposition in the United States have been monitored by the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) since 1978. The program, run by the cooperative efforts of Federal, state, and local agencies, monitors rural background concentrations at more than 200 atmospheric-deposition-sampling stations in the United States. In the study area, long-term temporal trends in atmospheric chemistry are measured at the Oxford NADP/NTN station in northwestern Butler County, Ohio. Precipitation-weighted, mean annual atmospheric wet-deposition chemistry and loading estimates for the 5-year period from 1993–97 at the Oxford station are presented in table 2.

Table 2. Median mean annual wet-deposition data and loading estimates for the Oxford, Ohio, National Atmospheric Deposition Program/National Trends Network station in the Great and Little Miami River Basins, 1993–97

[mg/L, milligrams per liter; mg/m², milligrams per square meter; data from National Atmospheric Deposition Program/National Trends Network, 1998]

Component	Median concentration[1] (mg/L)	Median load (mg/m²)
Acidity (pH)	4.37	47
Calcium	.130	136
Magnesium	.020	23
Potassium	.029	25
Sodium	.067	66
Chloride	.140	134
Ammonium	.290	290
Nitrate	1.460	1,558
Sulfate	2.230	2,245

[1]Median-concentration data given in units of mg/L, except for acidity value which is given in standard pH units.

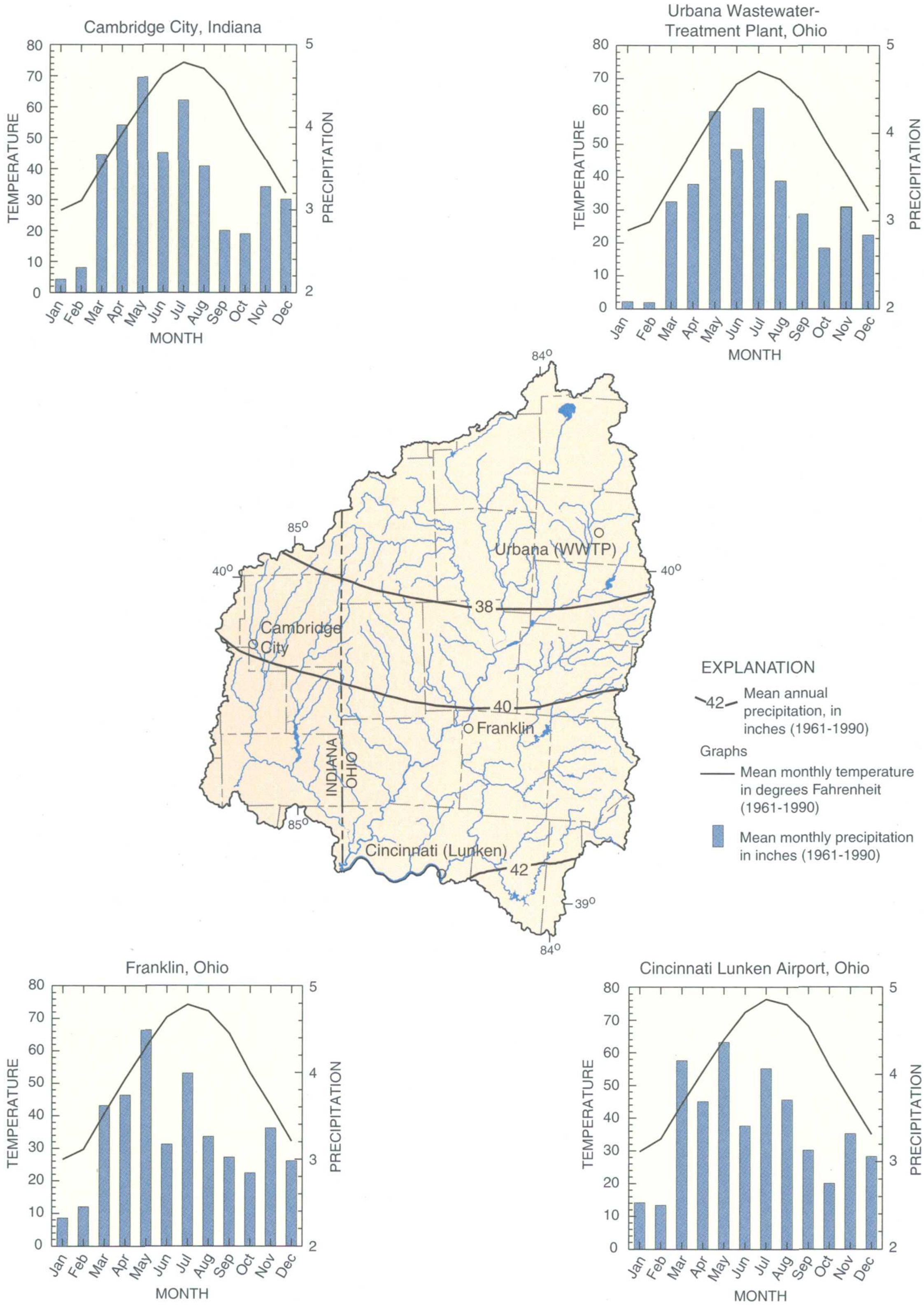


Figure 2. Mean monthly temperature and precipitation at selected National Weather Service stations and mean annual precipitation in the Great and Little Miami River Basins, Ohio and Indiana, 1961–90. (Data from Midwestern Climate Center, 1997.)

Major-ion concentrations measured in atmospheric wet deposition are small compared to concentrations measured in surface and ground water; however, constituent loading (mass distributed over a specific area) from atmospheric wet deposition can be substantial. For example, the amount of nitrogen derived from the atmosphere on an annual basis in the study area may approach or exceed the amount of nitrogen applied as manure and may constitute upwards of 10 percent of the total amount of nitrogen applied as chemical fertilizer (Puckett, 1995). Nitrogen, sulfate, and associated acidity are major contributors to wet-deposition chemistry and are derived primarily from the burning of fossil fuel, particularly coal, for electric-power generation. The estimated mean annual wet-deposition rate for inorganic nitrogen (5.8 kg/ha [kilograms per hectare]) for the study area is generally lower than 5-year averages recorded at other midwestern NADP/NTN sites for the period 1993–97 (fig. 3). In contrast, sulfate and hydrogen ion-deposition rates (23 and 0.46 kg/ha, respectively) are relatively high and follow regional trends towards increased deposition rates south and east of the study area. Despite the high deposition rates, stormwater in the study area rarely has acidic pH values because of the abundance of acid-neutralizing carbonate material found in soils, unconsolidated glacial sediments, and limestone and dolomite bedrock.

Physiography

The study area is almost entirely within the Till Plains section of the Central Lowland physiographic province (Fenneman, 1938). With the exception of a few areas near the Ohio River, nearly all of the study area was affected by Pleistocence glaciation. Advance and retreat of the glacial ice sheets produced a flat to gently rolling land surface that is cut by steep-walled river valleys of low to moderate relief (fig. 4). In the southern part of the study area, glacial deposits are thin or absent, and erosion of less-resistant shale has produced a dissected hilly terrain of higher stream density. The general topographic gradient is from north to south. The study area contains the highest and lowest elevations in the State of Ohio—Campbell Hill in Logan County, with an elevation of 1,550 ft (feet) above sea level, and areas along the banks of the Ohio River in Hamilton County (fig. 1), with an elevation of 451 ft.

The Till Plains section of the Central Lowland province is divided further in the study area. The physiographic subunits were defined individually for Ohio and Indiana, and no reference currently exists that correlates subunit boundaries across the Ohio-Indiana state line. In western Ohio, the Till Plains section has been divided into four subunits—the Central Ohio Clayey Till Plain, Southern Ohio Loamy Till Plain, Illinoian Till Plain, and the Dissected Illinoian Till Plain (Brockman, 1998). Topographic variations in each subunit depend largely on the bedrock geology and glacial history of the region. In east-central Indiana, the Till Plain subunits defined by Malott (1922) are distinguished by the thickness of glacial till; this distinction is not made under the classification scheme defined by Brockman (1998) for Ohio.

In southwestern Ohio, the Central Ohio Clayey Till Plain is characterized by clayey till with ground moraines and intermorainal lake basins, landforms resulting from till deposits that form a moderately flat blanket over existing bedrock or older glacial sediment. Indian Lake, which marks the headwater of the Great Miami River, occupies one of the larger intermorainal lake basins in western Ohio. The Southern Ohio Loamy Till Plain, which includes most of the northern and central parts of the Great and Little Miami drainage basins, is characterized by end and recessional moraines between relatively flat-lying ground moraine. These morainal features are cut by steep-valleyed streams, with alternating broad and narrow flood plains. Buried valleys filled with glacial-outwash deposits are common. This subunit also contains interlobate areas (for example, the Mad River Basin) characterized by extensive outwash deposits, outwash terraces, and border moraines; as such, they are areas of focused ground-water discharge in the form of cold, perennial, ground-water-fed springs and streams. Glacial deposits in both regions are underlain by Devonian and Silurian carbonates (north and east) and by Ordovician shale and limestone (south).

The Illinoian Till Plain in the southern part of the study area is characterized by rolling ground moraines of older till and numerous buried valleys. The southwestern corner of the study area is characterized by the Dissected Illinoian Till Plain.

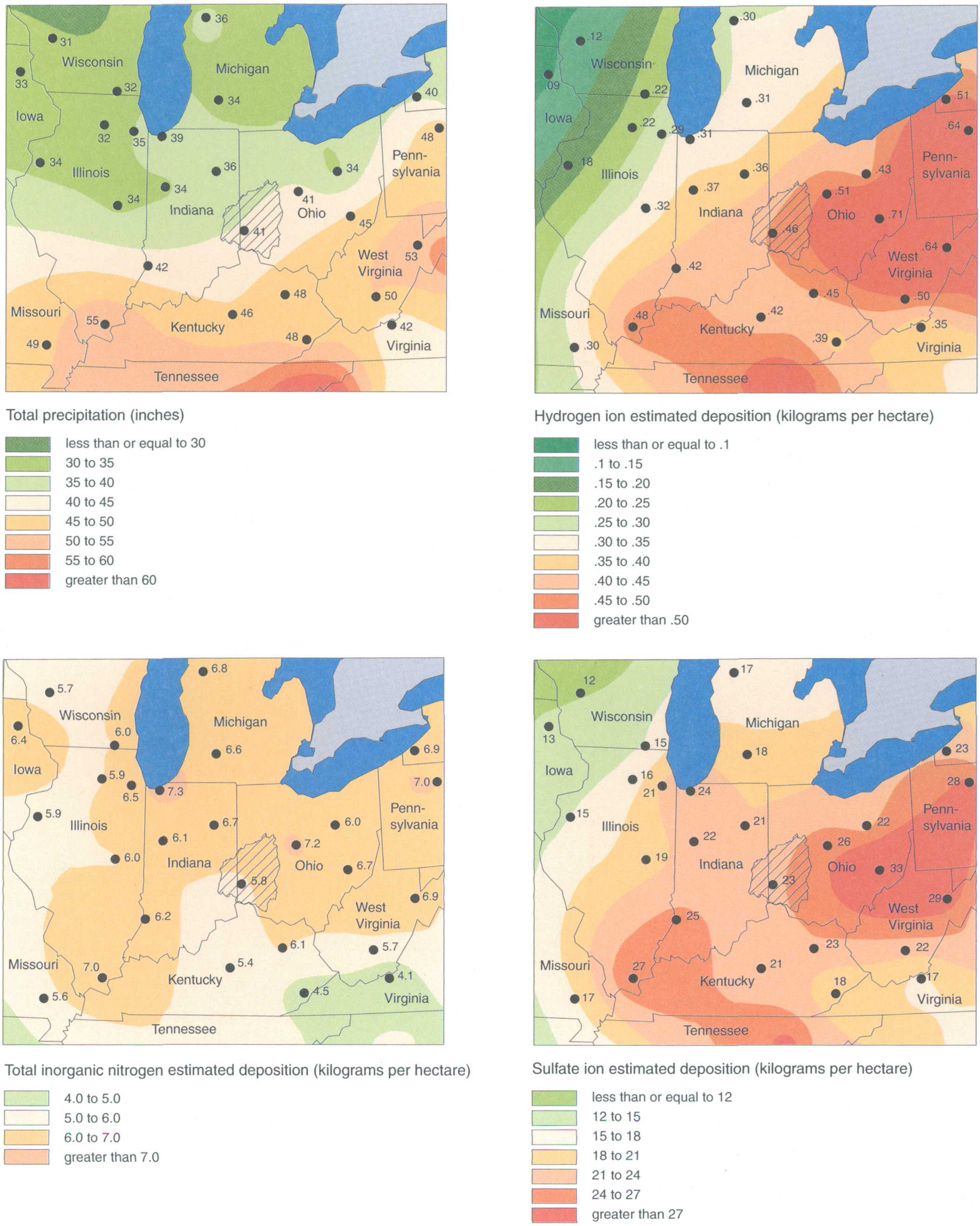
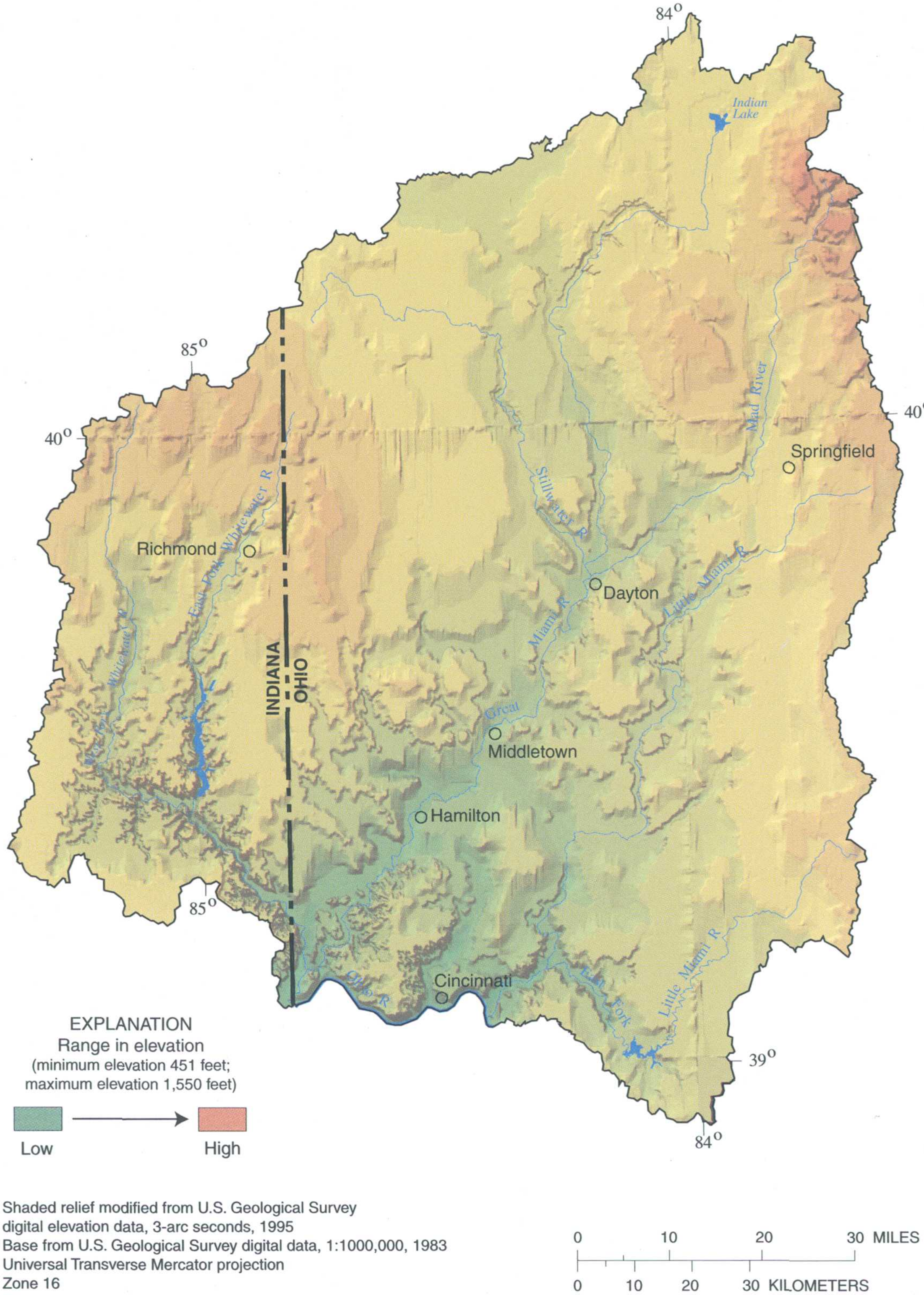


Figure 3. Mean annual atmospheric wet deposition of hydrogen ion and selected major constituents measured at National Atmospheric Deposition Program stations, 1993–97.



Shaded relief modified from U.S. Geological Survey digital elevation data, 3-arc seconds, 1995
Base from U.S. Geological Survey digital data, 1:1000,000, 1983
Universal Transverse Mercator projection
Zone 16

Figure 4. Physiographic relief in the Great and Little Miami River Basins, Ohio and Indiana.

This subunit is a former till plain where glacial deposits have been eroded from valley sides, resulting in a hilly topography and higher stream density. Stream channels in the Illinoian and Dissected Illinoian Till Plain typically flow over exposed Ordovician shale and limestone.

The Whitewater River Basin in Indiana is divided into the Tipton Till Plain and the Dearborn Upland (Malott, 1922). The flat to gently rolling topography of the Tipton Till Plain covers the northern one-third of the basin. This subunit is underlain by glacial till with a thickness of less than 50 ft near the southern boundary to greater than 400 ft in the northern part of the basin (Woodfield, 1994). The Tipton Till Plain consists of geomorphic features dominated by moraines and, to a lesser extent, kames (mounds of stratified drift deposited by glacial meltwater), ice channel fills (eskers), outwash plains, and valley trains. Bedrock is exposed at the southern margin where headwater tributaries have cut into the Tipton Till Plain. The broad southern transition boundary of the Tipton Till Plain is thin and reveals the bedrock relief of the Dearborn Upland. The southern boundary of the Wisconsinan glaciation extends to the lower one-third of the Whitewater River Basin into the Dearborn Upland subunit. The Dearborn Upland is a bedrock plateau with rugged relief covering the southern two-thirds of the Whitewater River Basin. The plateau is overlain by 15 to 50 ft of glacial till (Woodfield, 1994). Bedrock in the Dearborn Upland consists of Silurian dolomite and limestone and Ordovician shale and limestone.

Geology and Stratigraphy

Geology of the study area is dominated by Quaternary glacial deposits that overlie a thick sequence of Ordovician, Silurian, and Devonian sedimentary rocks (table 3). Geologic characteristics of the unconsolidated glacial deposits and underlying bedrock affect the physical characteristics of the land (topography, soil type, runoff, land use) and the quality of surface- and ground-water resources. The distribution of various types of geologic materials in the subsurface governs the transport and storage of ground water in aquifers; reactions between water, soil, and aquifer materials can influence the concentration of major ions, trace elements, radionuclides, and synthetic organic chemicals in ground water and surface water.

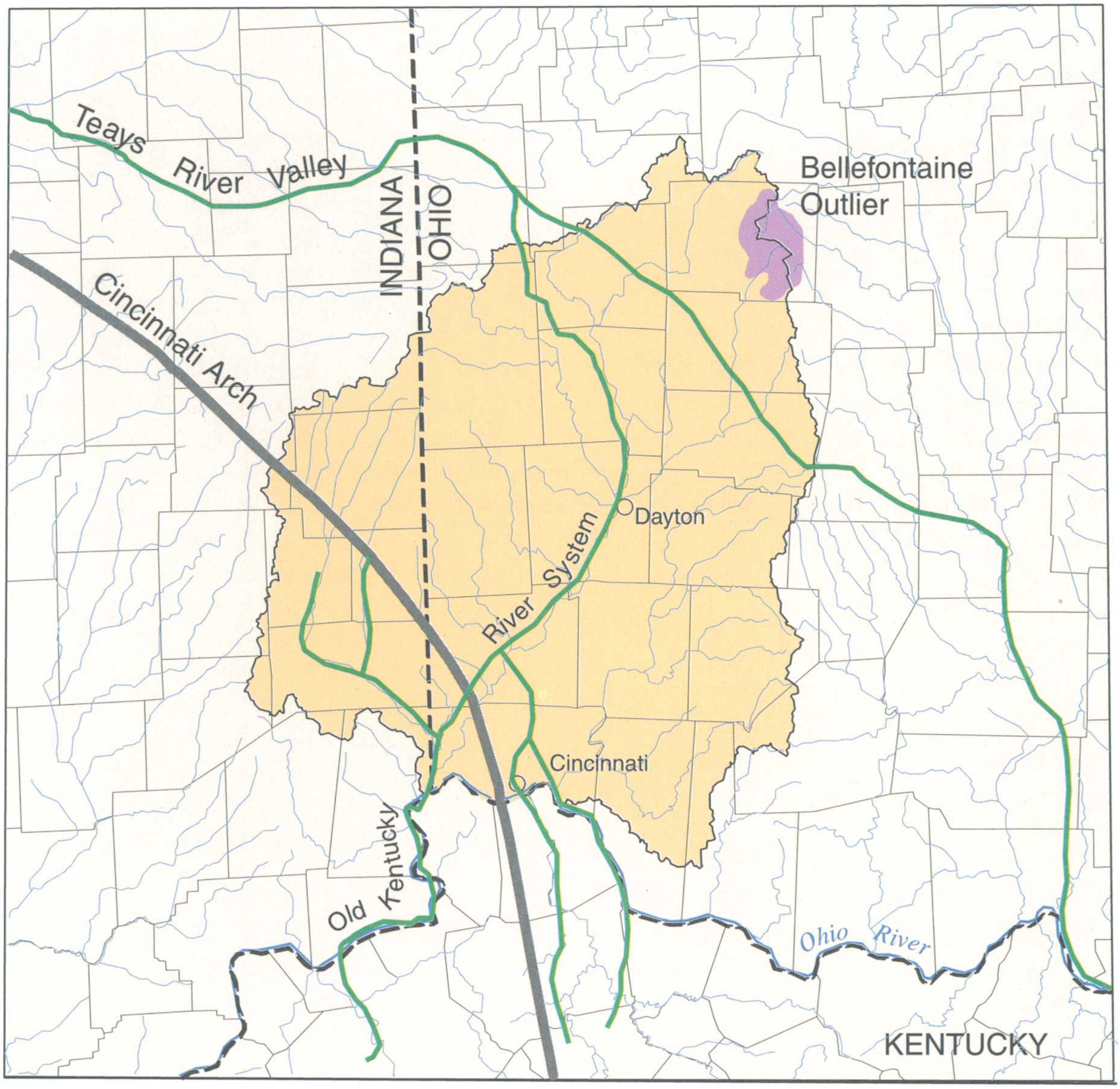
The Cincinnati Arch is the dominant geologic structure in the study area. The axis of the Cincinnati Arch is poorly defined and appears as a broad, low uplift that traverses southwestern Ohio in a north-south orientation before turning northwest, where it joins the Kankakee Arch in east-central Indiana (Casey, 1996) (fig. 5). Along the axis of the arch, bedrock is nearly horizontal but overall dips 5 to 10 ft/mi (feet per mile) towards the north-northwest. The crest of the structure is approximately 75 mi (miles) wide. During the Paleozoic Era, the arch was an area of emergent land in shallow seas, and its flanks were the sites of extensive sediment deposition. Near the end of the Paleozoic Era the shallow seas receded and a long episode of erosion occurred, forming a flat erosional surface that subsequently was dissected by streams. Because of this post-depositional erosion, older rocks are found in the center of the arch; younger rocks outcrop along the margins. The Bellefontaine Outlier (fig. 5), a prominence in the northeastern corner of the study area, contains the only outcrops of Middle and Upper Devonian rock in the study area (Swinford and Slucher, 1995). The origin of the Bellefontaine Outlier is controversial; Swinford and Slucher (1995) summarize the alternate hypotheses for the origin of this feature.

The most significant preglacial erosional feature in the study area is the Teays River Valley (fig. 5). The Teays River Valley is a series of buried valleys that represent the drainage network carved out of bedrock by the Teays River and its tributaries prior to the first Pleistocene glaciation. Headwater streams of the Teays River originated in the Piedmont of North Carolina and flowed westward across West Virginia, Ohio, Indiana, and Illinois, and ultimately into the Mississippi River Basin (Stout and others, 1943;

Table 3. Geologic chart showing selected formations and generalized hydrogeologic units in the Great and Little Miami River Basins, Ohio and Indiana

[Shaded areas represent unconformities caused by periods of non-deposition or erosion; geologic names and descriptions from Larsen, Ohio Department of Natural Resources, written commun., 1998; Casey, 1992; 1996; Schumacher, 1993; Indiana Department of Natural Resources, 1988; Shaver and others, 1986; Gray and others, 1985; Shaver, 1985. Nomenclature may vary from that of the U.S. Geological Survey]

System	Series or Group	Generalized geologic units: East-central Indiana	Generalized geologic units: Southwestern Ohio			Lithology: East-central Indiana	Lithology: Southwestern Ohio	Hydrologic unit
Quaternary	Holocene	Recent alluvial deposits				Unconsolidated gravel, sand, silt, and clay		Glacial aquifers and confining tills
	Pleistocene	Glacial alluvial deposits						
Devonian	Upper		Ohio Shale				Shale	Upper confining unit (where present)
	Middle							
			Columbus-Lucas Undifferentiated				Dolomite	Carbonate-bedrock aquifer
	Lower							
Silurian	Upper		Salina Group				Dolomite, shale	
	Lower	Salamonie Dolomite	Lockport Dolomite	Cedarville Dolomite	Peebles Dolomite	Dolomite, limestone; argillaceous in lower part to the south	Dolomite	
				Springfield Dolomite	Lilley Formation			
				Euphemia Dolomite	Bisher Formation			
			Sub-Lockport Undifferentiated	Massie Shale	Estill Shale		Dolomite, limestone, shale	
				Laurel Dolomite				
				Osgood Shale				
				Dayton Limestone				
		Brassfield Limestone		Brassfield Dolomite/Limestone		Dolomite/Limestone		
Ordovician	Cincinnatian	Maquoketa Group: Whitewater Formation	Undifferentiated Cincinnatian rocks			Shale, limestone	Shale, limestone	Upper weathered zone Minor aquifer
		Maquoketa Group: Dillsboro Formation						Basal confining unit
		Maquoketa Group: Kope Formation						
	Middle	Trenton Limestone				Limestone, dolomite		Oil and gas producer



EXPLANATION

Great and Little Miami River Basin

Bellefontaine Outlier

Teays River Valley and tributaries

Axis of geologic structural arch

Figure 5. Structural geology of the Great and Little Miami River Basins and surrounding area. (Modified from Goldthwait, 1991; Teller and Goldthwait, 1991; Gray, 1991; Melhorn and Kempton, 1991.)

Fullerton, 1986; Goldthwait, 1991). The Teays River entered Ohio near Portsmouth, where it flowed north then turned northwest, flowing across Clark, Champaign, Logan, Shelby, and Mercer Counties in the study area before continuing into Indiana and Illinois. The main-stem buried valley that marks the ancestral Teays River Valley is about 10 mi north of Springfield, Ohio, and is filled to depths exceeding 600 ft, with glacial sediments consisting primarily of silt and clay; despite the depth of the main-stem valley, it is not a major aquifer. In contrast, a tributary valley to the Teays River Valley that generally is followed by the present-day course of the Great Miami River (fig. 5) (the Old Kentucky River of Teller and Goldthwait [1991] or the Hamilton River of Stout and others [1943]) was deepened later and filled with glacial-outwash deposits consisting primarily of sand and gravel. The thickness of sand and gravel deposits in this buried-valley system approaches 300 ft. The Old Kentucky River (or the Hamilton River) Buried-Valley Aquifer System is the primary source of water to Dayton and other communities along the Miami Valley.

Consolidated deposits in the study area are mostly from the Ordovician and Silurian System (fig. 6). Because of extensive glacial deposits, outcrops of bedrock at land surface are uncommon. Most outcrops are found in the walls of stream valleys where glacial cover has eroded away or in quarries. As noted previously, the distribution and thickness of bedrock is controlled largely by the Cincinnati Arch and post-depositional erosion events. Of the latter, erosion that occurred along main-stem and tributary valleys of the Teays River Valley before, during, and after the Illinoian and Wisconsinan glaciations was most important in determining the current topography of the bedrock surface (Goldthwait, 1991; Lloyd and Lyke, 1995; Casey, 1996). Stratigraphic relations, lithology, and generalized hydrogeologic units of consolidated and unconsolidated deposits in the study area are shown in table 3.

Ordovician Rocks

The oldest rocks that crop out in the study area are from the Upper Ordovician System (fig. 6) and were derived from marine sediments deposited approximately 450 million years ago. These sediments formed thick beds of shale interbedded with thin beds of coarse, fossiliferous limestone. The thin limestone beds constitute approximately 20 percent of the sequence and are most common in the uppermost part of the Ordovician sequence (Gray, 1972). With the exception of weathered and fractured strata at or near land surface, the Ordovician bedrock is impermeable and forms the basal confining unit for the overlying carbonate-bedrock aquifer. The confining unit thickens toward the east as it dips into central and eastern Ohio; from west to east, the thickness of the basal confining unit ranges from approximately 800 to 1,100 ft (Casey, 1992, 1996). The shale confining unit prevents the upward migration of oil, natural gas, and associated brines from the underlying Middle Ordovician Trenton Limestone. In the southern half of the study area, erosion and glaciation have removed the overlying carbonate bedrock; in areas where glacial deposits are thin or absent, outcrops of Ordovician rocks are common.

Silurian Rocks

Silurian System bedrock subcrops in the northern half of study area (fig. 6) and consists mostly of thick beds of crystalline limestone and dolomite interbedded with thin layers of shale. In some areas, the limestones and dolomites are argillaceous (impure and mixed with mudstone). Variable depositional environments as well as post-depositional erosion and dissolution resulted in sequences of brecciated dolomite, shaley dolomite, fossiliferous limestone and dolomite, and karst (Bugliosi, 1990). Upper Silurian formations are absent in the Whitewater River Basin in Indiana and are restricted in southwestern Ohio to occurrences of Salina Group rocks in the northeastern part of the study area near the Bellefontaine Outlier (fig. 5).

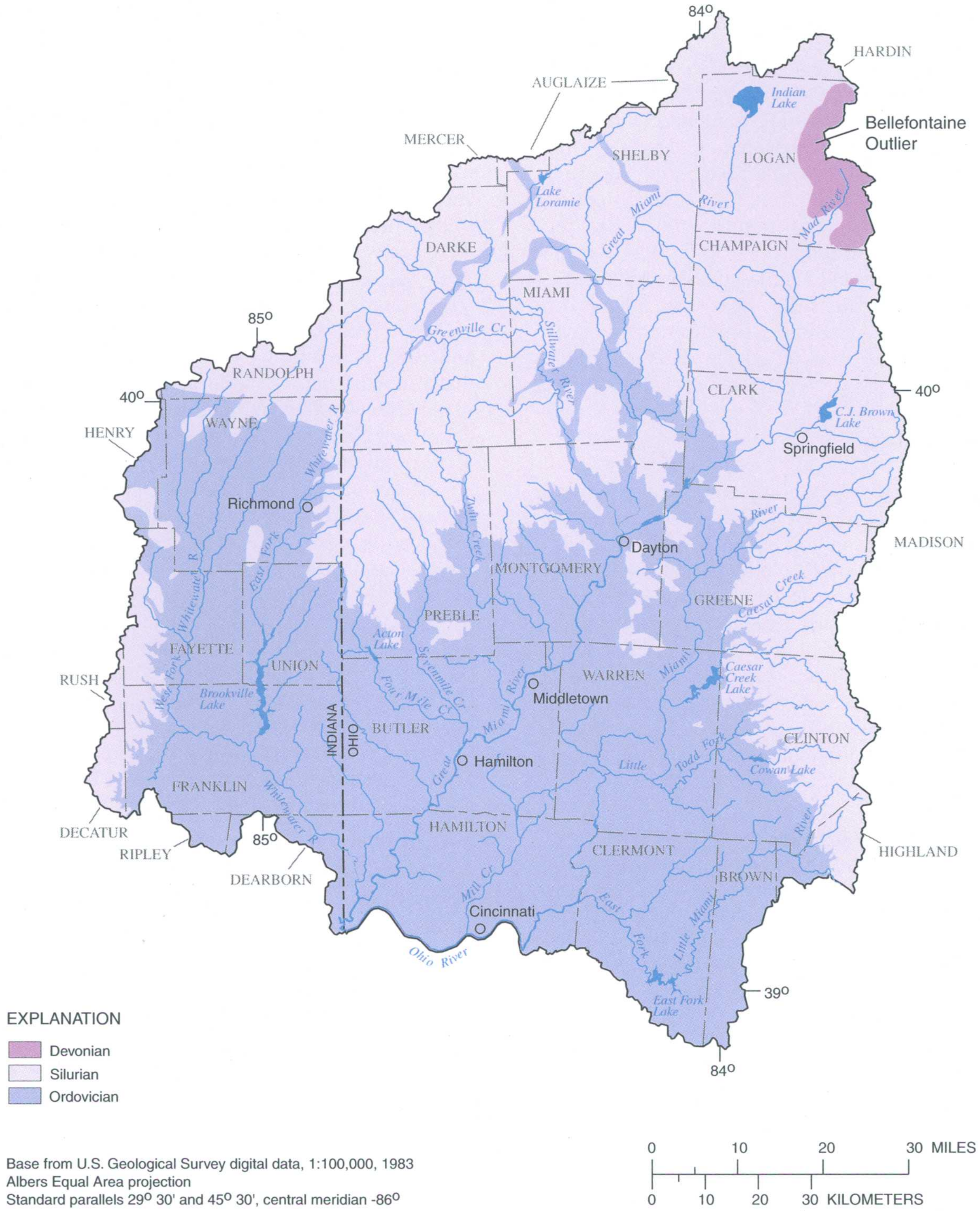


Figure 6. Generalized bedrock geology in the Great and Little Miami River Basins, Ohio and Indiana. (Modified from Casey, 1996.)

In most parts of the study area, thickness of Silurian bedrock is less than 100 ft; however, the Silurian sequence thickens in the northeastern part of the study area. In the vicinity of the Bellefontaine Outlier, total thickness of the Silurian rocks increases to several hundred feet (Swinford and Slucher, 1995). Two formations—the Cedarville Dolomite and Springfield Dolomite—form hard, resistant cliffs that yield scenic gorges and waterfalls in the Little Miami and Mad River Basins. The oldest Silurian formation is the Brassfield Limestone that unconformably overlies the Ordovician shale and is up to 30 ft thick. The lower part of the Brassfield is massively bedded and very pure. The Brassfield, along with other Silurian dolomites and limestones, is extensively quarried for production of building stone, Portland cement, road ballast and aggregate, and agricultural lime.

Devonian Rocks

Devonian System rocks subcrop only in the northeastern section of the study area in the Bellefontaine Outlier in Logan County, Ohio (fig. 6). Bedrock in this area includes Middle Devonian dolomite and Upper Devonian shale (table 3). The dolomite unit is 85 to 100 ft thick; the overlying shale has a total thickness exceeding 200 ft (Swinford and Slucher, 1995). In some areas, the Middle Devonian dolomite contains chert and is interbedded with shale. The Upper Devonian sequence is predominantly brownish-black shale with some thin layers of siltstone.

