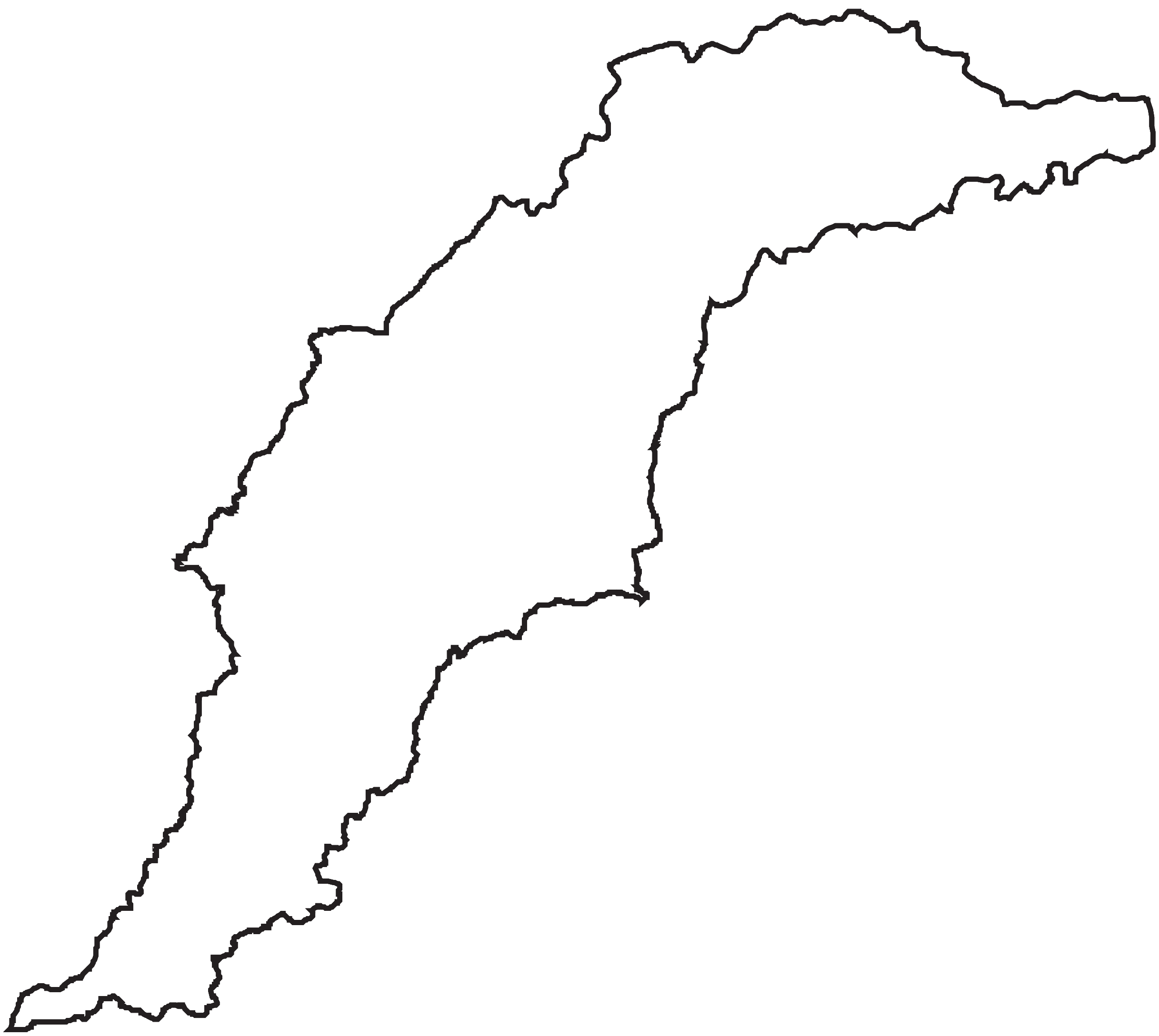
INDIANA DEPARTMENT OF NATURAL RESOURCES

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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Water Resource Assessment 2002-6

Printed By Authority of the State of Indiana
Indianapolis, Indiana: 2002

STATE OF INDIANA
Frank O'Bannon, Governor

DEPARTMENT OF NATURAL RESOURCES
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For sale by Division of Water, Indianapolis, Indiana

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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)

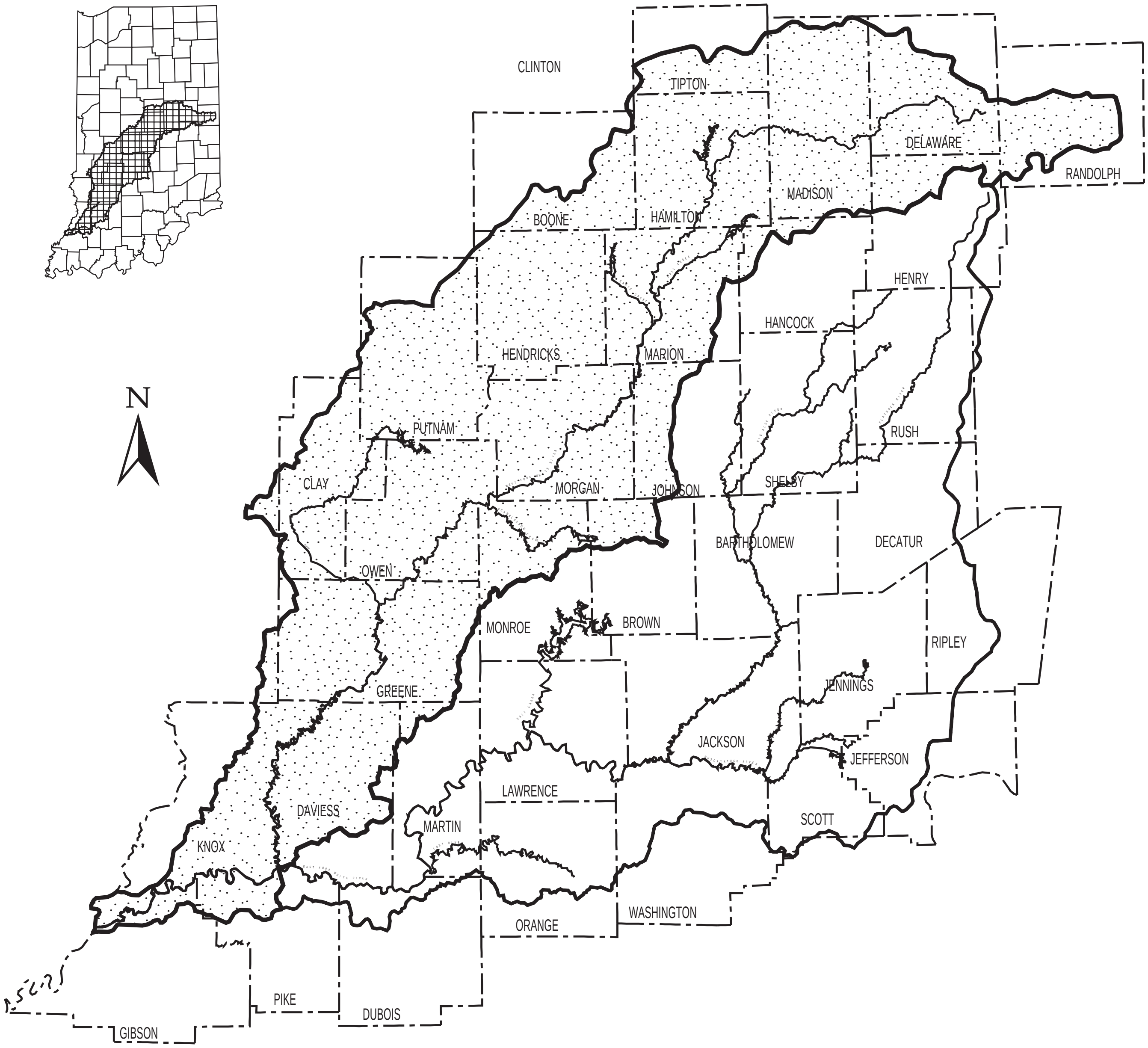


Figure 1. Location of White and West Fork White River basin

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

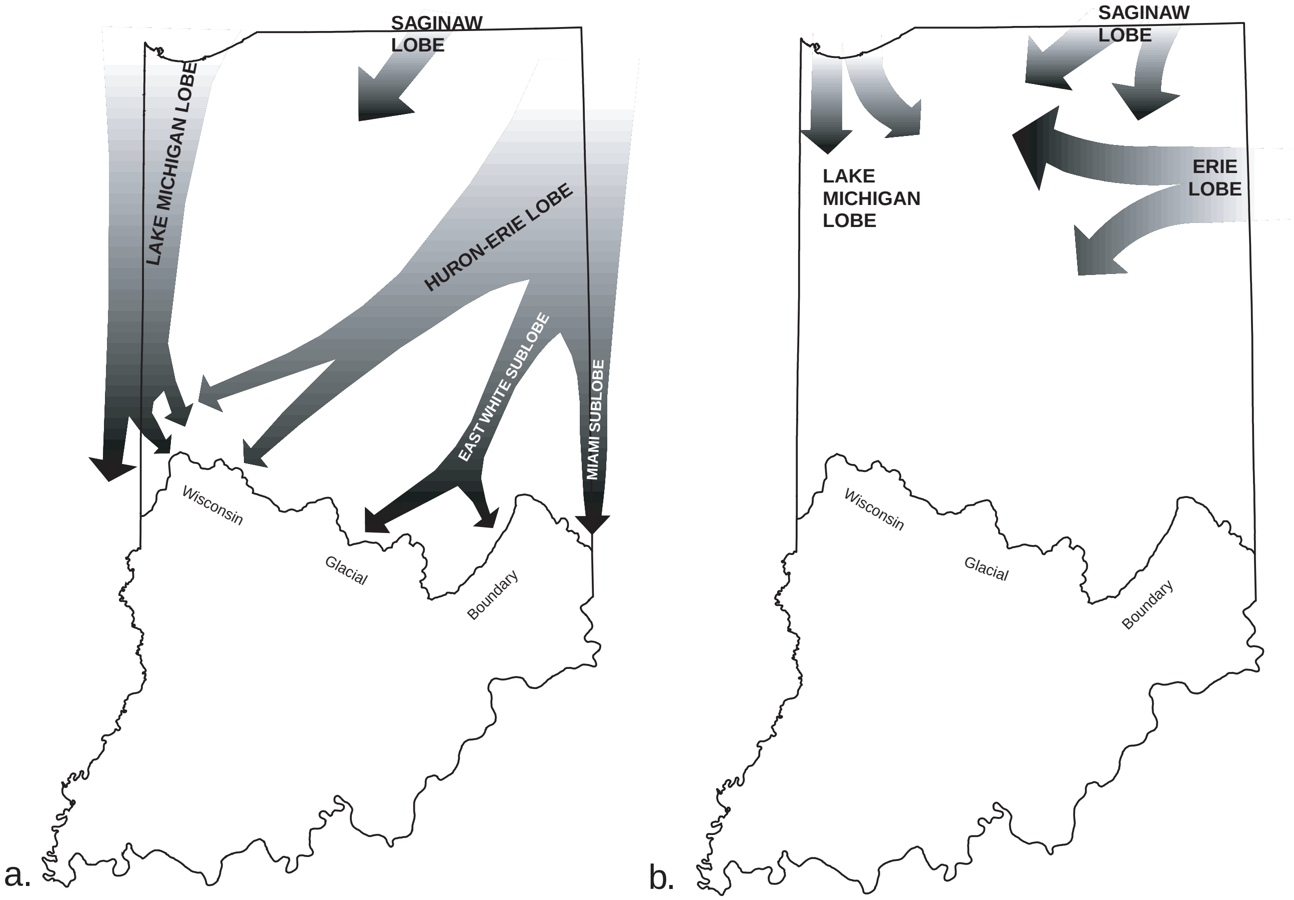


Figure 2. Sketch maps showing generalized flow direction of the several ice streams that made up the Wisconsin glacier in Indiana: a) about 20,000 years ago; b) about 15,000 years ago. Because of the vacillating activity of the several lobes and in some places extensive overriding of one lobe over another, 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

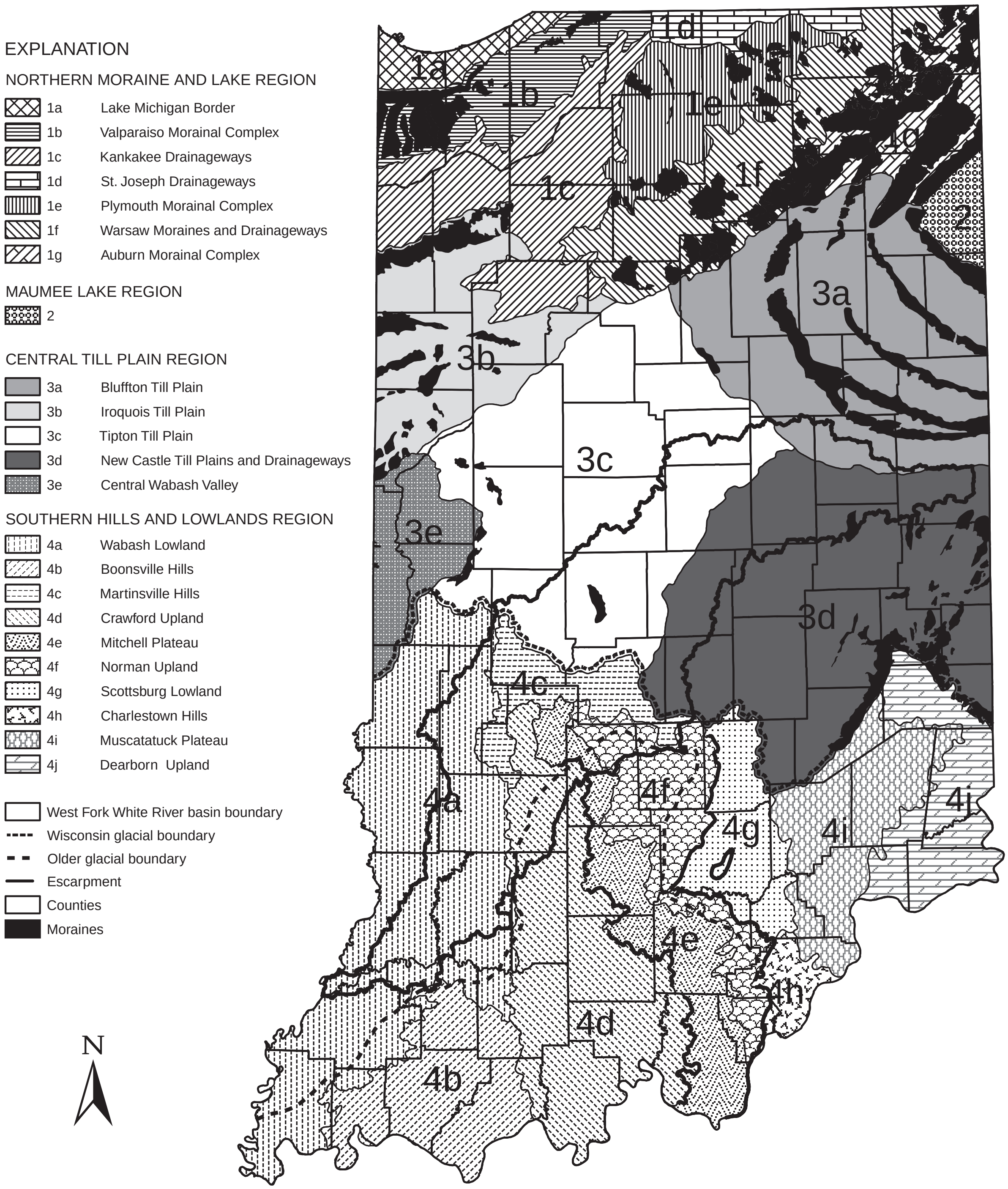


Figure 3. Physiographic divisions of Indiana (adapted from Gray, 2000)

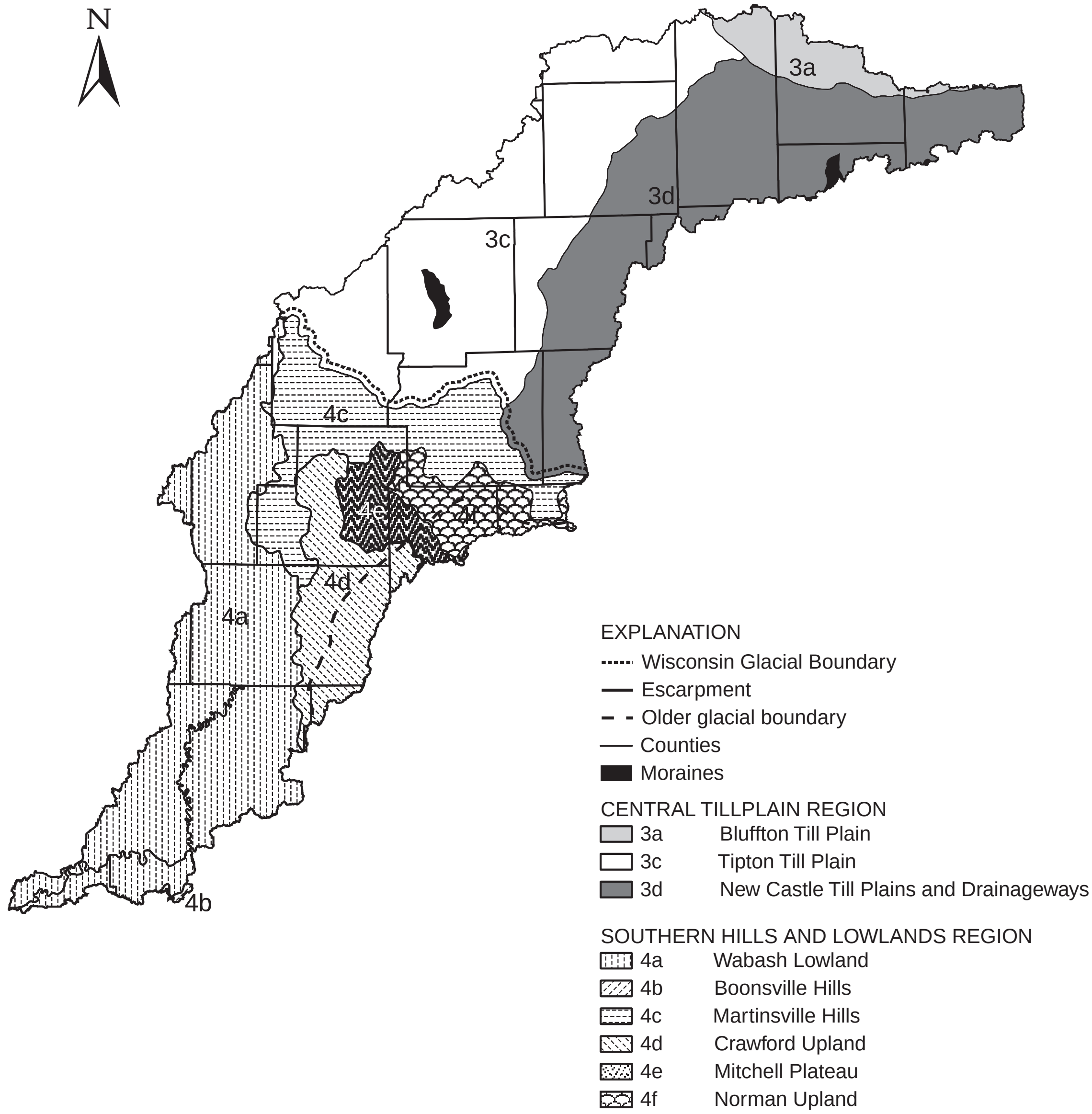


Figure 4. Physiographic divisions of the White and West Fork White River basin (adapted from Gray, 2000)

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).

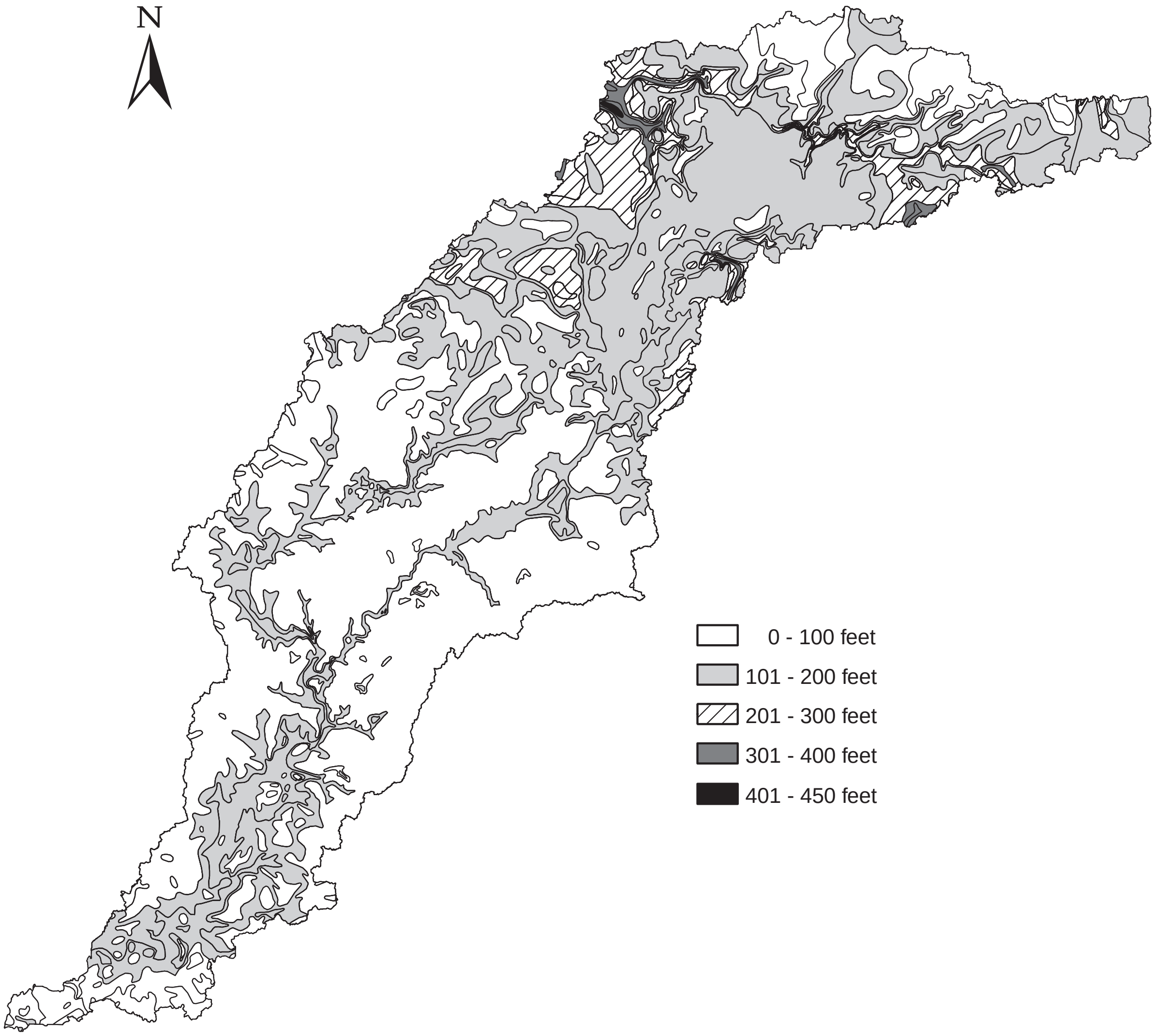


Figure 5. Thickness of unconsolidated deposits (adapted from Gray, 1983)

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.

