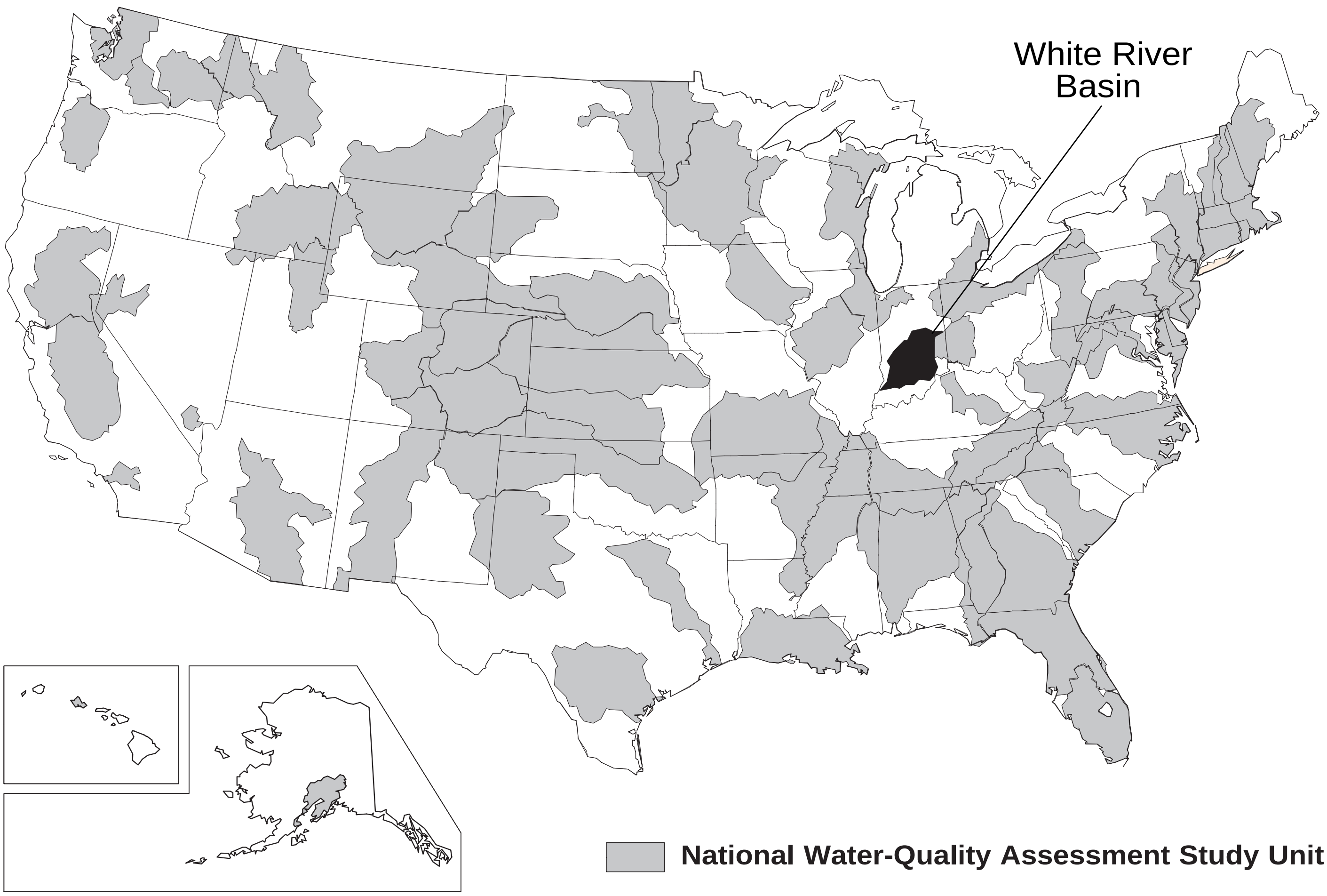
U.S. Department of the Interior
U.S. Geological Survey

Environmental Setting and Natural Factors and Human Influences Affecting Water Quality in the White River Basin, Indiana

Water-Resources Investigations Report 97-4260



USGS
science for a changing world

National Water-Quality Assessment Program

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

Environmental Setting and Natural Factors and Human Influences Affecting Water Quality in the White River Basin, Indiana

By Douglas J. Schnoebelen, Joseph M. Fenelon, Nancy T. Baker, Jeffrey D. Martin, E. Randall Bayless, David V. Jacques, and Charles G. Crawford

National Water-Quality Assessment Program
Water-Resources Investigations Report 97-4260

Indianapolis, Indiana
1999

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Charles G. Groat, Director

For additional information, write to:
District Chief
U.S. Geological Survey
Water Resources Division
5957 Lakeside Boulevard
Indianapolis, IN 46278-1996

Copies of this report can be purchased from:
U.S. Geological Survey
Branch of Information Services
Box 25286
Federal Center
Denver, CO 80225-0286

Information regarding the National Water-Quality Assessment (NAWQA) Program is available on the Internet via the World Wide Web. You can connect to the NAWQA Home Page using the Universal Resource Locator (URL) at:
<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 59 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 the 59 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

Robert M. Hirsch
Chief Hydrologist

Contents

Contents—Continued

Illustrations

Contents—Continued

Illustrations—Continued

Tables

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

Multiply	By	To obtain
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 squared per day[1] (ft^2/d)	0.0929	meter squared per day
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
cubic foot per day per foot ($ft^3/d/ft$)	0.09290	cubic meter per day per meter
mile (mi)	1.609	kilometer
mile per hour (mph)	1.609	kilometer per hour
square mile (mi^2)	2.590	square kilometer
people per square mile ($people/mi^2$)	0.3861	people per square kilometer
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
pound per acre (lb/acre)	1.121	kilogram per hectare
ton per acre per year (ton/acre/yr)	2.242	megagram per hectare per year
bushel (bu)	0.03524	cubic meter
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

[1]This unit is used to express transmissivity, the capacity of an aquifer to transmit water. Conceptually, transmissivity is cubic feet (of water) per day per square foot (of aquifer area) per foot (of aquifer thickness). In this report, the unit is reduced to its simplest form.

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

°C = (°F – 32) / 1.8

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). 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. 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).

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

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
NAWQA	National Water-Quality Assessment
NPDES	National Pollutant Discharge Elimination System
NWS	National Weather Service
RCRA	Resource Conservation and Recovery Act
STATSGO	State Soil Geographic Data Base
pH	Negative log (base-10) of the hydrogen ion activity, in moles per liter
$7Q_{10}$	The average streamflow for 7 consecutive days below which streamflow recedes on average once every 10 years

Environmental Setting and Natural Factors and Human Influences Affecting Water Quality in the White River Basin, Indiana

By Douglas J. Schnoebelen, Joseph M. Fenelon, Nancy T. Baker, Jeffrey D. Martin, E. Randall Bayless, David V. Jacques, *and* Charles G. Crawford

Abstract

The White River Basin drains 11,349 square miles of central and southern Indiana and is one of 59 Study Units selected for water-quality assessment as part of the U.S. Geological Survey's National Water-Quality Assessment Program. Defining the environmental setting of the basin and identifying the natural factors and human influences that affect water quality are important parts of the assessment.

Interrelated natural factors help determine the quality of surface and ground water in a river basin. The White River Basin has a humid continental climate, characterized by well-defined winter and summer seasons. Geologic features in the basin include glaciated and nonglaciated areas; a region of karst geomorphology that is characterized by caves and sinkholes; and a thick, sedimentary bedrock sequence underlying the entire basin. Unconsolidated glacial deposits of clay, silt, sand and gravel cover more than 60 percent of the basin. Soils developed in unconsolidated glacial deposits are typically fertile, naturally or artificially well drained, and farmed. Soils in the unglaciated south-central part of the basin are thin, have low fertility, and are best suited for forest or pasture.

Agriculture is the principal land use in the White River Basin. Approximately 70 percent of the basin is used for agriculture, and about 50 percent of the basin is cropland. Corn and soybeans are the major crops. Other significant land uses are forest (22 percent) and urban and residential (7 percent). The population of the basin was 2.1 million in 1990. Water use in the White River Basin totaled 1,284 million gallons per day in 1995, of which 84.5 percent was surface water and 15.5 percent was ground water. Despite the predominant use of surface water, ground water was the primary source of drinking water for approximately 56 percent of the population.

The general water chemistry in the White River Basin is determined by natural factors such as soils and geologic materials that water contacts as it moves through the hydrologic system. In the southern part of the basin, bedrock upland areas are dominated by non-carbonate bedrock, thin soils, and high runoff-rainfall ratios. These areas have small chemical concentrations in streamwater. Conversely, in the northern part of the basin where glacial deposits are thick and in the southwestern part of the basin where loess deposits are thick, water has longer periods of time to react with soils and aquifers and to acquire substantial quantities of dissolved constituents. As a result, streams in the till plain and glacial lowland have higher concentrations of most constituents than streams in the unglaciated parts of the basin. Water quality is significantly modified by human influences. Water quality is affected locally by point sources of contamination that include combined-sewer overflows, power-generation-plant cooling stations, and wastewater-treatment-plant effluents that are

generally associated with densely populated areas. Water quality is additionally affected by non-point sources of contamination related to agriculture, urban runoff, and mining.

Six hydrogeomorphic regions of the White River Basin are delineated on the basis of distinct and relatively homogeneous natural characteristics. These six regions are used in the White River Basin study as a framework for examining the effects of natural factors on water quality in the basin. Bedrock is exposed or near the surface in three hydrogeomorphic regions—the bedrock uplands, bedrock lowland and plain, and karst plain; streams and shallow aquifers in these regions are susceptible to contamination, especially in the karst plain, and show rapid response to rainfall. The other three hydrogeomorphic regions—the fluvial deposits, till plain, and glacial lowland—are in the glaciated part of the basin. Where thick fine-grained unconsolidated sediments are present, primarily in the till plain, ground-water supplies are protected from contamination, and extreme high and low streamflows are moderated.

Introduction

The need for a nationally consistent description of the status and trends in the quality of the Nation's ground- and surface-water resources prompted the U.S. Geological Survey to implement the National Water-Quality Assessment (NAWQA) Program (Hirsch and others, 1988). In addition to describing status and trends, another goal of the NAWQA Program is improving the scientific understanding of the natural factors and human influences that affect water quality.

Background

In 1986, NAWQA Program pilot studies were started by the U.S. Geological Survey to develop, test, and refine methods useful for the full-scale NAWQA Program that would begin in 1991. The NAWQA Program targets major hydrologic systems of the United States. Fifty-nine hydrologic systems, referred to as Study Units, were selected for investigation. These systems include parts of most river basins and aquifer systems used for public-supply water (Leahy and others, 1990). Study Units encompass areas from about 1,000 to more than 70,000 mi^2 and represent 60 to 70 percent of the Nation's water use. Assessment activities for each Study Unit consist of 2 years of planning and analysis of existing data, 3 years of intensive data collection, followed by 6 years of less intensive monitoring (Leahy and others, 1990). The NAWQA Program is structured such that about one-third of the Study Units are under intensive investigation at any given time. The White River Basin study was one of 20 Study Units begun in 1991. A brief summary outlining the White River Basin study is given in Jacques and Crawford (1991).

Purpose and Scope

This report identifies some of the natural factors and human influences that affect surface-water and ground-water quality in the White River Basin. The report will be used as a basis for sampling designs implemented during intensive sampling periods of the White River Basin study and will provide a context for analysis of data collected during these periods.

The report is limited to a brief examination of the major environmental factors that affect water quality in the basin and is based primarily on information described in previous studies. The effects on water quality in the White River Basin from natural factors (climate, geology, physiography, soils, and hydrology) and human influences (land use, population, waste-disposal practices, agricultural practices, and water use) are described.

Acknowledgments

The authors thank the Indiana Agricultural Statistics Service for providing information on Indiana agriculture. The Indiana Department of

Environmental Management (IDEM) provided information on municipal and industrial return flows and much of the surface-water-quality data used in this report. The Indiana Department of Natural Resources provided water-use and water-withdrawal information. Henry Gray and John Rupp, Indiana Geological Survey, provided maps and advice for delineating the hydrogeomorphic boundaries. Donald Franzmeier, Purdue University, provided descriptions of Indiana soils. William Hosteter, Natural Resources Conservation Service, provided assistance in interpreting information from the State Soil Geographic (STATSGO) data base for Indiana.

Environmental Setting of the White River Basin: Natural Factors

The White River Basin encompasses 11,349 mi^2 of central and southern Indiana and includes all or parts of 43 counties (fig. 1). Interrelated natural factors help determine the water quality in the basin. For example, the geology in the basin is variable—some areas have 400 ft of glacial till covering the bedrock surface while, in non-glaciated areas, bedrock can be exposed at the land surface. The climate and geology partially control the physiography and soils that develop in the basin. These four factors, in turn, influence the characteristics of stream discharge and the types of aquifers in the basin. Together, these natural factors influence the surface- and ground-water quality.

Climate

The White River Basin has a humid continental climate. The climate is characterized by well-defined winter and summer seasons accompanied by large annual temperature ranges (Shampine, 1977). Tropical maritime air masses dominate Indiana's climate during late spring, summer, and early fall; sources of moisture are the Gulf of Mexico and the subtropical Atlantic Ocean. Polar continental air masses dominate weather patterns in late fall, winter, and early spring (Glatfelter and Newman, 1991).

Precipitation and Temperature

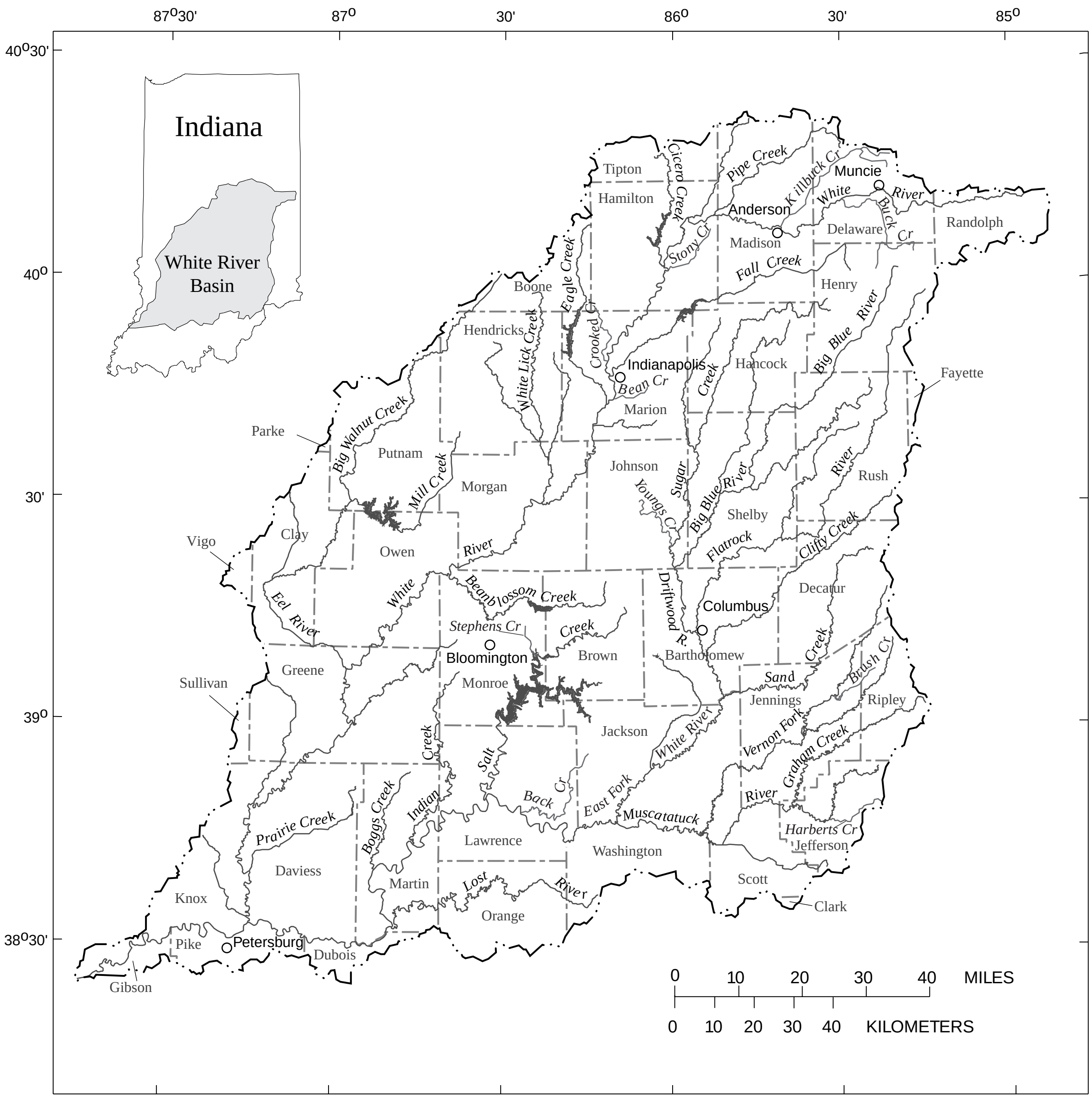
Precipitation and temperature data are available from a network of 48 National Weather Service (NWS) stations distributed throughout the basin. All temperature and climate data presented in this report are based on the period of record 1961 through 1990.

Mean annual temperature in the White River Basin ranges from about 51°F in the north to about 55°F in the south. Mean monthly temperatures at Columbus, in the central part of the basin, range from about 27°F in January to about 75°F in July. Figure 2 shows the mean monthly temperature for four NWS stations in the basin. Winds in the basin generally trend east to northeast, with an average velocity of 11 mph (Peters and Bonelli, 1982).

Mean annual precipitation in the study area ranges from 38 inches in the northern part of the basin to 44 inches in the south-central part (fig. 3). Precipitation in the cooler months is generally of long duration and mild intensity, whereas precipitation in late spring and summer tends to be of shorter duration and higher intensity. Figure 4 shows mean monthly precipitation for four NWS stations in the basin. Estimated evapotranspiration in the basin is 26 in/yr (Clark, 1980).

Precipitation Quality

Precipitation can be contaminated by a variety of compounds. During the latter part of the 20th century, "acid rain" (precipitation with a pH of 4.0 or less) in the northern United States and Canada has been the subject of most precipitation-contamination studies. In a 3-month study of atmospheric deposition across the north-central and northeastern United States, Peters and Bonelli (1982) showed that the average pH for precipitation in the White River Basin was 4.2 to 4.4, except for southwestern Indiana where the pH was typically greater than 4.8. Daily calcium



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°

EXPLANATION

—— · · —— White River Basin boundary

Figure 1. Location of the White River Basin in Indiana.

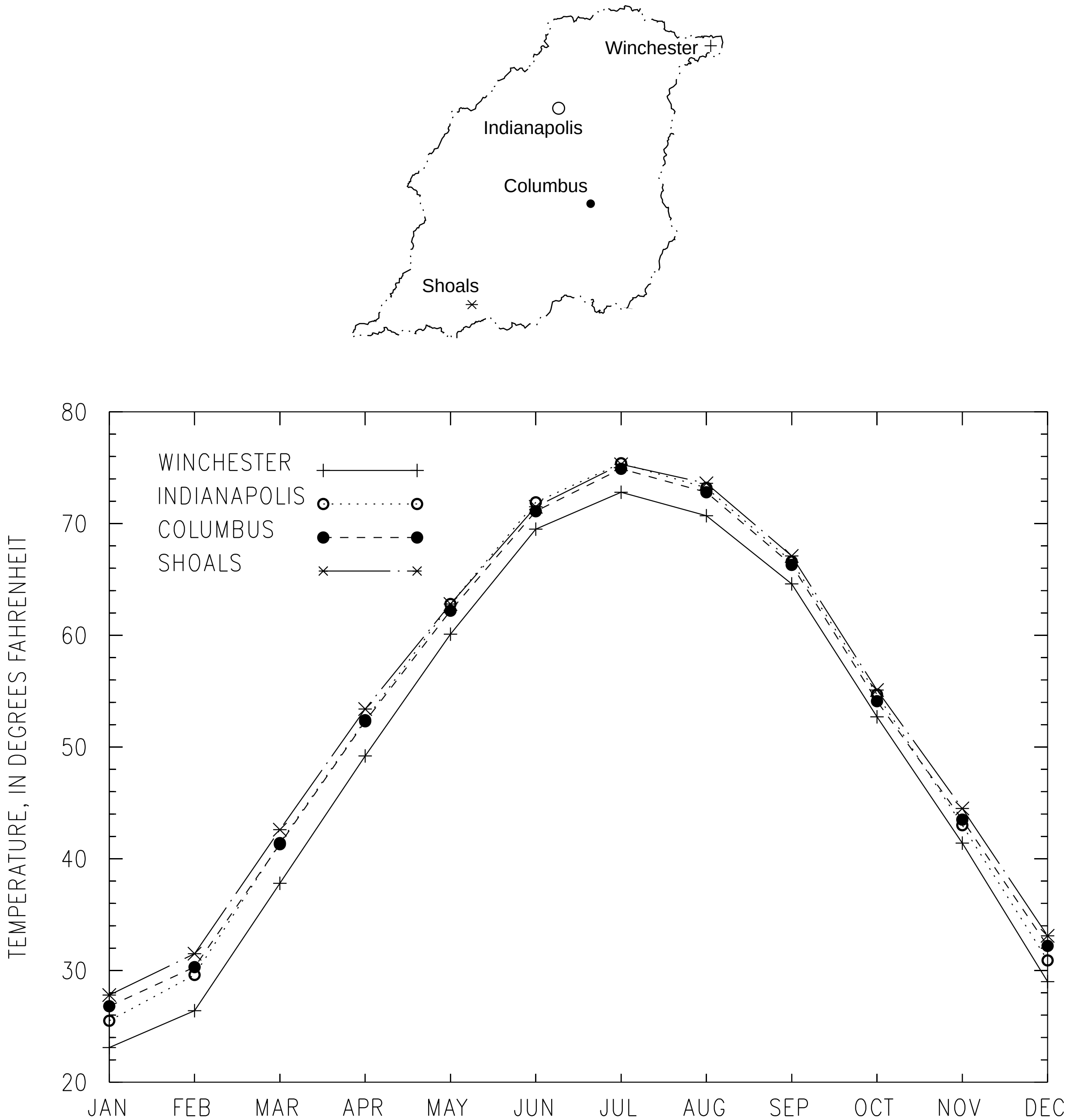


Figure 2. Mean monthly temperature at four selected stations in the White River Basin, Indiana, 1961–90. (Data from National Weather Service, 1997.)

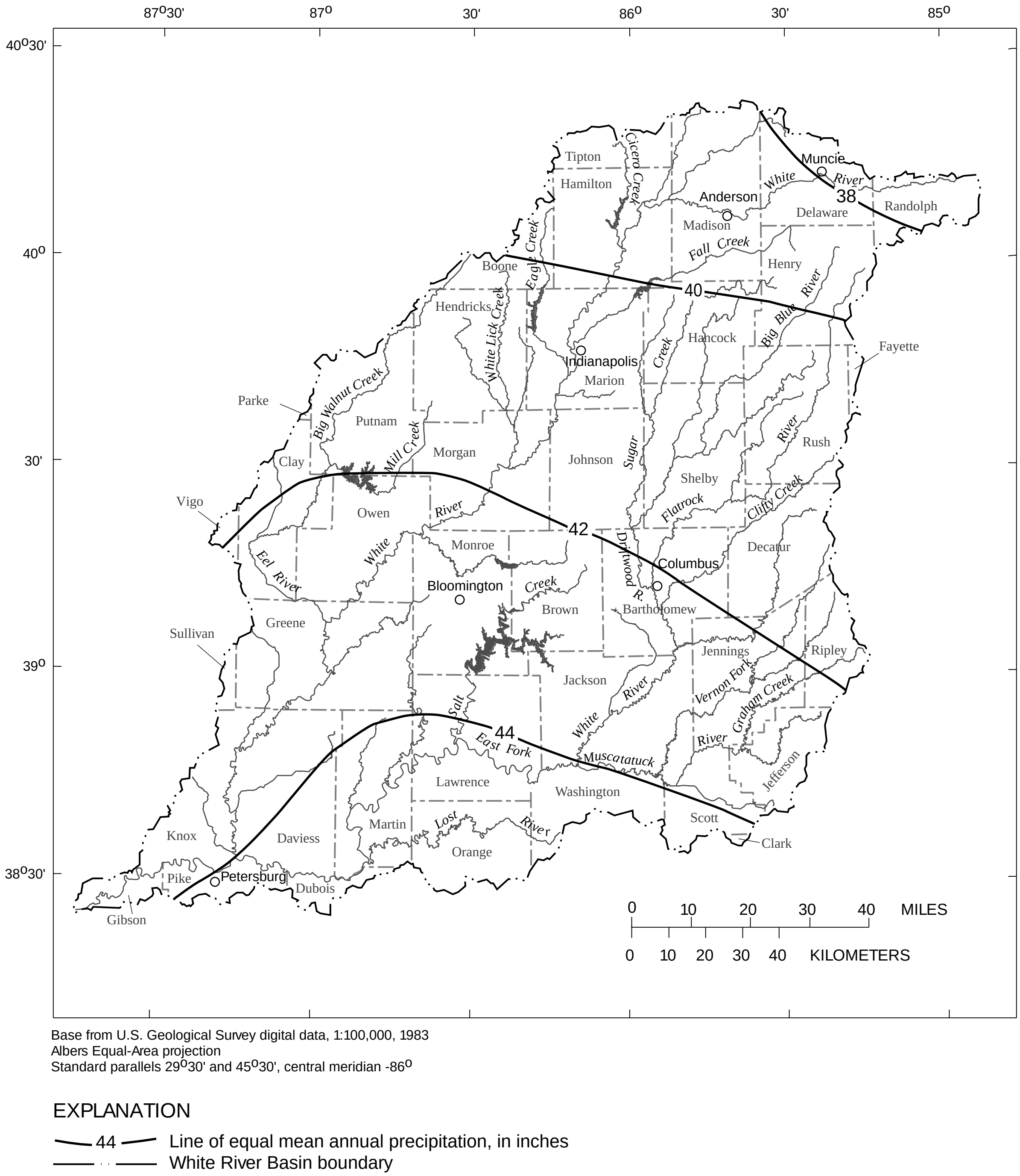


Figure 3. Mean annual precipitation in the White River Basin, Indiana, 1961–90. (Data from Wendlund and others, 1992.)

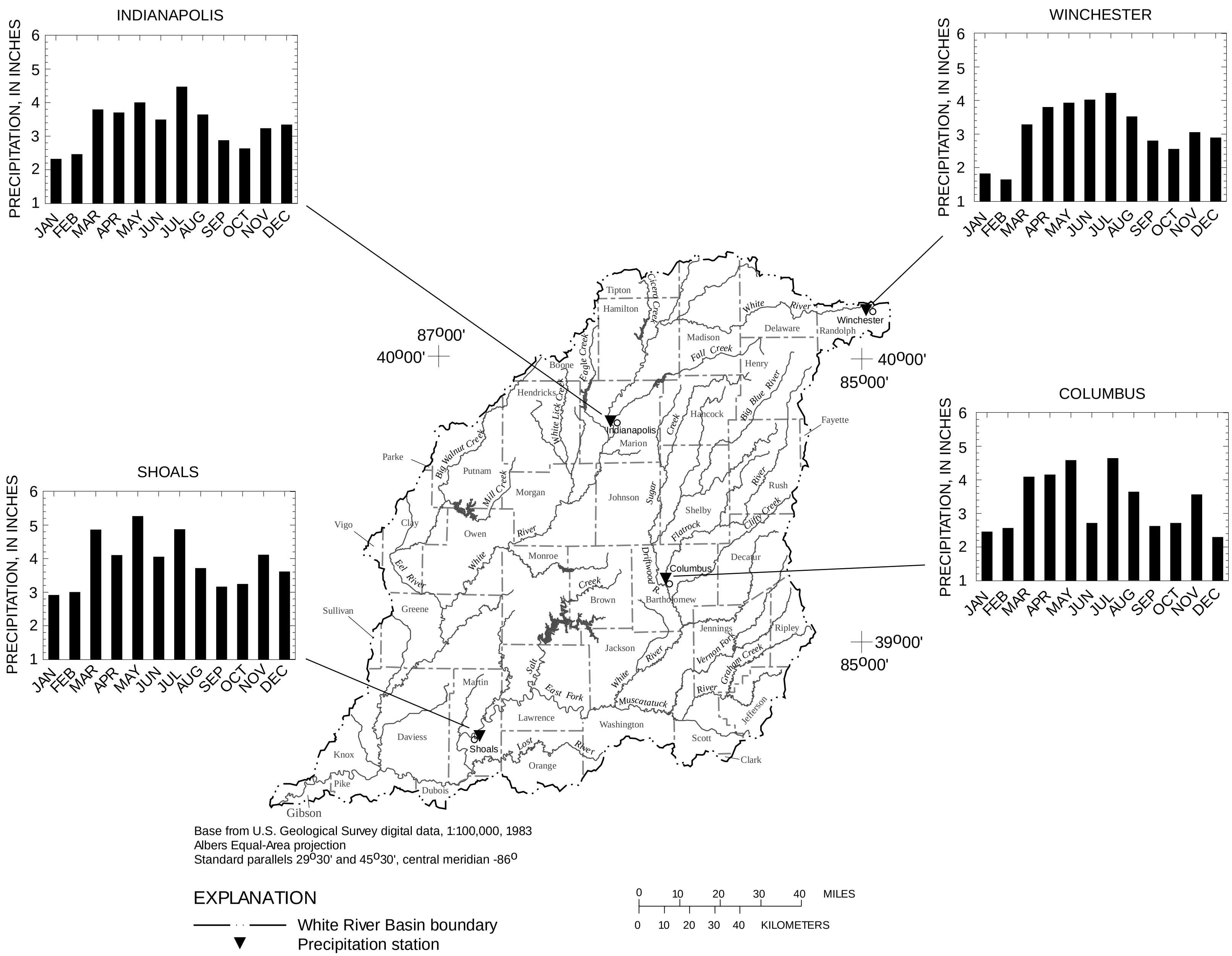


Figure 4. Mean monthly precipitation at four selected stations in the White River Basin, Indiana, 1961–90. (Data from National Weather Service, 1997.)

loads in atmospheric deposition in southwestern Indiana are generally greater than 2.0 mg/m^2, compared to 1.0 to 2.0 mg/m^2 for the remainder of the basin. Daily loads are generally less than 0.5 mg/m^2 for sodium, chloride, and fluoride.

Atmospheric deposition also may be a significant pathway for the dispersal of pesticides and nutrients (Grennfelt and Jultberg, 1986; Grover, 1988; Taylor and Glotfelty, 1988; Aber and others, 1989; Johnson and others, 1991; Majewski and Capel, 1995). Herbicides were detected in more than 50 percent of the atmospheric deposition samples in the upper Midwest taken during May to June 1990 (Goolsby and others, 1991). Average daily loads of ammonium (as nitrogen) and nitrate (as nitrogen) in southwestern and south-central Indiana range from 0.6 to 1.0 mg/m^2 and 0.4 to 2.0 mg/m^2, respectively (Peters and Bonelli, 1982).