Quaternary Glacial Deposits

Unconsolidated glacial deposits from three episodes of Pleistocene glaciation are found in the study area. The oldest deposits are undifferentiated drift associated with pre-Illinoian glaciations that occurred more than 300,000 years ago; these deposits are exposed along the Ohio River near Cincinnati. Glacial drift deposited during the Illinoian glaciation (130,000 to 300,000 years ago) is confined mostly to the southeastern part of the study area, mainly in the Todd Fork and East Fork Little Miami River subbasins of the Little Miami River Basin. The remainder of the glaciated regions is covered with glacial sediments deposited during the most recent glaciation, the Wisconsinan, which occurred between 14,000 and 24,000 years ago (Hansen, 1997).

Several types of unconsolidated glacial sediment were deposited throughout the study area. These deposits can be subdivided into three general categories based on lithology: (1) till (sediment consisting of an unsorted mixture of clay, silt, sand, and gravel); (2) outwash (coarse-grained stratified sediment consisting of well-sorted sand and gravel); and (3) lacustrine deposits (fine-grained stratified sediment consisting of alternating well-sorted silt and clay layers) (fig. 7). Till was deposited by advancing glaciers or by melting stagnant ice. Coarse-grained stratified sediments were deposited by glacial meltwater and are termed "outwash deposits." When the ice sheets melted, large volumes of meltwater flowed through stream valleys carved out by previous erosional events and filled them with well-sorted sand and gravel. Such outwash deposits are found beneath most major stream valleys in the study area. Outwash deposits were deposited during Pleistocene glacial disintegration and were covered by recent alluvial deposits. Fine-grained stratified sediments consisting of layered silt and clay were deposited in lacustrine environments formed in basins or valleys dammed by glacial ice. The most extensive deposits of fine-grained lacustrine sediments are found in the vicinity of Indian Lake in the northeastern corner of the study area (fig. 7). Patches of Quaternary sediment in the southern part of the study area are composed of glacial and recently deposited alluvium with some exposed bedrock. Quaternary sediment is absent or sparse near the limit of glaciation and in the dissected area within the glaciated region (Soller, 1992).

Glacial deposits in most parts of the study area are relatively thin (less than 100 ft) but increase in thickness to as much as 400 ft to the north in Indiana. Till and outwash deposits several hundred feet thick fill buried valleys associated with the ancient Teays River. Clay and silt confining units and sand and gravel sediments are complexly distributed throughout the basin (Lloyd and Lyke, 1995).

Soils

Soil characteristics influence ground- and surface-water quality. Soils are classified by composition of parent material, native vegetation, texture, color, structure, depth, and arrangement

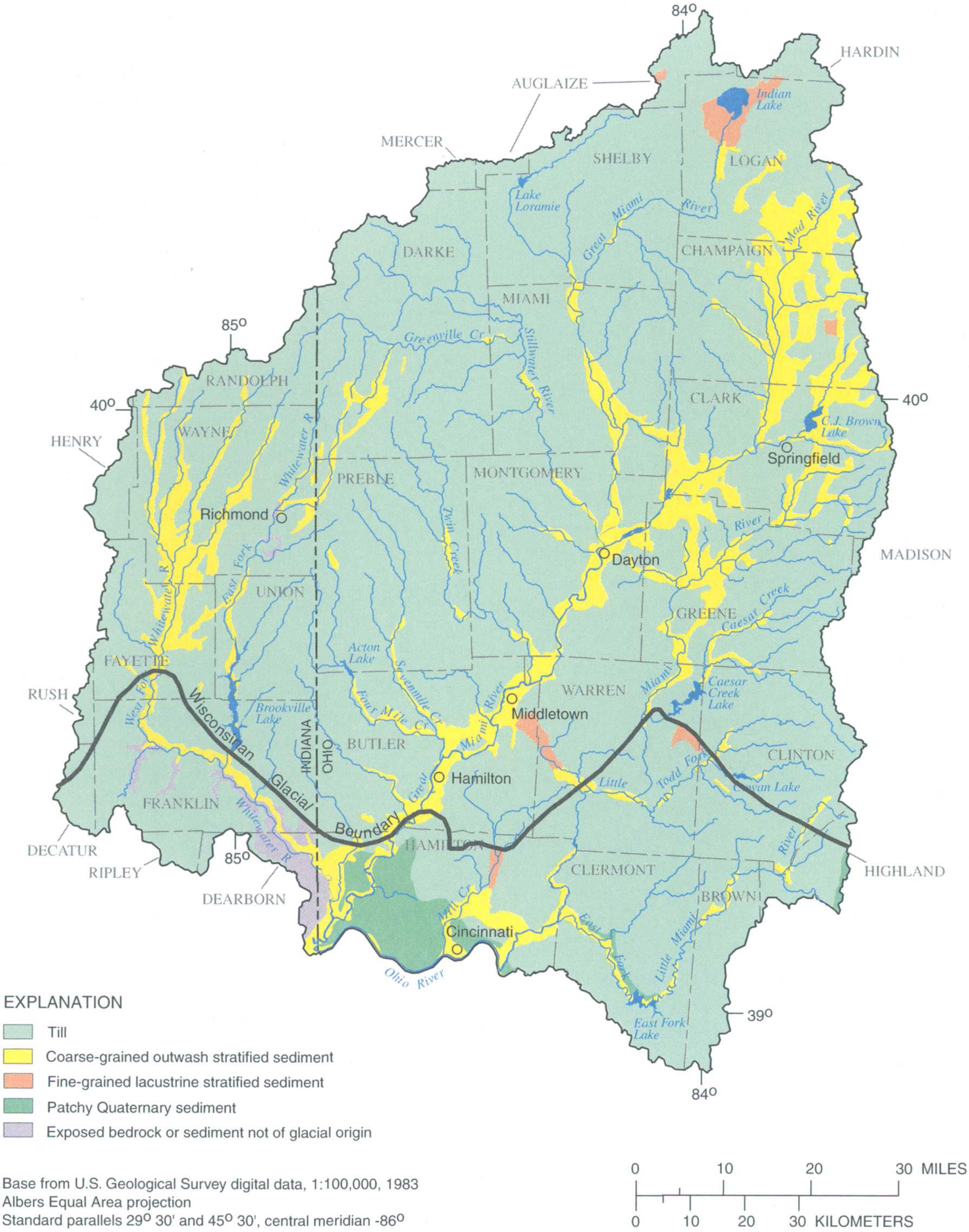


Figure 7. Generalized glacial geology in the Great and Little Miami River Basins, Ohio and Indiana. Exposed glacial deposits of Illinoian age are restricted to the southernmost part of the study area; the boundary marking the southernmost advance of the Illinoian ice sheets is south of the study area. (Data from Soller, 1993, 1998.)

and thickness of horizons (Ulrich, 1966). Physical properties of soils influence runoff, sedimentation, and infiltration rates. Chemical properties controlled by organic material, microorganisms, and gases available in soils influence dissolution, precipitation, adsorption, and oxidation-reduction reactions.

The 11 soil regions of the study area can be grouped into four types developed (1) from loess or glacial till (81 percent), (2) along flood plains (12 percent), (3) from bedrock (5 percent), and (4) from lake sediments (2 percent) (fig. 8). Soils developed from loess or glacial till are the most common and cover large, generally continuous areas throughout the study area. These soils mostly comprise Wisconsin-age loamy and clayey glacial till that often are overlain by thin to moderately thick loess. These soils typically have poor to moderate drainage, high base content, and high fertility. Soils developed along flood plains of major streams and tributaries include alluvial and outwash deposits. These soils generally are well drained and fertile and have high base contents. Till and outwash soils support intensive row-crop agriculture and livestock farming (Woods and others, 1998). Soils developed from bedrock are less common in the study area. These soils comprise discontinuous loess over weathered limestone and shale, mainly in the southernmost unglaciated parts of the study area, and loamy till over limestone bedrock, mainly in parts of Miami County adjacent to the Stillwater and Great Miami Rivers (fig. 8). These soils generally are well drained (Soil Conservation Service, 1982). Soils developed from lake sediments are less common in the study area and mainly are composed of silty and clayey lake deposits and are poorly drained. Areas with these types of soils typically are ditched or have tile drains installed to improve drainage.

The substratum soils of the study area are fertile and have a relatively high lime content because of the limestone, dolomite, and limy shale bedrock. In Ohio, soils in the central part of the study area are coarser grained than those to the north (Ohio Department of Natural Resources, 1996). Most of the soils have more than 3 percent organic matter in the upper 10 in. Soils to the south have lower organic contents than the rest of the study area. The southernmost boundary of the study area is characterized by older, more weathered, and less fertile soils derived from Illinoian and pre-Illinoian glacial deposits. These soils tend to be acidic and have a higher clay content and less organic matter than those in the rest of the study area. In Indiana, the northern two-thirds of the Whitewater River Basin is predominantly loamy and silty soils derived from loess and loamy Wisconsin-age glacial till (Indiana Department of Natural Resources, 1988). The southwestern part of the Whitewater River Basin is characterized by moderately thick to thin and discontinuous loess over weathered parent materials. Stream valleys throughout the study area are characterized by moderate to well-drained soils developed from fine to coarse-grained flood-plain deposits that overlie older alluvial or outwash sediments.

Hydrologic Setting

The hydrologic setting of the study area is described by characterizing surface- and ground-water flow and surface-water/ground-water interactions. Precipitation, runoff, evapotranspiration, and infiltration rates affect the transport and fate of chemicals and sediments introduced to surface- and ground-water systems. Dissolved solutes and microbiota can be transferred from surface-water bodies to aquifers under natural and induced hydraulic gradients. Streamwater chemistry may be influenced by the composition of ground water discharged into streams as base flow. Water quality within the basin is affected by the composition and volume of these inputs.

A water budget for the study area was prepared, assuming steady state conditions and using data averaged over the 30-year period 1961–90 for three major natural components: precipitation, streamflow, and evapotranspiration (table 4). These data are expressed in units of acre-feet ($x10^6$) or inches of water spread evenly over the surface of the study area. The water budget shows that a little more than two-thirds of the 39 in. of precipitation that falls on the land surface is returned to the atmosphere by evapotranspiration. The remaining third flows into the Ohio River as streamflow.

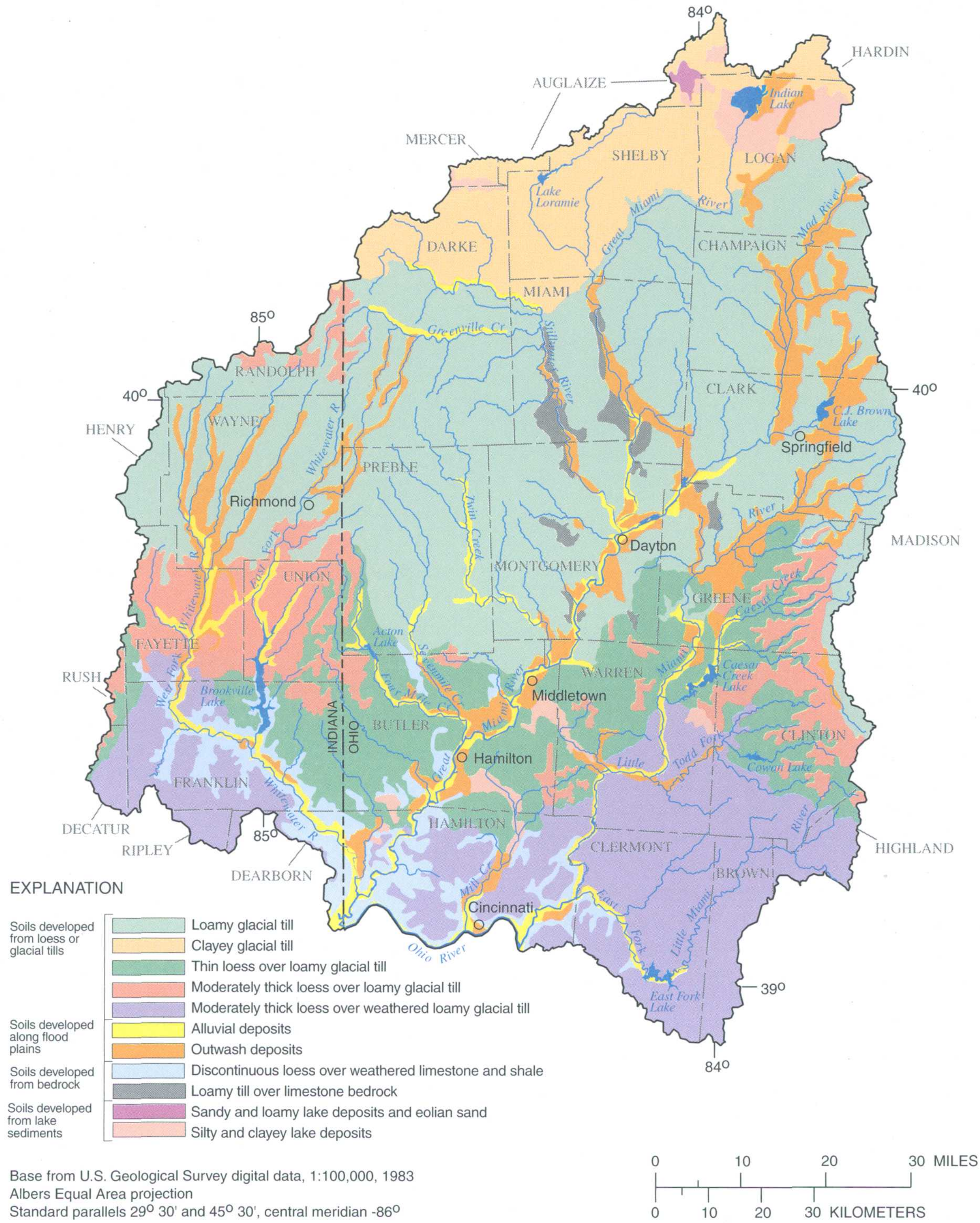


Figure 8. Major soil regions in the Great and Little Miami River Basins, Ohio and Indiana. (Data from Franzmeier and others, 1989; William Hosteter, Indiana Natural Resources Conservation Service, written commun., 1998; John Gerken, Ohio Natural Resources Conservation Service, written commun., 1998.)

Table 4. Average water budget for the Great and Little Miami River Basins, Ohio and Indiana, 1961–90

[Inflow and outflow totals differ slightly because of computations from independent data sets. Data from Midwestern Climate Center, 1997; Shindel and others, 1997; Stewart and others, 1997; Traci Hasse, Midwestern Climate Center, written commun., 1998]

Basin inflow (average annual values)		Basin outflow (average annual values)	
Acre-feet ($x10^6$)	Inches	Acre-feet ($x10^6$)	Inches
Precipitation		Runoff from streamflow	
15.4	39.1	4.7	12.1
		Evapotranspiration	
		10.4	26.5
Total		Total	
15.4	39.1	15.1	38.6

In contrast with other large watersheds, the water budget for the study area is simple. Except for water pumped from the Ohio River to supply the City of Cincinnati and subsequently discharged back to the Ohio River as wastewater, no major intrabasin water transfers (artificial or natural) occur across the study-area boundaries. Within the study area, minor transfers across subbasin boundaries occur; these typically involve the transfer of ground water pumped from one basin to a water user in an adjacent basin. For example, ground water pumped from the Great Miami buried-valley aquifer near Fairfield, Ohio (fig. 1), is pumped to industrial users that discharge their wastewater into the Mill Creek Basin in Cincinnati. Such transfers occur on a regular basis and do not affect the water-budget data given in table 4. Similarly, water-use data are not included in the basin-wide water budget; they represent a "closed-loop system" within the study area in which water pumped from a stream or aquifer is later returned to nearby streams as wastewater. Significant changes in ground-water storage are unlikely over the period 1961–90, and the net flux of ground water into and out of major aquifers in the study area is assumed to be zero.

Streams

Streams in the study area are tributary to the Ohio River, which represents the southern boundary of the study area (fig. 1). The Great Miami River drains the largest area in the study area (5,330 mi^2) and includes the Upper Great Miami River Basin (2,480 mi^2), the Lower Great Miami River Basin (1,390 mi^2), and the Whitewater River Basin (1,460 mi^2) (Seaber and others, 1987). The Little Miami River drains a 1,757-mi^2 area (Cross, 1967). The remainder of the study area consists of several small basins whose streams are direct tributaries of the Ohio River in the vicinity of Cincinnati. The largest of these is Mill Creek, which drains an area of 164 mi^2 (Cross, 1967). Headwater streams originate in northern and eastern parts of the study area in agricultural areas consisting of rolling hills and steep-walled but shallow valleys. Large streams usually are underlain by buried bedrock valleys filled with sand and gravel deposited by glacial meltwaters. Stream drainage is generally south-southwest into the Ohio River and ultimately to the Mississippi River.

The subsequent sections include descriptions of major tributaries within each basin.

Great Miami River Basin

Indian Lake in Logan County, Ohio, marks the headwaters of the Great Miami River (fig. 1). The Great Miami River and its tributaries drain three large cities in the study area—Dayton, Hamilton, and Springfield, Ohio. Significant tributaries in the Upper Great Miami River Basin are the Stillwater River (676 mi^2), designated an Ohio State Scenic River, and the Mad River (657 mi^2) (Cross, 1967). The confluence of the Stillwater and Mad Rivers with the Great Miami River is near downtown Dayton, Ohio. Before the construction of flood-control dams in the Dayton area, parts of the Miami Valley downstream from the confluence were particularly prone to flooding. Major tributaries in the Lower Great Miami Basin include Twin Creek (316 mi^2) and Four Mile Creek (315 mi^2). The Great Miami River joins the Ohio River west of Cincinnati.

The headwaters of the Whitewater River are split between the West Fork (842 mi^2) and East Fork (382 mi^2) Whitewater Rivers. The West Fork and East Fork drain the largest cities in the Whitewater River Basin—Connersville and Richmond, Ind., respectively. The two tributaries join near Brookville in Franklin County, Ind. The confluence of the Whitewater and Great Miami Rivers is in Hamilton County, Ohio.

Little Miami River Basin

The headwaters of the Little Miami River are in the southeastern part of Clark County, Ohio (fig. 1). Major tributaries of the Little Miami River are Caesar Creek (242 mi^2), Todd Fork (261 mi^2), and East Fork Little Miami River (499 mi^2) (Cross, 1967). The headwaters of these tributaries are along the far eastern part of the study area; the confluence of the Little Miami River with the Ohio River is just east of Cincinnati. The Little Miami River is a designated State of Ohio and National Scenic River because of its high-quality aquatic communities, a largely intact riparian corridor, scenic views, and historic sites.

Mill Creek Basin

Mill Creek (fig. 1) drains central Hamilton County, including the industrial sector of Cincinnati, the largest city in the study area. The headwaters to Mill Creek are east of the city of Hamilton, Ohio. The creek joins the Ohio River in Cincinnati. The Mill Creek Basin became one of the major industrial centers of the Cincinnati area because of its flat topography and its proximity to the Ohio River, a major route of transportation (Spieker and Durrell, 1961).

Streamflow Characteristics

Variations in streamflow were determined by use of discharge data collected at USGS streamflow-gaging stations. The USGS in 1999 operated 14 streamflow-gaging stations in the study area (fig. 9). Seven of these streamflow-gaging stations are in the Great Miami River Basin (including the Whitewater River Basin in Indiana), one is in the Mill Creek Basin, and six are in the Little Miami River Basin. An additional 21 streamflow-gaging stations are operated on a cooperative basis with the Miami Conservancy District (MCD) as part of MCD's flood-control program in the Great Miami River Basin. The flow patterns described in this report are based on the daily mean streamflow data collected by the USGS and MCD; streamflow data are stored in the USGS National Water Information System (NWIS) data base.

The daily mean streamflow, the 7-day low-flow rates, and flow-duration curves were determined for select sites and are discussed below. The 7-day low-flow rate of a stream is the 7-day minimum discharge for a specified recurrence interval. Flow-duration curves also are used to describe the flow characteristics of a stream throughout the range of measured discharge values. A flow-duration curve is a cumulative frequency curve that shows the percentage of time that a specified discharge value is equaled or exceeded during a given period (Searcy, 1959; Johnson and Metzker, 1981). The daily mean streamflow characteristics at selected gages with data collected over the 30-year period 1968–97 also are presented in a flow-duration table (table 5). The Great Miami River at Hamilton, Ohio, has a median flow rate of 2,030 ft^3/s (cubic feet per second); the Little Miami River at Milford, Ohio, has a median flow rate of 632 ft^3/s; the Whitewater River at Brookville, Ind., has a median flow rate of 772 ft^3/s.

Streamflow is regulated by reservoirs, dams, or intrabasin transfers in some parts of the study area. Dams associated with large reservoirs were constructed on the Mad, Whitewater, and Little Miami River Basins in the 1960's and 1970's, partly for flood control and partly for recreation and supply purposes. In addition, there are five "dry" dams and associated retarding basins that were constructed for the sole purpose of flood control in the Great Miami River Valley; these structures do not regulate streamflow, except during floods. There are eight low dams along the main stem of the Great Miami River, starting at Dayton. The low dams were constructed to provide pooled areas for recreation or to provide water to power plants for cooling or steam generation. Recently, low dams on other streams, including the Little Miami River, have been removed in an effort to restore streamflow and instream habitat to more natural conditions (Robert Gable, Ohio Department of Natural Resources, oral commun., 1998).

Figure 9. Location of streamflow-gaging stations in the Great and Little Miami River Basins, Ohio and Indiana.

Table 5. Summary of daily mean streamflow characteristics at selected streamflow-gaging stations in the Great and Little Miami River Basins, Ohio and Indiana, 1968–97 water years

[mi^2, square miles; %, percent; ft^3/sec, cubic feet per second]

Station	Drainage area, (mi^2)	Percentage of time that daily mean streamflow was greater than or equal to value shown, in cubic feet per second								
		95%	90%	75%	50%	25%	10%	5%	1%	90%[a] [$ft^3/s/mi^2$]
Massies Creek at Wilberforce, Ohio 03241500	63.2	4.42	5.89	13.9	33.9	74.9	161.8	250	610	0.09
Little Miami River at Oldtown, Ohio 03240000	129	16.2	20.7	37.4	74.9	147	281	429	1,010	.16
Little Miami River at Milford, Ohio 03245500	1,203	145	182	301	632	1,480	3,520	5,240	11,400	.15
East Fork Little Miami River at Williamsburg, Ohio 03246500[b]	237	1.50	3.67	20.9	64.2	220	707	1,580	3,850	.02
Mill Creek at Carthage, Ohio 03259000	115	10.8	13.4	22.1	46.9	117	325	576	1,250	.11
Mad River near Dayton, Ohio 03270000	635	226	257	339	499	785	1,300	1,830	3,600	.40
Stillwater River at Englewood, Ohio 03266000	650	40.2	55.0	102	241	565	1,600	3,150	5,600	.08
Great Miami River at Troy, Ohio 03262700	926	65.0	82.2	145	349	859	2,350	3,910	8,110	.09
Great Miami River at Dayton, Ohio 03270500	2,511	307	389	646	1,306	2,650	5,950	9,970	18,600	.15
Great Miami River at Hamilton, Ohio 03274000	3,630	517	645	1,020	2,030	4,080	8,620	13,600	24,500	.18
Whitewater River at Alpine, Indiana 03275000	529	95.5	115	175	331	635	1,280	2,150	5,500	.22
East Fork Whitewater River at Abington, Indiana 03275600	200	27.6	34.5	54.0	117	232	466	770	2,200	.17
Whitewater River at Brookville, Indiana 03276500	1,224	178	227	394	772	1,590	3,260	4,770	11,700	.18

[a]Indicator of base flow.

[b]Period of record 1968 to 1974.

Intrabasin transfers of ground water also affect streamflow in a few subbasins; the approximately 17 Mgal/d (million gallons per day) of ground water pumped from the Great Miami buried-valley aquifer to industrial users in the Mill Creek Basin in 1998 accounted for nearly 23 percent of the median long-term streamflow (46.9 ft^3/s; table 5) recorded for Mill Creek at Carthage, Ohio (streamflow-gaging station 03259000, fig. 9).

Five-year averages were calculated from daily mean discharges of the Great Miami River, the Little Miami River, and the Whitewater River (fig. 10). The data show an increase in streamflow for the Great Miami River and Whitewater River since 1966; little change is observed in the 5-year averages for the Little Miami River. The sharp decrease in discharge after the 1961–65 interval probably was caused by drought conditions in Ohio and Indiana. A trend analysis (Mann-Kendall trend test) was performed on the 7-day low-flow data for the Little Miami River at Milford, Ohio, to determine whether there was a statistically significant increase in discharges. The test indicated a statistically significant increase in the 7-day low flow for the Little Miami River (fig. 11) has occurred over the period analyzed (1927–97). This trend has been attributed to increases in the discharge of treated wastewater in the Little Miami River that have accompanied rapid urban development in Greene and Warren Counties (Buchberger and others, 1997).

The 90-percent low-flow data were used to calculate base flow, the component of streamflow that is contributed from ground water, in streams throughout the study area (Todd, 1980). The 90-percent low-flow rate of a stream is the streamflow value that is exceeded 90 percent of the time. The highest unit base-flow values are observed at streamflow-gaging stations on the Mad River in Ohio and the Whitewater River at Alpine, Ind. (table 5). The drainage basins for these streams consist mainly of glacial interlobate areas that have extensive glacial-outwash deposits. In the Mad River Basin, these deposits form high-yielding aquifers that discharge large amounts of ground water into area streams (Koltun, 1995). In contrast, streams draining the Till or Drift Plains areas of the study area, such as the Stillwater River or East Fork of the Little Miami River, have unit base-flow values that are much lower than those observed in the Mad River. These differences are related to soil type, thickness and lithology of glacial sediments and bedrock, and local topography. Flow-duration curves for the Mad River, Stillwater River, and East Fork Little Miami River illustrate these differences for sites representing three different hydrogeomorphic settings in the study area (fig. 12). The flow-duration curve for the Mad River has a flatter slope than the other two rivers because of the large amount of ground-water discharge to the Mad River; the flow-duration curve for the Stillwater River, which drains a Till Plains setting, has a moderate slope; the curve for the East Fork Little Miami River Basin has the steepest slope of the three rivers. The East Fork Little Miami River drainage basin is underlain mostly by impermeable Ordovician shale, has poorly drained soils, and has a hilly terrain that is conducive to high runoff rates. As a result, the flow-duration curve for the East Fork Little Miami River declines sharply around 70 percent, and its watershed has the lowest unit base-flow value in the study area (0.02 $ft^3/s/mi^2$ [cubic feet per second per square mile]; table 5).

Mean monthly discharge at several sites throughout the study area show similar seasonal variations in streamflow, with highest flows observed during late winter and spring and lowest flows observed during summer and early fall (fig. 13). Periods of highest monthly streamflow do not correspond exactly with periods of highest monthly precipitation. The highest monthly precipitation typically occurs during spring and early summer (fig. 2). As a result of higher evapotranspiration and greater water use, however, streamflow is lower in summer than in spring, even though the amount of rainfall is comparable.

Floods and Droughts

Floods and droughts can adversely affect water quality. During floods, large quantities of water and sediments are flushed into streams,

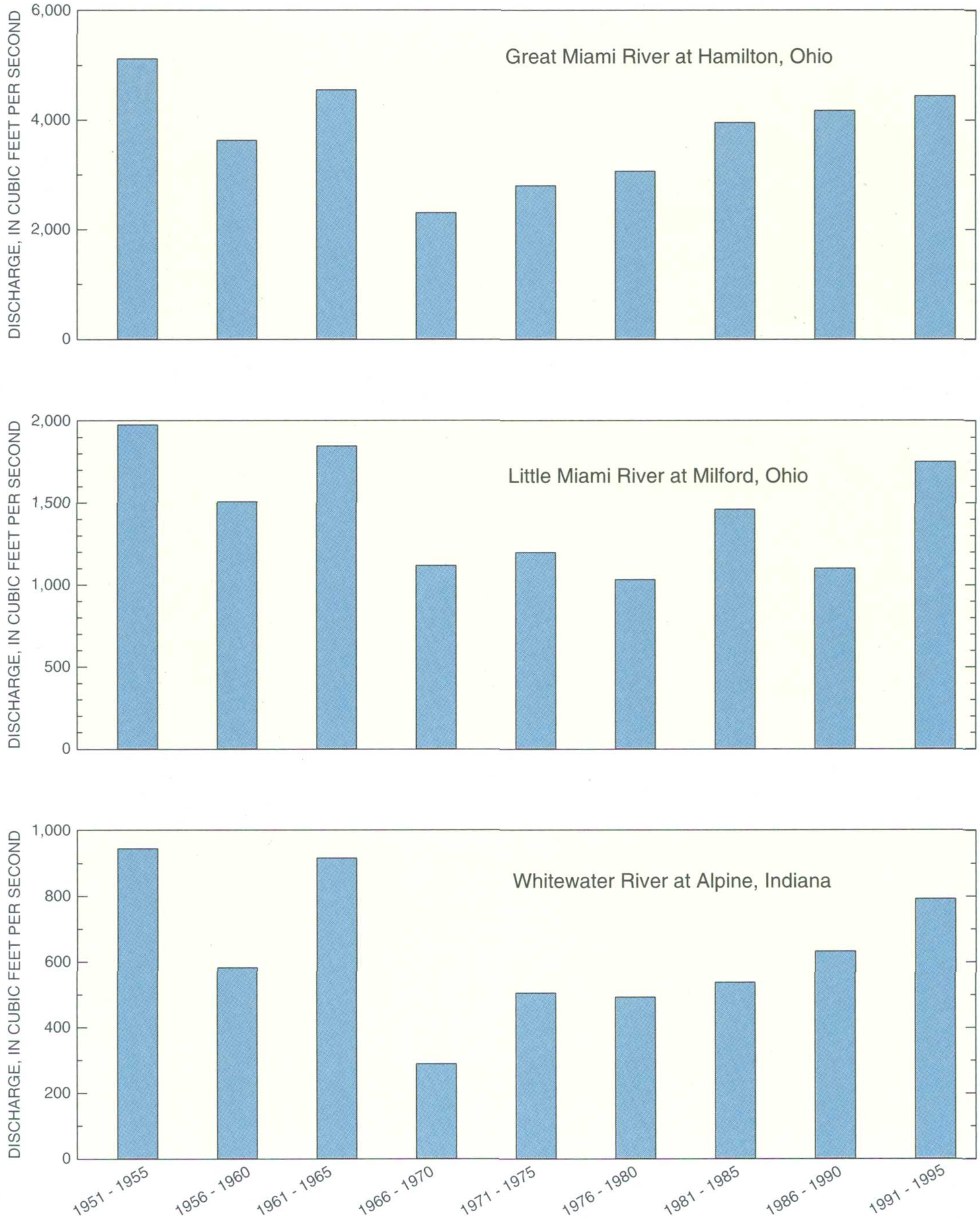


Figure 10. Mean daily discharge by 5-year intervals for the Great Miami River at Hamilton, Ohio; Little Miami River at Milford, Ohio; and Whitewater River at Alpine, Indiana.

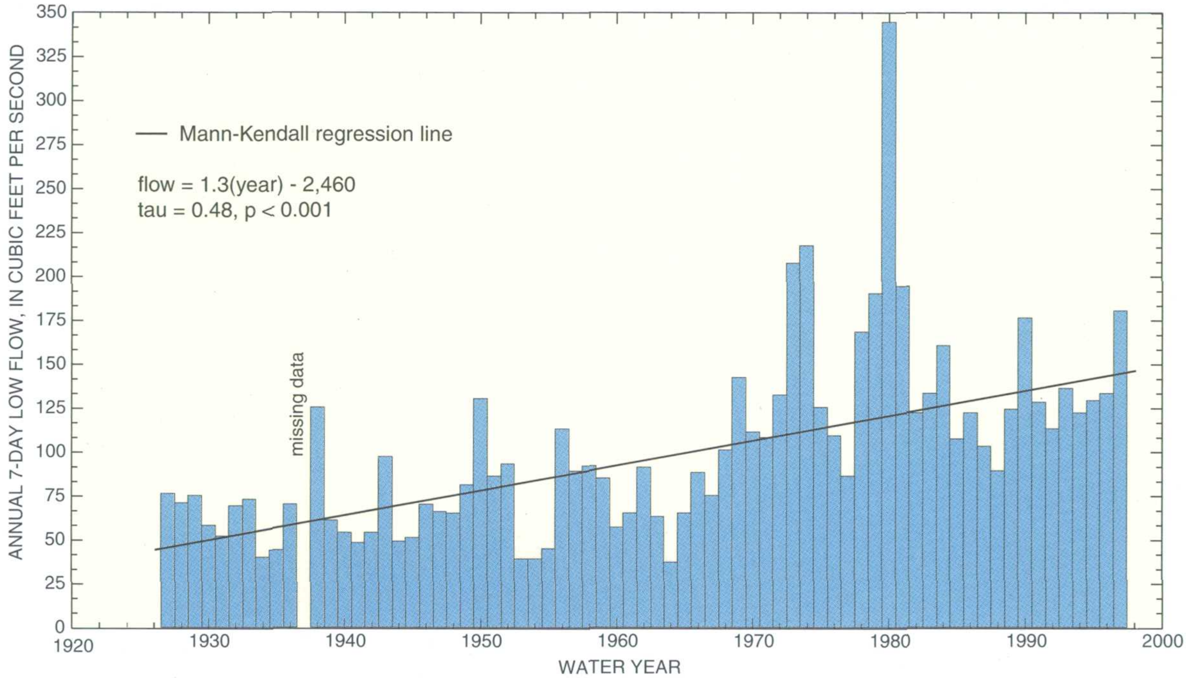


Figure 11. Annual 7-day low flow for the Little Miami River at Milford, Ohio.

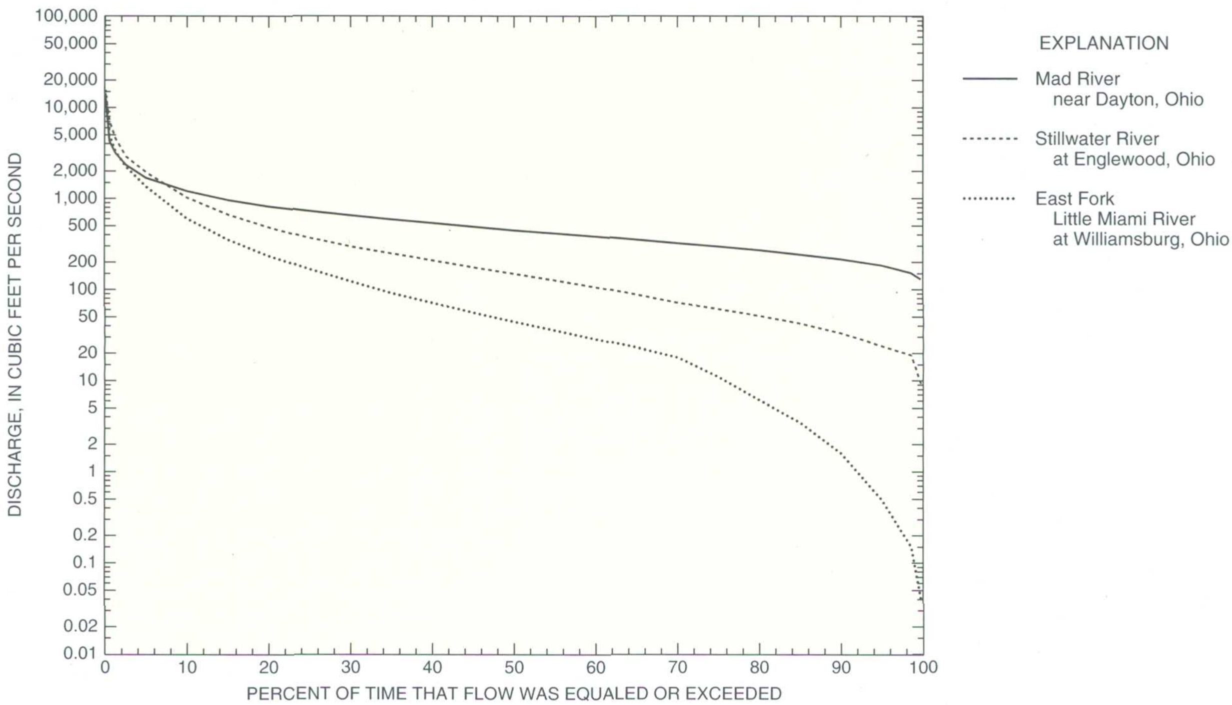


Figure 12. Flow-duration curves for three sites representing different hydrogeomorphic regions in the Great and Little Miami River Basins, Ohio and Indiana.