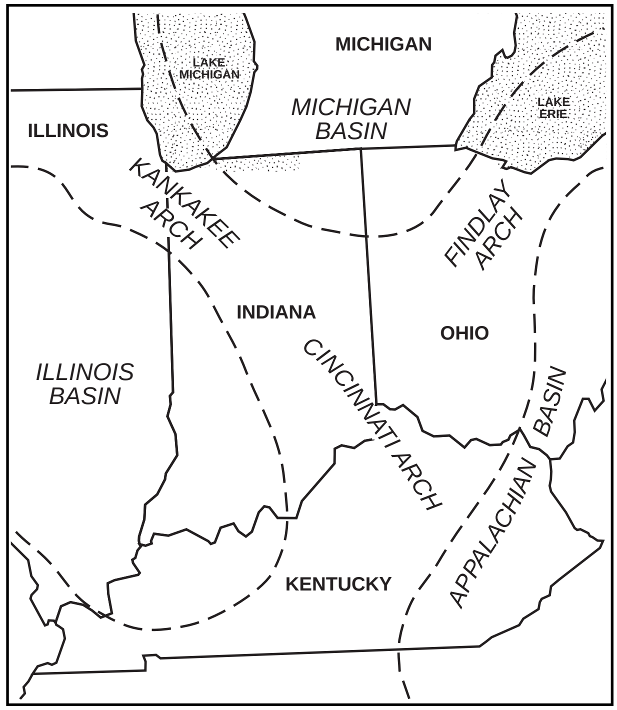


Figure 6: Regional bedrock structure

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

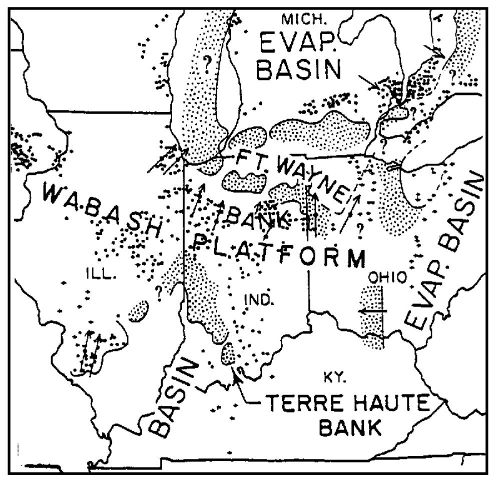
Deposition of the preserved sedimentary rocks in Indiana began in the late Cambrian Period as the sea invaded the state, including the area that is now the White and West Fork White River basin (plate 1). Beach sands derived through erosion of the *igneous basement rocks* were deposited to form the Mount 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 non-marine 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.

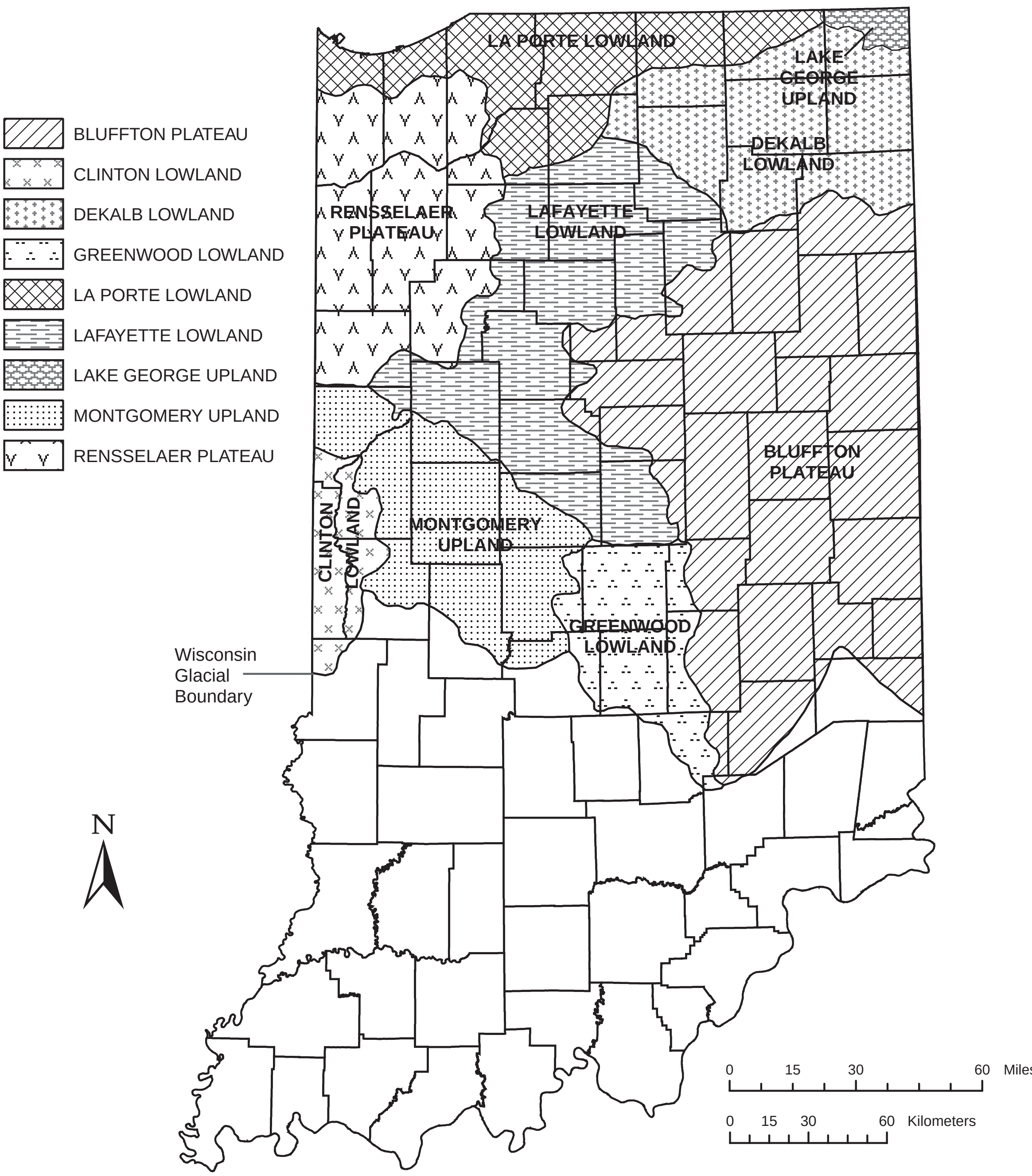


Figure 7. Map of Indiana showing the topographic divisions of the buried bedrock surface north of the Wisconsin glacial boundary (adapted from Henry Gray, 2000).

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.

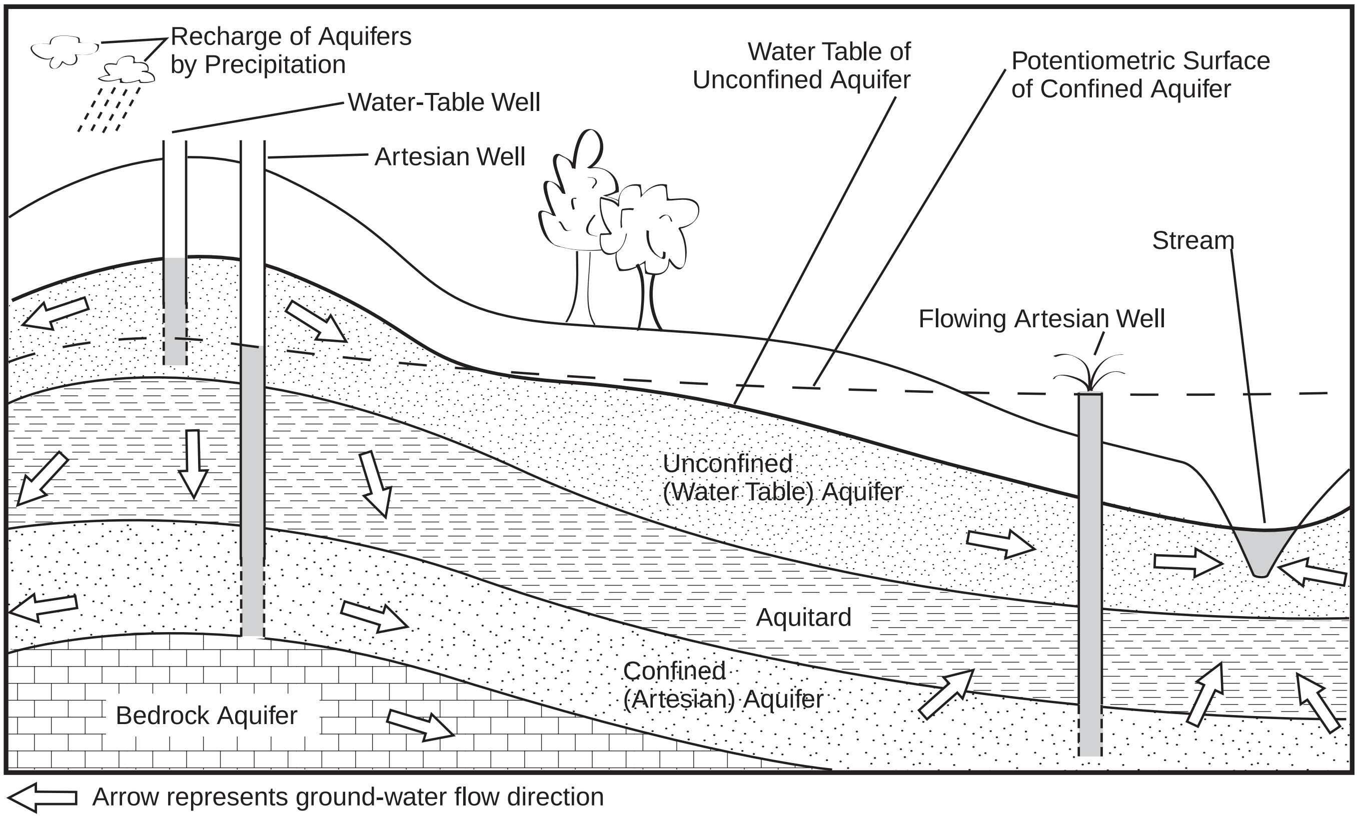


Figure 8: Aquifer types and ground-water movement

To study natural or man-induced stresses on an aquifer, an observation well is completed in the aquifer of interest and the water level is monitored periodically. Significant fluctuations in the water level in the observation well may be an indication of natural or man-induced stresses on the aquifer.

The observation well monitoring program in the West Fork White River basin was started in 1935 by the U.S. Geological Survey (USGS) in cooperation with the Indiana Department of Natural Resources. Currently, the observation well network in the West Fork White River basin includes 10 active observation wells and 30 discontinued observation wells (table 2, figure 9). In addition, five active observation wells are located just beyond the basin boundary. Table 2 also includes information on two discontinued project wells where water level data have been collected in Marion County. Water level is recorded automatically in each of the active observation wells. Records of ground-water levels are collected periodically by the U.S. Geological Survey and published annually in water-resource data reports.

Observation wells in the West Fork White River are categorized into three groups: 1) unaffected by pumpage, 2) affected by pumpage, and 3) special purpose. However, classification can be difficult in cases where the observation well has a short period of record. The observation wells in the basin that are categorized as "special purpose" were monitored in the past for various purposes including earthquake response, but have all been discontinued.

Of the eight active observation wells completed in unconsolidated deposits in the basin, two record natural water-level fluctuations, five record water-levels that are definitely affected by pumpage, and one records water-levels that may be affected by pumpage. One of the two bedrock wells in the basin records natural water-level fluctuations, the other records water levels affected by pumpage.

Hydrologic data are often presented in water years (October through September) instead of calendar years (January through December) because the annual peak in river stage commonly occurs from December to June. If a major precipitation event occurs from late December to early January and calendar year data are used for plotting, the single event can be interpreted as two annual peaks in two calendar years.

Normal temporal trends in the ground-water levels are illustrated by the hydrographs of Morgan 4, Delaware 4, and Randolph 3 (figures 10a, b, and c). All three observation wells are classified as "unaffected". Ground-water levels in aquifers are highest during the wet season of spring, and decline during summer and fall because of increased evapotranspiration and reduced recharge. The fluctuations are the result of natural stresses, and thus may indicate trends in the natural rates of ground-water recharge and discharge from the aquifers. All three hydrographs reveal lower ground-water levels during the latter part of 1999 and early 2000 as a result of drought conditions.

Observation well Morgan 4 is completed in a shallow *unconfined* aquifer. The annual water-level fluctuation ranges from about five feet to eight feet. The difference between the maximum high and low for the period 1978 to 1999 is 13.16 feet.

Observation well Delaware 4 is completed in a *confined* unconsolidated aquifer. The annual water-level fluctuation ranges from about three feet to 4.5 feet. The difference between the maximum high and low for the period 1971 to 1999 is 7.29 feet. Observation well Randolph 3 is completed in a limestone bedrock aquifer. The annual water-level fluctuation ranges from about 4.5 feet to nearly six feet. The difference between the maximum high and low for the period 1966 to 1999 is 7.5 feet.

Most of the observation wells in the West Fork White River basin are classified as "affected" by pumpage. Observation well Marion 34 illustrates a dramatic change in water level related to nearby pumpage (figure 11). The rapid decline in water level shown for April and May 1998 reflects temporary dewatering during construction of a nearby sewer line. Water levels returned to more normal levels after constructions was completed, but have begun to decline again related to nearby pump age by a public water supply facility. Not all pumpage-induced effects are as dramatic as those shown in observation well Marion 34.

Potentiometric surface maps

Ground-water level measurements can provide important information about the local ground-water resources. For example, ground-water availability and estimates of aquifer yield are determined by analyzing changes in water levels related to pumpage. Also, because differences in water-level elevation provide potential for flow, spatial mapping of water-level elevations can permit identification of regional ground-water flow direction, as well as areas of recharge and discharge.

The potentiometric surface map of selected counties in the West Fork White River basin (plate 4) depicts the elevation to which water levels will rise in wells. The map is created by plotting elevations of the *static water level* and then generating contours or lines of equal elevation. Static water levels used to develop the potentiometric surface map are from wells completed in *aquifer systems* at various depths and under confined and unconfined conditions. The generalized map was developed for the in-basin portions of the northernmost tier of ten counties, including: Randolph, Delaware, Henry, Madison, Hancock, Tipton, Hamilton, Boone, Clinton, Hendricks, and Marion.

In general, the composite potentiometric surface follows the overlying land-surface topography and intersects the land surface at major streams. The expected flow path is downslope or perpendicular to the potentiometric surface contours. Natural ground-water flow is from areas of recharge toward areas of discharge. Depths to the potentiometric surface **do not** represent appropriate depths for water wells. Instead, wells must be completed in the water-yielding formation, with depth into the aquifer based primarily on local geologic conditions, such as thickness and lateral extent of the aquifer, in combination with the potentiometric surface.

In the counties mapped, ground-water level elevations in the basin range from 1150 feet m.s.l. (mean sea level datum) in Randolph County in the upper reaches of the drainage basin to 650 feet m.s.l. in Marion County near the Morgan/Johnson County lines. This range is a function of the basin topography and the ground-water flow from areas of recharge to areas of ground-water discharge. Regional ground-water flow is toward the White River and its major tributaries. Ground-water flow is generally away from the drainage divide in the north and east and toward the south and west.

Aquifer Systems

In this report, the ground-water resources of the West Fork White River basin are mapped and described as regional aquifer systems (plate 5). Lack of data in many parts of the basin and complexity of the deposits preclude detailed aquifer mapping.

Ground-water supplies in the West Fork White River basin are obtained from unconsolidated and bedrock aquifer systems. Seven unconsolidated aquifer systems are defined in this report according to hydrologic characteristics of the deposits and environments of deposition (plate 5). Table 3 summarizes various hydrologic characteristics of the unconsolidated and bedrock aquifer systems. Nine bedrock aquifer systems are defined in the basin on the basis of hydrologic and *lithologic* characteristics; however, not all of the bedrock formations are productive aquifers.

The most productive unconsolidated aquifers in the West Fork White River basin are the outwash deposits that are adjacent to the major streams of the basin and transect the other unconsolidated aquifers from the northeast headwaters of the basin to the far southwestern tip where the White River system empties into the Wabash. The least productive are the weathered bedrock *residuum* and thin till deposits that cover much of the southern half of the basin and the *lacustrine* and *backwater* deposits that occupy many of the tributary stream valleys in the southern part of the basin.

The most productive bedrock aquifer system is the Silurian and Devonian carbonates that directly underlie the northeastern third of the basin. The least productive are the Mississippian shales that cover the mid-section of the basin and the Pennsylvanian interbedded shales and sandstones that cover the southern tip of the basin.

In general, in the northern half of the basin unconsolidated aquifers are most often chosen for wells, even though productive carbonates are available in the northern third of the basin. In the southern part of the basin bedrock aquifers, although not very productive, are most often used because overlying unconsolidated materials are shallow and less productive.

Unconsolidated aquifer systems

The unconsolidated aquifer systems mapped in the West Fork White River basin include the Tipton Till Plain, Tipton Till Plain Subsystem, Dissected Till and Residuum, White River and Tributaries Outwash, and White River and

Table 2. Summary of active and discontinued wells

Well number: U.S.Geological Survey county code and well number. Well locations are shown in figure 9.
Period of record: Refers to calendar year, whether or not data encompasses entire year.
Aquifer system: WR, White River and Tributaries Outwash; WRS, White River and Tributaries Outwash Subsystem; TTP, Tipton Till Plain; TTPS, Tipton Till Plain Subsystem; BV, Buried Valley; DTR, Dissected Till and Residuum; LB, Lacustrine and Backwater Deposits; S, Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian
Aquifer type: SG, sand and gravel; LS, limestone; SS, sandstone; SH, shale; STS, siltstone
Aquifer classification: A, affected by pumping; A/R, affected by a river; UA, unaffected by pumping; SP, special purpose

Status	County	Well number	Period of record	Aquifer system	Aquifer Type	Aquifer Condition	Well Diameter (in.)	Well Depth (ft.)	Aquifer Class
ACTIVE									
	Boone	BN 17	1986-	TTP	SG	Confined	6	171.8	A?
	Clay	CY 6 *	1987-	P	SS	Confined	6	400	A
	Clay	CY 7 *	1988-	P	SS	Confined	6	121	UA
	Delaware	DW 4	1966-1971; 1974-present	TTP	SG	Confined	6	91	UA
	Grant	GT 8*	1966-1971; 1974-present	S/D	LS	Confined	6	35	UA
	Hendricks	HD 4	1966-1971; 1974-present	M	SS	Confined	6	85	A
	Knox	KN 8*	1989-	P	SS,SH,Coal	Confined	6	137	UA
	Marion	MA 34	1986-	WR	SG	Unconfined	6	66	A
	Marion	MA 35	1987-	WR	SG	Confined	6	83	A
	Marion	MA 36	1987-	WR	SG	Confined	6	70.6	A
	Marion	MA 37	1988-	WRS	SG	Unconfined	6	74	A
	Marion	MA 38	1997-	WR	SG	Unconfined	6	64	A
	Morgan	MG 4	1978-	WR	SG	Unconfined	6	64	UA
	Parke	PA 6	1967-1971; 1981-present	P	SS	Confined	6	155	UA
	Randolph	RA 3*	1966-	S/D	LS	Confined	6	54	UA