Geology

The varied geology of the White River Basin affects topography, runoff, land use, ground-water storage, and surface- and ground-water quality. Geologic features in the White River Basin include glaciated and nonglaciated areas; a region of karst geomorphology that is characterized by caves and sinkholes; and a thick, sedimentary bedrock sequence underlying the entire basin. Glaciation during the Quaternary age left extensive deposits of unconsolidated material in the basin. Bedrock includes Paleozoic-age carbonates (limestone and dolomite), sandstones, siltstones, shales, and coals (Shaver and others, 1986; Gray and others, 1987; Gray, 1989; and Rupp, 1991). A generalized bedrock geology map of the White River Basin is shown in figure 5. A chart showing geologic ages, groups, selected formations, and lithologies for aquifers and confining units is given in table 1.

The structural geology of Indiana is influenced by the Cincinnati and Kankakee Arches. These two regional features separate the Michigan structural basin from the Illinois structural basin and are positioned to the north and east of the White River Basin (fig. 6). The White River Basin is primarily influenced by the Illinois structural basin. Sedimentary strata dip westward and southwestward from the axis of the Cincinnati Arch into the Illinois structural basin with a slope of 10 to 30 ft/mi (Gutschick, 1966). Geologic units thicken to the west and southwest toward the center of the Illinois structural basin.

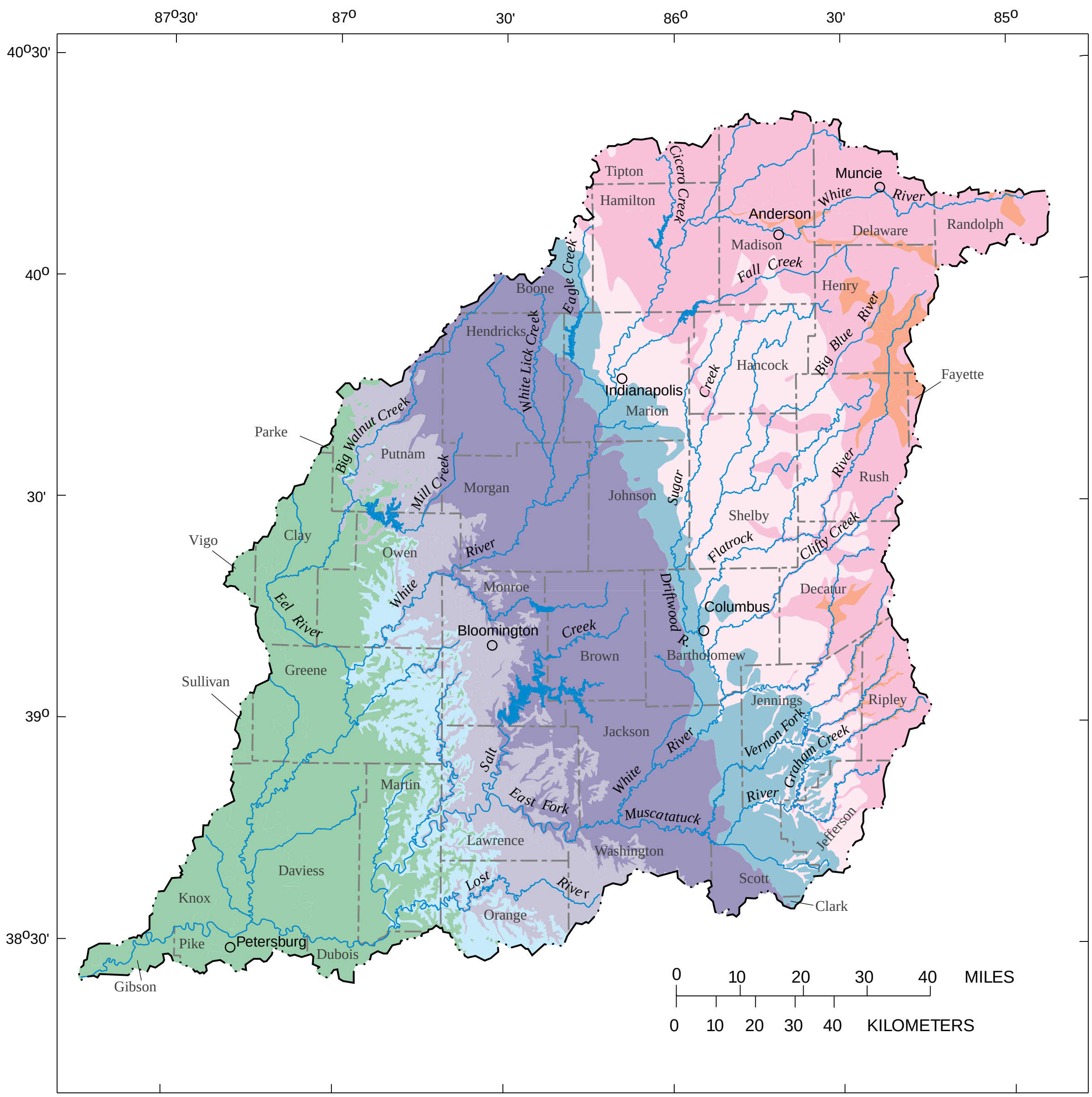
Two major faults interrupt bedrock stratigraphy in the White River Basin (fig. 6). The Mt. Carmel fault system can be traced at land surface for about 55 mi, and rock units may be displaced vertically up to 200 ft (Tanner, 1986). The Fortville fault trace is approximately 45 mi long, and the vertical displacement of bedrock is estimated to be no more than 50 to 100 ft (Dawson, 1971). The Fortville and Mt. Carmel fault systems are inactive.

In southern and central Indiana, the sedimentary strata are exposed or near the surface, providing many benefits to the local inhabitants. For example, where Mississippian limestones are near or exposed at the land surface, karst features such as caves, sinkholes, and disappearing streams are popular attractions with tourists and spelunkers. In addition to the aesthetic appeal, the karst plain of south-central Indiana is a refuge for unique flora and fauna like the blind crayfish. Sedimentary rocks also are mined for their economic value (see “Mines and Quarries” section).

In the northern part of the basin, unconsolidated glacial deposits overlie the bedrock. Glaciers covered parts of present-day Indiana at least three times during the Pleistocene Epoch (Wayne, 1966). Wisconsin- and pre-Wisconsin- (Kansan and Illinoian) age glaciers covered more than 60 percent of the basin and left deposits of till containing clay, silt, sand and gravel (fig. 7). Unconsolidated deposits may be 400 ft thick in the northern part of the basin but, in the southern part, glacial deposits are limited to thin veneers of windblown silt.

Physiography

The White River Basin contains seven physiographic units originally defined by Malott (1922) (fig. 8). Differences in land-surface features among



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°

EXPLANATION

Bedrock group or formation and lithology

- McLeansboro, Carbondale, and Racoon Creek Groups–shale; sandstone; thin beds of limestone, clay, and coal
- Buffalo Wallow, Stephensport, and West Baden Groups–shale; sandstone; limestone
- Blue River and Sanders Groups–limestone
- Borden Group plus Rockford Limestone–siltstone and shale
- New Albany Shale–black shale
- Muscatatuck Group–limestone and dolomite
- Silurian rocks–limestone and dolomite
- Maquoketa Group–shale and limestone
- White River Basin boundary

Figure 5. Generalized bedrock geology in the White River Basin, Indiana. (Modified from Gray and others, 1987.)

Table 1. Geologic chart showing geologic ages, groups, selected formations, and lithologies for aquifers and confining units in the White River Basin, Indiana

[Geologic names are from Shaver and others, 1986.]

Erathem	System	Series or Group	Selected Formations	Lithology	Hydrogeologic unit
Cenozoic	Quaternary	Holocene		Alluvial sand, silt, and clay; dune sand; loess; outwash sand and gravel; lake clay; clay-loam till	Glaciofluvial aquifers; Till aquifers; Till and clay confining units
		Pleistocene: Wisconsin	Trafalgar Formation		
		Pleistocene: Pre-Wisconsin	Jessup Formation		
Paleozoic	Pennsylvanian	McLeansboro Group Carbondale Group Raccoon Creek Group	Mansfield Formation	Shale, siltstone, sandstone, limestone, and coal	Pennsylvanian sandstone aquifers; Minor limestone, shale, and coal aquifers; Shale and siltstone confining units
	Mississippian	Buffalo Wallow Group Stephensport Group West Baden Group		Shale, siltstone, sandstone, and limestone	Mississippian sandstone and thin (<30 ft) limestone aquifers; Shale and siltstone confining units
		Blue River Group Sanders Group	Paoli Limestone Ste. Genevieve Limestone St. Louis Limestone Salem Limestone	Limestone	Mississippian carbonate aquifer
		Borden Group	Edwardsville Formation Spickert Knob Formation New Providence Shale	Siltstone and shale; minor limestone and sandstone	Confining unit
	Mississippian / Devonian		New Albany Shale	Shale	Confining unit
	Devonian	Muscatatuck Group		Limestone and dolomite	Silurian and Devonian carbonate aquifer
	Silurian	Salina Group or Bainbridge Group	Wabash Formation Pleasant Mill Formation Louisville Limestone Salamonie Dolomite Cataract Formation Brassfield Limestone	Limestone and dolomite	
	Ordovician	Maquoketa Group		Shale and limestone	Confining unit
			Trenton Limestone	Limestone	Not used for water in basin
		Black River Group Ancell Group		Limestone, dolomite, and sandstone	Not used for water in basin
	Ordovician / Cambrian	Knox Supergroup		Dolomite	Not used for water in basin
	Cambrian	Potsdam Supergroup	Mt. Simon Sandstone	Sandstone	Not used for water in basin
Precambrian		Basement complex—includes granite, basalt, and arkose			

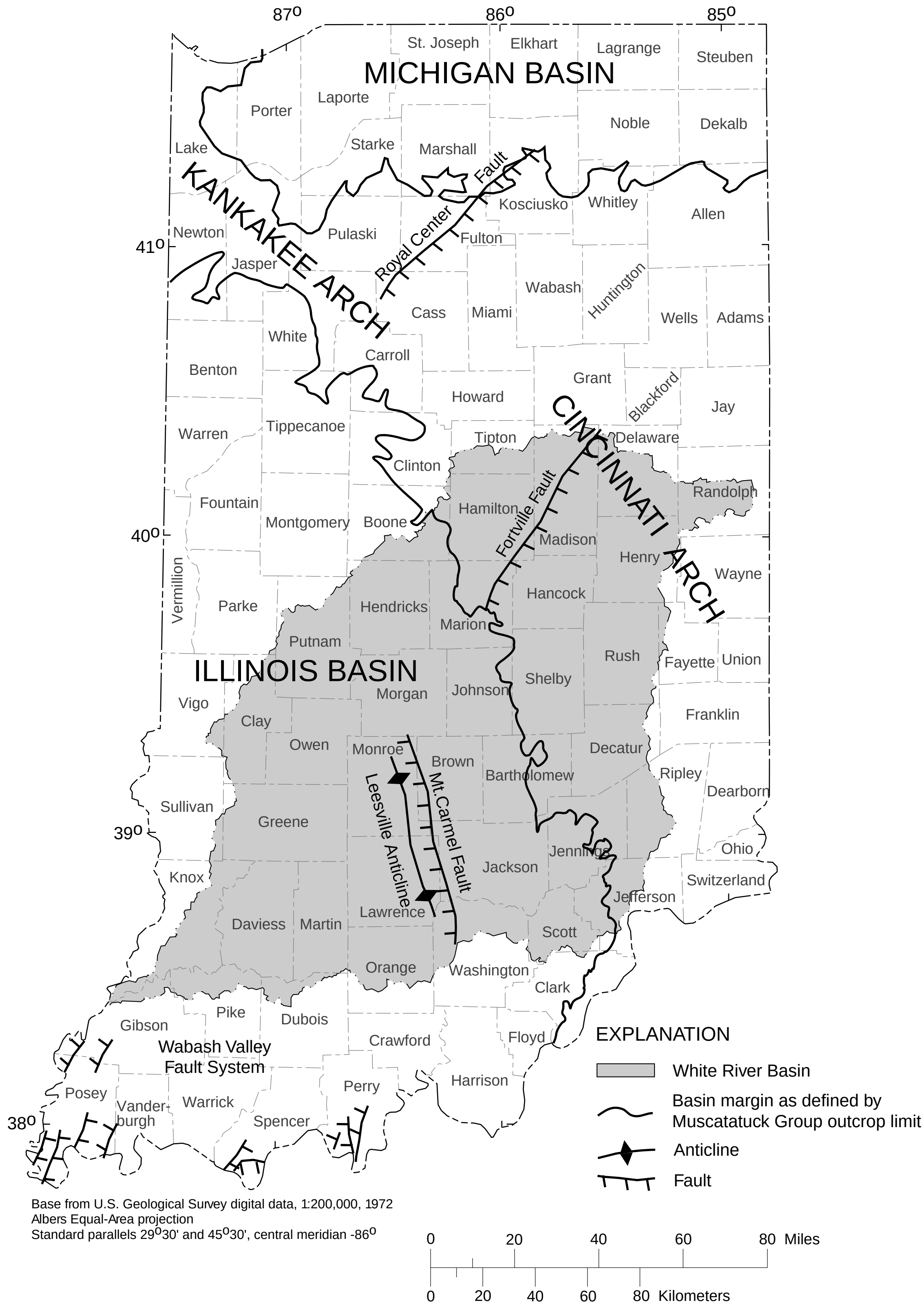
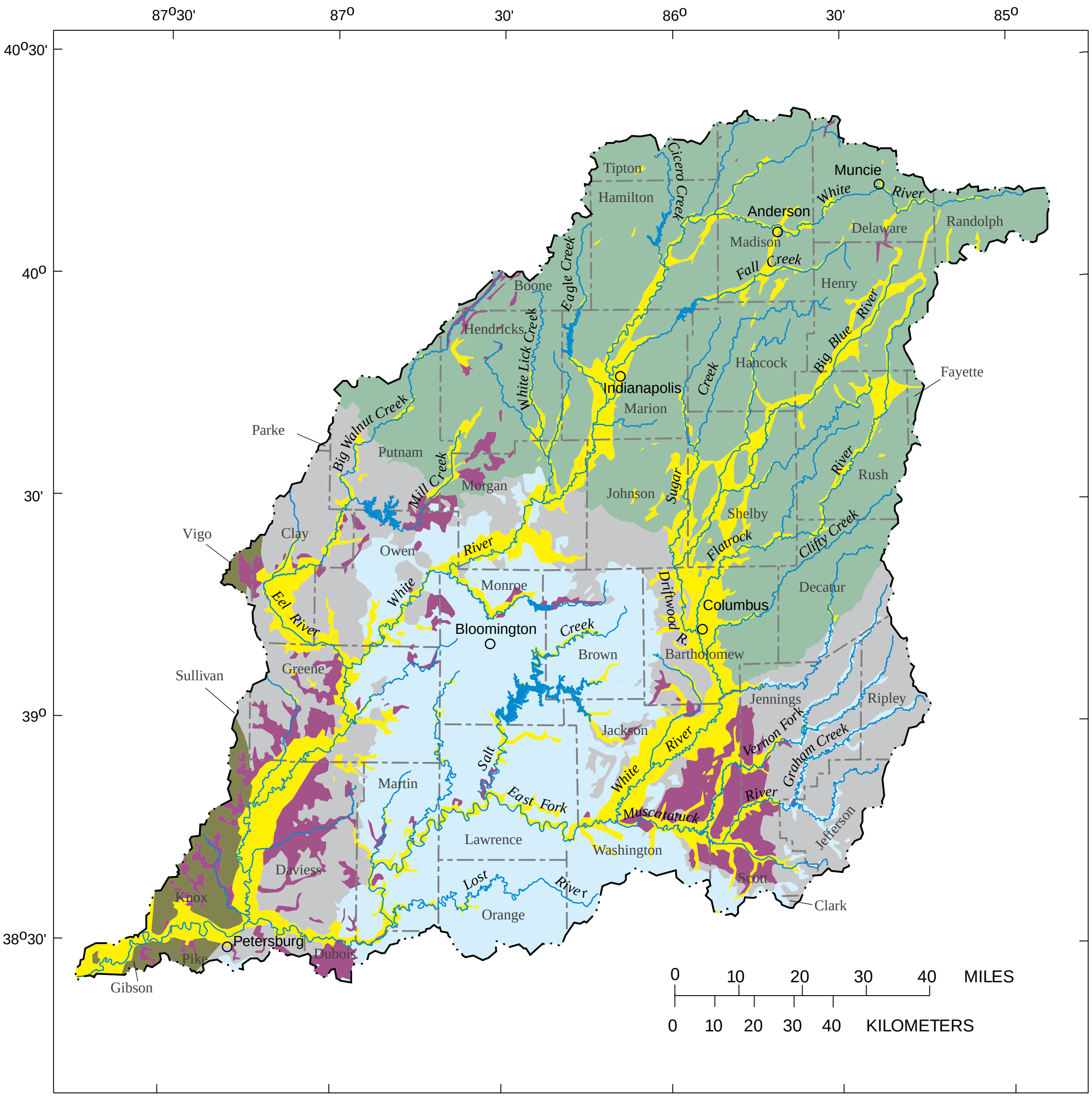


Figure 6. Structural geology in Indiana and the White River Basin, Indiana. (Modified from Rupp, 1991.)



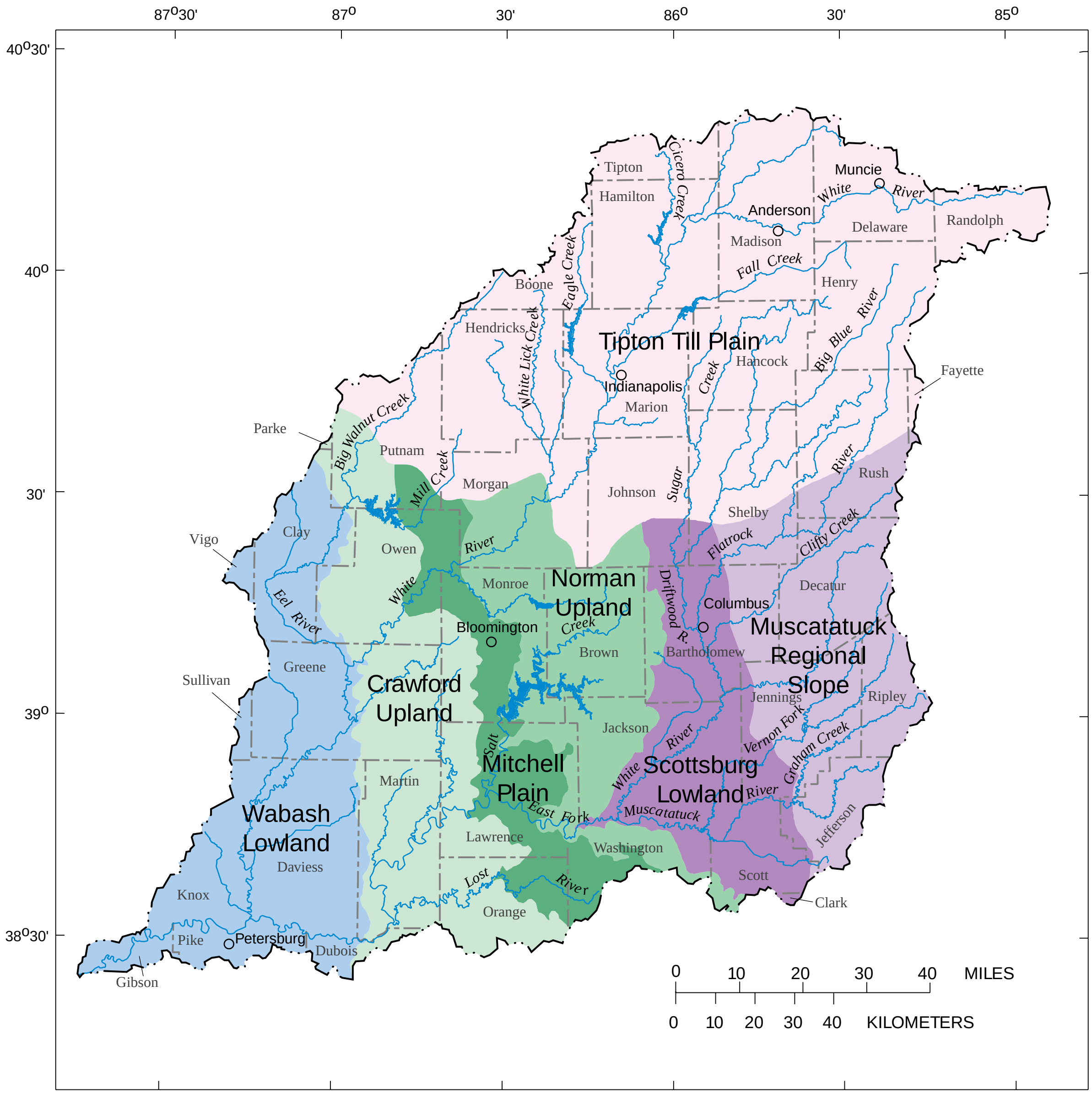
Base from U.S. Geological Survey digital data, 1:100,000, 1983
Albers Equal-Area projection
Standard parallels 29°30' and 45°30', central meridian -86°

EXPLANATION

Unconsolidated surficial deposits

- Sand, silt, and some gravel–Holocene alluvium and Pleistocene glacial outwash
- Clay, silt, and sand–Wisconsin-age lake deposits
- Silt deposits–Wisconsin-age loess
- Loam to sandy loam deposits–Wisconsin-age till
- Loam to sandy loam deposits–Pre-Wisconsin-age till
- Bedrock–Paleozoic sandstone, shale, and limestone
- White River Basin boundary

Figure 7. Surficial geology in the White River Basin, Indiana. (Modified from Soller, 1993 and Gray, 1989.)



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°

EXPLANATION

Physiographic units

- Tipton Till Plain
- Wabash Lowland
- Crawford Upland
- Mitchell Plain
- Norman Upland
- Scottsburg Lowland
- Muscatatuck Regional Slope
- White River Basin boundary

Figure 8. Physiographic units in the White River Basin, Indiana. (Modified from Schneider, 1966).

these units are caused by bedrock geology and the extent of glaciation. The Tipton Till Plain, defined by glacial features, is a flat to rolling glacial till plain that covers the northern half of the basin. The Wabash Lowland is in the southwestern part of the basin and is an area of broad, flat valleys and gently rolling plains. The remaining five physiographic units are controlled principally by bedrock. The Crawford Upland and the Norman Upland are westward-sloping, unglaciated upland areas with narrow ridge tops and steep slopes. The Mitchell Plain lies between the two upland units and is a karst plain with numerous sinkholes and solution features. The Scottsburg Lowland is east of the Norman Upland and is an area of low relief and extremely broad, flat valleys. The Muscatatuck Regional Slope, in the southeastern part of the basin, is a westward-sloping plain characterized by moderate relief and by bedrock outcrops in the stream channels.

Soils

Thirteen soil regions characterize the soils in the White River Basin (fig. 9). The soil regions are classified by parent material, natural vegetation, and topography (Franzmeier and others, 1989). The basin is covered by soil regions of four primary groups with similar geologic properties: (1) soils developed from loess or glacial tills (composed primarily of the soil regions "thin loess over loamy glacial till" and "moderately thick loess over weathered loamy glacial till"); (2) soils developed along floodplains (composed primarily of the soil regions "alluvial deposits" and "outwash deposits"); (3) soils developed from bedrock (composed of the soil regions "discontinuous loess over weathered limestone" and "discontinuous loess over weathered limestone and shale"); and (4) soils developed from lake deposits. Soils developed from loess or glacial tills are found in Wisconsin-age tills in the northern part of the basin and pre-Wisconsin-age tills in the western and eastern parts of the basin. These soils are developed in calcareous parent material and commonly have poor natural drainage, high base content, and high fertility (Ulrich, 1966). Soils along the floodplains are found in and along stream and river valleys throughout the basin and are typically well drained, fertile, and have high base content (Ulrich, 1966). Soils developed from bedrock are located in the unglaciated area in the south-central part of the basin. The soils are typically well drained, thin, acidic, and have low organic matter and poor fertility (Ulrich, 1966). Most are best suited for forest or pasture. Soils developed from lake deposits are poorly drained and are not areally extensive in the White River Basin.

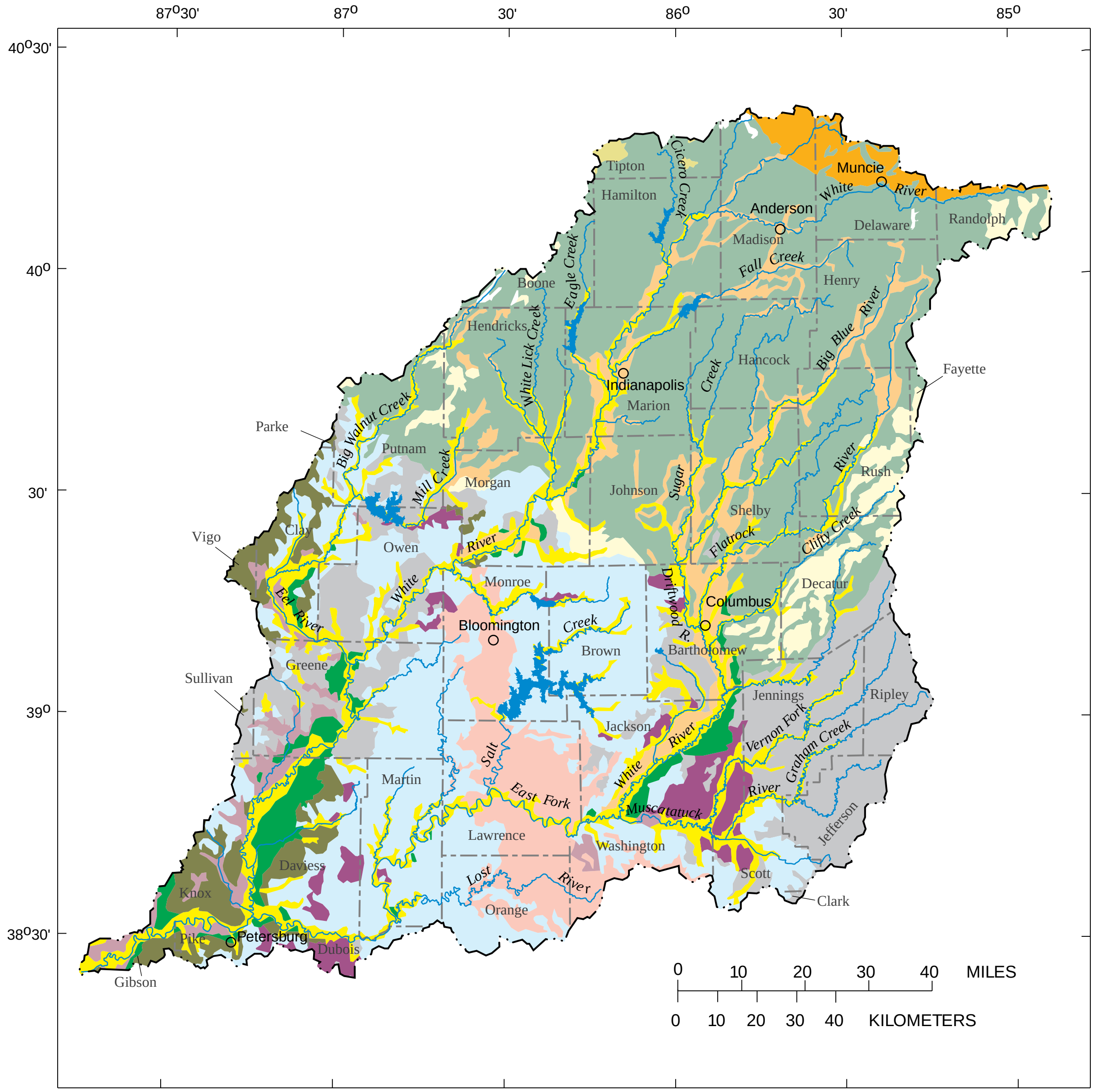
Hydrology

The hydrology of the White River Basin is described by characterizing surface-water flow and quality, ground-water flow and quality, and surface-water and ground-water interactions.

Surface Water

The White River drains 11,349 mi^2 of central and southern Indiana and joins the Wabash River in southwestern Indiana (Hoggatt, 1975). Most of the basin is divided into two nearly equal subbasins—the East Fork White River and the White River (locally called the "west fork" of the White River) upstream from its confluence with the east fork. East Fork White River drains 5,746 mi^2 and joins the White River at river mile 49.5 near Petersburg (fig. 1). White River, upstream from its confluence with East Fork White River, drains 5,372 mi^2. Only 2 percent (231 mi^2) of the drainage area of the White River Basin is downstream from the confluence of the east and west forks.

The major tributaries (drainage areas greater than 500 mi^2) to the East Fork White River are the Driftwood River (1,165 mi^2), the Flatrock River (542 mi^2), the Muscatatuck River (1,140 mi^2), and Salt Creek (636 mi^2) (fig. 1). The Driftwood River may be the shortest river in Indiana. Formed by the confluence of the Big Blue River and Sugar Creek, the Driftwood River flows 15 mi to its confluence with the Flatrock River, where the



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°

EXPLANATION

Soil regions

Soils developed from loess or glacial tills
- Thin loess over loamy glacial till
- Moderately thick loess over loamy glacial till
- Moderately thick loess over loamy glacial till with prairie vegetation
- Moderately thick loess over weathered loamy glacial till
- Thick loess deposits
- Clayey glacial till

Soils developed along floodplains
- Alluvial deposits
- Outwash deposits
- Eolian sand deposits

Soils developed from bedrock
- Discontinuous loess over weathered limestone and shale
- Discontinuous loess over weathered limestone

Soils developed from lake deposits
- Silty and clayey lake deposits
- Moderately thick loess over weathered lake deposits

White River Basin boundary

Figure 9. Major soil regions in the White River Basin, Indiana. (Modified from Franzmeier and others, 1989.)