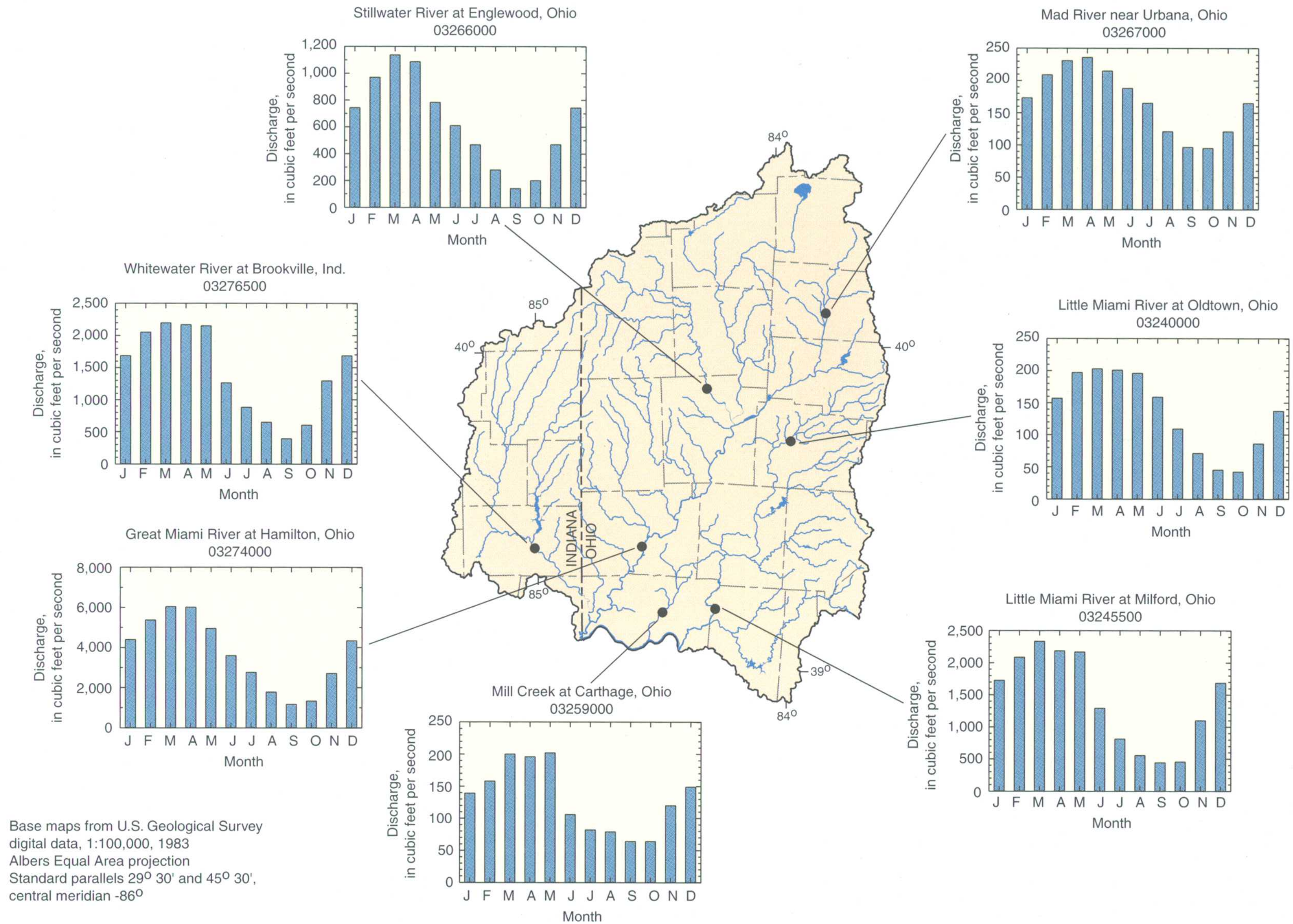


Figure 13. Mean monthly discharge at selected U.S. Geological Survey streamflow-gaging stations in the Great and Little Miami River Basins, Ohio and Indiana, 1968–97.

lakes, and reservoirs, disrupting sensitive habitats. Although often diluted by large volumes of water, contaminants in water or sediment rapidly are transported downstream. Floods also are beneficial; they provide nutrients and soils to flood plains, recharge ground water to unconsolidated and bedrock aquifers, and form and shape the stream channel. During droughts, ground-water levels may decline, decreasing the amount of base flow in streams and the amount of water available for supply and wildlife. Reduced streamflow can cause the percentage of treated wastewater or other contaminants in the stream to increase. Because of reduced streamflow, these contaminants may not be diluted. Major floods and droughts recorded in the study area are listed in table 6.

Floods can be local or regional and vary in length from a few hours to several days. Widespread flooding results from excessive frontal-system precipitation, often in combination with snowmelt in late winter. Local flooding is caused by precipitation from convection storms, mainly in spring and summer. The historic flood of 1913 was the largest and deadliest on record in Ohio and Indiana, with the greatest loss of lives and property in the Great Miami River Valley. From March 23 to March 27, 9 to 11 in. of rain fell on ground already saturated with previous rainfall and snowmelt; nearly 4 trillion gallons of water flowed through the Great Miami River Valley during the flood (Becker and Nolan, 1988). Although communities throughout the study area were affected by flood waters, the Dayton area was particularly hard hit because it is at the confluence of four large streams—Wolf Creek, the Stillwater River, the Mad River, and the Great Miami River. In response to the devastation wrought by the 1913 flood, a series of flood-retention dams and levees were constructed on the Great Miami River and its tributaries by the Miami Conservancy District. The flood-control project was designed to contain a flood 40-percent larger than the 1913 flood. The design was shown to be effective during the 1959 flood—the largest since the 1913 flood—when the Great Miami River channel near Dayton only filled to 60-percent capacity and none of the five retarding basins exceeded a storage capacity of 32 percent (Becker and Nolan, 1988; Paulson and others, 1991).

Droughts are caused by weather patterns that divert storms or prevent moisture from entering an area. Atmospheric circulation patterns that cause droughts are influenced by sea and land-surface-temperature anomalies originating outside the study area. Long-duration droughts in Indiana and Ohio can be attributed to two causes. First, as the Bermuda High forms over the Gulf of Mexico or the Atlantic Ocean in spring and summer, it strengthens and moves northwestward over the southeastern states. The hot, dry air transported with the high diverts cyclonic storms and prevents moisture from reaching the study area. Second, in winter, persistent northwesterly winds in the upper atmosphere can prevent moisture in the Gulf from entering the area (Paulson and others, 1991). Droughts generally begin and end subtly and are measured in months and years. Surface runoff, soil moisture, stream discharge, and ground water are affected by drought conditions.

Reservoirs

The study area contains many manmade reservoirs that are used for flood control, water supply, and recreation. The effects of natural and human influences on water quality in reservoirs depend on land use in the surrounding areas, use of the water bodies, and management of wastes and other by-products of human activities. The natural processes of eutrophication and sedimentation can affect reservoir water quality. Recreational activities, agricultural practices, and urban areas also affect reservoir water quality.

The two largest reservoirs in the study area are Indian Lake in Ohio (5,800 acres) and Brookville Lake in Indiana (5,280 acres) (table 7). Indian Lake, originally a cluster of small natural lakes formed by Pleistocene glacial activity, is near the headwaters of the Great Miami River. Four tributaries contribute to the lake—South Fork and North Fork Great Miami River, Black Hawk Creek, and Van Horn Creek. Indian Lake (formerly called Lewiston Reservoir) was constructed in 1860 as a water supply for the Miami and Erie Canal system (Ohio Department of Natural Resources, written commun., 1998). In 1898, as use of the canal system declined, the lake was opened to the public for recreational use.

Table 6. Chronology of major and other noteworthy floods and droughts in Ohio and Indiana, 1773 to 1997[1]

Floods/ droughts	Date	Area affected	Recurrence interval (years)	Remarks
		Ohio		
Flood	1773	Great Miami River	Unknown	Largest of record at several sites in Great Miami River Basin before flood of March 1913.[2]
Flood	March 1907	Great Miami River	10 to >100	Caused by intense rain on previously saturated ground.
Flood	March to April 1913	Statewide	50 to >100	Largest of record in Ohio. Multistate, caused by intense rain. Deaths, at least 467; damage, $143 million. Most deaths and property damage in Great Miami River Basin.
Drought	1930 to 1936	Statewide	20 to 70	Regional, with serious water shortages; loss of gross farm income estimated at $58 million during 1930.
Flood	January 1937	Southern part of State	2 to 5	Considered first major test of flood-control system built in the Great Miami River Basin after the flood of 1913. Retarding basins on Great Miami River and its tributaries filled 10 to 15 percent with no serious flooding reported in basin.
Drought	1939 to 1946	Statewide	15 to 60	Water shortages.
Drought	1952 to 1957	Statewide	10 to 60	Regional; more severe in southwestern Ohio than drought of 1930–36.
Flood	January 1959	Wide band from southwestern to northeastern Ohio	2 to >100	Intense rain on frozen, snow-covered ground. Deaths, 16; damage, $101 million.
Drought	1959 to 1968	Statewide	10 to 60	Most severe in east-central and northwestern Ohio.
Flood	March 1963	Scattered areas in southern part of State	10 to >100	Intense rain on frozen, snow-covered ground. Deaths, 2; damage, $28 million.
Flood	March 4 to 12, 1964	Southern part of State	2 to 100	Intense rain on saturated ground. Deaths, 8; damage, $30 million.
Drought	1975 to 1977	Southwestern part of State	5 to 15	Mild; interrupted periods of greater-than-average streamflow (1968–87).
Drought	1988	Statewide	Unknown	Short but severe. Rapid declines in streamflow, ground-water levels, and reservoir levels. Mandatory water-use restrictions instituted in many municipalities.
Flood	May 1989	Wide band from southwestern to northeastern part of State	15 to 25	Several lives lost when temporary bridge spanning Great Miami River near Miamitown, Ohio (Hamilton County), collapsed during high-flow conditions; estimated damage statewide, $20 million.
Flood	June 1990	Southern and eastern part of State	25 to >100	Localized flooding caused by intense thunderstorms. Deaths, 26; damage, $10 million.
Drought	1991 to mid-1992	Statewide	Unknown	For Ohio, 1991 ranks as eighth-driest year of 109 years of record. Short but moderately severe drought ended by above-normal rainfall in July 1992.

Table 6. Chronology of major and other noteworthy floods and droughts in Ohio and Indiana, 1773 to 1997[1]—Continued

Floods/ droughts	Date	Area affected	Recurrence interval (years)	Remarks
		Ohio—Continued		
Flood	July 1992	Statewide	Unknown	Logan and Shelby Counties in northern part of Great Miami River Basin among hardest hit counties. Deaths, 2.
Flood	May to June 1996	Statewide	Unknown	1996, one of wettest years on record; Butler and Clermont Counties among 14 Ohio counties designated as Federal Disaster Areas.
Flood	March 1997	Ohio River corridor from West Virginia to Cincinnati	<2 to >100	Worst flooding on Ohio River in 30 years. Deaths, 5; property damage; $180 million. Great and Little Miami River Basins only minimally affected.
		Indiana		
Flood	March 1913	Statewide	25 to >100	Worst in Indiana history. Multistate flood. Deaths, at least 90; damage, $15 million.
Drought	March 1930 to August 1931	Statewide	10 to 20	Began decade of low-flow conditions. Streamflow generally greater than 7-day, 10-year value in central and northern Indiana.
Drought	June 1933 to September 1936	Statewide	25 to 60	Streamflow less than 7-day, 10-year value in central and northern Indiana.
Flood	January to February 1937	Whitewater River Basin	10 to >100	Caused by widespread rainfall.
Drought	May 1939 to January 1942	Statewide	20 to 60	Central Indiana severely affected. Most streams had flow less than 7-day, 10-year value.
Drought	April 1952 to March 1957	Statewide	10 to 60	Streamflow less than 7-day, 10-year value.
Flood	January to February 1959	Whitewater River Basin	5 to >50	Caused by runoff from rainfall on frozen ground during two storms. Ice jams on larger rivers. Deaths, 3.
Drought	April 1962 to November 1966	Statewide	20 to 60	Streamflow less than 7-day, 10-year value. Floods occurred in 1963 and 1964 in central and southern Indiana.
Flood	March 1963	Whitewater River Basin	5 to >50	Intense rains falling on deeply frozen ground covered by snow. Deaths, 2; widespread damage.
Flood	June to August 1979	Whitewater River Basin	5 to >100	Three storms in central and southern Indiana. July storms were remnants of hurricanes. Damage, $50 million.
Drought	December 1986 to December 1988	Statewide	Unknown	Nationwide attention. Affecting agriculture, water supply, and electric-power generation.

[1]Data from Morgan, 1951; Paulson and others, 1991; Shindel, 1991; Cashell, 1989, 1990, 1991, 1992, 1996; Jackson and Vivian, 1997, and G.F. Koltun, U.S. Geological Survey, written commun., 1998.

[2]Citing historical data, Becker and Nolan (1988) report that prior to the great flood of 1913, flooding occurred in the Great Miami River Basin during the years 1805, 1814, 1828, 1832, 1847, 1866, 1882, 1884, 1893, 1897, 1898, 1904, 1906, 1907, 1908, 1909, 1910, and 1911.

Table 7. Reservoirs and flood-control structures in the Great and Little Miami River Basins, Ohio and Indiana, with a normal capacity of at least 5,000 acre-feet or a maximum capacity of at least 25,000 acre-feet

[Normal capacity equals total volume at normal retention level; maximum capacity equals total volume at maximum attainable water-surface elevation; mi^2, square mile; C, flood control; R, recreation; S, water supply. Data from Ruddy and Hitt, 1990, and Miami Conservancy District, 1998]

Name of reservoir or flood-control structure	Name of stream	Capacity (acre-feet)		Surface area (acres)	Drainage area (mi^2)	Year completed	Use[1]
		Normal	Maximum				
Acton Lake	Four Mile Creek	7,650	19,500	625	102	1956	R
Cowan Lake	Cowan Creek	10,273	24,974	648	51	1948	R
Clarence J. Brown Reservoir	Buck Creek	36,900	63,700	2,120	82	1973	CR
Indian Lake	Great Miami River	45,900	69,900	5,800	100	1860	R
Lockington Reserve	Loramie Creek	70,000	126,000	4,020	261	1922	C
William A. Harsha Lake	East Fork Little Miami River	90,400	284,470	4,450	342	1973	CRS
Caesar Creek Lake	Caesar Creek	102,000	242,200	2,830	237	1976	CRS
Germantown Reserve	Twin Creek	106,000	142,000	3,600	275	1922	C
Huffman Reserve	Mad River	167,000	297,000	9,180	635	1922	C
Brookville Lake	East Fork Whitewater River	184,008	694,366	5,280	379	1974	CRS
Taylorsville Reserve	Great Miami River	186,000	386,000	11,000	1,155	1922	C
Englewood Reserve	Stillwater River	312,000	413,000	7,900	650	1922	C

[1]Flood-control structures (C) retain water only during flood events.

Brookville Lake in Indiana is used for flood control, recreation, and water supply. Brookville Lake receives runoff from a 379-mi^2 drainage area, reducing flood stages in the Whitewater Valley and contributing to the reduction in flood flows to the Ohio River (U.S. Army Corp of Engineers, 1998). Since the start of dam operations, flooding downstream from Brookville Lake has been reduced significantly; the 100-year-flood discharge on the Whitewater River at Brookville is estimated to be 30,000 ft^3/s less than expected in the absence of regulated flow. Discharge during the 25-year and 10-year floods was reduced by 22,500 ft^3/s and 16,000 ft^3/s, respectively (Indiana Department of Natural Resources, 1988). Daily mean discharges near zero have been recorded on occasion; such values are likely a result of maintenance activities at the reservoir.

In 1923, five flood-control dams and associated retarding basins were completed in the Miami Valley: Lockington Dam, Germantown Dam, Huffman Dam, Taylorsville Dam, and Englewood Dam (table 7). Constructed by the Miami Conservancy District after the 1913 floods, the dams were designed with conduits that allowed water to pass through the dam during periods of normal streamflow (Spieker and Durrell, 1961). Retarding basins behind the dams are dry normally but, during floods, excess water is stored in those basins; subsequently, the water is released in a controlled manner that greatly reduces the magnitude of flood peaks.

Wetlands

An estimated 45 mi^2 of the study area are wetlands. Wetlands have numerous environmental functions: (1) regulate water quality as vegetation filters sediment, nutrients, and toxic chemicals from water entering a stream or lake; (2) decrease land erosion and increase stability; (3) decrease the velocity of floodwaters, capturing water and releasing it gradually; and (4) support rich biotic communities by providing unique habitats for waterfowl, fish, plants, and other terrestrial and aquatic animals.

Wetlands are classified according to their vegetation, soil type, and frequency of flooding. They are formed in areas periodically or permanently flooded by runoff, ground-water discharge, or precipitation. Soils in these areas are saturated and poorly drained. Runoff, evaporation, transpiration, and subsurface seepage are the only natural mechanisms for water removal. Water in wetlands is characterized by low dissolved-oxygen concentrations and high dissolved-organic-carbon concentrations; it may be moderately acidic or highly alkaline, and it may have low concentrations of nitrogen and phosphorus (Fretwell and others, 1996).

Palustrine and riverine wetlands are found along the Great Miami River and its tributaries and along the Little Miami River in Ohio. Palustrine wetlands are freshwater wetlands found in open water bodies and are characterized by trees, shrubs, erect-rooted herbaceous plants, and submerged/floating plants. Riverine wetlands are characterized by fresh flowing waters in a channel and nonpersistent emergent plants (Stone and Lindley-Stone, 1994). In the Ohio part of the study area, natural wetland areas that have been the focus of special preservation and/or restoration efforts include Cedar Bog in Champaign County, the Beavercreek Wetlands in Greene County, and flood-plain wetlands at the mouth of the Great Miami River in Hamilton County. The Whitewater River Basin contains approximately 28 mi^2 and 38 mi^2 of wetlands and deepwater habitats, respectively (Indiana Department of Environmental Management, 1996). Deepwater habitats, which are permanently flooded environments below the deepwater boundary of wetlands, are distributed along the East Fork Whitewater River in Indiana.

Major and Minor Aquifers

Aquifers in the study area are considered to be part of the Midwestern Basins and Arches Glacial and Carbonate Regional Aquifer System (Casey, 1996). The hydrogeologic setting of aquifers used for water supply in the study area can broadly be characterized by two major categories: (1) unconsolidated glaciofluvial sediments that fill buried valleys that often underlie present-day stream valleys, and (2) upland areas where ground water is withdrawn from unconsolidated and consolidated aquifers (fig. 14). Of these two settings, the coarse-stratified glaciofluvial deposits that fill the preglacial buried valleys constitute the most important aquifer system and, collectively, are termed the Buried-Valley Aquifer System (BVAS). In upland areas, three aquifers are used for water supply: (1) discontinuous sand and gravel lenses found in clay-rich till, (2) fractured and permeable zones in Silurian/Devonian carbonate bedrock; and (3) water-bearing fractured and weathered zones in Ordovician shale bedrock. Major features of the four aquifers used for water supply in the study area are summarized in table 8.

The BVAS consists of highly permeable sand and gravel deposits filling in buried ancestral river valleys—the preglacial Teays River Valley (fig. 5). The BVAS supplies the greatest quantity of water in the study area and has been designated by the U.S. Environmental Protection Agency (USEPA) as a sole-source aquifer (U.S. Environmental Protection Agency, 1998a); it is the principal source of drinking water for 1.6 million people in the study area (Yost, 1995). Supply wells completed in the BVAS commonly yield more than 1,000 gal/min (gallons per minute) and, when placed next to large streams, are capable of sustained yields approaching 2,000 gal/min (Norris and Spieker, 1966; Spieker, 1968; Indiana Department of Natural Resources, 1988; Ohio-Kentucky-Indiana Regional Council of Governments, 1988; Miami Valley Regional Planning Commission, 1991; Dumouchelle, 1998a).

The BVAS deposits range in thickness from 0 to nearly 400 ft; typical thickness of most BVAS deposits is 150 to 200 ft (Norris and Spieker, 1966; Ohio-Kentucky-Indiana Regional Council of

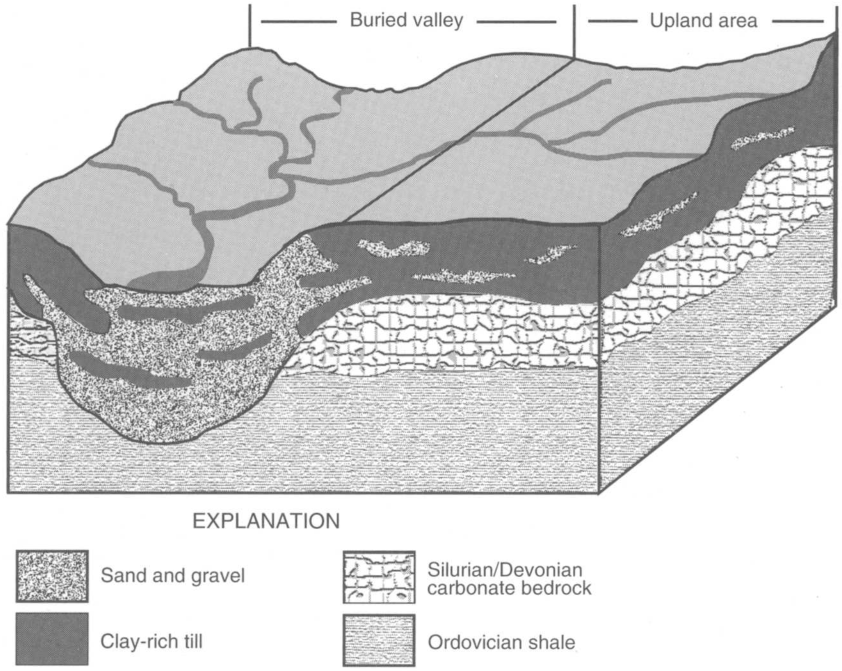


Figure 14. Major aquifer types in the Great and Little Miami River Basins, Ohio and Indiana

Table 8. Major features of aquifer settings in the Great and Little Miami River Basins, Ohio and Indiana

[Ag, Agriculture; Mgal/d, million gallons per day]

Aquifer	Regional aquifer system	Physiographic province	Major geology	Percentages of dominant land uses	Contamination potential	Estimated withdrawals in 1995 (Mgal/d)[1]
Buried valley sand and gravel deposits	Surficial aquifer system	Central Lowland	Recent fluvial and glacial outwash deposits	Urban: 21.5 Ag: 69.4	High	304.4
Discontinuous sand and gravel in clay-rich till	Surficial aquifer system	Central Lowland	Wisconsinan till	Urban: 11.9 Ag: 80.8	Low to medium	38.8
Silurian/ Devonian carbonate	Carbonate bedrock aquifer	Central Lowland	Carbonate bedrock	Urban: 6.1 Ag: 90.8	Low to medium	5.3
Ordovician shale	Ordovician aquifer system	Central Lowland and Interior Low Plateau	Shaly carbonate bedrock	Urban: 20.1 Ag: 68.9 Forest: 11.4	Low to medium	5.2

[1]Does not include withdrawal estimates for domestic use or withdrawals from supply wells whose source aquifer is unknown.

Governments, 1988; Miami Valley Regional Planning Commission, 1991; Woodfield, 1994; Casey, 1996; Dumouchelle, 1998a). In most parts of the study area, deep parts of the buried valleys were carved out of nearly impermeable Ordovician shale so that recharge from the bedrock to BVAS deposits is minimal (Dumouchelle and others, 1993). In the upper parts of the study area, valley walls may consist of more permeable Silurian/Devonian carbonate rock; flow of ground water from the bedrock to the BVAS may occur locally and is expressed as springs that crop out along the contact between the carbonate bedrock and the underlying Ordovician shale (Norris and Spieker, 1966; Dumouchelle and others, 1993). Static water levels in most parts of the BVAS are less than 30 ft below land surface (Indiana Department of Natural Resources, 1988; Yost, 1995). In some locations, laterally extensive till sheets may divide the BVAS into two or more distinct aquifer zones. Semiconfined or confined conditions may exist in the deeper BVAS subunits and, in some cases, artesian wells may occur (Norris and Spieker, 1966).

Regional ground-water flow within the BVAS tends to follow the regional topographic gradient. Along the main-stem buried-valley aquifer that underlies the Miami Valley, this flow is roughly northeast to southwest, with an average regional gradient of about 11 ft/mi (Ohio-Kentucky-Indiana Regional Council of Governments, 1988). On a local scale, ground water in the BVAS tends to flow from adjacent upland areas toward local streams, where it discharges as base flow. The wide range of hydraulic properties of the glacial sediments, variations in the topographic gradient of the buried-valley floor, and localized effects of pumping, however, make prediction of ground-water-flow directions difficult. Only in areas where the hydrogeology of the BVAS deposits is well characterized can ground-water-flow directions be predicted with a reasonable degree of certainty. Alternatively, the rate and direction of ground-water flow in complex BVAS deposits can be simulated with computer-generated numerical flow models at regional or local scales. Many local-scale models of the BVAS have been developed for the purpose of wellhead protection or for modeling the fate and transport of contaminants away from known or suspected hazardous-waste sites (Dumouchelle and others, 1993; Sheets and others, 1998). Regional-scale ground-water-flow models of the BVAS are less common; Dumouchelle (1998a) describes a three-dimensional, steady state numerical flow model of the BVAS in a 241-mi^2 area in and around Dayton, Ohio.

Of the three aquifer subunits found in the upland areas, discontinuous sand and gravel aquifers in clay-rich till are the second largest source of ground water in the study area; however, withdrawals from the till deposits are approximately an order of magnitude less than those from the BVAS (table 8). The till-rich deposits overlie Silurian/Devonian carbonate bedrock in northern and eastern parts of the study area and Ordovician shale and shale-rich limestone in other parts of the study area. Till deposits in upland areas are rich in clay and silt; discontinuous lenses of sand and gravel are scattered across the upland terrain. Norris (1959) reported that water-bearing sand and gravel layers with reasonable yields often are found just above the till-bedrock contact. The size and thickness of overlying clay-rich till deposits ultimately determines the yield of wells developed in the till-rich aquifers. Large-diameter, hand-dug wells completed in clay-rich till may yield enough water to supply a hand pump; drilled wells completed in sand and gravel layers in the clay-rich till commonly yield 10 to 25 gal/min and, infrequently, upwards of 100 gal/min (Norris, 1948, 1950, 1959; Norris and others, 1952; Schmidt, 1984; Spahr, 1991). Because of smaller amounts of recharge and storage, however, upland till aquifers generally yield much less water than the coarse-stratified outwash and valley-train deposits found in the BVAS. Till deposits in the Ohio and Indiana parts of the study area range from less than 100 ft thick to as much as 600 ft thick along the main-stem buried valley of the preglacial Teays River; the thickest till deposits are found in the northwestern part of the study area. Water-bearing sand and gravel layers in the till range from 0 to 20 or 30 ft thick.

The Silurian/Devonian carbonate-bedrock aquifer is found mainly in the northern and eastern parts of the study area. Thick Devonian-age units are the upper boundary of the carbonate-bedrock aquifer system on the northern, western, and eastern margins of the Silurian/Devonian subcrop (Bugliosi, 1990). In the northwestern part of the study area, Upper Silurian and Lower Devonian rocks have been removed by erosion and the carbonate aquifer consists primarily of Silurian consolidated dolomite; limestone and shale are present in the Lower Silurian. The carbonate-bedrock aquifer is confined in most areas but is unconfined locally along the Teays River Valley or where it is covered by thin layers of coarse-grained glacial deposits or fractured till (Norris and Fidler, 1973; Bugliosi, 1990). In some areas, joints, fractures, and solution features may produce enough water for domestic and livestock needs. The Silurian/Devonian aquifer is used for water supply in upland areas where water-bearing sand and gravel lenses in till are thin or absent; the aquifer typically yields between 5 and 60 gal/min (Woodfield, 1994). Well yields of several hundred gallons per minute are possible, however, in areas where uncased bedrock wells intersect a zone of solution-enhanced permeability found at the base of the Upper Silurian Salina Group strata and the top of the underlying Lockport Dolomite (the Newburg Zone of drillers) (Norris and Fidler, 1973; Norris, 1974; Casey, 1996). In the study area, these high-yield zones are restricted to selected parts of Champaign and Logan Counties (Norris and Fidler, 1973).

The Silurian/Devonian carbonate aquifer ranges from 0 to 100 ft thick in the study area. The thick beds of dolomite and limestone are interbedded and interlaminated with shale. The Silurian/Devonian carbonate aquifer thickens away from the crest of the Cincinnati Arch towards the northeastern part of the study area; it is underlain in all parts of the study area by Ordovician shale, which is considered to be a regional basal confining unit (Norris and Fidler, 1973; Bugliosi, 1990; Casey 1996). Flow of ground water in the Ordovician shale generally is restricted to weathered and fractured strata near the top of the sequence; wells completed in the shale bedrock rarely yield more than a few gallons per minute (Dumouchelle and others, 1993; Joseph and Eberts, 1994; Casey, 1996).

Available aquifer-test data for the study area show that hydraulic conductivities typically range from 0.33 to 2,500 ft/d (feet per day) in the BVAS, 0.1 to 500 ft/d in the Silurian/Devonian carbonate aquifer, and from 1.6×10^{-3} to 12 ft/d in the Ordovician shale (Norris and Spieker, 1966; Spieker, 1968; Ohio-Kentucky-Indiana Regional Council of Governments, 1988, 1991; Miami Valley Regional Planning Commission, 1991; Casey, 1992, 1996; Joseph and Eberts, 1994; Dumouchelle, 1998a). Transmissivities range from 4,170 to 60,300 ft^2/d (feet squared per day) and storage coefficients range from 5×10^{-5} to 0.21 in the BVAS. Transmissivities in the Silurian/Devonian carbonate aquifer range from 130 to 22,100 ft^2/d (Joseph and Eberts, 1994).

The amount of ground water available for use is influenced by the source and rate of aquifer recharge, physical properties of aquifer sediments and bedrock, surface-water/ground-water interactions, and rates of withdrawal by supply wells. In fine-grained tills, recharge rates are 3 to 5 in/yr (inches per year) or less; in areas where coarse-grained glacial materials are exposed at land surface, recharge rates between 6 and 15 in/yr are possible (Norris and Spieker, 1966; Dumouchelle and others, 1993, Dumouchelle, 1998a). Estimated recharge rates for the Silurian/Devonian carbonate aquifer vary from 3 to 6 in/yr (Bugliosi, 1990).

Induced infiltration of streamwater occurs when pumping of supply wells near streams reverses the local hydraulic gradient and causes streamwater to flow through the streambed into the shallow aquifer. Induced infiltration is an important source of water for many high-yielding supply wells in the study area; the City of Dayton diverts river water from the Mad and Great Miami Rivers into artificial recharge lagoons to maintain high rates of pumping at both of its municipal well fields (Norris and Spieker, 1966; Dumouchelle, 1998a; Rowe and others, 1999). Supply wells placed near streams also withdraw ground water that ultimately would discharge into streams; therefore, overpumping near small streams potentially can influence the quantity and quality of streamwater during periods of base flow.

The hydrogeology of the BVAS makes it vulnerable to contamination (Miami Valley Regional Planning Commission, 1990). The highly permeable sand and gravel deposits allow contaminants to travel rapidly throughout the system. Results from a ground-water age-dating study in 1993–94 of the BVAS in and around Dayton indicated that shallow parts of the aquifer are recharged in a few months or years; most ground water from deeper parts of the BVAS was 5 to 25 years old (Shapiro and others, 1998). At locations affected by induced infiltration of streamwater, even deep parts of the BVAS were recharged within a few weeks or months; thus, well fields that rely on induced infiltration can be vulnerable to spills or other accidents that severely affect stream quality on a short-term basis (Shapiro and others, 1998). Prior to the 1970's, most industrial and commercial development took place on or adjacent to major stream valleys directly on top of the BVAS. Waste generated by industrial and commercial facilities often was disposed of in abandoned gravel pits or unlined landfills, providing direct routes for transport of contaminants to the BVAS (Miami Valley Regional Planning Commission, 1990).

Aquifers in the upland settings have variable levels of vulnerability to contamination, depending on the thickness and permeability of overlying surficial deposits and on land use. Most land in upland areas is used for agriculture; urban and industrial development and areas of high population density are distributed irregularly. Most contaminants in these areas are derived from nonpoint sources. The major source of recharge to the Silurian/Devonian carbonate aquifer is infiltration through glacial deposits. The carbonate aquifer is most vulnerable in areas where it is in direct contact with overlying sand and gravel aquifers and where secondary porosity features are present (Miami Valley Regional Planning Commission, 1990).

Ecoregions

Ecoregions are distinguished by similarities in ecosystem and environmental resources and are identified by similarities in geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology (Omernik, 1987; U.S. Environmental Protection Agency, 1997). Ecoregion characteristics influence surface- and ground-water quality, biological communities, and the types of human activities that will occur in an area.

The study area lies within the Eastern Corn Belt Plains and the Interior Plateau ecoregions. Most of the study area is in the Eastern Corn Belt Plains, which is characterized by rolling till plains with local moraines; rich soils; and extensive corn, soybean, and livestock production. The Eastern Corn Belt Plains contain more than 75-percent cropland agriculture on till plains with end moraines, sheet, kames, and outwash plains (Rankin and others, 1997a). In Indiana and Ohio, the Eastern Corn Belt Plains ecoregion has been divided into six subecoregions—the Clayey, High Lime Till Plains; Loamy, High Lime Till Plains; Mad River Interlobate Area; Pre-Wisconsinan Drift Plains; Darby Plains; and Whitewater Interlobate Area (Woods and others, 1998) (fig. 15). The Northern Bluegrass subecoregion represents the Interior Plateau ecoregion in the study area.