*CY6, CY7, GT8, KN8, and RA3 are near, but outside the basin boundary

Table 2 continued

DISCONTINUED

Clay	CY 4	1957-1971	P	Coal, SS	Confined	8	86	A
Daviess	DV? 3	1955-1966	LB	drift	Unconfined	24	20	UA
Greene	GN 3	1946-1974	LB	SG	Confined	8	48.5	UA?
Hamilton	HA 2	1935-1961	S/D	LS	Confined	8	265	A
Hamilton	HA 4	1962-1971	S/D	LS	Confined	6	300	A
Hamilton	HA 5	1965-1971; 1974-1999	WR	SG	Unconfined	6	86	A
Hamilton	HA 6	1966-1973	WRS	SG	Confined	4	48.5	SP
Hendricks	HD 2	1948-1971***	DTR	SG	Confined	4	48	UA
Knox	KN 1	1944-1969	WRS	SG	Confined	30	38	UA?
Knox	KN 3	1956-1971	WR	SG	Confined ?	6	43.5	UA?
Knox	KN 5	1956-1970	WR	SG	Confined ?	6	49	UA?
Madison	MD 2	1935-1946	TTPS	SG	Confined	30	156	A
Madison	MD 8	1949-1971	S/D	LS	Confined	8	415	A
Madison	MD 10	1967-1971	S/D	LS	Confined	8	465	A
Marion	MA 2	1935-1970	WR	SG	Confined	8	90	SP
Marion	MA 3	1935-1974	S/D	LS	Confined	6	162	UA?
Marion	MA 10	1935-1970	S/D	LS	Confined	8	158	SP
Marion	MA 18	?-1966	WR	Drift?	?	24	28	?
Marion	MA 19	1943-1966	WR	Drift	?	1.25	24	?
Marion	MA 30	1948-1964	S/D	LS	Confined	12	400	A
Marion	MA 31	1954-1971	S/D	LS	Confined	8	347	A
Marion	MA 32	1958-1971; 1974-1988	S/D	LS	Confined	10	308	SP
Marion	MA 33	1978-1988	TTP	SG	Unconfined	6	94	UA
Marion	MA 48**	1976-1979	WR	SG	Unconfined	1.5	44.5	SP
Marion	MA 53**	1974-1986	WR	SG	Unconfined	1.5	44.8	SP
Owen	OW 7	1967-1981	M	LS	Confined	6	150	A/R
Parke	PA 4	1957-1966	P	unknown	Confined	6	112	SP
Putnam	PN 4	1957-1986	WR	SG	Unconfined	12	60	A
Putnam	PN 5	1957-1966	M	LS,SH,STS	Confined	8	410	A
Tipton	TP 2	1967-1972	TTP	SG	Confined	6	131	A
Vigo	VI 8	1978-1982	P	SS	Confined	6	180	UA
Vigo	VI 9	1983-1986	P	SS,SH	Confined	5	201	UA

** project wells, not included in the State's Observation Well Network

*** not continuous

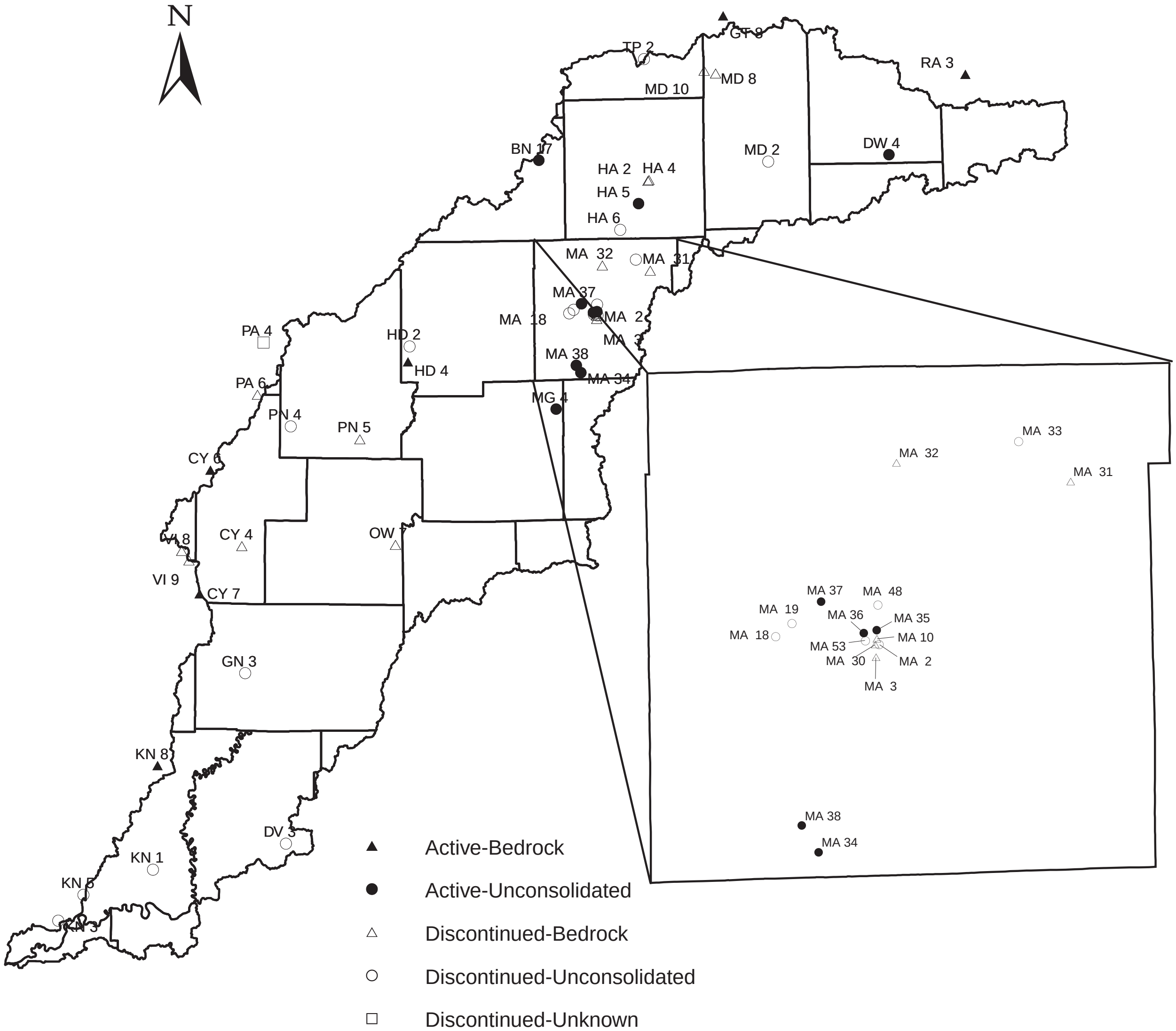


Figure 9. Locations of observation wells in the West Fork White River basin

Tributaries Outwash Subsystem, Lacustrine and Backwater Deposits aquifer systems and the Buried Valley. Sediments that comprise these aquifer systems were deposited by glaciers and their meltwaters during the Ice Age or are thin eroded residuum. Boundaries of the aquifer systems are gradational and individual aquifers may extend across aquifer system boundaries.

The most productive unconsolidated aquifer system is the outwash deposits of the White River and Tributaries Outwash Aquifer system. The least productive unconsolidated aquifer systems are the Dissected Till and Residuum and the Lacustrine and Backwater Deposits aquifer systems.

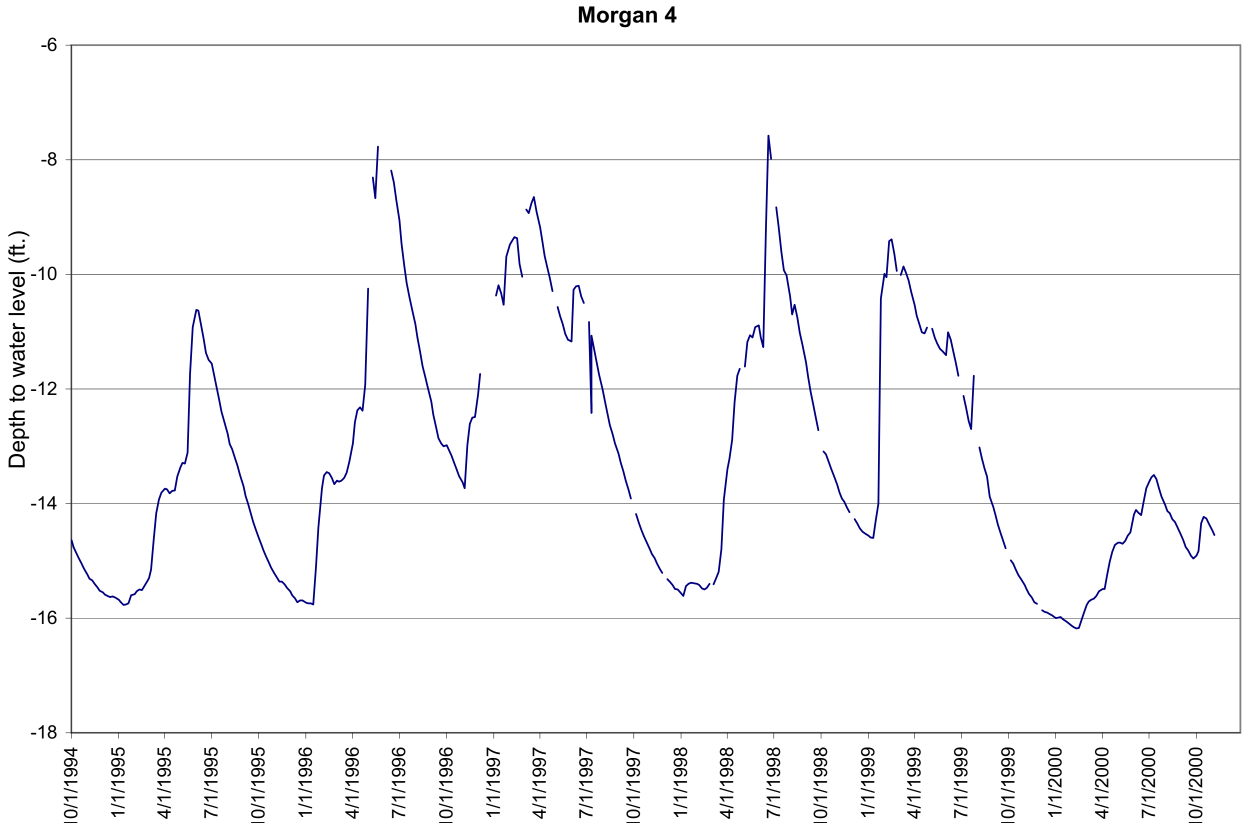
The following discussion of unconsolidated aquifer systems begins in the northern portion of the West Fork White River basin. The locations of the aquifer systems are shown in plate 5. In the northern part of the West Fork White River basin, unconsolidated aquifer systems are the primary source of ground water. Highly productive zones within the unconsolidated aquifer systems are encountered where thick, coarse-grained sand and gravel deposits occur.

Tipton Till Plain Aquifer System

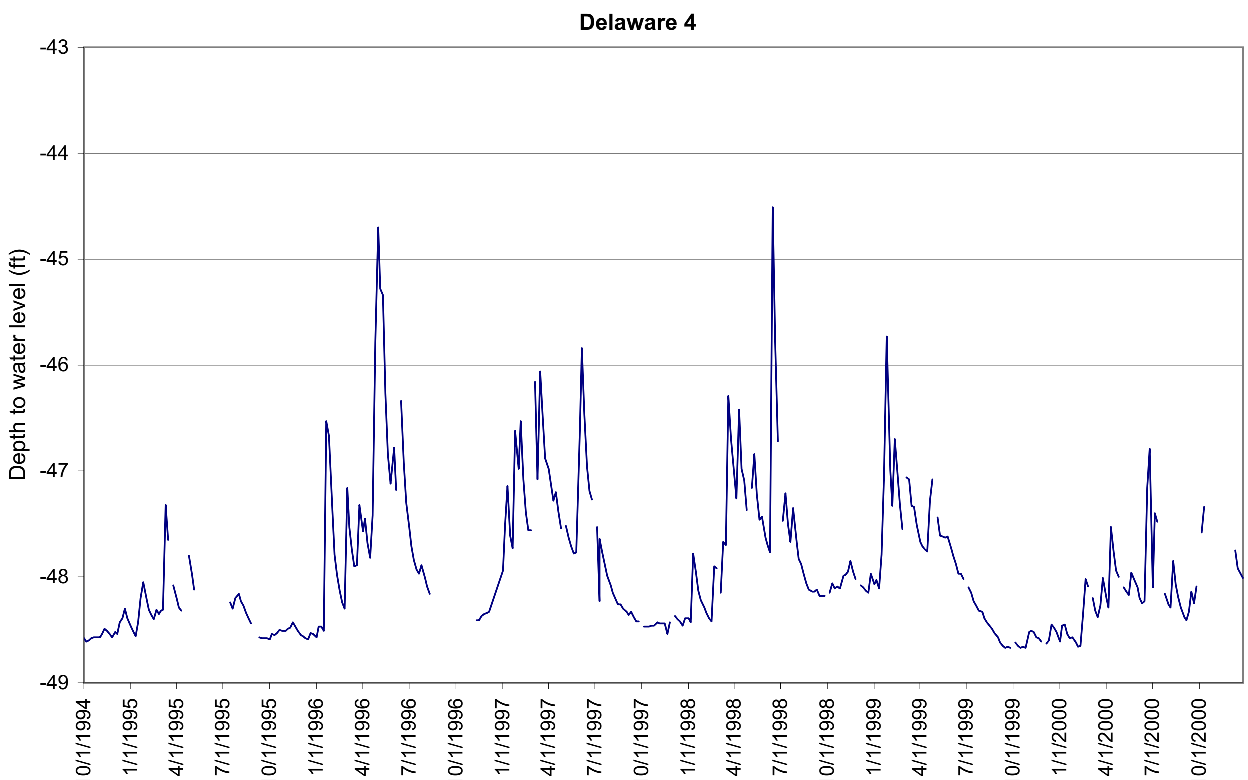
(Equivalent to the Wayne-Henry Aquifer System in the Whitewater River Basin)

The Tipton Till Plain Aquifer system dominates the northern part of the West Fork White River Basin (plate 5). The surficial deposits of this system are Wisconsin tills identified as *ground moraine* or *end moraine*.

The dominant aquifers within the Tipton Till Plain Aquifer system are intratill sand and gravel lenses. These aquifers are highly variable in depth and lateral extent and are confined by variably thick clay or till sequences. Aquifer materials range from very fine or muddy sand to coarse gravel. Individual

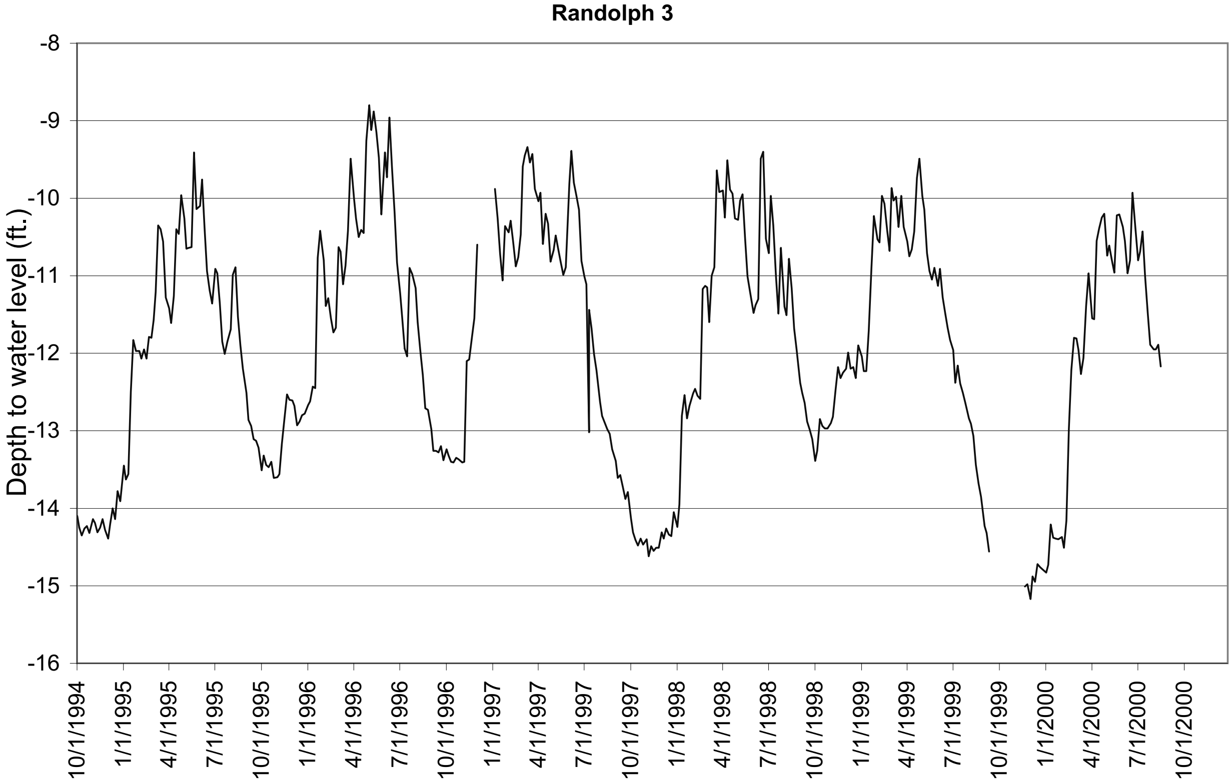


a. Unconfined outwash sand and gravel



b. Confined intratill sand and gravel

Figure 10: Water level fluctuations in selected observation wells



c. Confined limestone bedrock

Figure 10 continued: Water level fluctuations in selected observation wells

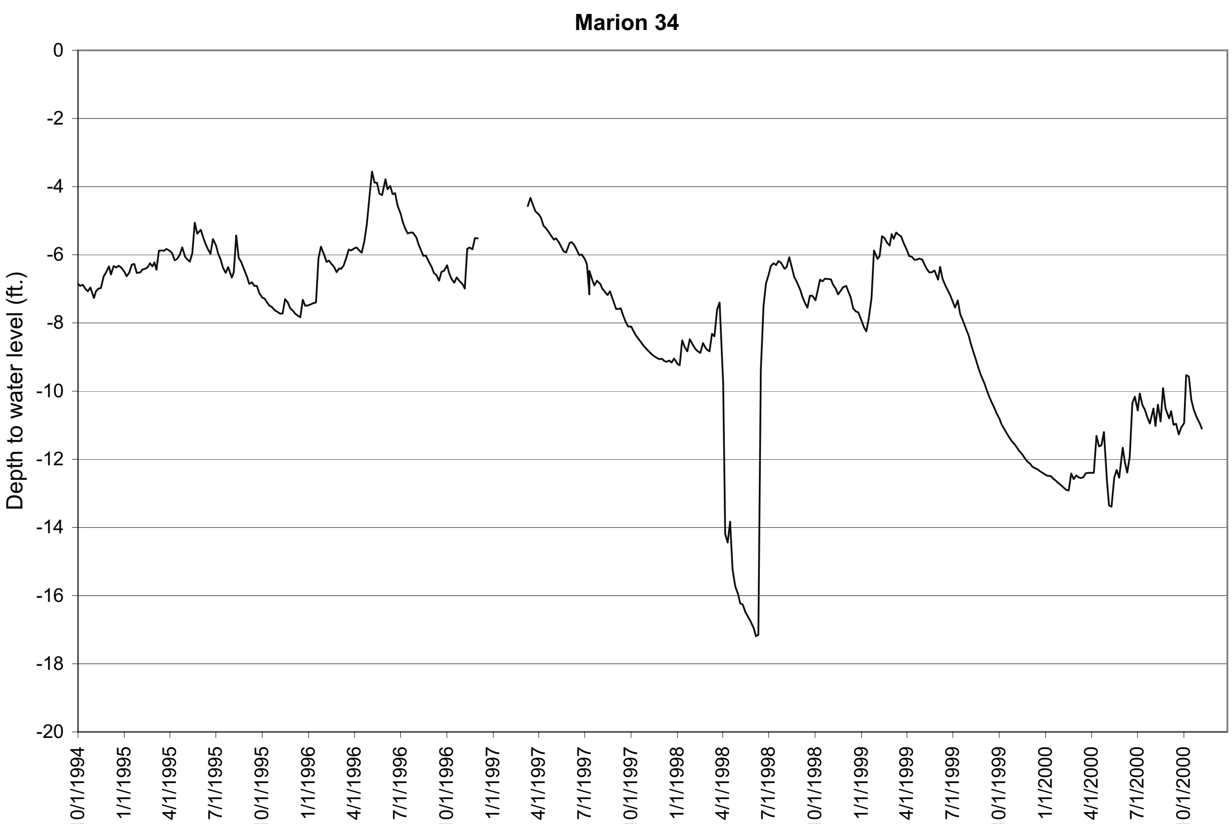


Figure 11: Water-level decline in observation well affected by nearby pumpage

aquifers within this system are usually not extensive.

The thickness of the Tipton Till Plain Aquifer system ranges from 15 feet or less in areas of near-surface bedrock to 200 feet or more in buried bedrock valleys. The thickness of aquifer materials within the system ranges from 0 feet to 40 feet. Typical aquifer thickness is 12 to 14 feet.

Well depths in the Tipton Till Plain Aquifer system are highly variable and are influenced by bedrock elevation and depth to productive sand and gravel zones within the tills. Although well depths in this system vary from 20 to 500 feet, most wells are constructed at 95 to 150 feet deep. The deepest wells are associated with buried bedrock valleys filled with till. The shallowest wells, 30 feet deep or less, are typically large-diameter bucket-rig wells producing water from thin sand and gravel layers or from clays overlying near-surface bedrock.

The elevations of water-bearing zones in the Tipton Till Plain Aquifer system vary substantially. In general, aquifer elevations reflect surface elevations and therefore are highest along basin boundaries and lowest near major drainageways. Aquifer elevations generally decline toward the south. Elevations in northern parts of the system range from 750 to 1135 feet m.s.l., but are typically in the range of 750 to 900 feet m.s.l. Along the southwestern boundary of the system, aquifer elevations range from 790 to 900 feet m.s.l. Along the southeastern border of the Tipton Till Plain Aquifer system many wells are producing from aquifers of elevation 700 feet m.s.l. or lower.

The confined intratill aquifers within the Tipton Till Plain Aquifer system commonly have poor hydrologic connections; therefore, static water levels may differ significantly within a small area. Static water levels in wells throughout the Tipton Till Plain Aquifer system occur from 0 feet (land surface or above) to 125 feet beneath the land surface. There are a few flowing wells throughout the system; however, most static water levels range from 20 to 35 feet below land surface.

Well yields in the Tipton Till Plain Aquifer system are generally adequate for domestic supply purposes; however, low-yielding wells and dry holes have been reported. Most domestic wells yield 35 gpm (gallons per minute) or less; but reported yields range from 0 to 150 gpm. There are, however, many large-diameter wells yielding 70 gpm or greater (high-capacity wells) in the intratill sand and gravel lenses.

