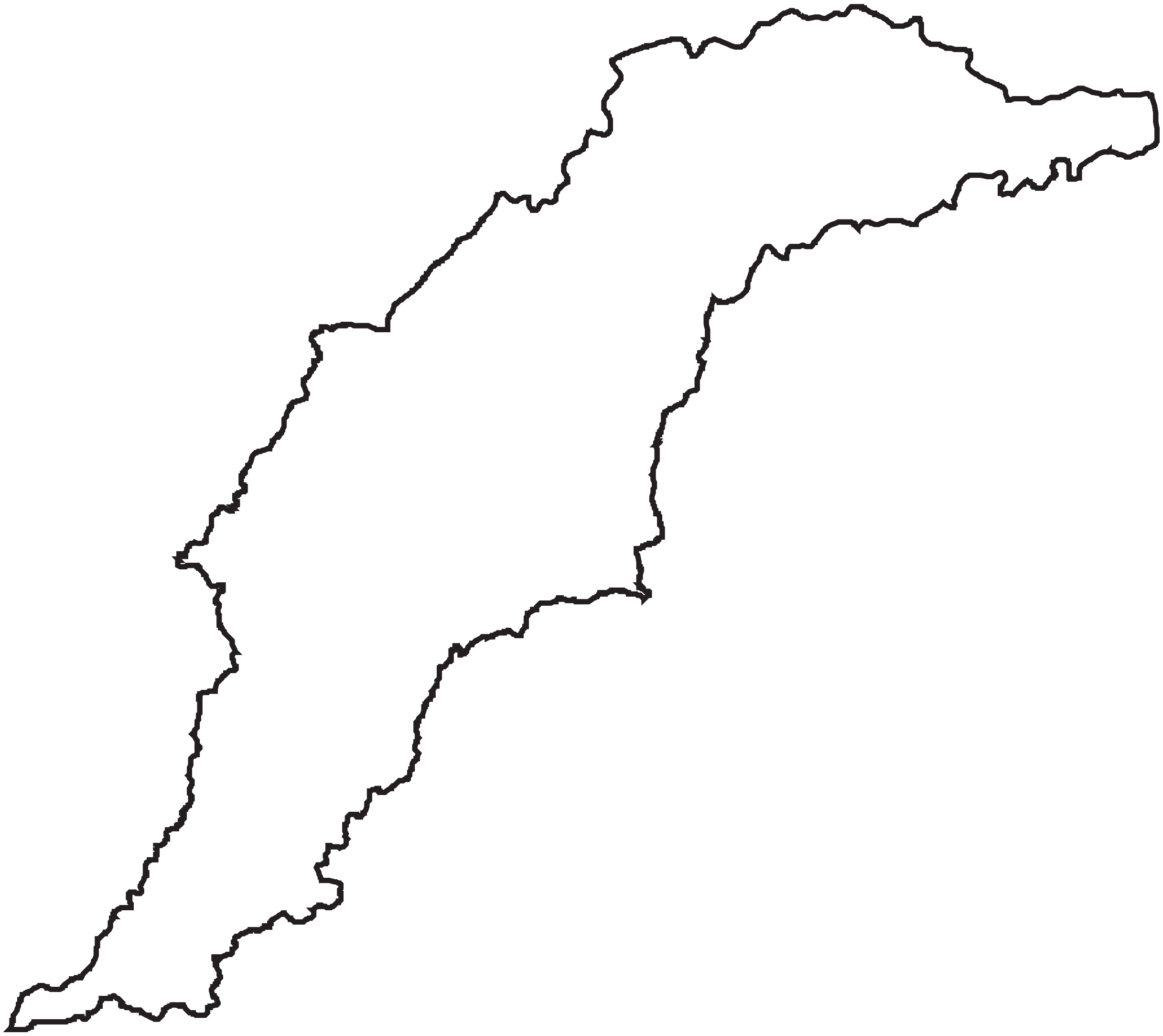
INDIANA DEPARTMENT OF NATURAL RESOURCES

GROUND-WATER RESOURCES IN THE WHITE AND WEST FORK WHITE RIVER BASIN, INDIANA



STATE OF INDIANA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATER
2002

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MAJOR ACRONYMS AND ABBREVIATIONS

DOW	Division of Water
IDEM	Indiana Department of Environmental Management
IDNR	Indiana Department of Natural Resources
IGS	Indiana Geological Survey
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
USACE	U.S. Army Corps of Engineers
bg	billion gallons
cfs	cubic feet per second
^{o}F	degrees Fahrenheit
I.C.	Indiana Code
m.s.l.	mean sea level
gpd	gallons per day
gpm	gallons per minute
MCL	maximum contaminant level
MG	million gallons
MGD	million gallons per day
mg/L	milligrams per liter
ml	milliliter
SMCL	secondary maximum contaminant level
sq. mi.	square miles

SELECTED CONVERSION FACTORS

Multiply	By	To obtain
	AREA	
Acres	43,560	Square feet
	0.001562	Square miles
	VOLUME	
Acre-feet	0.3259	Million gallons
	43,560	Cubic feet
	FLOW	
Cubic feet per second	0.646317	Million gallons per day
Gallons per minute	0.002228	Cubic feet per second
Gallons per minute	0.0014	Million gallons per day

GROUND-WATER RESOURCES IN THE WHITE AND WEST FORK WHITE RIVER BASIN, INDIANA

INTRODUCTION

Water is a vital resource that greatly influences Indiana's socio-economic development. Ground-water supplies serve a diversity of human needs, including public supply, industry, power generation, and agriculture. Demands on the ground-water resource are increasing and are expected to continue to increase as Indiana's economy and population continue to grow. Effective management of the ground-water resource is possible only through an assessment of ground-water availability.

Purpose and Scope

This report describes the availability, distribution, and quality of ground water in the White and West Fork White River basin, Indiana (figure 1). The report is intended to provide background hydrologic information for persons interested in managing and developing the basin's ground-water resource.

The White and West Fork White River basin in central and south-central Indiana spans the mid-section of the state. As defined in this study, the White and West Fork White River basin encompasses a total of approximately 5,600 square miles (sq. mi.) of land, or approximately 15 percent of Indiana's land area. The White and West Fork White River Basin drainage system lies entirely within the state and for this study does not include the East Fork White River basin.

The basin includes all or part of 29 counties: Boone, Brown, Clay, Clinton, Daviess, Delaware, Gibson, Grant, Greene, Hamilton, Hancock, Hendricks, Henry, Johnson, Knox, Madison, Marion, Martin, Monroe, Montgomery, Morgan, Owen, Parke, Pike, Putnam, Randolph, Sullivan, Tipton, and Vigo (table 1). The largest city within the basin is Indianapolis, in Marion County. Other major population centers are primarily located in the northern part of the basin, including: Muncie, Anderson, Carmel, Fishers, and Noblesville. In the southern part of the basin, larger population centers include: Greencastle, Linton, Martinsville, Spencer, and Washington.

Major streams of the basin include White River, West Fork White River, Eel River, and an extensive network of tributary streams and ditches. Streamflow leaving the basin enters the Wabash River, then the Ohio and Mississippi Rivers, and eventually reaches the Gulf of Mexico.

The information presented in this report should be suitable as a comprehensive reference source for public and private interests, including: environmental, governmental, agricultural, commercial, industrial, and recreational. However, the report is not intended for evaluating site-specific water resource development projects. Persons involved in such projects should contact the Division of Water for further information.

Because the report is written for a wide spectrum of readers, key technical words within the text are italicized the first time they appear, and where appropriate thereafter. Brief definitions are given in the glossary. An appendix includes data tabulations and illustrations that supplement the information found within the body of the report.

Field investigations conducted by the Division of Water and the Indiana Geological Survey in 1989 and 1990 provided data on the ground-water quality of the basin. Samples were collected and analyzed for 372 water-wells to yield information on ambient ground-water quality throughout the basin.

The remainder of the information in this report was derived, summarized, or interpreted from data, maps, and technical reports by various state and federal agencies. Specific sources of data are referenced within the report. A list of selected references is included at the end of the report.

Previous Investigations

Because published and unpublished documents relating to the White and West Fork White River basin in Indiana are numerous, only the primary sources used to prepare this report are discussed below. These primary documents and other major references are cited at the end of the report. Additional sources of information are listed within these cited references.

Various aspects of the geology and hydrology of several Indiana counties, lying wholly or partly within the White and West Fork White River basin, are addressed in numerous reports by the Indiana Department of Natural Resources (IDNR) and the U.S. Geological Survey (USGS).

Maps and reports by the Indiana Geological Survey (formerly part of the Department of Natural Resources) describe the surficial and bedrock geology of central Indiana (Wayne, 1956, 1958, 1963; Shaver and others, 1961, 1978, 1986; Pinsak and Shaver, 1964; Burger and others, 1971; Gray, 1972, 1978, 1979, 1982, 1983, 1988, 1989, 2000; Johnson and Keller, 1972; Becker, 1974; Bleuer, 1974, 1989, 1991; Doheny and others, 1975; Droste and Shaver, 1982; Gray and others 1987; Rupp, 1991; and Fleming and others, 1995).

Ground water availability maps have been completed for the entire state of Indiana by Bechert and Heckard (1966). A report by the Indiana Department of Natural Resources (1980)

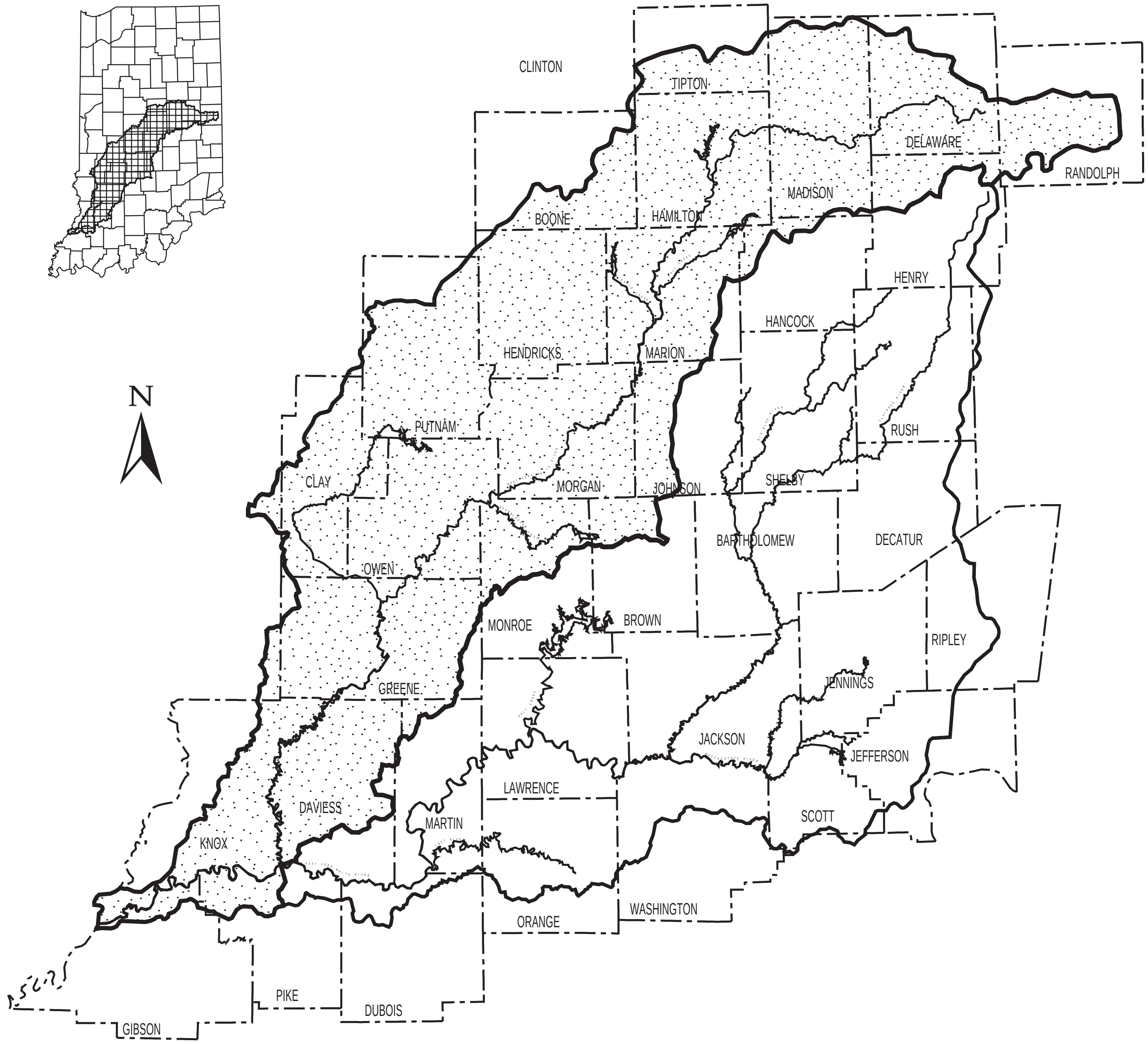


Figure 1. Location of White and West Fork White River basin

assesses various aspects of water availability and use for 18 planning and development regions in the state of Indiana. The White and West Fork White River basin lies primarily in five of these planning and development regions.