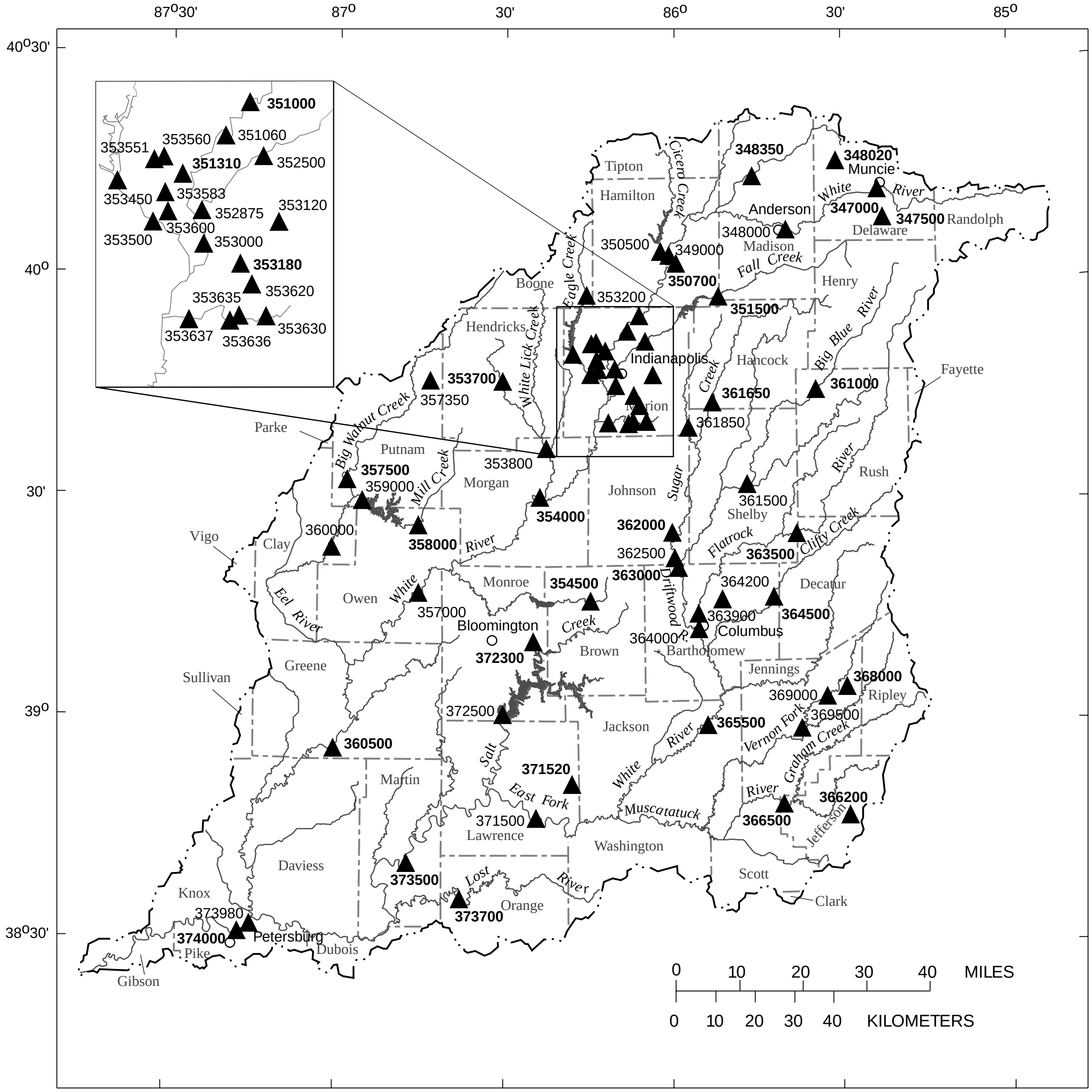
East Fork White River is formed. The Big Blue River is considered the headwaters of the East Fork White River (Stewart and Nell, 1991). The Eel River (1,208 mi^2) is the only major tributary to the White River, excluding the East Fork White River (Hoggatt, 1975). The reaches of the White River and the East Fork White River upstream from their confluence are referred to as the “west fork” and “east fork” of the White River in this report when comparing streamflow or water quality of the two rivers.

Characteristics of Streamflow

Streamflow information is collected by the U.S. Geological Survey at streamflow-gaging stations throughout the basin (fig. 10). The information is used by scientists, planners, and regulators for a variety of purposes including forecasting floods; delineating floodplains; operating and designing reservoirs; setting permit requirements for the discharge of wastewater; designing bridges and culverts; establishing and monitoring minimum streamflows; performing scientific studies of hydrology; and allocating water for multiple, competing users. Statistical summaries of streamflow information for Indiana have been compiled by Arvin (1989), and low-flow characteristics of Indiana streams have been compiled by Fowler and Wilson (1996). Methods for estimating the magnitude and frequency of floods in Indiana have been developed by Glatfelter (1984), and methods for estimating the magnitude and frequency of low flows in Indiana have been developed by Arihood and Glatfelter (1986).

The flow of water can be described by many technical terms and expressed in different units of measure (Langbein and Iseri, 1960). The distinction among terms often is subtle and can lead to confusion. In this report, mean annual runoff is used to describe the water yield of a drainage basin and is expressed in inches to allow a direct comparison with precipitation. Mean annual runoff is not surface runoff. Surface runoff is a mechanism of streamflow generation where precipitation quickly flows over the surface of the land (rather than through the soil or ground water) to reach the stream. Streamflow is used to describe the volume flow rate of water measured at a streamflow-gaging station and is expressed in cubic feet per second (ft^3/s). Because the magnitude of streamflow is a function of the size of the drainage basin, streamflow also may be expressed in cubic feet per second per square mile ($ft^3/s/mi^2$) to allow comparison of streamflow among stations with different-sized drainage basins. Adjustment of streamflow for basin size, however, often results in peak flows that are inversely correlated to basin size (Gregory and Walling, 1973). To minimize this correlation, characteristics of streamflow were compared among basins of approximately similar sizes.

Daily mean streamflow at selected streamflow-gaging stations in the White River Basin was summarized for the 1971 through 1990 water years (table 2) to describe the characteristics of streamflow in the basin. (This 20-year period was selected rather than 1961-90 to increase the number of stations available for analysis. Many of the streamflow-gaging stations in the basin were not installed until the late 1960’s.) Characteristics of streamflow generally are described by a variety of statistical computations of the daily mean streamflow (the average rate of streamflow during a particular calendar day). These computations are of two types in this report: (1) mean streamflow for specified periods of time, such as mean monthly streamflow or mean annual runoff, and (2) frequency analyses of daily mean streamflow or some other statistic of streamflow. For example, the mean monthly streamflow for March is the average of the 620 daily mean streamflows for March for water years 1971 through 1990. Frequency analysis of streamflow (also called flow-duration analysis) provides information on the percentage of time a particular value of daily mean streamflow (or some other statistic of streamflow) is equaled or exceeded. For example, the 1-percent flow duration for the White River at Muncie is 2,330 ft^3/s (table 2). This means that only 1 percent (73) of the 7,309 daily mean streamflows from water years 1971 through 1990 were equal to or greater than 2,330 ft^3/s. In this report,



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°

EXPLANATION

White River Basin boundary

▲ 371500 U.S. Geological Survey streamflow-gaging station and abbreviated station number. Complete station number includes a "03" prefix. Abbreviated station numbers in bold are in table 2.

Figure 10. Location of U.S. Geological Survey streamflow-gaging stations in the White River Basin, Indiana.

Table 2. Summary of daily mean streamflow characteristics at selected streamflow-gaging stations in the White River Basin, Indiana, 1971–90 water years

[Station locations shown in figure 10; $7Q_{10}$, the average streamflow for 7 consecutive days below which streamflow recedes on average once every 10 years; ft^3/s, cubic feet per second—numbers not in brackets; $ft^3/s/mi^2$, cubic feet per second per square mile—numbers in brackets; mi^2, square mile; %, percent]

Station name and identifier	Drainage area (mi^2)	$7Q_{10}$ (ft^3/s and $ft^3/s/mi^2$)	Percentage of time that daily mean streamflow was greater than or equal to value shown (ft^3/s and $ft^3/s/mi^2$)							
			95%	90%	75%	50%	25%	10%	5%	1%
White River at Muncie (03347000)	241	4.7 [.020]	9.2 [.040]	17 [.069]	35 [.15]	89 [.37]	221 [.92]	518 [2.1]	894 [3.7]	2,330 [9.7]
Buck Creek near Muncie (03347500)	35.5	7.5 [.21]	11 [.30]	13 [.37]	18 [.50]	26 [.74]	41 [1.2]	69 [2.0]	107 [3.0]	276 [7.8]
Killbuck Creek near Gaston (03348020)	25.5	1.0 [.040]	1.9 [.075]	2.8 [.11]	5.3 [.21]	12 [.47]	26 [1.0]	58 [2.3]	99 [3.9]	255 [10]
Pipe Creek at Frankton (03348350)	113	4.2 [.038]	7.4 [.065]	9.1 [.081]	17 [.15]	39 [.35]	95 [.84]	257 [2.3]	450 [4.0]	1,060 [9.4]
Stony Creek near Noblesville (03350700)	50.8	3.1 [.061]	4.5 [.089]	5.8 [.11]	9.8 [.19]	22 [.44]	54 [1.1]	116 [2.3]	183 [3.6]	431 [8.5]
White River near Nora (03351000)	1,219	133 [.11]	172 [.14]	202 [.17]	314 [.26]	619 [.51]	1,350 [1.1]	2,790 [2.3]	4,420 [3.6]	9,220 [7.6]
Crooked Creek at Indianapolis (03351310)	17.9	.65 [.034]	1.4 [.078]	1.9 [.11]	3.5 [.20]	7.6 [.42]	18 [.98]	38 [2.1]	68 [3.8]	199 [11]
Fall Creek near Fortville (03351500)	169	16 [.095]	30 [.18]	36 [.21]	55 [.32]	102 [.60]	196 [1.2]	362 [2.1]	582 [3.4]	1,350 [8.0]
Bean Creek at Indianapolis (03353180)	4.4	.67 [.16]	1.1 [.25]	1.3 [.30]	1.8 [.41]	2.7 [.61]	4.8 [1.1]	11 [2.5]	18 [4.1]	46 [11]
West Fork White Lick Creek at Danville (03353700)	28.8	.00 [.000]	.11 [.004]	.40 [.014]	2.2 [.076]	9.9 [.34]	31 [1.1]	81 [2.8]	146 [5.1]	390 [14]
White River near Centerton (03354000)	2,444	274 [.11]	383 [.16]	469 [.19]	764 [.31]	1,490 [.61]	3,030 [1.2]	5,830 [2.4]	9,470 [3.9]	18,000 [7.3]
Beanblossom Creek at Beanblossom (03354500)	14.6	.00 [.000]	.01 [.001]	.12 [.008]	.65 [.045]	4.2 [.29]	16 [1.1]	36 [2.5]	68 [4.6]	215 [15]
Big Walnut Creek near Reelsville (03357500)	326	8.9 [.027]	23 [.071]	36 [.11]	74 [.23]	174 [.53]	394 [1.2]	834 [2.6]	1,430 [4.4]	3,710 [11]
Mill Creek near Cataract (03358000)	245	3.3 [.014]	8.3 [.034]	13 [.054]	34 [.14]	92 [.38]	244 [1.0]	648 [2.6]	1,290 [5.3]	3,240 [13]
White River at Newberry (03360500)	4,688	443 [.095]	666 [.14]	861 [.18]	1,490 [.32]	3,220 [.69]	6,760 [1.4]	12,600 [2.7]	18,300 [3.9]	29,500 [6.3]
Big Blue River at Carthage (03361000)	184	27 [.15]	43 [.23]	54 [.29]	73 [.40]	125 [.68]	219 [1.2]	421 [2.3]	657 [3.6]	1,530 [8.3]
Sugar Creek at New Palestine (03361650)	93.9	3.5 [.037]	6.6 [.070]	9.2 [.098]	19 [.20]	47 [.50]	106 [1.1]	242 [2.6]	396 [4.2]	877 [9.3]
Youngs Creek near Edinburgh (03362000)	107	2.4 [.022]	4.1 [.038]	5.7 [.053]	14 [.13]	40 [.37]	103 [.96]	249 [2.3]	436 [4.1]	1,160 [11]
Driftwood River near Edinburgh (03363000)	1,060	101 [.095]	150 [.14]	186 [.18]	310 [.29]	665 [.63]	1,380 [1.3]	2,820 [2.7]	4,450 [4.2]	8,630 [8.1]

Table 2. Summary of daily mean streamflow characteristics at selected streamflow-gaging stations in the White River Basin, Indiana, 1971–90 water years—Continued

Station name and identifier	Drainage area (mi^2)	$7Q_{10}$ (ft^3/s and $ft^3/s/mi^2$)	Percentage of time that daily mean streamflow was greater than or equal to value shown (ft^3/s and $ft^3/s/mi^2$)							
			95%	90%	75%	50%	25%	10%	5%	1%
Flatrock River at St. Paul (03363500)	303	4.4 [.015]	15 [.049]	21 [.068]	59 [.19]	168 [.55]	372 [1.2]	842 [2.8]	1,330 [4.4]	2,760 [9.1]
Clifty Creek at Hartsville (03364500)	91.4	.00 [.000]	.19 [.002]	1.4 [.015]	7.7 [.080]	35 [.38]	97 [1.1]	230 [2.5]	372 [4.1]	1,050 [12]
East Fork White River at Seymour (03365500)	2,341	191 [.082]	286 [.12]	365 [.16]	661 [.28]	1,490 [.64]	3,070 [1.3]	6,110 [2.6]	9,790 [4.2]	21,500 [9.2]
Harberts Creek near Madison (03366200)	9.3	.00 [.000]	.04 [.004]	.12 [.013]	.63 [.068]	2.6 [.28]	9.1 [.98]	27 [2.9]	60 [6.5]	205 [22]
Muscatatuck River at Deputy (03366500)	293	.69 [.002]	3.5 [.012]	8.4 [.029]	25 [.086]	95 [.32]	300 [1.0]	831 [2.8]	1,570 [5.4]	4,840 [17]
Brush Creek near Nebraska (03368000)	11.4	.00 [.000]	.01 [.001]	.05 [.004]	.49 [.043]	2.5 [.22]	8.2 [.72]	26 [2.2]	60 [5.3]	242 [21]
Back Creek at Leesville (03371520)	24.1	.00 [.000]	.16 [.007]	.41 [.017]	1.9 [.079]	9.9 [.41]	31 [1.3]	76 [3.1]	134 [5.6]	397 [16]
Stephens Creek near Bloomington (03372300)	10.9	.00 [.000]	.05 [.005]	.15 [.014]	.77 [.071]	3.9 [.36]	14 [1.3]	34 [3.1]	61 [5.6]	169 [16]
East Fork White River at Shoals (03373500)	4,927	388 [.079]	563 [.11]	713 [.14]	1,410 [.29]	3,700 [.75]	7,730 [1.6]	14,400 [2.9]	19,300 [3.9]	31,900 [6.5]
Lost River near West Baden Springs (03373700)	287	9.4 [.033]	18 [.063]	24 [.084]	54 [.19]	164 [.57]	441 [1.5]	976 [3.4]	1,550 [5.4]	2,970 [10]
White River at Petersburg (03374000)	11,125	1,050 [.094]	1,610 [.14]	2,090 [.19]	3,720 [.33]	8,600 [.77]	17,500 [1.6]	31,300 [2.8]	42,800 [3.8]	70,000 [6.3]

the 1-percent flow duration is used to describe peak (high) streamflows. The statistic of streamflow that is used to characterize low streamflow (base flow) is the 7-day, 10-year low flow ($7Q_{10}$). The $7Q_{10}$ is the minimum average streamflow for 7 consecutive days that has a 10-percent probability of not being exceeded in any year (Fowler and Wilson, 1996). The $7Q_{10}$ is commonly used to allocate wastewater discharges to streams. Additional explanation of streamflow statistics are given in Arvin (1989) and Fowler and Wilson (1996).

Streamflow in small drainage basins (drainage areas less than 36 mi^2, table 2) was distributed differently in the northern part of the basin than in the southern part. Buck Creek, Killbuck Creek, Crooked Creek, and Bean Creek are small streams in the northern part of the basin; Beanblossom Creek, Harberts Creek, Brush Creek, Back Creek, and Stephens Creek are small streams in the southern part. Streamflow in the northern basins exhibited well-sustained base flow ($7Q_{10}$ ranged from 0.034 to 0.21 $ft^3/s/mi^2$) and moderate peak flows (streamflow exceeded 1 percent of the time ranged from 7.8 to 11 $ft^3/s/mi^2$). In contrast, streams in the southern basins went dry during base flow ($7Q_{10}$ of 0.000 $ft^3/s/mi^2$) and had higher peak flows (streamflow exceeded 1 percent of the time ranged from 15 to 22 $ft^3/s/mi^2$).

Streamflow-duration curves are cumulative frequency curves of daily mean streamflows that graphically show the percentage of time a particular value of streamflow is equaled or exceeded. Duration curves for three small streams illustrate differences in the distribution of streamflow in the White River Basin (fig. 11). The shapes of the duration curves are determined by the hydrologic response to the natural characteristics and human influences in the drainage basins. Curves with steep slopes indicate highly variable streamflow, whereas gentle slopes indicate less-variable streamflow. Curves with a steep slope at high streamflows indicate streams substantially affected by surface runoff. Curves with a flat slope at low streamflows indicate basins that store and yield water readily and result in well-sustained base flow.

The difference in streamflow characteristics between the northern and southern parts of the basin is related to natural characteristics that include the thickness and water-yielding capacity of glacial deposits, the water-yielding capacity of bedrock, the permeability of soils, and the slope and relief of the landscape. Streams in the northern part of the basin drain relatively flat areas of thick glacial deposits. The flat landscape promotes ponding and infiltration of rainfall which moderates surface runoff and peak flows. Thick glacial deposits contain aquifers that discharge water to streams, which contributes to sustained base flow. Streams in the southern part of the basin generally drain more steeply sloping areas that lack or have thin glacial deposits. Steep slopes promote surface runoff, and the limited water-yielding capacity of bedrock and thin glacial deposits contribute less water to base flow. Many of the soils that have developed on relatively level areas of older tills south of the Wisconsin glacial boundary have fragipans that inhibit infiltration and promote surface runoff. The higher amounts of surface runoff in the south may contribute to greater amounts of erosion in the unglaciated south-central part of the basin (approximately 11 ton/acre/yr) than in the glaciated northern part of the basin (approximately 5 ton/acre/yr) (Governor's Soil Resources Study Commission, 1984).

The West Fork White Lick Creek exhibits streamflow characteristics different from the generalizations made above; the reason for this discrepancy is not known. Although West Fork White Lick Creek is located in an area of thick glacial deposits, the magnitude of base flow and peak flow is similar to the streams located in the southern part of the basin.

Streamflow in moderately sized drainage basins (drainage areas from 90 to 326 mi^2, table 2) generally exhibited characteristics similar to those of base flow and peak flow discussed previously for small drainage basins. Most moderately sized streams are located in the northern part of the White River Basin and have sustained base flow and moderated peak flows. Except for the Flatrock River, peak flows (11 to 13 $ft^3/s/mi^2$) for streams with part of the drainage basin located near or south of the Wisconsin glacial boundary (Big Walnut Creek, Mill Creek, and Youngs Creek) were greater than peak flows (8.0 to 9.7 $ft^3/s/mi^2$) for streams located farther to the north (White River at Muncie, Pipe Creek, Fall Creek, Big Blue River, and Sugar Creek). The higher peak streamflows may have been caused by increased surface runoff from steeper slopes and fragipans in soils near and south of the Wisconsin glacial boundary.

Similar to the small streams in the southeastern part of the White River Basin, Clifty Creek and the Muscatatuck River have poorly sustained base flow and high peak streamflow. Lost River drains a large area of a karst plain in the southern, unglaciated part of the basin. Base flow is sustained in the Lost River, probably because of groundwater discharge from the karst aquifer.

Streamflow at stations on the west fork of the White River (03351000, 03354000, and 03360500) was compared to that at stations located in similar positions on the east fork (03363000, 03365500, 03373500; table 2 and fig. 10). Base flow in the west fork ($7Q_{10}$ ranged from 0.095 to 0.11 $ft^3/s/mi^2$) was higher than base flow in the east fork ($7Q_{10}$ ranged from 0.079 to 0.095 $ft^3/s/mi^2$), probably because of municipal and industrial wastewater discharged to the west fork. Peak streamflows were greater at stations in

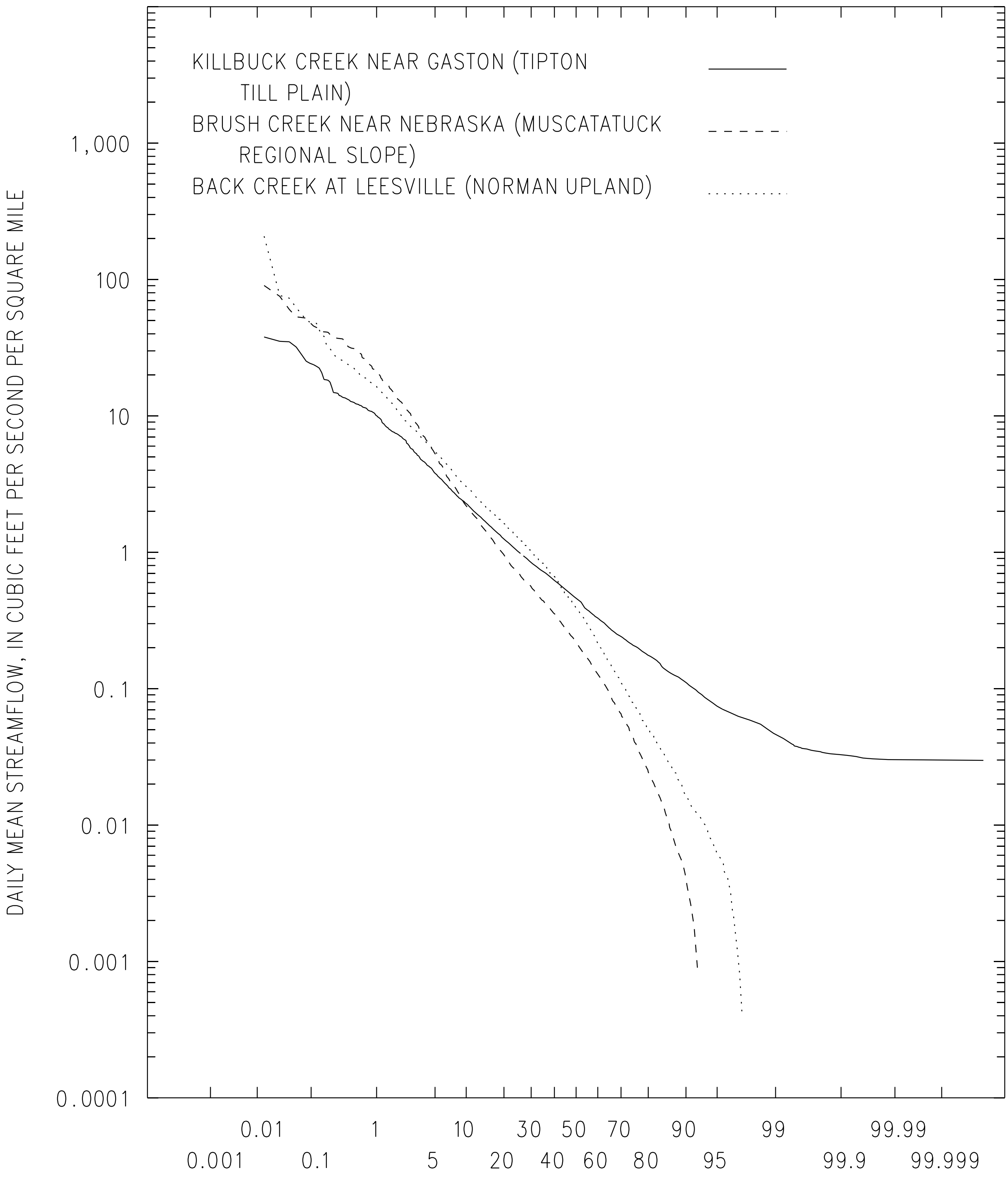


Figure 11. Flow-duration curves of daily mean streamflow for three small streams in different physiographic units of the White River Basin, Indiana, 1971–90 water years.

the upper, middle, and lower reaches of the east fork (8.1, 9.2, and 6.5 $ft^3/s/mi^2$, respectively) than at similarly located stations on the west fork (7.6, 7.3, and 6.3 $ft^3/s/mi^2$, respectively). Lower peak discharges in the west fork probably can be attributed to the capture of surface runoff in numerous flood-control and water-supply reservoirs located in the headwaters of the west fork (see "Recreation and Reservoirs" section).

Mean monthly streamflow in the White River, the East Fork White River, and their major tributaries is highest in March and lowest in October (fig. 12). Although mean monthly streamflow is highest in March, annual peak streamflow (the highest daily mean streamflow measured each year) can occur in any month of the year. Streamflow in September varies most from year to year (the month with the highest relative standard deviation of daily mean streamflow), whereas streamflow in April varies least from year to year.

Mean annual runoff in the White River Basin ranged from 12 in. in the north to 17 in. in the south (fig. 13). Although most of the difference in runoff can be attributed to higher precipitation in the southern part of the basin (fig. 3), there is some indication that factors other than precipitation influence water yield in the basin. Mean annual runoff, expressed as a percentage of mean annual precipitation, ranged from approximately 30 percent in the north to 40 percent in the south. The greater proportion of precipitation that is reflected in streamflow in the south relative to the north might be related to the greater importance of surface runoff as a streamflow-generation process in the south. Surface runoff promotes the rapid movement of water from land to streams and may result in reduced soil moisture and reduced evapotranspiration from soils.

Floods and Droughts

Excessive spring rainfall in conjunction with snowmelt causes the most severe floods in the basin. Frozen or saturated ground during late winter and early spring increases the risk of flooding. Summer floods, resulting from intense thunderstorms, are generally more localized than spring and winter floods. The four largest recorded floods in the White River Basin occurred in March 1913, January and February 1937, June and July 1957, and June and August 1979 (Glatfelter and Butch, 1994). The March 1913 flood is the most severe in Indiana history, with a recurrence interval estimated to exceed 100 years. Flood peaks were generally less during the 1937 flood than during the 1913 flood but lasted for a longer period of time. The 1957 and 1979 floods were not as areally extensive as the 1913 and 1937 floods. The 1979 flood was caused by three intense, sequential thunderstorms and caused damage estimated at 50 million dollars (Gold and Wolcott, 1980).

Dry-weather periods in the basin can last from weeks to months, depleting public-water supplies and adversely affecting the health of crops and livestock. The most severe droughts on record occurred during March 1930 to August 1931, May 1939 to January 1942, April 1962 to November 1966, and January to December 1988 (Fowler, 1992). The 1988 drought caused major reservoirs in the State to approach or reach record low levels; ground-water levels and streamflow also were affected. The 1988 drought was rated "severe" according to the Palmer Drought Severity Index but was of shorter duration than the earlier droughts (Fowler, 1992).

Surface-Water Quality

Surface-water quality in the White River Basin can be affected by natural and human factors including geology and point and nonpoint contamination sources. Water-quality problems in the basin are related primarily to agriculture, urbanization, industrialization, and mineral-resource extraction (Indiana Department of Environmental Management, 1988, 1990; Jacques and Crawford, 1991). Water-quality standards have been adopted by the State to protect legally designated water uses. Nearly all rivers and streams in the White River Basin are designated for full-body-contact recreation and for aquatic-life uses (327 Indiana Administrative

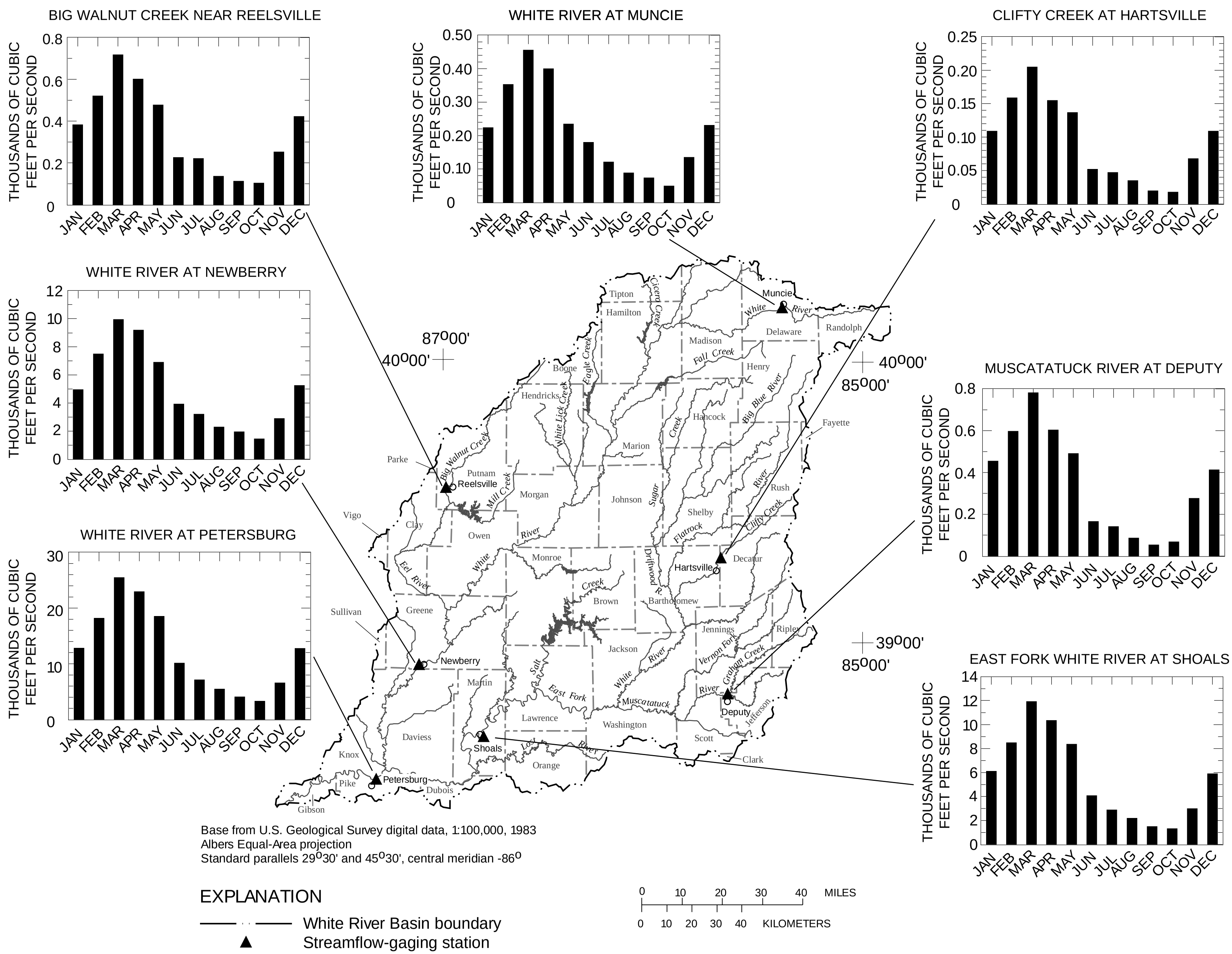
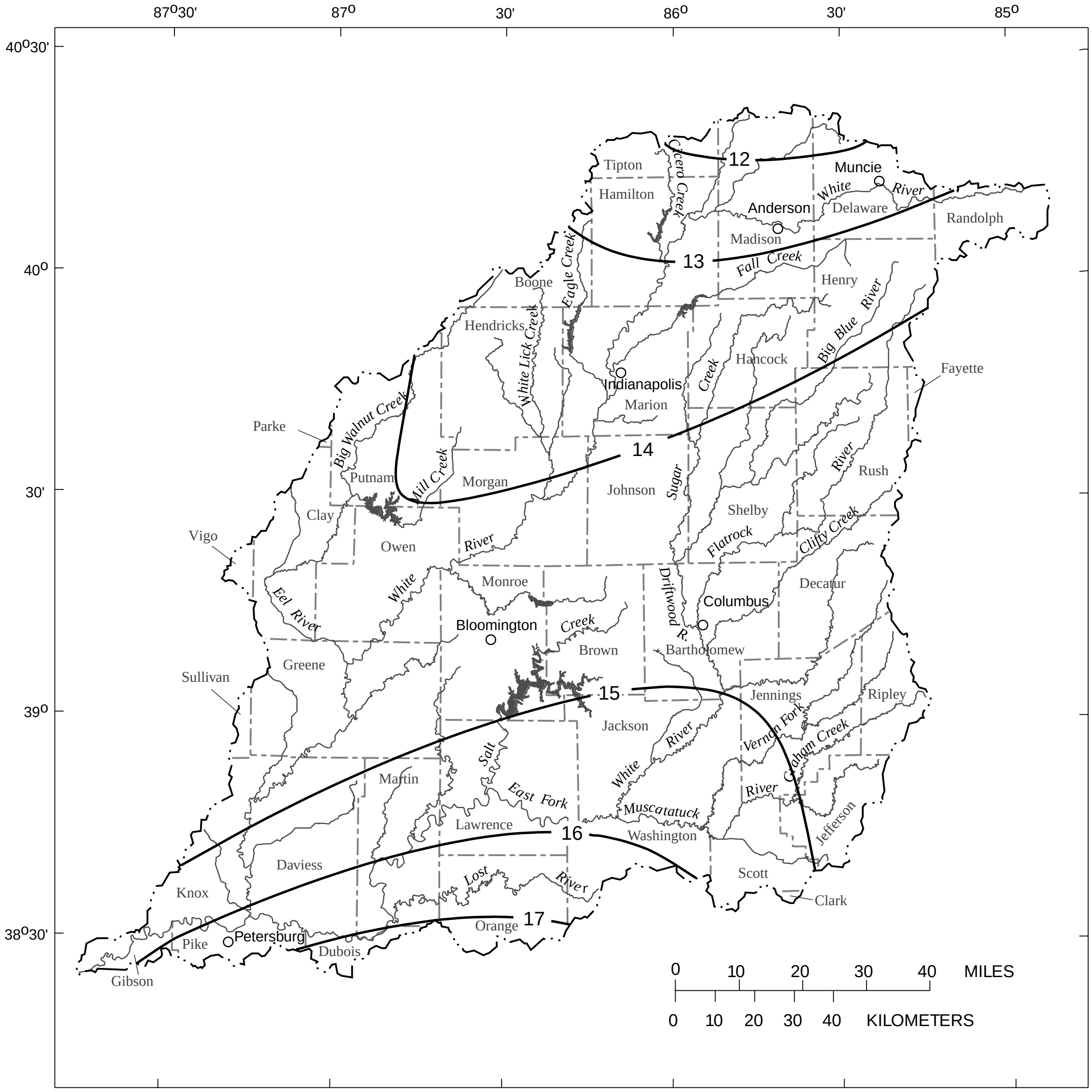


Figure 12. Mean monthly streamflow at seven selected streamflow-gaging stations in the White River Basin, Indiana, 1961–90 water years.