The Clayey and Loamy, High Lime Till Plains subecoregions cover 4,357 mi^2 (60 percent) of the study area. The Till Plains subecoregions drain from north to south-southwest toward Cincinnati; they are characterized by high lime, late Wisconsinan glacial till with a well-developed drainage network and fertile soils. The original beech forests and elm/ash swamp forests have been replaced by corn, soybean, wheat, livestock, and dairy farming on artificially drained clayey soils. Soils of the Loamy, High Lime Till Plains have better drainage than the clay-rich soils of the Clayey, High Lime Till Plains subecoregion. Like the Clayey, High Lime Till Plains, the Loamy, High Lime Till Plains once were covered with beech forests and elm/ash swamp

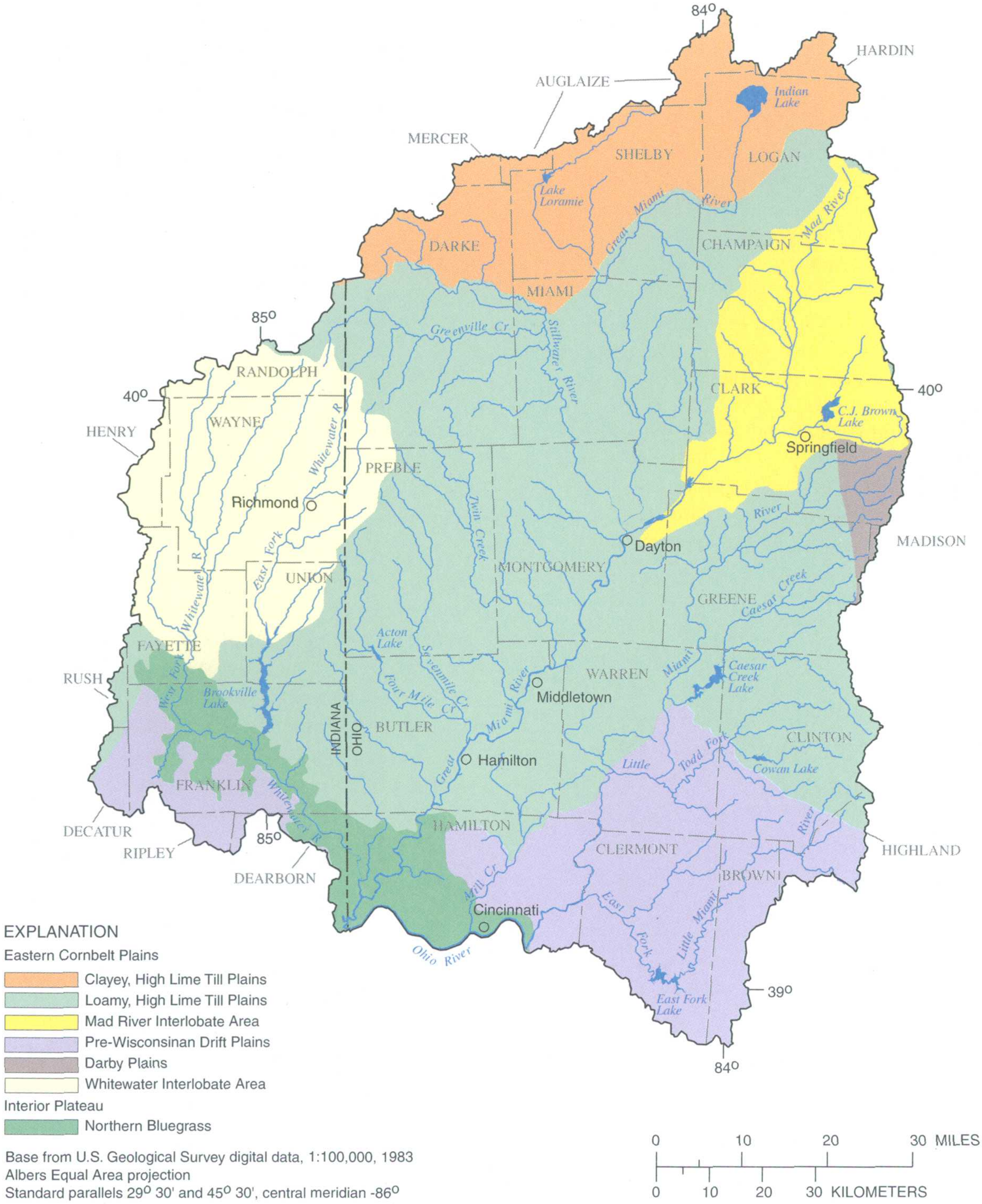


Figure 15. Ecoregions and subecoregions in the Great and Little Miami River Basins, Ohio and Indiana. (Data from Woods and others, 1998.)

forests; oak/sugar-maple forests also were present. Corn, soybean, wheat, and livestock farming is widespread on the Loamy, High Lime Till Plains as well (Woods and others, 1998).

The Mad River Interlobate Area drains the northeastern part of the study area, totaling 616 mi^2 (8 percent of the study area). It is distinguished by extensive glacial-outwash deposits that are high-yielding aquifers. Historically, this area contained beech forest, mixed oak forest, and wet prairies; some wooded areas can be seen today along steep slopes and riparian corridors (Woods and others, 1998). Current land use includes corn, soybean, dairy, and livestock farming as well as residential, commercial, and industrial activity.

The Pre-Wisconsinan Drift Plains subecoregion covers the southeastern part of the study area in Ohio and the southwestern part of the study area in Indiana, totaling 1,081 mi^2 (14 percent of the study area). It is characterized by dissected, deeply leached, acidic, clay-loam glacial till and thin loess (Wood and others, 1998). The soils in this region are poorly drained. Historically, beech forests and elm/ash swamp forests were common. Soybean, corn, tobacco, and livestock farming are common in nonurbanized parts of this subecoregion.

The Darby Plains subecoregion is 1 percent of the study area. Loamy, high lime, late Wisconsinan drift material covers carbonate bedrock. This subecoregion is characterized by an abundance of prairies; mixed oak forests; and productive corn, soybean, and wheat farming (Woods and others, 1998).

The Whitewater Interlobate Area covers most of the Whitewater River Basin in Indiana and Ohio, totaling 822 mi^2 (11 percent of the study area). It is characterized by high-volume, ground-water-fed streams. The area contains loamy, high lime, Wisconsinan glacial till; outwash; and alluvium covering limestone, calcareous shale, and dolomitic mudstone. Beech forest and elm/ash swamp forest are common. The area is characterized by corn, soybean, and livestock farming and some riparian woodlands (Woods and others, 1998).

The Northern Bluegrass subecoregion is in the southern and southeastern section of the study area, totaling 384 mi^2 (5 percent of the study area). It is characterized by rugged terrain; woodlands; and hay, grain, cattle, hog, and poultry farming (Woods and others, 1998). Unlike the soils in the Eastern Corn Belt Plains, Northern Bluegrass soils are derived predominantly from sandstone, siltstone, shale, and limestone bedrock. The subecoregion has a mixture of glaciated and unglaciated soils and is characterized by limestone bedrock, flat rubble streambeds, and high relief near the Ohio River (Woods and others, 1998).

Biological Communities

Biological communities form in response to five main environmental factors—chemistry, energy source, habitat, flow regime, and biotic (Karr and others, 1986). Changes in these factors are caused by natural and human processes that, in turn, are reflected in aquatic biological communities. Response time to these changes varies among different classes of aquatic biota; among the groups traditionally used for environmental monitoring, algae and benthic invertebrates respond quickly (days to weeks) while fish communities respond to changes in their environment over longer time scales (months to decades).

Biological criteria for the protection of aquatic life were developed by the Ohio Environmental Protection Agency (Ohio EPA) to restore and maintain the physical, chemical, and biological integrity of surface waters (Ohio Environmental Protection Agency, 1987a, b; 1989a, b). Biological criteria are incorporated into the Ohio Water Quality Standards (WQS) (Ohio Environmental Protection Agency, 1990) and primarily are used to determine protection and restoration requirements as part of regular water-quality surveys. Fish and macroinvertebrates are used as the routine monitoring organisms for two reasons: (1) they have been used widely in environmental assessments; and (2) differences in their response to environmental stressors, spatially and temporally, tend to be complementary in an environmental evaluation.

Biological communities in the Ohio part of the study area have been characterized in detail by the Ohio EPA (Ohio Environmental Protection Agency, 1983; 1984a, b; 1985; 1986; 1991; 1992a, b; 1994a, b; 1995a, b; 1996a, b; 1997b, c), and criteria for five different aquatic-life-use categories have been established. The three aquatic-life-use designations that broadly characterize the study area are Warmwater Habitat (WWH), Exceptional Warmwater Habitat (EWH), and Coldwater Habitat (CWH). These designations are based on biological and physical criteria determined by a series of numeric values. The values account for the diversity and sensitivity of the fish and macroinvertebrate populations and consider attributes of habitat that may be important in explaining the composition of the fish communities (Ohio Environmental Protection Agency, 1987b; Rankin, 1989). Criteria associated with the WWH aquatic-life-use designation represent the principal restoration targets for the majority of water-resource-management efforts in the study area; the EWH aquatic-life-use designation represents a protection goal for watershed-management efforts in the highest-quality watersheds in the study area.

Criteria used to determine the aquatic-life-use designation of a specific stream reach are based on biological indices that provide numeric scores for sites where surveys of fish, macroinvertebrates, and stream habitat are conducted. Biological indices developed and used by the Ohio EPA include the Index of Biotic Integrity (IBI) and Modified Index of Well-Being (MIwb), both of which are based on fish-survey data; the Invertebrate Community Index (ICI), which is based on macroinvertebrate-survey data; and the Qualitative Habitat Evaluation Index (QHEI), which scores the quality of stream habitat by ranking characteristics such as substrate, instream cover, channel quality, riparian/erosion, pool/riffle, and gradient (Ohio Environmental Protection Agency, 1987a, b; 1989a, b; Rankin, 1989). The ICI is influenced positively by taxa richness and the percentage of mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera). The ICI is negatively influenced by pollution-tolerant species such as aquatic segmented worms (Oligochaeta), selected midge species (*Cricitopus bicintus* and *Polypedilum illinoense*), limpets *Ferrissia* spp., and the pond snail *Physella* spp. (Ohio Environmental Protection Agency, 1987b). Criteria for the biological index are specified for each of Ohio's five ecoregions (as described by Omernik, 1987) and are organized further by organism group, index, site type, and aquatic-life-use designation (Ohio Environmental Protection Agency, 1996a).

The WWH aquatic-life-use designation refers to streams that support the "typical" warmwater assemblage of aquatic organisms found throughout much of the Great Miami River Basin. Certain fish are associated with the designated WWH streams in the Great Miami River Basin, including the redhorse (*Moxostoma* genus), blackbass (*Micropterus* genus), carpsuckers (*Carpiodes* genus), and various darters (*Etherostoma* and *Percina* genera) (Harrington, 1999). Protecting and maintaining existing WWH-designated streams is the principal goal of water-resource-management efforts in the Great Miami River Basin. Mill Creek, which drains the industrial sector of Cincinnati, is an example of a stream with impaired habitat and biological community (Ohio Environmental Protection Agency, 1994a). Other examples of impaired habitat can be found in the main stem Great Miami River downstream from Dayton (Ohio Environmental Protection Agency, 1997b) in pooled areas behind low dams and in reaches affected by industrial and wastewater discharges, combined-sewer overflows, and nonpoint sources of pollution. High numbers of the Oligochaeta worms in the Great Miami River downstream from the Mad River and Wolf Creek (in Dayton, Ohio) raised the percentage of tolerant organisms, resulting in a decline in performance of the macroinvertebrate community downstream from these tributaries. High percentages of tolerant organisms without a decline in the diversity (as observed in these examples) usually indicate nutrient enrichment (Ohio Environmental Protection Agency, 1997b). Another indication of nutrient enrichment is heavy growth of narrow-leaf pondweed (*Potamogeton*), the alga *Cladophora* which was abundant in the upper sections of the Mad River, and watercress (*Nasturtium*) which was abundant where the riparian canopy was open

(Ohio Environmental Protection Agency, 1986). High densities of *Cladophora* also were noted during a survey of 12 sites in the Little Miami River conducted by the University of Cincinnati. During summer low-flow periods (1996–98), blooms of planktonic algae turned pooled areas of the Lower Great Miami River green (Dr. Michael C. Miller, University of Cincinnati, oral commun., 1999).

The EWH aquatic-life-use designation is reserved for waters that support "unusual and exceptional" assemblages of aquatic organisms. EWH streams are characterized by diverse numbers of species, particularly those that are highly intolerant, rare, threatened, or endangered (declining species). Endangered fishes in Ohio that have been collected in the main stem of the Little Miami River (Ohio's longest EWH stream) include the mooneye (*Hiodon tergisus*), silver chub (*Macrhybopsis storeriana*), river redhorse (*Moxostoma carinatum*), mountain madtom (*Noturus eleuthrus*), blue sucker (*Cycleptus elongatus*), and tonguetied minnow (*Exoglossum laurae*) (Harrington, 1999). Although selected reaches of the Little Miami River have received the EWH aquatic-life-use designation, the chemical and biological integrity of the Little Miami River as a whole has not been able to achieve full attainment of EWH. Only 9 of the 35 sites on the main stem of the Little Miami River monitored in 1994 were rated as being in full attainment of the EWH aquatic-life-use criteria (Ohio Environmental Protection Agency, 1995a). The best example of an exceptional macroinvertebrate community and the second most-exceptional fish community in Ohio is in Twin Creek, a tributary to the Great Miami River (Ohio Environmental Protection Agency, 1997b). Twin Creek, is downstream from Dayton and upstream from Middletown. With a drainage area of 316 mi^2, Twin Creek provides habitat for many niche-specific organisms that inhabit cool, oxygen-rich riffles; these organisms include the rare mayflies *Acerpenna macdunnoughi* and *Paracloeodes* sp. 3, caddisfly *Chimarra aterrima*, snail-cased caddisfly *Helicopsyche borealis*, and flathead mayfly *Stenonema mediopunctatum*. In addition, the coldwater fishfly, *Nigronia fasciatus*, that inhabits coldwater boulder-strewn riffles and runs is found there (Ohio Environmental Protection Agency, 1987b, 1997b). Twin Creek was rated as being in full attainment of the EWH rating throughout the 46 river miles of the main stem, with the exception of two reaches that were designated as being in partial attainment of EWH. Of these two reaches, one is a wetland/headwater site and the other site is near a large gravel quarry.

Other tributaries to the Great Miami River, such as the Stillwater River above Dayton, have been classified EWH; however, parts of the Stillwater River and its tributaries have been recommended for WWH designation (Ohio Environmental Protection Agency, 1991). In 1990, 44 percent of the 41 sites sampled in the Stillwater River Basin were rated as being in full attainment of EWH status, 51 percent were in partial attainment, and 5 percent were in nonattainment. Causes of partial and nonattainment were attributed to point-source contamination from wastewater-treatment plants, habitat modifications (channelization, impoundments), and nonpoint-source contamination (runoff from animal-feedlot operations, failing on-site septic systems). These aquatic-life-use designations reflect agricultural impacts in the Upper Stillwater Basin (Darke County, Ohio), which is the part of the study area subject to intense row-crop and livestock production; the lower main stem of the Stillwater River above Dayton, however, maintains an intact riparian corridor and an EWH aquatic-life-use designation.

In 1997, the Indiana Department of Environmental Management (IDEM) conducted a detailed biological and water-quality assessment of 19 locations in the Upper Whitewater River Basin. The survey focused on wadeable streams and found exceptional water quality and fish communities at many of the sites sampled. The occurrence of endangered species such as the variegate darter (*Etheostoma varigatum*) and the redside dace (*Clinostomus elongatus*), which had not been recorded in Indiana in the past 100 years, added to the exceptional character of the fish communities (Harrington, 1999). IDEM is developing aquatic-life-use criteria for Indiana, based on chemical and biological assessments of more than 830 stream segments throughout the State. On the basis of the preliminary statewide model, the Whitewater River Basin ranks among the highest-scoring watersheds in Indiana (Ronda Dufour, Indiana Department of Environmental Management, written commun., 1999). The Lower Whitewater River in Ohio was upgraded from WWH to EWH status (Ohio Environmental Protection Agency, 1997b).

The CWH aquatic-life-use designation describes waters capable of supporting assemblages of coldwater organisms and/or those water bodies that are stocked with salmonids with the intent of providing a recreational fishery on a year-round basis. Streams meeting the CWH aquatic-life-use designation are found in the Mad River Basin and include the main stem Mad River (Ohio's longest CWH stream) and its tributaries north of Springfield, Ohio (Ohio Environmental Protection Agency, 1986). Although many fish species associated with WWH such as northern hog sucker (*Hypentelium nigricans*), rock bass (*Ambloplites rupestris*), and central mottled sculpin (*Cottus bairdi*) also are found in CWH streams such as the Mad River, certain coldwater species such as the brown and rainbow trout (*Salmo trutta* and *Oncorhynchus mykiss*) are found only in CWH streams (Harrington, 1999). Although not native to Ohio, trout were introduced for sport fishing in the early 1900's, with varying degrees of success, into ponds and streams in the Mad River Basin (Trautman, 1981). To maintain a viable trout fishery, brown and rainbow trout are stocked in the Mad River by the Ohio Department of Natural Resources, Division of Wildlife. Coolwater to coldwater macroinvertebrate taxa, found in the Mad River main stem include the caddisflies *Chimarra atterima, Lype diversa, Symphitopsyche slossonae, Symphitopsyche sparna, Glossosoma* sp. and the midge groups *Eukiefferiella devonica* and *Tvetenia bavaria,* which rarely have been collected in streams exceeding 20°C (Bode, 1983).

Biological recovery of many streams in the study area is indicated by the reoccurrence of more intolerant taxa such as the endangered blue sucker (*Cycleptus elongatus*) and several redhorse species. This recovery is attributed to upgrades made at many wastewater-treatment plants since 1972 and to stricter enforcement of regulations governing point-source releases of industrial and sewage effluent. Still, a relatively high percentage of fish with external abnormalities (deformities, erosion of fins, lesions, and tumors—"DELT anomalies") has been recorded at main-stem sites on the Great and Little Miami Rivers during recent water-quality surveys (Ohio Environmental Protection Agency, 1995a, 1997b). The percentage of fish with DELT anomalies is found to increase downstream from wastewater-treatment plants. Such anomalies are believed to be a response mechanism to stress caused by marginal dissolved-oxygen concentrations and/or chronic or acute exposure to toxic contaminants (Ohio Environmental Protection Agency, 1995a, 1997b; Sanders and others, 1999).

In addition to traditional water-quality problems such as eutrophication caused by the release of nutrient-rich effluent, the role of other chemicals released in industrial and wastewater-treatment-plant effluent on the health of aquatic (and terrestrial) organisms is being investigated in the study area and elsewhere in the Nation. These chemicals include endocrine disruptors, which are chemicals that interfere with or mimic natural hormones responsible for the development, maintenance, reproduction, and/or behavior of an organism (Smith and Muir, 1998). Potential endocrine disruptors include pesticides, insecticides, fungicides, phenols, phthalates, polychlorinated biphenyls (PCB's) and synthetic and natural hormones excreted in human and animal waste. Much of the recent research on the effects of endocrine disruptors has focused on fish health and reproduction (Jobling and others, 1998; Smith and Muir, 1998). The Proctor and Gamble Company, using river water pumped from the East Fork of the Little Miami River, has conducted research on the effects of specific chemicals (such as household-cleaning products and surfactants) on invertebrate and algal communities (Belanger and others, 1994). Such studies provide information on seasonal effects and the relative sensitivity of the different classes of organisms to specific chemicals and can help provide a better understanding of the effects of chemical stressors associated with wastewater-treatment-plant effluent on the environment (Belanger 1994; Belanger and others, 1995). The effect of wastewater on the health of aquatic organisms is a water-quality issue that will continue to receive attention from regulators and water-resource managers in the study area; significant and recurring residential/commercial development near urban areas will result in increased amounts of treated wastewater discharged to streams.

Population

Estimated population in the study area in 1995 was 2.8 million. Major urban areas in the study area include Cincinnati and Dayton, Ohio. In 1990, the Cincinnati Metropolitan Area was the 31st largest in the United States, the Dayton-Springfield Metropolitan Area was 54th, and the Hamilton-Middletown Metropolitan Area was the 146th largest (American Map Corporation, 1993). The population of the individual basins and major cities and towns (populations greater than 35,000) in the study area are listed in table 9. The population-density distribution clearly defines a nearly continuous urban corridor that extends southwest along the Miami Valley from Springfield to Cincinnati (fig. 16). Approximately 62 percent of the total population of the study area live in Hamilton, Montgomery, and Butler Counties in Ohio; these counties represent only about 18 percent of the total study area.

Population in the study area increased approximately 44 percent from 1940–45, with the most rapid rise occurring from 1940–70 when large factories associated with post-World War II expansion were built in Dayton and Cincinnati. Since 1970, the overall rate of population growth in the study area has slowed significantly (fig. 17). In contrast, the populations of Cincinnati and Dayton have declined steadily since peaking in the 1960's. This trend reflects the migration of city residents into suburban areas that surround Cincinnati and Dayton. Such migration usually is accompanied by the conversion of agricultural land to residential and commercial areas, resulting in development that adversely can affect water quality and aquatic ecosystems. This migration is reflected in the high growth rates experienced by counties that border the Cincinnati and Dayton Metropolitan Areas—Clermont County (80 percent), Warren County (77 percent), Greene County (75 percent), and Butler County (62 percent). These counties had the highest growth rates in the study area from 1940–95.

Table 9. Population of the Great and Little Miami River Basins, including major urban areas, Ohio and Indiana

[1995 data estimated from 1990 census data. Data from U.S. Bureau of the Census, 1998a; Donald Arvin and Ronald Veley, U.S. Geological Survey, written commun., 1998]

Basin	1995 Population
Upper Great Miami	584,041
Lower Great Miami	784,916
Little Miami	647,779
Mill Creek	617,599
Whitewater	161,587
Cities	**1995 Population**
Cincinnati, Ohio	349,027
Dayton, Ohio	174,459
Springfield, Ohio	67,951
Hamilton, Ohio	62,117
Kettering, Ohio	58,671
Middletown, Ohio	47,931
Fairfield, Ohio	41,826
Huber Heights, Ohio	38,927
Richmond, Indiana	37,900

Land Use

Historically, streams and aquifers of the study area have played a significant role in the development of the region's economy and land-use patterns. European settlement of the Cincinnati and Dayton areas in the late 1700's was tied to the

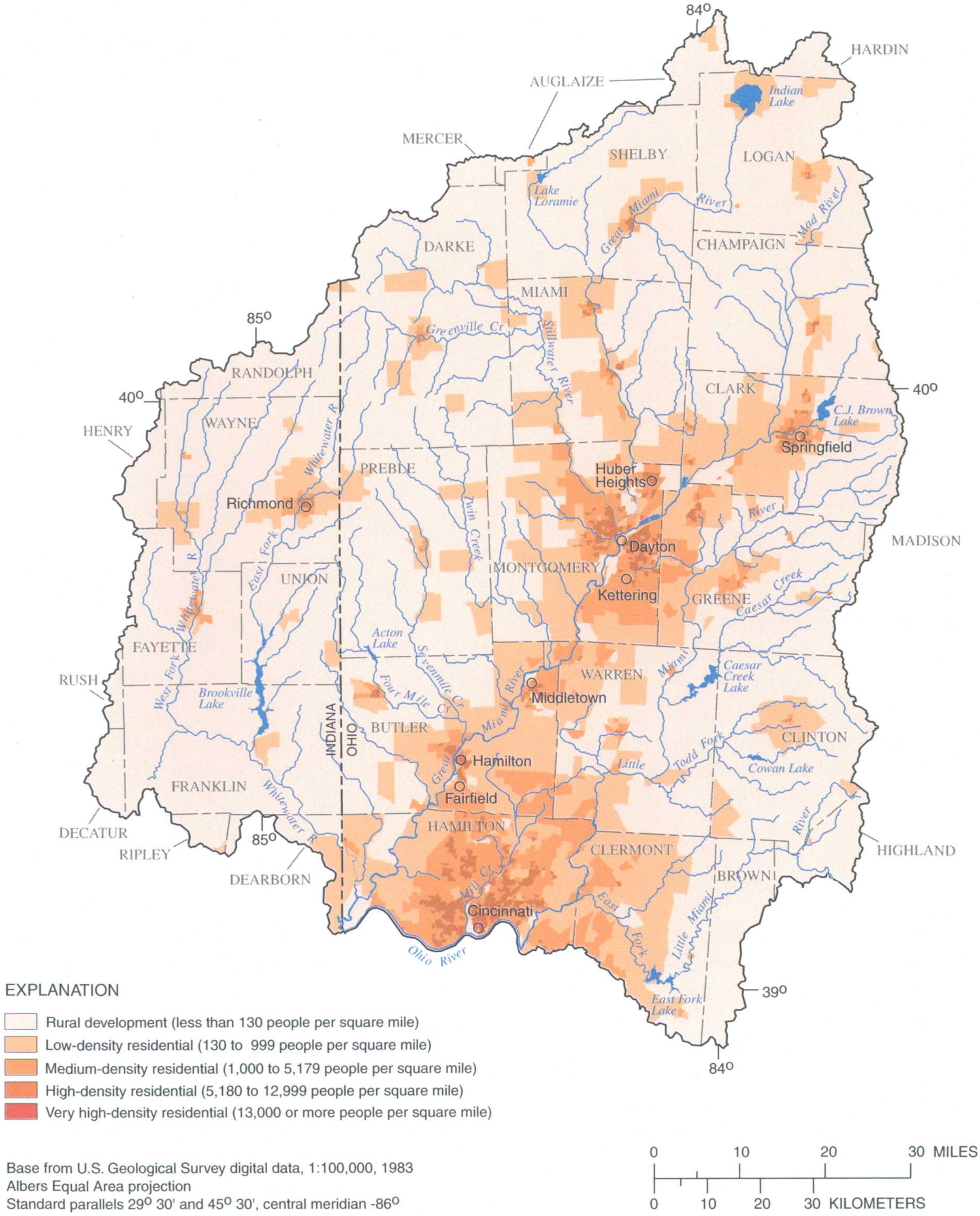


Figure 16. Population density in the Great and Little Miami River Basins, Ohio and Indiana, 1990. (Data from U.S. Bureau of the Census, 1990, 1991a, 1991b, 1991c, 1991d.)

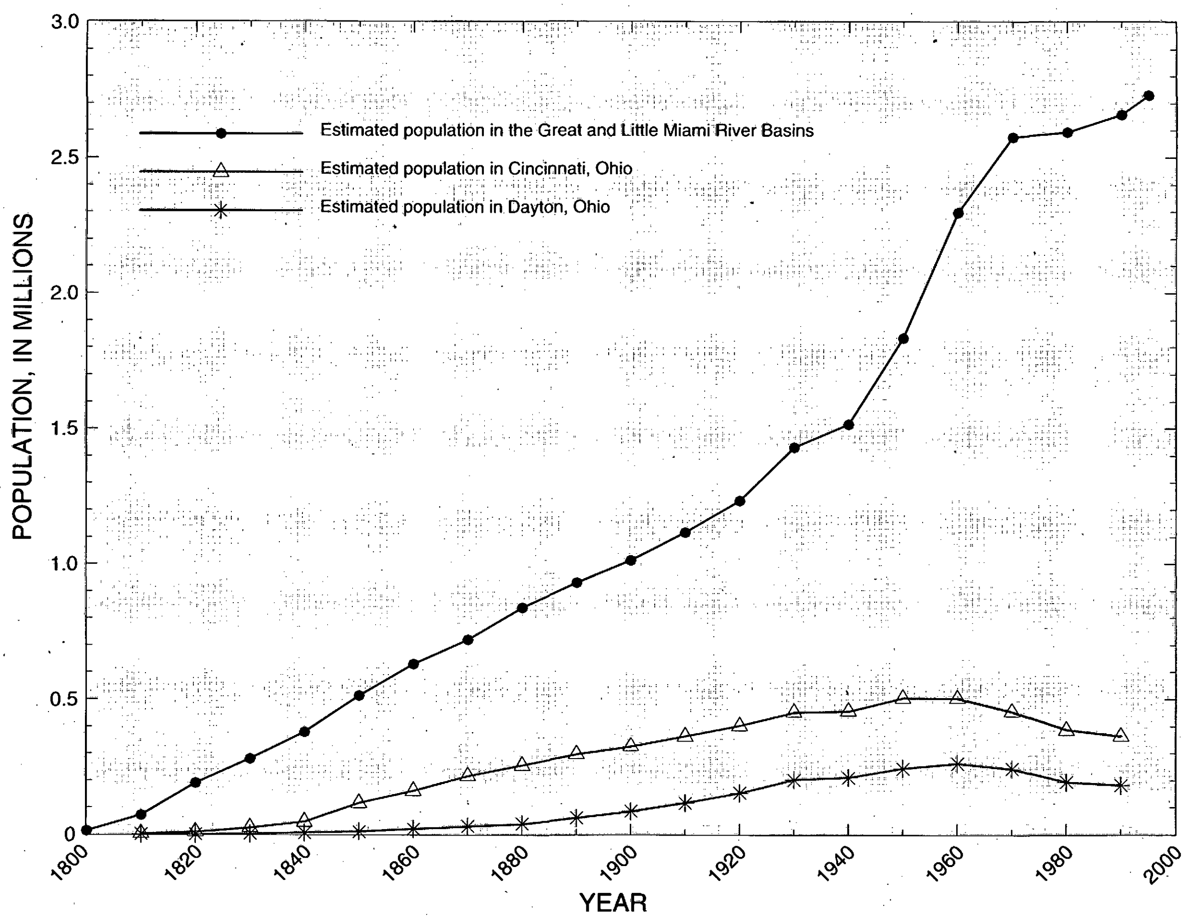


Figure 17. Population growth in the Great and Little Miami River Basins, Ohio and Indiana, 1800–1995. (Data from John Bittle, State Library of Ohio, written commun., 1998; U.S. Bureau of the Census, 1998b.)

sites' proximity to large, navigable rivers. Farms of the early settlers were concentrated on fertile flood plains next to streams and rivers. Rapid economic growth in the study area followed completion of the Miami Canal in 1829. The canal, which linked Dayton to Cincinnati, provided low-cost transportation of agricultural products to national and world markets. Canal traffic peaked in 1850 and declined as railroads were constructed across the study area. Rail transportation promoted the rise of manufacturing in towns and cities, and by the 1870's Cincinnati and Dayton were nationally important industrial centers (Becker and Nolan, 1988). As towns and factories in the study area grew, more wells were completed in the buried-valley aquifer. The abundant supply of ground water was critical to the development that continued through the twentieth century. Deforestation and urbanization that accompanied the transition from an agrarian to industrial society, however, adversely affected the quality of water in streams and aquifers in the study area.

Population increases that accompanied settlement and subsequent industrial development affected stream habitat and biological communities in the study area (Trautman, 1981; Harrington, 1999). Before the 1800's, streams normally were clear and contained little soil in suspension, except during floods. The native fish population required clear waters with clean stream bottoms of sand, gravel, boulders, bedrock, and organic debris and/or aquatic vegetation. As human population increased, there was a corresponding increase in the amounts of forest removed, land ditched and drained, and virgin prairie plowed. Conversion of forest land to farms and towns was accompanied by construction of dams and water mills and pollution by sawdust, brewery, and slaughterhouse waste. In the 1900's, discharge of increasing amounts of industrial- and domestic-sewage wastes further contributed to modifications of the instream fauna (Trautman, 1981; Harrington, 1999).

Land-use and land-cover information for the study area is based on a national data set compiled from topographic maps and high-altitude aerial photographs. The land-use and land-cover data from 1973 to 1981 are available as Geographic Information and Retrieval System (GIRAS) files (U.S. Geological Survey, 1990). The USGS land-use and land-cover data set is coded by use of the Anderson classification system (Anderson, 1976), which is a hierarchical system of general (Level 1) to more specific (Level 2) classes. Although the data base is somewhat outdated and of relatively coarse resolution, it can be used to illustrate general patterns of land use and to establish a base line for evaluating changes in land use since the mid-1970's. The GIRAS data set was used as the foundation for a refined land-use-classification scheme that used U.S. Bureau of the Census 1990 population data to define areas of new urban and residential development in the study area (Hitt, 1994a, b).

The updated Level 1 land-use data show that agriculture is the principal land use throughout the study area, encompassing more than 79 percent of the total land area (fig. 18). Urban land use (residential, industrial, and commercial) makes up slightly more than 13 percent of total land use. While urban land use has increased from 10.7 percent in the 1970's to 13.1 percent in 1990, other uses have remained relatively constant. The remaining land consists of forest (7 percent) mainly in the southern part of the study area, water bodies or wetlands (0.7 percent), and barren land (0.3 percent). Strip mines, quarries, and exposed bedrock are considered "barren land."

Agriculture

Most land in the study area is used for agricultural activities. More than 3 million acres of farmland are in the study area, and approximately 84 percent are used for crop production. Counties in the northern part of the study area have the highest percentage of farmland used for crop production. More than 90 percent of the cropland in the study area was planted in corn, soybeans, and wheat (fig. 19), with production highest in Darke County, Ohio, in 1997. Corn and soybeans are planted in the spring and early summer and harvested in the fall. Winter wheat crops are planted in the fall and harvested in the summer. Hogs, pigs, and cattle were the main livestock raised in the study area (fig. 20), with the highest production in Darke County, Ohio. Based on 1995 county-level data, an estimated 720,000 hogs and pigs were raised in the study area; county-level data are not available after 1995 in Indiana. Based on 1997 data, an estimated 300,000 cattle were raised in the study area.

The use of fertilizers and chemical pesticides often are associated with agricultural practices and the degradation of surface- and ground-water quality. Commercial fertilizers (nitrogen, phosphate, and potash) are used widely in the study area. Micronutrients, livestock manure, sulfur, and lime also are applied alone or in combination with commercial fertilizers (Indiana Agricultural Statistics Service, 1996). Fertilizer and manure associated with row-crop farming and livestock production are major sources of nutrients in surface and ground water. Nutrients applied in quantities exceeding the amount used by crops and held by soil are carried to surface water through runoff and subsurface drainage systems and to ground water through infiltration (Nokes and Ward, 1997).

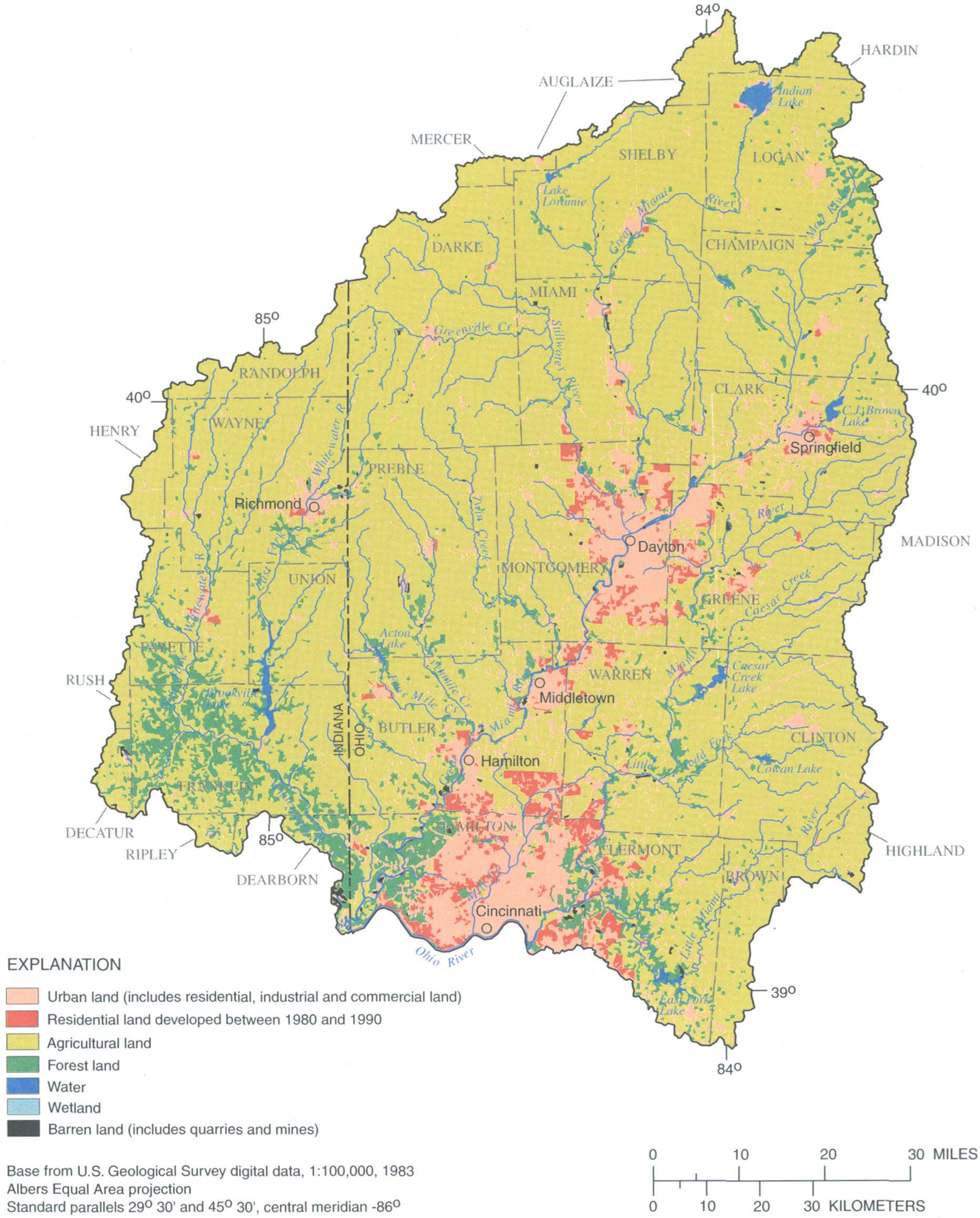


Figure 18. Land use and land cover in the Great and Little Miami River Basins, Ohio and Indiana. (Data from U.S. Geological Survey, 1990; Hitt, 1994a.)