The Indiana Department of Natural Resources, Division of Water, has also published various ground-water availability maps and reports that include information on the ground-water resources and ground-water quality that delineate major aquifers along with recorded and potential well yields for numerous counties in the basin, including: Morgan (Heckard, 1964), Johnson (Uhl, 1966), Hendricks (Steen, 1968), Madison (Steen, 1970), Hamilton (Herring, 1971), Henry (Uhl, 1973), Marion (Herring, 1974, 1976), Hancock (Uhl, 1975), and Boone (Steen and others, 1977). A report by Barnhart and Middleman (1990) detailed the hydrogeology and ground-water quality of Gibson County.

The U.S. Geological Survey (USGS), in cooperation with the Division of Water, Indiana Department of Natural Resources (formerly Department of Conservation), have produced numerous ground-water resource studies for portions of the White and West Fork White River basin.

Some of the earliest of these cooperative studies describe the ground-water resources of a number of southwestern Indiana counties within the White River basin, including: Greene County (Watkins and Jordan, 1961), Clay County (Watkins and Jordan, 1962b), and Owen County (Watkins and Jordan, 1963b); the authors published well logs, delineated which lithologies were aquifers, and evaluated ground-water availability.

The U.S. Geological Survey in cooperation with the Indiana Department of Conservation also prepared some of the earliest descriptions of ground-water quality in areas of the West Fork White River basin. They developed basic data reports on the ground-water resources for several counties in the basin.

Table 1. Area of Indiana counties within the West Fork White River Basin

County	Total Area (sq. mi)	In-basin Area (sq. mi)	Percent of county in basin	Percent of total basin area
Boone	423.49	158.45	37.41	2.83
Brown	316.60	70.72	22.34	1.26
Clay	359.34	295.72	82.29	5.28
Clinton	403.66	2.51	0.62	0.04
Daviess	435.44	318.99	73.26	5.70
Delaware	397.62	274.96	69.15	4.91
Gibson	500.56	36.09	7.21	0.64
Grant	415.37	0.17	0.04	0.00
Greene	543.93	499.15	91.77	8.92
Hamilton	401.68	401.68	100.00	7.17
Hancock	307.15	38.96	12.69	0.70
Hendricks	407.08	402.54	98.88	7.19
Henry	393.89	100.55	25.53	1.80
Johnson	320.99	122.04	38.02	2.18
Knox	523.37	293.89	56.15	5.25
Madison	451.62	426.36	94.41	7.62
Marion	402.98	352.56	87.49	6.30
Martin	342.05	23.74	6.94	0.42
Monroe	407.68	182.11	44.67	3.25
Montgomery	505.76	0.01	0.00	0.00
Morgan	410.56	410.56	100.00	7.33
Owen	386.69	386.69	100.00	6.91
Parke	447.46	3.88	0.87	0.07
Pike	341.01	71.14	20.86	1.27
Putnam	484.31	388.76	80.27	6.94
Randolph	452.31	156.97	34.70	2.80
Sullivan	452.64	26.99	5.96	0.48
Tipton	259.73	125.15	48.18	2.24
Vigo	410.26	27.27	6.65	0.49
Total	11905.22	5598.61		100

These reports contain brief descriptions of the levels of major constituents in well samples from these counties

Cable and others (1971) of the U.S. Geological Survey prepared a report on hydrogeology of the principal aquifers in Vigo and Clay Counties. This report includes a description of ground-water chemistry from partial analysis of over 750 water samples and complete analysis of 35 water samples.

Cable and Robison (1973) of the U.S. Geological Survey prepared a report on the hydrogeology of the principal aquifers in Sullivan and Greene Counties for the Department of Natural Resources, Division of Water. The report includes a description of ground-water chemistry from partial analysis of over 300 samples and complete analysis of 20 samples.

A report by Wangsness and others (1981) summarized available hydrologic data for an area that includes the lower half of the White River basin downstream from Gosport, Indiana. The report includes surface-water, ground water, and water-quality information.

In the northern part of the basin, many studies have also been completed on ground water. A series of reports by the U.S. Geological Survey describes the ground-water resources of five counties within the northern part of the basin: Madison (Lapham, 1981), Delaware (Arihood and Lapham, 1982), Hamilton and Tipton (Arihood, 1982), and Randolph (Lapham and Arihood, 1984). The authors of these studies examined the hydrogeology of the White River basin within each respective county and modeled expected yields given a variety of pumping schemes, geohydrologic characteristics of the aquifers, and locations of induced recharge.

Other studies that focused on northern counties in the basin include reports on the hydrogeology of Delaware County (Hoggett and others, 1968), Madison County (Wayne, 1975), and Hamilton County (Gillies, 1976). Studies of the outwash aquifer along the White River in Marion County (Meyer and others, 1975; Smith, 1983) focused on the characteristics of the aquifer and modeling of the hydrology and water availability for Indianapolis.

Bailey and Imbrigiotta (1982) studied the outwash aquifer along the White River in Johnson and Morgan Counties to estimate the geometry and hydraulic characteristics of the aquifer and to establish the nature and extent of the hydraulic connection between surface and subsurface hydrology

Nyman and Pettijohn (1971) studied the hydrogeology of the entire White River basin. The report is a brief description of the important aquifers in the basin, and includes information on well yields and potential yields, ground-water quality, and ground-water discharge to the major streams in the basin.

Jacques and Crawford (1991) of the U.S. Geological Survey conducted a major study from 1991-97 for the White and East Fork White River basins as part of the National Water-Quality Assessment Program. The study assessed the water quality of the surface- and ground-water resources of the White and East Fork White River basins. The U.S. Geological Survey published numerous reports as offshoots from the National Water-Quality Assessment Program.

Hoover and Durbin (1994) of the U.S. Geological Survey prepared maps and cross-sections of aquifer types in the White and West Fork White River basin for ground water protection purposes.

Acknowledgements

The Indiana Geological Survey made significant contributions during the preparation of this report

The authors of this report thank residents of the White and West Fork White River basin for their cooperation during a 1989-1990 ground-water sampling project. In addition, well-drilling contractors contributed water-well records and cooperated with a *gamma-ray* logging project.

The project manager extends special appreciation to former staff members of the Basin Studies Section: Kimberly A. Wade, Cynthia J. Clendenon, Timothy Kroeker, Sally Letsinger, and Surender Sayini for the invaluable contributions they made to the study.

GEOLOGY

Geology of the West Fork White River basin affects water-resource availability by influencing the distribution of precipitation between surface-water and ground-water regimes. Near-surface geology greatly influences *topography* and soil development that, in turn, control runoff and *infiltration* of precipitation. Geology also helps control movement and storage of surface water and ground water.

Perhaps the largest single geologic influence upon the availability of the water resource in the West Fork White River basin has been that of glaciation. During the *Pleistocene* Epoch (Ice Age), *glacial lobes* repeatedly entered Indiana from at least three directions (figure 2). The glacial episodes altered all aspects of the area's hydrology and hydrogeology. Because each successive advance and retreat of glacial ice caused erosion and redeposition of earth materials, glacial sediments and their hydrogeologic properties are very complex.

Little is known about the basin's oldest glacial deposits or the glacial episodes that produced them. This report therefore focuses on the most recent glacial episodes. Most of the landforms in the northern part of the basin were produced by these glacial and subsequent events. These deposits contain most of the readily available ground-water resources.

In the northern portion of the basin, although productive *carbonates* are available, most ground-water resources occur in unconsolidated aquifers of glacial origin. In the southern part of the basin, although not very productive, bedrock aquifers are most often used because overlying unconsolidated materials are shallow and less productive.

The White and West Fork White River basin because of its size, shape, and location (plate 1) includes rocks from nearly all the geologic column for the state. A comprehensive discussion of the geology of the basin is beyond the scope of this report. Rather, an overview of the geology is presented to provide a context in which to place the hydrogeology and ground-water quality discussions prepared by the Division of Water.

Sources of geologic data

Basic geologic data and numerous geologic studies were used to prepare this report. The basic geologic data include water well records, oil and gas records, coal data, engineering borings, *seismic* studies, geophysical logs, and *exposure* descriptions.

Much of the information about aquifer systems, *lithology*, and bedrock topography in the basin was derived from water well records. More than 35,000 field-located water well records for the West Fork White River basin are on file with the Indiana Department of Natural Resources, Division of Water, Ground Water Section. Since 1959, water well drilling contractors have been required to submit to the Indiana Department of Natural Resources (IDNR) a record of all water wells drilled in the state, including information about the geologic materials penetrated. Although these records are not always complete and the quality of the data varies, these water well records are the most comprehensive set of subsurface geologic and hydrogeologic data existing for the basin.

A significant portion of the physiographic and glacial geology information for the basin was derived from two reports: "Physiographic Divisions of Indiana" (Gray, 2000) and "Atlas of Hydrogeologic Terrains and Settings of Indiana" (Fleming and others, 1995). Much of the bedrock geology information was taken from the "Compendium of Paleozoic Rock-Unit *Stratigraphy* in Indiana-A Revision" (Shaver and others, 1986) and "Structure and Isopach Maps of the Paleozoic Rocks in Indiana" (Rupp, 1991). Many additional sources of geologic information are listed in the **Selected References** chapter of this report.

Oil and gas records and maps from the IDNR, Division of Oil and Gas and the Indiana Geological Survey, although of limited value to the overall study, provided basic information necessary to identify major *lithologic* sequences and areas of petroleum exploration.

Regional *Physiography*

The modern landscape of northern and central Indiana reflects a predominance of glacial influence, but the drift is thinner in central Indiana than in the northern part of the state and in many places, especially along streams, bedrock appears at or very near the surface. The landscape of southern Indiana reflects a predominance of bedrock influence.

Malott (1922) divided Indiana into nine *physiographic regions* according to topography and the effect of glaciers on the landscape. Relatively minor revisions have been made to his definitions until recently (Gray, 2000). In his "Physiographic Divisions of Indiana", Henry Gray redefines and describes physiographic sections of Indiana by grouping them into four regions: the Northern *Moraine* and Lake Region, the Maumee Lake Plain Region, the Central *Till Plain* Region, and the Southern Hills and Lowlands Region (figure 3). Within each region, he provides boundaries and descriptions of further subdivisions. He also compares and contrasts the newly defined sections to Malott's divisions. Gray's definitions of Indiana's physiographic regions were strongly influenced by recent interpretations of Indiana's glacial geology by Fleming and others (1994). The following descriptions of physiographic regions in the West Fork White River are taken almost entirely from Gray's report.

Central Till Plain Region

This region, extending across Ohio, Indiana, and Illinois, is a region of limited topographic diversity. It is nearly coincident with Malott's (1922) Tipton Till Plain except along the southeastern margin. Gray has extended the southeastern boundary of Malott's *till* plain to the Wisconsin glacial boundary. The Central Till Plain Region occupies the northern half of the West Fork White River basin (figures 3 and 4). The source of surface material throughout most of this region in the West Fork White River basin is till of eastern, or Huron-Erie Lobe origin.

Gray adopted the name Central Till Plain for this region and subdivides it into sections based, in part, on the "terrains" observed by Fleming and others (1994). The sections of the Central Till Plain Region that fall within the West Fork White River basin include (figure 4):

- the **Bluffton Till Plain**, large areas of till plain with a concentric series of *end moraines* (located along the northeastern fringe of the West Fork White River basin);
- the **New Castle Till Plains and Drainageways**, till plains of low relief crossed by many major tunnel-valleys that covers the northeastern headwater area of the basin;
- the **Tipton Till Plain**, a region of low relief with extensive areas of ice-disintegration features corresponding to the northwestern portion of the basin.

Southern Hills and Lowlands Region

The Southern Hills and Lowlands Region bounds the Central Till Plain Region on the south. The boundary that marks the southern limit of the Wisconsin glacial advances forms the definitive boundary between these two regions. The Southern Hills and Lowlands Region is the only part of the state that has not been profoundly affected by the latest (Wisconsin) glaciation. Bedrock is at or near the surface in much of the region and defines the character of the subdivisions within the region.