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°

EXPLANATION

— 16 — Line of equal mean annual runoff, in inches

—— · · —— White River Basin boundary

Figure 13. Mean annual runoff in the White River Basin, Indiana, 1961–90 water years.

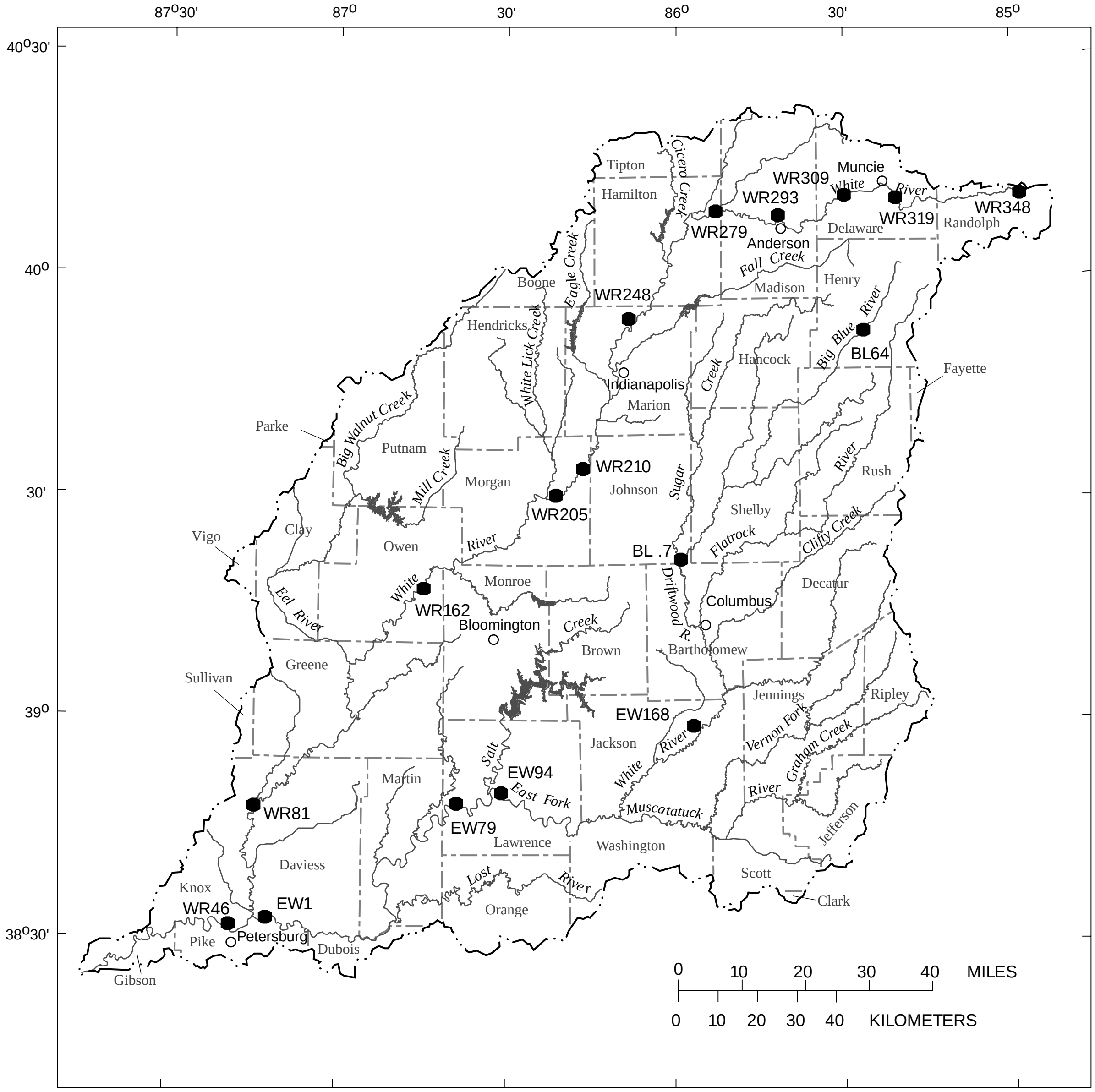
Code 2-1-3). Spills, point-source discharges, and storm runoff can render a stream reach unsuitable for its designated use. Water-quality data and other information were evaluated by the Indiana Department of Environmental Management to assess progress in meeting the fishable and swimmable water-quality goals of the Clean Water Act.

In the East Fork White River Basin, 54 percent of the assessed stream miles fully supported aquatic-life uses, but none of the assessed stream miles fully supported full-body-contact recreation. In the remainder of the White River Basin, 82 percent of the assessed stream miles fully supported aquatic-life uses, but only 5 percent fully supported full-body-contact recreation (Indiana Department of Environmental Management, 1994). A primary cause of streams failing to fully support aquatic-life uses were polychlorinated biphenyls or chlordane in fish tissue that resulted in fish-consumption advisories. Bacterial contamination of stream water (Indiana Department of Environmental Management, 1994) was a primary cause of streams failing to support full-body-contact recreation. Other constituents that have impaired water quality in the basin are ammonia, metals, suspended solids, biochemical-oxygen demand, and low concentrations of dissolved oxygen (Indiana Department of Environmental Management, 1994). Statewide, the major sources of impaired stream quality are agricultural non-point sources, municipal or semi-public discharges, industrial discharges, urban runoff, and combined-sewer overflows (Indiana Department of Environmental Management, 1994). (See “Waste-Disposal Practices” section for discussions on the effects of these point and non-point sources on water quality.)

Several water-quality-monitoring stations on White River and East Fork White River have been sampled regularly from 1957 to the present by the IDEM to describe physical characteristics and concentrations of nutrients and inorganic constituents in the streams (fig. 14 and table 3). The IDEM data indicate that streams in the White River Basin are calcium-bicarbonate water types and are very hard (greater than 150 mg/L as calcium carbonate). Streams in the basin also generally are well buffered and alkaline, with a median pH ranging from 7.7 to 7.9.

Trimmed boxplots (Helsel and Hirsch, 1992) were constructed to graphically display the variation in hardness and alkalinity in the White River Basin for water years 1981 through 1990 for the IDEM data (figs. 15 and 16). The boxplots show that hardness and alkalinity decrease with distance downstream in the west fork of the White River and the east fork of the White River. In the northern part of the White River Basin, high concentrations of hardness and alkalinity result from the dissolution of carbonate minerals in the glacial deposits as rainfall infiltrates the till and discharges as ground water to nearby streams. In the southern part of the basin, sources of hardness and alkalinity are less abundant because unconsolidated deposits are thinner (resulting in lower amounts of carbonate minerals) and the underlying bedrock, even where it is composed of carbonate minerals, is less soluble than the calcareous minerals that are ground up in the till. In addition, streams in the northern part of the basin have sustained base flow, resulting in a larger percentage of streamflow being comprised of ground-water discharge than occurs for streams in the southern part of the basin. Ground-water discharge contributes higher concentrations of alkalinity and hardness than does surface runoff.

As part of the White River Basin study, the U.S. Geological Survey sampled 48 small streams in the basin during a period of base flow in March 1992 (fig. 17). Names and locations of the 48 stations are given in Carter and others (1995). Because small streams receive water primarily from ground-water seepage during periods of base flow, the sample chemistry approximates the maximum mineralization present in the streamwater. Results of the study indicate that the upland physiographic areas (Crawford Upland and Norman Upland) had the lowest concentrations of dissolved solids (median concentration of 140 mg/L), and the Tipton Till Plain and Wabash Lowland had the highest (median concentration



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°

EXPLANATION

MONITORING SITES

White River Basin boundary

EW168 Indiana Department of Environmental Management surface-water-quality-monitoring station and identifier

Figure 14. Location of Indiana Department of Environmental Management surface-water-quality-monitoring stations on the White, Big Blue, and East Fork White Rivers, Indiana.

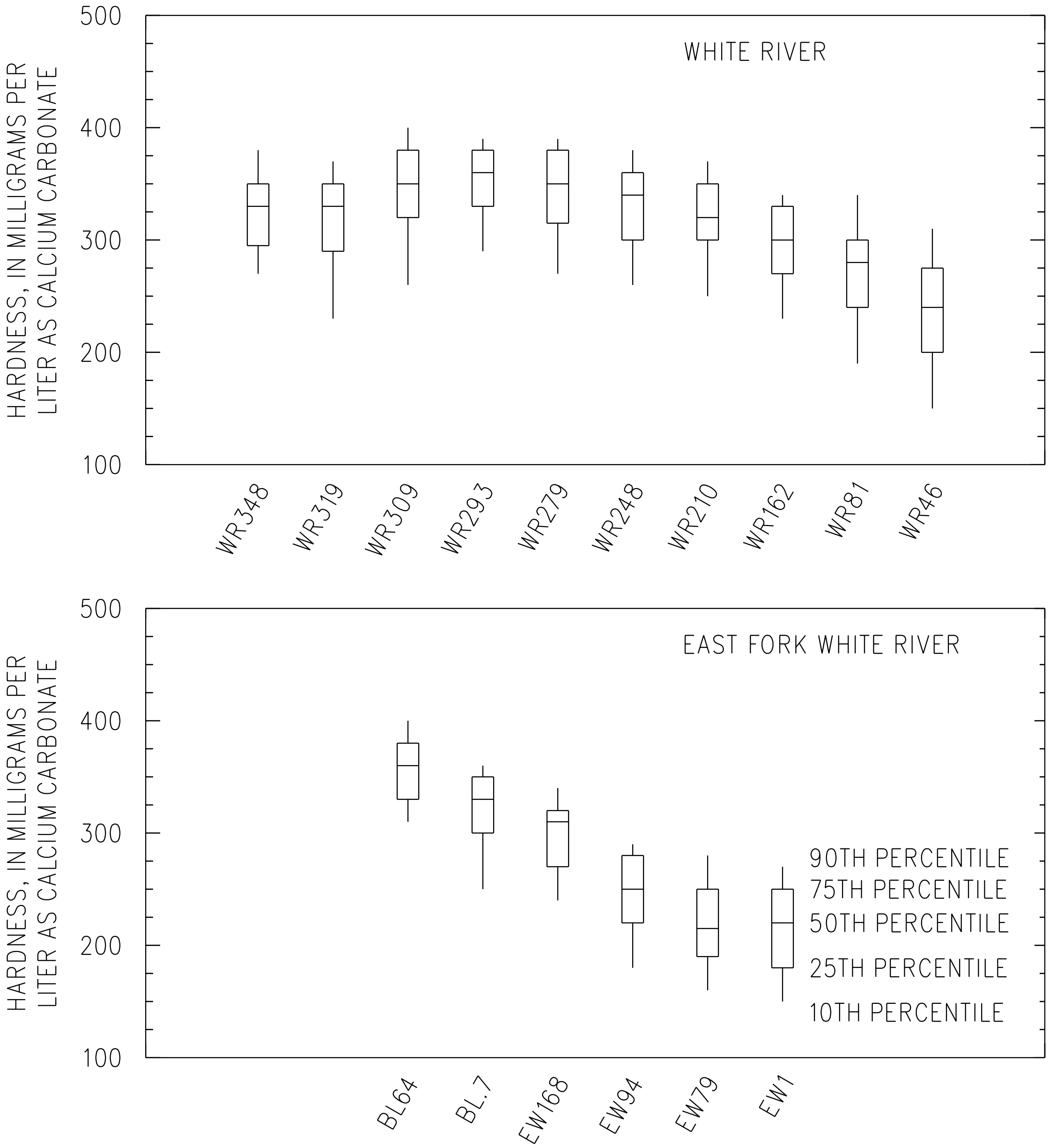


Figure 15. Distribution of hardness concentrations at surface-water-quality-monitoring stations on the White, Big Blue, and East Fork White Rivers, Indiana, 1981–90 water years. (Data from Indiana State Board of Health, 1981–85, and Indiana Department of Environmental Management, 1986–91. Locations of monitoring stations are shown in figure 14.)

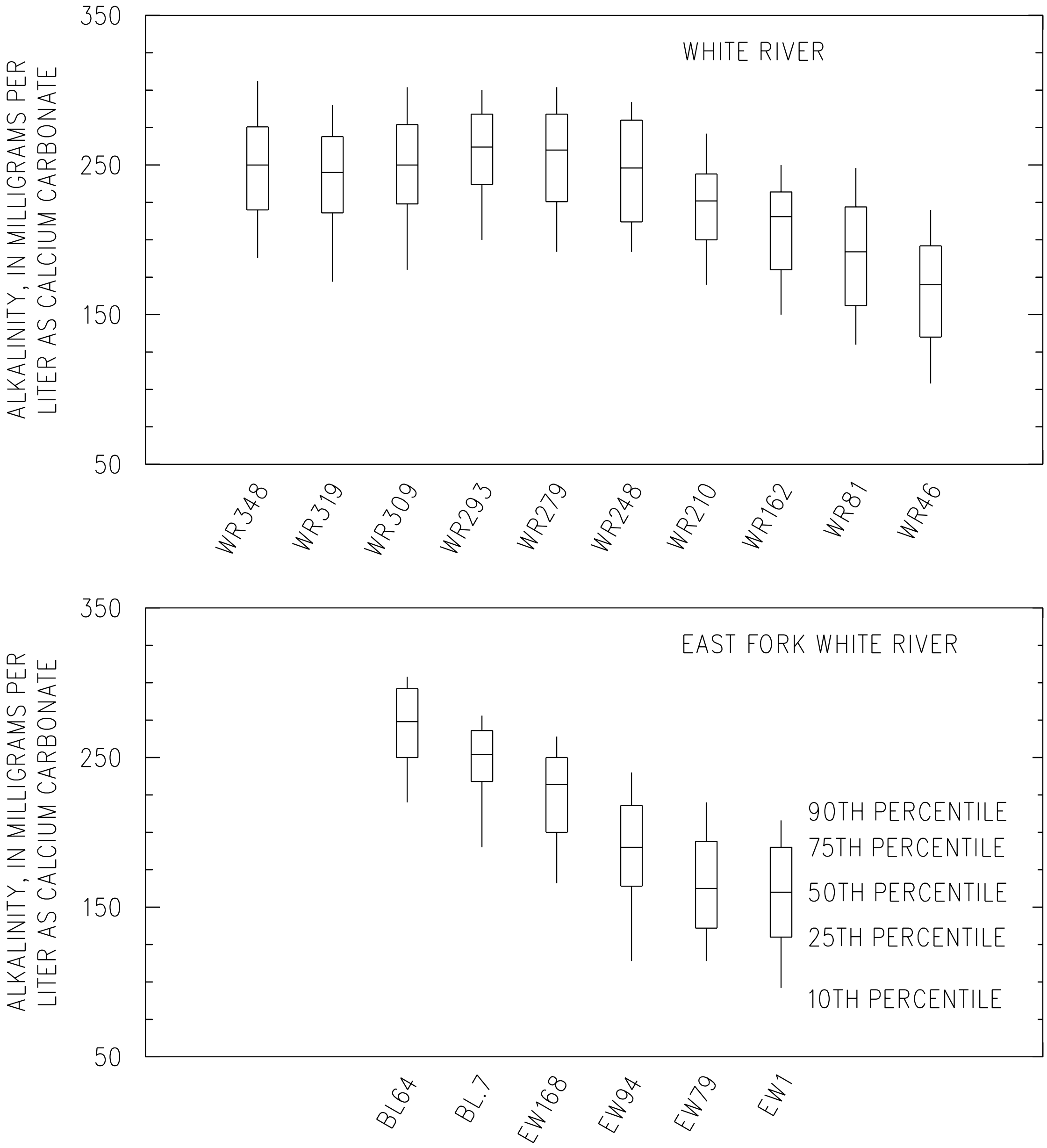
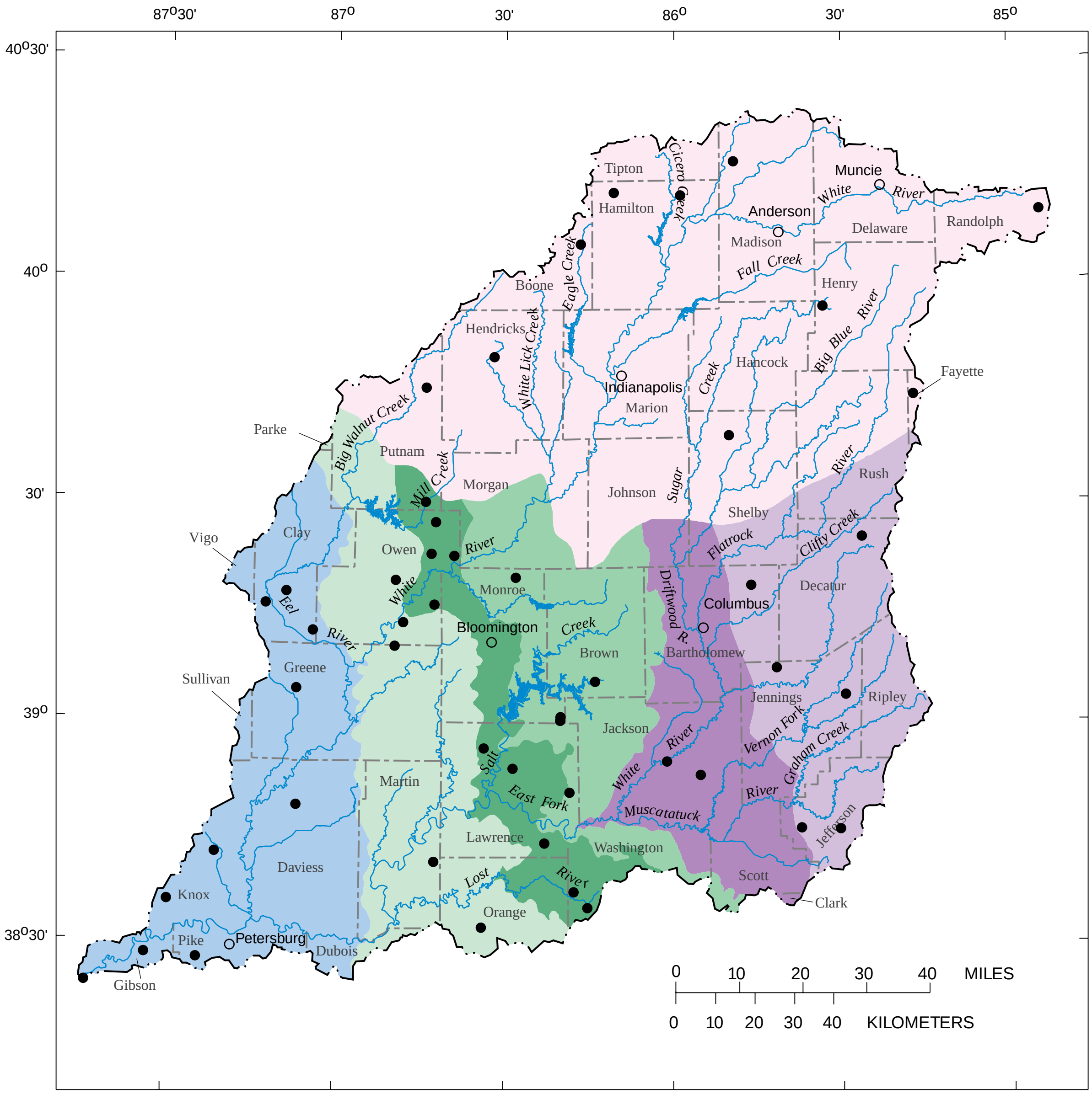


Figure 16. Distribution of alkalinity concentrations at surface-water-quality-monitoring stations on the White, Big Blue, and East Fork White Rivers, Indiana, 1981–90 water years. (Data from Indiana State Board of Health, 1981–85, and Indiana Department of Environmental Management, 1986–91. Locations of monitoring stations are shown in figure 14.)



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°

EXPLANATION

Physiographic units

- Tipton Till Plain
- Wabash Lowland
- Crawford Upland
- Mitchell Plain
- Norman Upland
- Scottsburg Lowland
- Muscatatuck Regional Slope
- White River Basin boundary
- Base-flow water-quality-sampling site

Figure 17. Location of small-stream, base-flow water-quality-sampling sites in the White River Basin, Indiana, March 1992.

Table 3. Description of selected Indiana Department of Environmental Management surface-water-quality-monitoring stations on the White, Big Blue, and East Fork White Rivers, Indiana

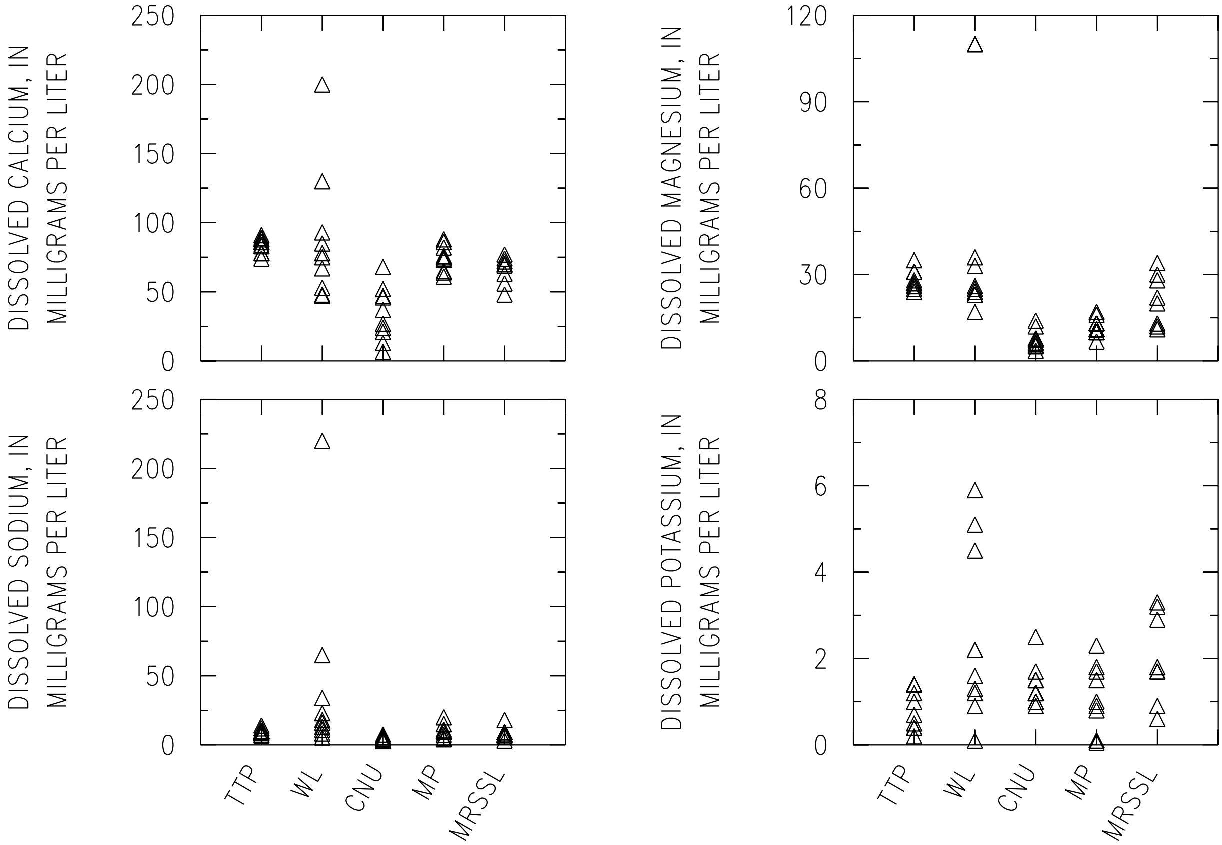
[Station locations shown in figure 14; mi^2, square miles; U.S., United States highway; US, upstream; DS, downstream; SR, state road; WTP, wastewater-treatment plant; CR, county road]

Site number	Site name	Drainage area (mi^2)	Sampling frequency	Location and comments
		Sites on White River		
WR348	White River at Winchester	35	Monthly	At U.S. 27
WR319	White River at Muncie	220	Monthly	US from Memorial Street
WR309	White River at Yorktown	248	Monthly	2.8 miles DS from Muncie WTP
WR293	White River at Anderson	406	Monthly	At West 10th Street
WR279	White River at Perkinsville	555	Monthly	At SR 13, 11 miles DS from Anderson WTP
WR248	White River at Nora	1,219	Monthly	At SR 100, 3 miles DS from Carmel WTP
WR210[1]	White River at Waverly	2,026	Monthly	At SR 144, DS from Indianapolis WTP's
WR162	White River at Spencer	2,988	Monthly	At SR 43 and SR 46
WR81	White River at Edwardsport	5,012	Monthly	At SR 358
WR46	White River at Petersburg	11,125	Monthly	At SR 61
		Sites on East Fork White River		
BL64	Big Blue River near Spiceland	66	Quarterly	At CR 400S, DS from New Castle WTP
BL.7	Big Blue River at Edinburg	583	Quarterly	At U.S. 31, DS from Edinburg WTP
EW168	East Fork White River at Seymour	2,340	Monthly	At Seymour Waterworks intake
EW94	East Fork White River at Bedford	4,047	Monthly	At SR 37
EW79	East Fork White River at Williams	4,720	Monthly	DS from Williams Dam, DS from Bedford WTP
EW1	East Fork White River at Petersburg	5,744	Monthly	At SR 57

[1]Data fromWR205, White River at Centerton, were merged with data from WR210.

of 358 and 366 mg/L, respectively). The geology of the upland areas, dominated by noncarbonate bedrock, thin soils, and high runoff-rainfall ratios, results in small chemical concentrations in water discharged to streams from ground water. The thick, flat, glacial deposits that blanket the till plain or the loess deposits in the Wabash Lowland, conversely, allow long periods for ground water to react with soils and aquifers and to acquire substantial quantities of dissolved constituents. Ground-water seepage into streams in the till plain and Wabash Lowland, as a result, has higher concentrations of most constituents than ground water in the unglaciated parts of the basin (figs. 18 and 19).

Surface-water quality in the White River Basin varies seasonally because of changes in temperature, amount of daylight, agricultural and other human activity, surface runoff, and ground-water input. The IDEM water-quality-monitoring data suggest that the concentration of dissolved oxygen (an important indicator of surface-water quality) is lowest from late spring to fall. Lower dissolved-oxygen concentrations occur despite increased photosynthesis (which increases dissolved-oxygen concentrations) in surface water during the growing season. Three factors can be identified to explain the low dissolved-oxygen concentrations: (1) temperature-dependent processes such as biochemical oxygenation of sewage effluents occur at a faster rate during



EXPLANATION

TTP – TIPTON TILL PLAIN   WL – WABASH LOWLAND   CNU – CRAWFORD AND NORMAN UPLANDS
MP – MITCHELL PLAIN   MRSSL – MUSCATATUCK REGIONAL SLOPE AND SCOTTSBURG LOWLAND

Figure 18. Major cation concentrations measured during base-flow conditions in small streams of the White River Basin, Indiana, March 1992.