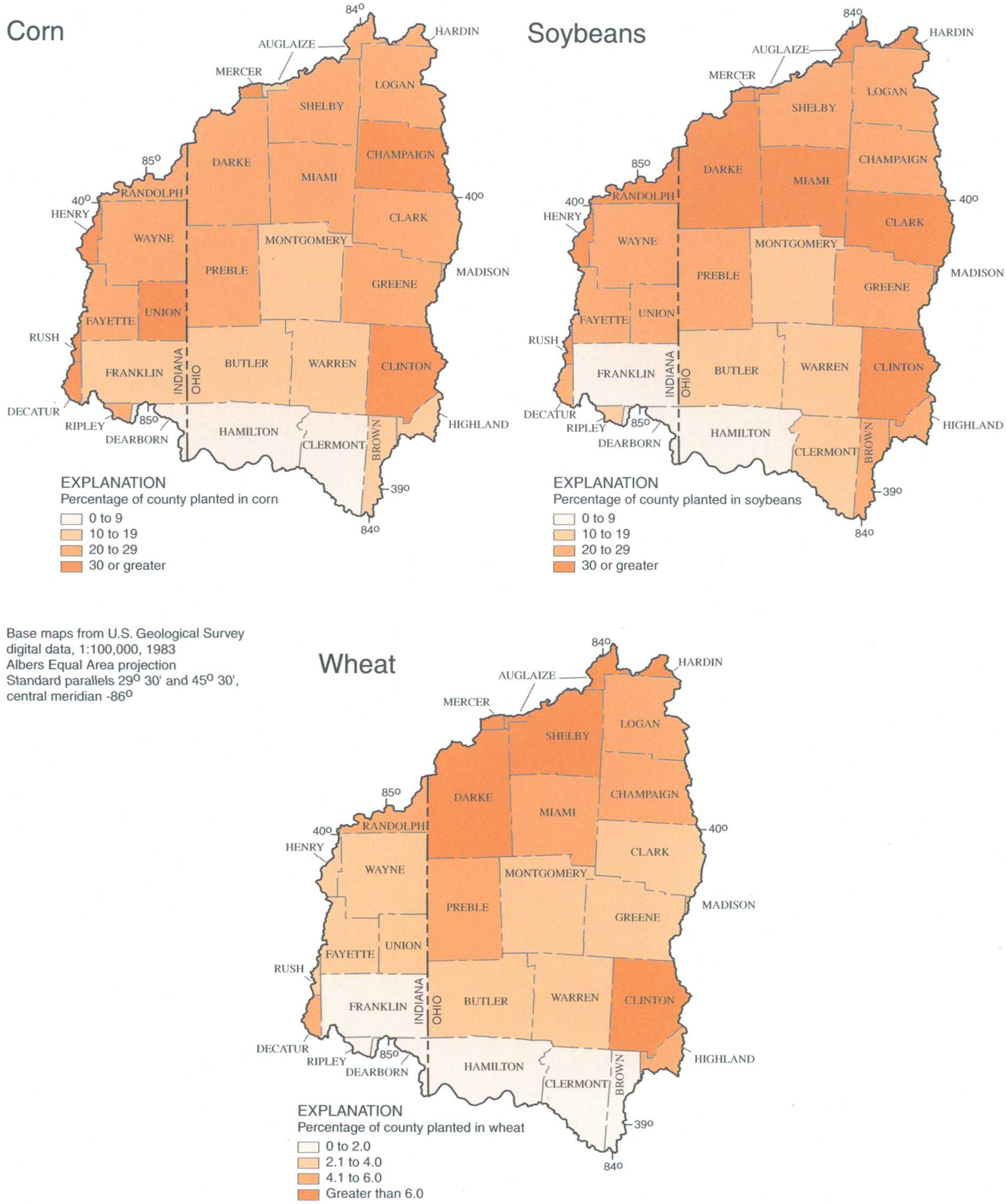


Figure 19. Percent of land planted in corn, soybeans, and wheat in the Great and Little Miami River Basins, Ohio and Indiana, 1997. (Data from Indiana Agricultural Statistics Service, 1998; Ohio Department of Agriculture, 1998.)

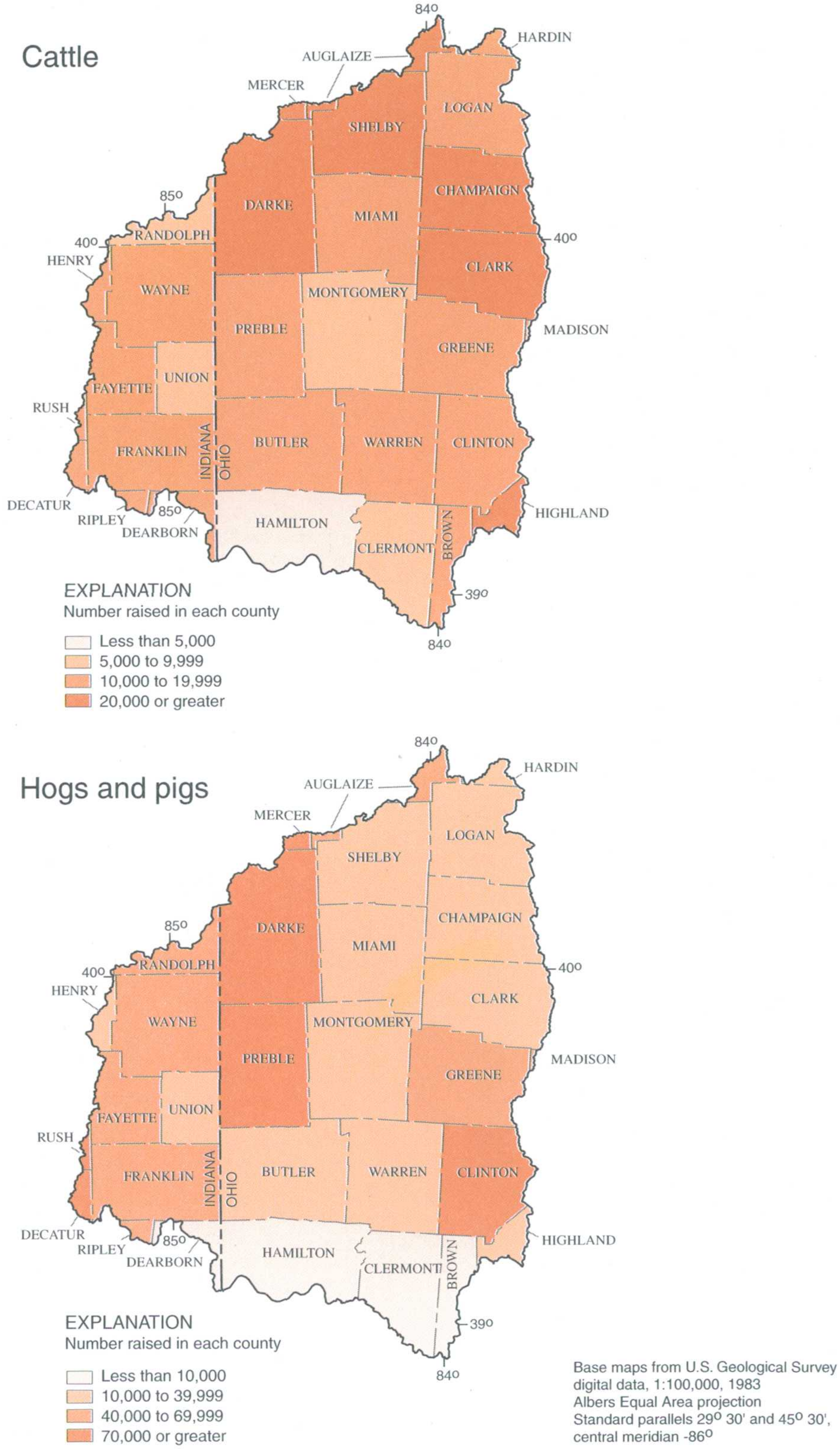


Figure 20. Livestock raised in the Great and Little Miami River Basins, Ohio and Indiana. (Data from Indiana Agricultural Statistics Service, 1996; Ohio Department of Agriculture, 1997.)

Nitrogen and phosphorus fertilizer-application rates were estimated from county-level data for 1991 (fig. 21). Application rates were highest in Rush and Decatur Counties, Ind., and Mercer County, Ohio. Estimates of the nitrogen and phosphorus content of animal manure produced in 1992 were highest in Mercer and Darke Counties, Ohio; nitrogen content is also high in Decatur County, Ind. (fig. 22). Although the timing of applications varies by crop, fertilizers generally are applied in the fall before planting. Manure is applied in the fall and winter (Dennis Baker, Darke County Extension, oral commun., 1998). For corn, fertilizers generally are applied at the time of planting or in the spring before planting. For wheat, phosphorus is applied at planting; nitrogen may be applied in spring through mid-April. Application methods vary with the type of product and crop and most frequently include broadcast, banded, and injection methods.

Pesticides are applied to agricultural croplands to enhance crop production and to control weeds (herbicides), insects (insecticides), and fungi (fungicides). These chemicals enter streams by way of runoff and eroded soil, wind transport to water bodies, and subsurface tile drains in areas of poor drainage. In areas underlain by permeable glacial deposits, leaching of pesticides to shallow ground water and subsequent discharge to local streams is another potential transport mechanism. In addition to leaching through the soil profile, contamination of aquifers can occur through poorly constructed wells or by induced infiltration of surface water that contains pesticides.

Estimated agricultural pesticide use in the study area indicates that 25 commonly applied pesticides accounted for nearly 95 percent of all agricultural pesticide use in the study area in 1992 (table 10). Of these, the most commonly applied pesticides were atrazine and metolachlor, which are used as pre- and post-emergent herbicides to control broadleaf and grassy weeds for corn and soybean production. Pesticides are applied mainly in spring and early summer by ground application; air application is rare. Farmers in the study area often rely on pre-plant herbicide applications for corn and soybeans (late April and early May). Post-planting applications (in June) often are applied for rescue treatment on corn and soybeans and occasionally on wheat crops, although few farmers rely solely on this method (Roger Bender, Shelby County Extension, oral commun., 1998).

Chlorpyrifos and terbufos are the most commonly applied insecticides in the study area (table 10). Insecticides generally are applied in the spring. Seed corn generally is treated with a combination insecticide/fungicide at low rates (Roger Bender, Shelby County Extension, oral commun., 1998). Although efforts are being made by the agricultural community to reduce insecticide use, applications are required during infestations and spot applications are applied in late summer. Soybean and wheat crops typically do not receive insecticide treatment. Fungicides are used as a seed treatment or seed-box treatment for soybeans.

Many agricultural activities traditionally result in the degradation or removal of native stream vegetation and instream habitat or bank erosion that cause sedimentation and siltation. Much of the observed stream-quality degradation in the study area is related to poor agricultural practices that often result in habitat modification around the banks of streams and other surface-water bodies (Rankin and others, 1997b). Often these modifications reduce riparian buffers and allow nutrients and sediment to enter streams. Runoff from fertilizers and organic wastes from livestock contribute to nutrient and organic enrichment of receiving waters. Buffers and filter strips (grassy areas planted next to drainage paths) filter sediment and chemicals before they reach waterways as well as reduce the loss of soil, fertilizers, and pesticides (Roger Bender, Shelby County Extension Office, oral commun., 1998). Preserving riparian vegetation adjacent to streams can provide a buffer zone that helps surface-water bodies better assimilate runoff from agricultural land use.

Sedimentation from poor agricultural practices is the largest nonpoint-source threat to stream and river integrity (Rankin and others, 1997a, b). Soils in the study area have a high erosion potential that makes nonpoint-source-management activities a priority for water- and soil-resource managers.

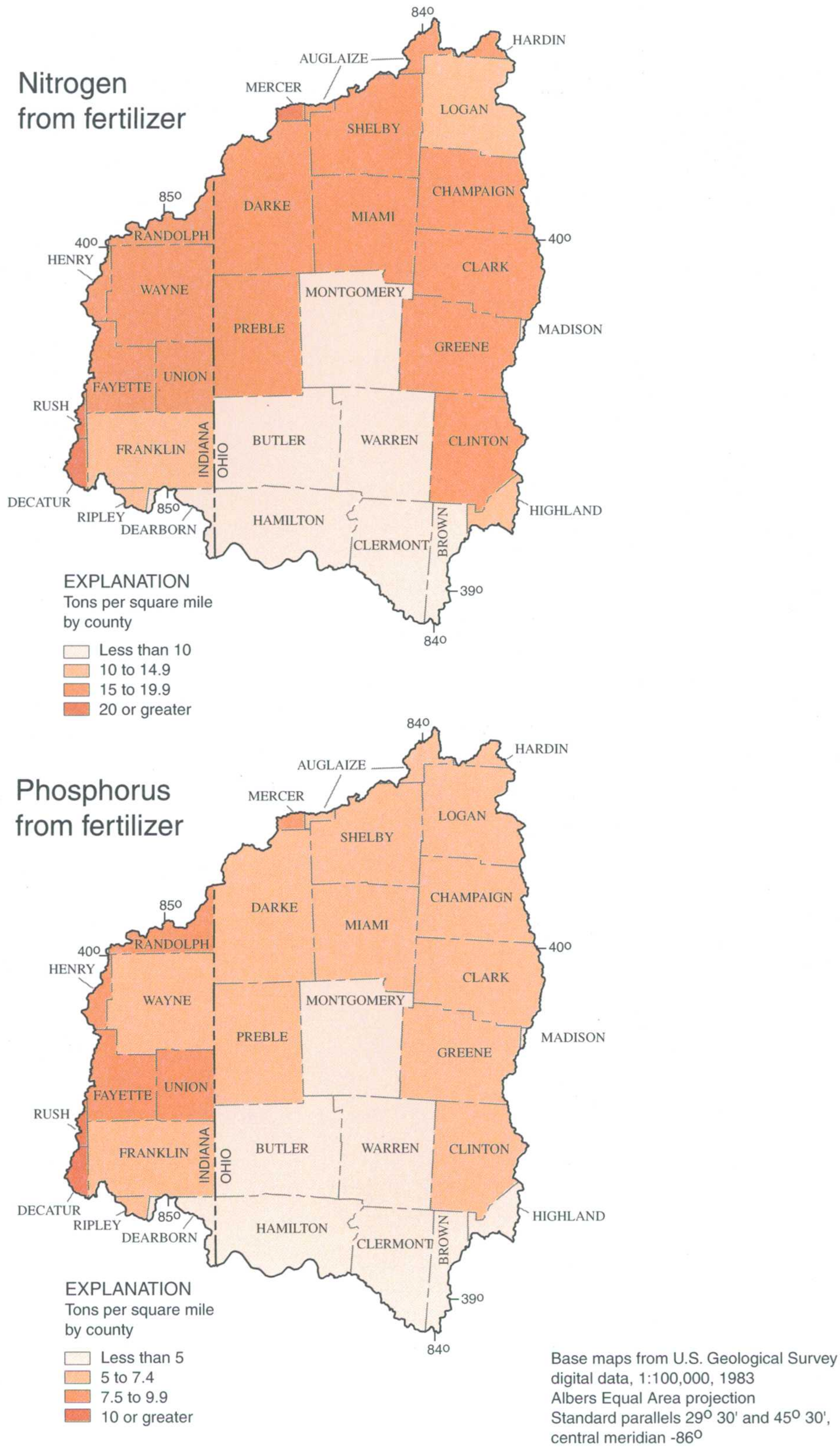


Figure 21. Fertilizer application rates in the Great and Little Miami River Basins, Ohio and Indiana, 1991. (Data from Battaglin and Goolsby, 1994; Puckett and others, 1998.)

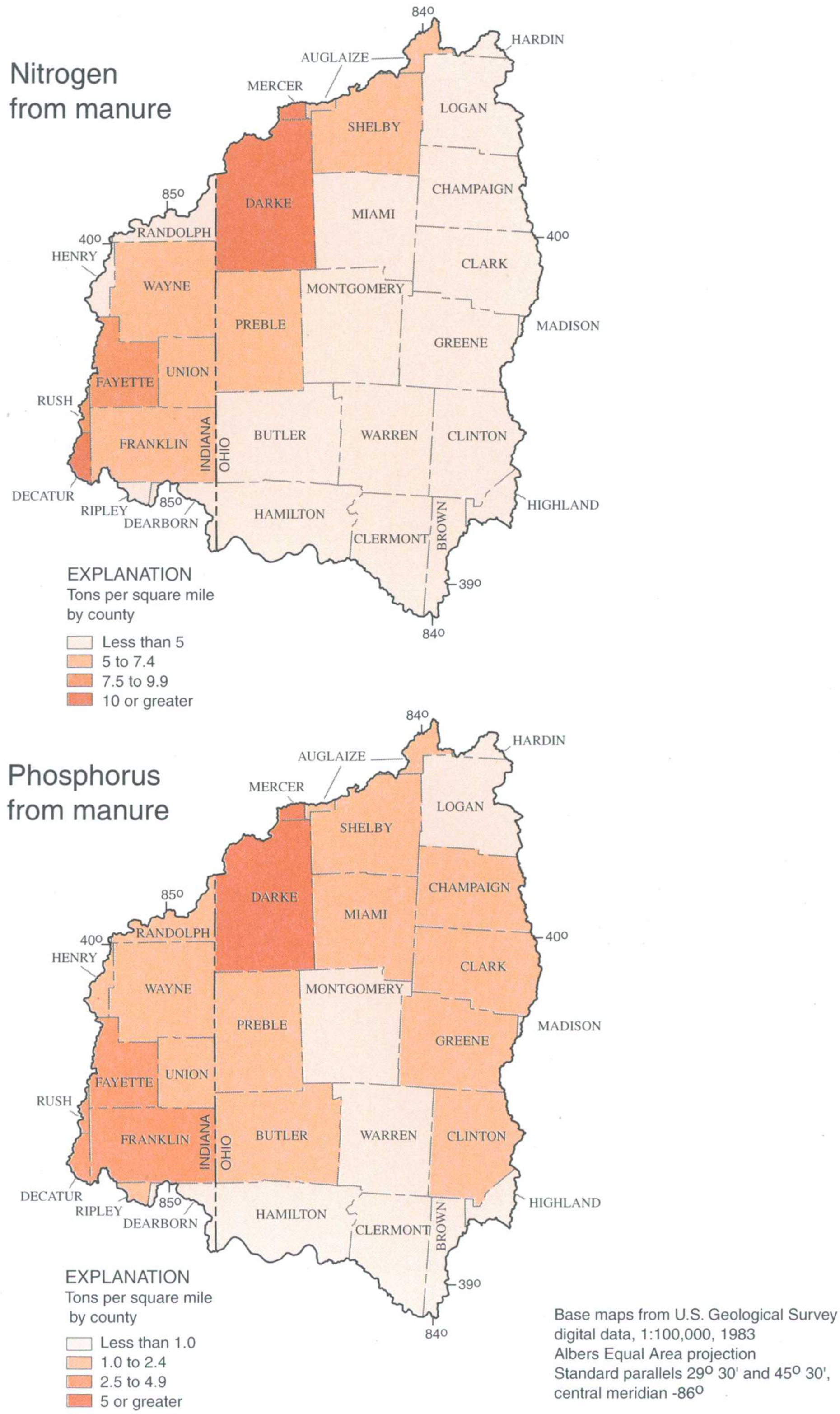


Figure 22. Nitrogen and phosphorus from animal manure in the Great and Little Miami River Basins, Ohio and Indiana, 1992. (Data from Puckett and others, 1998.)

Table 10. Estimated agricultural pesticide use in the Great and Little Miami River Basins, Ohio and Indiana

[Data modified from Michael S. Majewski, written commun., U.S. Geological Survey, 1998[1]; lb, pound; lb/acre, pound per acre]

Compound	Type	Active ingredient applied (lb)	Acres treated	Application rate of active ingredient (lb/acre)	
				Treated cropland	Total study area
2,4-d	Herbicide	141,284	297,729	0.47	0.03
Acetochlor	Herbicide	439,270	216,950	2.02	.09
Alachlor	Herbicide	439,130	227,553	1.93	.09
Atrazine	Herbicide	1,042,409	843,791	1.24	.22
Bentazon	Herbicide	94,904	124,668	.76	.02
Butylate	Herbicide	182,492	51,781	3.52	.04
Carbofuran	Insecticide	24,680	22,830	1.08	.01
Chlorpyrifos	Insecticide	84,644	79,940	1.06	.02
Clomazone	Herbicide	24,688	37,414	.66	.01
Cyanazine	Herbicide	471,913	220,984	2.14	.10
Dicamba	Herbicide	103,086	325,427	.32	.02
Dimethenamid	Herbicide	53,960	54,505	.99	.01
Eptc	Herbicide	89,614	22,218	4.03	.02
Ethalfluralin	Herbicide	25,205	28,061	.90	.01
Fonofos	Insecticide	31,282	31,000	1.01	.01
Glyphosate	Herbicide	245,929	411,757	.60	.05
Linuron	Herbicide	52,754	87,311	.60	.01
Metolachlor	Herbicide	966,176	498,051	1.94	.21
Metribuzin	Herbicide	55,746	173,436	.32	.01
Paraquat	Herbicide	38,493	66,342	.58	.01
Pendimethalin	Herbicide	238,539	255,835	.93	.05
Phorate	Insecticide	43,257	36,731	1.18	.01
Simazine	Herbicide	68,409	63,337	1.08	.01
Terbufos	Insecticide	69,070	59,939	1.15	.01
Trifluralin	Herbicide	60,294	58,147	1.04	.01

[1]Pesticide-use estimates are based on data taken from National Center for Food and Agricultural Policy and 1992 Census of Agriculture data bases. Sources and limitations of the data used to produce the estimates are described by U.S. Geological Survey (1998).

Sedimentation increases turbidity of waters, which reduces light penetration, alters oxygen availability, and reduces food supply for aquatic organisms. Sediments also cover spawning beds, reducing fish populations and increasing nutrient levels. Phosphorus attached to soil particles is carried into water during erosion (Hill and Mannering, 1995), and increased nutrient concentrations may cause algal blooms.

Many farmers have adopted conservation-tillage practices to control soil loss and reduce runoff. Conservation tillage is defined as any tillage and planting system that covers 30 percent or more of the soil surface with crop residue after planting to reduce soil loss from wind and water erosion (Anne Baird, Ohio State University Extension, Southwest District, written commun., 1998). Conservation-tillage systems reduce erosion rates by at least 50 to 60 percent and include no-till, ridge-till, strip-till, and mulch-till methods (Hill and Mannering, 1995). After harvesting season, plant residue generally is chiseled under or left on top of the soil. No-till and ridge-till methods and forms of strip tillage leave the soil undisturbed until planting and leave residual plant material on the soil surface. While conservation-tillage practices generally are increasing, no-till methods are decreasing in some areas because destructive crop diseases sometimes are carried over to the next season (Dennis Baker, Darke County Extension, oral commun., 1999). Conservation-tillage systems also may change physical properties of soils over time. Under the right conditions, untilled macropores (small channels created by earthworm activities, soil cracking, and root growth) can increase infiltration rate and increase the potential for leaching of fertilizers and pesticides into shallow aquifers (Hill and Mannering, 1995).

Tile-drain systems are common in areas where natural soil drainage is poor. New and replaced tiles generally are composed of plastic; older tiles are ceramic. Poorly permeable, clay-rich soils that require tile drainage generally are found in the northern part of the study area and cover large areas of Darke and Shelby Counties, Ohio (fig. 8). Surface-drainage systems are used throughout the basin and include ditches and grass waterways that drain and filter soils.

Urban Development and Industry

Since the 1970's, the percentage of urban land in the study area has increased about 2.4 percent (approximately 177 mi^2). Most of the recent urbanization is the result of conversion of agricultural land to new suburban and residential developments and is concentrated in zones bordering the major metropolitan areas of Dayton and Cincinnati (fig. 18). The effects of converting agricultural land to residential and commercial uses on water quality and aquatic organisms are not fully known. The effects may include increased erosion and channel instability, sediment loads, loss of aquatic habitat, runoff, and flooding frequency and intensity; reductions in groundwater recharge; and introduction of "urban" contaminants (deicing chemicals, heavy metals, volatile and semi-volatile organic compounds) to streams and aquifers. Residential and commercial development also will increase the amount of treated sewage effluent discharged into streams so that treated wastewater may become the dominant source of water to a stream during periods of low flow. This appears to have occurred in the Little Miami River in response to development in Greene and Warren Counties, Ohio, in the last couple of decades (Buchberger and others, 1997).

Major industries in the study area produce automobile and aircraft parts, business and computer equipment, steel, chemicals, household goods and appliances, paper products, and processed foods and beverages (Rowe and Baker, 1997). Industrial facilities generally are within or near the large urban areas of Dayton and Cincinnati. Liquid and solid wastes produced by industrial processes are a significant source of contamination as treated wastewater and cooling waters are discharged to streams and solid wastes are disposed of in landfills or by incineration.

Recreation

Recreational activities and facilities are available at 14 state parks in the study area. Many of these parks are developed around lakes where the use of boats and other watercraft can affect water quality. Many parks restrict the type and size of boat motors in an attempt to protect water resources. Reservoirs, constructed for flood control, also provide outdoor activities like hunting, fishing, camping, swimming, hiking, and boating. Camp sites along these protected areas often have primitive latrines that can threaten water quality. Hundreds of lakes, ponds, and gravel pits in the study area also are used for recreation, fishing, or aesthetic purposes (Indiana Department of Natural Resources, 1988).

Mineral, Oil, and Gas Resources

Industrial minerals mining accounts for less than 1 percent of land use in the study area. Industrial minerals are mined for commercial and industrial uses, as opposed to coal and gas that primarily are mined for energy production. Consolidated and unconsolidated geologic materials (limestone, shale, sand, and gravel) are mined for their economic value. There are approximately 176 active stone quarries in the study area. Active quarries include sand and gravel; limestone and dolomite; crushed stone; and several peat, clay, and shale operations. These industries require variable amounts of water to process their products.

Mining-related water withdrawals from streams can reduce streamflow; the discharge of waste or process water to surface-water bodies from quarries can alter the quality of the receiving waters (Herricks and others, 1974). Ground-water resources also are affected; mining operations may remove protective surficial materials, creating large cavities and exposing the water table to surface-derived contaminants. Mining operations also can disrupt ground-water flowpaths and alter recharge rates to aquifers; higher infiltration rates can increase aquifer storage but may increase the potential for ground-water contamination. Where pumping is done to keep mines and quarries free of water, ground-water levels near the quarry operation may decline (Howard and Wright, 1974). Mining and associated activities also can reduce or eliminate terrestrial and aquatic habitat (Herricks and others, 1974).

The spatial distribution of industrial minerals operations and oil and gas wells in the study area reflects geologic and economic factors (fig. 23). Limestone and dolomite quarries are located in the northern half of the study area, where sufficiently thick deposits of high-quality Silurian limestone and dolomite beds are accessible below thin (less than 75 ft thick) glacial drift (Stout, 1941). Most active quarries in the study area extract limestone and dolomite from the Salamonie Dolomite, Brassfield Limestone, Dayton Limestone, or Laurel Dolomite formations. Quarries in Clinton, Greene, and Miami Counties were the three largest producers of limestone and dolomite in the Ohio part of the study area and, together, produced 67 percent of the total tonnage sold in the study area in 1997 (Wolfe, 1998). Production data were not available for counties in Indiana. Limestone and dolomite produced in the study area are used for commercial building stone; road construction; and the production of Portland cement, lime, and agricultural lime.

Sand and gravel mining operations generally follow the spatial distribution of coarse-stratified glacial deposits in the study area (fig. 7) and are clustered along main-stem segments of the Great and Little Miami Rivers (fig. 23). Sand and gravel operations are found in 16 counties of the study area, with the majority of sand and gravel pits concentrated near major transportation corridors in the Dayton and Cincinnati Metropolitan Areas. Hamilton and Butler Counties ranked first and third in Ohio in 1997 sand and gravel production, respectively, and together were responsible for producing nearly half the total tonnage sold in the entire study area (Wolfe, 1998). Minor amounts of crushed stone, clay, shale, and peat also are produced in the study area.

Minor amounts of oil and natural gas are produced in the study area, primarily from wells completed in the Ordovician Trenton Limestone along the Lima-Indiana trend. The Lima-Indiana

Figure 23. Location of mineral industries and oil and gas wells in the Great and Little Miami River Basins, Ohio and Indiana. (Data from Wolfe, 1998; Nelson Shaffer, Indiana Geological Survey, written commun., 1998.)

oil and gas trend was the first giant petroleum field developed in the United States and was drilled extensively in the late 1800's and early 1900's (Wickstrom and others, 1992). The Lima-Indiana oil and gas fields trend northeast along the northwestern boundary of the study area; past production of oil and natural gas occurred in Darke, Logan, and Shelby Counties, Ohio, and in Randolph and Wayne Counties, Ind. There were a total of 146 active oil and gas wells in the study area in 1997, with most located in Shelby and Logan Counties, Ohio (fig. 23). Leakage of petroleum hydrocarbons or saline brines from abandoned or improperly sealed oil wells into adjacent surface-water bodies or underlying freshwater aquifers can degrade water supplies. Such degradation has been reported in other parts of Indiana and Ohio but is not considered to be a significant problem in the study area.

Waste Disposal

Waste-disposal practices differ by waste type and can have an adverse effect on water resources. Methods of waste disposal include landfills, treatment facilities, subsurface injection, and incineration. In Ohio, more than 80 percent of solid waste is landfilled, and landfill capacities range between 5 and 10 years. Almost 70 percent of Indiana's solid waste is disposed of in landfills with capacities greater than 10 years (Levy, 1997a). Municipal and private solid-waste landfills receive materials from residential, commercial, and industrial sources and contain paper, plastic, household garbage, metal, glass, and yard trash. Permitted landfills are regulated by the Ohio EPA and IDEM. Clay and rubber liners, caps, and leachate-collection systems are used to help prevent liquids from entering or leaving the sites; ground-water-monitoring networks are installed to detect the migration of contaminants from the landfill. Numerous landfills, particularly along the Great Miami River, are old sand and gravel pits that have been filled with municipal and industrial waste. Such sites were used for waste disposal with little regard to their potential effect on the environment; at the time many of these sites were in operation, the effects of waste disposal on the environment were neither widely known nor considered. As a result, contaminants in landfill leachate have migrated to the BVAS or nearby surface-water bodies, and many of these sites are undergoing remediation and cleanup.

Of the 35 solid-waste landfills in the study area, 6 have capacities greater than 750 tons per day (table 11). Two facilities within the study area are among the 10 solid-waste landfills in Ohio with the largest waste receipts (Ohio Environmental Protection Agency, 1997d). These facilities, in Hamilton and Montgomery Counties, received approximately 1.3 million and 603,000 tons of waste in 1996, respectively.

Table 11. Large municipal solid-waste landfills in the Great and Little Miami River Basins, Ohio and Indiana
[Modified from Levy, 1997b]

Name	Location	Capacity (tons per day)
ELDA Recycling and Disposal Facility	Hamilton County, Ohio	1,500 to 2,000
Rumpke Sanitary Landfill, Inc.	Hamilton County, Ohio	>2,000
Cherokee Run/Bellefontaine Landfill	Logan County, Ohio	1,000 to 1,499
Stoney Hollow Landfill	Montgomery County, Ohio	>2,000
Bigfoot Run Landfill	Warren County, Ohio	1,000 to 1,499
Randolph Farms Landfill	Randolph County, Indiana	750 to 999

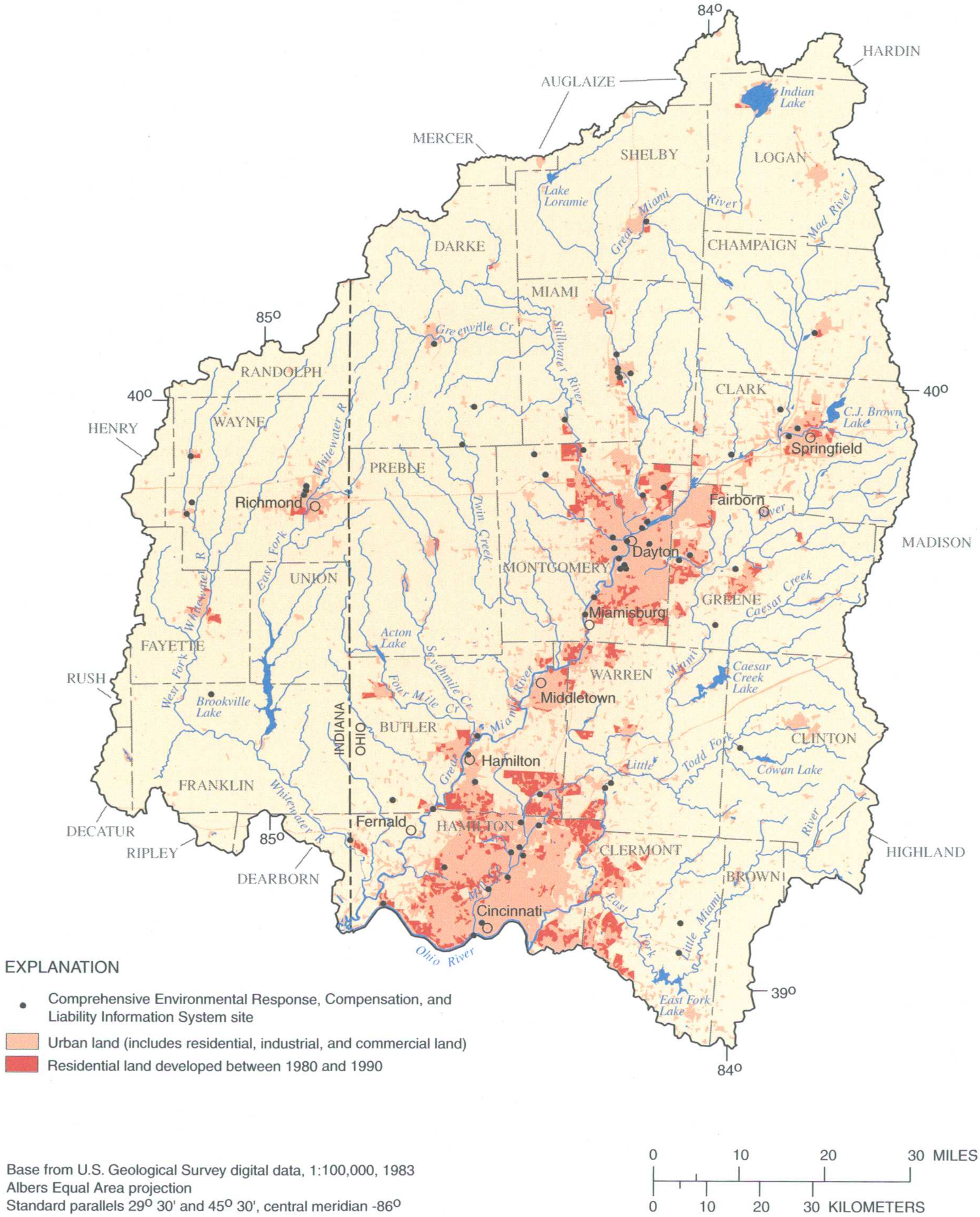
Hazardous wastes are those wastes that have toxic, ignitable, explosive, corrosive, reactive, or radioactive properties, making them harmful to human health (Miami Valley Regional Planning Commission, 1987). Management and disposal of solid, hazardous, and medical wastes and underground storage tanks are regulated under the Resource Conservation and Recovery Act (RCRA) passed by Congress in 1976. Prior to RCRA, many wastes were disposed of improperly, including indiscriminate dumping of hazardous waste on the ground, in waterways, and in unlined landfills and disposal pits dug out of permeable sand and gravel deposits. In 1980, through the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Congress created a tax on the chemical and petroleum industries. This tax provides a trust fund for the cleanup of abandoned or uncontrolled hazardous-waste sites ("Superfund" sites). Hazardous-waste sites (warehouses, manufacturing facilities, processing plants, and landfills) are tracked by the USEPA on the Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS) list; 68 CERCLIS sites are in the study area (fig. 24). Of these, 12 sites are listed on the National Priority List and receive Federal funding for cleanup. Nine sites are privately owned and represent a mix of old landfills and industrial facilities. The other three sites (fig. 24) are Federal facilities: the Feed Materials Production Center in Fernald, Ohio; the Mound Plant in Miamisburg, Ohio; and Wright-Patterson Air Force Base in Fairborn, Ohio.