Although the overall effect of glaciation on the region has not been profound, the region was not entirely unmodified by glaciation. One or more pre-Wisconsin ice sheets covered nearly three-fifths of the region leaving extensive deposits that have since been modified extensively by erosion. Major rivers of the region, including the White, the Wabash and the Ohio, carried large volumes of *meltwater* that significantly modified the river valleys during Wisconsin time.

Gray's subdivisions of the Southern Hills and Lowlands region embrace Malott's (1922) seven physiographic divisions of southern Indiana. The common element in this region is that for the most part differences in bedrock character define the several sections. The major subsections of the Southern Hills and Lowlands Region that fall within the West Fork White River basin include (figure 4):

- the **Martinsville Hills**, bedrock hills of high relief strongly modified by pre-Wisconsin glacial activity covers a small area in Morgan, Putnam, and Owen Counties in the mid-section of the basin (a new transitional subdivision not recognized by Malott);
- the **Norman Upland**, bedrock hills of high relief encompassing portions of northwest Brown County and northeast Monroe County in the basin;
- the **Mitchell Plateau**, a rolling clay-covered upland of low relief and large areas of *karst*, entrenched by major valleys (in the basin occupies a narrow northwest-trending terrain that includes the town of Spencer in Owen County and Bloomington in Monroe County);
- the **Crawford Upland**, bedrock hills of high relief that extend through the center of Owen, eastern Greene, and southwestern Monroe counties in the basin; and
- the **Wabash Lowland**, broad terraced valleys and low till-covered hills in much of the southwestern portion of the basin.

Overview of glacial history and glacial deposits

The West Fork White River basin is characterized by a variety of landscapes and unconsolidated deposits. The great majority of glacial deposits in the basin represent the main or maximum episode of glacial activity during late *Wisconsin Age*, which took place between about 22,000 and 10,000 years ago.

The great variability in thickness of the unconsolidated sediments in the southern and northern parts of the basin, generally less than 100 feet and 100 to 200 feet, respectively (figure 5), is an indication of the differences in glacial activity in the northern and southern parts of the basin. In the northern part of the basin where glacial activity was prominent, thicknesses of more than 400 feet of unconsolidated deposits occur in some areas.

Most deposition associated with glaciers takes place at or near the ice margin. The particular type of deposit and its expression as a landform depend on the dynamics of the glacier, the mechanics of sediment transport within the glacier, and the method of sediment deposition.

Through time, accumulation of ice toward the center of a glacier is balanced by melting at and near the margin. This equilibrium has two important consequences. First, the outward flow of ice within the glacier transports sediment to the ice margin where it is deposited by a variety of processes. Second, the melting ice front feeds meltwater streams that flow both away from and parallel to the ice margin. The high energy typical of most meltwater streams results in the removal of silt and clay from the glacial debris. This process commonly concentrates sand and gravel in the form of *outwash* deposits. Within a depositional system, the relative coarseness of the outwash sediments tends to decrease with increasing distance from the ice front. Outwash bodies range from narrow and discontinuous channels to broad, regionally extensive plains and *fans*. The detailed geometry of outwash bodies depends on such factors as the configuration of the landscape over which the meltwater flows, the size and location of meltwater outlets from the ice front, the sediment load each meltwater stream carries, and the behavior and duration of the ice front at a particular location.

Outwash constitutes several landforms within the West Fork White River basin (plate 2). It forms *valley trains* along the White River, Fall Creek, Eagle Creek, Mud Creek, other tributaries, and numerous high-level channels, as well as broader fans like the one referred to by Fleming and others (1995) as the Glenns Valley fan in the vicinity of Greenwood. Some of the outwash units that occur in central Marion and

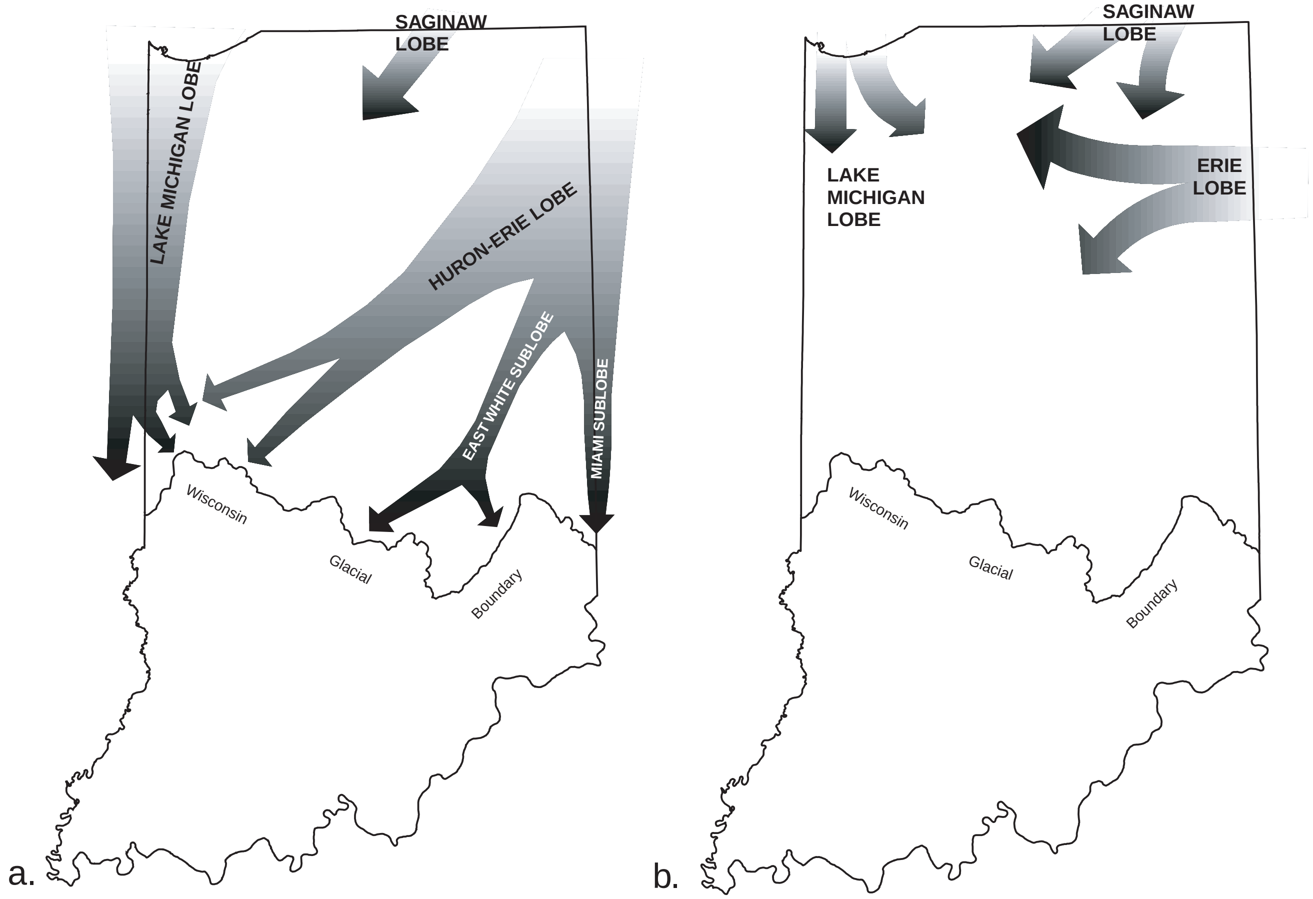


Figure 2. Sketch maps showing generalized flow direction of the several ice streams that made up the Wisconsin glacier in Indiana: a) about 20,000 years ago; b) about 15,000 years ago. Because of the vacillating activity of the several lobes and in some places extensive overriding of one lobe over another, it is not possible to show lobe margins in any meaningful way. Figure adapted from Henry H. Gray, 2000.

extend to northwestern Johnson and northeastern Morgan counties appear to comprise an extensive *outwash plain* that was deposited as the Huron-Erie Lobe advanced. The outwash plain is typically underlain by thick, composite sections, although lenses and sheets of till locally divide the outwash into discrete aquifers (Fleming and others, 1995). Large buried outwash bodies also occur at many places within the basin.

Outwash plains and *sluiceways* tend to be relatively channelized features associated with major river valleys. Most were formed episodically and exhibit complex intertongueing relationships with various sand and gravel bodies and with certain *till* units along their flanks. Most of these terrains are broad alluvial plains flanked by a variety of *outwash terraces* and fans. The primary distinction between outwash plains and sluiceways is one of relative dimensions; the former tend to be much broader, generally flatter in overall aspect, and tend to blend into adjacent terrains, whereas the latter tend to form well-developed troughs that may be significantly entrenched into surrounding terrains. The White River and its major tributaries form northeast-to-southwest trending sluiceways between Muncie and Indianapolis. The White River and its major tributary the Eel River form major sluiceways in southwestern Indiana (plate 2).

The land surface over the greater part of the West Fork White River basin is underlain by glacial till, a fine- to medium-grained, poorly-sorted sediment that was transported near the base of the glacier and deposited directly by ice with minimal reworking by meltwater and *mass movement*. Most till contains scattered rock fragments set in an *overconsolidated* fine-grained matrix. Each ice advance tends to produce a characteristic till sheet that can usually be distinguished from other till sheets on the basis of grain-size distribution, combinations of rock and mineral fragments unique to a particular source area, and other diagnostic attributes. The relative proportions of sand, silt, and clay that form the matrix of any particular till unit depend on the *source area* of the glacier as well as on the kinds of processes that release the sediment from the ice.

The surface tills in most of the West Fork White River basin are part of the Trafalgar Formation (Wayne, 1963) of the Huron-Erie Lobe, and are typically silty or *loamy* in texture and are dominated by particles derived from a mixed bedrock source (plate 2).

A common type of terrain related to till deposits is a till plain-generally a gently rolling to nearly flat landscape that formed during relatively uniform deposition of till from a retreating ice margin. This type of depositional pattern appears to have repeated itself many times over large parts of central Indiana, resulting in a thick stack of till units, with the boundaries between the till units essentially representing buried former till plain surfaces.

Debris flow deposits are a significant component of the

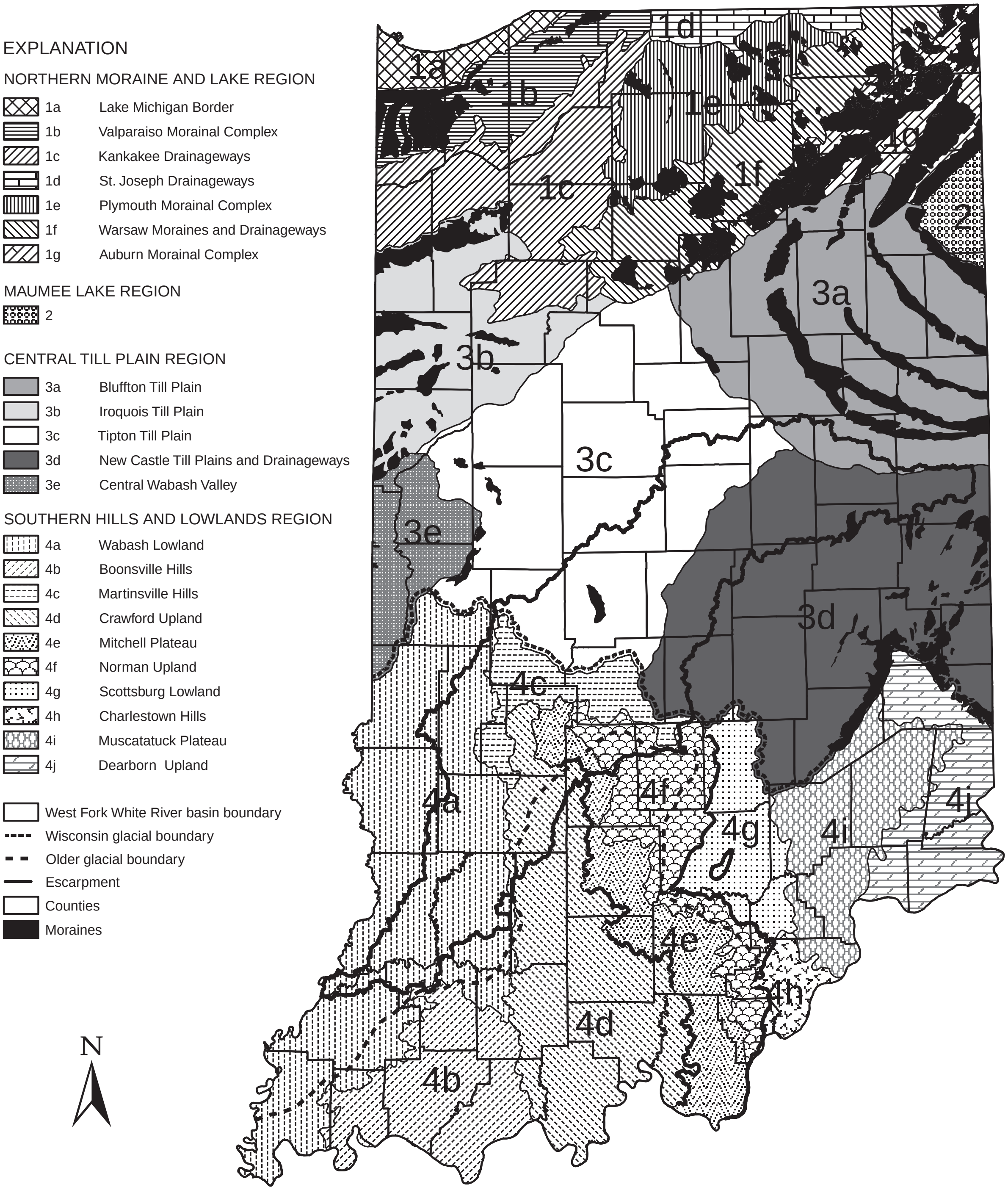


Figure 3. Physiographic divisions of Indiana (adapted from Gray, 2000)