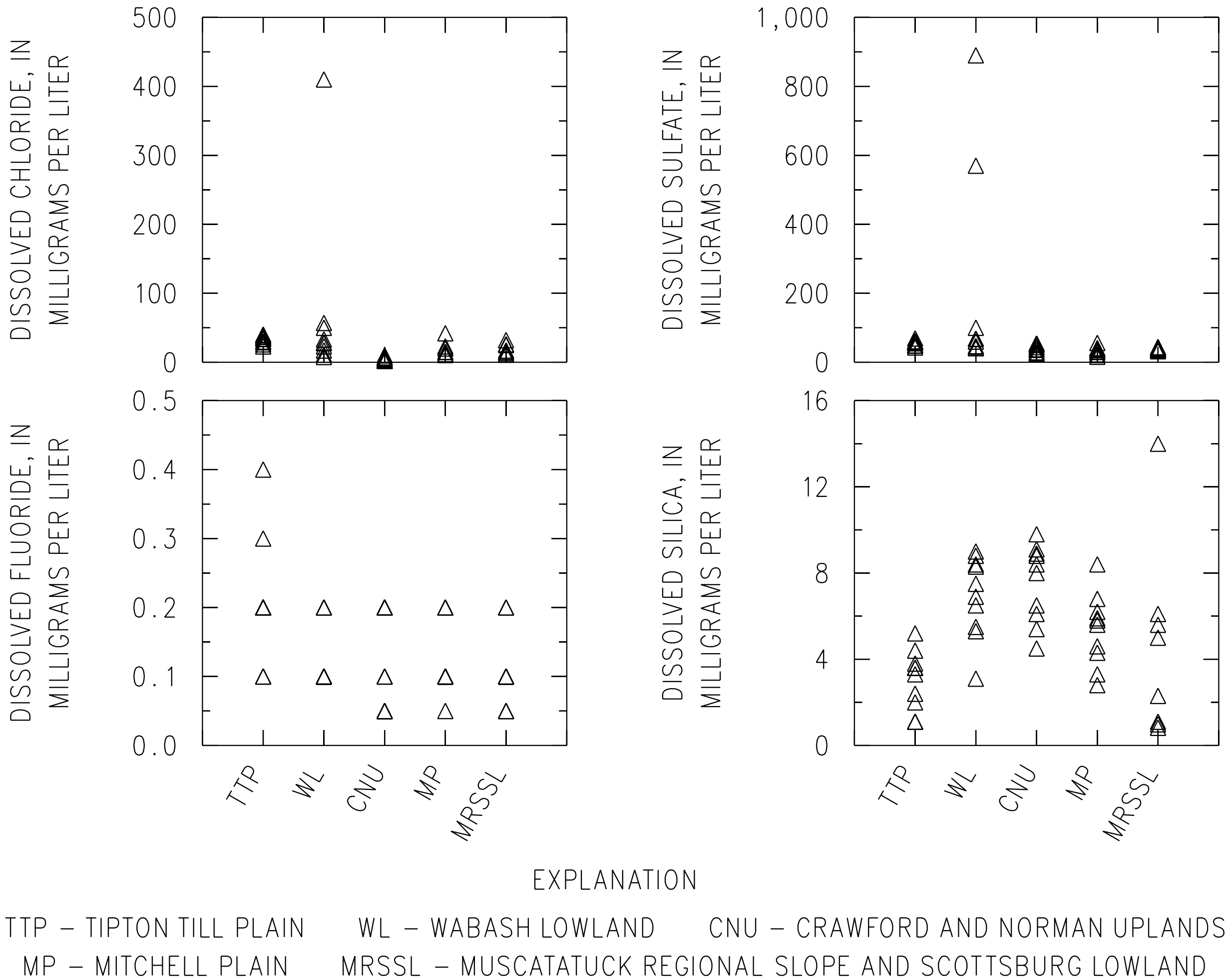


Figure 19. Major anion concentrations measured during base-flow conditions in small streams of the White River Basin, Indiana, March 1992.

the warm months; (2) water thermodynamically retains less oxygen at higher temperatures; and (3) ground water, which typically has low concentrations of dissolved oxygen, is the principal source of flow to most streams during the dry periods of summer and early fall. Other constituent concentrations that vary seasonally in streams in the White River Basin include herbicide concentrations that increase in late spring following herbicide application to cropland (Carter and others, 1995). Nutrient concentrations in the White River Basin also vary seasonally and are described in Martin and others (1996). Seasonal variations of some constituent concentrations in the coal-mining region in the southwestern part of the White River Basin are described in Martin and Crawford (1987).

Ground Water

Two general types of aquifers are present in the White River Basin—unconsolidated aquifers and bedrock aquifers. The primary unconsolidated aquifers are glaciofluvial aquifers and till aquifers. Unconsolidated aquifers occur throughout the northern part of the basin. The principal bedrock aquifers are Silurian and Devonian carbonate aquifers and Mississippian carbonate aquifers. Minor aquifers that cannot support large withdrawls include sand lenses in pre-Wisconsin-age till, Pennsylvanian-age coal-bearing bedrock, Mississippian-age clastic bedrock, and Devonian-age shale. Comprehensive discussions of the aquifers in the White River Basin are given in Hoover and Durbin (1994) and Fenelon and Greeman (1994).

Ground-water quality and quantity vary as a result of many factors, such as aquifer composition, aquifer depth, ground-water flow-regime, and surficial land use. The quantity and quality of the ground water in the White River Basin meet the needs of most users. Withdrawal rates range from 10 to 600 gal/min from wells in the bedrock aquifers to as much as 2,000 gal/min from wells in thick glaciofluvial deposits. Ground water in Indiana generally is very hard—100 to 600 mg/L as calcium carbonate—with the highest concentrations in bedrock aquifers. Iron and sulfate concentrations also are high in many aquifers. The following sections describe the aquifer types in the White River Basin.

Glaciofluvial Aquifers

The glaciofluvial aquifers consist of sand and gravel deposited by glacial meltwaters and are covered by a thin layer (0 to 15 ft) of finer-grained alluvium deposited by post-glacial streams. The aquifers typically are unconfined and are among the most productive in the State. The glaciofluvial aquifers are restricted to a narrow band beneath and along rivers and streams throughout the White River Basin. The aquifers may be 0.1 to 0.5 mi wide on smaller streams (drainage areas less than 100 mi^2) but range from 2 to 6 mi wide on larger streams such as the White River and East Fork White River. Glaciofluvial aquifers are widest adjacent to and beneath the White River in Marion, Knox, Daviess, Pike, and Gibson Counties and on the East Fork White River in Bartholomew and Jackson Counties.

The thickness and permeability of the glaciofluvial aquifers make them productive. Aquifer thicknesses generally range from 20 to 80 ft but are greater than 100 ft thick in several places along the White River and East Fork White River (Gray, 1983). The aquifers are predominately homogeneous sand and gravel deposits, with a few interbedded layers of finer-grained silt and clay. The silt and clay layers are commonly discontinuous but, where present, locally may reduce the vertical hydraulic conductivity enough to create semi-confined conditions. Measured hydraulic conductivities of glaciofluvial deposits in Marion County were 415 ft/d for gravel, 240 ft/d for sand and gravel, 40 ft/d for sand, and 1 to $7x10^{-2}$ ft/d for clay (Meyer and others, 1975). Aquifer-test data indicate a ratio of vertical to horizontal hydraulic conductivity of 1:10. The depth to water in glaciofluvial aquifers is generally 10 to 25 ft, and wells are typically 20 to 80 ft deep. Infiltration rates are rapid, and transmissivity rates in the sand and gravel deposits can be over 20,000 ft^2/d (Meyer and others, 1975; Gillies, 1976). Because glaciofluvial aquifers are highly permeable and commonly unconfined, these aquifers are some of the most easily contaminated in the basin.

Glaciofluvial aquifers have high dissolved-solids concentrations (median 546 mg/L) and very hard water (median 340 mg/L, as calcium carbonate) (Banaszak, 1988). In addition, compared to other aquifers in the White River Basin, the glaciofluvial aquifers have high concentrations of nitrate (median 1.4 mg/L as nitrogen) and chloride (median 16 mg/L) and low concentrations of iron (median 0.10 mg/L) (Banaszak, 1988). High concentrations of nitrate (greater than 10 mg/L) occurred in more than 10 percent of water samples collected from the glaciofluvial aquifers (Banaszak, 1988).

Till Aquifers

The till aquifers are located primarily in till sequences north of the Wisconsin glacial boundary. The aquifers consist of sand and gravel deposits that are commonly laterally discontinuous and enclosed in thicker sequences of silty-clay and clay till of Wisconsin and pre-Wisconsin age. As many as six sand and gravel units, all productive aquifers, can be contained within one till sequence (Lapham, 1981); however, fewer aquifers typically are present in a sequence. The thickness of individual sand and gravel aquifers ranges from 5 to 50 ft but is typically 5 to 10 ft. Aquifers can be connected vertically but generally the silty-clay and clay till layers, which are 5 to 100 ft thick, function as confining units between sand and gravel aquifers. Most wells screened in the till aquifers are 20 to 100 ft deep (Banaszak, 1988).

Recharge rates of the till aquifers are approximately 2 in/yr (Lapham, 1981). High clay content of the till units slows recharge and promotes runoff, but it also protects the aquifers by retarding migration of surface contaminants such as agricultural chemicals. Pesticide concentrations have been shown to decrease in till aquifers with increasing well depth (Indiana Farm Bureau Inc., 1994). Decreasing pesticide concentrations with depth probably result from the filtration capabilities of the clay-rich tills and the long residence times that the agricultural chemicals have to react with the fine-grained materials and metabolizing bacteria. Median concentrations reported for some constituents in till aquifers are 0.2 mg/L nitrate as nitrogen, 9 mg/L chloride, 1.9 mg/L iron, 358 mg/L dissolved solids, and 320 mg/L as calcium carbonate hardness (Banaszak, 1988). The high concentrations of iron and low concentrations of nitrate may result from anaerobic conditions in the till aquifers.

Silurian and Devonian Carbonate Aquifers

The Silurian and Devonian carbonate aquifers underlie the Tipton Till Plain and Scottsburg Lowland physiographic units. These aquifers almost always are confined and consist of fractured carbonates of Silurian and Devonian age. Silurian and Devonian carbonate aquifers can yield water from the entire 500- to 600-ft-thick section, although the uppermost 200 ft are generally the most productive. Depths of wells completed in Silurian and Devonian carbonate aquifers are generally 50 to 250 ft. Well yields vary from 20 to 600 gal/min. Representative transmissivities for bedrock aquifers vary widely, but values range from 500 to 10,000 ft^2/d and average 2,000 ft^2/d.

The high dissolved solids and hardness concentrations in the Silurian and Devonian carbonate aquifer (medians of 513 mg/L and 333 mg/L, as calcium carbonate, respectively) were similar to concentrations of these water-quality parameters in the glaciofluvial aquifers (Banaszak, 1988). The median concentration of nitrate was low (0.1 mg/L as nitrogen), whereas iron was high (1.1 mg/L) compared to that in the glaciofluvial aquifers (Banaszak, 1988).

The Silurian and Devonian carbonate aquifers are overlain by the New Albany Shale (Devonian and Mississippian age). The New Albany Shale is exposed at the surface in the Scottsburg Lowland.

This shale is an organic-rich, black shale that contains some beds with high amounts of trace metals, arsenic (Leininger, 1981; Ripley and others, 1990), and radon (Hasenmueller and Nauth, 1988). The New Albany Shale may contribute constituents to surface water and ground water that may adversely affect the quality of the resources.

Mississippian Carbonate Aquifer

The Mississippian carbonate aquifer is at or near land surface throughout the Mitchell Plain physiographic unit. Much of the carbonate aquifer system has dual porosity, whereby dissolution-widened joints and fractures allow rapid transmission of ground water relative to the bulk volume of the aquifer. Ground water and surface water are connected and many streams periodically disappear into surface openings, flow underground for a distance, and reappear at a downgradient surface opening.

Aquifer recharge is derived locally from precipitation. Ground-water levels in the Mississippian carbonate aquifer respond rapidly to intense rainfall or snowmelt. Well yields are variable and largely dependent on the number and dimensions of fractures intercepted by the screened interval of a well. Wells that do not intercept a water-bearing fracture may not produce enough water to supply domestic needs of a single residence. Average well yield is 5 gal/min but may be as high as 30 gal/min. Transmissivity values can be high in open, free-flowing fractures.

The direct hydraulic connection between land surface and the aquifer makes the Mississippian carbonate aquifer highly susceptible to contamination. Agricultural chemicals, accidental spills, and other sources of contamination may be transported directly from the surface to the aquifer. Septic systems and other waste-disposal systems pose additional threats to water quality in the aquifer. Nitrate derived from fertilizers and animal waste has been detected in water samples collected from domestic wells (Wells and Krothe, 1989). Sulfate concentrations from wells in the Mississippian carbonate aquifer in Orange County have exceeded 600 mg/L (Indiana Department of Environmental Management, 1990); the U.S. Environmental Protection Agency recommends that sulfate concentrations in public drinking water be less than 250 mg/L (U.S. Environmental Protection Agency, 1996) because of odors or unpleasant taste. Radon has been detected in the terra rosa soil that covers the bedrock (Hasenmueller and Nauth, 1988).

Minor Aquifers

Minor aquifers in the White River Basin include sand lenses in pre-Wisconsin-age till south of the Wisconsin glacial boundary, Pennsylvanian-age coal-bearing bedrock (commonly sandstone), Mississippian-age clastic bedrock, and Devonian-age shale. These aquifers are found in the southern and southwestern parts of the basin. Water wells in the minor aquifers are suitable only for domestic use; many wells yield less than 10 gal/min. Water from the Pennsylvanian-age coal-bearing bedrock and the Devonian shale generally contain significant concentrations of iron, causing an unpleasant taste as well as stains in laundry and sinks. Water-quality indicators such as hardness, chloride, and nitrate are similar to other aquifers in the basin. Median concentrations in the minor aquifers were hardness, 314 mg/L as calcium carbonate; chloride, 12 mg/L; and nitrate, 0.5 mg/L as nitrogen (Banaszak, 1988). In the southwestern part of the basin, primarily in Clay and Greene Counties, wells completed in coal seams or sandstone aquifers greater than 100 ft deep produce soft, sodium-chloride type water. Concentrations of sodium and chloride in these deep wells may be as high as 500 mg/L and 250 mg/L, respectively. Other characteristics of Clay and Greene County “soda water” are pH exceeding 9.0, dissolved solids concentrations as high as 1,600 mg/L, and fluoride as high as 4 mg/L (Forbes, 1984).

Surface-Water and Ground-Water Interaction

Understanding the interaction between surface water and ground water is necessary to understanding the hydrology of the White River Basin. In the White River Basin, ground water generally flows into streams through the permeable sediments that line the stream channel. Meyer and others (1975) showed that streams in Marion County gain water from the ground-water system throughout the year; estimated seepage rates into the White River were 42 ft^3/d/ft of channel length. Similar rates of ground-water seepage (40.5 ft^3/d/ft of channel length) were calculated for the White River near Carmel, Ind. (Gillies, 1976).

Although ground water typically discharges to streams, the hydraulic gradient may be reversed in some situations and surface water may flow into the aquifer. Bobay (1988) determined that during flooding, water levels in the White River rose to a point at which gradients were reversed and surface water seeped into the adjacent sand and gravel aquifers. Some reaches of the White River lose water to the underlying aquifers during dry periods because ground-water levels fall below the water level in the stream; this condition has been observed in headwater reaches of the White River in Hamilton County (Arihood, 1982) and Randolph County (Lapham and Arihood, 1984). Flow restrictions that cause local increases in stream water levels, such as lowhead dams, also may cause water to infiltrate into the adjacent aquifer.

The degree of interaction between surface water and ground water is influenced partly by the thickness and water-storage capacity of the aquifer deposits. Peak flows are typically much higher for streams in areas where bedrock is near the surface, compared to regions where glacial deposits dominate the landscape. The water-storage capacity of glacial deposits tends to minimize extremes in peak flows. In addition to regional changes in geologic characteristics, local changes in geology or human influences can affect the degree of surface-water and ground-water interaction. For example, the water-storage capacity of spoil banks in surface-coal-mined areas have been shown to sustain base flow in mined basins where nearby streams in unmined basins had no flow (Corbett, 1965). The occurrence of impounded water bodies in the mined areas enhances base flow and, where the water bodies contact bedrock, enhances recharge to bedrock (Martin and others, 1990).

The interaction between surface water and ground water has implications for water quality. Ground water can acquire chemical constituents from natural sources in soils and aquifers and anthropogenic sources such as agricultural chemicals and landfills that eventually seep into nearby streams. Chemical processes in aquifers, such as mineral precipitation, ion exchange, oxidation-reduction reactions, and biochemical transformations, however, also can remove chemicals that might otherwise reach surface-water bodies. In the case of streamwater that leaks into an adjacent aquifer, especially after flooding, constituents in surface water can enter the aquifer (Squillace and others, 1996).

Environmental Setting of the White River Basin: Human Influences

The effects of human activities on the quality of ground water and surface water are generally unintentional but can be significant. In the White River Basin, human-related activities most strongly affect water quality in areas where urban and agricultural land uses are predominant. Major non-point sources of contamination include (1) pesticide and nutrient applications related to farming; (2) siltation related to farming, grazing, mining, and construction; and (3) urban runoff. Major point sources of contamination include outfalls related to wastewater-treatment plants, industrial discharges, power-generation-plant cooling-tank releases, combined-sewer overflows, and landfills.

Land Use

Agriculture is the principal land use in the White River Basin. Approximately 70 percent of the basin is used for agriculture, primarily for row crops and pasture. Other land uses are forest (22 percent), urban and residential (7 percent), water and wetlands (0.7 percent), and barren land (0.4 percent) (fig. 20). (Strip mines, quarries, and exposed bedrock are considered "barren land.") The Geographic Information Retrieval and Analysis System (GIRAS) is the source for this land-use information, which was interpreted from aerial photography taken during the 1970’s and mid-1980’s (U.S. Geological Survey, 1990) and revised by Hitt (1994).

Agriculture

Indiana is an important agricultural state. In 1991, Indiana ranked fourth nationally in soybean production (172,770,000 bu), fifth in corn production (510,600,000 bu), fourth in hog production (4,600,000 head), and seventh in turkey production (15,000,000 birds) (Indiana Agricultural Statistics Service, 1992). Indiana also produced significant amounts of winter wheat (28,800,000 bu), cattle (1,280,000 head), and chickens (25,900,000 birds). Based on county-level data, approximately 1.2 million hogs and 385,000 cattle were raised in the basin in 1991 (Indiana Agricultural Statistics Service, 1992).

More than 80 percent of the agricultural land in the White River Basin is used for crop production. Of the estimated 3.6 million acres of cropland in the basin in 1992, 43 percent were planted for corn, 35 percent were planted for soybeans, 4 percent were planted for winter wheat, and 6 percent were harvested for hay. Other crops planted to a much lesser extent include apples, barley, cucumbers, green beans, melons, oats, potatoes, pumpkins, rye, sorghum, strawberries, tobacco, and tomatoes. South of Indianapolis, winter wheat often is planted in fields harvested for soybeans to achieve a double crop in those fields.

Agricultural activities may significantly affect concentrations of sediment, nutrients, bacteria, and pesticides in surface and ground water. The U.S. Department of Agriculture described Indiana as “the State with the most threatened water supply in the country” as a result of the nitrate and pesticide concentrations that were found in the State’s drinking-water supplies (Taylor, 1989). The northern, southwestern, and southeastern parts of the White River Basin have the greatest row-crop production; consequently, these are the areas where the most varieties and quantities of nutrients and pesticides are used. The south-central part of the basin has less row-crop agriculture than other areas in the basin because of greater relief and thinner soils; as a result, fewer pesticides and nutrients are applied to the land surface in this area. Agricultural emphasis in the south-central part of the basin is cattle and swine production (fig. 21). Instead of pesticides, surface and ground water in this part of the basin may show elevated concentrations of bacteria and nitrogen compounds produced by animal waste.

Forest

Most forested areas in the White River Basin are in the Crawford and Norman Uplands physiographic units. Forested areas are not large, contiguous tracts of land but are intermixed with agricultural land; the area identified as forest land use in figure 20 includes mixed forest and pasture land uses. Virgin stands of timber are rare and consequently most wooded areas are second- or third-growth forests. No streams in the basin with a drainage area greater than 10 mi^2 drain only forested land. Forest areas are generally on ridges and have steep (10 to 50 percent) slopes.

Urban and Industry

Most of the urban land in the White River Basin is residential. The population of the White River Basin was approximately 2.1 million in 1990. The largest cities are located in the northern part of the basin. In 1990, Indianapolis was the 12th largest city in the United States, and the

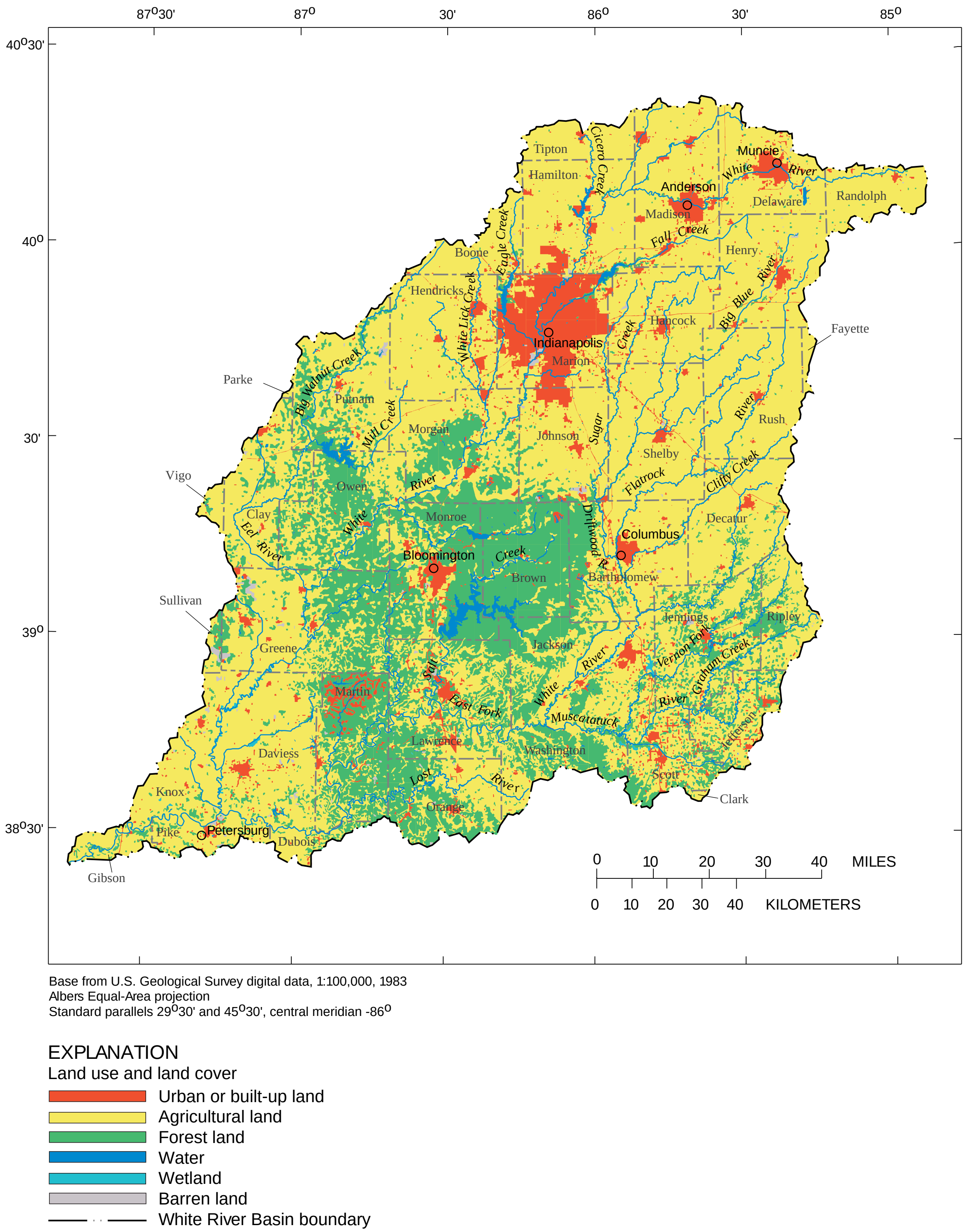


Figure 20. Land use in the White River Basin, Indiana. (Data from U.S. Geological Survey, 1990, as modified by Hitt, 1994.)

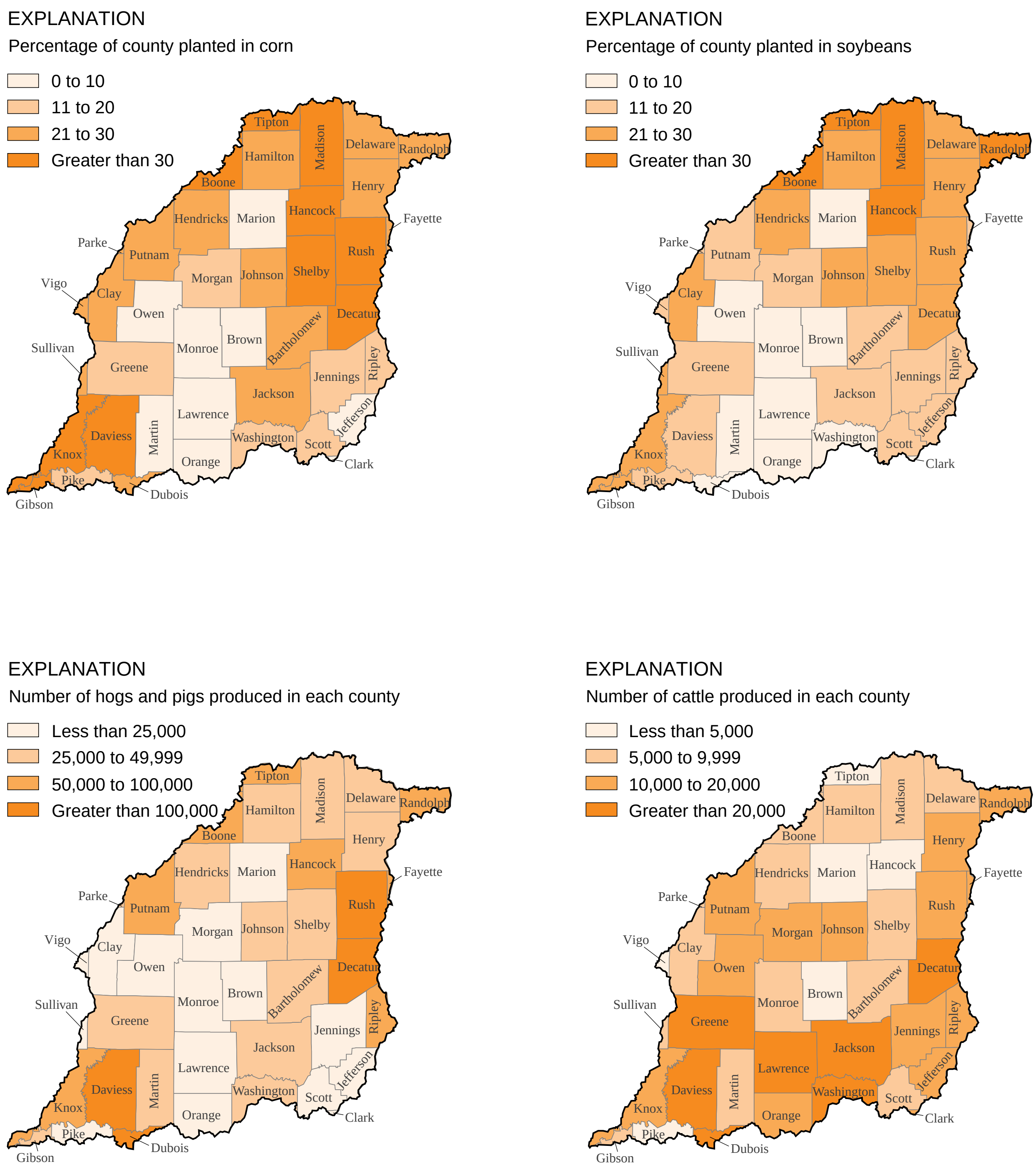


Figure 21. Percent of land planted in corn and soybeans and cattle and swine production in the White River Basin, Indiana, 1992. (Data from U.S. Department of Commerce, 1994.)

Indianapolis Metropolitan Area was the 29th largest metropolitan area. The population of the Indianapolis Metropolitan Area (Boone, Hamilton, Hancock, Hendricks, Johnson, Madison, Marion, Morgan, and Shelby Counties), nearly all of which is contained in the northern part of the White River Basin, was 1,380,491 in 1990 (U.S. Department of Commerce, 1992). The populations of Muncie and Anderson, in the northern part of the basin, and Bloomington, in the southern part of the basin, were between 50,000 and 75,000 in 1990. Population density ranges from 44 people/mi^2 in Brown County, in the forested south-central part of the basin, to 2,000 people/mi^2 in Marion County, in the urbanized north-central part of the basin. Population density in the basin is shown in figure 22.

Significant population growth has occurred during the last 50 yrs in the White River Basin (fig. 23). Much of this growth occurred in the Indianapolis Metropolitan Area and, in the last 20 yrs, high rates of population growth have occurred along the main transportation arteries entering Indianapolis. Counties with the greatest increase in population during 1940 to 1990 are Marion County and surrounding counties—Hamilton, Hendricks, and Johnson Counties (fig. 24). Delaware and Monroe Counties also have had significant increases in population.

Most industry in the White River Basin is located near large urban areas. Major industries include primary metal processing, fabricated metal products, transportation-equipment manufacturing, electrical-equipment manufacturing, and heavy-machinery production (Crompton and Graves, 1987). Storm runoff, discharges from municipal wastewater systems and power-generation plants, and other processes associated with intense urbanization and industrialization may affect ground- and surface-water quality.

