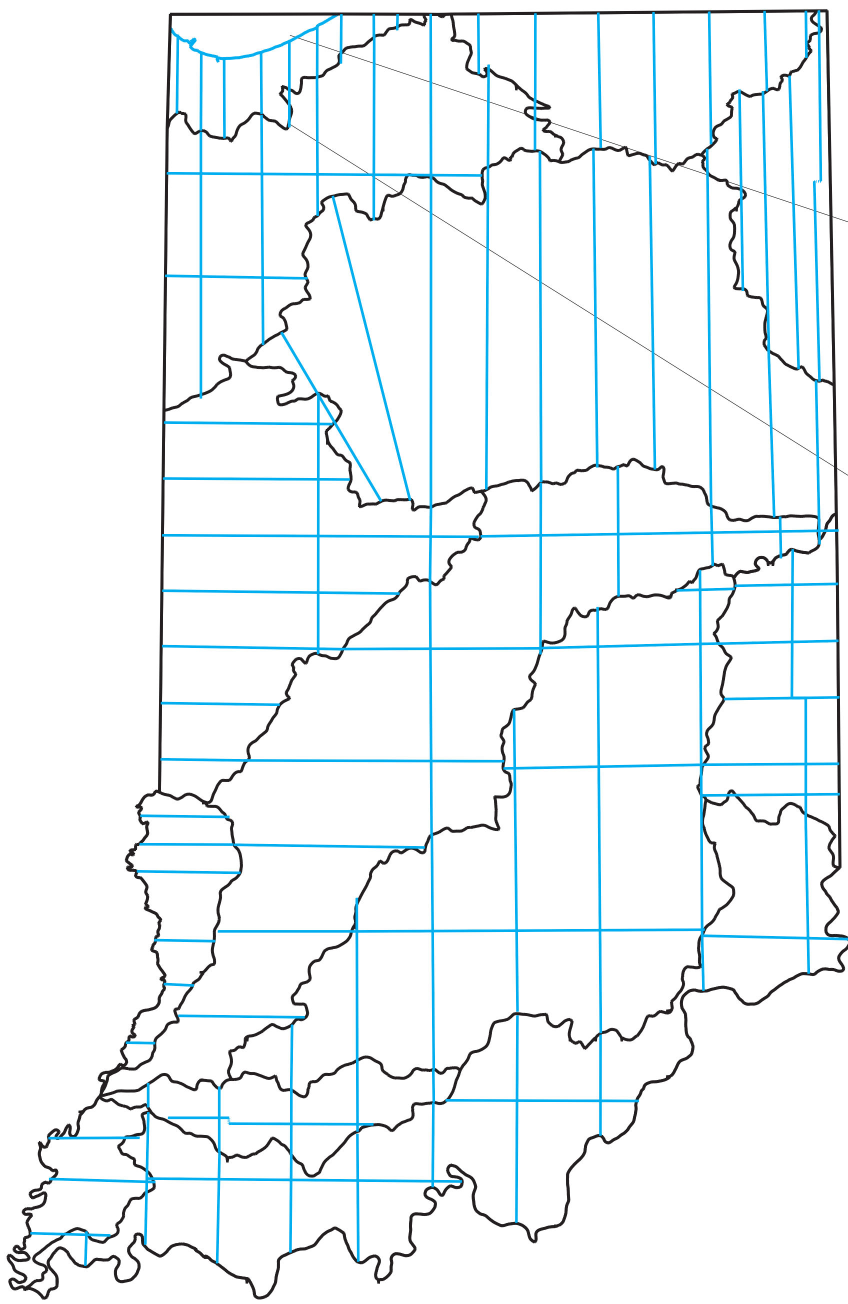
HYDROGEOLOGIC ATLAS OF AQUIFERS IN INDIANA



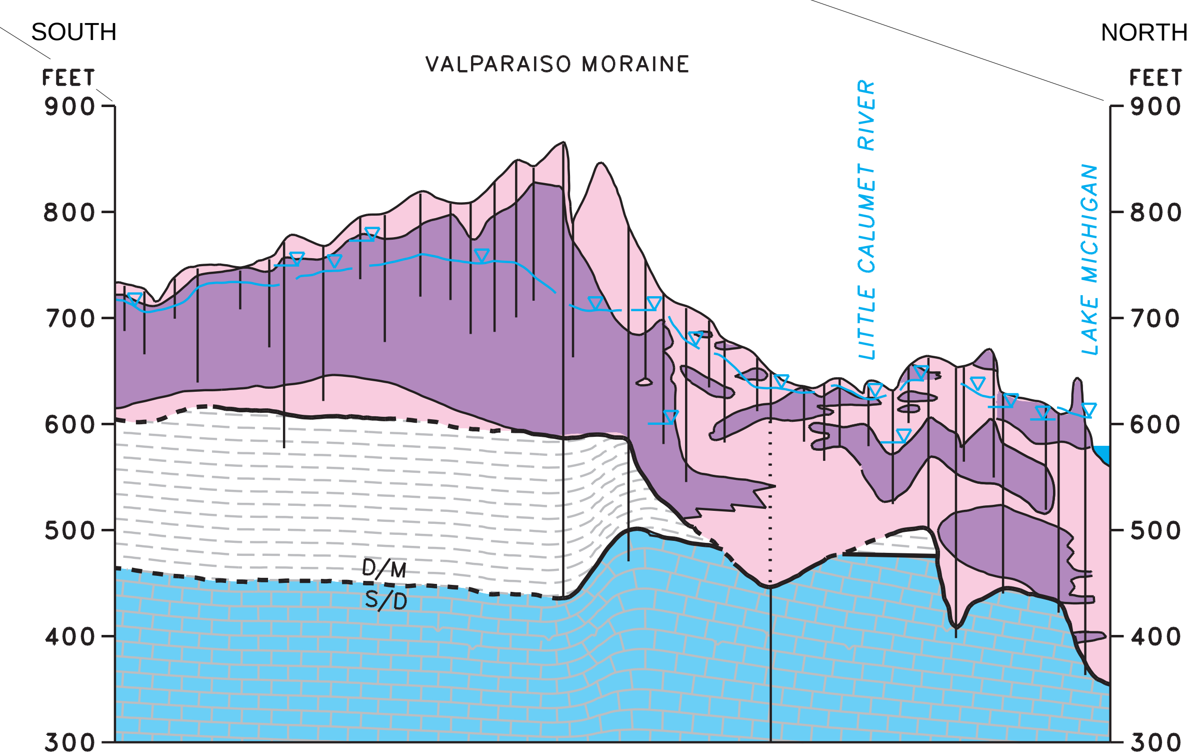
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4142

Prepared in cooperation with the

INDIANA DEPARTMENT of NATURAL RESOURCES, DIVISION of WATER

INDIANA DEPARTMENT of ENVIRONMENTAL MANAGEMENT



COVER: A hydrogeologic section depicts sand and gravel aquifers (colored purple) and a carbonate bedrock aquifer (colored blue) adjacent to Lake Michigan in northern Indiana. The hydrogeologic section is one of 104 sections that were drawn for this atlas. Section lines (shown as blue lines on the State map) were drawn within each of Indiana's 12 water-management basins. The sections and maps included in this atlas provide a three-dimensional picture of the hydrogeology in Indiana.

Hydrogeologic Atlas of Aquifers in Indiana

By JOSEPH M. FENELON, KEITH E. BOBAY, and OTHERS

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
inch per year (in/yr)	2.54	centimeter per year
foot per day (ft/d)	0.3048	meter per day
mile per hour (mi/h)	1.609	kilometer per hour
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	3.785	liter per minute
gallon per day (gal/d)	3.785	liter per day
gallon per day per foot (gal/d/ft)	12.42	liter per day per meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per year (Mgal/yr)	3,785	cubic meter per year
billion gallons per day (Bgal/d)	43.81	cubic meter per second
billion gallons per year (Bgal/yr)	3,785,000	cubic meter per year

Temperature, in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°C = 5/9 (°F - 32)

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

Hydrogeologic Atlas of Aquifers in Indiana

By Joseph M. Fenelon, Keith E. Bobay, *and* others

Abstract

Aquifers in 12 river basins (water-management basins) in Indiana are identified in a series of 104 hydrogeologic sections and 12 maps. Details of water-bearing units, including a generalized potentiometric surface, are derived from logs of more than 4,200 wells along 3,500 miles of section lines. Logs were obtained from water-well records, oil- and gas-well completion reports, coal-drilling records, and observation-well records. Well logs generally are plotted at 0.5- to 2-mile intervals. Hydrogeologic sections are spaced 6 to 20 miles apart. The horizontal scale of the sections is 1:250,000; vertical scale is greatly exaggerated. The scale of the maps depicting aquifers is 1:500,000. Aquifer maps are based on information from hydrogeologic sections and from previous studies. Where a type of aquifer was less than 15 square miles in areal extent, it was not mapped because of scale limitations. Types of aquifers depicted in the illustrations include unconsolidated and bedrock aquifers.

Unconsolidated aquifers are the most widely used aquifers in Indiana. Types of unconsolidated aquifers include surficial, buried, and discontinuous layers of sand and gravel. Most of the surficial sand and gravel is located in large outwash plains in northern Indiana and along the major rivers in the southern two-thirds of the State. Buried sand and gravel aquifers underlie much of the northern two-thirds of Indiana, where they are typically interbedded with till deposits and can be 10 to 400 ft deep. Discontinuous sand and gravel deposits are present as isolated lenses, primarily in glaciated areas.

Wells completed in the bedrock aquifers generally have lower yields than wells in most of the sand and gravel aquifers, but the bedrock aquifers are areally widespread and a major source of water for many domestic users and some large users of ground water. Carbonate rocks (limestone and dolostone); sandstones; complexly interbedded sandstone, siltstone, shale, limestone, and coal; and an upper weathered zone in low permeability rocks comprise the types of bedrock aquifers. Aquifers in carbonate rocks of Silurian, Devonian, and Mississippian age underlie about one-half of Indiana and are the most important of the bedrock aquifers in terms of yield and areal extent. The other principal type of bedrock aquifer is sandstone, which underlies large areas in the southwestern one-fifth of Indiana. The mapped sandstones are located within deposits of complexly interbedded sandstone, siltstone, shale, limestone, and coal of Mississippian and Pennsylvanian age. These complex deposits yield small quantities of water of variable quality, but they are important if they are the only available aquifer in a particular area. The remaining bedrock aquifer, which is used when it is the sole source of water for an area, is an upper weathered zone developed primarily in siltstone and shale of Mississippian and Devonian age and, to a lesser extent, in some of the shale and limestone of Ordovician age. No aquifer is mapped in the southeastern corner of Indiana, which is underlain by shale and limestone of Ordovician age.

INTRODUCTION

Ground water is the source of drinking water for nearly 60 percent of the residents of Indiana. Approximately 425 community water systems, 3,000 noncommunity water systems, 500 mobile-home parks, and 500,000 private homes are supplied by wells (Indiana Department of Environmental Management, 1990, p. 223; Indiana Department of Natural Resources, 1989, written commun.). In addition to drinking-water supplies, ground water is withdrawn for energy production, irrigation, and industrial, commercial, and agricultural uses. In 1991, about 204 Bgal (billion gallons) of ground water, or a daily average of 559 Mgal (million gallons), was withdrawn. The combined capability of registered ground-water withdrawal facilities in 1991 was 3,540 Mgal/d (million gallons per day) (Indiana Department of Natural Resources, 1993, written commun.).

Ground water is an important and abundant natural resource in Indiana; however, detailed maps and descriptions of the major **aquifer**s[1] that pertain to the entire State have not been available. Published reports are currently limited to county-wide studies, a few basin studies, detailed site-specific investigations, and large-scale maps and assessments of the aquifers in the State.