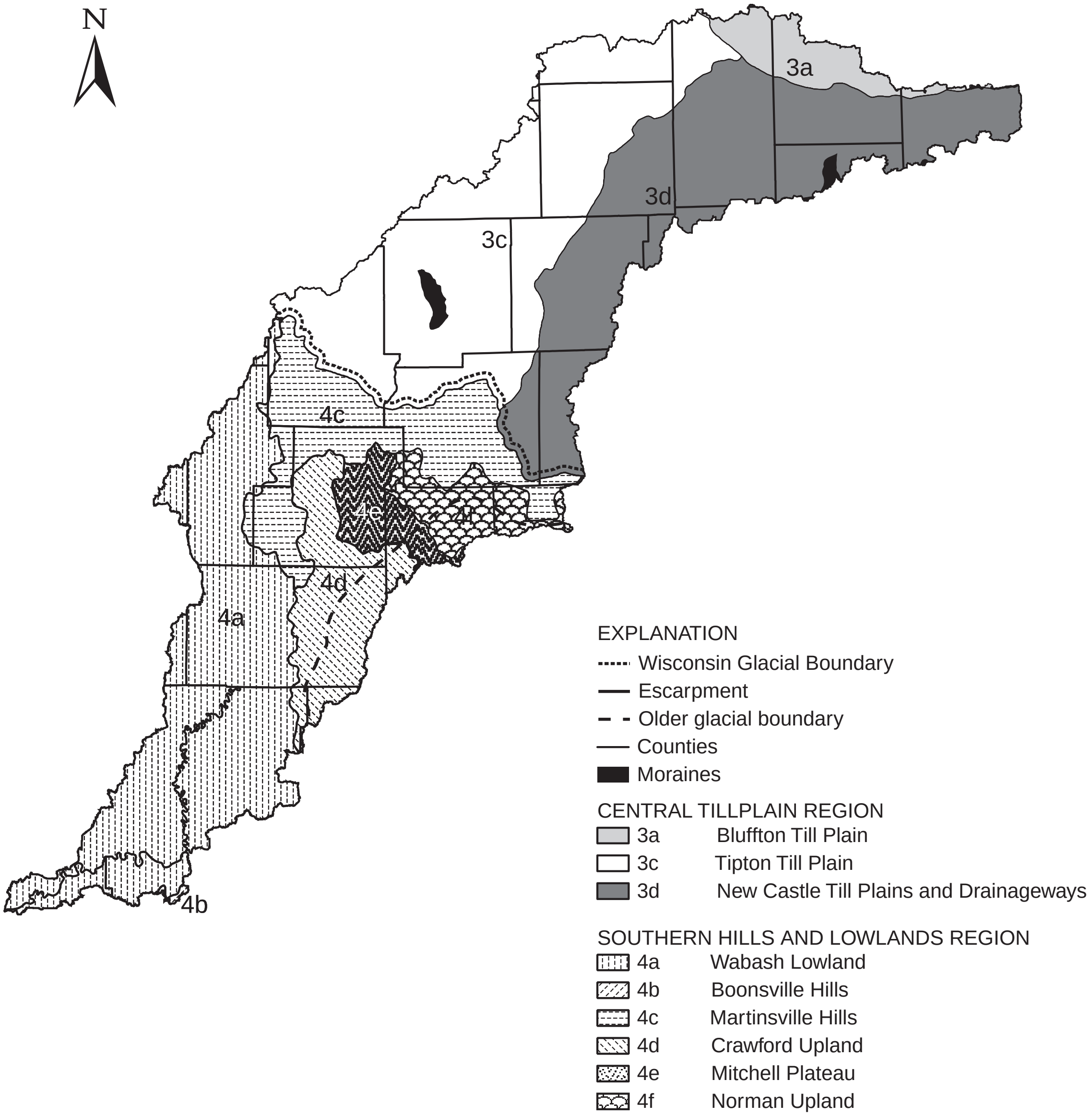


Figure 4. Physiographic divisions of the White and West Fork White River basin (adapted from Gray, 2000)

glacial sediments in the West Fork White River basin. Although a variety of processes can be involved in the formation of these mass movement deposits, most debris flows of glacial origin form when the loss of supporting ice induces the slumping and sliding of recently thawed supersaturated sediments. Many debris-flow deposits closely resemble glacial till and are sometimes referred to as *flow tills* and *mud flows*. Because of their similarity, the distinction between debris flows and true glacial till can be problematic in Pleistocene deposits. This is especially true where the two occur together in the subsurface within the same depositional sequence. It is best in such instances, therefore, to refer to the entire assemblage as *till-like sediment*, which acknowledges the variety of processes and sediment types represented.

Debris flows can be formed from almost any kind of preexisting sediment and are found in widely scattered places in the northern glaciated part of the West Fork White River basin. However, flowage of glacial sediments was most commonly triggered by the melting of adjacent or *subjacent* ice blocks. Hence, debris flows are most abundant where they are associated with bodies of *ice-contact stratified drift*. The latter are composed mainly of sand and gravel deposited by meltwater in, on, or against disintegrating ice. Subsequent melting of the surrounding ice caused these sediments to collapse, giving them their characteristically irregular form. Common types of ice-contact stratified deposits include narrow, linear, and commonly sharp-peaked ridges of sand and gravel referred to as *eskers*; and irregular masses of sand, gravel, and till-like sediment known as *kames*, that range in shape from semi-conical mounds to broad-crested, *hummocky* ridges. Good examples of ice-contact drift are present in southern Madison and northern Hancock counties. Debris-flow deposits are common in southwestern Randolph, southeastern Delaware, and northeastern Henry counties in the area of collapsed *tunnel valleys* (plate 2).

Ice-contact stratified deposits, debris flows, small bodies of outwash in channelized form, and localized pond sediments commonly occur together as *ablation complexes* formed during the melting of an ice sheet. Ablation complexes can be quite thick and widespread when large debris-covered parts of an ice lobe become stagnant and melt via the process of downwasting. In the northern part of the basin, large-scale *ablation* deposits occur within which individual sediment bodies commonly have little homogeneity and extent. Such deposition appears to have predominated in certain parts of the central till plain (Fleming and others, 1995).

Lakes were widespread during and after glaciation, and small to very large bodies of *lacustrine sediments* can be found embedded within sequences throughout the *glacial terrains*. Deposits that formed in glacial lakes are widespread in the West Fork White River basin, particularly along former ice margins where meltwater was impounded by ice or debris. Because these ice margins shifted over time, most of the glacial lakes were ephemeral features with generally little accumulation of *lacustrine sediments*.

In the northern part of the basin, most of the lakes are shallow post-glacial; a few are located in Delaware County and southern Madison County southwest of Anderson. Another group are also located in southern Boone and northern Hendricks counties in the upper Walnut Creek *watershed* (plate 2).

Various kinds of glacial and *periglacial* lakes existed at many places in southern Indiana during the Wisconsin and *pre-Wisconsin* glaciations. Many of these were created when rapid outwash deposition along the major rivers caused tributaries to become blocked, creating extensive *slackwater* lakes that extended upstream for miles. In the West Fork White River basin, slack water deposits are most abundant in western Greene County; large areas also extend into Knox and Daviess County near the White River valley. Extensive *glaciolacustrine* sequences of predominantly fine-grained aspect filled large bedrock valleys in many of these tributaries. Other lake basins came into existence as *proglacial* lakes in front of various ice margins in southeast and southwest Indiana. Many of these basins covered tens or hundreds of square miles, and some also occupied large bedrock valleys, resulting in major sequences of lacustrine sediments.

Summary of major Quaternary deposits in the West Fork White River basin

The unconsolidated deposits in the West Fork White River basin are many and varied. Describing them in detail is beyond the scope of this report. A brief description of major Quaternary deposits, as described and mapped by Gray, 1989, follows. The major Quaternary deposits occurring in the basin are generally described, from north to south (plate 2).

In the northeastern part of the White and West Fork White River basin, a large area of Wisconsin Age is composed of silty clay-*loam* to clay loam till of the Lagro Formation.

Most of the northern part of the West Fork White River basin is described as loam till of the Trafalgar Formation of Wisconsin Age. In Putnam, western Hendricks, and parts of Morgan counties, the somewhat older Trafalgar Formation loam till occurs. Cutting across these vast expanses of loam till are a couple of large areas, one in Delaware County south of the city of Muncie and the other in Boone County southwest of the town of Lebanon, that are described as complex or mixed drift that includes till and stratified drift in lineated form that are an indication of collapse associated with subice tunnels and open ice-walled channels.

Another major type of Quaternary deposit that transverses the till plain following the valleys of major streams and their tributaries is undifferentiated outwash, mainly as valley train sand and gravel of the Atherton Formation. These outwash deposits also traverse other Quaternary deposits and bedrock along the valleys of major streams and their tributaries. Superimposed upon some of these ice age outwash deposits are *alluvial* deposits of silt, sand, and gravel deposited by present-day streams.

Adjacent to the Eel River valley in Hendricks, Putnam, Owen, and Daviess counties are deposits described as a lowland silt complex that is comprised of poorly stratified sand and silt, in part alluvial and *colluvial* and in part windblown. Where present as terrace remnants in narrow valleys, this material has been assigned to the Prospect Formation.

Wisconsin age lacustrine silt and clay deposits formed as slack-water deposits of finger lakes adjacent to major outwash-carrying streams in southern Indiana are abundant in western Greene County; large areas also extend into Knox and Daviess Counties near the White River valley

South of the Wisconsin glacial limit, therefore of pre-Wisconsin age, there are mapped deposits that are capped by a thick *relict* (presumable Sangamonian) paleosol and a surface layer of loess as much as 5 feet thick. Forming a fringe along the southern margins of the loamy Trafalgar tills in southwestern Putnam, western Owen, Clay, Greene, and Daviess counties are the older loam to sandy loam tills of the Jessup Formation. Other pre-Wisconsin deposits mapped in the basin include: undifferentiated outwash, mainly as isolated scraps of valley train sand and gravel; mixed drift of till and stratified drift in chaotic form; loam to sandy loam till of the Jessup Formation; and lake silt and clay in terrace remnants of slack-water deposits of finger lakes adjacent to outwash-carrying streams.

Large areas in the southern half of the basin encompassing much of Clay, Knox, Daviess, Pike, and Gibson counties are overlain by loess or windblown silt.

There are also areas in the basin that have little or no Quaternary deposits, including large portions of southwestern Morgan, northwestern Monroe, eastern Owen and eastern Greene counties. In these areas, bedrock crops out or lies beneath a relatively thin cover of unconsolidated deposits. In areas beyond the glacial limit, the unconsolidated deposits include regolith and *colluvium* that in part are pre-Quaternary in age. In most places these deposits have a surface layer of loess that is less than 3 feet thick. In areas that have been glaciated, the unconsolidated deposits commonly are similar to those in adjacent areas (Gray, 1989).