Recreation and Reservoirs

Numerous recreation areas are located in the White River Basin (fig. 25). Hill and valley landscapes in the southern half of the basin are scenic and most state and federal parks, forests, and wildlife refuges in the basin are located in this area. Fish and wildlife areas and a variety of wildlife habitats (including forests, grasslands, and wetlands) are maintained in conjunction with recreation areas. Several reservoirs, originally built for flood control or continuous water supply, are adjacent to State-owned recreation areas. In the southern half of the White River Basin, where streamflow is variable and ground-water supplies are limited, reservoirs have been constructed to

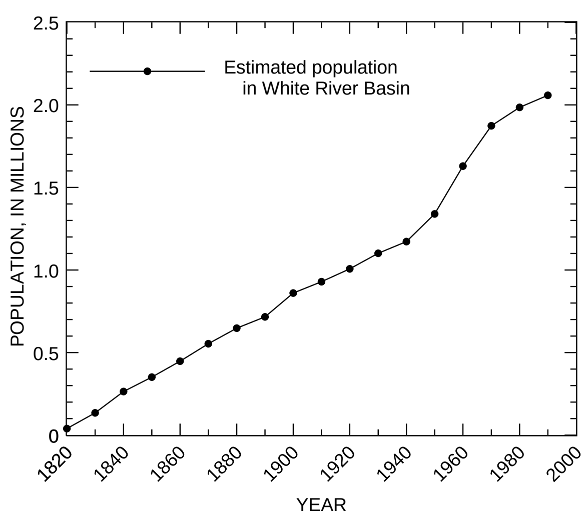
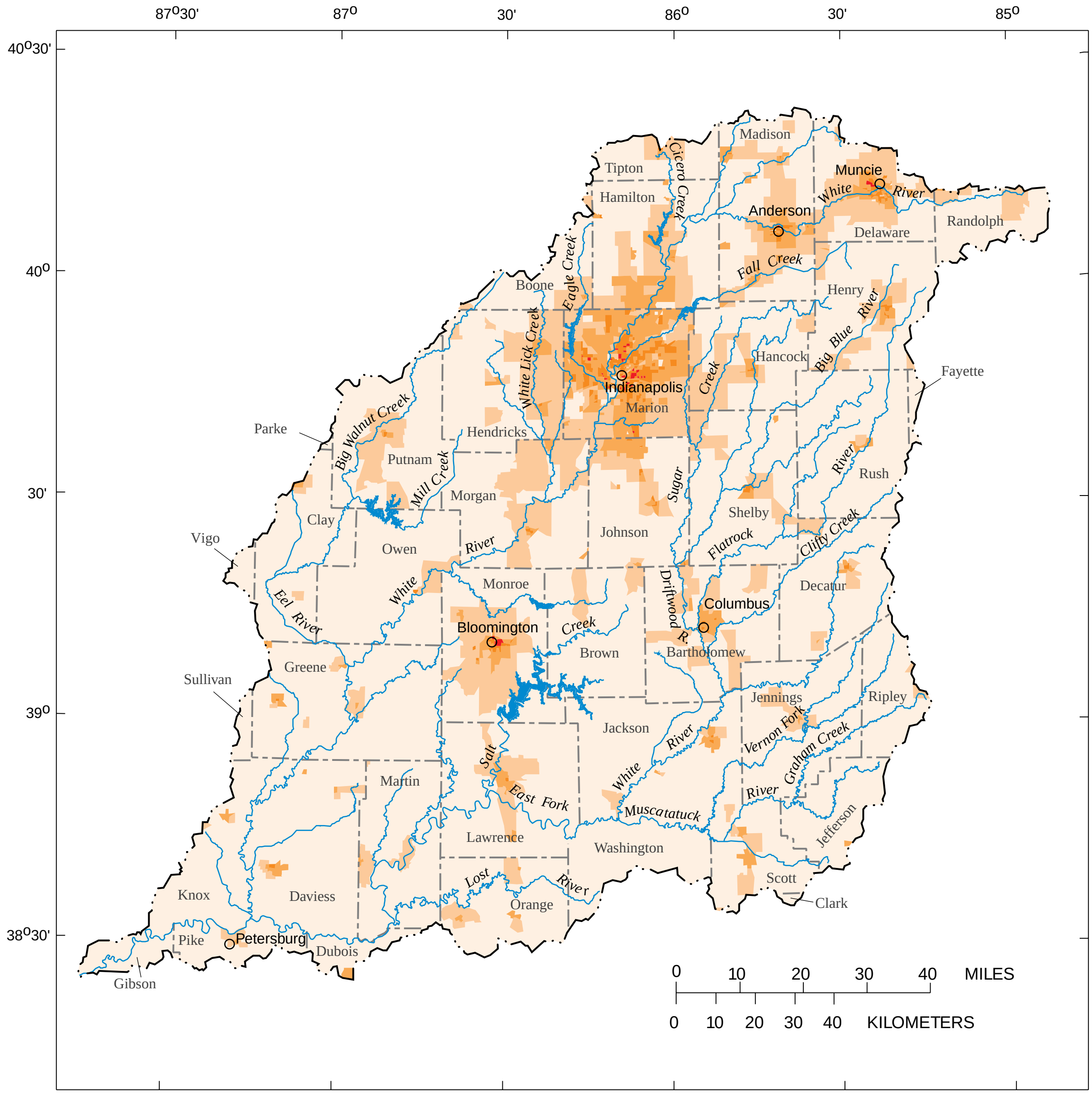


Figure 23. Population growth in the White River Basin, Indiana, 1820–1990. (Data from Forstall, 1996.)



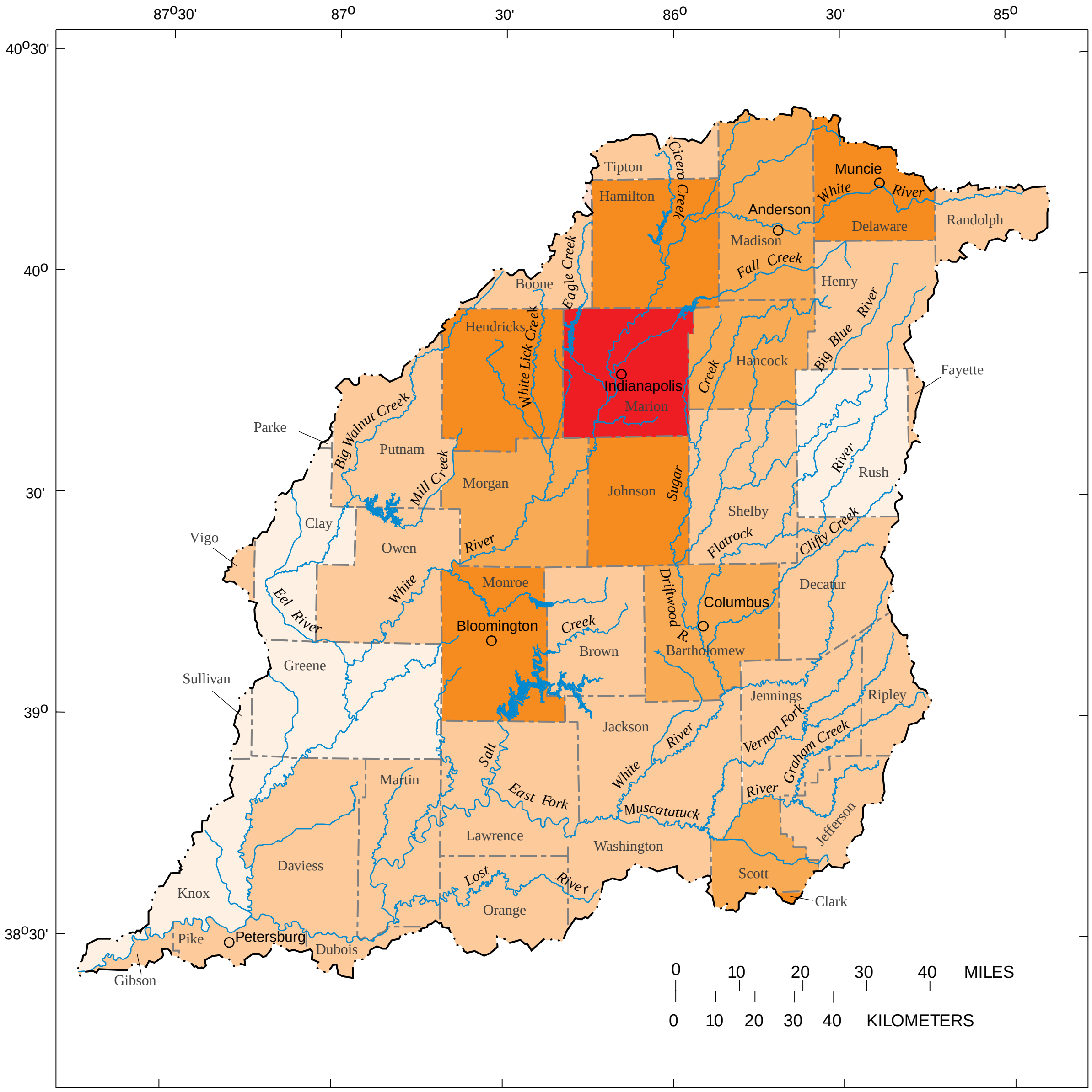
Base from U.S. Geological Survey digital data, 1:100,000, 1983
Albers Equal-Area projection
Standard parallels 29°30' and 45°30', central meridian -86°

EXPLANATION

Population density, in people per square mile

- Less than 100
- 100 to 799
- 800 to 3,999
- 4,000 to 10,000
- Greater than 10,000
- White River Basin boundary

Figure 22. Population density in the White River Basin, Indiana, 1990.

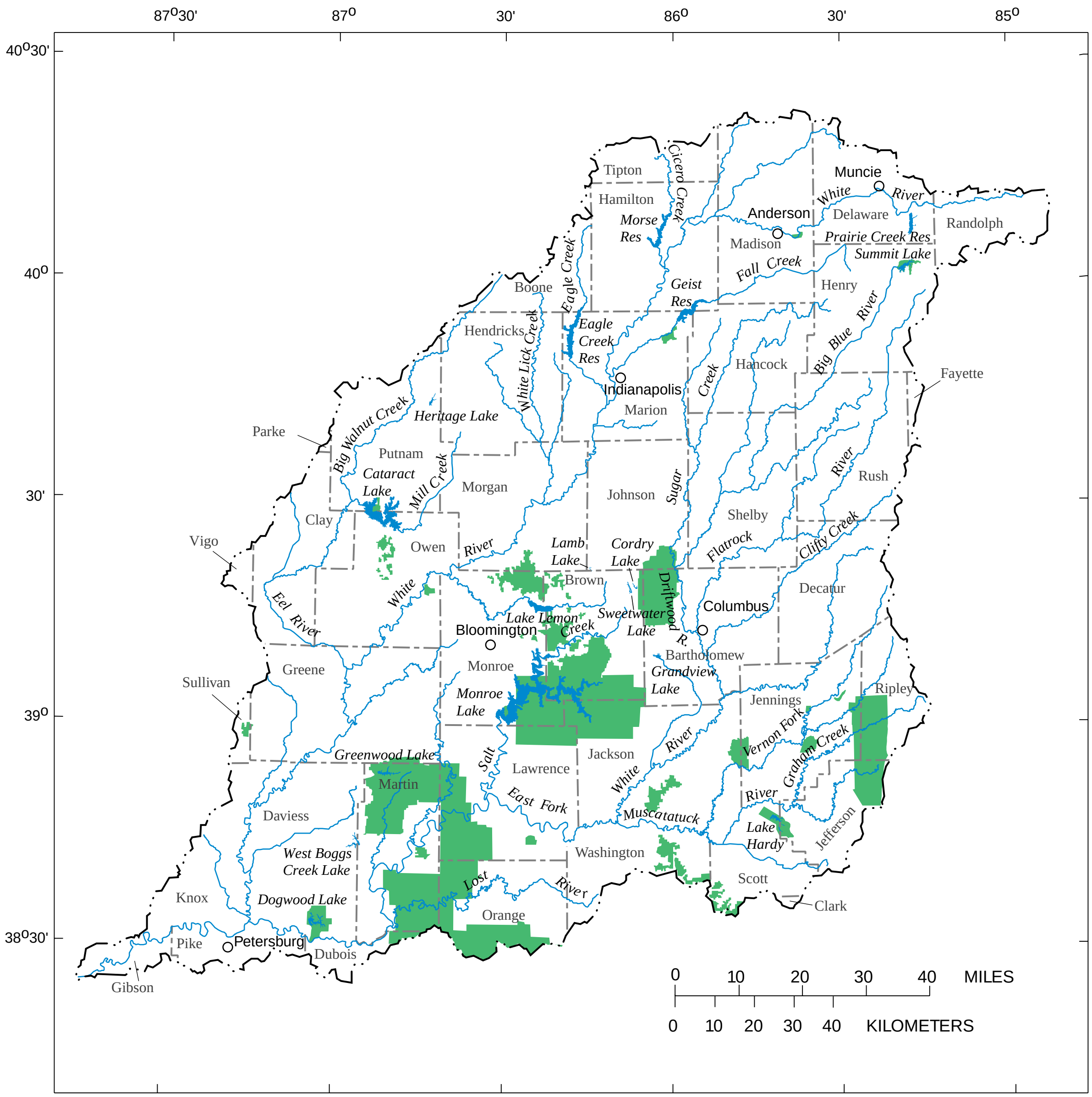


Base from U.S. Geological Survey digital data, 1:100,000, 1983
Albers Equal-Area projection
Standard parallels 29°30' and 45°30', central meridian -86°

EXPLANATION
Change in population density, in people per square mile, 1940-90

- -20 to 0
- 0 to 49
- 50 to 99
- 100 to 249
- Greater than 250
- White River Basin boundary

Figure 24. Change in population density in the White River Basin, Indiana, 1940–90. (Data from Forstall, 1996.)



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°

EXPLANATION

- Major reservoirs
- National forests; Federal military areas; State parks, forest, fish, and wildlife areas
- White River Basin boundary

Figure 25. Managed Federal and State lands and major reservoirs in the White River Basin, Indiana.

provide a sustained source of water. Table 4 lists reservoirs in the White River Basin that have a normal capacity of at least 5,000 acre-ft. The largest reservoir in the basin is Monroe Reservoir located in Monroe and Brown Counties. This reservoir, with a surface area of almost 17 mi^2, is the second largest in Indiana.

Water-quality problems in reservoirs generally are related to the land-use practices in the watershed. Agricultural practices affect reservoir water quality in a variety of ways, including sedimentation and seasonal pesticide and nutrient contamination (Scribner and others, 1996). Pesticides can accumulate in the tissues of aquatic organisms and cause chronic health problems. Nutrient accumulation in reservoirs can cause undesired algal growth that indirectly affects the health of other flora and fauna.

Mines and Quarries

Strip mining and stone quarrying account for about 0.4 percent of the land use in the White River Basin. Mines and quarries use small amounts of water to process their products and affect the local hydrology only if operators pump ground water to hold the water table below the depth of activity. Most quarries are small (less than 1 acre), and many have been abandoned.

Coal has been mined extensively from the Pennsylvanian rocks in the southwestern part of the White River Basin. Strip mining is the most commonly used method for extracting coal from the subsurface in Indiana. A by-product of strip mining is large quantities of permeable crushed rock that contain reactive minerals. When exposed to infiltrating rainfall, the reactive minerals readily dissolve and become constituents in ground and surface water. Runoff from strip mines has been shown to increase dissolved solids, sulfate, iron, manganese, and sediment and to decrease pH and the quality of biota in streams receiving the runoff (Corbett, 1969; Peters, 1981; Wangsness, 1982; Wilber and others, 1985; Martin and Crawford, 1987; Renn, 1989). The two Wabash Lowland samples with large sulfate concentrations in figure 19 are from small streams in the Wabash Lowland that partially drain strip-mined areas.

Limestone quarries are numerous in the karst area in the south-central part of the basin. The Salem Limestone outcrops near the east edge of the Mitchell Plain and has rock properties desirable for building construction. Stone quarries and mills in Monroe and Lawrence Counties are important local industries that supply building stone nationally and internationally. Other quarries produce high-calcium limestone used as flux in steel mills, road aggregate, concrete and cement, and agricultural lime; the Paoli Limestone, Ste. Genevieve Limestone, and St. Louis Limestone Formations are mined to supply these industries (Hartke and Gray, 1989).

Waste-Disposal Practices

Improper waste-disposal practices can result in point sources of contamination that strongly influence the quality of ground and surface water. Human-generated sewage, confined-feeding-operation wastes, and landfills are the most commonly identified sources of contamination from improper waste-disposal practices.

Aging septic systems are prone to failure. Indications of septic-system failure may be detected by changes in ground-water quality that commonly include increased concentrations of detergents, chloride (from water softeners), nutrients, and bacteria. In addition to septic systems, most rural residents also use shallow domestic-supply wells for water supplies. The safety of well water may be compromised by proximity to a failing septic system.

In urban settings, human sewage is processed through wastewater-treatment plants. Cities discharging treated sewage effluent to the west fork of the White River include Muncie, Anderson, Noblesville, Indianapolis, and Martinsville. Columbus and Seymour discharge treated sewage effluent to the East Fork White River. Thirty-five wastewater-treatment plants discharge at least

Table 4. Reservoirs in the White River Basin, Indiana, with a normal capacity of at least 5,000 acre-feet, 1988

[Data from Ruddy and Hitt, 1990, table 3; C, flood control; R, recreation; S, water supply; --, no data]

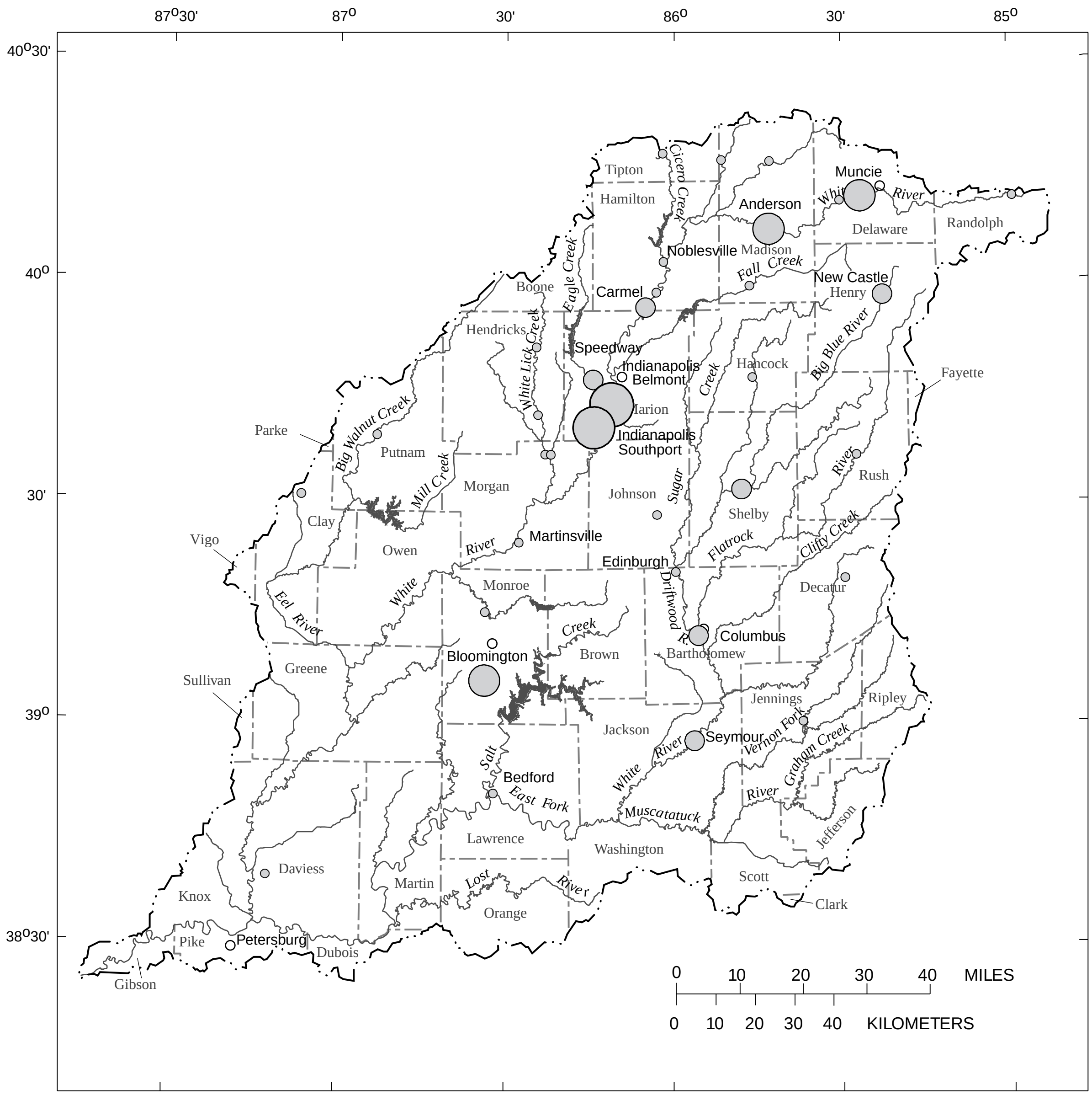
Name of reservoir (alternate names)	Name of stream	County	Normal capacity (acre/feet)	Maximum capacity (acre/feet)	Surface area (acres)	Drainage area (square miles)	Year com-pleted	Use
Cataract Lake (Cagles Mill Lake; Lieber Reservoir)	Mill Creek	Owen and Putnam	27,112	390,731	4,840	295	1953	C, R
Cordry Lake	Saddle Creek	Brown	6,320	6,650	169	--	1953	R
Dogwood Lake (Glendale Reservoir)	Mud Creek	Daviess	20,400	36,600	1,300	--	1963	R
Eagle Creek Reservoir	Eagle Creek	Marion	24,000	110,000	1,350	162	1967	C, R, S
Geist Reservoir	Fall Creek	Marion and Hamilton	21,180	60,000	1,800	215	1944	R, S
Glenn Flint Lake	Little Walnut Creek	Putnam	5,900	15,844	379	--	1976	C, R
Grandview Lake	East Fork White Creek	Bartholomew	9,235	11,935	321	--	1967	R, S
Greenwood Lake	First Creek	Martin	12,780	29,800	800	15	1937	C, R, S
Heritage Lake	Clear Creek	Putnam	5,000	9,800	330	--	1971	R
Lake Hardy	Quick Creek	Scott and Jefferson	12,000	27,465	741	--	1970	C, R, S
Lake Lemon	Beanblossom Creek	Monroe and Brown	13,300	45,700	1,650	64	1952	R, S
Lamb Lake	Indian Creek	Johnson and Brown	7,250	13,000	95	--	1967	S
Monroe Lake	Salt Creek	Monroe and Brown	182,250	861,080	10,750	430	1965	C, R
Morse Reservoir	Cicero Creek	Hamilton	25,380	49,300	1,375	214	1955	S
Prairie Creek Reservoir	Prairie Creek	Delaware	22,000	36,670	1,275	17	1959	S
Summit Lake	Big Blue River	Henry	15,800	25,550	700	10	1980	C, R, S
Sweetwater Lake	Sweetwater Creek	Brown	9,500	11,700	275	--	1966	R
West Boggs Creek Lake	West Boggs Creek	Daviess and Martin	8,148	18,438	622	--	1972	C, R
Williams Dam	East Fork White River	Lawrence	5,333	5,333	--	--	1910	R, S

1 Mgal/d of effluent to surface waters of the White River Basin (fig. 26). Primary and secondary wastewater-treatment plants eliminate solids and reduce concentrations of constituents through a variety of biological, filtration, chemical, and settling processes. Semi-solid wastes from human sewage (commonly called sludge) that cannot be discharged to nearby streams are disposed in landfills, as fertilizer to cropland, or by incineration. In the Indianapolis area, the White River has experienced water-quality problems from extensive organic loading in wastewater-treatment-plant effluent (Shampine, 1975). In the early 1980's, two tertiary treatment plants were installed near Indianapolis to reduce point-source contamination by sewage effluent. The tertiary treatment plants significantly reduced biochemical-oxygen demand, fecal-coliform bacteria, and ammonia—indicators of sewage contamination. As a result, water quality in White River improved (Crawford and Wangsness, 1991; Crawford and others, 1992).

Combined-sewer overflows and urban runoff contribute pollutants to streams in the White River Basin. Martin and Craig (1990) studied dissolved-oxygen concentrations in the White River downstream from Indianapolis during the summers of 1986 and 1987. Twelve periods of low dissolved-oxygen concentrations (less than the Indiana water-quality standard of 4.0 mg/L) were measured. These periods of low dissolved-oxygen concentrations lasted from less than 1 hour to almost 84 hours (median 5 hours), and the minimum concentrations were 1.0 to 3.9 mg/L (median 2.8 mg/L). The low dissolved-oxygen concentrations occurred during periods of storm runoff (Martin and Craig, 1990). A study of Fall Creek in Indianapolis during the summer of 1987 concluded that increased concentrations of ammonia, biochemical-oxygen demand, copper, lead, zinc, and fecal coliform bacteria during storm runoff were caused by combined-sewer overflows and urban runoff (Martin, 1995).

A confined-feeding operation is any animal-feeding operation with 300 or more cattle, 600 or more hogs or sheep, 30,000 or more poultry, or any animal-feeding operation causing a water-quality violation (Indiana Department of Environmental Management, 1993). Animal wastes from confined-feeding operations most commonly are stored in earthen lagoons or concrete waste pits prior to disposal by land application. Waste-storage systems constructed after July 1, 1993, are required to have the capacity to store 120 days of animal waste. Many confined-feeding operations, however, have less than 120-day storage capacity and, consequently, less flexibility to manage animal wastes. The IDEM encourages farmers to apply animal wastes to their fields twice a year—prior to spring tillage and in the fall after harvest but before the ground freezes. These recommendations are intended to decrease the potential for nutrient runoff. Although the size of the waste-storage system and field and weather conditions are important factors related to nutrient runoff, usually the most important factor is the operator's commitment to effective animal-waste management (Dennis Lasiter, Indiana Department of Environmental Management, oral commun., 1995). Water contamination from animal waste can occur if State-mandated regulations for application are not followed, if retaining-pond integrity is compromised, or if significant runoff events follow field fertilizing. Contamination from animal wastes generally is indicated by elevated concentrations of nutrients and bacteria and by decreased concentrations of dissolved oxygen.

Landfills, including solid and hazardous-waste sites, provide potential sources of contamination to ground water and nearby streams. Permitted landfills in Indiana are regulated by the IDEM; as of 1997, more than 40 active solid-waste landfills were in the White River Basin (John Guerrettaz, Indiana Department of Environmental Management, oral commun., 1997).



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°

EXPLANATION

Mean daily discharge from municipal wastewater-treatment plants, 1991, in million gallons per day

- 1 to 2.9
- 3 to 9.9
- 10 to 20
- 75 to 90
- White River Basin boundary

Figure 26. Location of municipal wastewater-treatment plants that discharged more than one million gallons of effluent per day in the White River Basin, Indiana, 1991. (Data from the Indiana Department of Environmental Management, written commun., 1992.)

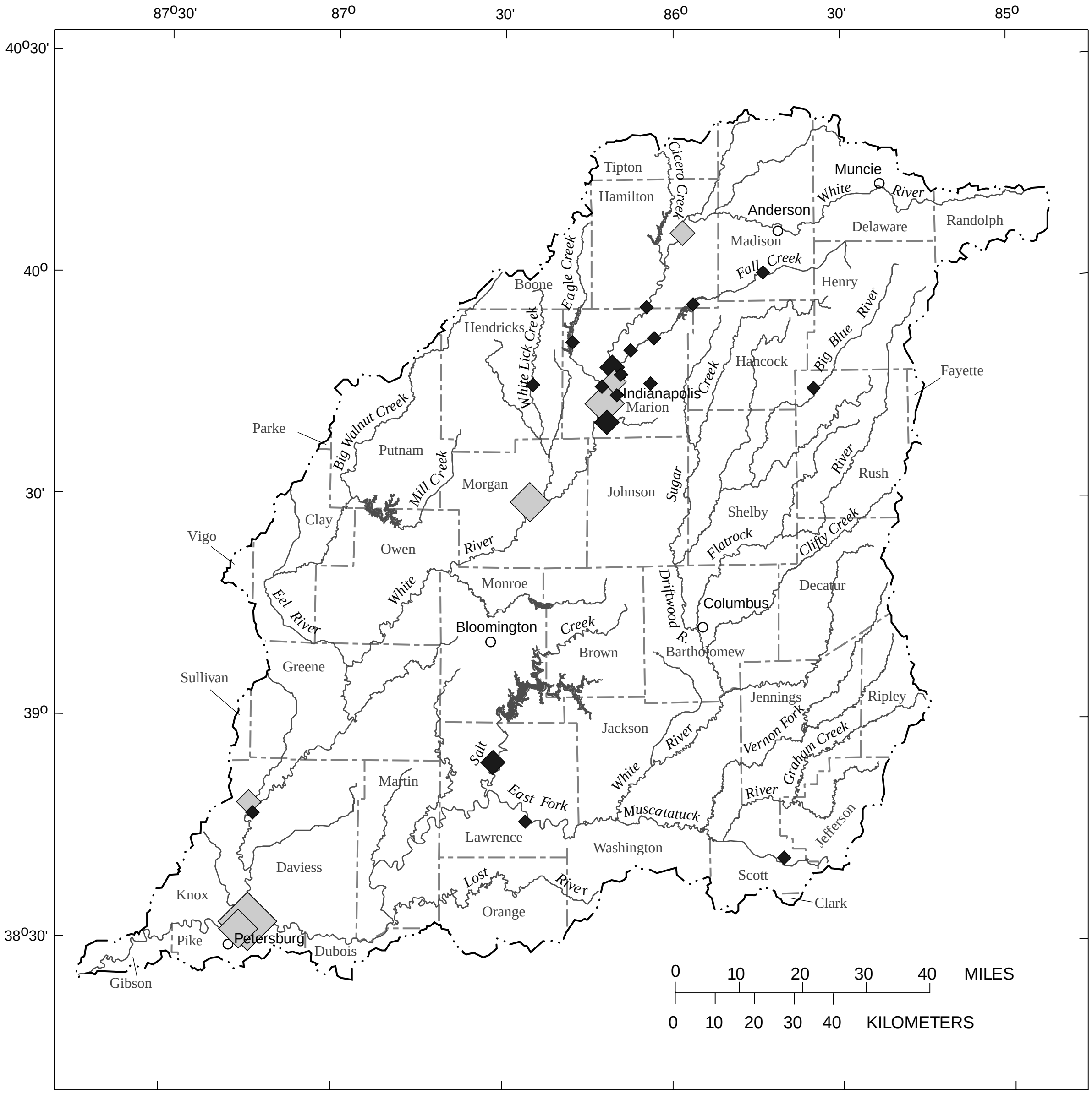
Modified existing landfills and newly constructed landfills are designed to prevent leachate from leaking into adjacent streams and underlying aquifers by use of several mechanisms, including clay and rubber liners and caps, gas-venting systems, and leachate-collection systems. Leachate constituents from “leaky” landfills, such as waste-disposal sites that predate current construction practices and regulations, can be as varied as the waste. Fourteen sites in the basin were on the U.S. Environmental Protection Agency’s Superfund National Priorities List in 1993; most of these sites are in Indianapolis, Bloomington, and Columbus. An additional 12 sites in the basin were State cleanup sites (Indiana Department of Environmental Management, 1994). In addition, 47 sites in the basin were on the active U.S. Environmental Protection Agency’s Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS) list in 1997. These sites are considered potential Superfund or State cleanup sites. Numerous Resource Conservation and Recovery Act (RCRA) facilities are present in the basin. These facilities generate, transport, treat, store, or dispose of hazardous waste and are regulated by the IDEM to ensure that hazardous wastes do not leave the facility through the ground or surface water. Four defense facilities—Fort Benjamin Harrison, Jefferson Proving Grounds, the Naval Air Warfare Center, and the Naval Surface Warfare Center—are present in the basin; all but the Naval Surface Warfare Center were closed in the mid-1990’s and are being converted to civilian use. Each of the defense facilities has a variety of known or potentially contaminated sites that, as of 1987, are being monitored or cleaned.