The Indiana Ground-Water Protection and Management Strategy lists the delineation and mapping of aquifers as a primary need (Indiana Department of Environmental Management, 1987). The Strategy states that nearly all aspects of ground-water regulation, research, and utilization in the publ and private sectors can benefit from maps and descri tions of the aquifers in the State. Therefore, one of th short-term goals of the strategy was the creation of a ground-water atlas of Indiana that would identify generic aquifers on a large scale (Indiana Departmen of Environmental Management, 1987, p. 5). The terr "generic" was used to imply that aquifers do not nece sarily conform to geologic age, group, or formation.

In response to the need for such an atlas, the U.S. Geological Survey (USGS), in cooperation witl the Indiana Department of Natural Resources (IDNF and the Indiana Department of Environmental Management (IDEM), prepared a series of hydrogeo logic sections and maps that identify aquifers in 12 water-management basins of Indiana (fig. 1).

Purpose and Scope

This atlas describes and delineates aquifers in the Lake Michigan, St. Joseph River, Kankakee Rive Maumee River, Upper Wabash River, Middle Wabas River, Lower Wabash River, White River, East Fork White River, Whitewater River, Patoka River, and Ohio River water-management basins in Indiana. Tl hydrogeologic sections were constructed at a horizontal scale of 1:250,000, whereas the maps were drawn at a scale of 1:500,000. The vertical scale of tl sections is greatly exaggerated. Also included are maps that show the location of the hydrogeologic section lines, the thickness of unconsolidated deposi (from Gray, 1983), and the bedrock geology (from Gray and others, 1987) for each basin at a scale of 1:500,000.

[1]Terms in bold are defined in the "Definitions of Selected Terms" at the back of this report

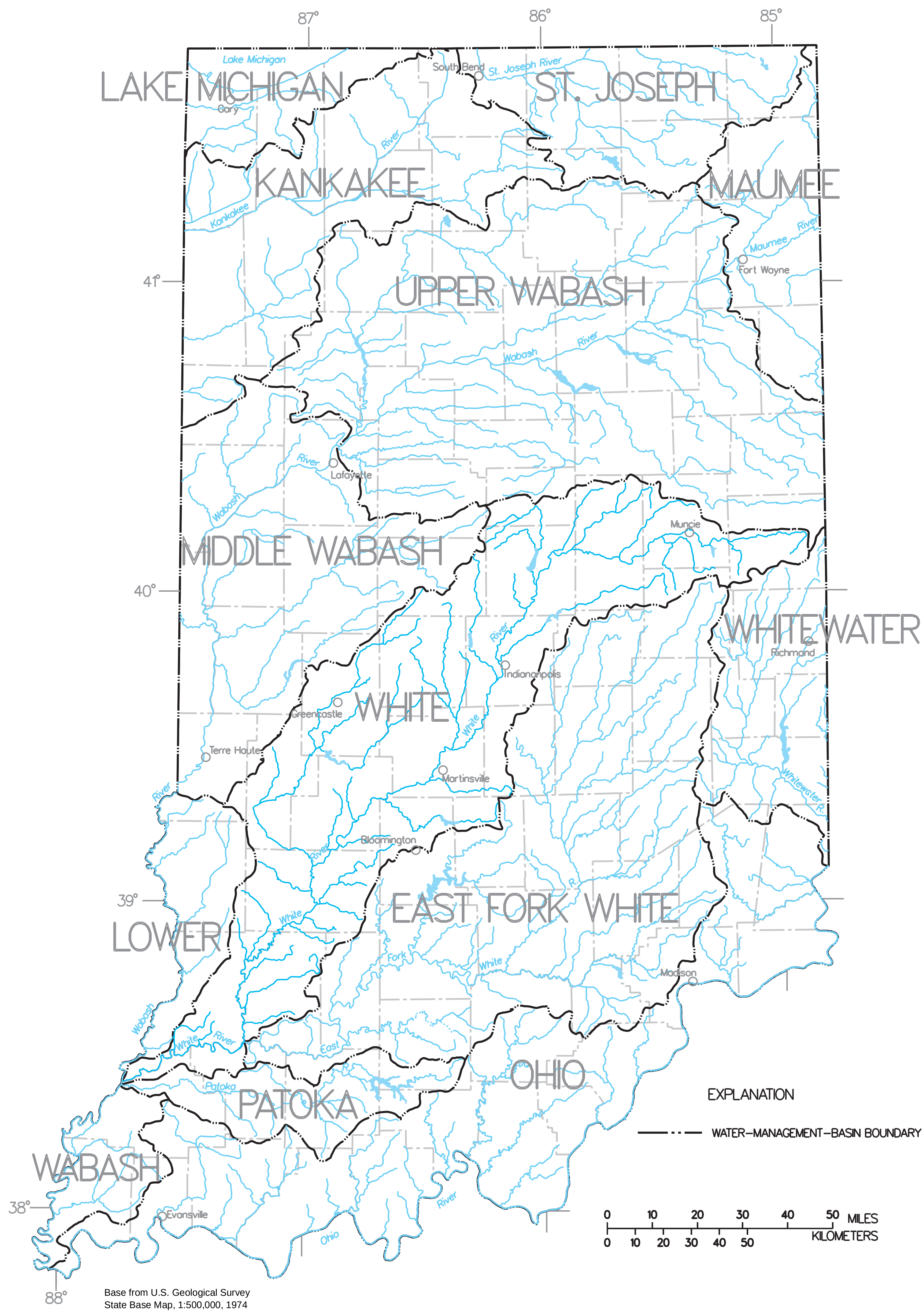


Figure 1. The 12 water-management basins of Indiana.

As defined in this atlas, an aquifer is a geologic formation, group of formations, or part of a formation that contains sufficient **saturated** permeable material to **yield** quantities of potable water adequate for domestic purposes (Lohman and others, 1972, p. 2). Location and delineation of aquifers throughout Indiana is the primary goal of this atlas. Types of aquifers are distinguished by lithology, thickness, depth, and continuity.

The hydrogeologic sections and areal maps can be used to understand and evaluate aquifer systems on a regional scale. This regional evaluation can then be used as a base for site-specific studies. **The sections and maps, however, do not replace site-specific hydrogeologic data**. The well logs used to plot sections were obtained from a 2 mile-wide path that bounded the traces of the sections. Thus, the data shown at a given location might not represent site-specific hydrogeology.

A glossary of hydrogeologic terms used herein is at the end of this report. Bedrock geologic names in this report follow the nomenclature of Shaver and others (1986).

Previous Studies

The ground-water resources of Indiana have been studied by many authors since the early 1900's. Harrell (1935) described the general physiographic features, hydrology, geology, and ground-water resources of each county in the State. Bechert and Heckard (1966) discussed the availability, flow, quality, and uses of ground water in Indiana. Bloyd (1974) summarized the ground-water resources of a region that includes greater than 80 percent of Indiana and provided regional estimates of hydraulic conductivity, specific yield, storage, **recharge**, and current and projected withdrawals. Clark (1980) characterized the availability, use, regulation, and future needs of ground water in Indiana. Geosciences Research Associates, Inc. (1982) summarized the "potential yield capability" and the water quality of the major bedrock hydrostratigraphic units in the State. The USGS (1988, p. 245-250) described the water quality of the principal aquifers of Indiana. The USGS is studying the flow and water quality in the regional carbonate bedrock and glacial aquifer system in Indiana (Bugliosi, 1990; Casey, 1992; Schnoebelen, 1992).

The location and extent of ground-water resources or aquifers in Indiana have been mapped by a few authors. Bechert and Heckard (1966, p. 109) mapped the availability of ground water on the basis of yields from "properly sized and developed" wells in eight ground-water provinces of Indiana. Gray (1973) mapped the general location and described "the principal resource units in ground-water production" for Indiana. Clark (1980, p. 33) updated the ground-water availability map of Bechert and Heckard using seven potential yield categories that were devised from a "range of probable maximum yields which can be expected from a properly constructed large-diameter well penetrating the full thickness of the aquifer." Geosciences Research Associates, Inc. (1982) mapped the structure and contour of the major bedrock hydrostratigraphic units in Indiana on the basis of geologic age and formation. The USGS (1985, p. 207) mapped the principal aquifers of Indiana as glaciofluvial, glacial **outwash**, sand and gravel lenses in **till** of Wisconsinan age, carbonate rocks of Mississippian age, and carbonate rocks of Silurian and Devonian age (1:5,000,000 scale); however, a large area of southwestern and south-central Indiana was mapped as being without a principal aquifer.

The Indiana Department of Natural Resources is preparing water-resource availability studies for the 12 water-management basins in Indiana. Published reports are currently (1990) available for the St. Joseph River, Whitewater River, and Kankakee River basins. These reports include maps that show the extent of aquifers, composite **potentiometric surface** maps for unconsolidated and **bedrock aquifer**s, a discussion of hydrogeologic characteristics, and information on ground-water quality and use. This atlas differs from these studies in the method used to delineate and name aquifers (generic aquifer types as compared to formal aquifer names for different geologic settings) and in the emphasis on the vertical distribution of the aquifers as shown in many detailed hydrogeologic sections.

Acknowledgments

The staff of the Indiana Department of Environmental Management and the Indiana Department of Natural Resources were helpful in all aspects of the atlas project including planning, format, and review of the Atlas. Special thanks are extended to the following people: Robert Hilton[2], Martin Risch[2], James Nowacki[2], Mike Yarling, Gregg Lemasters, and James Harris from the Indiana Department of Environmental Management; John Simpson, Thomas Bruns[2], William Steen, John Clark[2], John Barnhart[2], Michael Saul[2], and Sally Letsinger[2] from the Indiana Department of Natural Resources, Division of Water; and Norman Hester, Ned Bleuer, Anthony Fleming, Eric Kwale, John Rupp, and Henry Gray[2] from the Indiana Department of Natural Resources, Geological Survey.

The authors also wish to thank David Sperry and David Zetzl for providing the technical support to produce or help produce virtually every illustration in this atlas.

PHYSICAL SETTING OF INDIANA

The physical setting of Indiana, which includes the physiography, climate, and geology, controls the distribution, availability, and flow of ground water.

Physiography

Indiana has been divided into 13 major physiographic units (fig. 2) on the basis of similarities in topography and geology (Schneider, 1966, p. 41). The 13 units occupy 3 broad physiographic zones that trend in an east-west direction across the State. The zones are the Northern Lake and Moraine Region, the Central Drift Plain, and a southern zone dominated by bedrock landforms.

The Northern Lake and Moraine Region is subdivided into five lake (lacustrine) or morainal units: the Calumet Lacustrine Plain, the Valparaiso Morainal Area, the Kankakee Outwash and Lacustrine Plain, the Steuben Morainal Lake Area, and the Maumee Lacustrine Plain (fig. 2). A variety of glacial and postglacial landforms are in this 8,500 mi^2 area. Glacial depositional features include end moraines, till plains, **outwash plain**s and **valley train**s, kames, and lake plains. These landforms have a diverse mix of sediments with highly variable hydrogeologic properties and numerous lithologic discontinuities. Related postglacial landforms include the many lakes of northeastern Indiana, the sand dunes along Lake Michigan, and peat bogs (Schneider, 1966, p. 40-42). Principal moraines and the extent of glaciation in Indiana are shown in figure 3.

The Tipton Till Plain, or Central Drift Plain, is a nearly flat glacial till plain covering central Indiana (fig. 2). This area of about 12,000 mi^2 is underlain by thick till and has been slightly eroded by postglacial streams. Most of the boundary between the Till Plain and the southern physiographic units coincides with the maximum extent of Wisconsinan glaciation, except in southeastern Indiana where the physiographic boundary is north of the Wisconsinan glacial boundary. The southeastern Indiana boundary was arbitrarily drawn along the edge of a broad transitional zone of thin glacial **drift** that does not obscure the bedrock physiography (Schneider, 1966, p. 40, 49).