This aquifer system is bounded indistinctly to the south by the Tipton Till Plain subsystem. The boundaries of other individual areas of the subsystem mapped within the Tipton Till Plain Aquifer system are also indistinct. Although both the Tipton Till Plain Aquifer system and Tipton Till Plain subsystem are intratill systems, the Tipton Till Plain Aquifer system has thicker, more numerous, and more productive sand and gravel zones than the subsystem.

The Tipton Till Plain Aquifer system contrasts sharply with the White River and Tributaries Outwash Aquifer system, which transects it. The intratill Tipton Till Plain aquifers are generally deeper than the White River aquifers and are confined within till sequences dominated by clays. Whereas, the water-bearing units of the White River and Tributaries Outwash Aquifer system are unconfined, usually fairly shallow, and are characterized by thick sequences of sand and gravel with little clay.

Tipton Till Plain Aquifer Subsystem

(Equivalent to the Fayette-Union Aquifer System in the Whitewater River Basin)

The Tipton Till Plain Aquifer subsystem is located in the northern part of the West Fork of the White River basin. The subsystem is discontinuous, occurring as individual areas within and forming the southern boundary of the Tipton Till Plain Aquifer system. The subsystem is similar to the Tipton Till Plain system in character and *provenance,* so the contacts with the Tipton Till Plain Aquifer system are gradational. The aquifers within the two systems are similar in their origin and placement, but differ in thickness and extent.

The Tipton Till Plain Aquifer subsystem is composed primarily of glacial tills that contain intratill sand and gravel aquifers of limited thickness and extent. The grain size of aquifer materials in the intratill deposits varies locally and ranges from fine or muddy sand to coarse gravel.

Thickness of intratill sand and gravel lenses within the system ranges from 2 to 80 feet throughout the Tipton Till Plain Aquifer subsystem, but is generally about 5 to 12 feet. Thicker layers may be found in areas near the White River and Tributaries Outwash Aquifer system, which occupies the White River Valley.

Well depths in the Tipton Till Plain Aquifer subsystem are variable and are influenced by bedrock elevation and the depth to productive sand and gravel layers within the thicker tills. Well depths range from 25 to 260 feet, but most wells are 70 to 150 feet deep.

Intratill aquifer elevations range from 600 to 1050 feet m.s.l. Aquifer elevations are highest in the northeast part of the basin. The lowest aquifer elevations occur in areas adjacent to the White River and Tributaries Outwash Aquifer system. Aquifers most commonly occur between 750 and 1050 feet m.s.l. in upland areas and between 600 and 750 feet m.s.l. in lowland areas.

Well yields in the Tipton Till Plain Aquifer subsystem are variable, but yields adequate for domestic use are expected. Wells drilled in this system produce from 0 to 300 gpm; however, most wells produce approximately 10 to 25 gpm. Because thick sand and gravel aquifer zones are commonly absent in much of the Tipton Till Plain Aquifer subsystem, bucket-rig wells may be used to increase yield. The large diameter of such wells permits them to store water from thin sand zones or as seepage from fractures within the till. However, several wells yielding 70 gpm or greater (high-capacity wells) are also present in this subsystem, although they do not generally produce as much as the high-capacity wells in the Tipton Till Plain Aquifer system.

The southern boundary of the Tipton Till Plain subsystem with the Dissected Till and Residuum Aquifer system is more distinct than its northern boundary with the Tipton Till Plain Aquifer system; and it approximately coincides with the limit

Table 3. Hydrologic characteristics of unconsolidated and bedrock aquifers

Aquifer System	Range of Aquifer Thickness (ft)	Common Aquifer Thickness (ft)	Expected Yield (gpm) Domestic	Expected Yield (gpm) High-capacity	Hydrologic Condition
Unconsolidated					
White River Outwash Aquifer System	10-150	50-100	10-50	500-2000	Unconfined
White River Outwash Aquifer Subsystem	12-54	20-40	10-50	70-1000	Unconfined/confined
Tipton Till Plain Aquifer	0-40	12-14	10-35	70-300	Confined
Tipton Till Plain Aquifer Subsystem	2-80	5-12	10-25	70-100	Confined
Lacustrine and Backwater Deposits Aquifer System	insufficient data	<5	0-35	not expected	Confined
Buried Valley Aquifer System	insufficient data	insufficient data	10-50	70-500	Confined
Dissected Till and Residuum Aquifer System	0-15	0-5	0-5	not expected	Confined/unconfined
Bedrock					
Ordovician/Maquoketa Group			5-15	not expected	Confined
Silurian and Devonian Carbonates			10-40	50-350	Confined
Devonian and Mississippian/New Albany Shale			0-5	not expected	Confined
Mississippian/Borden Group			1-5	not expected	Confined
Mississippian/Blue River and Sanders Groups			2-25	not expected	Confined
Mississippian/Buffalo Wallow, Stephensport, and West Baden Groups			3-16	not expected	Confined
Pennsylvanian/Raccoon Creek Group			2-10	not expected	Confined
Pennsylvanian/Carbondale Group			1-12	not expected	Confined
Pennsylvanian/McLeansboro Group			1-9	not expected	Confined

of the Wisconsin glacial advance. The unglaciated area of the southern half of the West Fork White River Basin, which includes the Dissected Till and Residuum Aquifer system, contrasts sharply with the thick glacial cover of the Tipton Till Plain Aquifer subsystem.

Dissected Till and Residuum Aquifer System

(Equivalent to the Dearborn Aquifer System in the Whitewater River Basin)

The Dissected Till and Residuum Aquifer system, covering much of the southern half of the West Fork White River Basin, has the most limited ground-water resources of the unconsolidated aquifer systems in the basin. Unconsolidated materials of the Dissected Till and Residuum consist of thin, eroded residuum and predominantly pre-Wisconsin tills.

Clay commonly overlies the bedrock in the Dissected Till and Residuum Aquifer system, but thin layers of intratill sand and gravel may be present. The water-bearing sand and gravel lenses may approach 15 feet in total thickness, but are more commonly 0 to 5 feet thick. Well depths in these aquifers range from 20 to 200 feet; although most wells are less than 75 feet deep. The deepest wells are in the northern part of the aquifer system near the boundary with the Tipton Till Plain Aquifer subsystem.

Aquifer elevations are typically between 450 and 850 feet m.s.l. Because the unconsolidated materials covering the bedrock are so thin in most places, the aquifer elevations closely match the elevation of the bedrock surface. Therefore, the highest aquifer elevations are at the northern end of the aquifer system, whereas the lower elevations are towards the southern end. Static water levels in wells developed in these aquifers range from flowing to 180 feet beneath the surface; but most static water levels range from 10 to 50 feet beneath ground level.

Well yields range from 0 to 150 gpm, but yields of 0 to 5 gpm are more common. Dry holes are also common in parts of the counties south of Morgan and Hendricks counties. Large-diameter bucket-rig wells may produce water from thin sands, gravels, or clay or till units in this system.

The Dissected Till and Residuum Aquifer system is transected by the White River and Tributaries Outwash Aquifer system. The boundary between these two systems is sharply defined by geologic materials, aquifer elevations, and water availability.

White River and Tributaries Outwash Aquifer System

The White River and Tributaries Outwash Aquifer system occupies the valleys of the White River and its major tributaries. The system has a very wide main trunk with long, narrow, north-south to northeast-southwest trending tributaries that transect the other unconsolidated aquifer systems in the basin.

The system contains large volumes of sand and gravel that were deposited by glaciers and that fill the present major stream valleys. As the glaciers melted, the sediment contained within them was delivered to adjacent streams in quantities too large for the streams to transport. As a result, the increased sediment load was stored in the valleys as vertical and lateral *accretionary* deposits. As long as the retreating glaciers continued to provide sediment in quantities too large for the streams to transport, the valleys continued to be filled. In this way, thick deposits of outwash sand and gravel accumulated in the valleys of the White River and its tributaries, forming the most prolific aquifer system in the basin.

The sand and gravel deposits of the White River and Tributaries Outwash Aquifer system range from less than 20 feet to more than 200 feet in thickness. Throughout the basin, the thick sands and gravels of the White River and Tributaries Outwash Aquifer system abruptly contrast with the clay-rich or bedrock environments of the surrounding aquifer systems. However, not all the sand and gravel is saturated with water. Actual aquifer thickness of the White River and Tributaries Outwash Aquifer system ranges from 10 to 150 feet, but most of the system has an aquifer thickness between 50 and 100 feet.

The elevation of the aquifer system varies uniformly from north to south. Along the northern extent of the aquifer system in Henry and Delaware Counties, the top of the aquifer system is present at about 850-900 feet m.s.l. Where the system leaves the state in Knox and Gibson Counties, the elevation is approximately 400 feet m.s.l. for the upper terraces and approximately 350 feet m.s.l. for the modern flood plain.

Because the system is largely unconfined, static water levels are more consistent than in the surrounding aquifer systems. Average static water levels of 25 feet or less are common throughout the system.

The White River and Tributaries Outwash Aquifer system is by far the most productive aquifer system in the basin and has the potential to consistently meet the needs of high-capacity water users. Well yields of 500 gpm or greater can be expected throughout most of the system. Presently, there are a few wells that have the capacity to produce up to 2000 gpm.

White River and Tributaries Outwash Aquifer Subsystem

In some areas of the White River and Tributaries Outwash Aquifer system, thick zones of sand and gravel have been covered by a layer of clay or till. The areas are surficially similar to the Tipton Till Plain Aquifer system, but are depositionally related to the White River and Tributaries Outwash Aquifer system. These areas have, therefore, been named the White River and Tributaries Outwash Aquifer subsystem.

The White River and Tributaries Outwash Aquifer subsystem is very similar to the White River and Tributaries Outwash Aquifer system but is less productive, contains thinner sand and gravel zones, and contains greater amounts of clay material. Sand and gravel zones in the subsystem range in thickness from 12 to 54 feet, but are typically 20 to 40 feet thick. The upper portions of the sand and gravel zones in the system, however, are commonly unsaturated.

The White River and Tributaries Outwash Aquifer subsystem has well depths ranging from 30 to 170 feet below surface, but they are typically about 70 feet below surface. Aquifer materials in the subsystem occur at elevations ranging from 850 feet m.s.l. in the northern part of the basin, to 350 feet m.s.l. in the southern part of the basin. Static water levels in the wells in the subsystem occur between 10 and 125 feet below the land surface, but commonly occur at 20 to 40 feet beneath the surface.

Domestic wells in the White River and Tributaries Outwash Aquifer subsystem yield from 10 to 50 gpm; but high-capacity wells producing up to 1000 gpm have been reported. The largest yields in this subsystem are in the northern portion of the basin, adjacent to the thick till cover of the Tipton Till Plain Aquifer system.

Buried Valley Aquifer System

The Buried Valley Aquifer system consists of aquifer materials deposited in pre-glacial bedrock valleys in the West Fork of the White River basin. During valley development, layers of bedrock were dissected to create valleys that were subsequently filled with unconsolidated glacial sediment of variable thickness. Although there are additional buried bedrock valleys in the West Fork White River basin, only the larger buried valleys that contain significant water-bearing sediments have been included as mapped units of the Buried Valley Aquifer system.

There are two significant buried bedrock valleys located in West Fork White River basin; both cut into Mississippian bedrock. One, a narrow valley having appreciable outwash, trends northeast/southwest in southern Hendricks, Morgan, Putnam, and Owen Counties. The other, part of a larger buried valley system that extends into Putnam and Montgomery Counties in the Middle Wabash River basin, is in northwestern Hendricks County.

Wells in the Buried Valley Aquifer system are completed at depths ranging from 75 to 250 feet, although well depths ranging from 100 to 175 feet are most common. Static water levels in the wells range from 10 to 80 feet below the ground surface, but static water levels between 25 and 40 feet below ground surface are most common. Domestic wells typically yield from 10 to 50 gpm, but high-capacity wells may yield as much as 300 to 1000 gpm. The highest yields are found in the buried valley in northwestern Hendricks County.

Lacustrine and Backwater Deposits Aquifer System

The Lacustrine and Backwater Deposits Aquifer system, located primarily in the southern third of the basin, is made up of discontinuous bodies of deposits extending along areas of outwash close to the West Fork White River Valley. The deposits were formed in bodies of currentless or relatively stagnant lake water and are marked by soft silt and clay. These lake deposits are generally confined to valleys that are tributary to the principle through valleys of southern Indiana, which carried most of the meltwater that poured from the waning ice sheets.

The larger valleys, like the White River, were choked with sand and gravel carried from the glaciers by meltwater. In the larger valleys, thick deposits of this material dammed and ponded tributary streams, creating lakes. Today, thick deposits of silt and clay sometimes called "slack water clay" mark the locations of these glacial lakes.

Also, when massive amounts of water were being released from the glaciers as they were retreating, from time to time, the existing valley was not sufficient to contain the water. Any pre-existing drainages or low spots in the bedrock surface were points of water collection. Temporary lakes formed in these areas, leaving fine-grained *glaciolacustrine* deposits.

The overall scarcity of productive zones of sand and gravel in this aquifer system is apparent from the number of ground-water wells completed in the underlying bedrock aquifers. Sand and gravel lenses, when present, are commonly less than 5 feet thick and are either confined within the glaciolacustrine deposits, or are directly overlying bedrock. Large-diameter bucket-rig wells are often employed when other means of extracting seepage from the fine-grained deposits are not available. Wells that penetrate the Lacustrine and Backwater Deposits Aquifer system commonly have depths that range from 30 to 70 feet, but some have depths of up to 120 feet. Static water levels in wells penetrating the aquifer system are typically less than 25 feet below the land surface.

Yields from domestic wells range from 0 (dry holes) to 35 gpm, but no known high-capacity well is completed in the aquifer system.

Bedrock aquifer systems

The occurrence of bedrock aquifers depends on the original composition of the rocks and subsequent changes which influence the hydraulic properties. *Post-depositional processes* which promote jointing, fracturing, and solution activity of exposed bedrock generally increase the *hydraulic conductivity* of the upper portion of bedrock aquifer systems. Because permeability is usually greatest near the bedrock surface, the upper bedrock units are generally the most productive aquifers. In the West Fork White River basin, rock types exposed at the bedrock surface range from unproductive shales to highly productive limestones and dolomites (plate 1).

The Silurian-Devonian Carbonate aquifer system, present in the northern third of the basin is the most laterally extensive and productive bedrock aquifer system in the basin. Solution-enlarged joints in this system yield water in quantity generally adequate for domestic, industrial, or municipal use. This bedrock aquifer system is a major aquifer over wide areas in northern part of the state where it directly underlies glacial drift.

Bedrock aquifer systems in the basin are overlain by unconsolidated deposits of varying thickness (plate 6 and figure 5). In northwest Hamilton County, as much as 400 feet of unconsolidated material overlies bedrock. Many other areas in the basin, especially in the southern part, have 50 feet or less of unconsolidated material overlying bedrock. Most of the bedrock aquifers in the basin are under *confined* conditions. In other words, the water level (*potentiometric* surface) in wells completed in the aquifer rises above the top of the aquifer.

In places, sand and gravel aquifers are located immediately overlying the bedrock surface. Many of these materials are found in association with buried bedrock valleys but also occur elsewhere along the bedrock surface. Where unconsolidated aquifers are in contact with the Silurian and Devonian Carbonate aquifer system, the two aquifers are hydraulically linked and have very similar hydraulic gradients.

The yield of a bedrock aquifer depends on its hydraulic characteristics and the nature of the overlying deposits. Shale and glacial till act as aquitards, restricting recharge to underlying bedrock aquifers. However, fracturing and/or jointing may occur in aquitards, which can increase recharge to the underlying aquifers.

On a general basis, the incidence of mineralized or even *saline* ground water in Indiana increases rapidly at bedrock depths below 300 feet, and even shallower in some areas. Therefore, a discussion and evaluation of the ground-water potential of the bedrock aquifers is essentially confined to those geologic units lying above the expected limits of non-potable water.

In this report nine bedrock aquifer systems are identified for the West Fork White River basin based on bedrock surface lithology. They are, from east to west and oldest to youngest: **Ordovician/Maquoketa Group; Silurian-Devonian Carbonate; Devonian and Mississipppian/New Albany Shale; Mississippian/Borden Group; Mississippian/Blue River and Sanders Groups; Mississippian/Buffalo Wallow, Stephensport, and West Baden Groups; Pennsylvanian/Raccoon Creek Group; Pennsylvanian/Carbondale Group; and the Pennsylvanian/McLeansboro Group** (plates 1 and 5). Hydraulic properties within the nine aquifer systems are highly variable.

Although this type of two-dimensional mapping is useful, it should be remembered that the Silurian-Devonian Carbonate rocks extend beneath the Devonian and Mississippian/New Albany Shale Aquifer system (plate 1) and are used as a water supply within the latter's boundaries. This is also true for other aquifer systems that extend beneath less productive systems.

The bedrock aquifer systems extend across the basin generally as a series of northwest/southeast trending bands of varying widths, equal approximately to their exposure at the bedrock surface (plates 1 and 5). In an area southwest of the basin's midsection, the nearly parallel bands of bedrock become truncated and overlapping. The overlapping pattern is the result of a long period of erosion that beveled entire systems of older rocks. Subsequent burial of the erosion surface by sedimentation during Pennsylvanian time created one of the most widespread regional unconformities in the world, the Mississippian-Pennsylvanian unconformity. Younger Pennsylvanian age rocks overlap onto progressively older Mississippian age rocks at increasing distances north of the Ohio River.

In general, bedrock aquifers are not used as much as the unconsolidated aquifers in the northern part of the West Fork White River basin because adequate ground water is usually available from the shallower unconsolidated materials. In the southern part of the basin, however, bedrock aquifers are more commonly used because the unconsolidated materials overlying the bedrock typically consist of relatively thin, non-productive glacial till or weathered bedrock residuum.

Ordovician/Maquoketa Group

The Maquoketa Group of Ordovician age is present at the bedrock surface in small areas in Randolph, Delaware, Henry, and Madison counties (plate 5). It is the least extensive bedrock aquifer system in the West Fork White River basin. The rocks in this group are the oldest at the bedrock surface in the basin, exposed only in preglacial valleys that have since been filled with glacial drift. The group consists of interbedded shales and limestones. Gray calcareous shale dominates the group, but brown carbonaceous shale characterizes the lowermost part of the group. Limestone, which constitutes about 20 percent of the group, is most abundant in the upper part.

The thickness of the Maquoketa Group is highly variable because the top of the group is an erosional *disconformity* and has local relief of more than 100 feet due to preglacial erosion of the bedrock surface (plate 1).

Wells completed in the Ordovician bedrock aquifer system in the West Fork White River basin range from 112 to 600 feet deep. Well depth depends upon bedrock elevation and unconsolidated material thickness. The bedrock surface elevation for a specific area may be estimated using plate 3a. The thickness of unconsolidated material for an area may be estimated by using plate 6 or figure 5. The amount of penetration of wells into bedrock in this aquifer system is also highly variable, and ranges from about 10 to more than 290 feet. Data are not sufficient to correlate yields with the amount of penetration. Static water levels in wells developed in this system range from 0 to 60 feet beneath the land surface, but are usually between 10 and 50 feet below ground.

In general, because of the high shale content, the Maquoketa Group is considered as an aquitard having poor yield potential. However, in the West Fork White River basin higher yields are reported than in other parts of the state because there is higher limestone content in the upper part of the group. The moderate yield potential in the basin is related to joints and solution cavities that formed in the limestone units.

Well yields from the Maquoketa Group, as indicated by drillers' tests, range from 0 to 200 gpm. Yields of 5 to 15 gpm are typical and yields above 15 gpm are not common. Some dry holes (for practical purposes) have been reported.

Because the Maquoketa is generally not highly productive it is typically used only when the overlying drift does not con-

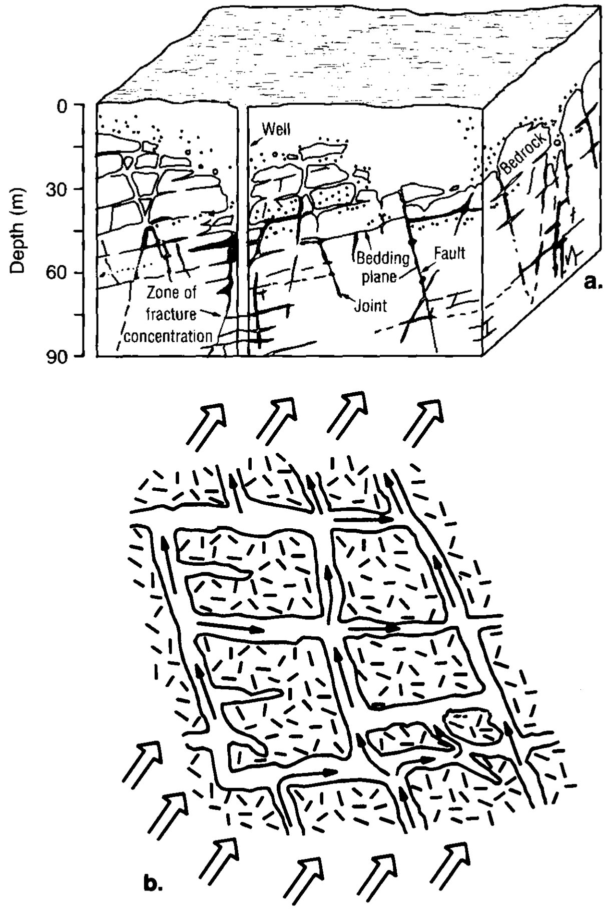
Ground-water flow and the dissolution of carbonate rocks

Over a long period of time, limestone and to a lesser extent dolomite, will gradually dissolve in the presence of ground water that was derived from precipitation. Carbon dioxide from the atmosphere and from the soil is incorporated into the precipitation as it changes from atmospheric moisture to ground water. Ground water containing dissolved carbon dioxide forms a mild acid which can slowly dissolve alkaline materials. The alkaline carbonate bedrock units are affected by this process when the slightly acidic ground water moves through the units and is neutralized by the carbonate. A portion of the carbonate unit is dissolved in this neutralization process thus increasing the size of the fracture in which the water is flowing. As this process continues through time larger openings, solution features, form in the rock allowing for increased ground-water flow.