Various industries and power-generation plants in the White River Basin use water in their operations. The treated wastewater or cooling water then is discharged to streams (fig. 27). Most of the industrial facilities discharging more than 1 Mgal/d are located in the Indianapolis Metropolitan Area. Seven coal-fired power-generation plants on the White River (fig. 27) discharged more than 1 Mgal/d of used cooling water in 1991. Power-generation plants return most of the water they use to the stream, although minor amounts are consumed during the process. The greatest effect on water quality is the 10 to 15°F increase in water temperature that occurs between the intake and discharge points. A study during 1965 to 1970 at the power-generation plant in Petersburg, Ind., did not find any major effects on aquatic biota as a result of elevated water temperature (Whitaker and others, 1973). All industries and power-generation plants discharging processed water into a river are required by the IDEM to have a National Pollutant Discharge Elimination System (NPDES) permit. The permit restricts the amount of pollutants that can be discharged into a river and also the concentrations of these pollutants and constituents in the effluent water.

Agricultural Practices

Farming practices affect the concentrations of pesticides and nutrients in surface water and ground water. The method of pesticide and fertilizer application, the timing relative to climate conditions, and the tillage practices can affect concentrations of contaminants (U.S. Environmental Protection Agency, 1988). For example, pesticides, nutrients, and sediment may be concentrated in streams during high runoff periods following applications in late spring. Data describing the distribution of nutrients and pesticides in surface and ground water of the White River Basin were compiled as part of the White River Basin study (Carter and others, 1995; Martin and others, 1996).

The growing season in the White River Basin is from early April to late September. The timing of spring planting and fall harvest depends on soil, crop, and weather conditions. Warm, dry conditions enable early planting and harvesting, whereas cool, wet conditions delay planting and harvesting. Traditionally, fields have been plowed and disked in preparation for planting between mid March and late May (Indiana Agricultural Statistics



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°

EXPLANATION

Mean daily discharge from industrial wastewater-treatment facilities (shown in black) and power-plant cooling-water discharge points (shown in gray), in million gallons per day

- 1 to 9.9
- 10 to 99
- 100 to 160
- 300 to 310

White River Basin boundary

Figure 27. Location of industrial wastewater-treatment plants and power-plant cooling-water discharge points that discharged more than one million gallons of effluent per day in the White River Basin, Indiana, 1991. (Data from the Indiana Department of Environmental Management, written commun., 1992.)

Service, 1992). More recently, many farmers are adopting no-till farming or other conservation tillage practices. Pre-emergent herbicides typically are applied to the soil immediately before planting or during planting. Weed growth during the growing season may be controlled further by the use of post-emergent herbicides. Insecticides are applied less frequently and typically later in the growing season.

Corn planting typically precedes soybean planting, and soybean harvest typically precedes corn harvest. In Indiana, most (80 percent) of the corn usually is planted between April 20 and May 31, whereas most of the soybeans typically are planted between May 4 and June 19 (Indiana Agricultural Statistics Service, 1992). In the fall, most of the corn is harvested between September 22 and November 17, whereas most of the soybeans are harvested between September 19 and November 5 (Indiana Agricultural Statistics Service, 1992). Following harvest, remaining plant residue typically is disked into the soil; if a no-till practice is used, the residue is left to stabilize the soil surface.

A major source of nutrients in surface water and ground water is fertilizer applied to row crops. Corn receives 90 percent of the nitrogen and 76 percent of the phosphorus of the fertilizer applied to fields planted in corn, soybeans, and wheat. Soybeans receive 1 percent of the nitrogen and 13 percent of the phosphorus. Wheat receives 8 percent of the nitrogen and 10 percent of the phosphorus. The types and quantities of fertilizers used in the White River Basin and their times of application vary depending on the weather, soil fertility, tillage systems, crop types, crop rotations, yield goals, and the personal preferences of farmers. The most widely used nitrogen-based fertilizers for corn are anhydrous ammonia, 28-percent-liquid nitrogen, and urea in the solid form (David Mengel, Purdue University, Department of Agronomy, oral commun., 1993). Corn in Indiana receives an average of two applications per year of nitrogen-based fertilizer (Indiana Agricultural Statistics Service, 1992). The first application is at planting (liquid nitrogen or urea) or 1 to 2 weeks before planting (anhydrous ammonia). A second, larger application usually is made after the corn has germinated and is about 1 ft tall. The second application typically occurs no later than mid-June because corn height limits movement of machinery in the fields. Some farmers may apply nitrogen-based fertilizers after harvest, especially if they plan to grow winter wheat.

Fertilizers are applied more frequently and in greater amounts per acre to corn than to soybeans or wheat. Statistics described in this paragraph are medians of annual estimates for 1980 to 1990. Statewide, Indiana farmers applied nitrogen-based fertilizers to 99 percent of the acres planted with corn, 30 percent of the acres planted with soybeans, and 95 percent of the acres planted with wheat. The median nitrogen application rate was 148 lb/acre for corn, 12 lb/acre for soybeans, and 75 lb/acre for wheat. Phosphorus-based fertilizers were applied to 96 percent of the corn, 38 percent of the soybeans, and 90 percent of the wheat. The median phosphorus application rate was 33 lb/acre for corn, 18 lb/acre for soybeans, and 26 lb/acre for wheat. Potassium-based fertilizers were applied to 88 percent of the corn, 45 percent of the soybeans, and 88 percent of the wheat. The median potassium application rate was 91 lb/acre for corn, 65 lb/acre for soybeans, and 56 lb/acre for wheat (data from Indiana Crop and Livestock Reporting Service, 1985; Indiana Agricultural Statistics Service, 1988; Indiana Agricultural Statistics Service, 1991).

Most of the agricultural pesticides in the White River Basin are used on corn (75 percent of all agricultural pesticides) and soybeans (22 percent) (Anderson and Gianessi, 1995). Of the pesticides applied, 92 percent are herbicides. The most common herbicides applied from 1992 to 1994—atrazine, metolachlor, alachlor, butylate, and cyanazine—account for 72 percent of all agricultural pesticides applied in the White River Basin. All five herbicides are used on corn; alachlor and metolachlor also are used on soybeans. Fonofos and chlorpyrifos were the most commonly applied agricultural insecticides in the basin (table 5).

Table 5. Estimated use of agricultural pesticides in the White River Basin, Indiana

[1992–94 average usage, except for acetochlor which is 1994 usage. Data from Anderson and Gianessi, 1995, tables 3–6]

Herbicide	Active ingredient applied, in pounds
2,4-D	265,000
2,4-DB	6,370
Acetochlor	125,000
Acifluorfen	24,000
Alachlor	1,250,000
Atrazine	2,220,000
Benefin	587
Bensulide	1,520
Bentazon	143,000
Bromoxynil	11,300
Butylate	887,000
Chloramben	74
Chlorimuron-ethyl	6,280
Clethodim	5,030
Clomazone	32,000
Cyanazine	791,000
DCPA	107
Dicamba	113,000
Dichlobenil	341
EPTC	83,200
Ethafluralin	38,200
Fenoxaprop-ethyl	7,070
Fluazifop-butyl	14,100
Fomesafen	18,800
Glyphosate	361,000
Imazaquin	44,000
Imazethapyr	27,300
Lactofen	10,100
Linuron	79,200
MCPA	4,970
Metolachlor	2,070,000
Metribuzin	73,700
Napropamide	1,150
Naptalam	1,010
Nicosulfuron	5,100
Oryzalin	128
Paraquat	35,900
Pendimethalin	357,000
Primisulfuron	3,020
Quizalofop-ethyl	3,140
Sethoxydim	16,300
Simazine	35,000
Terbacil	48
Thifensulfuron methyl	770
Tribenuron	110
Trifluralin	102,000

Fungicide	Active ingredient applied, in pounds
Anilazine	211
Benomyl	2,890
Captan	5,980
Chlorothalonil	57,900
Copper	6,650
Dinocap	177
Dodine	548
Mancozeb	45,500
Maneb	16,800
Metalaxyl	2,200
Metiram	6,240
Myclobutanil	180
Propiconazole	647
Streptomycin	1,470
Sulfur	21,000
Thiophanate-methyl	1,320
Triadimefon	857
Vinclozolin	39

Insecticide	Active ingredient applied, in pounds
Acephate	2,070
Azinphos-methyl	1,270
Carbaryl	14,400
Carbofuran	44,500
Chlorpyrifos	154,000
Diazinon	1,020
Dicofol	25
Dimethoate	5,080
Endosulfan	1,430
Esfenvalerate	230
Ethoprop	17
Fonofos	163,000
Formetanate hydrochloride	664
Malathion	4,090
Methamidophos	53
Methomyl	121
Methyl parathion	1,690
Oil	44,600
Oxamyl	557
Oxydemeton-methyl	11
Permethrin	11,000
Phorate	38,600
Phosmet	1,210
Propargite	1,950
Tefluthrin	6,800
Terbufos	84,900
Trimethacarb	18,900

Other pesticides	Active ingredient applied, in pounds
Chloropicrin	1,400
Maleic hydrazide	3,510
Methyl bromide	4,340
NAA	22

Indiana farmers use a variety of tillage systems that can be classified as conventional tillage or conservation tillage. With conventional-tillage methods, fields are plowed and disked from one to three times each year, and 0 to 15 percent of the previous year's crop residue is left on the land surface. Conventional tillage methods break up the existing soil structure and leave the soil exposed and susceptible to erosion. Conservation-tillage systems (the most common include no-till, mulch-till, and ridge-till) are designed to reduce soil erosion by minimizing soil disturbance, protecting the soil surface with growing plants or plant residues, and increasing surface roughness and permeability (MidWest Plan Service, 1992). These conservation methods may, however, require greater quantities of pesticides than are required with conventional tillage methods. Conservation tillage systems were used on 58 percent of Indiana's farmlands in 1992, an increase from 41 percent in 1990 (John Becker, Conservation Technology Information Center, oral commun., 1993).

Tillage practices can affect water quality by influencing the amount of sediment that is eroded from fields and transported to the streams, lakes, and reservoirs. Nutrients and pesticides often are adsorbed to eroded sediments and can increase concentrations of these constituents in surface water. In general, conservation-tillage systems improve surface-water quality, compared to conventional tillage systems, by increasing infiltration and decreasing surface runoff and evapotranspiration (MidWest Plan Service, 1992).

Drainage on many poorly drained soils in the White River Basin has been improved for farming by the installation of tile-drain systems. Water-saturated soils inhibit planting, harvest, and crop growth. Modern tile drains consist of perforated, flexible tubes buried in trenches in fields beneath the plow zone. The tile drains transport water to nearby ditches or streams, quickly removing standing water in fields, draining excess soil moisture in the unsaturated zone, draining seasonally high ground-water tables, thus "short circuiting" natural ground-water-flow systems in agricultural fields. Information on the number and location of tile-drain systems is not available, but agricultural experts expect that nearly all poorly drained farmlands in Indiana contain tile-drain systems (Eileen Kladivko, Purdue University, Department of Agronomy, oral commun., 1993). Tiling can influence water quality by shortening the period of time that water is in contact with the subsurface and the associated processes that naturally decrease concentrations of nutrients and pesticides in ground water. Tile drainage can be particularly problematic to surface-water quality if rainfall occurs immediately following application of fertilizers or pesticides.

Irrigation is not common in the White River Basin but is used in Bartholomew, Jackson, Knox, and Sullivan Counties (Indiana Department of Natural Resources, 1990). Irrigation in these counties is applied during the driest months of the growing season, approximately 90 days per year, and the amount of water applied ranges from 2 to 15 Mgal/d. Irrigation can affect water quality if agricultural chemicals or other constituents are applied with the water or if the application changes the predominant hydrology.

Water Use

Water use in the White River Basin totaled 1,284 Mgal/d in 1995, of which 84.5 percent was surface water and 15.5 percent was ground water (table 6). Total water withdrawals in 1990 were highest for Marion, Hamilton, and Morgan Counties (Indiana Department of Natural Resources, 1990).

The major water use in the basin was cooling water for fossil-fuel thermoelectric power-generation plants (about 63 percent of the total water use). Seven power-generation plants withdrew at least 1 Mgal/d of surface water from the White River in 1991 (Indiana Department of Environmental Management, written commun., 1991). Virtually all water withdrawn for cooling at power-generation plants is returned to the stream. The East Fork White River does not have power-generation-plant water intakes.

Table 6. Water use in the White River Basin, Indiana, 1995

[Data compiled by Donald Arvin, U.S. Geological Survey, written commun., 1997. Original data source is 1995 withdrawal data obtained from Indiana Department of Natural Resources, Division of Water]

	Water-use category	Withdrawals, in millions of gallons per day	Percent of total water use in basin
Surface water	Public-supply water	158	12.3
	Self-supplied domestic	0	.0
	Self-supplied commercial	9.62	.7
	Self-supplied industrial	28.5	2.2
	Fossil-fuel thermoelectric power	806	62.8
	Mining	64.4	5.0
	Irrigation	14.1	1.1
	Livestock	5.44	.4
	Total surface water	1,086	84.5
Ground water	Public-supply water	109	8.5
	Self-supplied domestic	38.4	3.0
	Self-supplied commercial	13.8	1.1
	Self-supplied industrial	20.9	1.6
	Fossil-fuel thermoelectric power	3.74	.3
	Mining	.65	.1
	Irrigation	4.93	.4
	Livestock	7.04	.5
	Total ground water	198	15.5

Public-supply water accounted for about 21 percent of the total water use. Public-supply water is delivered to multiple users and is used in the White River Basin principally for domestic, commercial, and industrial uses. Almost 80 percent of the residents in the White River Basin obtained water from public supplies. Of the water withdrawn for public supply, 59 percent was surface water and 41 percent was ground water. Public-supply water was the primary use of ground water in the basin. Ground water was the primary source of drinking water for approximately 56 percent of the population (Donald Arvin, U.S. Geological Survey, written commun., 1997). The largest ground-water withdrawals in 1990 (5–15 Mgal/d) for public supply were in Bartholomew, Hamilton, Johnson, Madison, and Marion Counties (Indiana Department of Natural Resources, 1990).

Self-supplied domestic, self-supplied industrial, and mining uses each had at least 3 percent of total water use in the White River Basin in 1995. Self-supplied domestic water supplies were obtained from private wells and provided water for approximately 500,000 residents in the basin (Donald Arvin, written commun., 1997). Irrigation water use was minor (1.5 percent of total use) in the basin. Although the basin is extensively farmed, irrigation is not necessary in most parts of the basin because the soils tend to hold water for long periods of time. Irrigation is used to increase production on some croplands on well-drained soils in the major flood plains in the south-central and southwestern parts of the basin.

Hydrogeomorphic Regions of the White River Basin

One of the goals of the NAWQA Program is to understand the natural and human factors that affect water quality. To examine the effects of natural factors on water quality, the White River Basin was subdivided into discrete "hydrogeomorphic regions" that have distinct and relatively homogeneous natural characteristics (Gilliom and others, 1995). The natural factors include bedrock and glacial geology, physiography, major soil associations, and hydrology. Three hydrogeomorphic regions include areas where bedrock is exposed or near the land surface: the bedrock uplands, bedrock lowland and plain, and karst plain. The remaining three hydrogeomorphic regions are overlain with glacial deposits and include the till plain, glacial lowland, and fluvial deposits (fig. 28).

The effects of human influences on water quality can be examined by investigating the relations between land use and water quality. Agriculture, urban, and coal mining are the major land uses likely to have detrimental effects on water quality. The percentage of each land-use and other selected characteristics of the hydrogeomorphic regions are shown in table 7.

Till Plain

The till plain hydrogeomorphic region is the Tipton Till Plain physiographic unit (fig. 8). This region is the largest of the six hydrogeomorphic regions and is in the northern half of the basin (fig. 28). The southernmost edge of the till plain region approximates the farthest advance of Wisconsin-age glaciation; however, the southern boundary of the till plain is not at the limit of Wisconsin-age glaciation. For example, Bartholomew and Decatur Counties have some areas with till deposits as much as 100 ft thick but are grouped in the bedrock lowland and plain hydrogeomorphic region because the topography is more representative of this bedrock region than of the till plain.

The land surface of the till plain is flat to gently rolling. Topographic features include several low end moraines, eskers, and shallow streams. Many areas contain shallow, closed depressions. Glacial deposits are 50 to 400 ft thick but generally range from 100 to 200 ft thick. Glacial deposits of the till plain consist of clay loam till of Wisconsin age underlain by pre-Wisconsin-age till. Clay content in the till is generally 30 to 40 percent.

Till plain soils principally are mapped as "thin loess over loamy glacial till" and "clayey glacial till" (fig. 9). The soils have developed in 10 to 20 in. of loess overlying calcareous loam till and form a patchwork of light- and dark-colored areas. Dark, wet, organic-rich soils occur in swales and depressions; on swells, the water table is lower and soils are lighter colored, more oxidized, and lower in organic matter (Donald Franzmeier, Purdue University, Department of Agronomy, written commun., 1993). Most surface soils are silt loam, and the subsoil is slowly permeable in level areas or depressions. Nearly all soils on the till plain are used for farming, predominantly for corn and soybeans. Till plain soils are among the most productive in the world because they have good water-holding capacity and they are young and have not been leached of the nutrients provided by pulverized rock in the glacial material (Donald Franzmeier, written commun., 1993). Nearly all poorly drained areas in the till plain region have been drained by buried agricultural field tiles (William Hosteter, U.S. Natural Resources Conservation Service, oral commun., 1995).

Isolated lenses of sand and gravel occur in the till and are the primary aquifers where glacial deposits are thick. In areas of thinner deposits, the Silurian and Devonian aquifers commonly are used for water supply. The fine-grained deposits of the till reduce the potential for contamination of aquifers in this hydrogeomorphic region. Row-crop corn and soybean agriculture is the dominant land use in the till plain. The till plain contains 59 percent of the population in the White River Basin and includes the urban areas of Muncie, Anderson, and Indianapolis.

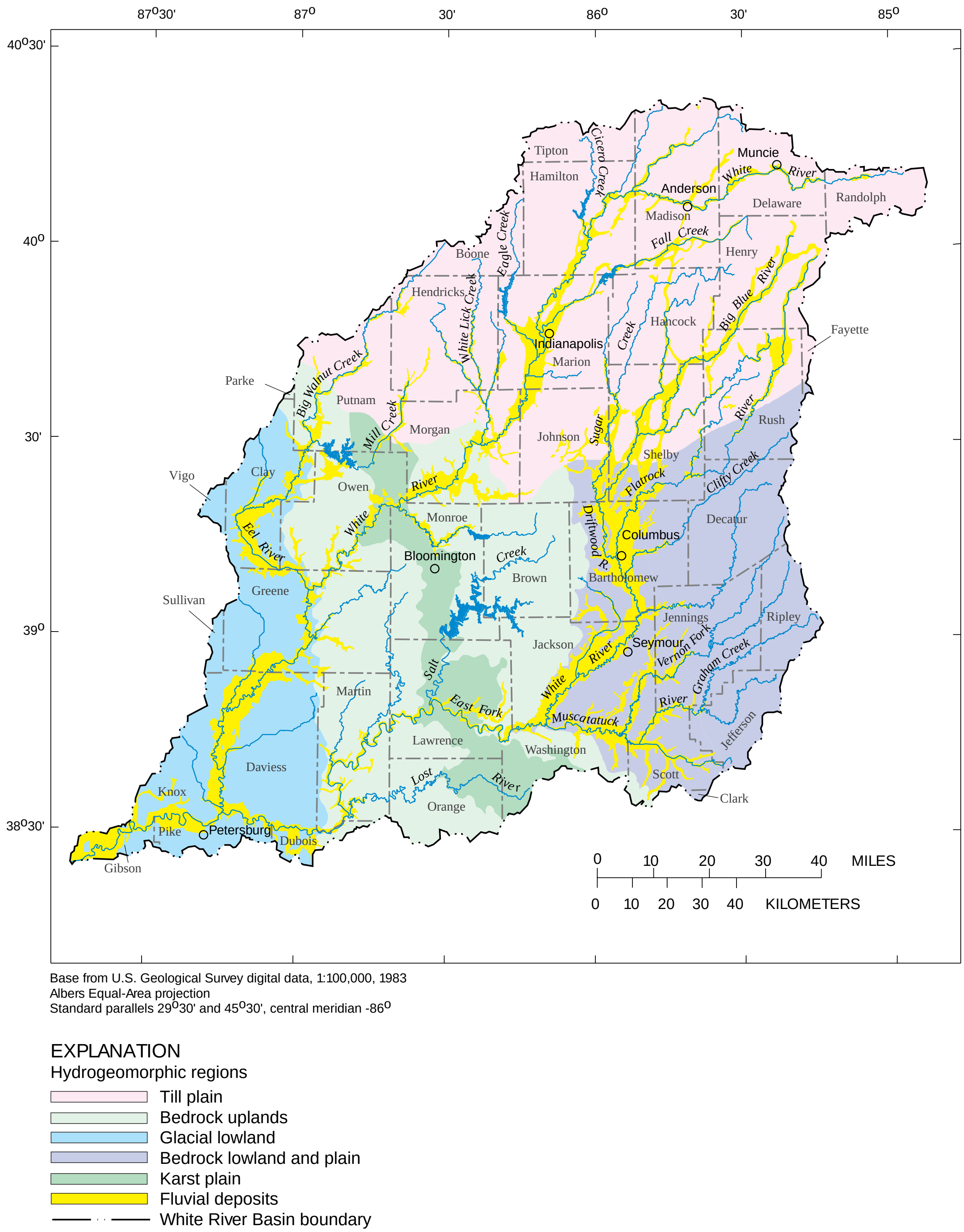


Figure 28. Hydrogeomorphic regions used to evaluate the effects of natural factors on water quality in the White River Basin, Indiana.

Table 7. Characteristics of hydrogeomorphic regions in the White River Basin, Indiana

[Population data from U.S. Department of Commerce (1992); land-use data from U.S. Geological Survey (1990) as modified by Hitt (1994); mi^2, square mile; Cr., Creek; R., River; fk., fork; --, not applicable]

Characteristic		Hydrogeomorphic region: Till plain	Glacial lowland	Bedrock uplands	Karst plain	Bedrock lowland and plain	Fluvial deposits	White River Basin
Estimated population (1990)		1,231,600	83,300	119,100	136,900	139,000	364,200	2,074,100
Population density (people/mi^2)		329	71	51	214	74	229	183
Area (mi^2)		3,740	1,170	2,328	639	1,885	1,587	11,349
Percent land use[1]	Agriculture	85.4	82.2	27.3	61.7	76.9	77.9	69.3
	Urban	11.2	4.2	2.9	9.1	4.5	8.6	7.2
	Forest	2.9	11.7	68.3	28.4	17.9	10.9	22.3
	Water and wetlands	.3	.6	1.2	.2	.3	1.9	.7
	Barren[2]	.2	1.3	.2	.5	.3	.6	.4
Typical soil characteristics		Slowly permeable silt loam	Well-drained to slowly permeable silt loam	Thin, acidic, slowly permeable, stony loam	Strongly acidic, highly erosive, silt loam	Slowly to very slowly permeable silt loam	Permeable loam	--
Commonly used aquifers		Silurian and Devonian carbonate bedrock; till aquifers	Minor aquifers (sandstone; some shale, coal, and limestone aquifers)	Mississippian carbonate and clastic bedrock; Pennsyl-vanian sandstone	Mississip-pian carbonate bedrock	Silurian and Devonian carbonate bedrock	Glacio-fluvial aquifers	--
Large streams (greater than 200 mi^2 drainage area)		Big Blue R. Big Walnut Cr. Cicero Cr. Driftwood R. Eagle Cr. Fall Cr. Mill Cr. Sugar Cr. west fk. of White R. White Lick Cr.	East Fork White R. Eel R. west fk. of White R.	East Fork White R. Eel R. Lost R. Muscatatuck R. Salt Cr.	East Fork White R. Lost R. Salt Cr.	Clifty Cr. Driftwood R. East Fork White R. Flatrock R. Graham Cr. Muscatatuck R. Sand Cr. Vernon Fk.	All large streams	--

[1]Some regions do not total 100 percent due to rounding.

[2]Barren land includes strip mines, quarries, and exposed bedrock.

Glacial Lowland

The glacial lowland hydrogeomorphic region, in the southwestern part of the basin (fig. 28), is the same as the Wabash Lowland physiographic unit (fig. 8). Bedrock underlying the glacial lowland region includes Pennsylvanian coal, shale, sandstone, and limestone. The bedrock is overlain by locally thick deposits of Illinoian-age till, loess, glacial lake deposits (typically clay), and sand dunes. Extensive, sediment-filled valleys are common. Landforms in the glacial lowland are characterized by broad, gently sloping valleys with smooth, rounded hills. Uplands are hilly or gently rolling, and relief is moderate.

Most glacial lowland soils have developed in thick loess deposits or in sand dunes (fig. 9). The well-drained, sand-dune soils form a narrow band along the eastern margin of the White River. Sand-dune soils have a low organic-matter content, low fertility, and low water-holding capacity. The surface texture is silt loam and the subsoil is permeable. Soils that have formed in the 5- to 25-ft-thick loess deposits are the most extensive in the glacial lowland (Ulrich, 1966). These soils are erosive, moderately to very acidic, and often have fragipans. Upland soils are low in organic matter, and lowland soils require drainage. The surface soils are silt loam, and the subsoils are moderately to slowly permeable. Subsoil permeability is less in the northern part of the region where thinner deposits of loess cover the pre-Wisconsin-age till plain (Bushnell, 1944). In areas of the region where sandy deposits are common, like Knox and Sullivan Counties, some farmers require irrigation to maintain adequate soil moisture. In other areas of the glacial lowland, drainage is poor and drainage ditches or tile drains are common. In cropland areas susceptible to soil erosion because of moderate relief, tile drains may have riser pipes that collect ponded surface water and transport it to nearby streams or ditches.

Ground-water supplies typically come from Pennsylvanian sandstone aquifers that can be as deep as 300 ft. Lesser-used aquifers include unconsolidated sand and other Pennsylvanian bedrock (shale, siltstone, coal, and limestone). Surface coal mining occurs only in this region of the basin, but row-crop corn and soybean agriculture is the dominant land use.

Bedrock Uplands

The bedrock uplands hydrogeomorphic region (fig. 28) comprises the Crawford Upland and Norman Upland physiographic units (fig. 8). The bedrock uplands hydrogeomorphic region, in the south-central part of the basin, is separated into two parts by the karst plain region.The eastern part of the bedrock uplands consists of resistant siltstone, sandstone, and shale of the Borden Group (early to middle Mississippian age). The western part consists of alternating sandstones, shales, and limestones from the Chester Series (late Mississippian age), unconformably overlain by sandstones and mudstones of the Mansfield Formation (early Pennsylvanian age). The bedrock uplands have not been glaciated except for a thin mantle of pre-Wisconsin-age till that covers the northernmost part.

Differential erosion of lithologic units has produced a high relief hill and valley landscape that characterizes the bedrock uplands. The highly dissected topography of the bedrock uplands exhibits narrow, flat-topped ridges; steeply sloping hillsides; and deep, V-shaped valleys. Local relief is as much as 300 ft, and flood plains are narrow or absent. Soils, mapped as discontinuous loess over weathered shale and limestone (fig. 9) are thin, acidic, and poorly suited for agriculture. The ridgetops have a thin layer of silt and contain fragipans that have developed in most soils with less than 12-percent slopes (Donald Franzmeier, written commun., 1993). The soil-surface texture is stony loam, and the subsoil is slowly permeable (Bushnell, 1944).

Ground-water supplies are derived primarily from bedrock aquifers in the bedrock uplands. Supplies typically are poor and well yields are sporadic. Aquifer types include minor aquifers consisting of Mississippian-age clastic bedrock (sandstone, fractured shale and siltstone, and minor limestone), Mississippian carbonates that underlie clastic bedrock in the western part of the bedrock uplands, and the Pennsylvanian Mansfield Formation in the far western part of the uplands (Fenelon and Greeman, 1994).

Most (68 percent) of the land is forested, although pasture and row crops commonly occur in the valleys and on some of the broader hilltops. The bedrock uplands are not suited for intensive agriculture, and large tracts of land are in State and National Forests; the population is sparse.

Karst Plain

The karst plain hydrogeomorphic region is the Mitchell Plain physiographic unit (fig. 8), located in the south-central part of the basin between the two areas that compose the bedrock uplands region (fig. 28). The karst plain is a small area that covers less than 6 percent of the White River Basin. It is a moderately sloping, undulating upland area of low relief that formed from soluble Mississippian limestone. Rock formations of the Blue River Group (particularly the Paoli, Ste. Genevieve, and St. Louis Limestones) are susceptible to development of karst features. Formations of the Blue River Group consist of soluble minerals and contain numerous fractures and joints that easily can be widened by natural dissolution. The Salem Formation, positioned directly beneath the Blue River Group, contains fewer karst features because the rock is a less pure limestone and, therefore, less susceptible to dissolution. Like the bedrock uplands region, only the northernmost part of the karst plain has been glaciated.

The karst plain, particularly the western half of the region, contains caves, numerous sinkholes, and solution features and is characterized by short, discontinuous surface streams that drain to sinkholes. More than 1,000 sinkholes were counted in 1 mi^2 in the center of this region (Schneider, 1966). Shapes of the sinkholes vary, but a typical sinkhole is funnel-shaped in cross section—10 to 30 ft deep and 150 ft in diameter.

Karst plain soils (discontinuous loess over weathered limestone in fig. 9) have developed in a thin, discontinuous layer of loess and a base-rich residuum of reddish clay called “terra rosa.” Terra rosa is speculated to be residuum produced by erosion of the limestone formations. In many areas, limestone underlies the slowly permeable red-clay residuum at a depth of 5 or 10 ft (Ulrich, 1966). In the Lost River Basin, the thickness of the terra rosa averages 17 ft in the eastern part of the basin and 34 ft in the western part (Ruhe and Olson, 1980). Soils are strongly acidic and low in organic matter and nutrients (Ulrich, 1966). The soils are silt loams and have developed fragipans on flat areas. Most soils in the region are erosive (Donald Franzmeier, written commun., 1993).

Most ground water withdrawn from the karst region comes from the Mississippian carbonate aquifers, which can have variable yields that are typically 1 to 50 gallons per minute (Fenelon and Greeman, 1994). The numerous sinkholes and solution features in the karst plain make aquifers in this hydrogeomorphic region particularly susceptible to contamination. Pasture and row crops are the dominant land uses throughout the karst plain region. Quarrying of limestone is important to the local economy; however, limestone quarries are not areally extensive. For example, in Monroe County, where quarrying is economically significant, 125 quarries occupy only 550 acres of land (Hartke and Gray, 1989). About one half the population in the karst plain lives in Bloomington, the third largest city in the basin.