The Feed Materials Production Center, in operation from 1952 to 1989, processed uranium ore for nuclear-weapon reactors for the U.S. Department of Energy. Waste-disposal practices resulted in on-site contamination, uranium-bearing effluent leaving the site through a storm-sewer ditch, and wastewater lines discharging to the Great Miami River (U.S. Environmental Protection Agency, 1998b). Wastes at the Production Center include low-level radioactive waste, mixed hazardous and radioactive waste, oils, solvents, and fly ash. The Mound Plant, in operation since 1948, is a research, development, and production facility formerly operated by the U.S. Department of Energy, with an emphasis on small explosive components and nuclear technology. Potential sources of ground- and surface-water contamination include tritium, plutonium, and volatile organic compounds (VOC's) in contaminated soils and in ditches, canals, and ponds carrying surface water from the facility to the Great Miami River (U.S. Environmental Protection Agency, 1998c). At Wright-Patterson Air Force Base, wastes (solvents, contaminated thinners, degreasing sludges, and miscellaneous hazardous chemicals) were disposed of in several unlined waste-disposal areas (U.S. Environmental Protection Agency, 1998d). Leaks of jet fuel and other hazardous materials from on-site storage facilities also have occurred. Surface water and ground water have been affected by releases of contaminants from several locations on the Base (Schalk and others, 1996).

The USEPA also regulates facilities that release, store, or transfer toxic chemicals and compounds. These facilities are monitored by use of the Toxic Release Inventory (TRI) and represent sites where spills or improper handling of hazardous materials could lead to the accidental release of contaminants to the environment. As of 1998, 627 facilities in the study area were listed in the TRI data base; most of these are found in or near the Dayton or Cincinnati Metropolitan Areas (fig. 25).

Improper on-site disposal of human wastes also can cause water-quality problems. Septic tanks and soil-adsorption systems are common features of on-site treatment facilities used to treat domestic sewage and wastewater in rural areas (Mancl, 1997). Septic tanks remove solids from wastewater. Soil adsorption fields filter and treat the clarified septic-tank effluent. Failed septic tanks allow solids to enter and clog the soil adsorption field, thereby releasing nutrient-rich effluent into the surrounding areas where it can migrate to underlying aquifers or flow to nearby surface-water bodies, possibly leading to eutrophication and nuisance algae blooms.

Residential, commercial, and industrial wastewater and some stormwater runoff are processed through wastewater-treatment plants.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Albers Equal Area projection
Standard parallels 29° 30' and 45° 30', central meridian -86°

Figure 24. Comprehensive Environmental Response, Compensation, and Liability Information System sites in the Great and Little Miami River Basins, Ohio and Indiana.

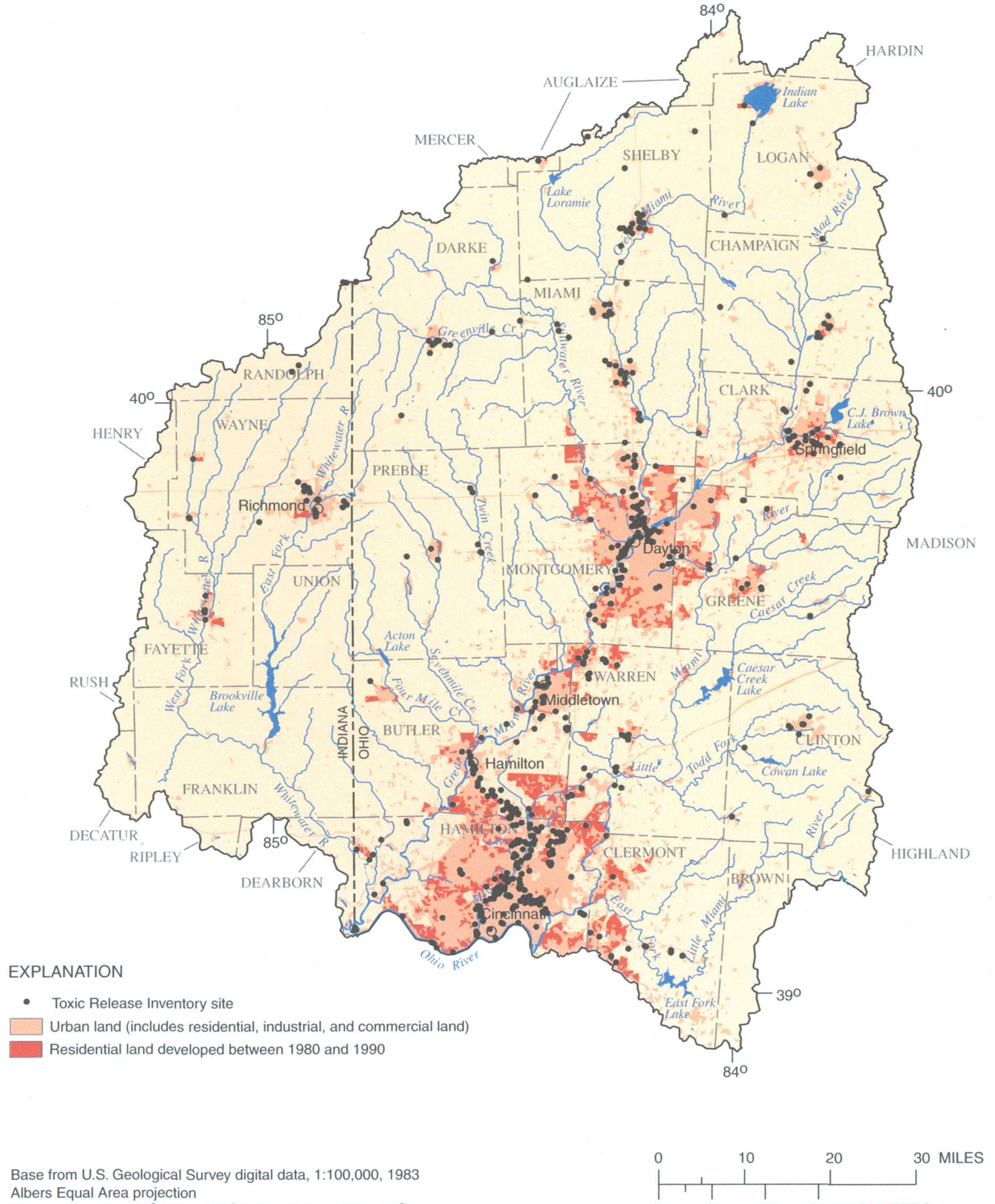


Figure 25. Toxic Release Inventory sites in the Great and Little Miami River Basins, Ohio and Indiana.

Wastewater contaminants include bacteria and viruses, suspended solids, organic solvents, nitrogen from human waste, phosphorus from detergents and water softeners, and oxygen-demanding wastes. Paint and paint removers, oven cleaners, floor-care products, insecticides and herbicides, automobile antifreeze, and waste oil are common chemicals that are transported to wastewater-treatment plants by drains and sewer lines.

Combined sewers collect and transport sanitary and industrial wastewater as well as stormwater runoff to treatment plants (Ohio Environmental Protection Agency, 1998a). Untreated water exceeding the capacity of the sewers during storms overflows into ditches, streams, rivers, or lakes. Such combined-sewer overflows (CSO's) are often a contributing cause of water-quality violations and designated-use impairments for surface-water bodies. The Lower Little Miami River, for example, receives periodic discharges of raw sewage and other pollutants from 55 CSO's, contributing to its partial- and non-attainment record. During a 12-month period, 13 of the 55 combined-sewer overflows in Hamilton County discharged 295 times and released a total 230 Mgal of untreated water into receiving water bodies (Ohio Environmental Protection Agency, 1995a).

Primary wastewater treatment involves processes like screening and settling that are capable of removing coarse solids; a reduction of 30 to 50 percent of the solids usually is possible. Secondary treatment turns waste to biomass by creating an environment that promotes the growth of naturally occurring microbes that digest waste products and incorporate the waste into new biomass. This biomass is separated from the treated water prior to discharge and recycled for further use. Excess biomass (sludge) is removed and disposed of by incineration or landfilling. Many facilities in the study area recycle sludge by applying it to soil on cropland. While secondary treatment normally is considered to provide 85-percent reduction in pollutants, many systems achieve efficiencies of 95 percent or more (James Simpson, Ohio Environmental Protection Agency, Southwest District, written commun., 1998). All large wastewater-treatment plants (processing 1 Mgal/d or more) in the study area use advanced secondary treatment. Advanced secondary treatment, also called tertiary treatment, includes a variety of processes that exceed the capabilities of conventional secondary treatment. It can provide further reduction of conventional pollutants such as suspended solids or oxygen demand, or it can target specific waste constituents such as ammonia or phosphorus. In the Ohio part of the study area, most advanced secondary treatment is directed towards reducing wastewater ammonia loads (Richard Shoemaker, Ohio Environmental Protection Agency, Southwest District, oral commun., 1998).

Discharges from municipal and industrial wastewater-treatment plants are regulated under the National Pollutant Discharge Elimination System (NPDES) Permit Program. A NPDES permit restricts the allowable amount of pollutants discharged into a stream as well as the concentration of pollutants in the effluent water. The USEPA tracks information regarding discharges from industrial and municipal wastewater-treatment plants under the Permit Compliance System (PCS) data base. There are 382 PCS facilities in the study area (fig. 26); of these, 251 were municipal wastewater-treatment plants. In 1995, these plants discharged an average 1,760 Mgal/d of treated wastewater to study-area streams or directly into the Ohio River (U.S. Geological Survey, 1995). Treatment plants typically are located near streams in low-elevation areas with permeable sand- or gravel-rich soils (Miami Valley Regional Planning Commission, 1987) and discharge treated water into surface-water bodies, where streamwater is used to dilute the effluent. Some wastewater is pretreated before it reaches a treatment facility. Under the Federal Clean Water Act, industrial facilities discharging wastewater to publicly owned treatment plants are required to pretreat the effluent to remove or greatly reduce the concentration of harmful chemicals (Ohio Environmental Protection Agency, 1998b). Because publicly owned treatment plants typically are not designed to treat these chemicals, pretreatment programs are used to eliminate these substances before they can be released into public sewer systems.

Figure 26. Location and discharge amounts from industrial and municipal wastewater-treatment plants under the U.S. Environmental Protection Agency Permit Compliance System in the Great and Little Miami River Basins, Ohio and Indiana.

Pollution from point sources such as industrial plants, wastewater-treatment plants, and CSO's declined substantially from 1988 to 1996 because of stronger regulations and financial-assistance efforts to improve wastewater treatment. Nonpoint sources (for example, urban and agricultural runoff and hydromodification) have increased in importance as major sources of impairment of rivers and streams in the study area (Rankin and others, 1997a, b). These sources of pollution are major factors that affect surface-water quality and aquatic life. Throughout Ohio, problems resulting from nutrients, habitat modification, and siltation have increased; problems associated with organic enrichment, ammonia, and metals have declined (Rankin and others, 1997b). Contamination of streams and stream sediments by heavy metals derived from industrial point sources at levels that violate human-health standards or aquatic-life-use criteria are uncommon and are restricted to a few localized parts of the study area.

Watershed assessments conducted by the Ohio EPA in the Little Miami and Upper Great Miami River Basins (Ohio Environmental Protection Agency, 1995a, 1996a) and the Preliminary Assessment of Use Attainability (PAUSE) study conducted by the University of Cincinnati (Buchberger and others, 1997) in the Little Miami River Basin found that point and nonpoint sources are important contributors to the total nutrient load in both watersheds. Although the PAUSE study found that nonpoint sources were the greatest contributors of total phosphorus to the Little Miami River, the study also found that point sources and nonpoint sources contribute about equally to the load of soluble reactive phosphorus in the Little Miami River. Results of an Ohio EPA survey of the Middle and Lower Great Miami River Basin show a general improvement in the water-quality conditions (Ohio Environmental Protection Agency, 1997b). Throughout the study area, improvements in the water-quality conditions and the use-attainment status of streams largely are attributed to upgrades at major wastewater-treatment plants in the study area. For example, mean annual ammonia loads discharged to the Great Miami River from five major wastewater-treatment plants were reduced from approximately 750 lb/d (pounds per day) in 1985 to less than 300 lb/d in 1995 (Ohio Environmental Protection Agency, written commun., 1996). Improvements in water quality in the main stem Little Miami River also have been attributed to upgrades at major wastewater-treatment plants in the basin.

Water Use

Water from streams and aquifers in the Great and Little Miami River Basins is used for municipal, industrial, and rural water supplies; irrigation; and the generation of energy. Instream water uses include hydroelectric-power generation, wastewater assimilation, recreational boating, fish and wildlife habitat, and swimming (Clark, 1980). Estimated water withdrawals from streams and aquifers in the study area averaged 745 Mgal/d in 1995 (table 12); of this amount, approximately 48 percent was derived from surface-water bodies (including the Ohio River) and 52 percent was pumped from study-area aquifers (fig. 27).

Table 12. Estimated water use in the Great and Little Miami River Basins, Ohio and Indiana, 1995

[Mgal/d, million gallons per day; data from U.S. Geological Survey, 1995]

Category	Total withdrawal (Mgal/d)	Percent of total water use[1]
Public supply[2]	377.46	50.6
Domestic	30.58	4.1
Commercial	20.33	2.7
Industrial/mining	97.57	13.1
Agricultural (irrigation/livestock/ animal specialties)	14.09	1.9
Thermoelectric power	205.34	27.5
Total	745.37	

[1]Column does not sum to 100 percent due to rounding.

[2]The City of Cincinnati withdrew an average of 114 million gallons per day from the Ohio River in 1995.

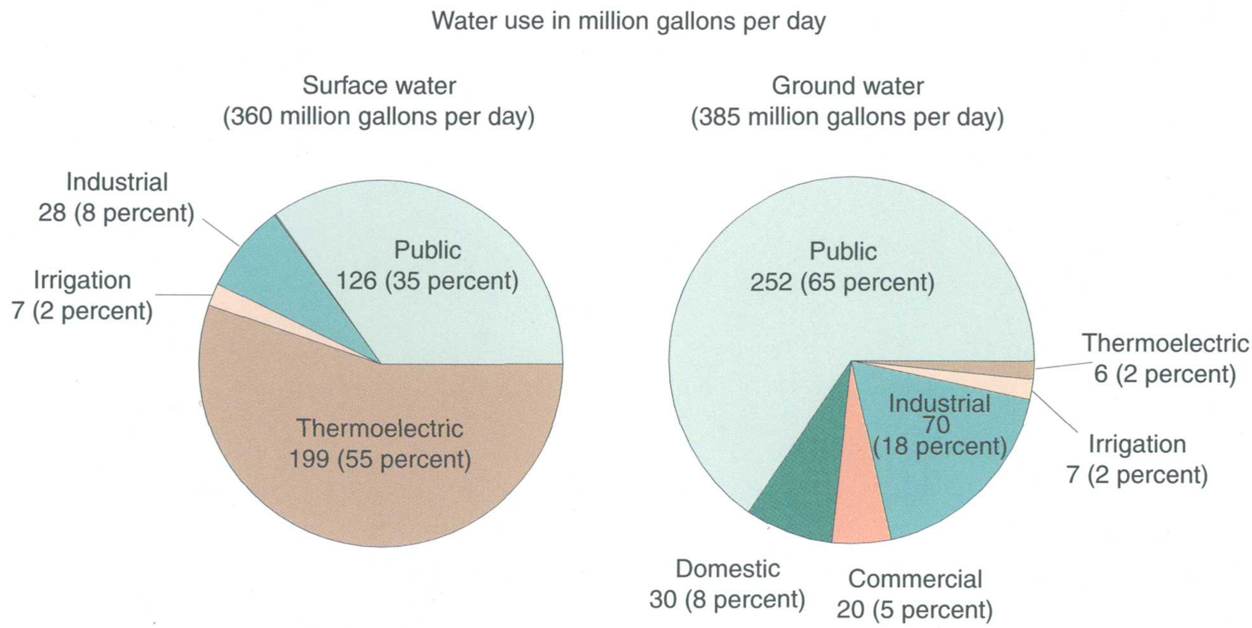


Figure 27. Estimated water use in the Great and Little Miami River Basins, Ohio and Indiana, 1995.

In terms of overall water use, the largest use categories in the study area were public supply (51 percent) and thermoelectric-power generation (28 percent). Public supply consumes 65 percent (252 Mgal/d) of total ground-water withdrawals. Of the 126 Mgal/d of surface water used for public supply, approximately 90 percent (114 Mgal/d) was water withdrawn by the City of Cincinnati from the Ohio River. Instream withdrawals for thermoelectric-power generation and cooling water represent 55 percent (199 Mgal/d) of total surface water used in 1995.

Ground water is the primary source of drinking water in the study area. The distribution of public and non-public ground-water users making withdrawals greater than 100,000 gal/d shows that most ground water is pumped from glaciofluvial sand and gravel deposits of the BVAS; most well fields are located near major streams or their tributaries (fig. 28). Water use is generally greater near largely populated or industrial areas. Freshwater withdrawals are greatest in the counties including and surrounding Dayton and Cincinnati, Ohio (Lloyd and Lyke, 1995).

Alternate sources of drinking water include small sand and gravel lenses in till, bedrock aquifers, and surface impoundments throughout the study area. In the Ohio part of the study area underlain by the BVAS, nearly 100 percent of the private and approximately 85 percent of the public water supply is obtained from wells completed in the buried-valley aquifer (Ohio-Kentucky-Indiana Regional Council of Governments, 1988). Only a few suppliers in the Ohio part of the study area rely on surface water instead of ground water: Piqua (Miami County), Wilmington (Clinton County), Greenville (Darke County), Batavia (Clermont County), and Arlington Heights and Norwood (Hamilton County). In Indiana, almost 100 percent of the public and private water supply in the BVAS area comes from ground water. A few small users concentrated in Wayne and Franklin Counties (Ohio-Kentucky-Indiana Regional Council of Governments, 1991) rely on surface water. None of the surface-water sources, however, has the capacity to supply the 11 Mgal/d of ground water drawn from the BVAS in Indiana.

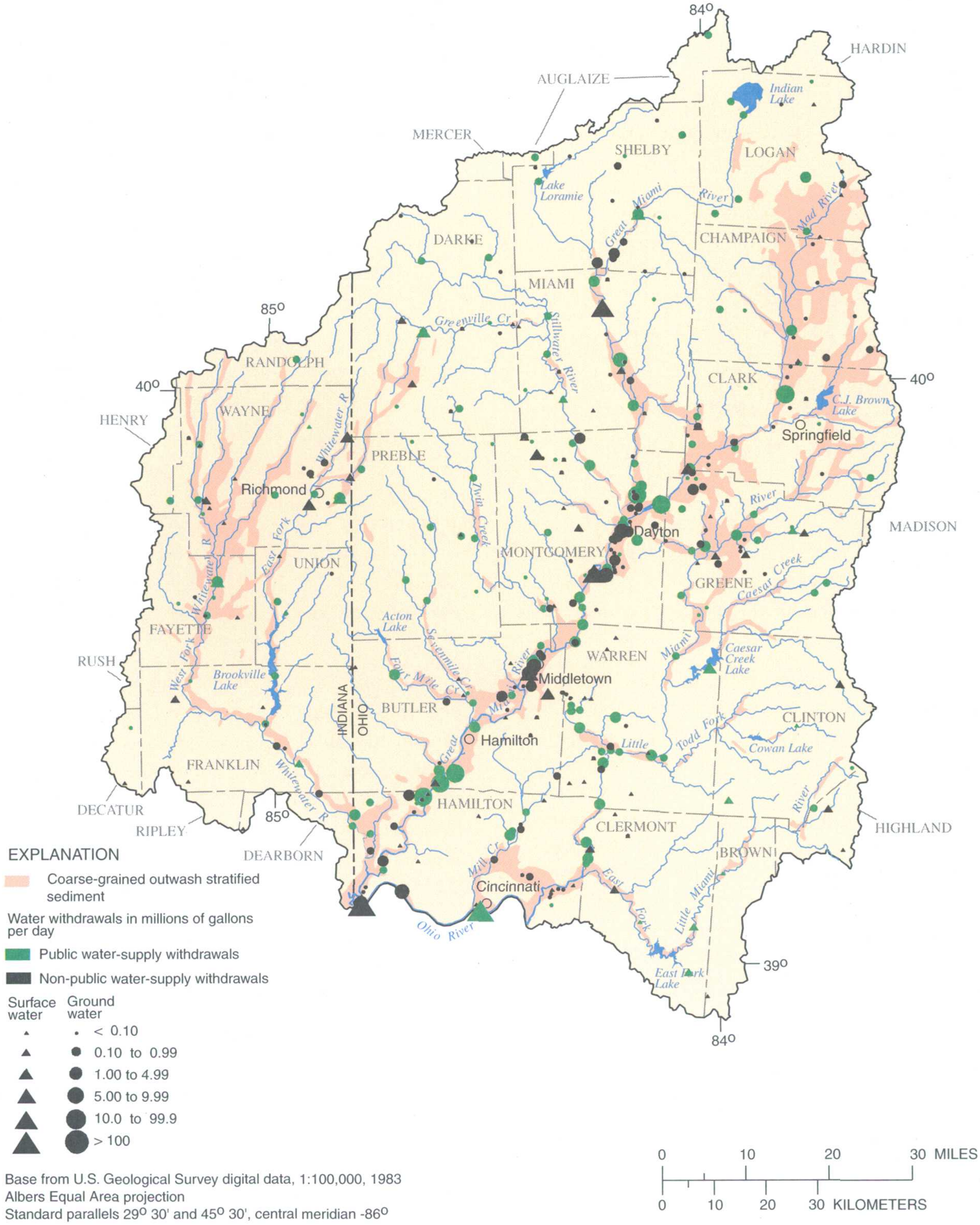


Figure 28. Locations of public and non-public water supplies withdrawing surface water or ground water at rates exceeding 100,000 gallons per day in the Great and Little Miami River Basins, Ohio and Indiana.

Effects of Environmental Setting on Water Quality

Surface-Water Quality

Surface-water quality in the study area is affected by a variety of natural and human factors. Natural factors include climate, physiography, geology, soil type, and ecology. Human factors include population density; land use; and release of contaminants to air, water, and soils from a variety of sources including industrial facilities, municipal wastewater-treatment plants, CSO's, and urban and agricultural nonpoint sources.

Federal, State, and regional government agencies and local universities collect water-quality data at a variety of locations in the study area. The Ohio EPA collects nutrient and major-ion samples at five sites on a routine (monthly) basis within the Ohio part of the study area. These sites are on the Little Miami River at Oldtown (streamflow-gaging station 03240000, fig. 9), the Stillwater River at Pleasant Hill (03265000, fig. 9), the Mad River at Eagle City (03267900, fig. 9), and the Great Miami River at Dayton (03270500, fig. 9) and Miamisburg (fig. 1) (water-quality-monitoring station 03271510). To assess current water-quality conditions in individual watersheds, the Ohio EPA and IDEM conduct comprehensive biological and water-quality synoptic surveys on a rotational basis within the study area. A list of recent watershed surveys is shown in table 13. Other agencies conducting water-quality sampling include the Ohio River Valley Water Sanitation Commission (ORSANCO), which collects monthly water-quality samples at two sites near the mouths of the Great and Little Miami Rivers. These data have been collected since 1975 as part of ORSANCO's manual sampling program and include determinations of pH, alkalinity, sulfate, major metals, nutrients, bacteria, and selected trace elements (Ohio River Valley Water Sanitation Commission, 1990). ORSANCO also conducts studies that examine specific water-quality issues, such as a recent study examining 1995 herbicide loadings in the Lower Ohio River Basin that included data from the Lower Great Miami River and the Lower Little Miami River (Ohio River Valley Water Sanitation Commission, 1997).

Two universities conducting water-quality work in the study area are Heidelberg College and the University of Cincinnati. Since 1996, Heidelberg College has collected major-ion, nutrient, and herbicide samples at the Great Miami River at Miamisburg (David Baker, Heidelberg College, written commun., 1997). The University of Cincinnati collected nutrient data within the Little Miami River Basin in 1996 and 1997 (Buchberger and others, 1997).

Water-quality samples were collected routinely by the USGS at four locations in the study area from the 1970's through 1993 as part of the National Stream Quality Accounting Network (NASQAN) Program. Sampling sites were located at the Little Miami River at Milford, Ohio (near streamflow-gaging station 03245500, fig. 9), Great Miami River at New Baltimore, Ohio (streamflow-gaging station 03274600, which is 14.3 mi downstream from 03274000 on fig. 9), and Whitewater River at Brookville, Ind. (03276500, fig. 9). The latter site was relocated to the Whitewater River near Alpine, Ind. (03275000, fig. 9), in 1984. Data collected from NASQAN sites are used to characterize surface-water quality in the study area. The NASQAN data indicate that the rivers and streams in the study area generally have a calcium-magnesium-bicarbonate composition. The trilinear diagram in figure 29 graphically groups water types on the basis of the milliequivalent percentages of major cations and anions in the water. Only a slight variation in the major-ion chemistry of surface water can be seen, indicating that the major-ion chemistry of the stream water does not vary significantly despite seasonal changes in streamflow and runoff composition (fig. 29). The Great Miami River data show a high percentage of sulfate and chloride relative to other sites, possibly caused by the influence of treated wastewater. The median values for water hardness at all sites were more than 180 mg/L (milligrams per liter) as calcium carbonate ($CaCO_3$); concentrations above this level are considered to be very hard (Durfor and Becker, 1964) and usually require softening prior to domestic or industrial use.

Measurements of pH indicate slightly alkaline waters, with recorded pH values generally between 7.7 and 8.5 (fig. 30). The median

Table 13. Biological and water-quality surveys conducted in the Great and Little Miami River Basins, Ohio and Indiana

Watershed	Sampling year	Reference
Ohio Environmental Protection Agency surveys		
East Fork Little Miami River	1984	Ohio Environmental Protection Agency, 1985
Mad River	1985	Ohio Environmental Protection Agency, 1986
Stillwater River	1990	Ohio Environmental Protection Agency, 1991
Sevenmile Creek	1991	Ohio Environmental Protection Agency, 1992a
Mill Creek Basin (Cincinnati)	1992	Ohio Environmental Protection Agency, 1994a
Lower Mad River and Hebble Creek	1993	Ohio Environmental Protection Agency, 1994b
Little Miami River	1993	Ohio Environmental Protection Agency, 1995a
Mill Creek (Dayton)	1994, 1995	Ohio Environmental Protection Agency, 1995b, 1996b
Upper Great Miami River	1994	Ohio Environmental Protection Agency, 1996a
Middle and Lower Great Miami River	1995	Ohio Environmental Protection Agency, 1997b
Twin Creek	1995	Ohio Environmental Protection Agency, 1997c
Indiana Department of Environmental Management surveys		
Whitewater River Basin	1997	Holdeman and others, 1999

alkalinity values range from 209 mg/L as $CaCO_3$ for the Great Miami River at New Baltimore, Ohio, to 279 mg/L as $CaCO_3$ for the Whitewater River at Alpine, Indiana. Specific conductance values are lowest at the Whitewater River sites and highest for the Great Miami River at New Baltimore, Ohio (fig. 30). Median values of percent saturation of dissolved oxygen were more than 90 percent at all four sites. Median values at the two locations on the Whitewater River were above 100 percent. Dissolved-oxygen concentrations vary seasonably and diurnally in streams within the study area. Seasonal changes in concentrations are largely temperature driven, with higher concentrations during the cooler months and lower concentrations during the warmer months. Diurnal variations reflect variations caused by biologic activity, such as photosynthesis. Other short-term changes may be in response to inputs of oxygen-consuming substances during storms or accidental discharges of organic-rich wastewater from industrial or municipal treatment plants.

Water quality in most streams and rivers in the study area is considered to be good and often exceeds minimum Clean Water Act goal criteria. Parts of the Great Miami River have had poor to very poor water quality in the past but recently have improved substantially. Results of an Ohio EPA 1995 survey of the Middle and Lower Great Miami River show a marked improvement in water quality relative to results of previous surveys conducted in 1980 and 1989 (Ohio Environmental Protection Agency, 1997b). The 1993 Ohio EPA survey of the Little Miami River also found improved water quality relative to previous surveys conducted in 1982 and 1983, with 96 percent of the total possible physical, chemical, and

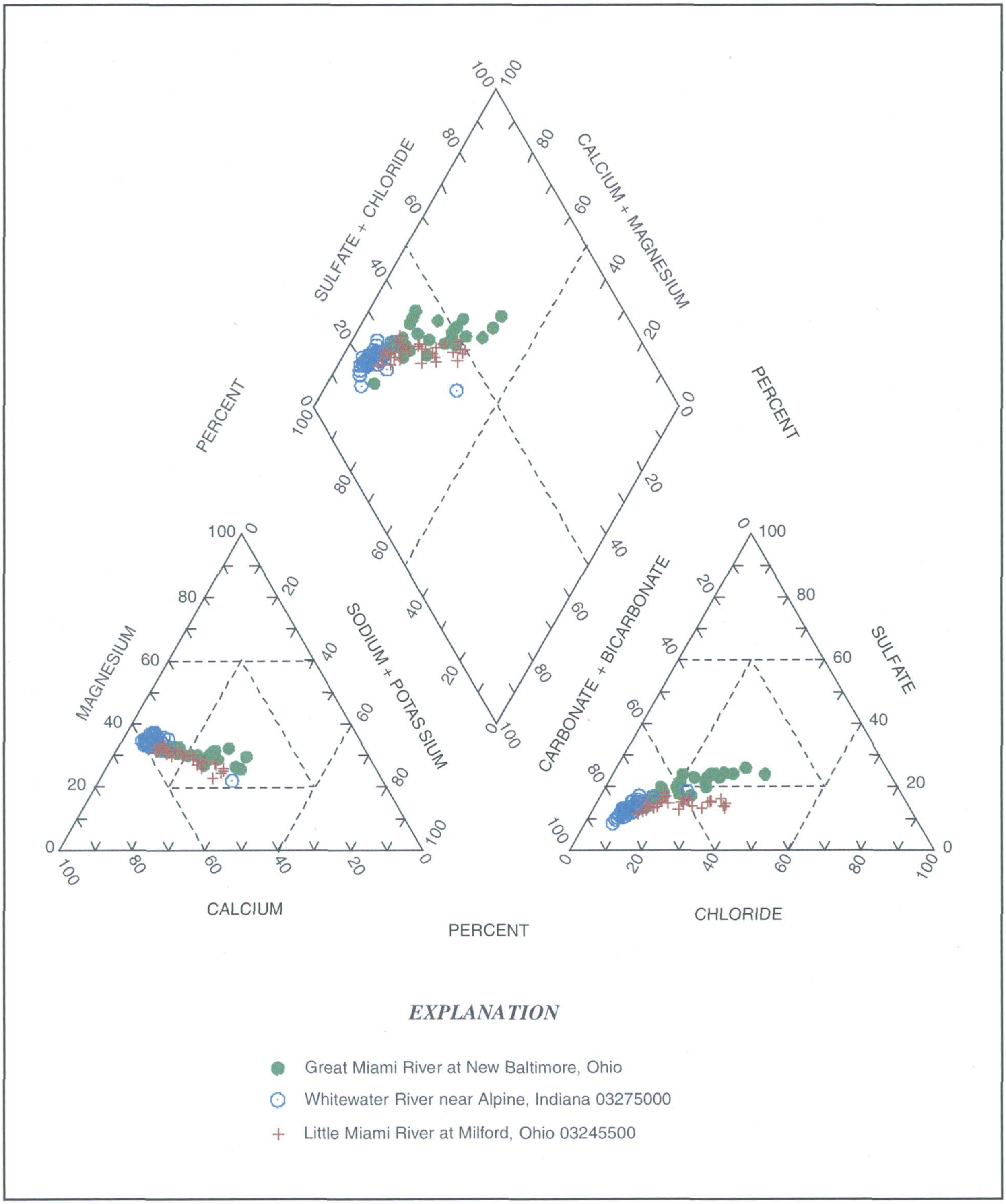


Figure 29. Trilinear diagram illustrating major-ion chemistry of selected streams in the Great and Little Miami River Basins, Ohio and Indiana.