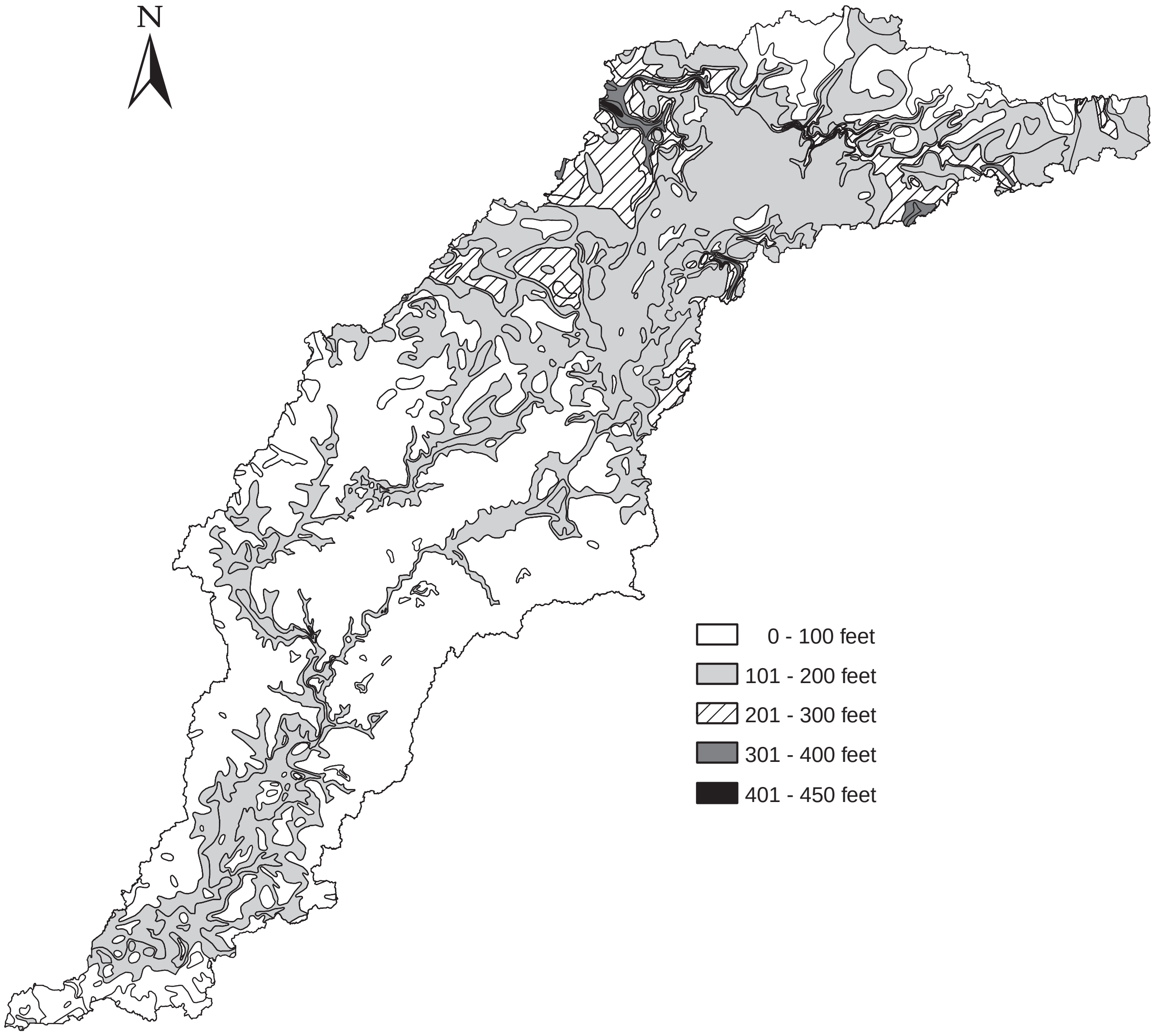


Figure 5. Thickness of unconsolidated deposits (adapted from Gray, 1983)

Glacial terrains

The previous sections dealt mainly with regional aspects of basin physiography and unconsolidated deposits. The following discussion emphasizes the relationships between internal sequence elements, landscape characteristics, and geologic processes within specific glacial terrains to provide a context for evaluating the availability of ground water and its relationship to surface water and to human activities at the land surface.

The relationship between landforms and underlying depositional sequences can be represented by the concept of glacial terrains. A glacial terrain is a geographically defined feature characterized by a particular type of landform or group of related landforms, and a closely associated sequence of sediments that constitute said landforms. Based on this definition, both the landforms and the underlying sediments in a terrain are indicative of a particular type of depositional environment. A glacial terrain is therefore expected to possess a characteristic range of physical properties that strongly influence surface water hydrology, the movement of ground water, soil development, and a host of other environmental attributes. Definition and analysis of glacial terrains thus provide a basis for understanding the geologic history of the basin as well as the distribution and character of a variety of important hydrogeologic parameters.

A study was initiated at the request of the Office of the Indiana State Chemist (OISC) to develop maps of hydrogeologic terrains and settings for Indiana. The hydrogeologic setting represents a basis for classifying and describing the relationships between ground water and the geologic terrains it occurs within. The resultant maps and descriptions were intended to support the Office of the Indiana State Chemist to develop the state pesticide management plan. Funding was provided by OISC and the U.S. Environmental Protection Agency. The mapping was a cooperative effort between the Indiana Geological Survey and the Department of Natural Resources, Division of Water.

The results of the study are in an atlas format "Atlas of Hydrogeologic Terrains and Settings of Indiana" (Fleming and others, 1995). Approximately 225 individual hydrogeologic settings and terrains are organized within larger hydrogeologic systems contained within eight individual sections. The text descriptions and associated schematic diagrams in the report are intended to accompany a set of 1:100,000 maps depicting glacial terrains, hydrogeologic settings, and several of their internal elements. As many as six types of coverages exist for each of the 35 individual 1:100,000 quadrangles that cover Indiana. These maps are primarily available as digital coverages and are intended for use in a geographic information system, such as ARC-INFO, or in such software design packages as AUTOCAD. Paper and (or) mylar versions of the coverages may be viewed by appointment at the offices of the Indiana Geological Survey.

The West Fork White River basin has 57 of the 225 individual hydrogeologic settings and terrains within its boundaries. Describing all of the mapped terrains is beyond the scope of this report. Therefore, a general overview is presented on major settings in the basin. The following descriptions are taken largely from Fleming and others, 1995. Plate 2 and figures 3 and 4 are helpful to understanding the following descriptions.

Central Till Plain

The Central Till Plain is a vast, nearly featureless plain that occupies the mid-section of Indiana and extends east and west through Ohio and Illinois. It generally corresponds to much of the area known as the "Tipton Till Plain" (Malott, 1922; Schneider, 1966). The unconsolidated deposits that form this landscape are primarily a result of the major Wisconsin glacial episode; therefore the southern boundary of the plain is the southernmost limit of Wisconsin glacial deposits. The depositional sequences and landscapes of the glacial deposits are very similar across the plain although they were formed by different ice lobes that advanced and retreated over a long period of time. The northern boundary of the plain is generally defined by somewhat younger glacial events and is, in places, marked by greater relief in the landscape. The major drainage feature of the till plain is the Wabash River.

In central Indiana, sequences associated with particular glacial episodes tend to be widespread, reflecting a gradual shift of ice margins that resulted in relatively uniform deposition of widespread blankets of sediment. Repetition of this pattern during successive glacial episodes led to numerous, areally extensive sequences being stacked atop one another.

The Central Till Plain is subdivided by Fleming and others (1995) into twelve segments or subdivisions differentiated by subtle contrasts in features of a transitional nature. Such features include: the general thickness and character of glacial sequences; the type of bedrock; character and depth of the bedrock surface; and landscape patterns that are or may be suggestive of certain conditions. Most of the segments contain from two to five internal terrains.

The limited relief of the plain results in poorly drained landscapes, characterized by very broad troughs or *swales*. Large parts of the till plain surface are underlain by extensive ablation complexes that are characterized by a variable thickness of interbedded mud flows, small sand and gravel bodies, silt units, and thin loamy tills. These complexes were deposited during large-scale disintegration of ice sheets in central Indiana. These deposits overlie one or more *basal till* units in many places, which tend to be highly overconsolidated and very slowly permeable.

The northern half of the West Fork White River basin lies within the Central Till Plain glacial terrain.

Southern Regions

The area south of the Wisconsin glacial boundary is differentiated into three regions based on the effects of pre-Wisconsin glaciation. These include the southeastern and southwestern glaciated regions, and the south-central driftless (unglaciated) area. The southeastern and southwestern glaciated regions were affected by one or more pre-Wisconsin glacial episodes and have, at least locally, significant thickness of unconsolidated sediments. The thickness and continuity of the glacial deposits in both of these regions decrease southward; unconsolidated sediment thus becomes less of a significant hydrogeologic factor relative to the bedrock. The south-central driftless (unglaciated) region appears to have not been directly affected by glaciation.

Fleming and others (1995) further subdivide these three regions into various segments according to the presence and nature of glacial deposits, the type of bedrock, and especially, the nature of the landscape and its relation to the bedrock surface and to surface water-ground water interaction.

The southern settings are crossed or fringed by several large sluiceways that contain massive outwash and alluvial sequences. These sluiceways are the most significant hydrogeologic entities in southern Indiana.

The southern half of the West Fork White River basin lies within the Southern Region glacial terrains.

Southwestern Glaciated Region Overview

The southwestern glaciated region lies within the western half of the southwestern quarter of the state. It is bounded on the west by the Wabash River Valley and on the south by the Ohio River Valley. The Crawford Upland forms a transitional eastern boundary on which unconsolidated sediments feather out. The southwestern glaciated region consists primarily of a north-south trending area of glacial and *periglacial* deposits that is generally centered on the area between the Wabash River and the West Fork White River.

The region is predominantly a moderate-relief upland interspersed with a large number of small to very extensive bottomlands. It is also crossed or bounded by several deeply incised large sluiceways. These sluiceways are commonly flanked by extensive low-lying areas of lake sediment formed in slackwater lakes when tributary valleys became blocked by outwash. The Eel River Valley is an example of one of the major sluiceways in this region of the West Fork White River basin.

A major feature of the region is the variety of periglacial sediments that were not deposited directly by glaciers or their major meltwater streams, but are an indirect result of glaciation. Examples are windblown, *colluvial*, and lake sediments.

The region is divided by Fleming and others (1995) into six main upland settings based on: the relative predominance of glacial versus periglacial sediments and their relationships to one another; the composition and water-bearing properties of the bedrock; the morphology of the bedrock surface; the internal surface morphology of the setting and its effect on water movement; and the general thickness and continuity of the unconsolidated cover.

Most of the southern half of the West Fork White River basin lies within this glacial terrain.

Southeastern Glaciated Region Overview

The southeastern glaciated region encompasses most of southeastern Indiana. It extends from the Ohio River northward to the Wisconsin glacial boundary and westward to the pre-Wisconsin glacial boundary (figure 3). The region is primarily a broad upland, but it has both uplands and lowlands in the west. Its western boundary extends slightly westward of the prominent Knobstone *Escarpment*.

The southeastern region is composed of five main upland settings (Fleming and others, 1995). These terrains are distinguished mainly on the basis of their internal morphology, predominant bedrock lithologies, and the character of unconsolidated cover.

Only a small portion of the southeastern region is included in the White and West Fork White River basin (northern Monroe, northwestern Brown, far southwestern tip of Johnson, and southern Morgan Counties).

South-Central Driftless Area

The south-central driftless (unglaciated) area is a broad upland located between the southwestern and southeastern glaciated regions (figure 3). It is bounded on the east and west by rugged escarpments and on the south by the Ohio River. The outcrops of its relatively resistant Upper Paleozoic rocks define its regional morphology. Most of the area has little or no unconsolidated cover.

Hydrogeologic settings are broadly defined by Fleming and others (1995) for the driftless area and generally correspond to the respective distribution of the different bedrock units mapped in this area and their associated physiographic regions.

Only the unglaciated portions of physiographic regions 4d, 4e, and 4f (figure 4) are within the West Fork White River basin.

Bottomlands south of the Wisconsin Glacial Margin Overview

A variety of bottomlands occur throughout southern Indiana. These include sluiceways, basins of former glacial lakes, and alluvial bottoms along streams that were not directly affected by meltwater. The majority of these are concentrated within the southeastern and southwestern glaciated regions; however, some large sluiceways cross the unglaciated region, and a number of former lake basins and alluvial bottoms are also present in or along the margin of that area (Fleming and others, 1995).

The bottomlands in southern Indiana commonly contain the thickest sequences of unconsolidated sediments south of the Wisconsin margin. In addition, they are often associated with large bedrock valleys, and the sluiceways in particular contain significant quantities of both late Wisconsin and pre-Wisconsin outwash (Fleming and others, 1995). These outwash deposits are the major ground-water resource for the entire southern part of the state.

Three major sluiceway systems are present in the West Fork White River basin: West Fork White River, Eel River, and Big Walnut Creek. Raccoon Creek sluiceway also extends south of the Wisconsin margin at places, but its origin and character are closely tied to that of the central till plain.