Bedrock Lowland and Plain

The bedrock lowland and plain hydrogeomorphic region (fig. 28) comprises the Muscatatuck Regional Slope and the Scottsburg Lowland physiographic units (fig. 8). These units are contiguous and are in the southeastern part of the basin. The Muscatatuck Regional Slope is a westward-dipping plain formed from resistant carbonate rocks of Silurian and Devonian ages. The Scottsburg Lowland is formed from soft shales of

Devonian and Mississippian ages. The entire extent of the bedrock lowland and plain region has been covered by pre-Wisconsin-age till or lake deposits, but the northern third also has been covered by Wisconsin-age till. Average thickness of glacial till is 20 to 25 ft but, in places, it is no more than 5 to 10 ft thick (Schneider, 1966). Upland areas of the bedrock lowland and plain region are broad and nearly flat. Streams cut deep valleys through the upland till and expose bedrock. Lowland areas of the region are located where highly erodible shale of late Devonian and early Mississippian ages outcrops (Schneider, 1966). Principal soils in the northern parts of the region are thin or moderately thick loess over loamy glacial till; principal soils in the southern part are moderately thick loess over weathered glacial till or lacustrine deposits (fig. 9). Most soils have developed in about 3 ft of loess and are either poorly drained or highly erosive (Ulrich, 1966). Surface soils are primarily silt loam, and the subsoil is slowly to very slowly permeable. Many of the soils have fragipans and require drainage for farming. Locating suitable outlets for tiles makes subsurface drainage difficult; when subsurface drainage is used, tiles tend to fill with silt.

Ground-water supplies typically are obtained from the Silurian and Devonian carbonate bedrock, which is a dependable aquifer except in the far eastern part of the region where supplies are sporadic (Fenelon and Greeman, 1994). The New Albany Shale (Devonian age), which underlies the western part of the bedrock lowland and plain, contains radioactive minerals and high concentrations of trace elements. Ground-water samples from wells affected by the New Albany Shale may show undesirable concentrations of radon and trace elements. Row-crop agriculture is the dominant land use throughout the bedrock lowland and plain region.

Fluvial Deposits

The fluvial deposits hydrogeomorphic region consists of a narrow band of river-lain deposits beneath and along most major rivers and streams throughout the White River Basin (fig. 28). The fluvial deposits primarily are sand and gravel and were deposited as valley fill as the glaciers melted; some of the surficial sediments are recent alluvium composed of sand, silt, and clay. In general, the fluvial deposits region corresponds to the areas of flood plains. The width of fluvial deposits is less than 0.1 to 0.5 mi along streams having drainage areas less than 100 mi^2, and 2 to 6 mi along major rivers such as the White River and East Fork White River. Fluvial deposits are most extensive in Marion County (near Indianapolis); in Bartholomew and Jackson Counties (near Columbus and Seymour); and in the southwestern part of the basin where the White River flows through Knox, Daviess, Pike, and Gibson Counties.

Soils of the fluvial deposits region are developed in alluvial and outwash deposits (fig. 9) that have a wide variety of characteristics and properties. In general, fine-textured material at the surface overlies coarse material at depth. Surface-soil textures generally are loams, and the subsoils are permeable. These soils are among the most productive in Indiana but, where the water table is deep, irrigation is required (Donald Franzmeier, written commun., 1993).

The fluvial deposits region contains the most productive and extensively used aquifers in the White River Basin. Most large cities near fluvial deposits use the aquifers for public supplies. In Bartholomew, Jackson, and Knox Counties, fluvial deposits also are used to supply water for irrigation agriculture. Fluvial deposits crossing the bedrock uplands and karst plain regions are particularly important as aquifers for residents in these areas because productive and reliable bedrock aquifers can be difficult to locate.

Although parts of Muncie, Anderson, Indianapolis, Columbus, and many small cities and towns are in this region, row-crop corn and soybean agriculture is the dominant land use. The fluvial deposits region was used in the White River Basin study only to examine factors affecting ground-water quality because the drainage basins of streams and rivers do not include substantial amounts of this hydrogeomorphic region.

Summary

The White River Basin encompasses 11,349 mi^2 in central and southern Indiana. Water quality in the basin is affected by natural factors such as climate, geology, physiography, soils, and hydrology and by human influences such as land use, waste-disposal practices, agricultural practices, and water use. Although the quality of ground water and surface water is suitable for most uses, water quality can be degraded by point and non-point sources of contamination.

Interrelated natural factors help determine the water quality in the White River Basin. The basin has a humid continental climate, characterized by well-defined winter and summer seasons. Rainfall in the cooler months is generally of long duration and mild intensity, whereas rainfall in late spring and summer tends to be of shorter duration and higher intensity. Geologic features in the White River Basin include glaciated and nonglaciated areas; a region of karst geomorphology that is characterized by caves and sinkholes; and a thick, sedimentary bedrock sequence underlying the entire basin. Unconsolidated glacial deposits of clay, silt, sand and gravel cover more than 60 percent of the basin. In the northern part of the basin, unconsolidated deposits may be 400 ft thick but, in the southern part of the basin, glacial deposits are limited to thin veneers of windblown silt. Bedrock includes Paleozoic-age carbonates (limestone and dolomite), sandstones, siltstones, shales, and coals. Physiography in the basin is defined by a glacial till plain in the northern part of the basin and a series of bedrock lowlands, uplands, and plains in the southern part of the basin. Soils developed in unconsolidated glacial deposits are typically fertile, naturally or artificially well drained, and farmed. Soils in the unglaciated south-central part of the basin are thin, have low fertility, and are best suited for forest or pasture.

Difference in streamflow characteristics between the northern and southern parts of the basin are related to natural characteristics that include the thickness and water-yielding capacity of glacial deposits, the water-yielding capacity of bedrock, permeability of soils, and the slope and relief of the landscape. Streams in the northern part of the basin drain relatively flat areas of thick glacial deposits. The flat landscape promotes ponding and infiltration of rainfall that moderates surface runoff and peak flows; the thick glacial deposits contain aquifers that discharge to streams and contribute to sustained base flow. Streams in the southern part of the basin generally drain more steeply sloping areas that lack glacial deposits or have thin deposits. Steep slopes promote surface runoff. Because the water-yielding capacity of bedrock and thin glacial deposits is poor, the bedrock and thin glacial deposits contribute little to base flow.

Surface-water quality is determined partly by local geology. In the southern part of the basin, bedrock upland areas are dominated by non-carbonate bedrock, thin soils, and high runoff-rainfall ratios. Streamwater fed by ground water in these areas has small chemical concentrations. Conversely, in the northern part of the basin where glacial deposits are thick and in the southwestern part of the basin where loess deposits are thick, ground water has long periods of time to react with soils and aquifers and to acquire substantial quantities of dissolved constituents. Ground-water seepage into streams in the till plain and glacial lowland, as a result, has higher concentrations of most constituents than ground water in the unglaciated parts of the basin.

Surface-water-quality problems in the White River Basin are related primarily to agriculture, urbanization, industrialization, and mineral-resource extraction. In the East Fork White River Basin, 54 percent of the stream miles assessed by the Indiana Department of Environmental Management fully supported aquatic-life uses, but none of the assessed stream miles fully supported full-body-contact recreation. In the remainder of the White River Basin, 82 percent of the assessed stream miles fully supported aquatic-life uses, but only 5 percent fully supported full-body-contact recreation. A primary cause of streams failing to fully support aquatic-life uses were polychlorinated biphenyls or chlordane in fish tissue that resulted in fish-consumption advisories.

Bacterial contamination of stream water was a primary cause of streams failing to support full-body-contact recreation. Other constituents that have affected water quality in the basin are ammonia, metals, suspended solids, biochemical-oxygen demand, and low concentrations of dissolved oxygen.

Two general types of aquifers occur in the White River Basin—unconsolidated aquifers associated with glacial deposits and bedrock aquifers. The primary unconsolidated aquifers are glaciofluvial aquifers and till aquifers. Unconsolidated aquifers are common in the northern part of the basin. The principal bedrock aquifers are Silurian-Devonian carbonate aquifers and Mississippian carbonate aquifers. Ground-water quality and quantity vary as a result of many factors such as aquifer composition, aquifer depth, ground-water-flow regime, and surficial land use.

The quantity and quality of the ground water in the White River Basin, however, meet the needs of most users. Withdrawal rates range from 10 to 600 gal/min in the bedrock aquifers to as much as 2,000 gal/min in thick glaciofluvial deposits. Ground water in Indiana is generally very hard—100 to 600 mg/L—with the highest concentrations in bedrock aquifers. Iron and sulfate concentrations are also high in many aquifers.

Human activities affect water quality most in areas of the White River Basin where urban and agricultural land uses are predominant. Major non-point sources of contamination include (1) pesticide and nutrient applications related to farming; (2) siltation related to farming, grazing, mining, and construction; and (3) urban runoff. Major point sources of contamination include outfalls related to wastewater-treatment plants, industrial discharges, releases from power-generation-plant cooling tanks, combined-sewer overflows, and landfills.

Agriculture is the principal land use in the White River Basin. Approximately 70 percent of the basin is used for agriculture. Of the 3.6 million acres of farmland in the basin, 43 percent were planted for corn, 35 percent were planted for soybeans, 4 percent were planted for winter wheat, and 6 percent were harvested for hay. Other land uses are forest (22 percent), urban and residential (7 percent), water and wetlands (0.7 percent), and active and abandoned quarries and coal mines (0.4 percent). Forested areas are primarily in the south-central part of the basin in bedrock upland areas. Most of the large urban centers in the basin are located in the northern part of the basin and include Indianapolis, Muncie, and Anderson. Coal mines are an important industry in the southwestern part of the basin.

Water use in the White River Basin totaled 1,284 Mgal/d in 1995, of which about 85 percent was surface water and 15 percent was ground water. Despite the predominant use of surface water in the basin, ground water was the primary source of drinking water for approximately 56 percent of the population.

To examine the effects of natural factors on water quality, the White River Basin was subdivided into discrete “hydrogeomorphic regions” that have distinct and relatively homogeneous natural characteristics. The natural characteristics include bedrock and glacial geology, physiography, hydrology, and major soil associations. Three hydrogeomorphic regions include areas where bedrock is exposed or near the land surface: the bedrock uplands, bedrock lowland and plain, and karst plain. The remaining three hydrogeomorphic regions are overlain with glacial deposits and include the till plain, glacial lowland, and fluvial deposits. The till plain region is the largest, most populated, and most extensively farmed of the six hydrogeomorphic regions. The bedrock uplands is the least densely populated and the most forested of the regions. The karst plain is the smallest of the regions and is unique because of many caves, sinkholes, and disappearing streams. The fluvial region, located along most of the major streams and rivers throughout the basin, is densely populated and heavily farmed.

References Cited

Aber, J.S., Nadelhoffer, K.J., Steudler, P., and Melillo, J. M., 1989, Nitrogen saturation in northern forest ecosystems: Bioscience, v. 39, no. 6, p. 378–386.

Anderson, J.E., and Gianessi, L.P., 1995, Pesticide use in the White River Basin: Washington, D.C., National Center for Food and Agricultural Policy, 99 p.

Arihood, L.D., 1982, Ground-water resources of the White River Basin, Hamilton and Tipton Counties, Indiana: U.S. Geological Survey Water-Resources Investigations Report 82-48, 69 p.

Arihood, L.D. and Glatfelter, D.R., 1986, Method for estimating low-flow characteristics of ungaged streams in Indiana: U.S. Geological Survey Open-File Report 86-323, 32 p.

Arvin, D.V., 1989, Statistical summary of streamflow data for Indiana: U.S. Geological Survey Open-File Report 89-62, 964 p.

Banaszak, K.J., 1988, Indiana ground-water quality, *in* U.S. Geological Survey, National water summary 1986—Hydrologic events and ground-water Quality: U.S. Geological Survey Water-Supply Paper 2325, p. 245-250.

Bobay, K.E., 1988, Ground-water flow and quality beneath sewage-sludge lagoons, and a comparison with the ground-water quality beneath a sludge-amended landfill, Marion County, Indiana: U.S. Geological Survey Water Resources Investigations Report 88-4175, 74 p.

Bushnell, T.M., 1944, The story of Indiana soils: Lafayette, Ind., Purdue University Agricultural Experiment Station Special Circular 1, 52 p.

Carter, D.S., Lydy, M.J., and Crawford, C.G., 1995, Water-quality assessment of the White River Basin, Indiana—Analysis of selected information on pesticides, 1972-92: U.S. Geological Survey Water-Resources Investigations Report 94-4024, 60 p.

Clark, G.D., ed., 1980, The Indiana water resource—Availability, uses, and needs: Indianapolis, Indiana Department of Natural Resources, 508 p.

Corbett, D.M., 1965, Water supplied by coal surface mines, Pike County, Indiana: Bloomington, Ind., Indiana University, Water Resources Research Center Report of Investigations no. 1, 67 p.

_____1969, Acid mine-drainage problem of the Patoka River watershed, southwestern Indiana: Bloomington, Ind., Indiana University, Water Resources Research Center Report of Investigations no. 4, 173 p.

Crawford, C.G., and Wangsness, D.J., 1991, Effects of advanced wastewater treatment on the quality of White River, Indiana: Water Resources Bulletin, v. 27, no. 5, p. 769–779.

Crawford, C.G., Wangsness, D.J., and Martin, J.D., 1992, Recovery of benthic-invertebrate communities in the White River near Indianapolis, Indiana, USA, following implementation of advanced treatment of municipal wastewater: Archives of Hydrobiologie, v. 126, no. 1, p. 67–84.

Crompton, E.J. and Graves, T., 1987, Indiana water supply and use, *in* U.S. Geological Survey, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, p. 243–250.

Dawson, T.A., 1971, Map of Indiana showing structure on top of Trenton Limestone: Bloomington, Ind., Indiana Geological Survey, Miscellaneous Map 17, scale 1:500,000.

Fenelon, J.M., and Greeman, T.K., 1994, East Fork White River Basin, *in* Fenelon, J.M., Bobay, K.E., and others, Hydrogeologic atlas of aquifers in Indiana: U.S. Geological Survey Water-Resources Investigations Report 92-4142, p. 135–156.

Forbes, Jeffrey, 1984, Occurrence and consequences of naturally soft groundwater in Indiana, *in* Martin, J.D., ed., Proceedings of the Fifth Annual Water Resources Symposium, June 20–22, 1984: Indianapolis, Indiana Water Resources Association, p. 111–121.

Forstall, R.L., ed., 1996, Population of states and counties in the United States, 1790–1990: U.S. Department of Commerce, Bureau of the Census, 225 p.

Fowler, K.K., 1992, Description and effects of 1988 drought on ground-water levels, streamflow, and reservoir levels in Indiana: U.S. Geological Survey Water-Resources Investigations Report 91-4100, 91 p.

Fowler, K.K., and Wilson, J.T., 1996, Low-flow characteristics of Indiana streams: U.S. Geological Survey Water-Resources Investigations Report 96-4128, 313 p.

References Cited—Continued

Franzmeier, D.P., Steinhardt, G.C., Sinclair, H.R., Jr., and Hosteter, W.D., [1989], Taxonomic and environmental factor keys to the soils of Indiana: West Lafayette, Ind., Purdue University Cooperative Extension Service, 20 p.

Gillies, D.C., 1976, Availability of ground water near Carmel, Hamilton County, Indiana: U.S. Geological Survey Water-Resources Investigations Report 76-46, 27 p.

Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program—Occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p.

Glatfelter, D.R., 1984, Techniques for estimating magnitude and frequency of floods on streams in Indiana: U.S. Geological Survey Water-Resources Investigations Report 84-4134, 110 p.

Glatfelter, D.R., and Butch, G.K., 1994, Instrumentation, methods of flood-data collection and transmission, and evaluation of streamflow-gaging network in Indiana: U.S. Geological Survey Water-Resources Investigations Report 91-4051, 75 p.

Glatfelter, D.R., and Newman, J.E., 1991, Indiana floods and droughts, *in* U.S. Geological Survey, National water summary 1988–89—Hydrologic events and floods and droughts: U.S. Geological Survey Water-Supply Paper 2375, p. 271–278.

Gold, R.L., and Wolcott, S.W., 1980, Floods in Indiana, June–August 1979: U.S. Geological Survey Open-File Report 80-1204, 64 p.

Goolsby, D.A., Coupe, P.H., and Markovchick, D.J., 1991, Distribution of selected herbicides and nitrate in the Mississippi River and its major tributaries, April through June 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4163, 35 p.

Governor’s Soil Resources Study Commission, 1984, Indiana’s erosion and sedimentation situation: Indianapolis, Governor’s Soil Resources Study Commission, 29 p.

Gray, H.H., 1983, Map of Indiana showing thickness of unconsolidated deposits: Bloomington, Ind., Indiana Geological Survey Miscellaneous Map 38, scale 1:500,000.

_____1989, Quaternary geologic map of Indiana: Bloomington, Ind., Indiana Geological Survey Miscellaneous Map 49, scale 1:500,000.

Gray, H.H., Ault, C.H., and Keller, S.J., 1987, Bedrock geologic map of Indiana: Bloomington, Ind., Indiana Geological Survey, Miscellaneous Map 48, scale 1:500,000.

Gregory, K.J., and Walling, D.E., 1973, Drainage basin form and process: New York, John Wiley and Sons, 458 p.

Grennfelt, P. and Jultberg, H., 1986, Effects of nitrogen deposition on the acidification of terrestrial and aquatic ecosystems: Water, Air, and Soil Pollution, v. 30, p. 945–963.

Grover, R., 1988, Nature, transport and fate of airborne residues, *in* Grover, R., and Cessna, A.J., eds., Environmental Chemistry of Herbicides, v. 2: Boca Raton, Fla., CRC Press, p. 89–117.

Gutschick, R.C., 1966, Bedrock geology, *in* Lindsey, A.A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 1–20.

Hartke, E.J. and Gray, H.H., 1989, Geology for environmental planning in Monroe County, Indiana: Bloomington, Ind., Indiana Geological Survey Special Report 47, 38 p.

Hasenmueller, N.R. and Nauth, D.E., 1988, Radon: Indianapolis, Indiana Department of Natural Resources Information Circular, v. 1, no. 2, 4 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier, 522 p.

Hirsch, R.M., Alley, W.M., and Wilber, W.G., 1988, Concepts for a National Water-Quality Assessment Program: U.S. Geological Survey Circular 1021, 42 p.

Hitt, K.J., 1994, Refining 1970’s land-use data with 1990 population data to indicate new residential development: U.S. Geological Survey Water-Resources Investigations Report 94-4250, 14 p.

Hoggatt, R.E., 1975, Drainage areas of Indiana streams: U.S. Geological Survey Report, 231 p.

Hoover, M.E., and Durbin, J.M., 1994, White River Basin, *in* Fenelon, J.M., Bobay, K.E., and others, Hydrogeologic atlas of aquifers in Indiana: U.S. Geological Survey Water-Resources Investigations Report 92-4142, p. 113–133.

Indiana Agricultural Statistics Service, 1988, Indiana agricultural statistics—1987: West Lafayette, Ind., Indiana Agricultural Statistics Service Report no. A 88-1, 117 p.

References Cited—Continued

_____1991, Indiana agricultural statistics—1990: West Lafayette, Ind., Indiana Agricultural Statistics Service Report no. A 91-1, 142 p.

_____1992, Indiana agricultural statistics—1991: West Lafayette, Ind., Indiana Agricultural Statistics Service Report no. A 92-1, 144 p.

Indiana Crop and Livestock Reporting Service, 1985, Annual crop and livestock summary—1984: West Lafayette, Ind., Indiana Crop and Livestock Reporting Service Report no. A 85-1, 144 p.

Indiana Department of Environmental Management,1986–91, Indiana water quality, Monitoring site records—Rivers and streams: Indianapolis, Indiana Department of Environmental Management, Office of Water Management, published annually.

_____1988, Indiana 305 (b) report, 1986-87: Indianapolis, Indiana Department of Environmental Management, Office of Water Management, 281 p.

_____1990, Indiana 305 (b) report, 1988-89: Indianapolis, Indiana Department of Environmental Management, Office of Water Management, 297 p.

_____1993, Indiana's confined feeding control law—Proposed recommendations for compliance: Indianapolis, Indiana Department of Environmental Management, Office of Water Management, 14 p.

_____1994, Indiana 305 (b) report, 1992-93: Indianapolis, Indiana Department of Environmental Management, Office of Water Management, 486 p.

Indiana Department of Natural Resources, 1990, Indiana's water use 1990: Indianapolis, Indiana Department of Natural Resources, Division of Water, 10 p.

Indiana Farm Bureau Inc., 1994, Nitrate and pesticides in private wells of Indiana—Part 1 State Summary: Indianapolis, Indiana Farm Bureau Inc., 38 p.

Indiana State Board of Health,1981–85, Water quality monitoring—Rivers and streams: Indianapolis, Indiana State Board of Health, Division of Water Pollution Control, published annually.

Jacques, D.V. and Crawford, C.G., 1991, National Water-Quality Assessment Program—White River Basin: U.S. Geological Survey Open-File Report 91-169, 2 p.

Johnson, D.W., VanMiegroet, H., Lindberg, S.E., Todd, D.E., and Harrison, R. B., 1991, Nutrient cycling in red spruce forests of the Great Smoky Mountains: Canadian Journal of Forest Research, v. 21, p. 769–878.

Langbein, W.B., and Iseri, K.T., 1960, General surface-water techniques; general introduction and hydrologic definitions, manual of hydrology; pt. 1: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

Lapham, W.W., 1981, Ground-water resources of the White River Basin, Madison County, Indiana: U.S. Geological Survey Water-Resources Investigations Report 81-35, 112 p.

Lapham, W.W., and Arihood, L.D., 1984, Ground-water resources of the White River Basin, Randolph County, Indiana: U.S. Geological Survey, Water-Resources Investigations Report 83-4267, 86 p.

Leahy, P.P., Rosenshein, J.S., and Knopman, D.S., 1990, Implementation plan for the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 90-174, 10 p.

Leininger, R.K., 1981, Inorganic geochemistry, *in* Hasenmueller, N.R., and Woodard, G.S., eds., Studies of the New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana: Bloomington, Ind., Indiana Geological Survey, prepared for United States Department of Energy, Morgantown Energy Technology Center, Morgantown, W.Va., contract No. DE-AC 21-76MC 05204, p. 53-61.

Majewski, M.S., and Capel, P.D., 1995, Pesticides in the atmosphere—Distribution, trends, and governing factors: Chelsea, Mich., Ann Arbor Press, 214 p.

Malott, C.A., 1922, The physiography of Indiana, *in* Handbook of Indiana geology, Part 2: Indiana Department of Conservation Publication 21, p. 59–256.

Martin, J.D., 1995, Effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek, Indianapolis, Indiana: U.S. Geological Survey Water-Resources Investigations Report 94-4066, 92 p.

Martin, J.D., and Craig, R.A., 1990, Effects of storm runoff on water quality in the White River and Fall Creek, Indianapolis, Indiana, June through October 1986 and 1987: U.S. Geological Survey Water-Resources Investigations Report 89-4185, 114 p.

Martin, J.D. and Crawford, C.G., 1987, Statistical analysis of surface-water-quality data in and near the coal-mining region of southwestern Indiana, 1957–80: U.S. Geological Survey Water-Supply Paper 2291, 92 p.

References Cited—Continued

Martin, J.D., Crawford, C.G., Frey, J.W., and Hodgkins, G.A., 1996, Water-quality assessment of the White River Basin, Indiana—Analysis of selected information on nutrients, 1980–92: U.S. Geological Survey Water-Resources Investigations Report 96-4192, 91 p.

Martin, J.D., Duwelius, R.F., and Crawford, C.G., 1990, Effects of surface coal mining and reclamation on the geohydrology of six small watersheds in west-central Indiana: U.S. Geological Survey Water-Supply Paper 2368, 71 p.

Meyer, William, Reussow, J.P., and Gillies, D.C., 1975, Availability of ground water in Marion County, Indiana: U.S. Geological Survey Open-File Report 75-312, 87 p.

MidWest Plan Service, 1992, Conservation tillage systems and management—Crop residue management with no-till, ridge-till, mulch-till: Ames, Iowa, MidWest Plan Service MWPS-45, 140 p.

National Weather Service, 1997, Historical climate summaries for Indiana: Internet Universal Resource Locator http://www.nws.noaa.gov.

Peters, J.G., 1981, Effects of surface mining on water quality in a small watershed, Sullivan County, Indiana: U.S. Geological Survey Open-File Report 81-543, 59 p.

Peters, N.E., and Bonelli, J.E., 1982, Chemical composition of bulk precipitation in the north-central and northeastern United States, December 1980 through February 1981: U.S. Geological Survey Circular 874, 63 p.

Renn, D.E., 1989, Streamflow and stream quality in the coal-mining region, Patoka River Basin, southwestern Indiana, 1983-85: U.S. Geological Survey Water-Resources Investigations Report 88-4150, 68 p.

Ripley, E.M., Shaffer, N.R., and Gilstrap, M.S., 1990, Distribution and geochemical characteristics of metal enrichment in the New Albany Shale (Devonian-Mississippian), Indiana: Economic Geology, v. 85, p. 1790–1807.

Ruddy, B.C., and Hitt, K.J., 1990, Summary of selected characteristics of large reservoirs in the United States and Puerto Rico, 1988: U.S. Geological Survey Open-File Report 90-163, 295 p.

Ruhe, R.V., and Olson, C.G., 1980, The origin of terra rossa in the karst of southern Indiana, *reprinted from* Field trips 1980, 14th annual meeting, North-Central Section, Geological Society of America: Bloomington, Ind., Indiana University, Water Resources Research Center, p. 84–122.

Rupp, R.A., 1991, Structure and isopach maps of the Paleozoic rocks of Indiana: Bloomington, Ind., Indiana Geological Survey Special Report 48, 106 p.

Schneider, A.F., 1966, Physiography, *in* Lindsey, A.A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 45–56.

Scribner, E.A., Goolsby, E.M., Thurman, M.T., Meyer, M.T., and Battaglin, W.A., 1996, Concentrations of selected herbicides, herbicide metabolites, and nutrients in outflow from selected midwestern reservoirs, April 1992 through September 1993: U.S. Geological Survey Open-File Report 96-393, 128 p.

Shampine, W.J., 1975, A river-quality assessment of the upper White River, Indiana: U.S. Geological Survey Water-Resources Investigations Report 75-10, 68 p.

_____1977, Indiana stream-temperature characteristics: U.S. Geological Survey Water-Resources Investigations Report 77-6, 55 p.

Shaver, R.H., Ault, C.H., Burger, A.M., Carr, D.D., Droste, J.B., Eggert, D.L., Gray, H.H., Harper, D., Hasenmueller, N.R., Hasenmueller, W.A., Horowitz, A.S., Hutchison, H.C., Keith, B.D., Keller, S.J., Patton, J.B., Rexroad, C.B., and Wier, C.E., 1986, Compendium of Paleozoic rock-unit stratigraphy in Indiana—A revision: Bloomington, Ind., Indiana Geological Survey Bulletin 59, 203 p.

Soller, D.R., 1993, Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains—Northeastern states, the Great Lakes, and parts of southern Ontario and the Atlantic offshore area: U.S. Geological Survey Miscellaneous Investigations Series Map I-1970-A, scale 1:1,000,000.

Squillace, P.J., Caldwell, J.P., Schulmeyer, P.M., and Harvey, C.A., 1996, Movement of agricultural chemicals between surface water and ground water, Lower Cedar River Basin, Iowa: U.S. Geological Survey Water-Supply Paper 2448, 59 p.

Stewart, J.A., and Nell, G.E., 1991, Water resources data—Indiana, water year 1990: U.S. Geological Survey Water Data Report IN-90-1, 340 p.

References Cited—Continued

Tanner, G.F., 1986, The Mt. Carmel Fault and associated features in south-central Indiana: Bloomington, Ind., Indiana University, M.S. Thesis, 66 p.

Taylor, M.Z., 1989, Water quality falls on farmer's shoulders: Farm Journal, April 1989, p. 19–21.

Taylor, A.W., and Glotfelty, D.E., 1988, Evaporation from soils and crops, *in* Grover, R., ed., Environmental chemistry of herbicides, v. 1: Boca Raton, Fla., CRC Press, p. 89–129.

Ulrich, H.P., 1966, Soils, *in* Lindsey, A.A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 57–90.

U.S. Department of Commerce, 1992, 1990 census of population, General population characteristics, Indiana: U.S. Department of Commerce, Bureau of the Census, variable pagination.

_____1994, 1992 census of agriculture, v. 1 Geographic area series, part 14 Indiana—State and county data: U.S. Department of Commerce, Bureau of the Census, variable pagination.

U.S. Environmental Protection Agency, 1988, Protecting ground water—Pesticides and agricultural practices: U.S. Environmental Protection Agency Report EPA 440/6-88-001, 53 p.

_____1996, Drinking water regulations and health advisories: Washington D.C., U.S. Environmental Protection Agency Office of Water, 20 p.

U.S. Geological Survey, 1990, Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps, Data users guide 4: Reston, Va., U.S. Geological Survey, 25 p.

Wangsness, D.J., 1982, Reconnaissance of stream biota and physical and chemical water quality in areas of selected land use in the coal mining region, southwestern Indiana, 1979–80: U.S. Geological Survey Open-File Report 82-566, 43 p.

Wayne, W.J., 1966, Ice and land—A review of the Tertiary and Pleistocene history of Indiana, *in* Lindsey, A.A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 21–39.

Wells, E.R. and Krothe, N.C., 1989, Seasonal fluctuation in δ15N of groundwater nitrate in a mantled karst aquifer due to macropore transport of fertilizer-derived nitrate: Journal of Hydrology, v. 112, p. 191–201.

Wendland, W.M., Kunkel, K.E., Conner, Glen, Decker, W.L., Hillaker, Harry, Naber-Knox, Pam, Nurnberger, F.V., Rogers, Jeffrey, Scheeringa, Kenneth, Zandlo, James, 1992, Mean 1961–1990 temperature and precipitation over the upper midwest: Champaign, Ill., Midwestern Climate Center Research Report 92-01, 27 p.

Whitaker, J.O., Schlueter, R.A., and Proffitt, M.A., 1973, Effects of heated discharge on fish and invertebrates of White River at Petersburg, Indiana: Bloomington, Ind., Indiana University, Water Resources Research Center Report of Investigations no. 6, 123 p.

Wilber, W.G., Renn, D.E., and Crawford, C.G., 1985, Effects of land use and surficial geology on flow and water quality of streams in the coal mining region of southwestern Indiana, October 1979 through September 1980: U.S. Geological Survey Water-Resources Investigations Report, 85-4234, 49 p.