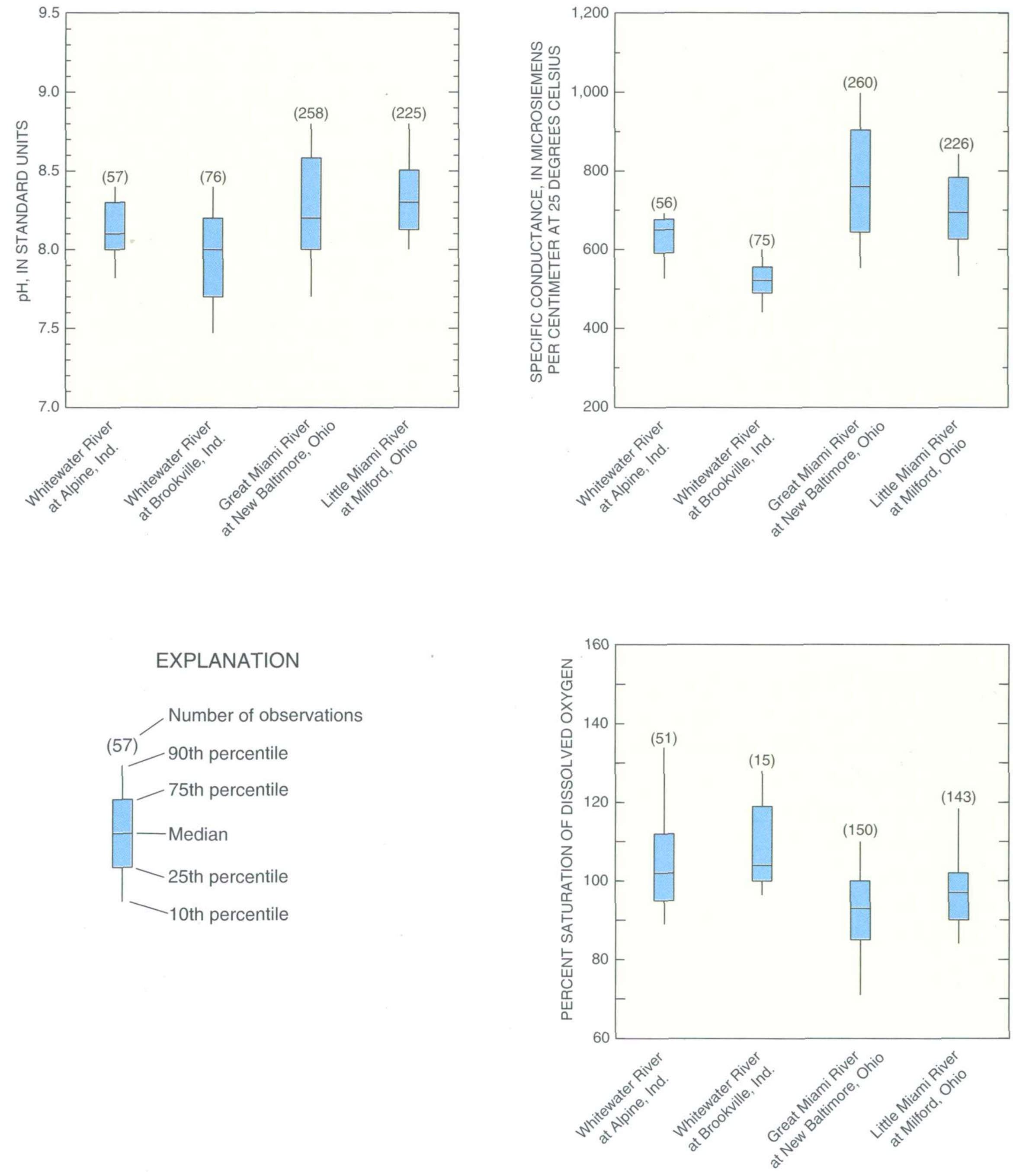


Figure 30. Specific conductance, pH, and percent saturation of dissolved oxygen for selected streams in the Great and Little Miami River Basins, Ohio and Indiana.

microbial test results meeting or exceeding Ohio Water Quality Standards (WQS) criteria and guidelines (Ohio Environmental Protection Agency, 1995a). The most common WQS exceedances for the Little Miami River Basin were for fecal bacteria and total phosphorus. The 1995 Ohio EPA survey of the Middle and Lower Great Miami River yielded even better results, with over 98 percent of all chemical-test results meeting or exceeding Ohio WQS criteria (Ohio Environmental Protection Agency, 1997b).

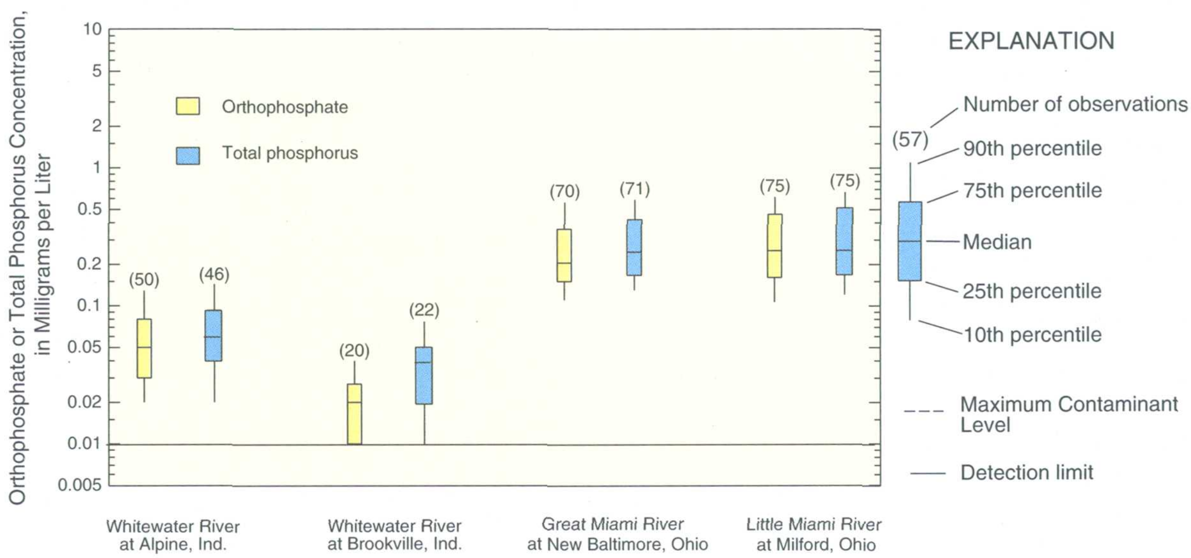
Water quality in the Mill Creek Basin in Cincinnati has been impaired severely over the years by industrial development, failing on-site septic systems, combined-sewer overflows, urban runoff, and inadequate wastewater treatment. Results of the comprehensive water-quality survey of Mill Creek and its major tributaries conducted by Ohio EPA documented numerous WQS exceedances pertaining to fecal coliform and *Escherichia coli* (*E. coli*) bacteria, dissolved oxygen, ammonia-N, cyanide, several trace elements (selenium, copper, lead) and numerous organic compounds (organochlorine pesticides, VOC's) (Ohio Environmental Protection Agency, 1994a). Major restoration efforts by the Metropolitan Sewer District of Cincinnati, the U.S. Army Corps of Engineers, private industry, and local watershed groups are underway to improve water quality and restore stream habitat in the Mill Creek Basin.

Since 1990, the Ohio EPA visited approximately 270 sites within the Ohio part of the study area and collected approximately 1,500 water samples for metals analysis. Most of these samples were measured for total concentrations of arsenic, cadmium, calcium, copper, chromium, lead, magnesium, nickel, selenium, and zinc. Fifty-two water samples collected from 20 sites also were analyzed for mercury. Of the water samples collected, cadmium, copper, iron, lead, mercury, selenium, and zinc exceeded the Ohio WQS at least once. Copper and iron, however, were the only metals to have more than 10 exceedances (Ohio Environmental Protection Agency, 1994a; 1995a; 1996a; 1997b, c). Values of WQS's for metals vary as a function of water hardness.

The water-quality samples collected at the four NASQAN sampling sites show that concentrations of total phosphorus and dissolved orthophosphate (the soluble reactive form of phosphorus, or "SRP") are higher in the Great Miami River and Little Miami River than in the Whitewater River (fig. 31). Data collected by the Ohio EPA suggest that the higher phosphorus concentrations in the Great and Little Miami Rivers are caused by phosphorus loadings from wastewater-treatment plants (Ohio Environmental Protection Agency, 1995a and 1997c). The median nitrite plus nitrate concentrations were below 5 mg/L for all of the stations and showed no statistically significant differences between the stations. Concentrations of nitrate greater than the USEPA Maximum Contaminant Level (MCL)[1] of 10 mg/L nitrate as nitrogen were found occasionally in water samples collected from the Great Miami River at New Baltimore, Ohio (streamflow-gaging station 03274600, which is 14.3 mi downstream from 03274000 on fig. 9).

The Ohio EPA, IDEM, the Ohio Department of Agriculture, Heidelberg College, and ORSANCO collect pesticide data in surface water within the study area. Available Ohio EPA monitoring-program pesticide data are restricted to organochlorine pesticides. Ohio EPA samples collected in reaches within the Little Miami and Great Miami Rivers showed dieldrin, endrin, endosulfan II, and lindane to be the most commonly detected organochlorine pesticides (Ohio Environmental Protection Agency, 1995a, 1997b). Personnel of the Heidelberg College Water Quality Laboratory have been collecting pesticide samples at the Great Miami River at Miamisburg (fig. 1) (water-quality-monitoring station 03271510) since March 1996 as part of their Ohio Tributary Loading Program (David Baker, Heidelberg College, written commun., 1998). Their data indicate that atrazine, alachlor, and metolachlor are the most common herbicides detected in the Great Miami River. The herbicides cyanazine, acetochlor, simazine, and trifluralin also commonly are

[1]Maximum Contaminant Level is an enforceable, health-based regulation that establishes allowable annual average concentrations for constituents known or anticipated to cause adverse health effects in humans (U.S. Environmental Protection Agency, 1996).



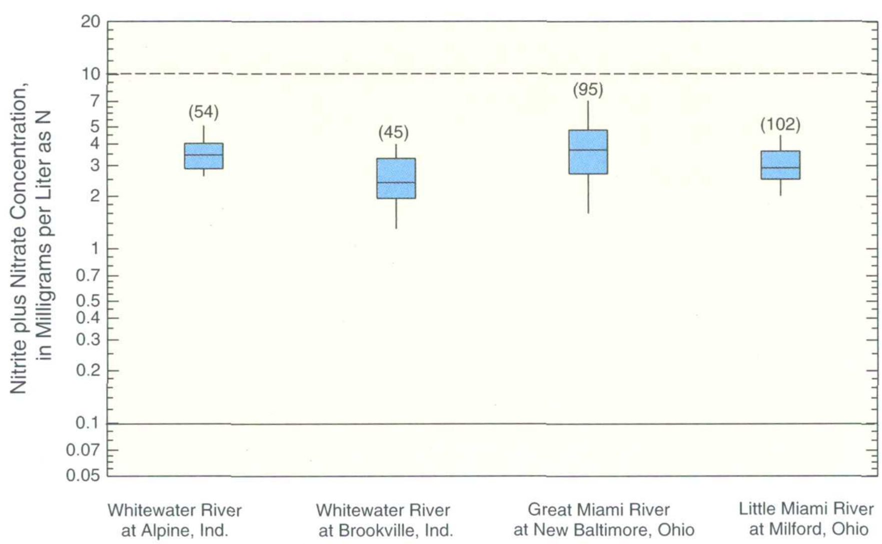


Figure 31. Dissolved orthophosphate, total phosphorus, and dissolved nitrite plus nitrate as nitrogen concentrations from selected streams in the Great and Little Miami River Basins, Ohio and Indiana.

detected, but only during the spring and summer. Peak concentrations of most pesticides typically are observed between May and July following post-application runoff (fig. 32). Similar results were reported for atrazine for sites on the main stem Great and Little Miami Rivers in a 1995 study conducted by ORSANCO (Ohio River Valley Water Sanitation Commission, 1997).

In 1997, IDEM conducted a detailed pesticide study at three locations in the Whitewater River Basin (Grady, 1998). Atrazine, metolachlor, and acetochlor were the most commonly detected herbicides with maximum concentrations 34, 35, and 5.1 µg/L (micrograms per liter), respectively. The data indicated that, on average, atrazine concentrations in the Whitewater River exceeded the MCL for drinking water (3 µg/L) two months out of the year (Grady, 1998). This finding is consistent with the data reported by the Heidelberg Water Quality Laboratory for the Great Miami River at Miamisburg. It is also consistent with the results of pesticide monitoring conducted by the NAWQA Program in other parts of the country, including the White River Basin and Lake Erie-Lake St. Clair Basins which are adjacent to the study area (fig. 1). These studies indicate that post-application runoff from agricultural areas causes spikes in the concentrations of the more mobile and frequently applied herbicides and pesticides, often in temporary exceedance of USEPA MCL's (Crawford, 1995; Fenelon, 1998; Jeffrey Frey, U.S. Geological Survey, oral commun., 1998; Larson and others, 1999). The MCL is based on the annual average concentration of the chemical in question in treated water. Despite occasional, seasonally based exceedances of the MCL during post-application runoff events, the annual average concentration of atrazine and other pesticides is usually less than the respective MCL's. To reduce peak concentrations of atrazine and other pesticides to acceptable levels, many of the larger water utilities have implemented policies whereby activated carbon is added as a treatment when pesticide concentrations in source waters exceed a set target (Ohio River Valley Water Sanitation Commission, 1997).

From a regional perspective, a study by ORSANCO conducted in 1995 found that the Great Miami River contributed 11 percent of the atrazine load measured in the lower half of the Ohio River, whereas the Little Miami River contributed less than 1 percent (Ohio River Valley Water Sanitation Commission, 1997). The seasonal peaks in pesticide concentrations described above imply that most of the annual pesticide load in study-area streams will be transported during post-application runoff between May and July (Fenelon, 1998).

Streambed-Sediment and Fish-Tissue Quality

Trace elements and hydrophobic organic compounds that persist in the environment and that have the potential to bioaccumulate in fish and other wildlife can degrade the quality of fish for human consumption, disrupt the normal endocrine function of fish and wildlife, and make cleanup and remediation of contaminated river sediments difficult and costly. The most contaminated sediments—those that have the potential to cause reproductive impairment, tumors, lesions, or other abnormalities in fish and wildlife—generally are found downstream from industrial outfalls, wastewater-treatment plants, landfills, CSO's, or other sites affected by urban runoff. Areas where sediments with high concentrations of trace elements and organic compounds are found include selected reaches of the Lower Great Miami River and its tributaries within and downstream from Dayton, the Little Miami River near its confluence with the Ohio River, and Mill Creek and its tributaries in Cincinnati.

Since 1990, the Ohio EPA has collected more than 100 stream-sediment samples in the Great Miami River, Little Miami River, and Mill Creek Basins as part of its 5-year watershed assessment program (Ohio Environmental Protection Agency, 1994b; 1995a, b; 1996a, b; 1997b, c). All sediment samples were analyzed for a suite of heavy metals (arsenic, cadmium, copper, chromium, lead, mercury, nickel, and zinc) and selected samples

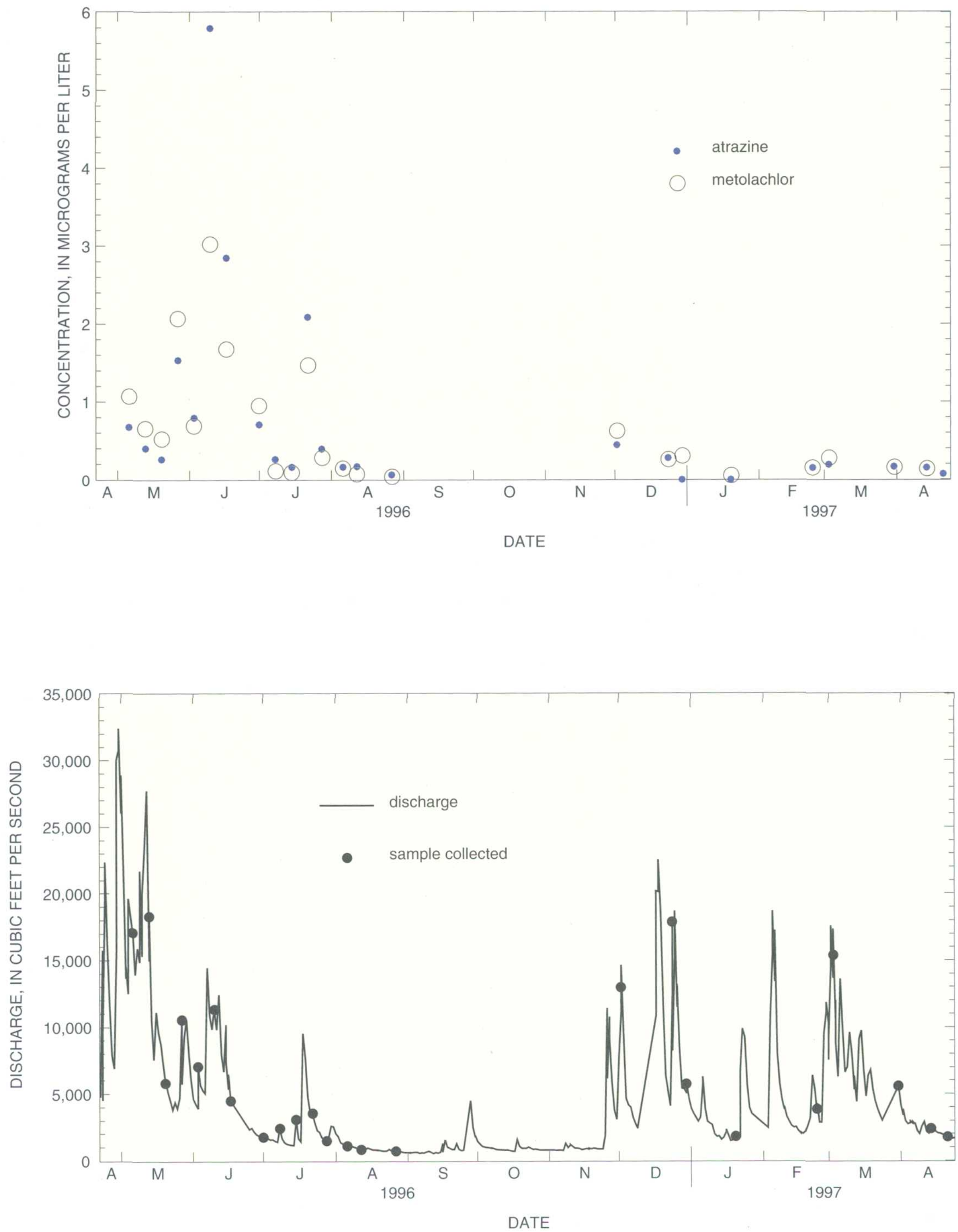


Figure 32. *Temporal patterns of atrazine and metolachlor concentrations and discharge, August 1996 to August 1997, for the Great Miami River at Miamisburg, Ohio. (Data from David Baker and Peter Richards, Heidelberg College, written commun., 1998.)*

were analyzed for VOC's, semi-volatile organic compounds including polycyclic aromatic hydrocarbons (PAH's), organochlorine pesticides, and polychlorinated biphenyls (PCB's). In the Great Miami River Basin, results of Ohio EPA surveys indicate that nearly two-thirds of all sites sampled had metal concentrations at background or slightly above background levels. Zinc was the trace element most commonly found at elevated (above background) levels in sediment samples collected at main-stem and tributary sites in the Lower Great Miami River. Elevated concentrations of aluminum, arsenic, barium, cadmium, chromium, and copper were found in samples from 10 of 13 sites on the main stem Lower Great Miami River below Dayton. The highest trace-element concentrations (including lead and mercury) were found in sediment samples below CSO's or in streams affected by industrial discharges (for example, Dicks Creek below Middletown, Ohio, which receives treated effluent from a large steel mill).

Similar results were reported for 39 sites in the Little Miami River Basin (Ohio Environmental Protection Agency, 1995a), with most sites having non-elevated or slightly elevated trace-element concentrations. Elevated concentrations of arsenic and zinc were found in samples at three sites. The main stem Little Miami River site with the greatest number of elevated metal concentrations was 3.5 mi north of the confluence with the Ohio River. This site is immediately downstream from Duck Creek, a stream affected by urban runoff, CSO's, spills, and other sources. Some of the highest trace-element concentrations in the study area were found in the lower half of Mill Creek, which is heavily affected by CSO's, industrial and wastewater-treatment-plant effluent, and discharges from leaking landfills. Concentrations of lead and mercury were found at levels considered to be elevated (Ohio Environmental Protection Agency, 1994a).

Although commonly detected in study-area sediments, the concentrations of persistent hydrophobic organic compounds such as PCB's, PAH's, and various organochlorine pesticides generally are low and, in the absence of specific point sources, are found at levels believed to pose minimal risks to the health of aquatic organisms (Ohio Environmental Protection Agency, 1994a; 1995a, b; 1996a, b; 1997b, c). Dieldrin, a banned insecticide previously used for termite control, was the most frequently detected organochlorine pesticide in sediment samples. DDT and its breakdown products, alpha-, beta-, and gamma-BHC; aldrin; heptachlor; endosulfan; methoxychlor; and mirex also have been detected (many pesticides currently used in the study area such as atrazine, glyphosate, 2-4-D, and metolachlor are not detected by the methods used by the Ohio EPA). Anthracene, bis(2-ethylhexyl) phthalate, benzo[b]fluoranthene, benzo[k]fluoranthene, fluoranthene, and pyrene, are the among the PAH's most frequently detected in study-area sediment samples. At sites downstream from industrial and military facilities and wastewater-treatment plants, concentrations of individual PAH compounds have been found at or above levels considered to be harmful to benthic organisms. Detections of PCB's mostly are restricted to the main stem of the Middle and Lower Great Miami River and to smaller streams heavily affected by industrial discharges, such as Mill Creek in Cincinnati and Dicks Creek below Middletown, Ohio.

In the Whitewater River Basin, IDEM collected sediment samples at 19 sites on the East and West Fork Whitewater Rivers during a 1997 survey. Samples were analyzed for chloride, cyanide, phosphorus, forms of sulfur and nitrogen, total organic carbon, and more than 30 trace elements. Fractions of cadmium, copper, lead, mercury, nickel, and zinc in the acid-volatile sulfide fraction of the sediment also were determined. Organic analyses included determination of base-neutral compounds, organochlorine pesticides, PCB's, and various phenols (Cynthia Martin, Indiana Department of Environmental Management, written commun., 1999).

The use of organochlorine pesticides and PCB's has been banned or severely reduced in the United States since the early 1970's, and concentrations of these chemicals in fish and wildlife have declined. Many of these chemicals, however, are resistant to degradation and, once released into the environment, will persist for many years or decades. In aquatic systems, organochlorine compounds such as PCB's will be biomagnified in the aquatic food chain in such a way that concentrations in the tissue of top-level predatory fish may reach levels that pose a threat to human health when these fish are consumed. In Ohio, contaminant levels in fish tissue are monitored by a State interagency work group consisting of the Ohio Environmental Protection Agency, the Ohio Department of Natural Resources, the Ohio Department of Health, and the Ohio Department of Agriculture (Johnson, 1998). The Ohio Department of Health is responsible for issuing fish-consumption advisories for the State. In Indiana, the Indiana Department of Natural Resources, the Indiana Department of Health, and the Indiana Department of Environmental Management are responsible for reviewing results of fish-tissue monitoring and for developing and issuing statewide fish-consumption advisories (Indiana Department of Health, 1999). Both states collect data on organochlorine pesticides, PCB's, and selected metals (cadmium, lead, mercury) concentrations in fish tissue from a variety of species. Species targeted include sport fish and species at various levels of the aquatic food chain.

Fish-consumption advisories vary from state to state because of current scientific uncertainties regarding the health effects of eating contaminated fish. People who regularly eat sport fish, women of child-bearing age, nursing or pregnant women, and children are advised to restrict their intake of fish to avoid potential adverse health effects associated with the buildup of contaminants in the human body (Indiana Department of Health, 1999). All waters of the study area are under limited-consumption advisories restricting consumption of fish from these waters to either one meal per week or one per month. These advisories pertain to channel catfish, common carp, several bass species, and sauger and are related to lead, mercury, and PCB contamination. "Do not eat" advisories caution against the consumption of sucker species at Dicks Creek, the Hamilton Hydraulic Canal, and the Great Miami River from Dayton to the Ohio River because of PCB contamination. Limited-consumption advisories also have been issued for the Mad River, Stillwater River, and Mill Creek Basins because of mercury or PCB contamination. In the Whitewater River Basin (Indiana), limited-consumption advisories have been issued for the East and West Fork Whitewater Rivers and Brookville Reservoir because of mercury and PCB levels. Fish species under this advisory include channel catfish, smallmouth bass, white crappie, black redhorse, largemouth bass, quillback, and freshwater drum.

Ground-Water Quality

Many factors contribute to the chemical makeup of ground water, including the initial composition of recharge water infiltrating the soil zone, composition and solubility of solid materials in the soil or aquifer matrix, water temperature, partial pressure of carbon-dioxide gas, acid-base reactions, and oxidation-reduction reactions (Indiana Department of Natural Resources, 1988; Hem, 1985). Other factors that will affect ground-water quality include mixing, adsorption-desorption, and the residence time of water in the aquifer. The initial composition of ground water in an aquifer will be determined largely by water-soil-gas reactions that occur in the unsaturated zone as well as by the introduction of any contaminants during the recharge process. Older ground water will be affected by chemical and microbial reactions that occur as the ground water flows from recharge to discharge areas; such reactions may increase the concentration of naturally derived contaminants that are leached from aquifer solids or may decrease the concentration of contaminants derived from human activities at the land surface.

Ground water in the study area generally is considered to be of high quality; where it is not, it can be made adequate for human consumption or industrial use by treatment. Most ground water has a calcium-magnesium-bicarbonate composition (Lloyd and Lyke, 1995) and is characterized by high alkalinity, high hardness, and slightly alkaline pH. Data from the USGS National Water

Information System and the Indiana Department of Natural Resources (1988) were used to characterize the general quality of ground water in different aquifer types in the study area (fig. 33). Some limitations and bias are inherent in these data sets; the data are for samples collected from a range of well types (for example, monitoring versus domestic versus high-capacity supply wells) that were sampled for different purposes, using a variety of analytical methods. Despite the potential inadequacies, these data provide general insights into the quality of ground water in the study area. The number of analyses available for each aquifer type is a reflection of water availability in the aquifers. Abundant data exist for wells completed in the highly productive sand and gravel aquifers that make up the BVAS; little data exist for wells completed in the marginally productive Ordovician bedrock.

Ground water in the study area is generally very hard, as defined by Durfor and Becker (1964), with median hardness values for ground water pumped from the BVAS, till, and Silurian/Devonian carbonate aquifers greater than 300 mg/L as $CaCO_3$ (fig. 33). Hardness at these levels typically requires treatment; most large treatment plants in the study area add lime or soda ash to precipitate out calcium and magnesium and soften the finished water. Chloride concentrations generally are below the Secondary Maximum Contaminant Level (SMCL)[2] of 250 mg/L, except in ground water from the Ordovician bedrock where concentrations range from 15.7 to 1,160 mg/L. Chloride concentrations in Ordovician bedrock that exceed the SMCL have been attributed to the presence of saline pore waters, sodium-chloride cementing material in the shale, or longer ground-water-residence times that allow enhanced leaching of sodium and chloride from the shale (Indiana Department of Natural Resources, 1988).

[2]Secondary Maximum Contaminant Levels are suggested concentration limits for substances in water that do not result in adverse health effects but may limit the use of water because of unpleasant taste, odor, or color. SMCL's are recommended only as reasonable goals and commonly are exceeded in untreated ground water (U.S. Environmental Protection Agency, 1996).

Chloride concentrations above the SMCL, in combination with corresponding concentrations of sodium, can impart a salty taste to drinking water; such high chloride concentrations also can accelerate corrosion of metal fixtures. Concentrations of dissolved solids are lowest in the BVAS and may be caused by shorter residence times or a lack of more soluble minerals in the BVAS sediments relative to the other three aquifer types. The 10th-percentile dissolved-solids concentrations in the three other aquifer types are above the SMCL of 500 mg/L (U.S. Environmental Protection Agency, 1996). Like chloride, dissolved-solids concentrations greater than the SMCL may cause a disagreeable taste and/or accelerated corrosion of metal plumbing fixtures.

The concentration of dissolved iron in ground water from study-area aquifers often exceeds the established SMCL of 300 µg/L (U.S. Environmental Protection Agency, 1996) (fig. 33). Manganese concentrations also often approach or exceed the SMCL of 50 µg/L (Schalk and others, 1996). As discussed by Hem (1985), concentrations of dissolved iron and manganese in the tens, hundreds, or even thousands of micrograms per liter are typical of anaerobic ground water. Such conditions are common in the BVAS, where dissolved oxygen in shallow ground water tends to react quickly with organic material in glacial sediments. The reaction causes reducing conditions that promote the dissolution of iron and manganese oxyhydroxide minerals. Under near-neutral to slightly alkaline pH conditions typically found in the BVAS and Silurian/Devonian carbonate aquifer, iron concentrations in excess of several milligrams per liter are possible. Water with iron or manganese concentrations that exceed the SMCL's can be treated to avoid a metallic taste and staining of laundry and bath fixtures.

Approximately 1 percent of the ground-water samples collected from study-area aquifers had nitrate concentrations greater than the USEPA MCL of 10 mg/L nitrate (as nitrogen). Median nitrate concentrations for all four aquifers are less than 0.5 mg/L. The highest median nitrate concentration is found in the BVAS (fig. 33), a reflection of the permeable, well-drained sand and gravel deposits that make up this aquifer

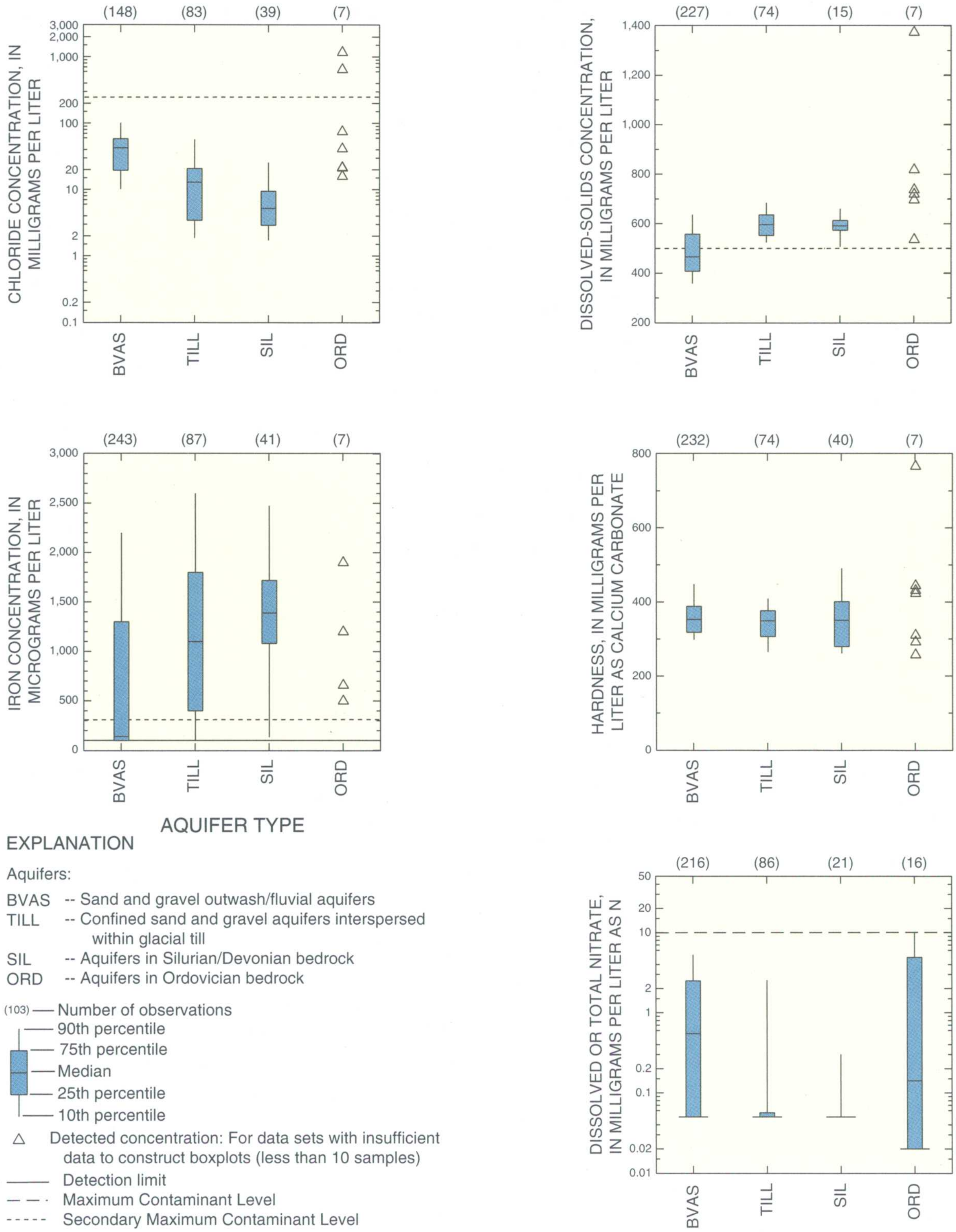


Figure 33. Water quality for major aquifer types in the Great and Little Miami River Basins, Ohio and Indiana.

system. Concentrations of nitrate greater than the MCL in drinking water are potentially hazardous to human health and can result in "blue baby syndrome" (a condition that reduces the amount of oxygen in the blood of infants to low, and sometimes fatal, levels).

The Water Quality Laboratory of Heidelberg College measured nitrate concentrations in private wells throughout Ohio and Indiana in the late 1980's and early 1990's as part of its cooperative Private Well Testing Program (CPWTP); ground-water samples from more than 2,500 domestic wells were collected within the study area (Baker and others, 1989; Barnett and others, 1994). The wells were not randomly selected because participation in the study was voluntary; therefore, the data may yield a biased picture of the distribution and occurrence of nitrate in private wells. The spatial distribution of wells throughout the study area, however, was good; the only county with a significant amount of land in the study area that did not participate in the testing program was Darke County, Ohio. Although most of the wells tested were in agricultural settings, the CPWTP study did not distinguish between nitrate contamination derived from agricultural activities and contamination from other nonpoint and point sources, such as on-site septic systems. Despite these limitations, the large data set provides general insight into the extent of nitrate contamination in private wells and some of the factors that affect well vulnerability. Some of the highest nitrate concentrations in Ohio and Indiana were found in ground-water samples from wells in counties within the study area. Several counties in the study area had a relatively high percentage of wells with a nitrate concentration greater than the MCL; more than 10 percent of the wells sampled in Wayne, Fayette, Union, and Franklin Counties in Indiana and Warren County in Ohio had nitrate concentrations that exceeded the MCL. Nitrate concentrations were compared to well characteristics and aquifer properties. In general, wells that were old, uncased, cased just below ground surface, or shallow were found to be more vulnerable to nitrate contamination than deep wells that were fully cased to the screened interval. The highest levels of nitrate contamination were found in wells completed in the permeable sand and gravel deposits of the BVAS.

Although nitrate concentrations greater than a few milligrams per liter have been reported in the BVAS and other aquifers in the study area, available data indicate that such concentrations generally are found in shallow, oxygenated parts of the aquifer where ground water is young. Temporal trends were derived from water-quality data (135 ground-water samples collected from wells completed in the BVAS near Dayton, Ohio) and results of a tritium-helium age-dating study (Shapiro and others, 1998). The data indicate that detectable concentrations of nitrate usually are found in ground water that had recharged the BVAS within the last 5 to 10 years (Rowe and others, 1999). Concentrations of nitrate were found to decrease markedly in the absence of detectable concentrations of dissolved oxygen. This observation, along with dissolved-gas data that showed significant amounts of excess nitrogen gas in ground-water samples, suggests that bacterially mediated denitrification occurs when anaerobic conditions exist in the aquifer (Rowe and others, 1999). These findings suggest that, given sufficient time, high concentrations of nitrate in shallow parts of study-area aquifers may be reduced by denitrification as ground water flows from shallow, oxygenated recharge areas to deeper, anaerobic parts of the aquifer.

The CPWTP survey also tested for the presence of pesticides in more than 600 private rural wells in 1988 and 1989 (Baker and others, 1989). About 130 wells in the study area were sampled for seven herbicides commonly used in the study area: four triazines (atrazine, cyanazine, metribuzin, and simazine), two acetanilides (alachlor and metolachlor), and one urea (linuron). Samples were analyzed by gas chromatography; the detection limit for all seven compounds was 0.05 µg/L. The wells targeted for pesticide sampling were wells known from previous sampling rounds to have high concentrations of nitrate and, therefore, were suspected of being vulnerable to contamination by surficial sources of pollutants.

Statewide, the majority of pesticide detections in ground water were below 1 µg/L. Within the study area, approximately 4 percent of the herbicides analyzed were detected above 0.05 µg/L. Few detections were found to be greater than USEPA drinking-water standards. Wells with concentrations exceeding the standards were often proximal to a point source or had questionable construction integrity. Atrazine was the most commonly detected pesticide. A combination of mobility, persistence, and high use makes atrazine the most frequently detected pesticide in the Midwest and United States (Kolpin and others, 1996; Larson and others, 1999).