Bedrock geology

Bedrock of the West Fork White River basin consists of *sedimentary rocks* deposited during the **Paleozoic Era** that lie upon much older **Precambrian** crystalline rocks (plate 1). The sidebar entitled *General History of Bedrock Deposition in Central and Southwestern Indiana* summarizes the major depositional environments found in the West Fork White River basin during the Paleozoic Era. The sedimentary rocks in the basin were deposited during the **Cambrian** through **Pennsylvanian** periods of the Paleozoic Era, and include *carbonates, sandstone, shale,* and coal. A broad uplift or upward bow of the bedrock surface known as the **Cincinnati Arch** (figure 6) controls the regional bedrock structure in the West Fork White River basin. The axis of the Cincinnati Arch extends north-northwest from Cincinnati, Ohio into Randolph County, Indiana. To the north, the arch splits into two branches, a northwest branch known as the Kankakee Arch that passes through northwest Indiana, and a northeast branch known as the Findley Arch that extends across Ohio to Lake Erie. The West Fork White River basin is positioned on the southwest-dipping flank of the Cincinnati Arch.

The northwest branch of the Cincinnati Arch (Kankakee Arch) defines the northeastern limit of a large sedimentary basin called the **Illinois Basin**. The crest of the arch has been planed off by erosion, and as a result, the oldest rocks that occur at the bedrock surface are near the crest of the arch, and progressively younger rocks are exposed at the bedrock surface sloping away from or *down-dip* from the arch into the neighboring Illinois Basin. The angle of dip of the individual rock units increases from northeast to southwest in the West Fork White River basin off the crest of the arch and into the Illinois Basin (figure 6 and plate 1).

The Paleozoic rock sequence in the West Fork White River basin also thickens in the down-dip direction. The coincidence of increasing thickness of individual Paleozoic sedimentary rock formations and increasing angle of dip from the crest of the arch to the center of the basin may indicate basin subsidence and increased deposition during the Paleozoic Era (plate1).

The thickening of the sedimentary sequence and the increased angle of dip of the strata are the result of the position of the West Fork White River basin relative to regional *tectonic* features (plate 1). The northern portion of the area that is now the West Fork White River basin was located on the stable Cincinnati Arch during the middle and late Paleozoic Era, whereas the southern portion was located in the area of the actively subsiding Illinois Basin.

Tectonic events coupled with fluctuations in sea level have created a minimum thickness of sedimentary rocks of less that 3,500 feet in the northeastern corner of the basin and a maximum thickness of over 12,000 feet in the southwestern corner (Rupp, 1991, p. 8) (plate 1). Natural bedrock *exposures* are common south of the Wisconsin glacial boundary, but rare in the northern portion of the basin.

Other structural features, including two *faults*, have been mapped in the West Fork White River basin (plate 1). The larger of these two faults, the Fortville Fault, extends from south-central Marion County into north-central Madison County. A second fault, the Mount Carmel Fault, extends from just north of the southern line of Morgan County, south through Monroe County terminating in southeastern Lawrence County. Seismic activity associated with stresses that formed these two faults has been minor in recorded history. Additional faulting and seismic activity has occurred in southwestern Indiana, where most epicenters of historic earthquakes in the State have occurred. This historic activity has been very minor with little damage reported.

Unconformities that represent gaps of several hundred million years in the geologic record are present at several geologic *contacts* including: the Precambrian/Paleozoic, the Mississippian/Pennsylvanian, and the Paleozoic/Pleistocene.

Although several bedrock *unconformities* exist in the sedimentary sequence (sidebar entitled General History of Bedrock Deposition in Central and Southwestern Indiana), two periods of erosion significantly affected the near-surface bedrock underlying the West Fork White River basin. The earlier of these occurred during the middle Paleozoic Era, at the close of the Mississippian period resulting in one of the most widespread regional unconformities in the world. Not only was erosion areally extensive, but also over arches and domes it beveled away entire systems of older rocks.

The erosion of Mississippian rocks in the southern and western portions of the basin resulted in Lower Pennsylvanian units being deposited atop Upper Mississippian shales and sandstones. As erosion progressed along the dipping Mississippian strata, progressively older units were removed. In the central portions of the basin, basal Pennsylvanian (Mansfield Formation) sandstone overlies Middle Mississippian strata (West Baden Group).

A more recent period of erosion occurred between the end of the Paleozoic and beginning of the Pleistocene. Erosion associated with glaciation further scoured the bedrock surface during the Quaternary. While glacial processes were acting on most of the basin, a small portion of the present West Fork White River basin remained unaffected by glaciation, thus continuing the slow erosion processes (Wayne, 1956, p. 14; Gray, 2000)(figures 3 and 4).

When compared to the upper portion of the West Fork White River basin, a variety of sedimentary lithologies occur at the bedrock surface in the southern half of the basin. The lithologic variation in the southern half of the basin is the result of several interrelated factors: 1) the change in the angle of dip of strata associated with the Illinois Basin and the Cincinnati Arch; 2) changes in upper Paleozoic sedimentation; 3) the Mississippian/Pennsylvanian unconformity; 4) and post-Paleozoic Era erosion.

Bedrock physiography

The topographical characteristics of the bedrock surface are influenced by the bedrock types (plates 1 and 3a, b, and c). Bedrock relief in the West Fork White River basin is the result of *differential erosion* acting on the various bedrock surface lithologies. Units that are more resistant to erosion, such as limestone and sandstone, tend to form broad bedrock highs and steep valleys. Units less resistant to erosion, shale for example, tend to form more gently sloping structures. Total relief on the bedrock surface in the West Fork White River basin is more than 700 feet (plates 3a, b, and c).

Regional bedrock highs in excess of 1,000 feet above sea level exist in the headwater area of the West Fork White River basin, which is located in Randolph County (plate 3a). In the northern portion of the West Fork White River basin, Silurian Carbonates form the surficial bedrock units. Erosion of these carbonates has resulted in broad upland areas with deeply *incised* bedrock valleys. This area is part of the regionally extensive Bluffton Plain bedrock physiographic unit (Wayne 1956, p. 19, 29, Gray, 2000) (figure 7).

Regional bedrock lows are found near the mouth or southern portion of the West Fork White River basin. Named the Wabash Lowland (Gray, 2000), this area can be described as having gently sloping bedrock topography with few deeply incised valleys. The Wabash Lowland bedrock physiographic unit was developed through erosional processes acting on units of Pennsylvanian age that are comprised predominately of shales (plate 3c).

Bedrock physiography in the central portion of the West Fork White River basin differs from the northern and southern portions of the basin. In the central portion of the basin limestone, shale, and sandstone of the Mississippian System and sandstone and shale of the lower Pennsylvanian System form the bedrock surface (plate 3b). This area is representative of a portion of the Norman Upland and Scottsburg Lowland (Wayne, 1956, p. 19-23, Gray, 2000) (figure 3). In the central portions of the West Fork White River basin the combination of variable lithologies, geologic structure, and degree of glaciation has resulted in a bedrock surface that has dendritic drainage features exhibiting a wide variety of slopes and landforms.

Bedrock *stratigraphy* and *lithology*

The West Fork White River basin because of its size, shape, and location relative to the Cincinnati Arch and the Illinois Basin (plate 1) includes rocks from a large percentage of the bedrock units that occur in the state. Cambrian and Ordovician rocks form a large part of the Paleozoic sedimentary sequence of rocks in the West Fork of the White River basin; however, these lower Paleozoic rocks are not generally present at the bedrock surface in the basin. Rocks occurring at the bedrock surface generally range in age from latest Ordovician through late Pennsylvanian (plate 1). The following is a brief discussion of major sedimentary rock units that occur in the West Fork White River basin. Detailed discussions of structure, stratigraphy, and sedimentology of these sedimentary sequences may be obtained from several sources, including Shaver and others (1986) and Rupp (1991). Additional details of various rock groups are also included in the **Ground-Water Hydrology** chapter of this report.

Cambrian and Ordovician

Although rocks of the Cambrian and Ordovician Periods comprise most of the total sedimentary rock volume that overlie the Precambrian rocks in the West Fork White River basin (plate 1), this discussion is confined to only those rocks that outcrop near the bedrock surface because of their importance as a source of *potable* ground water. Detailed discussion of Cambrian through Ordovician sedimentation and structure in the basin can be found in Shaver and others (1986), Rupp (1991), Becker, Hreha, and Dawson (1978), Droste and Patton (1985), Droste and others (1982), and Gray (1972).

Upper units of the Maquoketa Group of Ordovician age form the bedrock surface in deep valleys in the northern portions of the West Fork White River basin. The Maquoketa Group consists of interbedded shales and limestones.

Silurian

The **Silurian System** *unconformably* overlies the Maquoketa Group throughout the West Fork White River basin, except for local areas where the Maquoketa forms the bedrock surface. It is predominately composed of limestone units with variable dolomitization and lesser amounts of shale. The Silurian makes up the bedrock surface throughout much of the northern part of the basin (plate1). For this report, discussion of the Silurian System is limited to the geographic area bounded by the West Fork White River basin to the north and east, and by the Devonian System outcrop to the south and west. The common thickness of Silurian age deposits in this area is approximately 250 feet (Rupp, 1991, p. 40). The Silurian System within this boundary is composed of the following rocks, in ascending order: Brassfield Limestone, Salamonie Dolomite, Pleasant Mills Formation, and Wabash Formation.

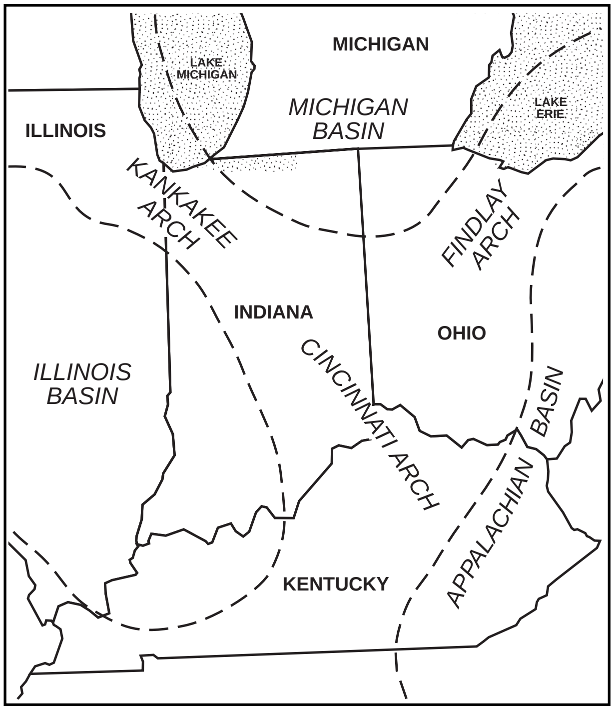


Figure 6: Regional bedrock structure

The basal unit in the Silurian System, the **Brassfield Limestone**, is generally a granular *fossiliferous* limestone having varying amounts of shale and some dolomite. In the extreme northern portions of the basin the Brassfield Limestone is in a *facies* relationship with the Manitoulin Dolomite and the overlying Cabot Head Shale Member of the northeastern Cataract Formation. The Brassfield may be absent in places, but is typically less than 20 feet thick and unconformably overlain by Salamonie Dolomite (Shaver and others, 1986, p. 20).

Where the Silurian System occurs near the bedrock surface in the West Fork White River basin the **Salamonie Dolomite** is mostly an off-white *bioclastic vuggy dolomite* approximately 50 feet thick, (Shaver and others, 1986, p. 131). Silurian *reef* complexes occur in the upper portion of the Salamonie but are most common in the overlying formations.

The **Pleasant Mills Formation** conformably overlies the Salamonie. The Pleasant Mills typically consists of rather pure carbonates with subtle lithologic differences. Reef complexes are common within the Pleasant Mills. In approximately the middle portion of the Pleasant Mills Formation lies an *argillaceous* member, the Waldron, that was formed during an interval of reef generation; whereas the lower Limberlost and the upper Louisville portions of the Formation were formed during intervals of reef abortions (Shaver and others, 1986, p. 115).

Conformably overlying the Pleasant Mills is the upper Silurian **Wabash Formation**. Within the area of *subcrop* in the West Fork White River basin the Wabash Formation consists primarily of three lithologies. In the lower portion of the formation is a silty dolomite to silty *dolomitic* limestone, the Mississinewa Shale. The upper portion of the Wabash formation contains the Liston Creek Limestone Member, a light colored limestone, dolomitic limestone, and dolomite that is fine grained and cherty. The third lithology commonly found in the Wabash Formation is associated with reef deposits. Lithologies associated with reefal material are characterized by light-colored massive granular vuggy dolomite and limestone with bluish-gray carbonate mudstone (Shaver and others, 1986, p. 163-164). Reef facies are also associated with the Pleasant Mills Formation and Salmonie Dolomite, although less commonly than the Wabash Formation. An unconformity separates the Wabash Formation from the overlying Devonian System.