Seven physiographic units composed of different bedrock types comprise 15,500 mi^2 in the southern one-third of the State (fig. 2). The bedrock is primarily sandstone, shale, siltstone, limestone, and dolomite. The physiographic units generally trend north-northwest following the strike of the bedrock. From east to west, the units are called the Dearborn Upland, the Muscatatuck Regional Slope, the Scottsburg Lowland, the Norman Upland, the Mitchell Plain, the Crawford Upland, and the Wabash Lowland (Schneider, 1966, p. 42-49). These southern units represent a sharply divided, alternating series of uplands and lowlands or plains. Large parts of the Wabash Lowland, Crawford Upland, Mitchell Plain, and Norman Upland were not glaciated during the Pleistocene Epoch. All seven bedrock physiographic units extend further north than shown in figure 2 but were buried by glacial deposits (Schneider, 1966, p. 54). Buried erosional surfaces of these units are evident in the hydrogeologic sections presented later in this report.

[2]Person is no longer employed with the agency.

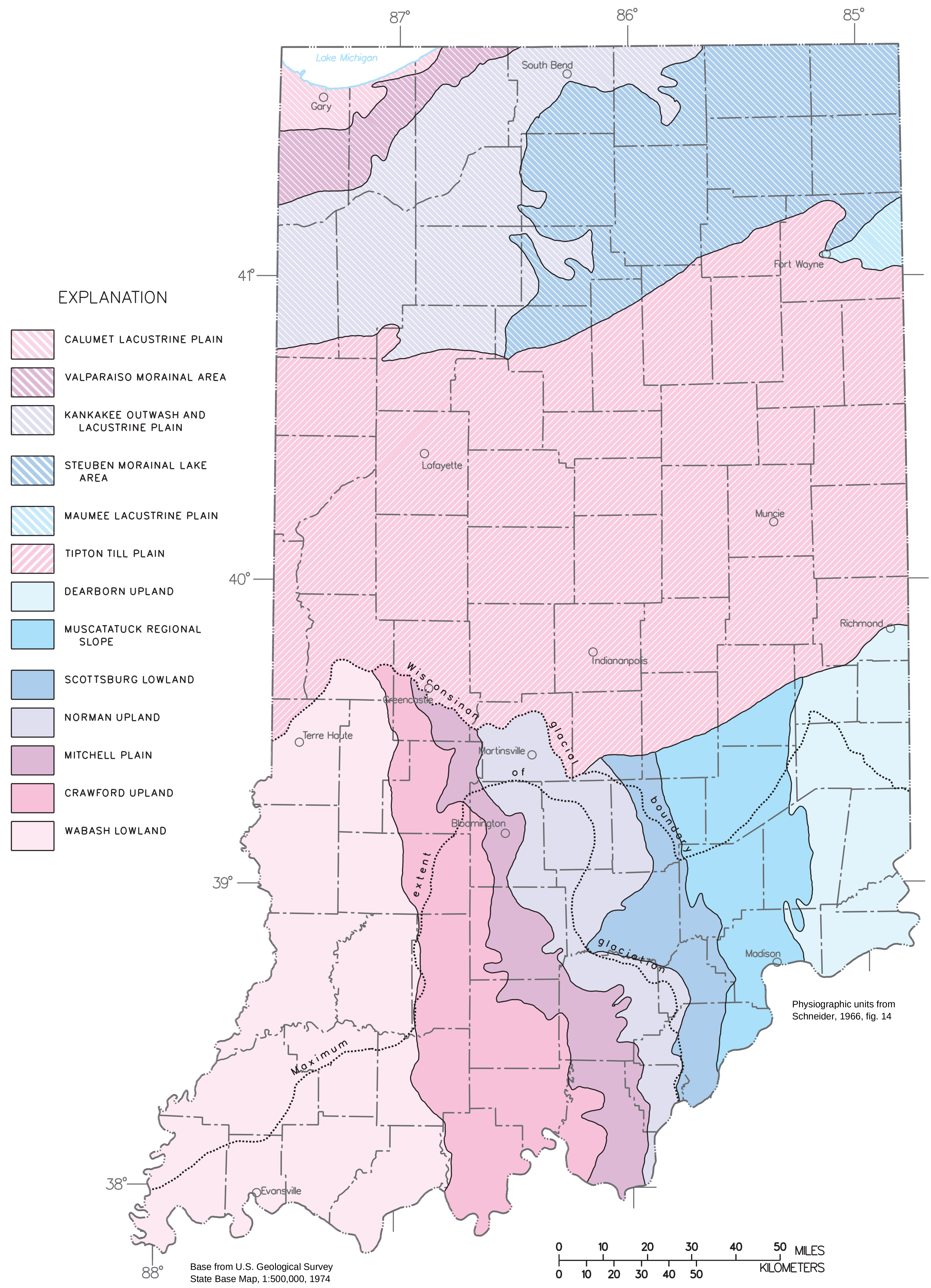


Figure 2. Physiographic units of Indiana.

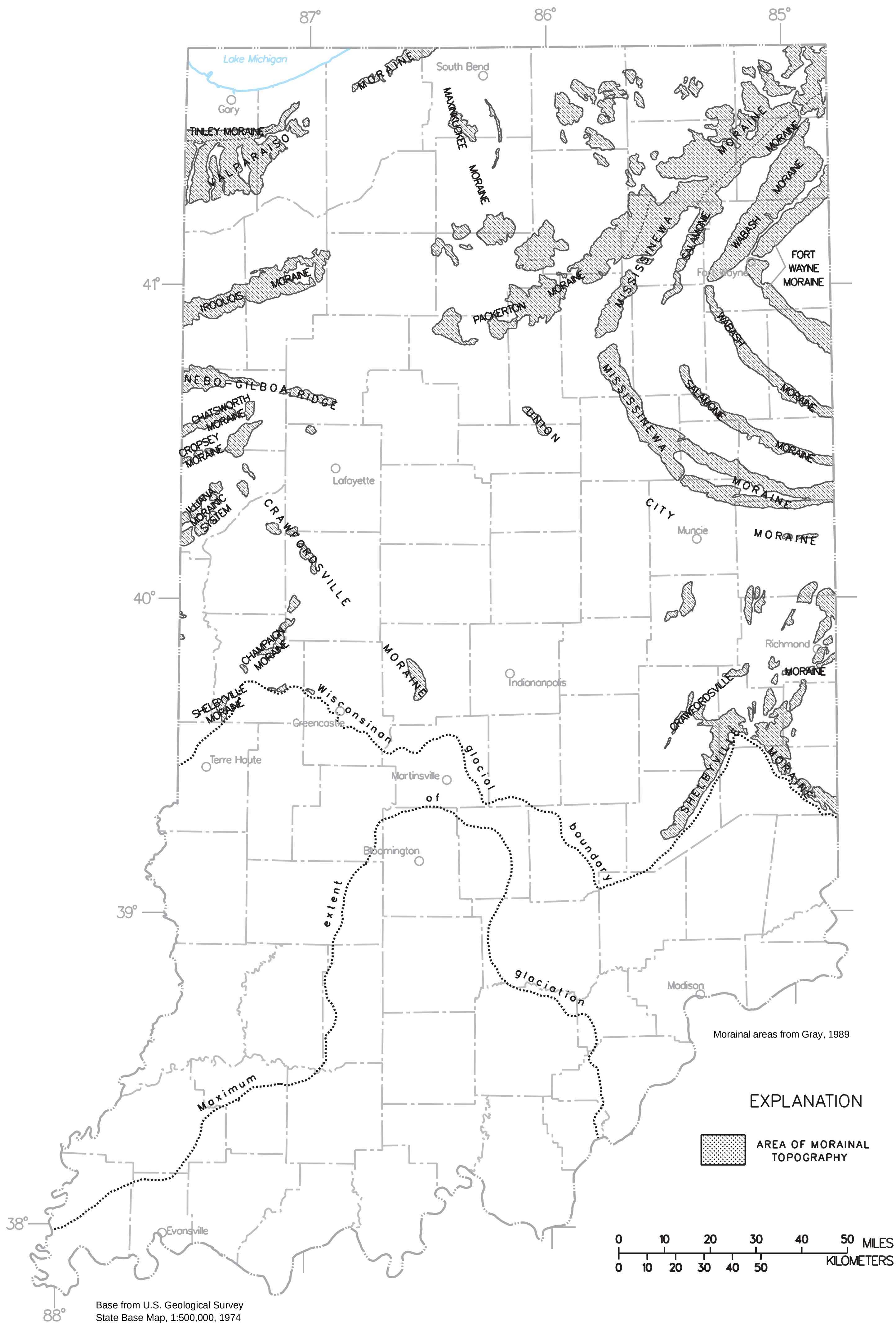


Figure 3. Principal moraines and extent of glaciation in Indiana.

The distribution of bedrock types and erosional characteristics determines the topography of the bedrock, which affects the thickness of unconsolidated deposits. Thick glacial sediments are present beneath moraines and in buried bedrock valleys. In the southern one-third of the State, unconsolidated deposits are thin and discontinuous, especially beyond the maximum extent of glaciation. The distribution, thickness, and hydraulic conductivity of these unconsolidated deposits control the near-surface occurrence and flow of ground water (Krothe and Kempton, 1988, p. 129).

Climate

Climate in Indiana is temperate with warm summers, cold winters, and no distinguishable wet or dry seasons. Precipitation is well-distributed throughout the year, although precipitation is somewhat greater during March through July because of increased frequency and intensity of showers and thunderstorms. The average length of the growing season, or freeze-free period, ranges from 173 days in northeastern Indiana to 199 days in southwestern Indiana (National Oceanic and Atmospheric Administration, 1988).

The interaction of tropical and polar air masses over Indiana normally results in abundant precipitation; however, temperature and precipitation vary considerably from year to year depending on the frequency of storms and frontal passages (National Oceanic and Atmospheric Administration, 1988). Average annual precipitation in Indiana ranges from 44 inches in the south to 36 inches in the northeast; average annual snowfall ranges from 10 inches in the south to 40 inches in northern Indiana. Average annual temperature ranges from 50° F in the north to 56° F in the southwest. Monthly evapotranspiration can be as much as 8 inches in southern Indiana in July (National Oceanic and Atmospheric Administration, 1988; Schaal, 1966; Visher, 1944, p. 450-461).

Geology

The regional structural features of Indiana bedrock include the Illinois Basin, the Michigan Basin, and the Cincinnati Arch (fig. 4). The two basins form the flanks of a saddle-like structure composed of the Cincinnati Arch and its branches, the Kankakee Arch and the Findlay Arch (in Ohio). The dip of the rocks into the two basins is about 10 to 30 ft/mi, although the dip can be less than 5 ft/mi at the top of the arches. Rocks of Ordovician, Silurian, Devonian, and Mississippian age crop out or are present as subcrops in both of the depositional basins, whereas rocks of Pennsylvanian age are present in Indiana only in the Illinois Basin. The older rocks are typically present on the crest of the arch; the progressively younger rocks are present in each of the basins. Individual beds in many formations are thin at the crest, but they thicken along the flanks and into the basins (Gutschick, 1966, p. 7-12). A geologic chart including age, group or stage, selected formations, and hydrogeologically important members or marker beds in Indiana is shown in figure 5.

Rocks of the Precambrian crystalline basement complex are found at estimated depths of 3,000 to 6,000 ft in the northeastern two-thirds of Indiana and 6,000 to 14,000 ft in the southwestern one-third (Rupp, 1991). Overlying the Precambrian bedrock is a Cambrian section of sandstone with lesser amounts of siltstone, and shale that is approximately 1,000 ft thick in eastern Indiana to 3,000 ft thick in northwestern Indiana. The Cambrian rock composes about one-third of the Paleozoic section in Indiana (Shaver and others, 1986, p. 119). Overlying the Cambrian rock is 20 to 4,500 ft of Lower Ordovician dolomite (Shaver and others, 1986, p. 70). The dolomite thickens toward the southwestern part of the State. The Lower Ordovician dolomite is unconformably overlain by 50 to more than 450 ft of dolomite, limestone, and sandstone of Middle Ordovician age (Shaver and others, 1986, p. 4).