Many types of solution features can result from this process, some subtle and others quite large. The most common features develop along preexisting fractures, joints, and bedding planes, which represent the initial flow path of the water through the rock (fig. a). Over time a variety of larger features can develop leading to cave systems with sinkholes and deep valleys as surface expressions.

As this process continued in the northern portion of the West Fork White River basin in the Silurian-Devonian Carbonate Aquifer system, a very complex system of fractures, solution channels, valleys, and sinkholes probably developed. Glacial events partially eroded the weakened surface of the carbonate rock and then covered the surface with glacial sediments. Consequently no direct surface expression of the probable pre-Pleistocene karst terrain (paleo-karst) currently exists in that part of the Basin.

The near-surface carbonate bedrock aquifers in the Mississippian carbonates contain a highly variable fractured section which greatly affects ground-water flow through the bedrock. Fractured rock represents one of the most complex types of hydrogeologic systems known. While regional ground-water flow can be very predictable, local flow can be highly varied both in terms of quantity and direction (fig. b). Consequently, determining the local direction of ground-water flow in fractured bedrock at the scale of a specific site may require elaborate instrumentation, monitoring, and dye tracing.



tain an adequate sand and gravel aquifer. It is bounded by the younger, overlying Silurian and Devonian Carbonate aquifer system.

Silurian and Devonian Carbonate Aquifer System

The Silurian and Devonian Carbonate Aquifer system, present at the bedrock surface in much of the northern third of the West Fork White River basin, is the most productive bedrock aquifer system in the basin. This aquifer system is composed primarily of limestones and dolomite with some interbedded shale units. Because most individual units of the Silurian and Devonian systems are composed of similar carbonate rock types and cannot be distinguished on the basis of water-well records, they are considered as a single water-bearing system.

In carbonate aquifers water is stored and transmitted in joints, fractures, bedding planes, and solution openings within the rock. The reef facies of the Silurian carbonates have high porosities (from 5 to 25 percent) and high permeabilities. The bank and inter-reef facies contain significantly lower porosities and permeabilities. Devonian carbonates have porosity values that are highly variable and range from 0 to 14 percent (John Rupp, written communication, 1988). Shale units within the Silurian and Devonian Carbonate Aquifer system, such as the Mississinewa shale and the Waldron shale, limit the hydraulic connection between the water-producing zones.

Ground-water flow in the Silurian and Devonian Carbonate aquifer system occurs predominately along bedrock joints, fractures, and bedding planes as well as along *solution* features (see sidebar, **Ground-water flow and the dissolution of carbonate rocks**). Because ground-water flow through carbonate rock is controlled by the geometry of its joints and fractures, the direction of site specific or local flow may differ from that of the regional ground-water flow path. Ground-water flow in these rocks can be complex because the type of fracturing and fracture patterns in a specific carbonate rock in a specific location are determined by many factors.

The original fracture patterns in carbonate rocks may be altered by pre-Pleistocene ground-water flow; and solution features are a result. In addition to complexities introduced by pre-Pleistocene events, Pleistocene erosion, weathering, and deposition have caused additional alterations to the carbonate aquifer system in the basin. All of these factors result in very complex local ground-water flow.

The maximum thickness of the Silurian and Devonian Carbonate aquifer system in the West Fork White River basin area is approximately 400 feet, but the common thickness in the crop area is approximately 100 feet in the east and 250 feet in the west (plate 7). Thickness of the most productive part of the aquifer system is uneven because the upper surface is an erosion surface.

Wells completed in the Silurian and Devonian Carbonate

Aquifer system range from 24 to 460 feet deep, but most wells are constructed at depths of 100 to 230 feet. Deep, high-capacity wells commonly penetrate 50 to 260 feet of carbonate rock, and some wells have been reported to penetrate up to 332 feet of rock. Domestic wells commonly only penetrate the upper 30 to 120 feet of the carbonate bedrock.

The elevations of water-bearing zones in the Silurian and Devonian Carbonate Aquifer system vary substantially. The approximate elevation of the bedrock surface for a specific location may be determined by using the bedrock topography map (plates 3a and b).

Static water levels in the wells completed in the carbonate aquifer vary from 0 feet to 180 feet beneath the land surface; however, static levels usually are between 10 and 40 feet below ground. Flowing wells have been reported at scattered locations in the basin.

Water well data indicate that the most productive part of the carbonate aquifer occurs within the upper 100 feet, and in many places, within a few feet of the bedrock surface. However, other zones of relatively high permeability do occur at greater depth. The deeper zones are most likely to be penetrated by large diameter, high-capacity wells in an attempt to increase available drawdown in the well and obtain maximum yield.

Well yields depend on the diameter of the well and aquifer characteristics. Most of the wells in this bedrock system are 4- to 6-inch-diameter domestic wells. Most domestic wells can be expected to produce between 10 and 40 gpm, but well yields range from one to 100 gpm. Yields of larger-diameter wells generally range from 50 to 350 gpm, but higher-yielding wells may be possible where several feet of sand and gravel are directly overlying the bedrock surface. Large wells, having 8- to 16-inch diameters, are usually industrial, municipal, or irrigation supply wells. The Silurian and Devonian carbonate system is one of the few bedrock systems in the West Fork White River basin generally capable of sustaining high-capacity well yields.

Silurian and Devonian Carbonate aquifers are an important source of water for many communities in the northern third of the basin and are also utilized by thousands of residents served by individual domestic wells. The Silurian and Devonian Carbonate aquifer system is bounded on the west by the New Albany Shale aquifer system. In some areas near the contact between the New Albany Shale and the Devonian carbonates, wells are drilled through the shale and into the more productive underlying carbonate rocks. Because the overlying shale inhibits recharge and because fracturing may not be well developed in the carbonates, these wells are less productive than wells completed in carbonates not overlain by shale.

Devonian and Mississippian/ New Albany Shale

The Devonian and Mississippian/New Albany Shale bedrock aquifer is present in the West Fork White River basin as a narrow strip extending from southeast Boone County across western Marion County, into northern Johnson County. The New Albany Shale overlies the Devonian carbonate bedrock and is primarily Devonian age, except for the upper few feet that are Mississippian age.

This bedrock aquifer system is predominately brownish-black carbon-rich shale having a thickness of about 100 to 120 feet near its subcrop in the center of the basin to 210 feet in the southwestern part of the basin. It is often mistakenly reported as slate. It contains minor amounts of dolomite and dolomitic quartz sandstone.

Although wells completed in the New Albany Shale vary in depth from 62 to 318 feet, most are constructed at depths of 130 to 220 feet. Wells developed in the New Albany Shale penetrate from 2 to 120 feet of shale; but most wells penetrate from 12 to 60 feet. Static water levels in wells completed in the shale aquifer range from 8 feet to 105 feet beneath the land surface; however, levels usually are between 25 and 70 feet below the surface.

The elevations of water-bearing zones in the New Albany Shale Aquifer system vary substantially. The approximate elevation of the bedrock surface for a specific location may be determined by using the bedrock topography map (plate 3b).

Although several dozen wells are reported producing water from the New Albany Shale, the formation is not considered as a significant aquifer. Most wells in the New Albany Shale yield 5 gpm or less, and dry holes are common; however, a few yields of up to 20 gpm have been reported. Wells are often drilled through the New Albany Shale into the underlying carbonates in an attempt to get higher well yields.

This bedrock aquifer system is often associated with "sulfur water", mineralized water, or saline water. The New Albany Shale Bedrock aquifer system is bounded on the west by the Mississippian/Borden Group Bedrock Aquifer system.

Mississippian Bedrock

The Mississippian age bedrock aquifers can be broken into three reasonably distinct groups. They include the lowermost (oldest) siltstone and shale formations of the Borden Group; the middle Mississippian age limestone sequence of the Blue River and Sanders Groups that is prominent in south-central Indiana; and the uppermost (youngest) alternating limestone-shale-sandstone units of Buffalo Wallow, Stephensport, and West Baden Groups.

Mississippian/Borden Group

The Mississippian Borden Bedrock Aquifer Group occupies much of the mid-section of the West Fork White River basin. It encompasses most of Hendricks and Morgan counties and portions of Boone, Putnam, Johnson, Brown, and Monroe counties. This bedrock aquifer system is composed primarily of siltstone and shale. Fine-grained sandstones are common. Carbonates are rare, occurring as discontinuous interbedded limestone lenses mostly in the upper portion of the group. The Rockford limestone, an important marker bed where present, separates the New Albany Shale and the Borden Group.

The Borden Group ranges from 0 to about 750 feet in thickness at its outcrop and subcrop in the basin. It generally thins as it dips to the southwest beneath younger rock formations.

Well depths in the Borden Aquifer system range from 28 to 400 feet. Most wells are completed at depths of 70 to 140 feet. The amount of Borden rock penetrated typically ranges from about 30 to 100 feet, with a maximum of 375 feet. Most of the water is found in the upper 100 feet of the rock, although data are not sufficient to correlate yields with the amount of penetration. Static water levels in the wells completed in the Borden aquifer range from 0 to 180 feet below land surface but commonly are between 10 and 40 feet.

The elevations of water-bearing zones in the Borden Aquifer system vary substantially. The approximate elevation of the bedrock surface is shown on plates 3b and c.

The Borden Group is often regarded as an aquitard; and attempts to get water from wells drilled into it have often failed. However, many wells are able to produce sufficient water for domestic purposes. Most domestic wells completed in the group yield from 1 to 5 gpm. A few wells have been tested at up to 50 gpm, but it is doubtful that many could sustain such a rate for very long. Although one 8-inch diameter well was reportedly tested at 154 gpm, overall there is almost no chance for development of high-capacity wells in the Borden Group aquifer system.

Because the Borden Group is generally not very productive, it is typically used only where overlying glacial drift or outwash deposits (if present) do not contain a sand or gravel aquifer. In the eastern portion of its outcrop area where the Borden is not more than about 300 feet thick, a few wells have been drilled through it and the New Albany Shale into the Silurian and Devonian Carbonate aquifer system. However, wells over about 500 feet deep may encounter non-potable (mineralized or salty) water. The Borden Group is bounded on the west by the Blue River and Sanders Groups.

Mississippian/Blue River and Sanders Groups

This Middle Mississippian age aquifer system, located in a narrow band in the south-central part of the West Fork White River basin, overlies the Borden Group. This aquifer system encompasses two groups: the lowermost Sanders and the overlying Blue River groups. The Sanders Group includes the Harrodsburg and Salem limestone formations. These are primarily limestone with some dolomitic limestone content. The Blue River Group includes the St. Louis, St. Genevieve, and the Paoli limestone formations. These are primarily limestones containing significant amounts of gypsum, anhydrite, shale, chert, and calcareous sandstone.

The combined Blue River and Sanders groups range in thickness from 0 to about 600 feet in the outcrop/subcrop area of the basin. However, as the strata dip to the southwest beneath younger rocks the thickness increases to about 1500 feet where the White River empties into the Wabash River. The Blue River Group is truncated in northern Putnam County by pre-Pennsylvanian erosion. There it is unconformably overlain by the Mansfield Formation of Pennsylvanian age. The Sanders Group is also truncated in the north by pre-Pennsylvanian erosion and is also overlain unconformably by the Mansfield.

Well depths in the Blue River and Sanders Group Aquifer system vary from 16 to 423 feet, but most wells are completed at depths of about 80 to 170 feet. The amount of rock penetrated by a well typically ranges from about 35 to 140 feet, with a maximum of 411 feet. Most of the water is found in the upper 100 feet of the rock. However, no attempt was made to correlate yields with the amount of penetration or the individual geologic formations.

The elevations of water-bearing zones in the Blue River and Sanders Groups aquifer system vary substantially. The approximate elevation to bedrock for a specific location may be determined by using the bedrock topography map (plates 3b and c).

Static water levels are quite variable in the wells completed in the aquifer. Water levels ranging from 0 feet to 202 feet below land surface have been reported; however, water levels usually are between 20 and 75 feet below ground.

The Blue River and Sanders Groups Aquifer system is not regarded as a major ground-water resource. However, most attempts to drill a domestic well into it are successful. Most domestic wells completed in the system have been tested at 2 to 25 gpm. A few public water supply wells have been tested at 9 to 192 gpm. Very few wells could sustain a pumping rate over 50 gpm for long.

The outcrop/subcrop area of the Blue River and Sanders Groups is well known for significant karst development. Because of the shallow rock, open joints, and solution channels the aquifer system is quite susceptible to contaminants introduced at and near land surface. The Blue River and Sanders Group is bounded on the west by the Buffalo Wallow, Stephensport, and West Baden Groups.

Mississippian/Buffalo Wallow, Stephensport, and West Baden Groups

This Upper Mississipppian bedrock aquifer system is limited to a small area in central Owen and east-central Greene Counties. It is laterally discontinuous and has been truncated northward as a result of pre-Pennsylvanian erosion. The present near-surface thickness and occurrence of the deposits forming this bedrock aquifer system have been altered by the Mississippian-Pennsylvanian unconformity throughout the West Fork White River basin.

This bedrock aquifer system, composed primarily of shale, limestone, and sandstone, consists of three groups, from oldest to youngest: West Baden, Stephensport, and Buffalo Wallow. The three groups comprising this bedrock aquifer system differ in their percentages of shale, limestone and sandstone.

The lowermost West Baden Group consists dominantly of gray to varicolored shale and mudstone (approximately 40 percent) and thin-bedded to cross-bedded sandstone (35 percent); but limestone in beds of variable thickness is an important lesser constituent (25 percent). Total thickness of the West Baden Group along the outcrop ranges from 100 to 140 feet. The beds in this group are 5 to 20 feet thick. A major feature of the West Baden Group is a southwestward-trending belt about 6 miles wide across which the limestones were not deposited and in which sandstone dominates the entire thickness of the group. In the basin this occurs in Owen and Greene Counties.

The Stephensport Group has more limestone (approximately 40 percent) than the West Baden Group, less shale (25 percent), and cliff-forming sandstone (35 percent).

The Buffalo Wallow Group is primarily shale, mudstone, and siltstone (approximately 75 percent); but it contains prominent beds of sandstone (20 percent) and limestone (5 percent), some of which are laterally extensive. The limestone and sandstone beds, principally in the lower part of the unit, are 1 to 15 feet thick and 5 to 90 feet thick, respectively. This Group thins progressively and is truncated northward as a result of pre-Pennsylvanian erosion, so that in the subsurface its northern margin crosses southwestern Sullivan County, Daviess County, and northeastern Dubois County. Along the outcrop it reaches no farther north than southwestern Orange County.

The depth to the bedrock surface is usually less than 20 feet. Well depths in the Buffalo Wallow, Stephensport, and West Baden Groups range from 40 to 450 feet, with most wells completed at depths of about 100 to 240 feet. The amount of rock penetrated by a well typically ranges from about 60 to 220 feet, with a maximum of 440 feet. Most of the water will be found in the limestone and sandstone beds. However, no attempt has been made in this report to correlate yields with the amount of penetration or the individual geologic formations used.

The elevations of water-bearing zones in the Buffalo Wallow, Stephensport, and West Baden Groups vary substantially. The approximate elevation to bedrock for a specific location may be determined by using the bedrock topography map (plates 3b and c)

Static water levels are highly variable in the wells completed in this aquifer system. Water levels range from 0 feet to 300 feet below surface but are usually between 35 and 150 feet below surface.

The Buffalo Wallow, Stephensport, and West Baden Groups aquifer system is not regarded as a major groundwater resource. However, most attempts to drill a domestic well into it are successful. Most domestic wells completed in the system have been tested at 3 to 16 gpm. A few wells have been tested as high as 50 gpm. However, very few wells can sustain a pumping rate over 30 gpm.

In the outcrop/subcrop area of the Buffalo Wallow, Stephensport, and West Baden groups the rock is predominantly shallow and contains numerous, irregular joints. In limited areas some karst has developed in the limestone beds. These conditions warrant considering the aquifer system as a whole to be somewhat susceptible to contaminants introduced at and near land surface. The Buffalo Wallow, Stephensport, and West Baden groups are bounded on the west by the Pennsylvanian/Raccoon Creek Group.

Pennsylvanian Bedrock

The Pennsylvanian age bedrock aquifers, although having many similarities, can be broken into three groups. They include the lowermost (oldest) Raccoon Creek Group, the Carbondale Group, and the McLeansboro Group that lies at the southwestern tip of the basin.

Aquifers contained within the Pennsylvanian age bedrock are generally of low yielding capability. However, their value is most significant to the homes and farms using these sources in southwestern Indiana, and to those water-flood oil operations requiring fresh water for injection and re-pressurization of oil-bearing formations.

In general, well depths are greater in the Pennsylvanian rocks than in other geologic systems in the state, and depths over 200 feet are common. Well casing diameters are usually six inches or greater, indicating the low yield capabilities of these aquifers. Because of the low permeability of the bedrock, the abundance of shale confining zones both above and below aquifer systems, and the limitation in available drawdown, it is seldom possible to divert large volumes of water into any particular pumpage center.

Pennsylvanian/Raccoon Creek Group

The outcrop/subcrop area of the Raccoon Creek Group in the West Fork White River basin consists of a north-south trending band through portions of Clay, Owen, Greene, Daviess, and Martin counties. The Pennsylvanian/Raccoon Creek Group consists in ascending order of the Mansfield, Brazil, and Staunton Formations. Because there was a long period of erosion prior to deposition of these Pennsylvanian age rocks, this group is underlain by rocks ranging in age from Middle Devonian to Late Mississippian. The lowermost Mansfield rests unconformably, with as much as 150 feet of local relief, on Mississippian rocks that are generally progressively older northward. This Group has variable thickness because of the irregular unconformity on the surface of underlying rocks.

Within this area the thickness of the group ranges from 0 to about 500 feet. However, as the strata dip to the southwest beneath younger rocks the thickness increases to about 700 feet where the White River empties into the Wabash River. Shale and sandstone compose approximately 95 percent of the group; and clay, coal, and limestone make up nearly all the rest. Shale is more common than sandstone, and most of it is light-gray to dark-gray shale and soft nonsilty shale to hard silty and sandy shale. The sandstone is mostly fine grained; coarse-grained size is rare. Where the sandstone is present in the subsurface, massive crossbedded sandstone seems to be most common. Coal beds are as thick as 7 feet in some areas. Clay beds as thick as 10 feet underlie coals. Limestone beds are 3 to 10 feet thick. The lowermost part of the Mansfield commonly consists of sandstone, generally crossbedded and containing a quartz-pebble and chert conglomerate in places.

The depth to the bedrock surface is generally less than 30 feet. Well depths in the Pennsylvanian/Raccoon Creek Group Aquifer system are highly variable, varying from 22 to 480 feet, but most are constructed at 110 to 270 feet deep. The amount of rock penetrated by a well typically ranges from 70 to 240 feet, with a maximum of 452 feet. Static water levels in the wells completed in the aquifer vary from 0 (flowing) feet to 190 feet beneath the land surface; however, water levels usually are between 18 and 75 feet below the surface.

The elevations of water-bearing zones in the Pennsylvanian/Raccoon Creek Group Aquifer system vary substantially. The approximate elevation to bedrock for a specific location may be determined by using the bedrock topography map (plate3c).

In general, the Raccoon Creek Group is considered a minor ground-water source, with most wells producing from the basal sandstone of the Mansfield Formation. Most domestic wells produce between 2 and 10 gpm with localized yields of up to 20 gpm. A few dry holes have been reported. Well yields for light industrial or small municipal usage (for example, the town of Staunton) of up to 70 gpm may be obtained locally.

Potentially higher yielding wells may be obtained in the thicker sandstone members of the Mansfield Formation along the eastern fringes of the outcrop area in Clay, Greene, and Daviess Counties.

Water quality is generally good, but in areas of surface and underground coal mining, some contamination has occurred. Contaminants are typically dissolved solids, including calcium, magnesium, sulfate, bicarbonate, and iron. Natural water quality gets progressively worse (more salty) in wells deeper than about 400 feet as the strata dip beneath younger rocks to the southwest. The Raccoon Creek Group is bounded on the west by the Carbondale Group.

Pennsylvanian/Carbondale Group

The outcrop/subcrop area of the Carbondale Group in the West Fork White River basin consists of a north-south trending band from western Clay County to northern Pike County. The Pennsylvanian/Carbondale Group consists in ascending order of the Linton, Petersburg, and the Dugger Formations. It overlies the Raccoon Creek Group and underlies the McLeansboro Group.

Within this area the thickness of the group ranges from 0 along its eastern outcrop edge to about 400 feet where it dips beneath younger rocks to the west. Most of the thickness of this group consists of variable shales and sandstones with some coal and limestone. This group includes some laterally persistent limestones and four of Indiana's commercially important coals. Persistent shales and underclays are associated with several of these coals. Coal beds 5 to 8 feet thick are widespread. Clay beds as much as 10 feet thick underlie coals. Two limestone beds are 5 to 15 feet thick.

The Linton, the lowermost formation in the Carbondale Group, includes two coal members, sandstone, shale, and clay. Of special interest, it includes the Coxville Sandstone member. The Coxville Sandstone is typically a fine- to coarse-grained thick bedded and cross-bedded sandstone, but shale partings a few inches thick are present in some sections. It ranges from 10 to 50 feet in thickness in the subsurface in Sullivan, Pike, Gibson, and Posey Counties.

The overlying Petersburg Formation includes three coals, limestone, and unnamed beds of shale, siltsone, sandstone and underclay. The uppermost Dugger Formation includes 4 coal members, including two commercially important ones. No units within the Petersburg or Dugger formations are regarded as significant aquifers.

The depth to the bedrock surface is generally less than 30 feet. Wells range in depth from 23 to 360 feet, but are typically 91 to 238 feet deep. Several of the deeper wells are located along the eastern crop line of the Carbondale Group and include some water from the underlying Raccoon Creek Group. The amount of rock penetrated typically ranges from 48 to 196 feet, with a maximum of 348 feet. Static water levels in the Carbondale Group range from 3 to 180 feet below land surface, but are typically between 13 and 69 feet below the surface.