Devonian

Where the **Devonian System** occurs near the bedrock surface in the central West Fork White River basin, it is composed of carbonates of the **Muscatatuck Group** with overlying New Albany Shale. In this area, the Muscatatuck Group is composed of carbonates of the Jeffersonville Limestone and the overlying North Vernon Limestone. A total thickness for the Group in the central portions of the basin is approximately 100 feet, with a range of 75 to 150 feet, (Rupp, 1991, p. 48). The Jeffersonville Limestone is a mixture of limestones that vary from pure and granular to shaley. An *arenaceous* zone at the base of the Jeffersonville Limestone forms a sandstone unit that is exposed in Fall Creek near Pendleton Indiana, thus the local and near-surface name, Pendleton Sandstone. Regionally this basal, Middle Devonian age sandstone is known as the Dutch Creek Sandstone. In the central portion of the basin, the North Vernon Limestone overlies the Jeffersonville Limestone unconformably. The North Vernon is also a mixture of carbonate lithologies but is generally more argillaceous and dolomitic than the underlying Jeffersonville.

The **New Albany Shale**, mostly correlative with the Antrim Shale of northern Indiana, *paraconformably* overlies the North Vernon Limestone throughout the area of New Albany outcrop (Shaver and others, 1986, p. 101). In the West Fork White River basin, the New Albany Shale is predominately a brownish-black carbon-rich shale 100 feet thick in the central part of the basin to 210 feet thick in the southwest part of the basin. The upper few feet of the New Albany are Mississippian in age.

Mississippian

In ascending order, the rocks of the **Mississippian System** present in the West Fork White River basin include: Borden, Sanders, Blue River, West Baden, and Stephensport Groups. Mississippian deposits occur at the bedrock surface in the south central portion of the basin (plate 1). Middle Mississippian units are primarily composed of carbonates, whereas the upper and lower portions of the Mississippian are dominated by *clastics*.

Lower Mississippian deposits in the basin begin in the upper few feet of the New Albany Shale that is overlain with apparent conformity by the **Rockford Limestone** (Shaver and others, 1986, p. 124). The Rockford Limestone, although it may be only a few feet thick, is an important stratigraphic marker unit lying between two extensive shale sequences.

The **Borden Group** unconformably overlies the Rockford Limestone in the West Fork White River basin (Shaver and others 1986, p. 18). Typical lithologies within the Borden are argillaceous shales and siltstones that become increasingly thick and arenaceous upward in the sequence. Carbonates are rare in the Borden, occurring mostly in the upper portions of the Group. In the outcrop/subcrop area in Putnam County, the Borden reaches nearly 750 feet in thickness. It thins to the west-southwest in the subsurface across Owen and Greene Counties. A minimum Borden thickness of less than 50 feet occurs near the mouth of the West Fork White River basin.

Middle Mississippian deposits in the basin are composed of carbonates of the Sanders and Blue River Groups. Together these carbonates are generally more than 400 feet thick at the margin of the outcrop or subcrop in the basin. *Karst* terrain of the Mitchell plain and eastern portions of the Crawford upland were developed on the outcrop area of these middle Mississippian carbonates (Wayne, 1956, p. 25-28: Gray, 2000, figure 3). The **Sanders Group** unconformably overlies the Borden Group throughout the basin. Near the subsurface exposure, the Sanders varies in thickness from less than 100 feet to approximately 250 feet (Rupp, 1991, p. 60) and is composed primarily of granular limestones with lesser amounts of dolomitic limestones. *Geodes* occur near the base of the group. The Sanders Group is conformably overlain by the Blue River Group in the basin. The **Blue River Group** is mostly composed of carbonates with significant amounts of *gypsum*, *anhydrite*, shale, chert, and *calcareous* sandstone (Shaver and others, 1986, p. 16).

Upper Mississippian deposits in the West Fork White River basin are composed of sandstones, limestones, and shales of the **West Baden, Stephensport, and Buffalo Wallow Groups**. Erosion resulting in the Mississippian/Pennsylvanian unconformity altered the present near-surface thickness and occurrence of these deposits throughout the basin. This Paleozoic erosion removed progressively older Mississippian deposits to the north. In the West Fork White River basin, deposits of the West Baden and Stephensport Groups are limited to a narrow outcrop area in central Owen and east central Greene Counties. However, sandstone units associated with these deposits and the overlying basal Pennsylvanian sandstone are important bedrock aquifers along the western edge of the outcrop belt (plates 1 and 5). Droste and Keller, (1989) provide an interpretation of this unconformity, the erosion of portions of the Mississippian deposits, and the associated early Pennsylvanian deposition.

Pennsylvanian

Characterized by shale, sandstone, coal, and limestone lithologies, the **Pennsylvanian System** makes up the bedrock surface throughout the southern third of the basin. The maximum thickness of the Pennsylvanian System in the West Fork

White River basin, approximately 1500 feet, occurs near the mouth of the basin (plate 1). Individual shale and sandstone units within the Pennsylvanian System average less than 50 feet in thickness and exhibit considerable local variability. The coal and limestone units exhibit more uniform thickness and greater lateral extent than the shale and sandstone units, even though individually they are typically less than 10 feet thick. Because of this greater uniformity, coal and limestone units are used to define the Formation and Group boundaries. All three Pennsylvanian Groups, and nine of the ten Formations (plate 1) found in Indiana occur in the West Fork White River basin.

The basal Pennsylvanian Mansfield Formation exhibits the widest variation in thickness of the Pennsylvanian Formations in the West Fork White River basin, ranging from 50 to 300 feet thick (Shaver and others, 1986, p. 86-88). This variation in thickness, including a general thinning to the north, is associated with the deposition of the basal Mansfield Sandstone atop the Mississippian/Pennsylvanian erosional surface.

Thin and variable Pennsylvanian units, in combination with the 25 foot-per-mile dip, complicate the near-surface bedrock lithology in the southern part of the West Fork White River basin. Pennsylvanian lithologies in the basin are predominately shales with locally thick sandstones; therefore, the surficial bedrock lithology in the Pennsylvanian outcrop area is often considered to be shale. However, each of the four lithologies (coal, shale, limestone, and sandstone) occurs at the bedrock surface within most townships of this area due to the cyclic nature of the depositional environments.

Sandstone units generally sufficient to provide at least marginal aquifer properties for domestic water production exist in the Pennsylvanian throughout most the basin, but some are at depths in excess of 300 feet. Some thicker and more porous sandstone units exist within the system, most of which are associated with narrow but long Pennsylvanian *fluvial* channels. Other Pennsylvanian sandstones occur as fine-grained beach and/or deltaic sand deposits.

General History of Bedrock Deposition in Central and Southwestern Indiana

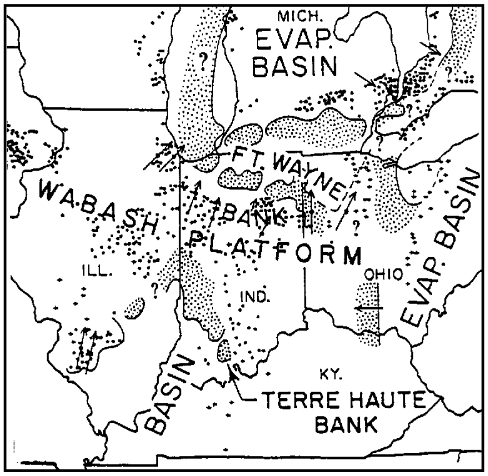
Deposition of the preserved sedimentary rocks in Indiana began in the late Cambrian Period as the sea invaded the state, including the area that is now the White and West Fork White River basin (plate 1). Beach sands derived through erosion of the *igneous basement rocks* were deposited to form the Mount Simon Sandstone. As sea level continued to rise through the early Ordovician Period, the depositional environment shifted to one progressively favoring shale and then limestone. Deposition of the Knox Supergroup, a carbonate deposited in shallow seas began in the late Cambrian and continued through early Ordovician time (Swann, 1968, p. 13). Toward the end of early Ordovician time, the shallow sea began to retreat or regress from the area, and erosion removed the upper portions of the Knox (Gutstadt, 1958).

Sea level again rose, known as *transgression*, and reached its maximum extent upon the North American continent in Middle Ordovician time. The basal St. Peter Sandstone of the Ancell Group was sporadically deposited along an irregular and potentially karst terrain of the Knox erosional surface (Swann, 1968, p. 13). Deposition of the St. Peter was followed by, and partially *contemporaneous* with, deposition of slightly argillaceous carbonates of the Dutchtown Formation and the Joachim Dolomite. These *argillaceous* carbonates were deposited in very shallow bays, bars, and lagoons (Swann, 1968, p. 13). Then a period of relative *tectonic* stability resulted in deposition of the extensive and fairly uniform Black River and Trenton Limestones (Gutstadt, 1958, p. 83).

An abrupt change at the end of Trenton Limestone deposition marked the end of widespread carbonate deposition in Indiana. Sediment that was being eroded as a result of the uplift of the Taconic Mountains to the east overfilled the Appalachian Basin and spilled over the Cincinnati Arch into the Illinois Basin (Swann, 1968, p. 13). Thinning westward of the Arch, these deposits consisted predominately of clays and some carbonates that became the Maquoketa Group (Gray, 1972, p. 1). Physical and biological environments changed rapidly as the shallow water in which the Maquoketa Group was deposited alternated between clear and muddy (Gutstadt, 1958, p. 9).

Following the end of Maquoketa deposition and prior to deposition of Lower Silurian carbonate units, a period of non-deposition and erosion occurred through the late Ordovician and early Silurian Periods. Depositional evidence indicates that the present outline of the Illinois Basin was formed during late Silurian time (Becker, 1974, p. 8). The Basin was however, open to the south and would remain so throughout Paleozoic deposition. Subsidence of the Illinois Basin during the Silurian Period exceeded the rate of deposition, resulting in a sediment-starved deep-water basin.

During the Silurian Period vertical development of reefs in Indiana became most pronounced along the flanks of the Illinois Basin. Some of the *pinnacle reefs* grew several hundred feet high but generally covered an area of less than one square mile (Becker and Keller, 1976, p. 1). Other reefs grew as part of barrier complexes, the Terre Haute and Fort Wayne Banks, where individual structures can be obscure. Lying between the two barrier complexes and roughly associated with, but larger than the Cincinnati and Kankakee Arches was a broad area called the Wabash Platform (accompanying figure). The Platform hosted innumerable reefs, many that were small and short-lived, while others attained areas and volumes much greater than the pinnacle reefs that flanked the Illinois and Michigan Basins (Shaver and others, 1978, p. 3). Approximately 10 percent of the Wabash Platform sediments of Silurian age are considered reef-related (John Rupp, personal communication, 1997).



Silurian paleogeographic map showing the location of some discrete reefs (dots), carbonate banks or barrier reefs (stipples), and gross structural-sedimentational features (Shaver and others, p. 3, 1978)

The subsidence and expansion of reefs along the flanks of the Illinois Basin determined the conditions under which the limestones and shales of the Silurian and Devonian Periods were deposited. Deposition of Silurian and Devonian carbonate and *clastic* sediments were largely influenced by local conditions which differed considerably from north to south in the area of the present West Fork White River basin.

A lowering of sea level during late Silurian through early Devonian resulted in erosion along the Wabash Platform that removed and altered the uppermost portions of some Platform reef structures. An erosional unconformity occurs throughout the area of the present day West Fork White River basin where Silurian and Devonian carbonates lie at or near the bedrock surface (plate 1). Sedimentation outside the area of reef development continued uninterrupted, comformably, from Silurian through early Devonian time, with deep-water deposits of carbonates predominating in the area that is now the lower West Fork White River basin.

Sea level transgression marks the beginning of Middle Devonian deposition. In the central area of the West Fork White River basin, the rise in sea level was accompanied by deposition of a shallow-water carbonate having an *arenaceous*

continued on next page

basal deposit that, in places, developed into the Dutch Creek Sandstone Member of the Jeffersonville Limestone (Shaver and others, 1986, p. 64). A period of *regression* and subsequent erosion separates the Jeffersonville from the overlying North Vernon Limestone. During the deposition of the North Vernon Limestone small amounts of clays from weathering of the Appalachians again reached the basin (Swann, 1968, p. 15). Subsequent transgression and regression during North Vernon carbonate deposition resulted in at least three partial unconformities in the northern and central areas of the West Fork White River basin. The last of these partial sea level regressions marked the end of widespread Devonian carbonate deposition.