Late Ordovician shale and limestone is exposed at the bedrock surface over large areas in southeastern Indiana (fig. 6). The shale and limestone range in thickness from approximately 500 ft in northwestern Indiana to 1,500 ft in southeastern Indiana (Shaver and others, 1986). The shale and limestone are unconformably overlain by Silurian limestone and dolomite. The Silurian rocks are present as subcrops or outcrops in east-central to northwestern Indiana (fig. 6), primarily along the axis of the Cincinnati Arch and the Kankakee Arch (fig. 4). The Silurian rocks generally range from 200 to 600 ft in thickness, except in the southeastern part of the State, where they were completely eroded. Large areas of carbonate platform and reef banks are present in these carbonate rocks along the flanks of the arches.

Figure 4. Regional structural features in Indiana.

GEOLOGIC AGE	Series or Group	Selected Formations	Selected Members
QUATERNARY	Holocene		
	Pleistocene: Wisconsinan	Wedron Formation; Lagro Formation Trafalgar Formation	
	Pleistocene: Pre–Wisconsinan	Jessup Formation	
PENNSYLVANIAN	McLeansboro Group	Mattoon Formation	Merom Sandstone Member
		Bond Formation	St. Wendel Sandstone Member
		Patoka Formation	Inglefield Sandstone Member
		Shelburn Formation	West Franklin Limestone Member Busseron Sandstone Member
	Carbondale Group	Dugger Formation	Danville Coal Member (Coal VII) Anvil Rock Sandstone Member Hymera Coal Member (Coal VI)
		Petersburg Formation	Springfield Coal Member (Coal V)
		Linton Formation	Survant Coal Member (Coal IV) Coxville Sandstone Member
	Raccoon Creek Group	Staunton Formation Brazil Formation Mansfield Formation	Seelyville Coal Member (Coal III) Upper Block Coal Member Lower Block Coal Member Buffaloville Coal Member
MISSISSIPPIAN	Buffalo Wallow Group	Tar Springs Formation	
	Stephensport Group	Glen Dean Limestone Hardinsburg Formation Haney Limestone Big Clifty Formation Beech Creek Limestone	
	West Baden Group		
	Blue River Group	Paoli Limestone Ste. Genevieve Limestone St. Louis Limestone	
	Sanders Group		
	Borden Group	Edwardsville Formation Spickert Knob Formation New Providence Shale	
MISSISSIPPIAN / DEVONIAN		Rockford Limestone Northern Indiana only: Coldwater Shale, Sunbury Shale, Ellsworth Shale, Antrim Shale	Southern Indiana: New Albany Shale
DEVO–NIAN	Muscatatuck Group	Traverse Formation (Northern Indiana) Jeffersonville Formation (Southern Indiana)	Geneva Dolomite Member
SILURIAN	Salina Group Bainbridge Group (Southwest Indiana)	Wabash Formation	Mississinewa Shale Member
		Northern Indiana: Louisville Limestone, Waldron Shale, Salamonie Dolomite, Cataract Formation	Southern Indiana: Louisville Limestone, Waldron Shale, Salamonie Dolomite
		Sexton Creek Limestone	Brassfield Limestone
ORDOVICIAN	Maquoketa Group	Southeastern Indiana: Whitewater Formation, Dillsboro Formation, Kope Formation	
		Trenton Limestone	Lexington Limestone (Southeastern Indiana)
	Black River Group		
	Ancell Group	Joachim Dolomite	St. Peter Sandstone
ORDOVICIAN / CAMBRIAN	Knox Supergroup		
CAMBRIAN	Munising Group	Franconia Formation Ironton Sandstone Galesville Sandstone Eau Claire Formation	
		Mt. Simon Sandstone	
PRE–CAMBRIAN	Basement Complex––Includes granite, basalt, and arkose of Middle Proterozoic age		

Figure 5. Geologic chart showing geologic age, group, and selected formations and members (geologic names from Shaver and others, 1986).

The Silurian carbonate rocks are unconformably overlain by Devonian dolomite and limestone (fig. 6), which attain thicknesses of 250 ft toward the centers of the Illinois Basin and the Michigan Basin (fig. 4). The carbonate rock sequence is overlain primarily by shales and siltstones of Late Devonian and Early Mississippian age. These shales and siltstones are present as subcrops in the Michigan Basin in the northeastern part of the State (fig. 6) and attain thicknesses of 800 ft in places. They also are present as subcrops or outcrops along the southwestern flank of the Cincinnati and Kankakee Arches in the south-central part of the State (fig. 6), where they range from 500 to 1,000 ft in thickness. Limestone of Middle Mississippian age overlies the shales and siltstones southwest of the arches. The area where the limestone is exposed at the bedrock surface trends northwest through the south-central part of the State. The Mississippian limestone ranges from 200 to more than 1,000 ft in thickness; the thicker deposits are in the southwestern corner of Indiana toward the center of the Illinois basin.

The limestone is overlain in the southwestern one-third of Indiana by rocks of Early Mississippian age and Middle and Late Pennsylvanian age (fig. 6). The rocks are composed of sandstone, shale, and thin but extensive beds of limestone, clay and coal. The beds of clay and coal are generally found above a major unconformity between the Mississippian and Pennsylvanian rocks. These rocks range from 1,000 to 2,000 ft in thickness.

There was little known deposition in Indiana between the end of the Pennsylvanian Period and the beginning of the Quaternary Period. During this time, the land surface was mostly an erosional surface that consisted of northwest-trending limestone plains, shale lowlands, and sandstone uplands (Wayne, 1966, p. 27). Rivers were entrenched in the bedrock; the main preglacial river valley in north-central Indiana was the Lafayette Bedrock Valley System (Bleuer, 1989), also known as the Teays valley, which drained most of the northern one-half of the State (fig. 7). The preglacial topography of most of the northern two-thirds of the State was buried beneath 50 to more than 400 ft of glacial debris during the Quaternary Period (Gray, 1983).

The earliest widespread evidence of continental glaciation in Indiana was from glaciers of pre-Illinoian and Illinoian Age. They extended through the northern three-quarters of Indiana (fig. 3; Wayne, 1966, p. 33). These pre-Wisconsinan glaciers deposited at least eight till units in Indiana that comprise approximately 75 percent of the glacial deposits in the Tipton Till Plain (A.J. Fleming, Indiana Geological Survey, 1990, written commun.) The only known pre-Wisconsinan deposits exposed at the surface are found over large areas south of the Wisconsinan glacial boundary (fig. 3). These deposits are composed of a sandy loam till of the Jessup Formation and deposits in proglacial lakes and outwash plains in southwestern Indiana (Gray, 1989). **Loess** was deposited downwind (east) of the valleys of the Wabash and Ohio Rivers.

There were several glacial advances in Indiana during Wisconsinan time by three different ice lobes (fig. 8). The furthest advance in the State was by the Erie Lobe, which covered the northern two-thirds of Indiana. The ice, which formed the Shelbyville Moraine in southeastern Indiana, was followed by another advance of the ice that formed the Crawfordsville Moraine (fig. 3). The two advances were from a northeastern source of ice and deposited till known as the Trafalgar Formation over large areas of central Indiana (Gray, 1989). As the ice receded, it left large amounts of sand and gravel in the form of valley train, kames, and eskers (Wayne, 1966, p. 36).

The next major Wisconsinan advance involved three ice lobes that competed for space in the northern one-third of Indiana. The Saginaw and Erie Lobes (fig. 8) advanced across north-central Indiana and formed the Packerton Moraine (fig. 3). The Saginaw Lobe left behind a complex suite of deposits of till, ice-contact stratified drift, and outwash (Gray, 1989) and formed most of the lakes in Indiana (Wayne, 1966, p. 36). The Lake Michigan Lobe (fig. 8) flowed out of the basin of Lake Michigan and formed the Maxinkuckee Moraine (fig. 3). The lobe receded and built the Valparaiso Moraine (fig. 3) and a large outwash fan south of the moraine. The Erie Lobe crossed into northeastern Indiana and formed the Union City Moraine and a series of concentric moraines to the northeast of the Union City Moraine (fig. 3). The ice lobe primarily deposited a clay-rich till of the Lagro Formation between the moraines (Gray, 1989).

Since the recession of the glaciers from Indiana about 8,000 years ago, deposition has been minor. The principal postglacial change was the redistribution of sand and silt of the glacial flood plains into windblown dune and loess deposits. Muck, peat, and marl formed in swampy areas and **alluvial deposits** formed along the modern rivers (Wayne, 1966, p. 37).

Hydrogeology and Ground-Water Flow

In northern Indiana, large areas of sand and gravel deposits in outwash plains and valley trains are capable of yielding as much as 2,000 gal/min of ground water. In addition, large yields (as much as several hundred gallons per minute) are available from productive Silurian and Devonian carbonate bedrock aquifers that underlie much of the area.

Significant ground-water resources are found in central Indiana along the valleys of the major rivers and streams (fig. 1). Intertill sand and gravel aquifers are present locally in the till plain throughout most of central Indiana. The Silurian and Devonian carbonate bedrock is a commonly used aquifer in central Indiana.

In the southern one-third of Indiana, major unconsolidated sources of ground water are limited to the valleys of the Wabash, White, Whitewater, and Ohio River systems (fig. 1). Mississippian, Devonian, and Silurian bedrock are sources of ground water in south-central and southeastern Indiana. Pennsylvanian sandstones are typically the most productive bedrock units in southwestern Indiana. Many areas in the southern one-third of the State lack adequate ground-water resources for purposes other than domestic (Clark, 1980, p. 34).

The productivity of different types of aquifers can differ greatly depending on certain fundamental characteristics. One fundamental characteristic of an aquifer is the ability to store water in pores. This **porosity** can be in the form of intergranular spaces as in sand and gravel; fractures and solution openings as in carbonate rocks; or intergranular spaces and fractures as in sandstones (Todd, 1980, p. 37-39). As unconsolidated sediment turns to stone, or becomes lithified, the original porosity of the sediment is reduced by cementation, compaction, and pressure solution (Davis, 1988, p. 325). Therefore, lithology is an important control on aquifer productivity, because it affects primary and secondary porosity and hydraulic conductivity. Different types of openings or pore spaces in geologic material are shown in figure 9. Openings that formed at the same time as the rock, such as pores in sedimentary deposits, are called primary openings (fig. 9a). Pores that formed after the rock is formed are called secondary openings (fig. 9b and 9c). The diameter of pores in sedimentary deposits can range from a few micrometers in clays to more than a centimeter in coarse gravel (Heath, 1988, p. 15) to the size of caves in carbonate rocks. An aquifer must be able to transmit water through such openings. This characteristic, called hydraulic conductivity, is dependent on the interconnected porosity of the material, the type of liquid, and the magnitude of the gravitational field (Lohman and others, 1972, p. 4). The hydraulic conductivity of an aquifer increases as grain size and the degree of sorting increase. Hydraulic conductivity is also usually greater in aquifers that have been enhanced by secondary porosity, such as fracturing. Finally, to be productive, an aquifer requires a source of water from precipitation or from adjacent geologic materials. Only 8 to 16 percent of the precipitation in Indiana, or about 3 to 8 inches per year, infiltrates into the ground-water system. Most of the precipitation is lost through evapotranspiration, and some runs off the land into surface waters (Bechert and Heckard, 1966, p. 100). Components of the hydrologic cycle are shown in figure 10.