In general, the Carbondale Group is considered a minor ground-water source with most wells producing from the thicker sandstone and coal units. Most domestic wells produce between 1 and 12 gpm with localized yields of up to 20 gpm. A few dry holes have been reported.

The elevations of water-bearing zones in the Pennsylvanian/Carbondale Group vary substantially. The approximate elevation to bedrock for a specific location may be determined by using the bedrock topography map (plate 3c).

Water quality is generally good and the aquifer system is not very susceptible to contamination from the land surface. However, in areas of surface and underground coal mining, some contamination has occurred. Contaminants are typically dissolved solids, including calcium, magnesium, sulfate, bicarbonate, and iron. The natural quality of well water gets progressively more mineralized (often changing from a calcium-magnesium-bicarbonate type to a sodium bicarbonate or sodium chloride type) as wells are drilled deeper than about 300 feet and the rock strata dip beneath younger rocks to the southwest.

The Carbondale Group is bounded on the west by the McLeansboro Group.

Pennsylvanian/McLeansboro Group

The outcrop/subcrop area of the McLeansboro Group in the West Fork White River basin consists of a north-south trending band from central Knox to northern Gibson County. Within this area the thickness of the group ranges from 0 to about 400 feet. The Pennsylvanian/McLeansboro Group consists in ascending order of the Shelburn, Patoka, Bond, and Mattoon. All but the Mattoon Formation are present in the West Fork White River basin. The first three formations consist primarily of shale (50 to 60 percent) and sandstone (40 to 45 percent) with minor amounts of coal, clay, and limestone.

Coal beds are typically less than 2 feet thick.

The Shelburn, the lowermost formation in the McLeansboro Group, contains the Busseron Sandstone member at or near its base. The sandstone is typically gray to tan in color, fine to medium-grained, and massive. It is interbedded in places with gray shale. It is fairly extensive and is used in places as an aquifer, even though its low permeability usually limits well yields to less than 5 gpm.

The overlying Patoka Formation contains another sandstone, the Inglefield, that is widely recognized as an aquifer in southwestern Indiana. The Inglefield Sandstone member is present in the basin in northern Gibson and southern Knox counties. The sandstone is gray to tan, fine-grained, thin to thick-bedded, and cross-bedded. It grades laterally into sandy shale. The Inglefield is 20 to 40 feet thick in Gibson County. North of Knox County it is rarely thicker than 20 feet. Wells tapping the Inglefield commonly produce 5 to 20 gpm.

The overlying Bond Formation is primarily (95 percent) sandstone, shale, and siltstone with minor amounts of limestone, clay, and coal. It is the youngest bedrock formation in the basin and only the lower portion is exposed. Its aquifer potential is very limited.

The depth to the bedrock surface in the McLeansboro Group is generally less than 35 feet. Wells range in depth from 22 to 340 feet, but are typically 80 to 180 feet deep. The amount of rock penetrated typically ranges from 40 to 130 feet, with a maximum of 300 feet. Static water levels in wells developed in the McLeansboro Group range from 1 to 125 feet below land surface, but are typically between 18 and 50 feet below the surface.

The elevations of water-bearing zones in the Pennsylvanian/McLeansboro Group vary substantially. The approximate elevation to bedrock for a specific location may be determined by using the bedrock topography map (plate 3c).

In general the McLeansboro Group is considered a minor ground-water source with most wells producing from the Busseron and Inglefield sandstone members. Most domestic wells produce between 1 and 9 gpm with localized yields of up to 20 gpm. A few dry holes have been reported.

Water quality is generally good and the aquifer system is not very susceptible to contamination from the land surface. However, in limited areas some improperly constructed or abandoned oil wells may have caused some contamination in the immediate vicinity of the wells. Expected contaminants would be dissolved solids, especially sodium and chloride, and crude oil. Natural water quality gets progressively worse (more salty) in wells deeper than about 300 or 400 feet as the strata dip below sea level.

Ground-Water Development Potential

The development potential or potential yield of an aquifer depends on aquifer characteristics such as hydraulic conductivity, aquifer thickness, storativity, areal extent, ground-water levels, available drawdown, and recharge. All aquifer properties are important, but three are particularly useful for basin-wide ground-water resource assessment: recharge, storativity, and transmissivity (hydraulic conductivity multiplied by aquifer thickness). If these properties can be determined for aquifer systems, and can be applied with a basic understanding of hydrogeology, a qualitative comparison can be made of ground-water development potential within a basin and between basins. These three aquifer properties are used in digital and analytical ground-water models.

Other factors such as water quality, potential contamination sources, demand, water rights, well design and well location influence actual ground-water development. This section of the report focuses primarily on transmissivity and recharge, two aquifer characteristics important for ground-water development. Water quality is discussed in the **Ground-water quality** chapter of this report.

Transmissivity

Transmissivity is a measure of the water-transmitting capability of an aquifer. Expressed as the rate at which water flows through a unit width of an aquifer, transmissivity is defined as the product of the hydraulic conductivity and the saturated thickness of an aquifer. Methods used to compute transmissivity are based upon a mathematical relationship between the pumping rate and the resultant drawdown of the water level in the aquifer for a given set of well and aquifer conditions.

The most reliable method for calculating transmissivity is a graphical approach based on detailed aquifer tests. The graphical approach can only be used when extensive water level data have been collected during the aquifer tests. Water levels are recorded simultaneously at observation wells while the test well is being pumped at a constant rate. The response of an aquifer is monitored over an areal extent that is determined by the spatial distribution of the observation wells. Graphical plots of time versus drawdown and distance versus drawdown can yield reliable estimates of the hydraulic parameters of the aquifer. However, unless an extensive well field is being developed, an aquifer test is often not warranted because the cost of installing observation wells and conducting the test exceeds the immediate benefit. There are only a few such aquifer tests available for the West Fork of the White River basin (figure 12).

A method using specific capacity data based on drawdown adjusted for well loss only was used to estimate aquifer transmissivity in the West Fork of the White River basin. Specific capacity is defined as the rate at which water can be pumped from a well per unit decline of water level in the well for a specified time period (commonly expressed as gallons per minute per foot of drawdown). Specific capacity tests are less expensive than aquifer tests because drawdown typically is measured only once at the pumped well just before the pumping is stopped. These tests are conducted by the driller after completion of the well. In reconnaissance ground-water investigations useful estimates of aquifer transmissivity can be based on specific capacity data (Walton, 1970).

Estimates of aquifer transmissivity in the West Fork of the White River basin were generated from specific capacity data

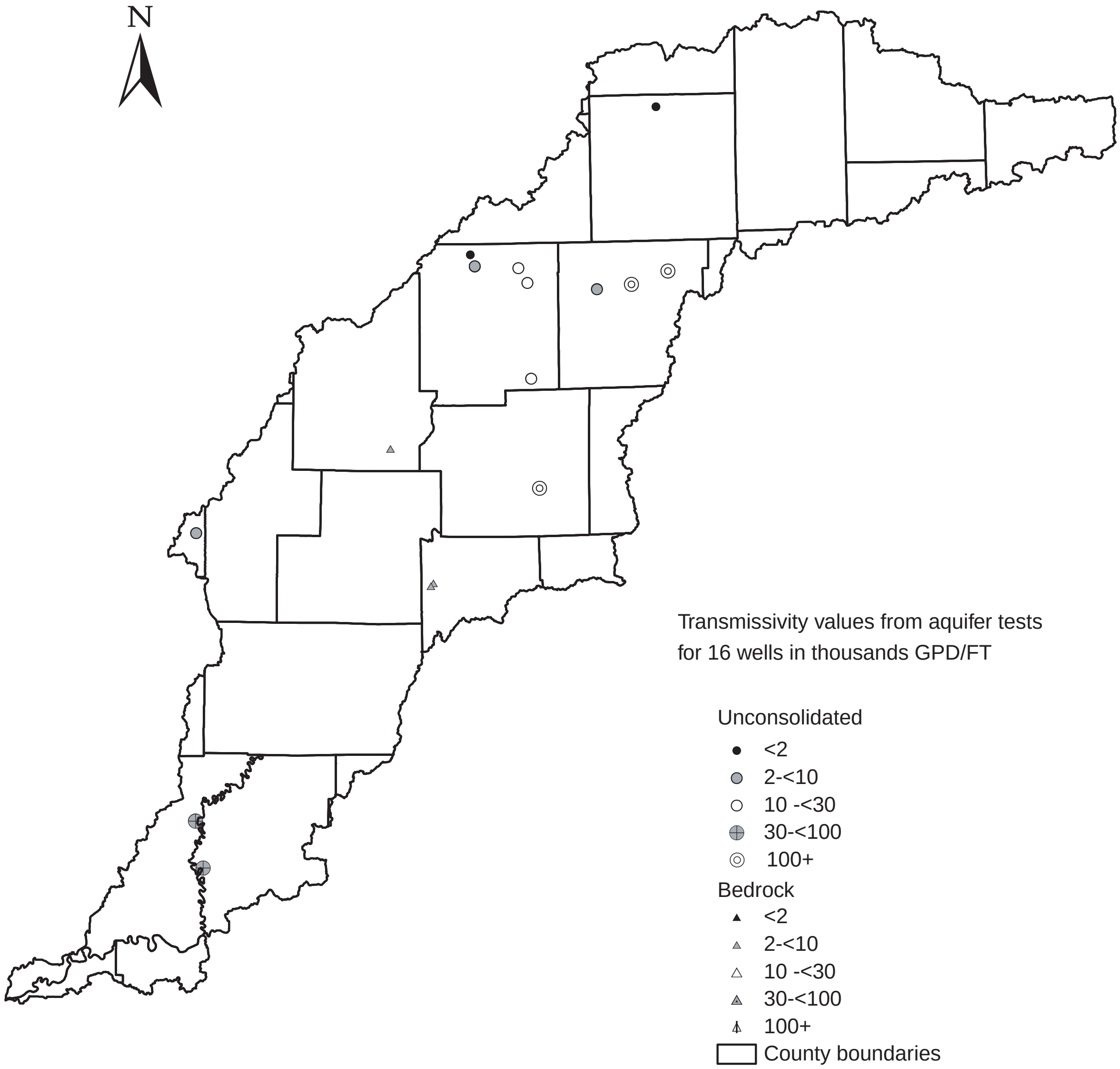


Figure 12. Transmissivity estimates from aquifer tests

from nearly 3,400 water well records by using a computer program called "TGUESS" (Bradbury and Rothschild, 1985) (plate 8). The computer program can adjust drawdown values from specific capacity tests to accommodate for well loss. It can also make a correction (rather than a drawdown adjustment) for the effects of partial penetration. In most cases consideration of these factors tends to increase estimates of specific capacity (Walton, 1970). However, if a well penetrates an aquifer of unknown thickness, drawdown from specific capacity tests cannot be accurately adjusted. In this case, aquifer thickness was assumed to be equal to the thickness of the aquifer penetrated by the well (unconsolidated) or open to the well (bedrock). "TGUESS" tends to overestimate values for aquifer transmissivity where less than 10 percent of the aquifer is open to the well. This assumption eliminates this problem for bedrock wells and the computed transmissivity of the aquifer can be considered to represent a local minimum transmissivity for the aquifer.

Transmissivity values generated for the basin using "TGUESS" were compared to values derived from aquifer tests nearby and were found to be both conservative and highly variable. The wide range in values is a result of the heterogeneity of the geologic formations and the nature of the data used to obtain the estimates. Data used in the analysis are from different types of wells, ranging from shallow, small-diameter domestic wells to deep, large-diameter high-capacity wells. So that only the most reliable data were used for estimating transmissivity, many wells were eliminated from consideration. These include: unconsolidated wells under 5 inches in diameter; bedrock wells under 4 inches in diameter; and wells that were not air or pump tested. Furthermore, there are differences in methods used by drillers to conduct and report specific capacity test results. This variability precludes developing reliable regional transmissivity estimates; however, a few general trends are observed.

Transmissivity values in the four most productive uncon-

Table 4 Typical transmissivity ranges for aquifer systems.

Aquifer System	Transmissivity (gpd/ft)
Unconsolidated Aquifer Systems	
White River and Tributaries Outwash Aquifer System	14,690-150,560
White River and Tributaries Outwash Aquifer Subsystem	1,940-54,870
Tipton Till Plain Aquifer System	2,950-29,700
Tipton Till Plain Aquifer Subsystem	1,370-11,700
Buried Valley Aquifer System	*
Lacustrine and Backwater Deposits Aquifer System	*
Dissected Till and Residuum Aquifer System	*
Bedrock Aquifer Systems	
Ordovician/Maquoketa Group	*
Silurian and Devonian Carbonates	190-3,810
Devonian and Mississippian/New Albany Shale	110-1,130
Mississippian/Borden Group	120-1,680
Mississippian/Blue River and Sanders Groups	80-1,050
Mississippian/Buffalo Wallow,Stephensport, andWest Baden Groups	40-730
Pennsylvanian/Raccoon Creek Group	40-330
Pennsylvanian/Carbondale Group	40-290
Pennsylvanian/McLeansboro Group	120-960

* not enough data is available to determine typical ranges of transmissivity values for these aquifer systems

solidated aquifer systems typically range from about 1,400 to 150,000 gpd/ft. (table 4) The Buried Valley, Dissected Till and Residuum, and Lacustrine and Backwater Deposits aquifer systems lacked sufficient data to determine typical transmissivity ranges. The most transmissive unconsolidated aquifers generally occur in the White River valley where locally thick outwash deposits are present. The highest transmissivity values are found in well-constructed high-capacity wells. Although many domestic wells are completed in highly transmissive outwash materials, the high-capacity wells are usually constructed to maximize production with well screens that are properly sized to the aquifer materials. High-capacity wells are usually more efficient at producing water from aquifers because they have smaller well losses. The resulting estimated transmissivity values are often greater than domestic wells in the same aquifer material. For specific capacity tests on low-capacity wells, pumping rates tend to be chosen to confirm the minimum necessary production, rather than to determine the maximum yield as with high-capacity wells.

Nearly 90 percent of the bedrock wells in the basin, for which transmissivity values have been estimated, are developed in one of four bedrock aquifer systems: Raccoon Creek Group; Blue River and Sanders Groups; Borden Group; or the Silurian and Devonian Carbonates. For bedrock aquifers in the basin, typical transmissivity values range from about 40 to 3,800 gpd/ft. (table 4). The Silurian and Devonian Carbonate aquifer system has by far the greatest transmissivity of those with enough data available to determine typical ranges. The least transmissive bedrock aquifer systems are the Carbondale Group and the Raccoon Creek Group.

Interpretation of many transmissivity values is complicated by the fact that the thickness of many aquifers, especially bedrock, is not well defined. A given transmissivity value could result from a thick sequence of relatively low-permeability materials or from a thin sequence of relatively high-permeability materials. Another complication is that some wells are open to more than one aquifer system and thus may not be properly assigned to the dominant aquifer. It must be noted that there are areas where transmissivity data are sparse (e.g., Greene County). This is due to a general lack of complete and reliable well construction and specific capacity test data on records for wells in those areas.

Recharge

In general, ground water is recharged by that portion of precipitation that infiltrates through the soil profile to underlying aquifers that have the ability to absorb, store, and transmit water. Aquifer yield is dependent upon aquifer permeability, aquifer storage, saturated thickness, available drawdown, areal extent, and upon the number, spacing, diameter, and pumping rates of the wells that tap the aquifer. The ultimate development potential of an aquifer is often equated to the total natural recharge to the aquifer. However, recharge will vary considerably from year to year due to climatic variations and will vary somewhat with pumping. Pumping can increase effective recharge by lowering the water level in relatively shallow aquifers, thereby reducing evapotranspiration losses. Vertical recharge to confined aquifers is proportional to the head difference between the aquifers and overlying source beds. Pumping can increase this head differential. By using

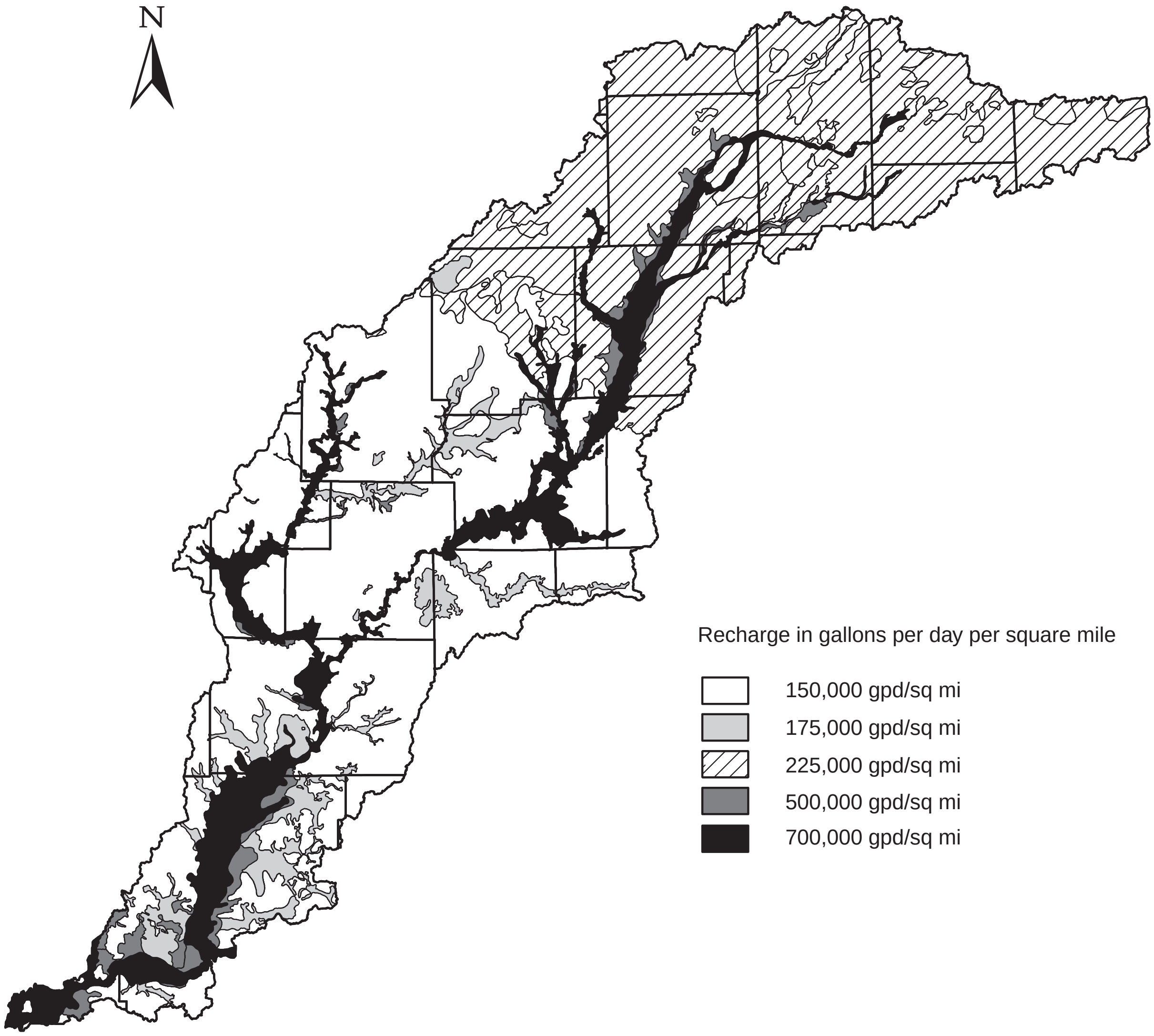


Figure 13a. Estimated recharge rates of unconsolidated aquifer systems

artificial recharge practices and inducing recharge from nearby streams, ground-water recharge can be significantly increased in some areas.

The ground-water development potential of the aquifer systems in the West Fork White River basin may be evaluated based on the natural recharge (derived chiefly from infiltration of direct precipitation) and areal extent of the aquifer systems. Estimates of natural recharge rates to the aquifer systems of the basin were based on several types of analyses. These included *base-flow* separation techniques and flow duration analysis of many years of data from stream gages in the basin. Also, comparisons and adjustments were made for each area of unconsolidated aquifer systems by considering especially how the hydrogeologic and spatial characteristics of the deposits overlying the aquifer systems would affect natural recharge rates. Qualitatively, the effects of upstream reservoirs, water withdrawals, consumptive uses, and reintroduction of used water to the streams (from sewage treatment plants) were also considered when evaluating the base-flow data.

The highest estimated rate of recharge to aquifers in the West Fork White River basin is approximately 700,000 gallons per day per square mile (gpd/sq mi) (14.70 inches per year) as shown in table 5. This high rate occurs in the unconfined White River and Tributaries Outwash Aquifer system (figure 13a), which occupies only 11.6 percent of the basin area but accounts for 32.2 percent of the recharge in the basin. Infiltration of direct precipitation to this aquifer system is high because of thinly-developed soils on thick, surficial sand and gravel.