Ohio EPA samples wells for pesticides as part of its Ambient Ground Water Monitoring Network. The purpose of the network is to assess the background quality of ground water from various aquifers in the State of Ohio. Wells that are known to be affected by point-source contamination are not included in the network. Most of the wells in the study area that are part of the Ohio EPA monitoring network are supply wells screened at various depths in the BVAS. Many are located in heavily populated areas along the Great Miami, Little Miami, and Mad Rivers. A total of 37 wells were sampled and analyzed for six common herbicides (alachlor, atrazine, cyanazine, metolachlor, metribuzin, and simazine) in spring 1996, 1997, and 1998. Three wells were sampled more than once. Pesticide concentrations were determined by gas chromatography; detection limits for individual compounds ranged from 0.1 to 0.2 µg/L. Few detections of the six compounds were recorded; in one well, atrazine was detected at a concentration of 0.4 µg/L.

The absence of detectable concentrations of pesticides in study-area ground water is somewhat unexpected. Most of the wells sampled by the Ohio EPA Ambient Ground Water Monitoring Network are completed in the BVAS, a significant percentage of which is overlain by soils that have a moderately high sensitivity to pesticide leaching (Schalk, 1998). The absence of pesticide detections recorded in the Ohio EPA data set may be related to one or more of the following factors: (1) the wells sampled do not target shallow aquifers that are most vulnerable to nonpoint-source contamination, (2) the wells sampled do not target agricultural settings where pesticide use is the heaviest, or (3) production wells sampled as part of the Ohio EPA monitoring network typically have long well screens and high pumping rates that can integrate water from more than one water-bearing zone and dilute depth-dependent differences in water quality. The lack of detections reported is consistent, however, with the findings of the committee responsible for formulating the State of Ohio's Pesticide Management Plan (State Coordinating Committee on Ground Water, 1996) and the results of the Heidelberg College CPWTP survey, the latter of which targeted wells in areas of heavy pesticide use.

Contaminants associated with urban and industrial activities also can be introduced into study-area aquifers by nonpoint sources. Nonpoint-source contamination is generally more areally extensive and exhibits lower concentrations than point-source contamination. Urban land surfaces and urban air are considered important nonpoint sources of VOC's to surface water and shallow ground water (Squillace and others, 1996; Lopes and Bender, 1998). Ohio EPA samples wells for VOC's as part of the Ambient Ground Water Monitoring Network. Thirty-two wells were sampled in the study area for more than 50 VOC's between 1994 and 1997. Some wells were sampled more than once. Detection limits were 0.5 µg/L for most compounds. Samples from seven wells had detectable concentrations of VOC's (Christopher Kenah, Ohio Environmental Protection Agency, written commun., 1998). Samples from only two wells had detectable concentrations of more than one VOC. Most detections were well below USEPA drinking-water standards; however, in one well, dichloromethane and trichloroethene were each detected above their respective MCL's. The production wells sampled for the Ambient Ground Water Monitoring Network do not target the shallow ground water that is most vulnerable to nonpoint-source contamination (see for example, Rowe and others, 1999). These data, however, suggest that VOC contamination of study-area aquifers derived from nonpoint sources is not significant.

Trace-element analyses indicate that ground water obtained from wells completed in the Silurian/Devonian carbonate aquifer in the northern part of the study area is characterized by unusually high concentrations of strontium. Although usually found at concentrations of less than 1 mg/L (Hem, 1985), concentrations of 5 to 10 mg/L are common in ground-water samples from the Silurian/Devonian carbonate aquifer, with maximum concentrations in excess of 30 mg/L reported (Feulner and Hubble, 1960; Dumouchelle, 1998b). The source of strontium is celestite, a strontium-sulfate mineral that is a minor constituent of the limestone and dolomite bedrock, particularly in the Upper Silurian Salina Group rocks that subcrop in the northeastern part of the study area. High strontium concentrations have been reported in the Mad River and its tributaries and have been used to estimate the amount of base flow contributed by the Silurian/Devonian aquifer to the Mad River Watershed (Feulner and Hubble, 1960; Sheets and Yost, 1994).

Two naturally occurring trace elements that have received attention in the study area are arsenic and radon. These elements, both of which are classified by USEPA as known human carcinogens (U.S. Environmental Protection Agency, 1999a, b), have been found at above-background concentrations in ground water from the Silurian/Devonian carbonate aquifer. Dumouchelle (1998b) reported that arsenic concentrations in 25 ground-water samples collected from domestic wells completed in the Silurian Lockport Dolomite ranged from less than 1 µg/L to 29 µg/L; 17 out of the 25 wells had arsenic concentrations greater than 10 µg/L. Similar findings were reported by the Ohio EPA in a small case study of six domestic wells completed in the Silurian/Devonian carbonate aquifer in Montgomery County (Rich Bendula, Ohio Environmental Protection Agency, written commun., 1997). The maximum arsenic concentration reported in these studies (34 µg/L) did not exceed the current MCL of 50 µg/L (U.S. Environmental Protection Agency, 1996). The drinking-water standard for arsenic is under review by the USEPA and may be lowered to a value close to the 10-µg/L standard set by the World Health Organization because of potential health risks associated with long-term exposure to this known human carcinogen (World Health Organization, 1996). Although arsenic may be derived from anthropogenic sources such as pesticides, it is believed that arsenic in the Silurian/Devonian carbonate aquifer system is derived from weathering of naturally occurring arsenic-bearing minerals in the bedrock (Rich Bendula, Ohio Environmental Protection Agency, written commun., 1997).

Data regarding the distribution and occurrence of radon in study-area aquifers have been reported by Baldwin and Treick (1991), Baldwin and others (1992), and Gall and others (1995). This research was motivated by the work of Paul and Lindstrom (1987), who found that 47 percent of 163 locations in and around the Dayton area had indoor-air radon concentrations above the USEPA guideline of 4 pCi/L (picocuries per liter in air). Radon concentrations measured in ground-water samples collected at various depths in the Silurian/Devonian carbonate aquifer at two locations ranged from approximately 250 to 2,000 pCi/L (Gall and others, 1995), with the majority of samples having radon concentrations greater than the USEPA proposed MCL of 300 pCi/L. The reported concentrations, however, are well below the proposed USEPA Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L (see U.S. Environmental Protection Agency, 1999b, for details on the proposed drinking-water rule for radon and its AMCL). Data regarding the concentration of radon in the BVAS within the study area were not available; however, radon concentrations in ground-water samples from 48 shallow wells completed in unconsolidated glaciofluvial aquifers in the White River Basin of Indiana ranged from 140 to 1,620 pCi/L, with a median concentration of 420 pCi/L (Fenelon and Moore, 1996).

Major Environmental Subdivisions of the Great and Little Miami River Basins

The preceding sections of this report describe many factors that affect the source, behavior, and effects of contaminants on water-quality conditions observed in the Great and Little Miami River Basins. The environmental setting includes natural and human-related factors such as climate, soils, geology, population, and land use that provide a unifying framework for making comparative assessments of water quality within the study area. The environmental setting, along with results of previous water-quality studies, is used by the NAWQA Program to compare and contrast findings on water quality within and among study areas in relation to causative factors and to develop inferences about the status and trends of water quality in areas that have yet to be studied (Gilliom and others, 1995).

The environmental setting initially is characterized by dividing the study area into several subareas that have distinct and relatively homogeneous combinations of natural features (climate, geology, and soil type) and land use (urban, agricultural) that affect surface- and ground-water quality. These subareas are mapped, and a conceptual stratification of the most important natural and human factors that affect surface- and ground-water quality is developed. This general, geographically based characterization is done for each NAWQA Study Unit, and the resulting environmental stratifications are used to design and prioritize data-collection activities at the Study Unit and at the national level (Gilliom and others, 1995). In the following sections, the rationale used to define homogeneous subareas for water-quality assessment is described. Properties of each subareas (termed "hydrogeomorphic regions" hereafter) are summarized. Stratification diagrams are developed to provide the environmental framework needed to design surface-water, ecological, and ground-water data-collection activities in the Great and Little Miami River Basins study area.

Hydrogeomorphic Regions

The study area was subdivided into four discrete hydrogeomorphic regions (fig. 34) to aid in the design of NAWQA studies that will examine the effects of natural factors on water quality. Subecoregions defined by Woods and others (1998) (see Ecoregions section of this report) with similar characteristics were combined to delineate three hydrogeomorphic regions—the Till Plains region, the Drift Plains region, and Interlobate region (table 14). These hydrogeomorphic regions can be used to examine natural factors that affect surface-water quality and aquatic biological communities. The Till Plains region (55 percent of the study area, fig. 34) is formed by combining the Clayey, High Lime Till Plains; Loamy, High Lime Till Plains; and the Darby Plains ecoregions. The Drift Plains/Unglaciated region (18 percent, fig. 34) is formed by combining the Pre-Wisconsinan Drift Plains and Northern Bluegrass ecoregions. The Interlobate region (14 percent, fig. 34) is formed by combining the Mad River and Whitewater Interlobate ecoregions. Together, these three hydrogeomorphic regions represent upland areas that are adjacent to major stream valleys and flood plains. The fourth hydrogeomorphic region, the Fluvial region (13 percent, fig. 34), generally occupies the major stream valleys and associated flood plains and is defined by the occurrence of coarse, stratified glacial-outwash deposits and recently deposited alluvium. The Fluvial region overlies the most productive parts of the BVAS and was included as a separate hydrogeomorphic region to address factors affecting ground-water quality in the most important aquifer system in the study area. The Fluvial region is also the setting where ground-water/surface-water interactions can have a significant impact on ground-water quality.

Environmental Settings for Surface-Water and Ecological Studies

To determine which environmental settings should be emphasized in planned NAWQA surface-water quality and ecological studies in the study area, individual watersheds in the study area were stratified according to an environmental framework of bedrock geology, hydrogeomorphic regions, and land use (fig. 35). Bedrock geology is used to subdivide watersheds into those underlain

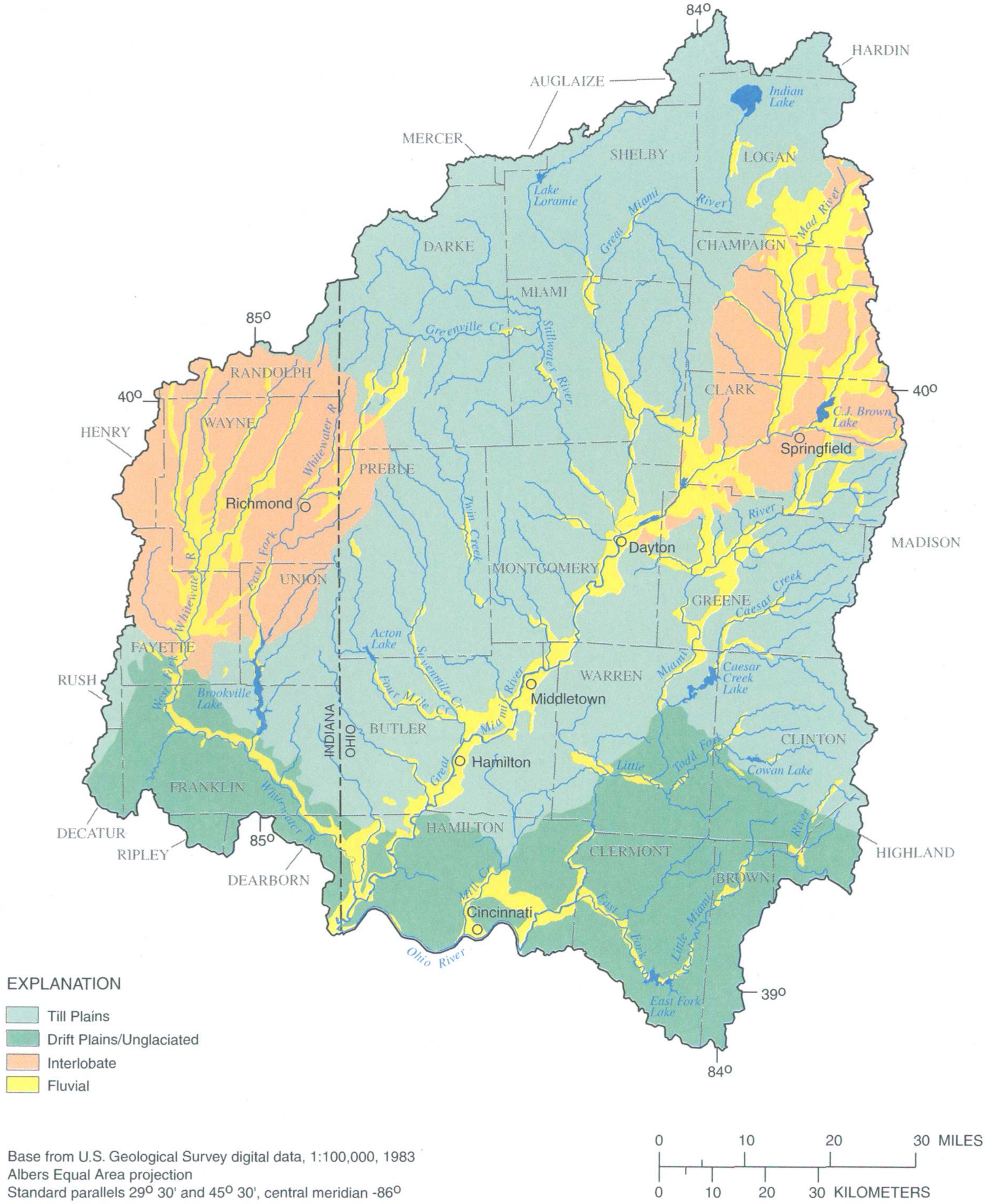


Figure 34. Hydrogeomorphic regions in the Great and Little Miami River Basins, Ohio and Indiana.

Table 14. Characteristics of hydrogeomorphic regions in the Great and Little Miami River Basins, Ohio and Indiana

[mi^2, square mile; - -, not applicable]

Characteristic		Till Plains region	Drift Plains/ Unglaciated region	Interlobate region	Fluvial region	Study area
Estimated population (1990)[a]		1,132,300	830,800	238,800	510,500	2,712,400
Population density (people/mi^2)		314	673	232	555	369
Area (mi^2)		4,074	1,315	1,034	919	7,342
Percent land use[b]	Agriculture	86.3	56.4	86.7	69.3	79.9
	Old urban	8.1	15.8	7.3	18.7	10.7
	New urban[c] (square miles)	2.0 (82.2)	4.5 (59.5)	.8 (8.2)	2.9 (27.1)	2.4 (177)
	Forest	3.0	22.4	4.8	5.1	7.0
	Water and wetlands	.5	.4	.2	2.6	.7
	Barren	.1	.4	.1	1.2	.3
Typical soil characteristics		slowly permeable calcareous silt loams	thin, acidic, poorly permeable silt loam	well-drained sandy loam to slowly permeable silt loam	well-drained calcareous sand and silt loams	- -
Commonly used aquifers		Silurian carbonate; sand and gravel lenses in till	sand and gravel in till; alluvial deposits along Ohio River; weathered fractured shale	sand and gravel in buried valleys and till; Silurian carbonate	sand and gravel in buried valleys	- -

[a]Population data from U.S. Bureau of the Census, 1990.

[b]Land-use data from Hitt (1994a, b). For percent land use, some columns do not sum to 100 percent because of rounding.

[c]New urban land use defined by the overlap of 1970's land-use coverage with 1990 population data updates by Hitt (1994b).

by Silurian/Devonian carbonate rocks and those underlain by Ordovician shale. The lithology of bedrock units will influence the major-ion chemistry of smaller streams (for example, sodium-chloride waters for shale bedrock and calcium-magnesium-bicarbonate waters for carbonate bedrock). The differences in the physical and hydrogeologic properties of the Silurian/Devonian and Ordovician rocks also will result in noticeable differences in stream geomorphology, sediment loads, aquatic biota, and base flow.

Differences in climate, soil type, physiography, and surficial geology also will affect the quality of streams and aquatic communities; these characteristics are incorporated into the hydrogeomorphic regions derived from the subecoregions. Combined with bedrock type, the hydrogeomorphic regions are stratified into five second-order settings (fig. 35). The Fluvial hydrogeomorphic region is not explicitly included in the surface-water settings because areas draining higher-order streams and rivers in the study area

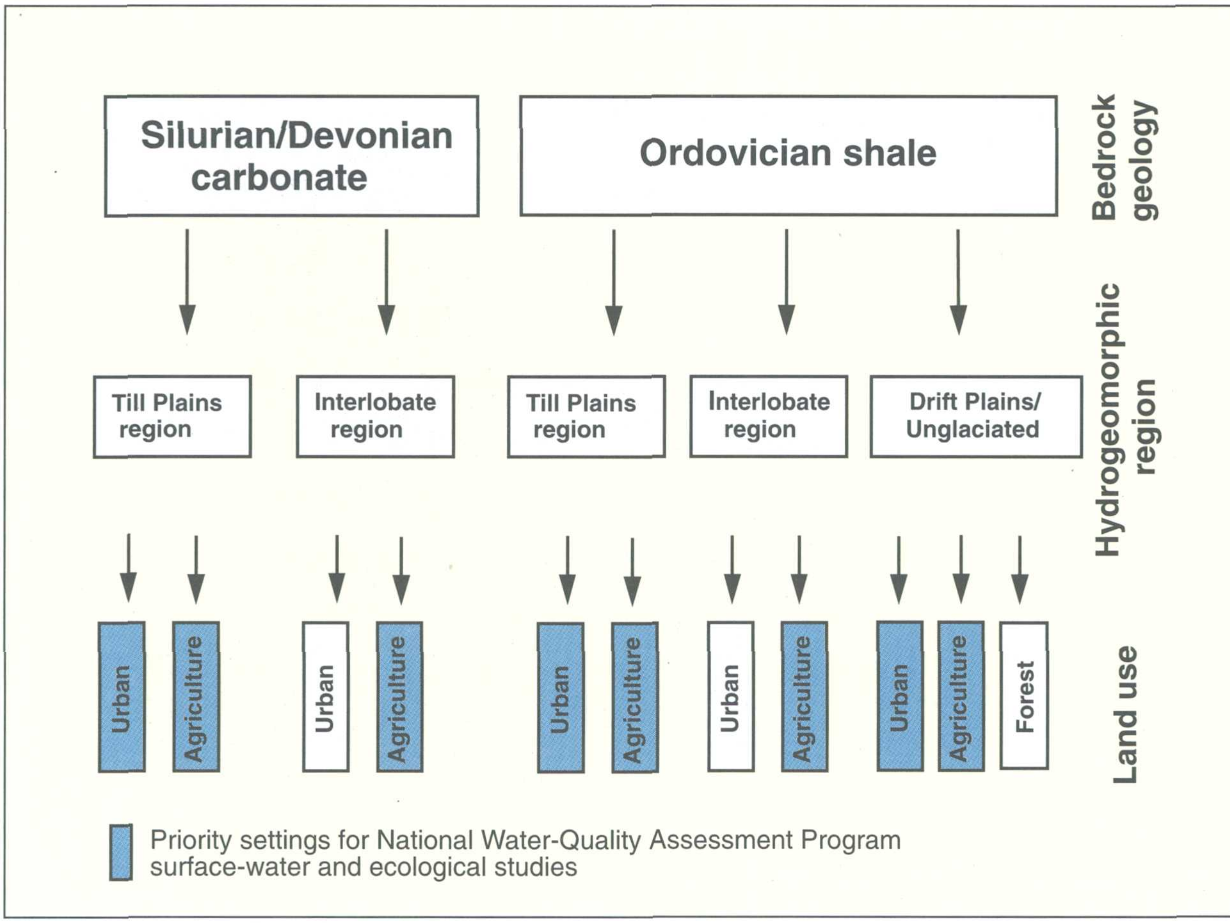


Figure 35. Environmental settings for the surface-water/ecological component of the Great and Little Miami River Basins, Ohio and Indiana.

are mostly outside the Fluvial region. The third factor used to stratify the watersheds is land use, which is used to assess human effects on water quality and aquatic ecosystems. Agriculture and urban are the dominant land-use categories in the study area; extensive forested areas are found predominantly in less populated, hillier areas of the Drift Plains/Unglaciated region.

Consideration of the major land-use categories yields 11 environmental settings that can be used to examine the effects of natural settings and land use on surface-water quality and aquatic communities in the study area (fig. 35). Of these, four of the settings occupy more than 10 percent of the study area: (1) carbonate Till Plains/agricultural areas (33.4 percent); (2) shale Till Plains/agricultural areas (17.6 percent); (3) shale Drift Plains/Unglaciated agricultural areas (10.2 percent); and (4) carbonate Interlobate/agricultural areas (10 percent) (fig. 36). These four settings will be priority settings (based on land use, population, and total area) for identifying candidate watersheds for NAWQA surface-water quality and ecological monitoring sites (Gilliom and others, 1995). Other priority settings include basins draining shale Interlobate/agricultural areas, carbonate Till Plains/urban areas, and shale Till Plains and shale Drift Plains/Unglaciated urban areas.

Environmental Settings for Ground-Water Studies

The Till Plains, Interlobate, and Drift Plains/ Unglaciated hydrogeomorphic regions are com-

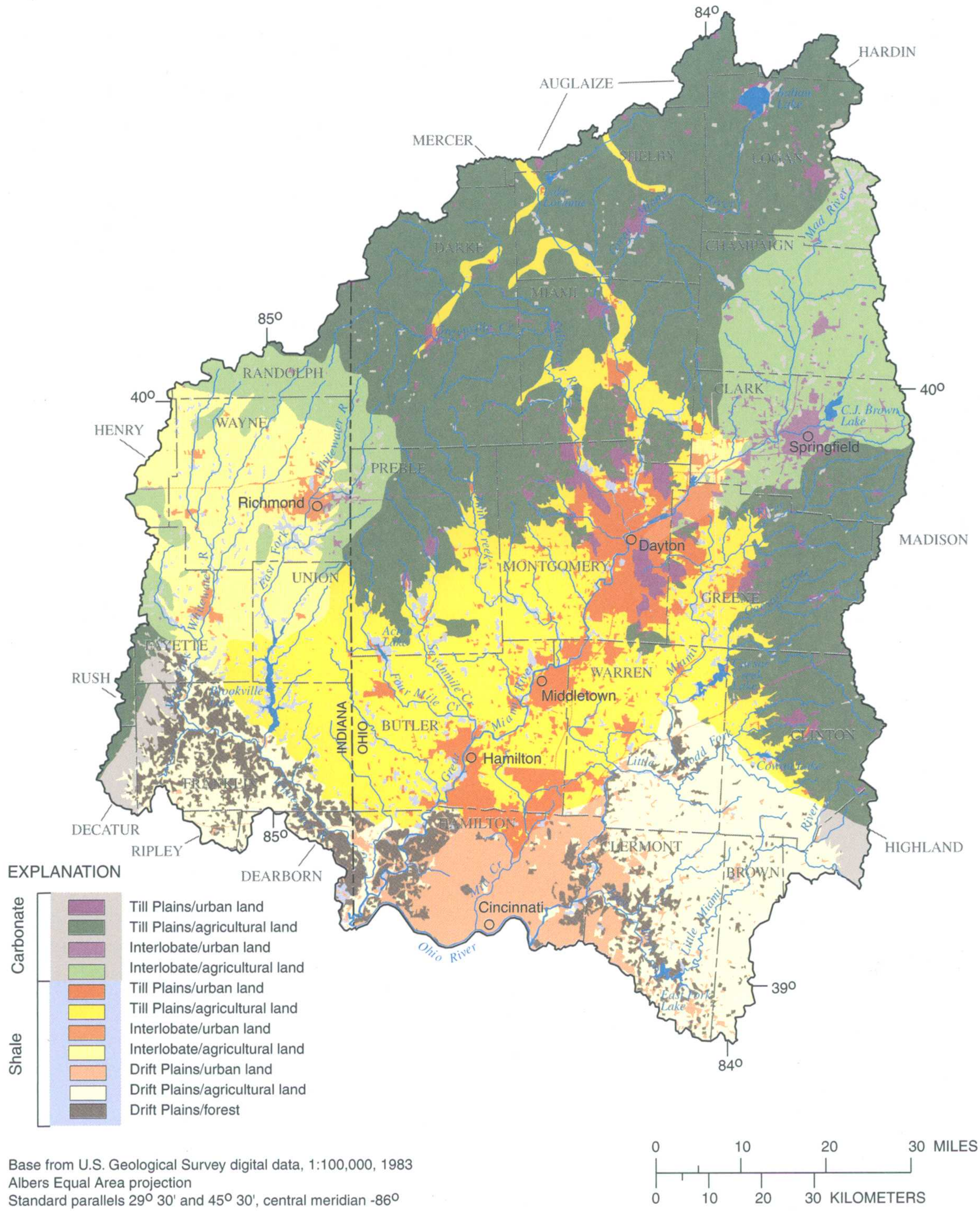


Figure 36. Distribution of surface-water/ecological settings defined by bedrock geology, hydrogeomorphic regions, and land use in the Great and Little Miami River Basins, Ohio and Indiana.

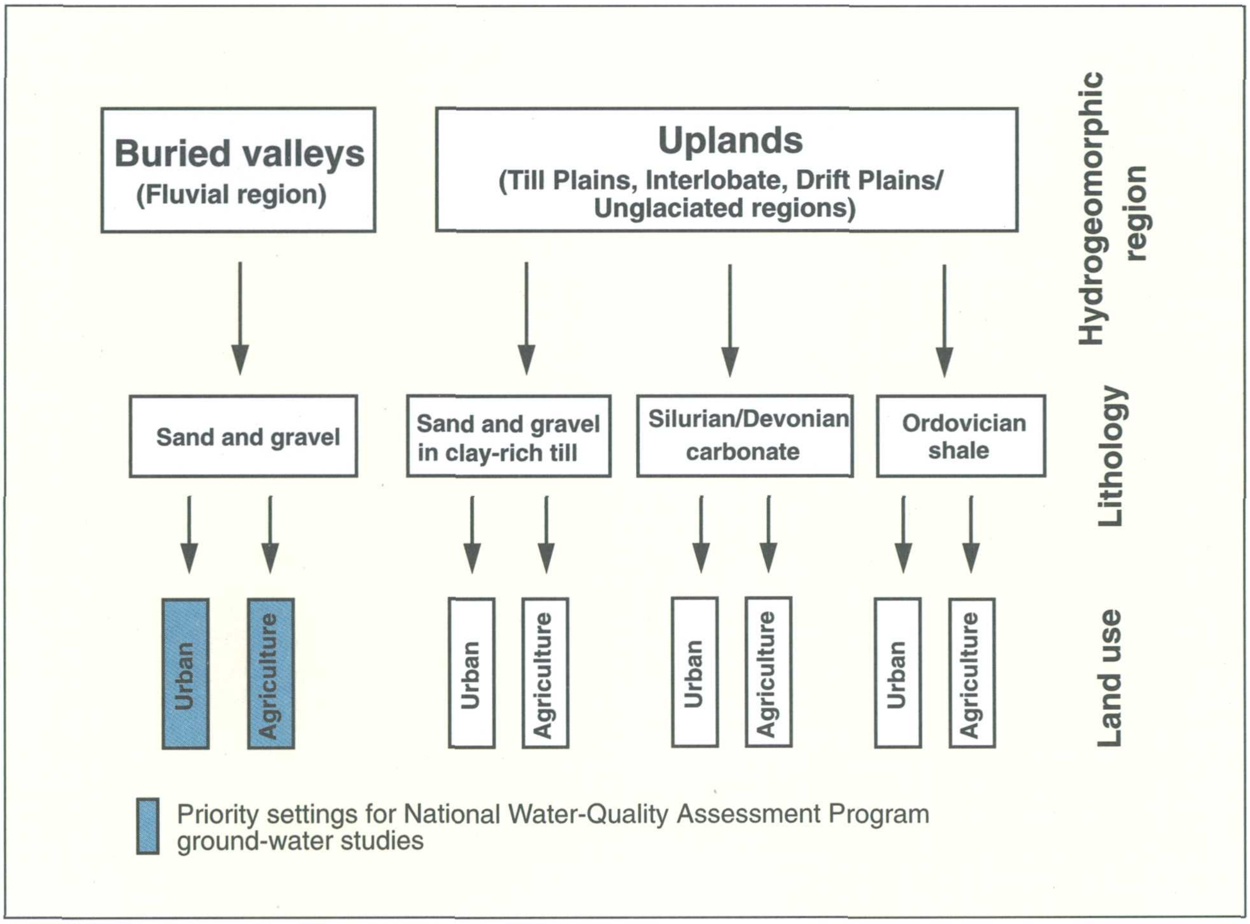


Figure 37. Environmental settings for the ground-water component of the Great and Little Miami River Basins, Ohio and Indiana.

bined into a single setting, the Uplands area, for the purpose of identifying environmental settings for NAWQA ground-water studies. The Fluvial region is now termed "buried valleys" because the upland and buried-valley terminology more accurately reflects the geomorphic setting of the aquifers used for water supply in the study area. With respect to the amount of water withdrawn for public and domestic supply, the most important aquifer is the BVAS, followed by isolated sand and gravel deposits in clay-rich till, the Silurian/Devonian carbonate aquifer, and fractured and weathered zones in Ordovician shale. Subdividing the aquifers on the basis of major land-use categories (agricultural, urban) results in eight environmental settings that can be used to design and prioritize planned NAWQA ground-water studies (fig. 37). Based on water-use data and susceptibility to contamination, priority environmental settings for NAWQA ground-water studies will be those parts of the BVAS overlain by agricultural and urban areas.

Summary

The Great and Little Miami River Basins study area is one of more than 50 large river basins and aquifer systems across the United States selected for the U.S. Geological Survey's National Water Quality Assessment (NAWQA) Program. The study area encompasses more than 7,354 square miles of southwestern Ohio (80 percent) and southeastern Indiana (20 percent). Principal streams are the Great Miami River and Little Miami River in Ohio and the Whitewater River in Indiana. The study area is almost entirely within the Till Plains section of the Central Lowland physiographic province. With the exception of a few areas near the Ohio River, the study area is covered with Pleistocene glacial deposits composed predominantly of clay-rich till. These glacial deposits overlie a thick sequence of Ordovician, Silurian, and Devonian bedrock composed mostly of dolomite, limestone, and shale of marine origin.

The estimated population of the study area was 2.8 million in 1995. Major urban areas within the study area include Cincinnati and Dayton, Ohio. Population density is greatest along the urban corridor that extends from Springfield to Cincinnati along the Miami River Valley. Despite the presence of three major urban areas, land use in the study area is devoted primarily to agricultural uses. Of the 3 million acres of farmland in the study area, more than 90 percent of cropland is devoted to row-crop production of corn, soybeans, and wheat. The most intense agricultural activity is found in the northern parts of the study area. Agricultural activities resulting in sediment loss as well as pesticide and nutrient runoff to surface water are significant nonpoint sources of contamination in the study area. The impact of agricultural activities and other nonpoint sources of pollution on surface- and ground-water quality are decreasing in selected parts of the study area. Upgrades to wastewater-treatment plants have improved the quality of point-source discharges.

Major industries in the study area produce automobile and aircraft parts, business and computer equipment, steel, chemicals, household goods and appliances, paper products, and processed foods and beverages. Industrial facilities are generally within or adjacent to the large urban areas of Dayton and Cincinnati, Ohio. Waste produced by industrial, government, and military facilities in the study area has been a significant source of contamination to streams and aquifers in the study area.

Bedrock valleys carved out before, during, and after Pleistocene glaciations were filled with sand and gravel deposited by melting Pleistocene glaciers. These outwash deposits make up the principal aquifer in the study area, the Buried-Valley Aquifer System. The aquifer is the principal source of drinking water for 1.6 million people and has been designated by the U.S. Environmental Protection Agency as a sole-source aquifer. Supply wells in this aquifer frequently yield 1,000 gallons per minute. Estimated water withdrawals from streams and aquifers in the study area averaged 745 million gallons per day in 1995. Approximately 48 percent of the total water withdrawn was derived from surface-water supplies (including the Ohio River) and 52 percent from ground-water supplies. Excluding the 114 Mgal/d withdrawn from the Ohio River by Cincinnati, more than 90 percent of the public supply was derived from ground water, with the majority provided by supply wells completed in the Buried-Valley Aquifer System.

Results of fish and macroinvertebrate surveys conducted in the study area reveal that most streams meet the Warmwater Habitat aquatic-life-use criteria. Such streams support assemblages of warmwater fish and macroinvertebrates considered to be typical of those found elsewhere in the Eastern Cornbelt Plains and Interior Plateau ecoregions in areas relatively unaffected by human activities. In several basins—notably Twin Creek, the Great Miami River above Dayton, the Little Miami River, and the Whitewater River—a significant percentage of the main-stem and tributary stream segments meet criteria set for the Exceptional Warmwater Habitat aquatic-life-use designation. Such segments possess relatively undisturbed high-quality habitat and are characterized by a high diversity of species including those that are highly intolerant, rare, threatened, or endangered. In addition, recent surveys of basins such as the Middle and Lower Great Miami River below Dayton that are affected by urban sources of pollution indicate significant improvements in the fish and macroinvertebrate communities.

These improvements largely are attributed to improved wastewater treatment that has resulted in large reductions in point-source loadings of nutrients and other oxygen-demanding wastes. Despite these improvements, continued residential/ commercial development in suburban areas bordering Dayton and Cincinnati likely will increase the amount of treated wastewater discharged into study-area streams.

Water quality in the study area is influenced by a variety of natural and human factors. Interaction of infiltrating rain water with carbonate-rich soils, glacial sediments, and bedrock leads to the formation of very hard, calcium-magnesium-bicarbonate-type surface and ground water. Dissolution of minerals contained in the glacial sediments and carbonate bedrock can lead to above-background concentrations of iron, manganese, sulfate, strontium, and arsenic in ground water. Chloride concentrations are generally below aesthetic limits, except in Ordovician bedrock. Under the reducing conditions commonly found in study-area aquifers, background iron and manganese concentrations often exceed aesthetic limits, and treatment is required to prevent iron staining of clothing and household fixtures. Some of the highest nitrate concentrations in Ohio and Indiana are found in wells from the study area. Nitrate (as nitrogen) concentrations are highest in the permeable, well-drained sand and gravel deposits. Under the reducing conditions commonly found in the Buried-Valley Aquifer System, however, denitrification of nitrate occurs and natural removal of nitrate from these aquifers is possible.

Pesticides enter surface and ground water through runoff, leaching, and infiltration, mainly from agricultural lands. Dieldrin, endrin, endosulfan II, and lindane are the most commonly detected organochlorine pesticides in the study area. Commonly used herbicides such as atrazine and metolachlor frequently are found in study-area streams at low levels; concentrations of these compounds can exceed U.S. Environmental Protection Agency Maximum Contaminant Levels (MCL's) during post-application runoff. Despite occasional exceedances of MCL's during spring and summer storms, the annual average concentration of pesticides in streams is usually well below the MCL. In contrast, pesticides rarely are detected in ground water. This may indicate that clay-rich soils and associated tills protect underlying aquifers or that available data sets do not reflect the true distribution and occurrence of these compounds. Atrazine was the most commonly detected pesticide in private wells in the study area. The few volatile organic compounds detected in wells generally were found at concentrations below respective MCL's.

Environmental settings for planned NAWQA surface-water quality and ecological studies in the Great and Little Miami River Basins were characterized using a framework based on bedrock geology, hydrogeomorphic regions, and land use. Four major environmental settings were identified, each of which occupies at least 10 percent of the study area: (1) carbonate Till Plains/agricultural areas (33.4 percent), (2) shale Till Plains/agricultural areas (17.6 percent); (3) shale Drift Plains/Unglaciated agricultural areas (10.2 percent), and (4) carbonate Interlobate/ agricultural areas (10 percent) settings. Basins that drain these four settings will be the focus of planned surface-water quality and ecological monitoring activities. Environmental settings for planned ground-water studies were characterized by use of a framework based on major aquifer type and dominant land use. Eight environmental settings were identified for potential ground-water studies; based on water-use data and susceptibility to contamination, the primary environmental setting for planned ground-water studies will be the Buried-Valley Aquifer System in urban and agricultural areas.

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