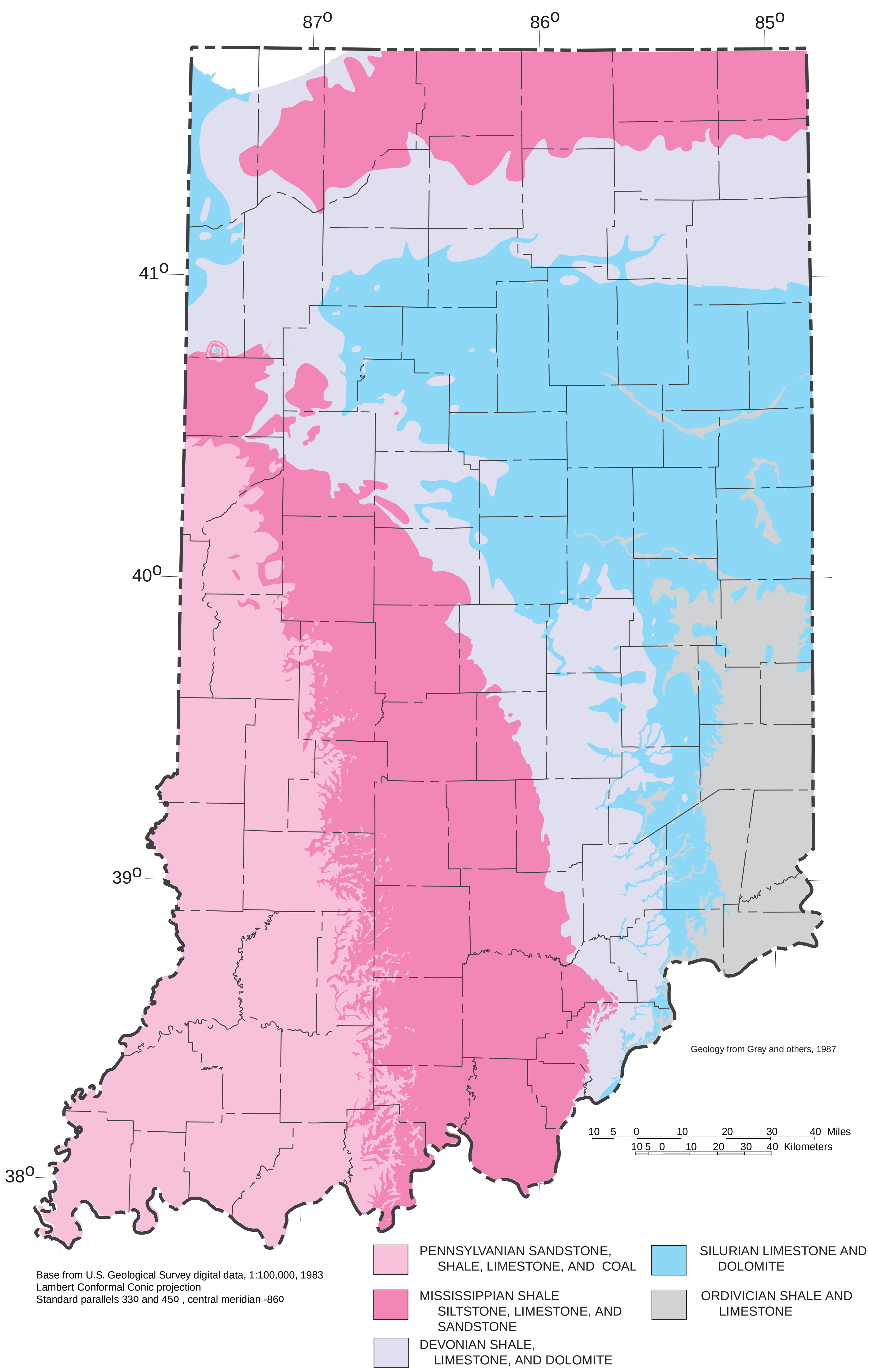


Figure 6. Bedrock geology in Indiana.

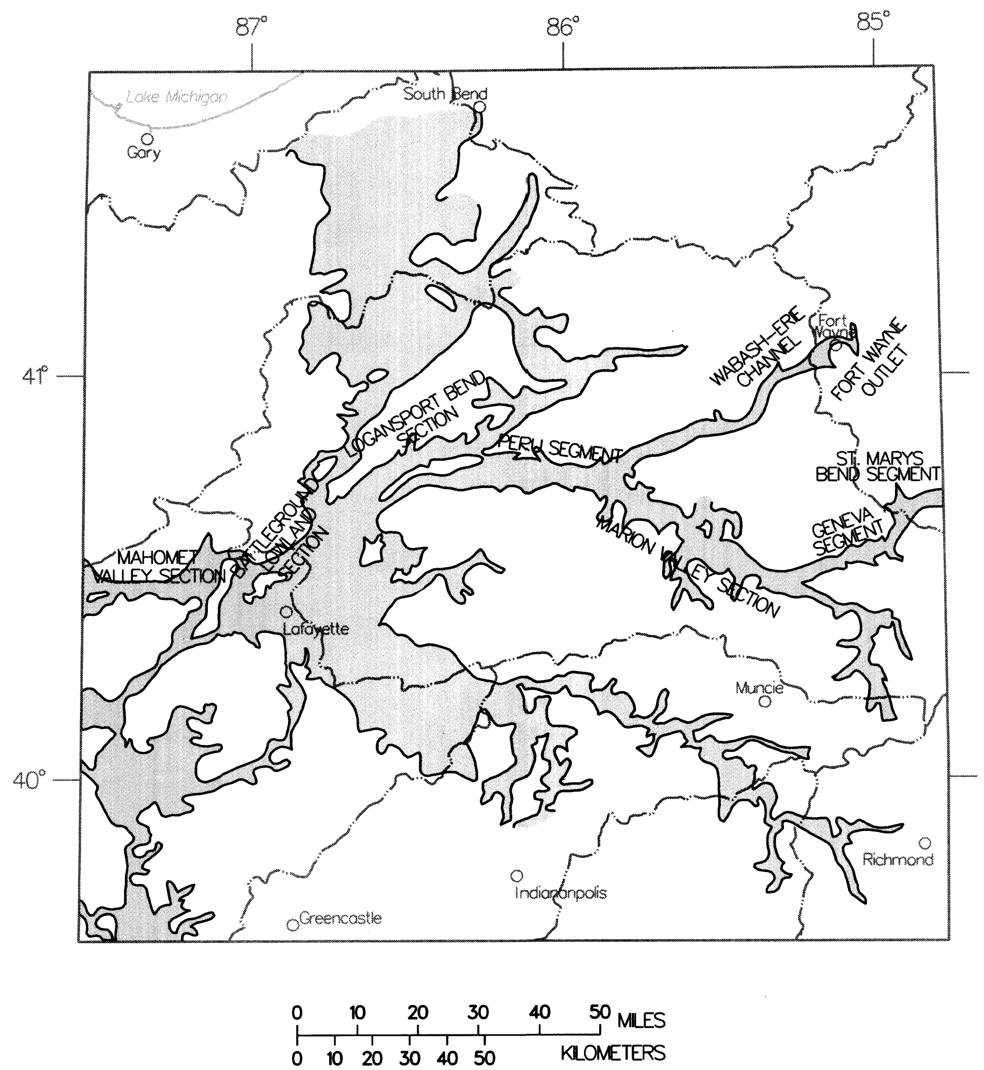


Figure 7. Location of buried bedrock valleys associated with the Lafayette Bedrock System in northern Indiana (modified from Bleuer, 1989).

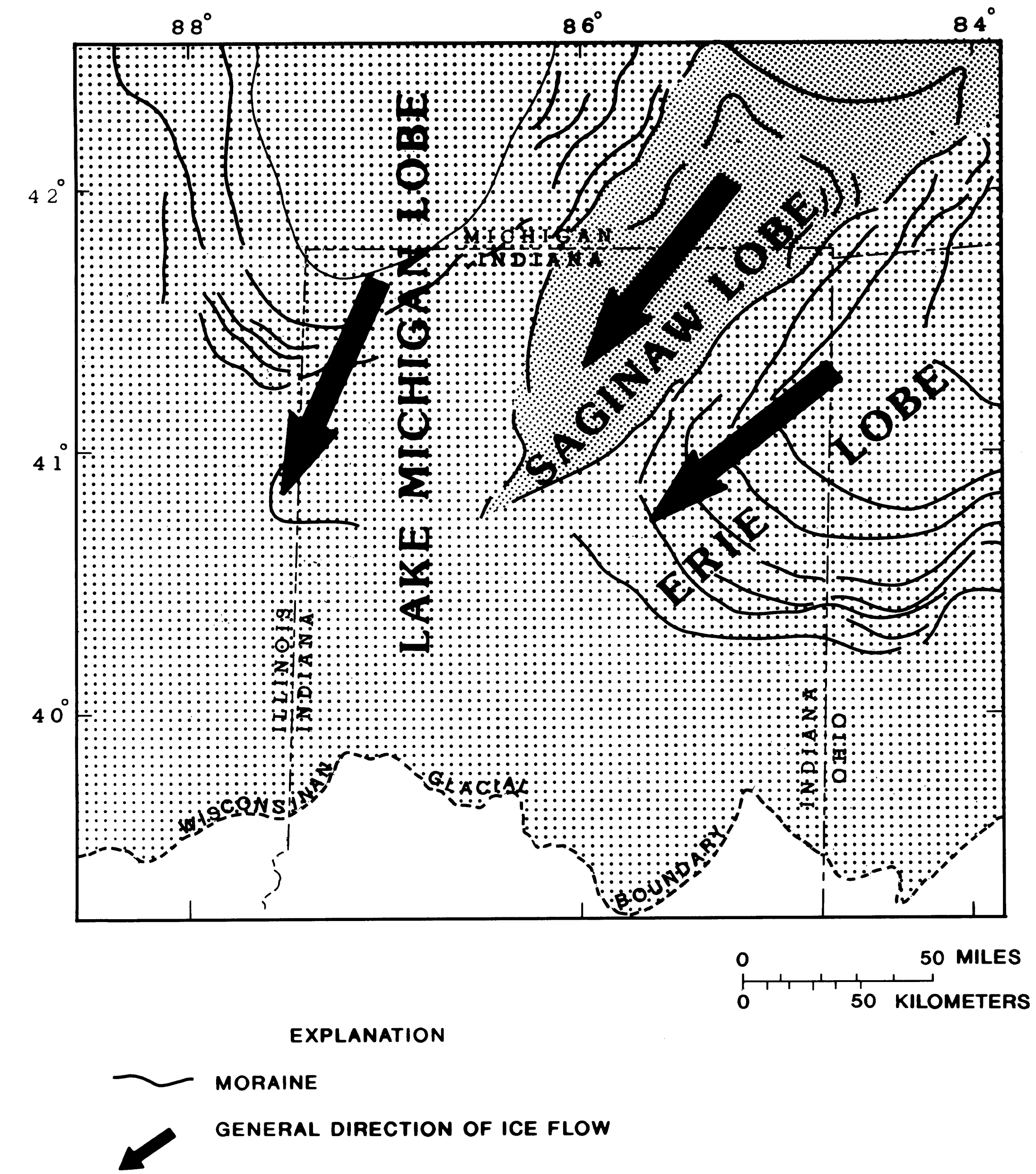
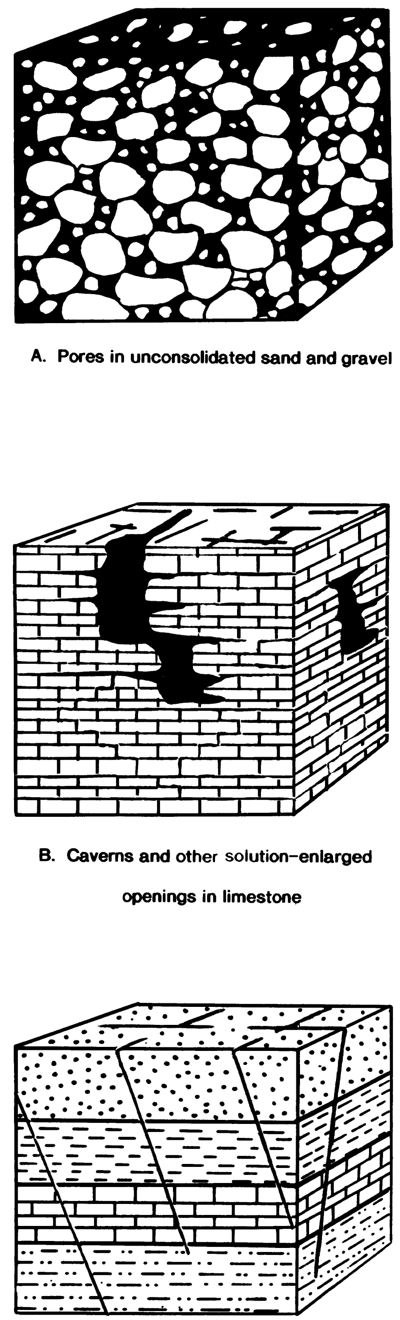


Figure 8. Primary glacial lobes and their principal directions of flow in Indiana during the Wisconsinan Age (modified from Wright and Frey, 1965).