Sediment that ultimately became the New Albany Shale was deposited in a transgressing *epicontinental* sea that covered much of Indiana. Anoxic conditions caused by lack of water circulation between the epicontinental waters and the open ocean resulted in an accumulation of organic matter as an important part of the sediment (Lineback, 1970, p. 42-48). Deposition of the New Albany continued through the close of the Devonian Period, ending in early Mississippian time. The deep-water carbonate deposition of the thin but persistent Rockford Limestone marks the end of New Albany shale deposition (Swann, 1968, p. 15).

Clastic deposits derived from weathering of the rising Franklin Mountains were transported to the Illinois Basin from the north, filling the Michigan Basin and spilling over into the Illinois Basin (Swann, 1968, p. 15). An advancing delta front that became the Borden Group was deposited in an otherwise deep-water basin. In the area of the central West Fork White River basin, the fully developed deltaic sediments accumulated to a thickness of over 700 feet, thinning considerably to the southwest as they grade to a *prodeltaic* environment followed by deposition of deep-water carbonate sediments (Gray, 1979, p. 8-9). A decrease in sediment load created a shift from clastic to carbonate deposition during the early part of the Middle Mississippian Period. Deposition of shallow-water carbonates predominated over the area where the thicker Borden deltaic deposits occurred, while deep-water carbonates continued to fill the remainder of the Illinois basin. After the Illinois Basin was filled, a variety of shallow-water carbonates, including some evaporites of the Middle Mississippian Period developed Basin-wide (Gray, 1979, p. 6).

Clastic sediment again reached the Illinois Basin at the close of Middle Mississippian time. Shoreline advances and retreats from the south, associated with deposition of clastics from the north, would dominate the remainder of the Mississippian Period. Alternating marine carbonate, beach, deltaic, and freshwater fluvial clastic deposits are typical of much of the Upper Mississippian deposition in the Illinois Basin. Fluvial sandstone channels, some over a mile wide, 100 feet thick, and tens of miles long can be traced in these deposits as the deltaic fronts migrated with the fluctuating sea level.

Upper Mississippian deposition was incomplete on the flanks of the Illinois Basin and probably did not extend to the current northeastern limit of the present West Fork White River basin. An upper limit of Upper Mississippian deposition in the central Indiana portion of the Illinois Basin is believed to be 50 to 100 miles north and east of the present outcrop of these deposits (Droste and Keller, 1989, p. 3-6). Near the end of the Mississippian Period the region of the present-day West Fork White River basin was uplifted above sea level and tilted up to the north. A period of erosion resulted in removal of progressively older portions of the Mississippian deposits to the north, resulting in a topographic surface having 50 to 150 feet of local relief. The resulting erosional surface displays long, straight ridges along the outcrop of the Middle Mississippian limestones. *Cuestas* were formed due to variability in resistance to erosion of the Upper Missippian units (Droste and Keller, 1989, p. 7-8).

Sea level again began to rise during the early Pennsylvanian Period. A basal sandstone, the Mansfield, was deposited upon the Mississippian/Pennsylvanian erosional surface as the sea transgressed from the southwest (Shaver and others, 1986, p. 86). It is apparent from the rocks deposited during the Pennsylvanian Period that advances and retreats of the seas were frequent and widespread. One of the most notable aspects of Pennsylvanian sedimentation in the middle and eastern states is the repetitive alternation of marine and nonmarine strata. At times the southern area of present-day West Fork White River basin was a vast coal swamp; at times a shallow sea covered it. This cyclic pattern of deposition that was common in the Pennsylvanian Period in the Illinois basin is called a *cyclothem*. These short-term oscillations in sea level in the area may have been caused by regional subsidence of the land to a level slightly below sea level so that marginal seas could spill onto the level swampy lowlands. A short time later, subsidence might cease and sediments be built up above sea level to extend the shoreline seaward and reestablish continental conditions; or dry land may have resulted from temporary regional uplifts. Glacial advances and retreats elsewhere may have caused changes in sea level; or there could have been a combination of factors.

Extensive erosion throughout the post-Paleozoic Eras, coupled with bedrock structure and lithology, resulted in the differential removal of Paleozoic units in the West Fork White River basin. As a result, bedrock deposits that date from late Ordovician through middle Pennsylvanian are found at the bedrock surface from north to south in the basin. This pre-Pleistocene bedrock topography reflects the surficial drainage associated with the extensive period of post-Paleozoic erosion.

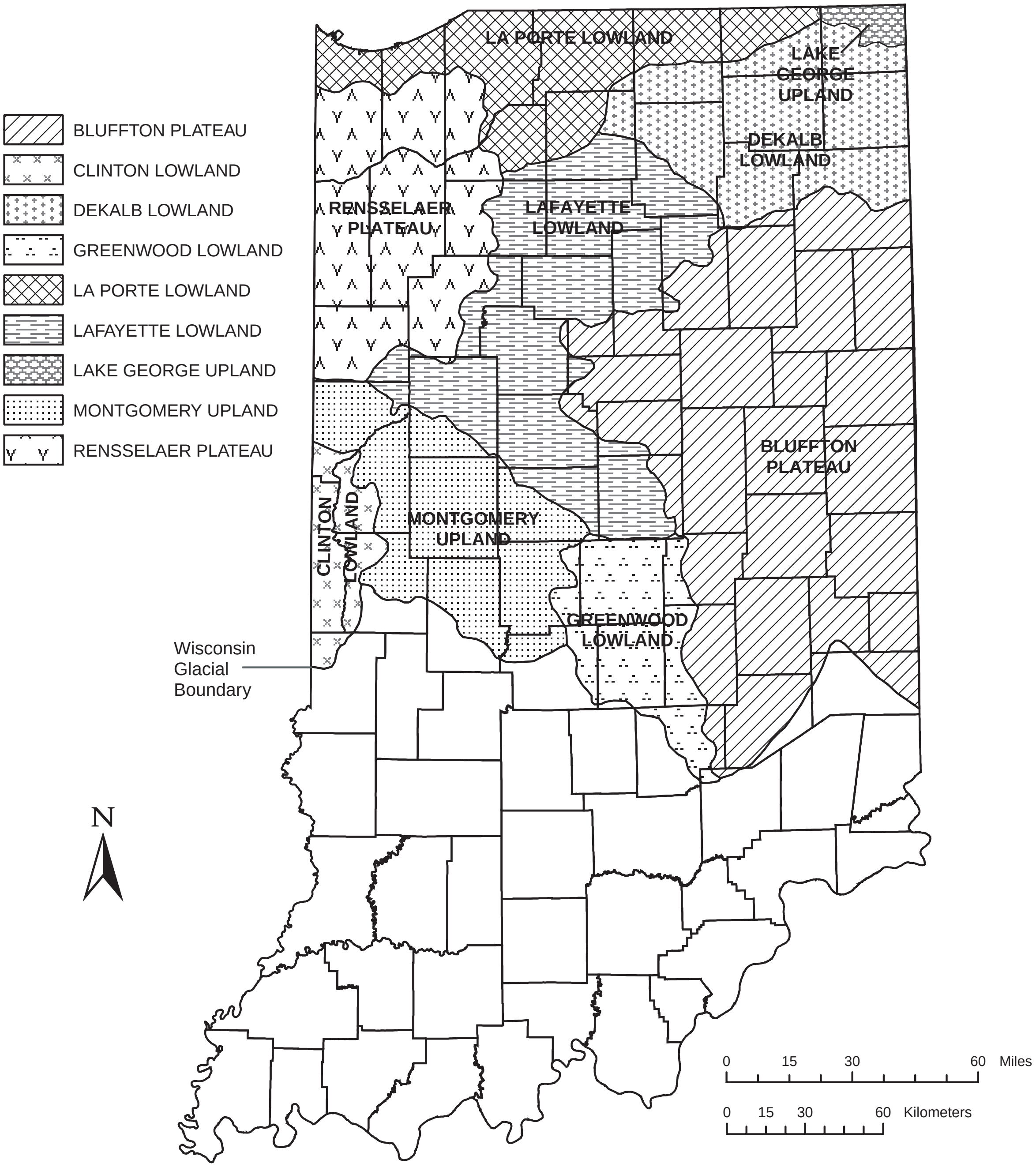


Figure 7. Map of Indiana showing the topographic divisions of the buried bedrock surface north of the Wisconsin glacial boundary (adapted from Henry Gray, 2000).

GROUND-WATER HYDROLOGY

Ground-water supplies are obtained from *aquifers*, which are subsurface units of rock and unconsolidated sediments capable of yielding water in usable quantities to wells and springs. The hydrologic characteristics of aquifers and natural chemistry of ground water determine the availability and suitability of ground-water resources for specific uses.

Ground-Water Resources

Ground water is the part of precipitation that enters the ground and *percolates* downward through unconsolidated materials and openings in bedrock until it reaches the *water table* (figure 8). The water table is the surface below which all openings in the rock or unconsolidated materials are filled with water. Water entering this zone of saturation is called *recharge*.

Ground water, in response to gravity, moves from areas of recharge to areas of *discharge*. In a general way, the configuration of the water table approximates the overlying topography (figure 8). In valleys and depressions where the land surface intersects the water table, water is discharged from the ground-water system to become part of the surface-water system.

The interaction between ground water and surface water can moderate seasonal water-level fluctuations in both systems. During dry periods *base flow*, or *ground-water discharge* to streams, can help maintain minimum stream flows. Conversely, during flood stages surface water can recharge the ground-water system by vertical recharge on the water-covered flood plain and bank storage through streambed sediments. The net effect of ground-water recharge is a reduction in flood peaks and replenishment of available ground-water supplies.

Aquifer properties that affect ground-water availability include aquifer thickness and the size, number, and degree of interconnection of pore spaces within the aquifer material. These properties affect the ability of an aquifer to store and transmit ground water. *Porosity*, the ratio of void space to unit volume of rock or soil, is an index of how much ground water the aquifer can store. *Permeability*, a property largely controlled by size and interconnection of pore spaces within the material, affects the fluid-transmitting capacity of materials.

The water-transmitting characteristics of an aquifer are expressed as *hydraulic conductivity* and *transmissivity*. Hydraulic conductivity is a measure of the rate that water will move through an aquifer; it is usually expressed in gallons per day through a cross section of one square foot under a unit *hydraulic gradient*. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer. The storage characteristic of an aquifer is expressed as the *storage coefficient*.

Pore spaces in bedrock occur as fractures, solution features, and/or openings between grains composing the rock. In unconsolidated deposits all of the pores are intergranular. However, fine-grained deposits such as clays and silts may also have secondary porosity, commonly in the form of fractures.

The size, shape, and sorting of material determine the amount and interconnection of intergranular pores. Sand and gravel deposits have a high proportion of pore space and high permeability; whereas, fine-grained or clay-rich deposits have a greater proportion of pores, but a lower degree of permeability.

Aquifers have porosity and permeability sufficient to absorb, store, and transmit water in usable quantities. *Aquitards* consist of materials with low permeability that restrict ground-water movement. An aquitard overlying an aquifer may limit the recharge to the aquifer but may also protect the aquifer from surface contamination.

Where an aquitard overlies an aquifer, the water in the aquifer is said to be *confined* because the aquitard prevents or restricts upward movement of water from the aquifer. Such an aquifer is referred to as a confined or *artesian* aquifer. Water in confined aquifers exists under hydrostatic pressure that exceeds atmospheric pressure; and wells completed in confined aquifers have water levels that rise above the water-bearing formation until the local *hydrostatic pressure* in the well is equal to the atmospheric pressure. Such wells may or may not be *flowing wells* (figure 8). A measure of the pressure of water in a confined aquifer is referred to as the *potentiometric* level.

In contrast, water in an *unconfined* aquifer exists under atmospheric pressure; and wells that are completed in such aquifers have water levels that correspond to the local water table. An unconfined aquifer is also referred to as a water table aquifer, and the spatial distribution of water levels in wells in unconfined aquifers is shown on a water table map. Water level maps for confined and unconfined aquifers are typically referred to as *potentiometric surface* maps.

As a well discharges water from an aquifer the water level drops in the well. The drop in water level, which is called *drawdown*, creates a *hydraulic gradient* and causes ground water around the well to flow toward the well. If an unconfined or confined aquifer is being pumped, an overall lowering of either the water table or the potentiometric surface, respectively, occurs around the well. The zone being influenced by pumpage is called the *cone of depression*. An increase in the pumping rate usually creates a larger cone of depression that may induce more recharge to the aquifer. However, the natural rate of recharge to confined aquifers is limited by the thickness and hydraulic properties of the confining layers.

Ground-water levels

The ground-water level within an aquifer fluctuates constantly in response to rainfall, *evapotranspiration*, barometric pressure, ground-water movement (including *recharge* and *discharge*), and ground-water pumpage. However, the response time for most natural ground-water level fluctuations is controlled predominantly by the local and regional geology.