In contrast to the permeable surficial sediments overlying the White River and Tributaries Outwash Aquifer system, materials of and overlying the Dissected Till and Residuum Aquifer system consist mostly of low-permeability glacial tills and weathered bedrock residuum on hilly topography, factors which promote surface *runoff*. The rate of recharge to this aquifer system is estimated at only 150,000 gpd/sq mi (3.15 inches per year). The Dissected Till and Residuum Aquifer system occupies approximately 42.8 percent of the

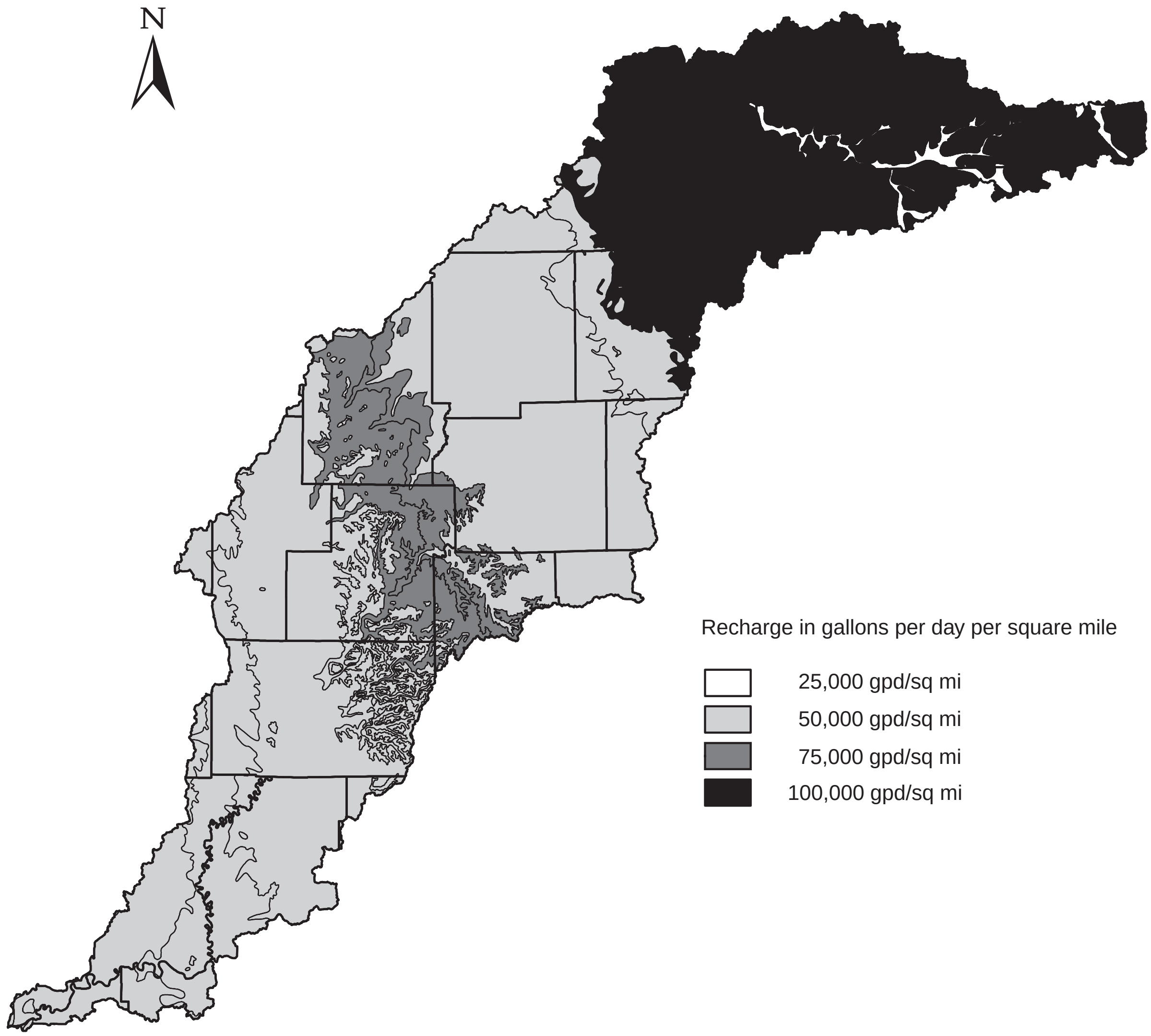


Figure 13b. Estimated recharge rates of bedrock aquifer systems

basin area but accounts for only 25.3 percent of the recharge in the basin.

The northern part of the basin has considerably less rugged topography than the southern part and surficial sediments are predominantly silty-clay till deposits of Wisconsin age. These deposits limit recharge to the Tipton Till Plain Aquifer system and subsystem to an estimated 225,000 gpd/sq mi (4.73 inches per year). These two aquifer systems cover 36.9 percent of the total area of the basin and account for 32.7 percent of the recharge.

Rates of recharge to bedrock aquifers in the West Fork White River basin are generally low, ranging from an estimated 25,000 to 100,000 gpd/sq mi. (0.53 to 2.1 inches per year) as shown in table 5. Locally, where the Silurian and Devonian Carbonates Aquifer system is overlain by outwash sand and gravel, it is expected to have a significantly higher recharge rate than where it is covered by glacial till. The other bedrock aquifer systems typically have very low recharge rates. The water-bearing rock units themselves generally have low permeability values. And, in many places there are bedrock units of even lower permeability, situated above the better water-bearing units, which severely limit vertical recharge.

Table 5. Estimated recharge rates for aquifer systems

Aquifer System	Area (sq mi)	Recharge Rate (in / yr)	(gpd / sq mi)	(mgd)	(cfs)	(cfs / sq mi)
Unconsolidated						
White River and Tributaries Outwash Aquifer System	652.19	14.70	700000	456.53	706.36	1.08
White River and Tributaries Outwash Aquifer Subsystem	163.59	10.50	500000	81.80	126.56	0.77
Tipton Till Plain Aquifer System	1560.83	4.73	225000	351.19	543.37	0.35
Tipton Till Plain Aquifer Subsystem	501.24	4.73	225000	112.78	174.49	0.35
Dissected Till and Residuum Aquifer System	2394.79	3.15	150000	359.22	555.79	0.23
Lacustrine and Backwater Deposits Aquifer System	246.6	3.68	175000	43.16	66.77	0.27
Buried Valley Aquifer System	79.31	3.68	175000	13.88	21.47	0.27
Basin Totals or Averages	**5598.55**	**5.32**	**253377**	**1418.55**	**2194.82**	**0.39**
Bedrock						
Maquoketa Group	67.65	0.53	25000	1.69	2.62	0.04
Silurian and Devonian Carbonates	1679.57	2.10	100000	167.96	259.87	0.15
New Albany Shale	211.51	1.05	50000	10.58	16.36	0.08
Borden Group	1247.73	1.05	50000	62.39	96.53	0.08
Blue River and Sanders Groups	500.86	1.58	75000	37.56	58.12	0.12
Buffalo Wallow, Stephensport, and West Baden Groups	220.92	1.05	50000	11.05	17.09	0.08
Raccoon Creek Group	997.82	1.05	50000	49.89	77.19	0.08
Carbondale Group	417.7	1.05	50000	20.89	32.31	0.08
McLeansboro Group	257.3	1.05	50000	12.87	19.91	0.08
Basin Totals or Averages	**5601.06**	**1.41**	**66927**	**374.86**	**580.00**	**0.10**

GROUND-WATER QUALITY

The geochemistry of ground water may influence the utility of aquifer systems as sources of water. The types and concentrations of dissolved constituents in the water of an aquifer system determine whether the resource, without prior treatment, is suitable for drinking-water supplies, industrial purposes, irrigation, livestock watering, or other uses. Changes in the concentrations of certain constituents in the water of an aquifer system, whether because of natural or *anthropogenic* causes, may alter the suitability of the aquifer system as a source of water. Assessing ground-water quality and developing strategies to protect aquifers from contamination are necessary aspects of water-resource planning.

Sources of ground-water quality data

The quality of water from the aquifer systems defined in the **Aquifer Systems** section of the Ground-Water Hydrology chapter is described using selected inorganic chemical analyses from 372 wells (157 completed in unconsolidated deposits and 215 completed in bedrock) in the West Fork White River basin. Sources of ground-water quality data are domestic, commercial or livestock-watering wells sampled during a 1989 and 1990 cooperative effort between the Indiana Department of Natural Resources, Division of Water (DOW) and the Indiana Geological Survey (IGS). The locations of ground-water chemistry sites used in the analysis are displayed on plate 9, and selected water-quality data from individual wells are listed in appendices 1 and 2.

The intent of the water-quality analysis is to characterize the natural ground-water chemistry of the West Fork White River basin. Specific instances of ground-water contamination are not evaluated. In cases of contamination, chemical conditions are likely to be site-specific and may not represent typical ground-water quality in the basin. Therefore, available data from identified sites of ground-water contamination were not included in the data sets analyzed for this publication. Samples collected from softened or otherwise treated water were also excluded from the analysis because the chemistry of the water was altered from natural conditions.

Factors in the assessment of ground-water quality

Major dissolved constituents in the ground water of the West Fork White River basin include calcium, magnesium, sodium, chloride, sulfate, and bicarbonate. Less abundant constituents include potassium, iron, manganese, strontium, zinc, fluoride, and nitrate. Other chemical characteristics discussed in this report include pH, alkalinity, hardness, total dissolved solids (TDS), and radon.

Although the data from well-water samples in the West Fork White River basin are treated as if they represent the chemistry of ground water at a distinct point, they actually represent the average concentration of an unknown volume of water in an aquifer. The extent of aquifer representation depends on the depth of the well, hydraulic conductivity of the aquifer, thickness and areal extent of the aquifer, and rate of pumping. For example, the chemistry of water sampled from high-capacity wells may represent average ground-water quality for a large cone of influence (Sasman and others, 1981). Also, because much of the bedrock in the southern part of the basin does not produce much ground water, it is not uncommon for bedrock wells to be deep and to intersect several different bedrock units. Because the quality of water may vary substantially from different zones individual wells may show an unusual mixture of ground water types.

To further complicate analysis of the ground-water chemistry data in this basin, the bedrock in the southern third of the basin was formed in complex depositional environments resulting in complex horizontal and vertical relationships of various bedrock units. In addition, there is an extensive major unconformity (old erosion surface) of Mississippian/Pennsylvanian age. Erosion and subsequent deposition of bedrock material that occurred during this time period has resulted in younger or more recent bedrock overlapping onto bedrock of different ages and types.

The order in which ground water encounters strata of different mineralogical composition can exert an important control on the water chemistry (Freeze and Cherry, 1979). Considering that hydrogeologic systems in the basin contain numerous types of strata arranged in a wide variety of geometric configurations, it is not unreasonable to expect that in many areas the chemistry of ground water exhibits complex spatial patterns that are difficult to interpret, even when good stratigraphic and hydraulic head information is available.

The nature of the bedrock in the southern two-thirds of the West Fork White River basin makes the use of aquifer systems to describe ground-water quality somewhat problematic. The boundaries of the bedrock aquifer systems are defined by 2-dimensional mapping techniques. Although this type of mapping is useful, it should be remembered that more productive aquifer systems extend beneath less productive systems and are often used as a water supply within the boundaries of the latter.

In addition to the factors discussed above, the chemistry of original aquifer water may be altered to some degree by contact with plumbing, residence time in a pressure tank, method of sampling, and time elapsed between sampling and laboratory analysis. In spite of these limitations, results of sample analyses provide valuable information concerning ground-water quality characteristics of aquifer systems.

Analysis of data

Graphical and statistical techniques are used to analyze the available ground-water quality data from the West Fork White River basin. Graphical analyses are used to display the areal distribution of dissolved constituents throughout the basin, and to describe the general chemical character of the ground water of each aquifer system. Statistical analyses provide useful generalizations about the water quality of the

Factors affecting ground-water chemistry

The chemical composition of ground water varies because of many complex factors that change with depth and over geographic distances. Ground-water quality can be affected by the composition and solubility of rock materials in the soil or aquifer, water temperature, partial pressure of carbon dioxide, acid-base reactions, oxidation-reduction reactions, loss or gain of constituents as water percolates through clay layers, and mixing of ground water from adjacent strata. The extent of each effect will be determined in part by the residence time of the water within the different subsurface environments.

Rain and snow are the major sources of recharge to ground water. They contain small amounts of dissolved solids and gases such as carbon dioxide, sulfur dioxide, and oxygen. As precipitation infiltrates through the soil, biologically-derived carbon dioxide reacts with the water to form a weak solution of carbonic acid. The reaction of oxygen with reduced iron minerals such as pyrite is an additional source of acidity in ground water. The slightly acidic water dissolves soluble rock material, thereby increasing the concentrations of chemical constituents such as calcium, magnesium, chloride, iron, and manganese. As ground water moves slowly through an aquifer the composition of water continues to change, usually by the addition of dissolved constituents (Freeze and Cherry, 1979). A longer residence time will usually increase concentrations of dissolved solids. Because of short residence time, ground water in recharge areas often contains lower concentrations of dissolved constituents than water occurring deeper in the same aquifer or in shallow discharge areas.

Dissolved carbon dioxide, bicarbonate, and carbonate are the principal sources of alkalinity, or the capacity of solutes in water to neutralize acid. Carbonate contributors to alkalinity include atmospheric and biologically-produced carbon dioxide, carbonate minerals, and biologically-mediated sulfate reduction. Noncarbonate contributors to alkalinity include hydroxide, silicate, borate, and organic compounds. Alkalinity helps to buffer natural water so that the pH is not greatly altered by addition of acid. The pH of most natural ground waters in Indiana is neutral to slightly alkaline.

Calcium and magnesium are the major constituents responsible for hardness in water. Their presence is the result of dissolution of carbonate minerals such as calcite and dolomite.

The weathering of feldspar and clay is a source of sodium and potassium in ground water. Sodium and chloride are produced by the solution of halite (sodium chloride) which can occur as grains disseminated in unconsolidated and bedrock deposits. Chloride also occurs in bedrock cementing material, connate fluid inclusions, and as crystals deposited during or after deposition of sediment in sea water. High sodium and chloride levels can result from upward movement of brine from deeper bedrock in areas of high pumpage, from improper brine disposal from peteroleum wells, and from the use of road salt (Hem, 1985).

Cation exchange is often a modifying influence of ground-water chemistry. The most important cation exchange processes are those involving sodium-calcium, sodium-magnesium, potassium-calcium, and potassium-magnesium. Cation exchanges occurring in clay-rich semi-confining layers can cause magnesium and calcium reductions which result in natural softening.

Concentrations of sulfide, sulfate, iron, and manganese depend on geology and hydrology of the aquifer system, amount of dissolved oxygen, pH, minerals available for solution, amount of organic matter, and microbial activity.

Mineral sources of sulfate can include pyrite, gypsum, barite, and celestite. Sulfide is derived from reduction of sulfate when dissolve oxygen concentrations are low and anaerobic bacteria are present. Sulfate-reducing bacteria derive energy from oxidation of organic compounds and obtain oxygen from sulfate ions (Lehr and others, 1980).

Reducing conditions that produce hydrogen sulfide occur in deep wells completed in carbonate and shale bedrock. Oxygen-deficient conditions are more likely to occur in deep wells than in shallow wells because permeability of the carbonate bedrock decreases with depth, and solution features and joints become smaller and less abundant (Rosenshein and Hunn, 1968a; Bergeron, 1981; Basch and Funkhouser, 1985). Deeper portions of the bedrock are therefore not readily flushed by ground water with high dissolved oxygen. Hydrogen sulfide gas, a common reduced form of sulfide, has a distinctive rotten egg odor that can be detected in water containing only a few tenths of a milligram per liter of sulfide (Hem, 1985).

Oxidation-reduction reactions constitute an important influence on concentrations of both iron and manganese. High dissolved iron concentrations can occur in ground water when pyrite is exposed to oxygenated water or when ferric oxide or hydroxide minerals are in contact with reducing substances (Hem, 1985). Sources of manganese include manganese carbonate, dolomite, limestone, and weathering crusts of manganese oxide.

Sources of fluoride in bedrock aquifer systems include fluorite, apatite and fluorapatite. These minerals may occur as evaporites or detrital grains in sedimentary rocks, or as disseminated grains in unconsolidated deposits. Ground waters containing detectable concentrations of fluoride have been found in a variety of geological settings.

Natural concentrations of nitrate-nitrogen in ground water originate from the atmosphere and from living and decaying organisms. High nitrate levels can result from leaching of industrial and agricultural chemicals or decaying organic matter such as animal waste or sewage.

The chemistry of strontium is similar to that of calcium, but strontium is present in ground water in much lower concentrations. Natural sources of strontium in ground water include strontianite (strontium carbonate) and celestite (strontium sulfate). Naturally-occurring barium sources include barite (barium sulfate) and witherite (barium carbonate). Areas associated with deposits of coal, petroleum, natural gas, oil shale, black shale, and peat may also contain high levels of barium.

basin, such as the average concentration of a constituent and the expected variability.

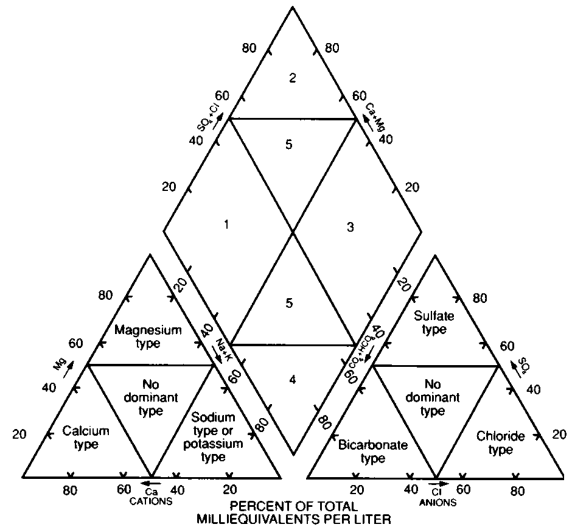
Regional trends in ground-water chemistry can be analyzed by developing trilinear diagrams for the aquifer systems in the West Fork White River basin (appendix 3). Trilinear plotting techniques developed by Piper (1944) can be used to classify ground water on the basis of chemistry, and to compare chemical trends among different aquifer systems (appendix 3) (see sidebar titled **Chemical classification of ground water using trilinear diagrams**). To graphically represent variation in ground-water chemistry, box plots (appendix 4) are prepared for selected ground-water constituents. Box plots are useful for depicting descriptive statistics, showing the general variability in constituent concentrations occurring in an aquifer system, and making general chemical comparisons among aquifer systems.

Symmetry of a box plot across the *median* line (appendix 4) can provide insights into the degree of skewness of chemical concentrations or parameter values in a data set. A box plot that is almost symmetrical about the median line may indicate that the data originate from a nearly symmetrical distribution. In contrast, marked asymmetry across the median line may indicate a *skewed* distribution of the data.

The areal distribution of selected chemical constituents, mapped according to aquifer system, is included among figures 14 to 26. Several sampling and geologic factors complicate the development of chemical concentration maps for the West Fork White River basin. The sampling sites are not evenly distributed in the basin, but are clustered around towns and developed areas (plate 9). Data points are generally scarce in areas where surface-water sources are used for water supply. Furthermore, lateral and vertical variations in geology can also influence the chemistry of subsurface water. Therefore, the maps presented in the following discussion only represent approximate concentration ranges.

Where applicable, ground-water quality is assessed in the context of National Primary and Secondary Drinking-Water Standards (see sidebar titled **National Drinking-water Standards**). The secondary standard referred to in this report is the *secondary maximum contaminant level* (SMCL). The

Chemical Classification of Ground waters Using Trilinear Diagrams



Trilinear plotting systems were used in the study of water chemistry and quality since as early as 1913 (Hem, 1985). The type of trilinear diagram used in this report, independently developed by Hill (1940) and Piper (1944), has been used extensively to delineate variability and trends in water quality. The technique of trilinear analysis has contributed extensively to the understanding of ground-water flow, and geochemistry (Dalton and Upchurch, 1978). On conventional trilinear diagrams sample values for three cations (calcium, magnesium and the alkali metals- sodium and potassium) and three anions (bicarbonate, chloride and sulfate) are plotted relative to one another. Since these ions are generally the most common constituents in unpolluted ground waters, the chemical character of most natural waters can be closely approximated by the relative concentration of these ions (Hem, 1985; Walton, 1970).

Before values can be plotted on the trilinear diagram the concentrations of the six ions of interest are converted into milliequivalents per liter (meq/L), a unit of concentration equal to the concentration in milligrams per liter divided by the equivalent weight (atomic weight divided by valence). Each cation value is then plotted, as a percentage of the total concentration (meq/L) of all cations under consideration, in the lower left triangle of the diagram. Likewise, individual anion values are plotted, as percentages of the total concentration of all anions under consideration, in the lower right triangle. Sample values are then projected into the central diamond-shaped field. Fundamental interpretations of the chemical nature of a water sample are based on the location of the sample ion values within the central field.

Distinct zones within aquifers having defined water chemistry properties are referred to as hydrochemical *facies* (Freeze and Cherry, 1979). Determining the nature and distribution of hydrochemical facies can provide insights into how ground-water quality changes within and between aquifers. Trilinear diagrams can be used to delineate hydrochemical facies, because they graphically demonstrate relationships between the most important dissolved constituents in a set of ground-water samples.

A simple but useful scheme for describing hydrochemical facies with trilinear diagrams is presented by Walton (1970) and is based on methods used by Piper (1944). This method is based on the "dominance" of certain cations and anions in solution. The dominant cation of a water sample is defined as the positively charged ion whose concentration exceeds 50 percent of the summed concentrations of major cations in solution. Likewise, the concentration of the dominant anion exceeds 50 percent of the total anion concentration in the water sample. If no single cation or anion in a water sample meets this criterion, the water has no dominant ion in solution. In most natural waters, the dominant cation is calcium, magnesium or alkali metals (sodium and potassium), and the dominant anion is chloride, bicarbonate or sulfate (accompanying figure). Distinct hydrochemical facies are defined by specific combinations of dominant cations and anions. These combinations will plot in certain areas of the central, diamond-shaped part of the trilinear diagram. Walton (1970) described a simple but useful classification scheme that divides the central part of the diagram into five subdivisions. In the first four of these subdivisions, the concentration of a specific cation-anion combination exceeds 50 percent of the total milliequivalents per liter (meq/L). Five basic hydrochemical facies can be defined with these criteria:

1. Primary Hardness; Combined concentrations of calcium, magnesium and bicarbonate exceed 50 percent of the total dissolved constituent load in meq/L. Such waters are generally considered hard and are often found in limestone aquifers or unconsolidated deposits containing abundant carbonate minerals.
2. Secondary Hardness; Combined concentrations of sulfate, chloride, magnesium and calcium exceed 50 percent of total meq/L.
3. Primary Salinity; Combined concentrations of alkali metals, sulfate and chloride are greater then 50 percent of the total meq/L. Very concentrated waters of this hydrochemical facies are considered brackish or (in extreme cases) saline.
4. Primary Alkalinity; Combined sodium, potassium and bicarbonate concentrations exceed 50 percent of the total meq/L. These waters generally have low hardness in proportion to their dissolved solids concentration (Walton, 1970).
5. No specific cation-anion pair exceeds 50 percent of the total dissolved constituent load. Such waters could result from multiple mineral dissolution or mixing of two chemically distinct ground-water bodies.