Aquifers traversed by perennial streams commonly contain thick, extensive sand and gravel deposits that can produce large quantities of water. These aquifers are generally bounded by the flood-plain edge or by valley terraces. The hydraulic conductivity of sand and gravel buried in till or in buried bedrock valleys may be similar to these river-channel deposits, but recharge to the buried aquifers can be restricted by overlying sediments. In addition, buried sand and gravel deposits in till and preglacial valleys can be discontinuous and difficult to trace because of their complex depositional environments (Rosenshein, 1988, p. 167). Therefore, these buried deposits typically are less productive than the surficial deposits. The most productive carbonate rock aquifers contain large areas of solution openings along vertical joints and bedding planes as shown in figure 9. Similarly, sandstone aquifers are most productive where heavily jointed or fractured along bedding planes or where intergranular spaces have not been completely filled by cementing materials. Many sedimentary rocks—such as limestone, shale, and sandstone—have more vertical joints near the ground surface than at depth. This distribution of joints in the upper weathered zone tends to increase hydraulic conductivity locally by at least an order of magnitude. The hydraulic conductivity of most fractured rocks decreases rapidly with depth (Davis, 1988, p. 324). Coals can function as aquifers where fractures or cleats are well developed, resulting in increased hydraulic conductivity. Shales typically are not considered to be aquifers, because fractures in shale tend to be small and closely spaced, causing the hydraulic conductivity of the shale to be less than for most other rocks (Heath, 1984, p. 13; Todd, 1980, p. 38-41); however, in some cases, bedding-plane partings can create rather large horizontal hydraulic conductivities in shale.

General rates of ground-water flow through geologic material can range from a few feet per second to less than a few feet per year (Todd, 1980, p. 92), although rates are typically on the order of a few feet to a few hundred feet per year. Ground-water flow can have three separate components: local, interbasin, and regional. A schematic diagram of local and regional ground-water discharge and recharge is shown in



A. Pores in unconsolidated sand and gravel

B. Caverns and other solution-enlarged openings in limestone

C. Fractures in sedimentary rock

Figure 9. Types of openings in selected aquifers (modified from Heath, 1988).

figure 10. Ground-water recharge is from precipitation, stream infiltration, infiltration from runoff and overland flow, and flow from adjoining aquifers. Ground-water discharge is by flow into surface water, evapotranspiration, and flow into adjoining aquifers. Local ground-water flow in shallow **unconsolidated aquifer**s tends to be nearly horizontal, reflecting the surface topography, whereas regional flow patterns can range from simple (as in figure 10) to complex depending on the hydrologic properties of the aquifer. The direction of ground-water flow is determined by the potentiometric surface, an imaginary surface representing the **hydraulic head** distribution in an aquifer. The hydraulic head is the level that water will rise in a properly constructed well open to an aquifer. Ground water flows from areas of high head to areas of low head. Hydraulic head consists of two separate components: head due to elevation and head due to pressure. If elevation were the only component, then all ground water would simply flow from areas of high elevation to areas of low elevation (that is, downhill). Pressure head, however, is created by the weight of overlying water on a water particle. This pressure can create an upward component in the ground-water flow regime. Upward pressure is common near large rivers that function as regional ground-water **discharge area**s.

Ground water in most surficial aquifers is at atmospheric pressure and is unconfined. Generally water only partly fills surficial aquifers, and water levels in the saturated zone are free to rise and decline (Heath, 1984, p. 6). All water pumped from an **unconfined aquifer** reaches the well through gravity draining, and the water is removed from storage.

Ground water in a **confined aquifer** fills the entire aquifer and is confined at higher than atmospheric pressure. The water is confined by overlying rocks and sediment that are substantially less permeable than the aquifer rocks. The pressure in a confined aquifer forces water in a well screened in the aquifer to rise above the top of the aquifer. The pressure gradient that moves water in a confined aquifer to the pumped well is created by the compression of the aquifer material and the expansion of the water as water is pumped from the aquifer. Some aquifers are under enough pressure to raise the potentiometric surface above the land surface; these wells are said to be "flowing" or "flowing artesian."

The direction of local ground-water flow can be opposite from the direction of regional flow, especially where aquifers are separated by geologic materials with low hydraulic conductivity. Generally, though, ground water tends to discharge to topographically low areas, such as rivers and wetlands. Discharge areas commonly cover 5 to 30 percent of the surface area of a watershed (Freeze and Cherry, 1979, p. 195-200).

Ground-Water Withdrawals

Most of Indiana has plentiful ground-water resources. The aquifers of Indiana contain approximately 100,000 Bgal of water (Bechert and Heckard, 1966, p. 106). Statewide ground-water withdrawals in 1991 were only about 0.20 percent of this estimated amount in storage (Indiana Department of Natural Resources, 1993, written commun.). At an average of 39 in/yr, total annual precipitation in Indiana is about 24,500 Bgal. Annual infiltration into Indiana aquifers, at 8 percent of precipitation, equals 1,960 Bgal/yr. Therefore, 1991 withdrawals (204 Bgal) were approximately 10 percent of annual recharge. Nearly 4,000 Bgal of water is stored in the outwash and alluvial aquifers of the White River and East Fork White River; estimated recharge to these aquifers is 2,500 Mgal/d (Bloyd, 1974, p. 12). In the two basins, withdrawals in 1991 were about 6 percent of the recharge and only about 1 percent of the ground water stored in the outwash and alluvial aquifers.

Total ground-water withdrawals from registered facilities in Indiana in 1991 was 204 Bgal, or an average of 559 Mgal/d. Withdrawals listed in table 1 are shown as totals and as daily averages (Indiana Department of Natural Resources, 1993, written commun.). Withdrawal-use categories in the table include energy, industrial, irrigation, public supply, rural supply, and miscellaneous. Categories not included in the table are domestic (self-supplied) and livestock. Also shown in table 1 is the capability of registered facilities to withdraw ground water from each basin. The withdrawal rates in table 1 reflect the demand for ground water, the availability of ground water, and the size and population of the basin.

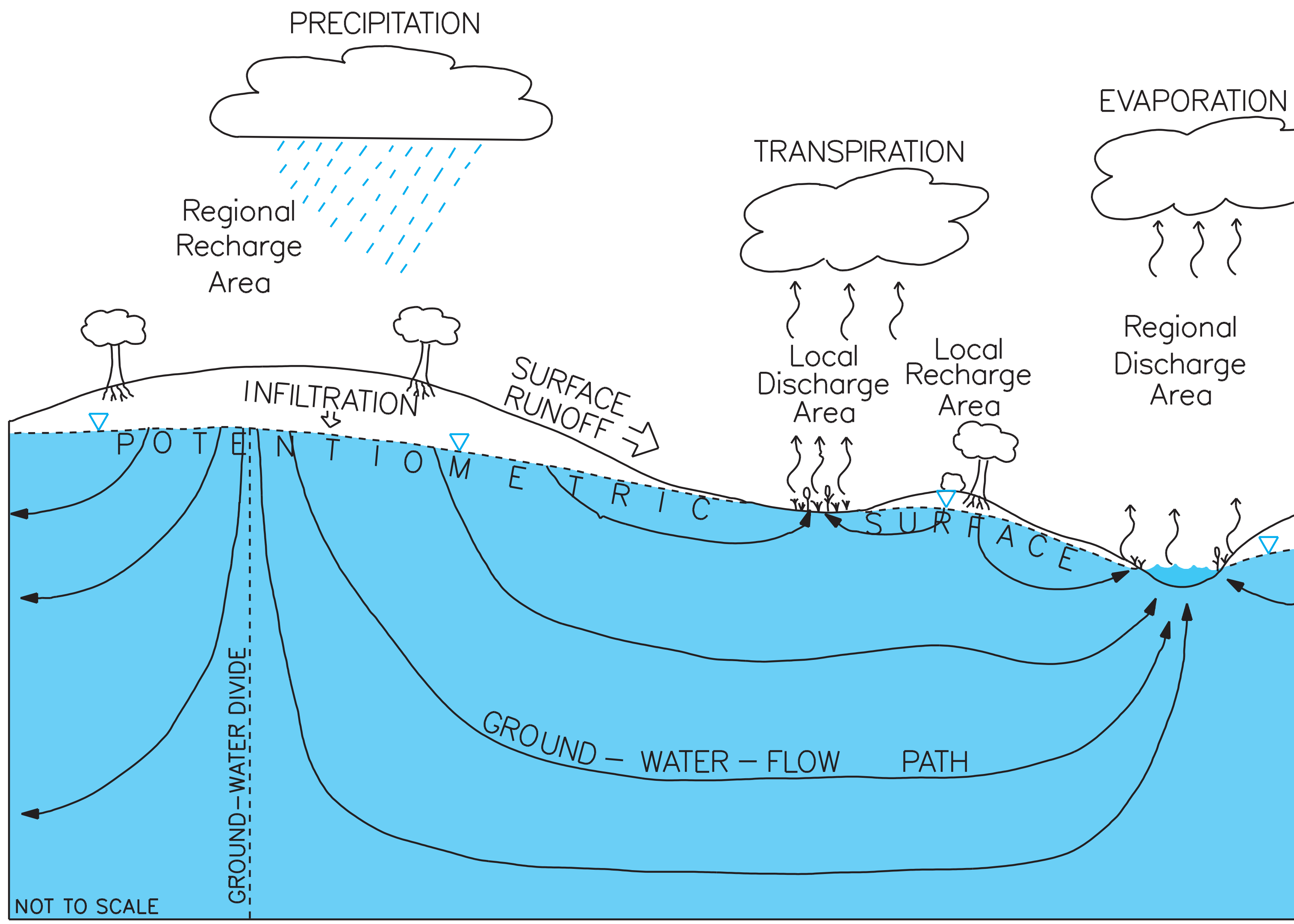


Figure 10. Generalized local and regional ground-water-flow paths and components of the hydrologic cycle.

More than 25,000 Mgal of ground water was withdrawn during 1991 in each of the White, St. Joseph, Middle Wabash, and Upper Wabash River basins. Amounts between 14,000 and 25,000 Mgal were pumped in the Ohio, Kankakee, and East Fork White River basins. Basins where between 3,000 to 7,500 Mgal were withdrawn in 1991 include Lake Michigan, Lower Wabash River, Whitewater River, and Maumee River. In the Patoka River basin, less than 32 Mgal of ground water were withdrawn in 1991.

METHODS OF STUDY

The Indiana Natural Resources Commission has divided the State into 12 water-management basins (fig. 1). The basin boundaries generally coincide with the surface-drainage divides of the major rivers in the State and with the State boundary. The management basins provide a hydrologic framework for surface-water and ground-water investigations in Indiana. The size of each basin (in square miles) is shown in table 2. Some river systems in Indiana drain into adjacent states. For these systems, the size of the water-management basin is not the same as the drainage area of the major river in the basin. These discrepancies are addressed in the individual discussions of each of the 12 basins.

Construction of Hydrogeologic Sections

Five to thirteen hydrogeologic sections were drawn for each basin to show the generalized hydrostratigraphy. Stratigraphic details in hydrogeologic sections are from water-well records on file at the IDNR Division of Water; well-completion reports and lithologic logs on file at the IDNR Division of Oil and Gas; coal-test drilling records available from the IDNR Geological Survey; State and Federal highway drilling logs; USGS observation-well logs; and core samples collected by the IDNR. After drilling a hole, a driller is required by the State to file a form that lists information on lithology, water level, pumping rates, and other selected information on the well construction. All wells other than water-supply wells are labeled with a "t" on the hydrogeologic sections to indicate that they are test wells; dry water-supply wells or holes

Table 1. Ground-water withdrawals and pumping capability in Indiana, 1991

[Withdrawal and pumping-capability data are from Indiana Department of Natural Resources, 1993, written commun.; Mgal, million gallons; Mgal/d, million gallons per day]

Basin	Withdrawal		Pumping capability
	Daily (Mgal)	Annual (Mgal)	(Mgal/d)
White River	104.	37,800	524
St. Joseph River	87.1	31,800	607
Middle Wabash River	84.7	30,900	366
Upper Wabash River	74.8	27,300	518
Ohio River	55.9	20,400	263
Kankakee River	55.3	20,200	574
East Fork White River	39.2	14,300	254
Lake Michigan	19.4	7,090	96.4
Lower Wabash River	17.5	6,390	206
Whitewater River	11.5	4,200	53.6
Maumee River	9.34	3,410	81.6
Patoka River	.086	31.5	0.3
TOTAL	559	204,000	3,540

are labeled with a “d” on the sections. A few wells in each basin represent the combined lithologic data from shallow water-supply well logs and nearby deep test-hole logs. These combined wells are labeled as test wells on the hydrogeologic sections.

In the first five basins for which hydrogeologic sections were completed (Lake Michigan, St. Joseph, Maumee, Upper Wabash, and Lower Wabash), all sections were oriented roughly perpendicular to the major surface-water drainage in each basin to depict ground-water discharge to surface water. The remaining seven basins included one or more sections perpendicular to the other sections in the basin. For convenience, most hydrogeologic section lines run south to north or west to east. Logs of wells located within 1 mi of a hydrogeologic-section line were plotted at a density of one to three wells per mile. Water levels shown on wells in the cross sections represent the hydraulic head in the aquifer in which the well is completed. Some of the water levels are connected to represent the generalized potentiometric surface in an aquifer that is being tapped by a group of wells along the section. Water levels were not indicated for all of the wells because they were not available from all drillers’ logs. The locations of all hydrogeologic sections presented in the atlas are shown in figure 11. The number of section lines, length of section lines, and number of wells plotted for each section are listed in table 2.

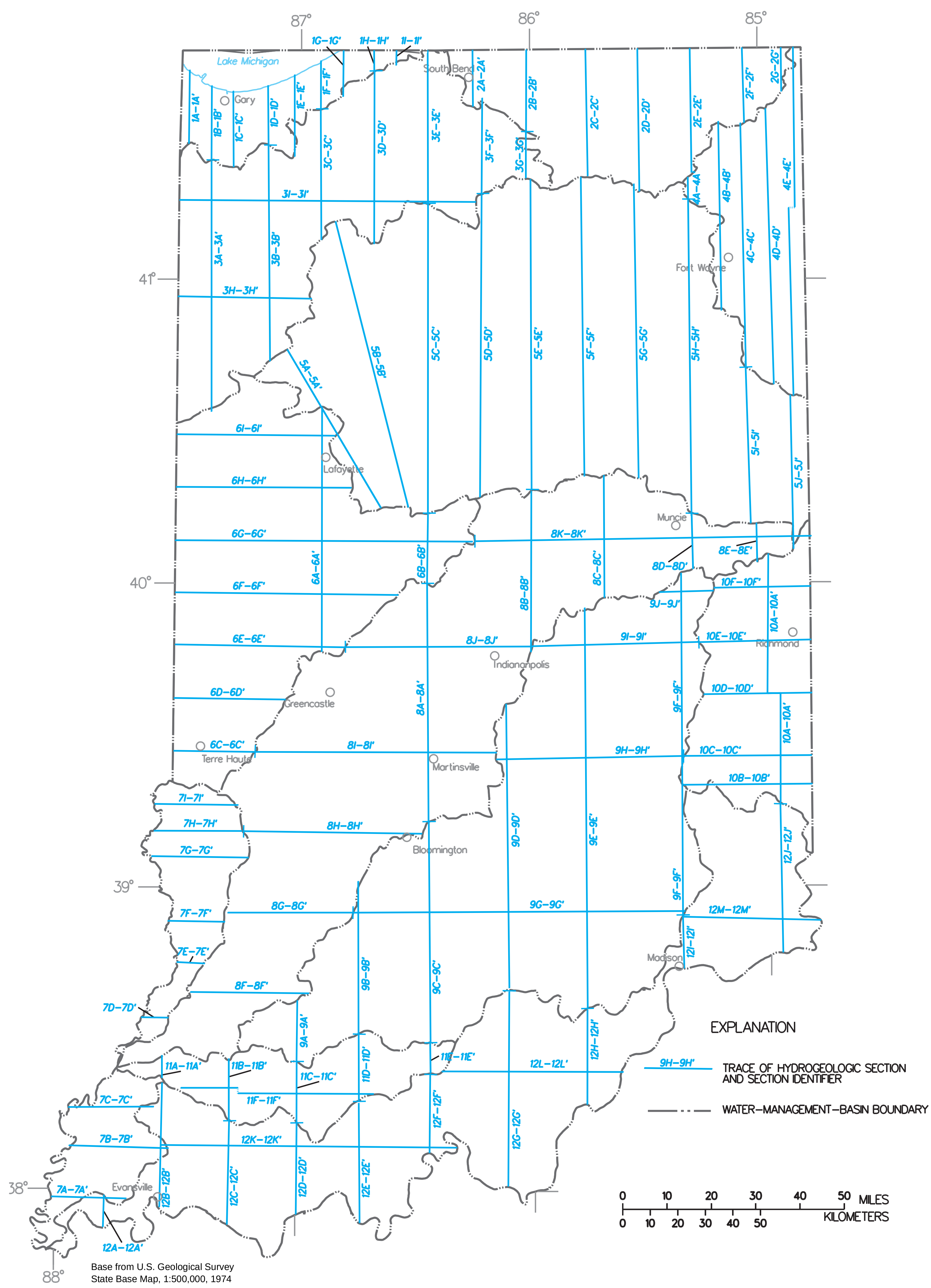
The surface elevation shown on the hydrogeologic sections reflects the land surface at the well and does not necessarily portray the true topographic relief along the section line. For example, all the wells in a certain area might be located in a stream valley; no wells can be plotted in adjacent uplands even though the uplands are within the 2-mile width of the section line. Therefore, the surface topography depicts a valley and does not reflect the actual relief along the section line. The hydrogeologic sections are generally drawn to a depth of 300 ft below the land surface or at least 50 ft below the bedrock surface, whichever is greater. Only a small percentage of the water wells in the State are greater than 300 ft deep. Therefore, relatively little information at greater depths is available. Furthermore, use of water at depths greater than 300 ft is limited by low yields and salinity (W.J. Steen, Department of Natural Resources, 1990, written commun.; Indiana Department of Environmental Management, 1990, p. 223).

Aquifer types depicted in the hydrogeologic sections are sand and gravel, carbonate rock, sandstone, an upper weathered zone in low permeability rock, and interbedded bedrock material. Most bedrock was depicted as aquifer only where it is known to produce water. (This information is available from drillers’ logs and previous studies.) If the bedrock formations are potentially water producing, then the material is mapped as “**aquifer—potential unknown**.” Much of the complexly interbedded bedrock of Mississippian and Pennsylvanian age, the weathered zones, and some of the Silurian and Devonian carbonate rock was mapped as “aquifer—potential unknown” because of low yields, **dry hole**s, or little knowledge about the productivity of the material. Almost all the Silurian and Devonian carbonate rock within 300 ft of land surface was depicted as aquifer even if no site-specific information was available to confirm its productivity. “Aquifer” and “aquifer—potential unknown” are colored on the hydrogeologic sections, whereas bedrock **nonaquifer material** and areas of unknown geologic material are not colored. In some sections, part of a formation is denoted as aquifer, but the rest is denoted as “aquifer—potential unknown” or nonaquifer—that is, a specific formation need not be hydrogeologically uniform throughout its extent. Unconsolidated material was grouped into two broad hydraulic categories: (1) sediments that have a relatively high hydraulic conductivity, such as sand and gravel; and (2) sediments that have a relatively low hydraulic conductivity, such as clay, silt, or mixed drift. Many of the sand and gravel deposits are aquifers, whereas the materials of low hydraulic conductivity were labeled as nonaquifer material. Areas where the geology is unknown are indicated by question marks.

Construction of Aquifer Maps

The maps showing lateral extent and continuity of aquifer types are based on interpretations of the hydrogeologic sections, on previously published surficial and bedrock geology maps, and on information available from previous studies of basin hydrogeology. The “Quaternary Geologic Map of Indiana” (Gray, 1989) was used to draw many of the surficial sand and gravel aquifers that were confirmed by the hydrogeologic sections. Bedrock geologic maps (Gray and others, 1987; Geosciences Research Associates, Inc., 1982; Gray, 1982) were used to indicate the extent of bedrock aquifers and the approximate boundaries where aquifers were buried by more than 300 ft of material.

The lithostratigraphic approach used in this study to define hydrogeologic settings resulted in seven aquifer types. Sand and gravel deposits are designated as surficial, buried, or discontinuous on the aquifer maps. **Surficial aquifer** indicates that the aquifer is covered by less than 10 ft of nonaquifer material. **Buried aquifer** indicates that the sand and gravel is covered by 10 ft or more of nonaquifer material and that the deposits are continuous in at least one direction for several miles or more. **Discontinuous aquifer**s refer to lenses of sand and gravel that are not laterally extensive (discontinuous aquifers are typical of morainal areas). Buried bedrock valleys were mapped where productive aquifers are within them. The three unconsolidated aquifer types are shown as sand and gravel on the hydrogeologic sections. Carbonate rock (limestone and dolostone); sandstone; complexly interbedded sandstone, shale, siltstone, limestone, and coal; and an upper weathered zone in low-permeability rock are shown on the sections and on the aquifer maps. All of the complexly interbedded material shown on the sections is shown on the map as “aquifer—potential unknown” because of the uncertainty in mapping the water-producing zones on a regional scale. Areas typically devoid of formations capable of producing yields sufficient for domestic purposes are indicated as nonaquifer material on the maps.



Base from U.S. Geological Survey
State Base Map, 1:500,000, 1974

Figure 11. Location of hydrogeologic sections in the 12 water-management basins.

Table 2. Summary of basin areas and hydrogeologic section characteristics
[mi^2, square mile]

Basin	Area (mi^2)	Number of section lines	Length of section lines (in miles)	Total number of wells	Number of wells per mile
Lake Michigan	604	9	108	212	2.0
St. Joseph River	1,699	7	148	213	1.4
Kankakee River	2,989	9	339	490	1.4
Maumee River	1,283	5	244	305	1.3
Upper Wabash River	6,918	10	594	833	1.4
Middle Wabash River	3,453	9	347	470	1.4
Lower Wabash River	1,339	9	145	193	1.3
White River	5,603	11	409	354	0.9
East Fork White River	5,746	10	499	616	1.2
Whitewater River	1,425	6	189	226	1.2
Patoka River	862	6	99	98	1.0
Ohio River	4,224	13	375	214	0.6
TOTAL	36,145	104	3,496	4,225	[1]1.2

[1]Statewide average

Limitations of the Methods

In areas where large numbers of well logs were available for plotting, the logs with the location nearest the section line, the most complete well-record information, and the deepest hole were chosen for the hydrogeologic sections. This search for stratigraphic and hydrologic information resulted in a bias toward deep wells and deep aquifers in many locations.

The hydrogeologic sections represent the interpretation of the well-log data by the author(s) for each basin. The sections do not represent the only possible explanation or representation of the hydrogeology at that location. The reliability of the sections can vary within each basin depending on the quantity and quality of information on the drillers' logs. Logs were not always available at the desired density of two per mile. Some hydrogeologic sections include areas where only one well log is plotted in a 5-mile interval.

The interpretation of the well-log data on the hydrogeologic sections is a simplified picture of the geology on the section. Where lithologies change over short lateral distances, such as in the unconsolidated glacial deposits and the Pennsylvanian rocks, well logs spaced every 1/2 to 1 mi do not provide the needed information to depict detailed variations in geology. In the Pennsylvanian rocks, lithologies were commonly lumped together to avoid over-interpretation of well logs and, hence, a misleading and inaccurate representation of the system.

Many of the hydrogeologic sections contain logs of wells that were not drilled to the bedrock surface. In these areas, the topography of the bedrock surface was transferred from the "Map of Indiana Showing the Topography of the Bedrock Surface" (Gray, 1982). In these same areas, the bedrock geology and hydrostratigraphy was mapped with reference to the "Bedrock Geologic Map of Indiana" (Gray and others, 1987), the "Hydrogeologic Atlas of Indiana" (Geosciences Research Associates, Inc., 1982), structural maps of the base and top of the New Albany Shale in Indiana (Bassett and Hasenmueller, 1979a; 1979b), structural maps of the top of the Ordovician, Silurian, and sub-Pennsylvanian surfaces in Indiana (Bassett and Hasenmueller, 1980; Hasenmueller and Bassett, 1980; Keller, 1990), and other sources.

Water levels shown on the hydrogeologic sections were measured at different times by different drillers in aquifers that are not necessarily hydrologically connected. Water levels may also be a composite head from several aquifers or stratigraphic intervals, especially in uncased bedrock wells.

The aquifer map may not reflect the actual lateral extent and boundaries of the aquifer types. Because the section lines are 6 to 20 mi apart, the continuity of areas between the hydrogeologic section lines was extrapolated from the sections or inferred from published sources.

REFERENCES CITED

Back, William, Rosenshein, J.S., and Seaber, P.R., eds., 1988, Hydrogeology: Boulder, CO., Geological Society of America, The Geology of North America, v. O-2, 524 p.

Bassett, J.L., and Hasenmueller, N.R., 1979a, Map showing structure on base of New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana: Indiana Department of Natural Resources, Geological Survey, EGSP Series 800, scale 1:500,000.

_____1979b, Map showing structure on top of New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana: State of Indiana Department of Natural Resources, Geological Survey, EGSP Series 801, scale 1:500,000.

_____1980, Map of Indiana showing structure on top of the Maquoketa Group (Ordovician): Indiana Department of Natural Resources, Geological Survey, METC/EGSP Series 812, scale 1:500,000.

Bechert, C.H., and Heckard, J.M., 1966, Ground water, *in* Lindsey, A.A., ed, Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 100-115.

Bleuer, N.K., 1989, Historical and geomorphic concepts of the Lafayette Bedrock Valley System (so-called Teays Valley) in Indiana: Indiana Department of Natural Resources, Geological Survey Special Report 46, 11 p.

Bloyd, R.M., Jr., 1974, Summary appraisals of the Nation's ground-water resources—Ohio region: U.S. Geological Survey Professional Paper 813-A, 41 p.

Bugliosi, E.F., 1990, Plan of study for the Ohio-Indiana carbonate-bedrock and glacial aquifer system: U.S. Geological Survey Open-File Report 90-151, 25 p.

Casey, C.D., 1992, Hydrogeology of the basal confining unit of the carbonate aquifer system in the midwestern basins and arches region of Indiana, Ohio, Michigan, and Illinois: U.S. Geological Survey Open-File Report 92-489.

Clark, G.D., ed., 1980, The Indiana water resource—availability, uses, and needs: Indianapolis, Governor's Water Resources Study Commission, Indiana Department of Natural Resources, 508 p.

Davis, S.N., 1988, Sandstones and shales, *in* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, Colo., Geological Society of America, The Geology of North America, v. O-2, p. 323-332.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Geosciences Research Associates, Inc., 1982, Hydrogeologic atlas of Indiana: Bloomington, Ind., 31 pl.

Gray, H.H., 1973, Properties and uses of geologic materials in Indiana: Indiana Department of Natural Resources, Geological Survey Regional Geologic Map Series, Supplementary Chart 1.

_____1982, Map of Indiana showing topography of the bedrock surface: Indiana Department of Natural Resources, Geological Survey Miscellaneous Map 35, scale 1:500,000.

_____1983, Map of Indiana showing thickness of unconsolidated deposits: Indiana Department of Natural Resources, Geological Survey Miscellaneous Map 37, scale 1:500,000.

_____1989, Quaternary geologic map of Indiana: Indiana Department of Natural Resources, 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: Indiana Department of Natural Resources, Geological Survey Miscellaneous Map 48, scale 1:500,000.

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

Harrell, Marshall, 1935, Ground water in Indiana: Indiana Department of Conservation, Division of Geology Publication 133, 504 p.

Hasenmueller, N.R., and Bassett, J.L., 1980, Map of Indiana showing structure on top of Silurian rocks: Indiana Department of Natural Resources, Geological Survey, METC/EGSP Series 811, scale 1:500,000.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

_____1988, Hydrogeologic setting of regions, *in* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, CO., Geological Society of America, The Geology of North America, v. O-2, p. 15-23.

Indiana Department of Environmental Management, 1987, Indiana ground water protection and management strategy: 127 p.

_____1990, Indiana water quality management 305(b) report for 1988-1989: Indiana Department of Environmental Management, Public Water Supply Section, 297 p.

Keller, S.J., 1990, Maps of southwestern Indiana showing geology and elevation of the sub-Pennsylvanian surface: Indiana Department of Natural Resources, Geological Survey Miscellaneous Map 51, scale 1:380,160.

Krothe, N.C., and Kempton, J.P., 1988, Central Glaciated Plains, *in* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, CO., Geological Society of America, The Geology of North America, v. O-2, p. 129-132.

Lohman, S.W.; Bennett, R.R.; Brown, R.H.; Cooper, H.H., Jr.; Drescher, W.J.; Ferris, J.G.; Johnson, A.I.; McGuinness, C.L.; Piper, A.M.; Rorabough, M.I.; Stallman, R.W.; and Theis, C.V.; 1972, Definitions of selected ground-water terms—revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

National Oceanic and Atmospheric Administration, 1988, Climatological data—annual summary, Indiana: Asheville N.C., v. 93, no. 13.

Rosenshein, J.S., 1988, Region 18, alluvial valleys, *in* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, CO., Geological Society of America, The Geology of North America, v. O-2, p. 165-175.

Rupp, J.A, 1991, Structure and isopach maps of the Paleozoic rocks of Indiana: Indiana Department of Natural Resources, Geological Survey Special Report 48, 106 p.

Schaal, L.A., 1966, Climate, *in* Lindsey, A.A., ed, Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 156-170.

Schneider, A.F., 1966, Physiography, *in* Lindsey, A.A., ed, Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 40-56.

Schnoebelen, D.J., 1992, Selected hydrogeologic data for the regional carbonate bedrock and glacial aquifers in eastern and central Indiana: U.S. Geological Survey Open-File Report 91-517, 102 p.

Shaver, R.H.; Ault, C.H.; Burger, A.M.; Carr, D.D.; Droste, J.B.; Eggert, D.L.; Gray, H.H.; Harper, Denver; 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: Indiana Department of Natural Resources, Geological Survey Bulletin 59, 203 p.

Todd, D.K., 1980, Groundwater hydrology: New York, John Wiley, 539 p.

U.S. Geological Survey, 1985, National water summary 1984—hydrologic events, related water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

_____1988, National water summary 1986—hydrologic events and ground-water quality: U.S. Geological Survey Water-Supply Paper 2325, 560 p.

Visher, S.S., 1944, Climate of Indiana: Bloomington, Ind., Indiana University Publications, Science Series 13, 511 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.

Wright, H.E., Jr., and Frey, D.G., eds., 1965, The Quaternary of the United States: Princeton, N.J., Princeton University Press, 922 p.

DEFINITIONS OF SELECTED TERMS

The following are definitions of selected terms as they are used in this report; they are not necessarily the only valid definitions of these terms.

Alluvial deposits (or alluvium). Unconsolidated sediment deposited in river channels or on flood plains by a stream.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield quantities of potable water for domestic purposes. An aquifer may include unsaturated parts of the permeable material.

Aquifer—Potential unknown. An aquifer-type classification that implies a formation of unknown or poor production capabilities. The use of the formation as a water supply may result in low yields and(or) dry holes.

Bedrock aquifer (or consolidated aquifer). An aquifer composed of limestone, dolostone, sandstone, coal, siltstone, or shale bedrock.

Buried aquifer. A sand and gravel aquifer whose upper surface is greater than 10 feet beneath the land surface; a buried aquifer is not discontinuous.

Confined aquifer. An aquifer whose potentiometric surface is higher than the top of the aquifer.

Discharge area. An area where water is lost from an aquifer; commonly a surface-water body or an area of intensive ground-water pumping.

Discontinuous aquifer. A sand and gravel aquifer composed of small, detached sand and gravel deposits that are less than about 15 square miles in extent, and separated from other aquifers by non-aquifer material. Discontinuous aquifers can be either surficial or buried.

Drift. A general term for all material transported by glacial processes and deposited directly from melting ice or by meltwater streams.

Dry hole. A hole abandoned during drilling for lack of water.

Hydraulic head (or static head). The height of the surface of a column of water above a standard datum that can be supported by the static pressure at a given point; the sum of the elevation head and the pressure head; the level to which water will rise in a properly constructed well.

Loess. A blanket of fine-grained material, typically silt, deposited by the wind.

Nonaquifer material. Sediments with low hydraulic conductivity that normally will not transmit quantities of potable water adequate for domestic purposes.

Outwash. Stratified unconsolidated material, typically sand and gravel deposited by meltwater streams flowing beyond the glacial ice; proglacial stratified drift.

Outwash plain. A broad, gently sloping sheet of outwash.

Porosity. The ratio of the volume of the voids or openings in a rock to its total volume.

Potentiometric surface (generalized). An imaginary surface representing the total head of ground water in an aquifer and defined by the level to which water will rise in a properly constructed well.

The generalized potentiometric surface of unconsolidated aquifers usually represents the static head from a discrete screened interval and generally is a subdued reflection of the land surface. The generalized potentiometric surface of bedrock deposits is typically a composite water level from a hole open through many lithologies.

Recharge. Water that is gained by an aquifer..

Saturated. The condition in which the pores of a material are filled with water.

Surficial aquifer. A type of aquifer whose upper surface is within 10 feet of the land surface; a surficial aquifer is not discontinuous.

Till. An unsorted, unstratified sediment deposited directly by glaciers with little or no reworking by meltwater. Till is composed of clay, silt, sand, gravel and(or) boulders. The term till is used in place of diamicton in the text.

Unconfined aquifer (or water-table aquifer). An aquifer whose upper surface is the water table.

Unconsolidated aquifer. A type of aquifer composed of sand, gravel, or a mixture of sand and gravel.

Valley train. A long, narrow body of outwash deposited by meltwater streams far beyond the margin of active glaciation, and confined laterally within a valley.

Yield (or potential well yield). The maximum pumping rate that can be sustained in a well without lowering the water level below the water intake. The maximum potential well yield is supplied by a properly constructed, fully penetrating, large diameter well.