Additional information on trilinear diagrams and a more detailed discussion of the geochemical classification of ground waters is presented in Freeze and Cherry (1979) and Fetter (1988).

SMCLs are recommended, non-enforceable standards established to protect aesthetic properties such as taste, odor, or color of drinking water. Some chemical constituents (including fluoride and nitrate) are also considered in terms of the *maximum contaminant level* (MCL). The MCL is the concentration at which a constituent may represent a threat to human health. Maximum *contaminant* levels are legally-enforceable primary drinking-water standards that should not be exceeded in treated drinking water distributed for public supply. General water-quality criteria for irrigation and livestock and standards for public supply are given in appendix 5.

Because of data constraints, ground-water quality can only be described for selected aquifer systems as defined in the **Aquifer Systems** section of this report (plate 5). Unconsolidated aquifer systems analyzed include the Tipton Till Plain, Tipton Till Plain subsystem, Dissected Till and Residuum, White River and Tributaries Outwash, White River and Tributaries Outwash subsystem, Buried Valley, and Lacustrine and Backwater Deposits aquifer systems. Bedrock aquifer systems analyzed include the Silurian and Devonian Carbonates, Devonian and Mississippian/New Albany Shale, Mississippian/Borden Group, Mississippian/Blue River and Sanders Group, Mississippian/Buffalo Wallow, Stephensport, and West Baden Group, Pennsylvanian/Raccoon Creek Group, Pennsylvanian/Carbondale Group, and Pennsylvanian/McLeansboro Group Aquifer systems. The bedrock Ordovician/Maquoketa Group Aquifer system is not included in the analysis as none of the wells sampled were completed in that aquifer (Data on ground-water chemistry of wells completed in Ordovician bedrock are available in the DOW Whitewater River Basin report). Because the number of samples from the White River and Tributaries Outwash, Dissected Till and Residuum, Lacustrine and Backwater Deposits, and Devonian and Mississippian/New Albany Shale Aquifer systems is 7 or less, the sampling results may not accordingly reflect chemical conditions in these aquifers.

NATIONAL DRINKING-WATER STANDARDS

National Drinking Water Regulations and Health Advisories (U. S. Environmental Protection Agency, 1993) list concentration limits of specified inorganic and organic chemicals in order to control amounts of contaminants in drinking water. Primary regulations list maximum contaminant levels (MCLs) for inorganic constituents considered toxic to humans above certain concentrations. These standards are health-related and legally enforceable. Secondary maximum contaminant levels (SMCLs) cover constituents that may adversely affect the aesthetic quality of drinking water. The SMCLs are intended to be guidelines rather than enforceable standards. Although these regulations apply only to drinking water at the tap for public supply, they may be used to assess water quality for privately-owned wells. The table below lists selected inorganic constituents of drinking water covered by the regulations, the significance of each constituent, and their respective MCL or SMCL. Fluoride and nitrate are the only constituents listed which are covered by the primary regulations.

Constituent	Secondary Maximum Contaminant Level (SMCL) (ppm)	Maximum Contaminant Level (MCL) (ppm)	Remarks
Total Dissolved Solids (TDS)	500	*	Levels above SMCL can give water a disagreeable taste. Levels above 1000 mg/L may cause corrosion of well screens, pumps, and casings.
Iron	0.3	*	More than 0.3 ppm can cause staining of clothes and plumbing fixtures, encrustation of well screens, and plugging of pipes. Excessive quantities can stimulate growth of iron bacteria.
Manganese	0.05	*	Amounts greater than 0.05 ppm can stain laundry and plumbing fixtures, and may form a dark brown or black precipitate that can clog filters.
Chloride	250	*	Large amounts in conjunction with high sodium concentrations can impart a salty taste to water. Amounts above 1000 ppm may be physiologically unsafe. High concentrations also increase the corrosiveness of water.
Fluoride	2.0	4.0	Concentration of approximately 1.0 ppm help prevent tooth decay. Amounts above recommended limits increase the severity and occurrence of mottling (discoloration of the teeth). Amounts above 4 ppm can cause adverse skeletal effects (bone sclerosis).
Nitrate**	*	10	Concentrations above 20 ppm impart a bitter taste to drinking water. Concentrations greater than 10 ppm may have a toxic effect (methemoglobinemia) on young infants.
Sulfate	250	*	Large amounts of sulfate in combination with other ions (especially sodium and magnesium) can impart odors and a bitter taste to water. Amounts above 600 ppm can have a laxative effect. Sulfate in combination with calcium in water forms hard scale in steam boilers.
Sodium	NL	NL	Sodium salts may cause foaming in steam boilers. High concentrations may render water unfit for irrigation. High levels of sodium in water have been associated with cardiovascular problems. A sodium level of less than 20 ppm has been recommended for high risk groups (people who have high blood pressure, people genetically predisposed to high blood pressure, and pregnant women).
Calcium	NL	NL	Calcium and magnesium combine with bicarbonate, carbonate, sulfate and silica to form heat-retarding, pipe-clogging scales in steam boilers. For further information on calcium and magnesium, see hardness.
Magnesium	NL	NL	
Hardness	NL	NL	Principally caused by concentration of calcium and magnesium. Hard water consumes excessive amounts of soap and detergents and forms an insoluble scum or scale.
pH	-	-	USEPA recommends pH range between 6.5 and 8.5 for drinking water.

NL No Limit Recommended.
* No MCL or SMCL established by USEPA.
** Nitrate concentrations expressed as equivalent amounts of elemental nitrogen (N).(Adapted from U.S. Environmental Protection Agency, 1993)
Note: 1 part per million (ppm) = 1 mg/L.

Also, although the two-dimensional mapping used to delineate the bedrock aquifer systems is useful, it should be remembered that, especially for deeper wells, a significant portion of the water produced could come from aquifer systems underlying the one mapped at the bedrock surface.

Trilinear-diagram analyses

Ground-water samples from aquifer systems in the West Fork White River basin are classified using the trilinear plotting strategy described in the sidebar titled **Chemical classification of ground water using trilinear diagrams**. Trilinear diagrams developed with the available ground-water chemistry data are presented in appendix 3.

Trilinear analysis indicates that most of the available ground-water samples from the unconsolidated aquifers (92 percent) are chemically dominated by alkaline-earth metals (calcium and magnesium) and bicarbonate. Sodium concentrations exceed 40 percent of the sum of major *cations* in only 8 samples, but variations in sodium levels are observed among samples. The combined chloride and sulfate concentration exceeds 50 percent of the sum of major *anions* in only 2 percent of the samples.

In contrast, approximately 70 percent of the ground-water samples from the bedrock aquifers are chemically dominated by alkaline-earth metals (calcium and magnesium) and bicarbonate. Two-thirds (approximately 22 percent) of the remainder are chemically dominated by sodium and bicarbonate. The combined chloride and sulfate concentration exceeds 50 percent of the sum of major anions in fewer than 4 percent of the samples.

Trilinear analysis suggests that the ground water from all but one of the unconsolidated aquifer systems belong to a distinct hydrochemical facies (appendix 3). Most samples from these aquifer systems are chemically dominated by calcium, magnesium, and bicarbonate (Ca-Mg-HCO_3). The one exception is the Lacustrine and Backwater Deposits Aquifer system in which only 2 of the 4 samples belong to this facies. Also, samples from a total of 6 wells in the White River and Tributaries Outwash Aquifer system, White River and Tributaries Outwash Aquifer subsystem, and the Lacustrine and Backwater Deposits system have sodium as the dominant cation with little calcium or magnesium.

In contrast to the ground-water samples from the unconsolidated aquifers, samples from some of the bedrock aquifers appear to originate from more than one hydrochemical facies. Although most of the samples in 6 of the 8 bedrock aquifer systems belong to the calcium-magnesium-bicarbonate facies, a large portion of the samples from the Pennsylvanian aquifer systems belong to the sodium bicarbonate facies. A few samples from the Pennsylvanian aquifer systems belong to the sodium-chloride facies. A small portion, 5 of the 215 ground-water samples from the bedrock aquifer systems, is chemically dominated by calcium, magnesium, and sulfate (Ca-Mg-SO_4) ions. Three of these are within an approximate 4-mile radius of each other in northeastern Greene and southeastern Owen counties.

Differences in hydrochemical facies within and between aquifer systems may indicate differences in the processes influencing ground-water quality. Variations in the mineral content of aquifer systems are probably a significant control on the geochemistry of ground water. For example, the calcium-magnesium-bicarbonate waters in some wells probably result from the dissolution of carbonate minerals. Calcium-magnesium-sulfate dominated ground water in the West Fork White River basin probably result from the dissolution of gypsum, pyrite, or other sulfur-containing minerals. Sodium bicarbonate dominated ground water may be due to cation exchange processes with surrounding clays and clay minerals. Ground-water flow from areas of recharge to areas of discharge and the subsequent mixing of chemically-distinct ground water may also influence the geochemical classification of ground water in the West Fork White River basin.

Assessment of ground-water quality

Alkalinity and pH

The alkalinity of a solution may be defined as the capacity of its solutes to react with and neutralize acid. The alkalinity in most natural waters is primarily due to the presence of dissolved carbon species, particularly bicarbonate and carbonate. Other constituents that may contribute minor amounts of alkalinity to water include silicate, hydroxide, borates, and certain organic compounds (Hem, 1985). In this report, alkalinity is expressed as an equivalent concentration of dissolved calcite ($CaCO_3$). At present, no suggested limits have been established for alkalinity levels in drinking water. However, some alkalinity may be desirable in ground water because the carbonate ions moderate or prevent changes in pH.

Median alkalinity levels vary among samples from different aquifer systems in the West Fork White River basin. In the unconsolidated aquifer systems, alkalinity levels tend to be higher in the northern part of the basin (figure 14a). In general, lower alkalinity levels are observed in the White River and Tributaries Outwash Aquifer system relative to the other unconsolidated aquifer systems (figure 14a and appendix 4). Median alkalinity values for the bedrock aquifer systems exhibit somewhat more variability than the unconsolidated ones (figure 14b and appendix 4). Of these, the Pennsylvanian systems show the greatest variability. Both the lowest and highest median alkalinity levels of all the aquifer systems occur in the bedrock aquifers. The lowest alkalinity levels are observed in the Mississippian/Buffalo Wallow, Stephensport, and West Baden Group Aquifer system, and the highest occur in the Pennsylvanian/Carbondale Group Aquifer system.

The pH, or hydrogen ion activity, is expressed on a logarithmic scale and represents the negative base-10 log of the hydrogen ion concentration. Waters are considered acidic when the pH is less than 7.0 and basic when the pH exceeds 7.0. Water with a pH value equal to 7.0 is termed neutral and is not considered either acidic or basic. The pH of most

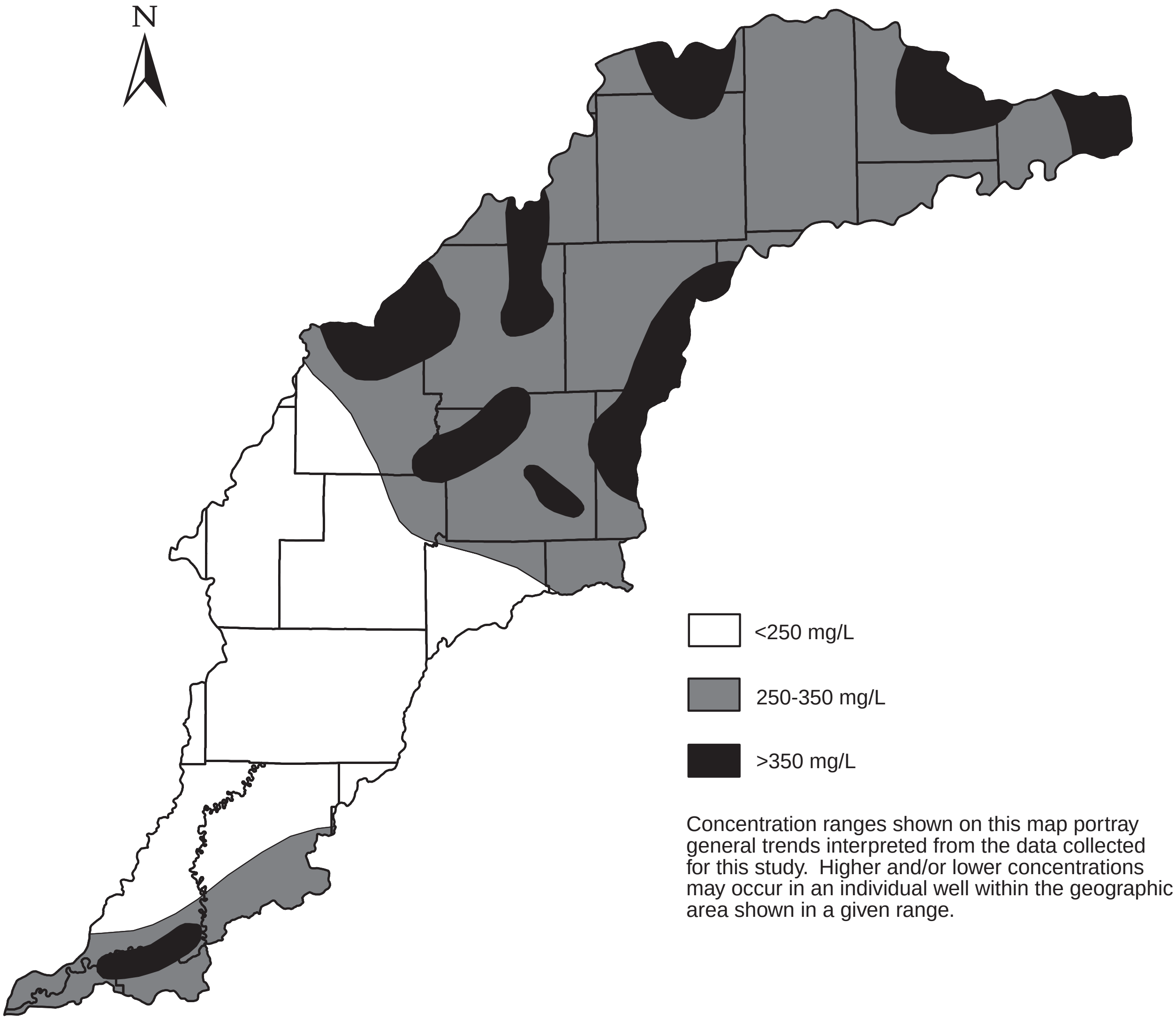


Figure 14a. Generalized areal distribution for Alkalinity - Unconsolidated aquifers

ground water generally ranges between 5.0 and 8.0 (Davis and DeWiest, 1970).

The types of dissolved constituents in ground water can influence pH levels. Dissolved carbon dioxide (CO_2), which forms carbonic acid in water, is an important control on the pH of natural waters (Hem, 1985). The pH of ground water can also be lowered by organic acids from decaying vegetation, or by dissolution of sulfide minerals (Davis and DeWiest, 1970). The United States Environmental Protection Agency (USEPA) recommends a pH range between 6.5 and 8.5 in waters used for public supply. Ninety-two percent of the ground-water samples in this study are within this range.

Of the 30 wells (23 bedrock and 7 unconsolidated) having a pH outside the 6.5 and 8.5 range, twenty-two occur in the southwest part of the basin in areas underlain by Pennsylvanian bedrock (figure 15a and b). The Raccoon Creek Group, which is Pennsylvanian in age, has the highest median pH of all aquifer systems studied; it also exhibits the greatest variability (appendix 4). The Carbondale Group, which is also Pennsylvanian in age, has the lowest median pH of all aquifer systems studied; it also exhibits great variability.

Two areas, one in Clay County, the other near the Daviess/Martin county line, display the greatest variability in pH values including high and low values from wells in close proximity to each other. The depth of wells and type of bedrock sampled appear to play an important role in the variability. The complex lithology of the Pennsylvanian bedrock and the presence of a major unconformity that creates a variable sequence of layers can explain the variability in ground-water chemistry. Human influence, especially previous mining nearby, may also play a role on a local level.

Hardness, calcium and magnesium

"Hardness" is a term relating to the concentrations of certain metallic ions in water, particularly magnesium and calcium, and is usually expressed as an equivalent concentration of dissolved calcite ($CaCO_3$). In hard water, the metallic ions of concern may react with soap to produce an insoluble residue. These metallic ions may also react with negatively-charged ions to produce a solid precipitate when hard water is

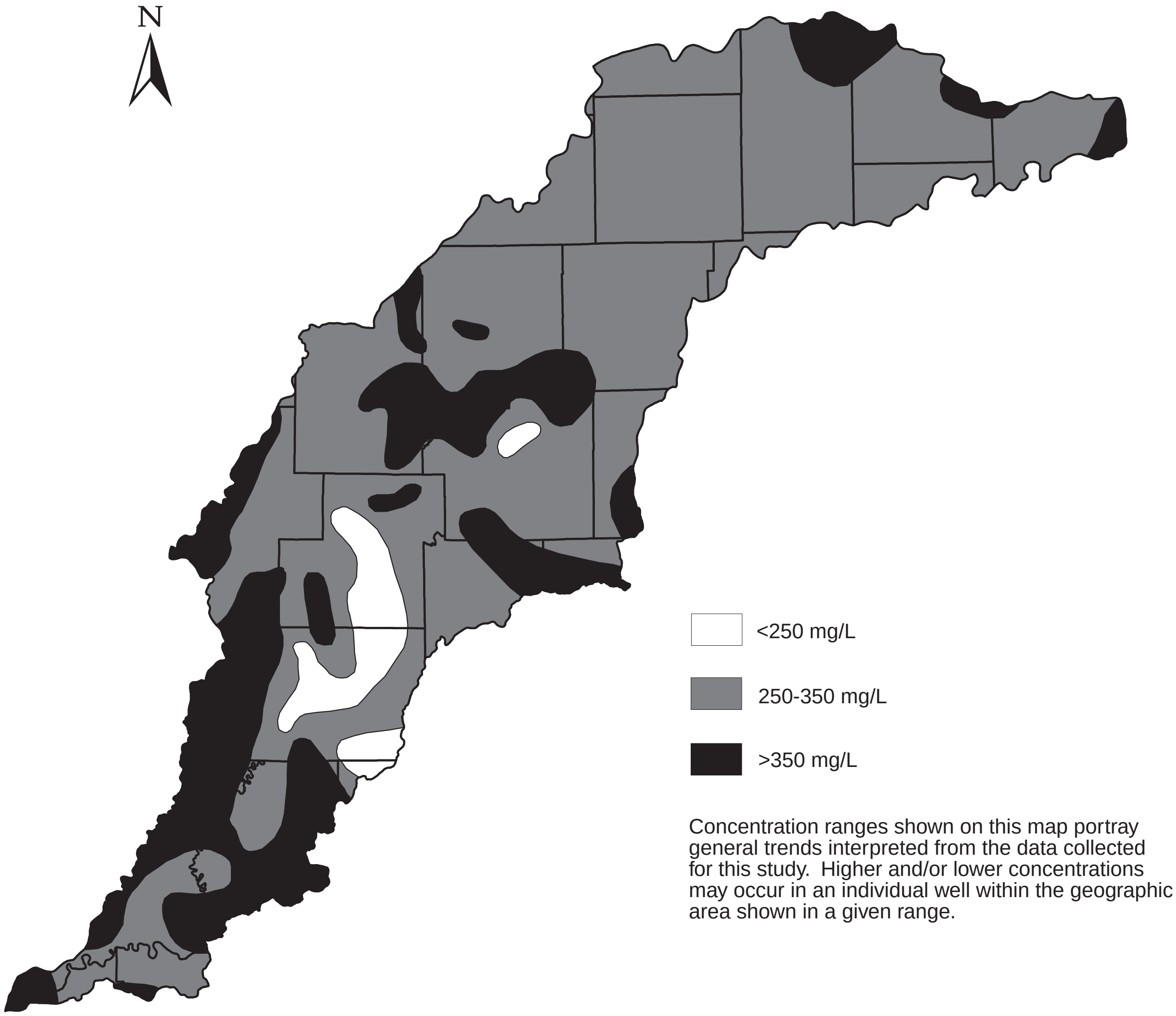


Figure 14b. Generalized areal distribution for Alkalinity - Bedrock aquifers

heated (Freeze and Cherry, 1979). Hard waters can thus consume excessive quantities of soap, and cause damaging scale in water heaters, boilers, pipes, and turbines. Many of the problems associated with hard water, however, can be mitigated by using water-softening equipment.

Durfor and Becker (1964) developed the following classification for water hardness that is useful for discussion purposes: soft water, 0 to 60 mg/L (as $CaCO_3$); moderately hard water, 61 to 120 mg/L; hard water, 121 to 180 mg/L; and very hard water, over 180 mg/L. A hardness level of about 100 mg/L or less is generally not a problem in waters used for ordinary domestic purposes (Hem, 1985). Lower hardness levels, however, may be required for waters used for other purposes. For example, Freeze and Cherry (1979) suggest that waters with hardness levels above 60-80 mg/L may cause excessive scale formation in boilers.

Ground water in the West Fork White River basin can be generally characterized as hard to very hard in the Durfor and Becker hardness classification system. The measured hardness level is below 180 mg/L (as $CaCO_3$) in fewer than 20 percent of the ground-water samples. Generally, the unconsolidated aquifer systems in the basin have higher hardness values than the bedrock aquifer systems (appendix 4). The Tipton Till Plain Aquifer system has the highest median hardness value of all the aquifer systems at 350 mg/L (appendix 4). Only two aquifer systems have median hardness values below 180 mg/L: The Pennsylvanian/Raccoon Creek Group, and Carbondale Group. Median hardness levels exceed 260 mg/L in samples from all other aquifer systems under consideration (appendix 4). Wells having hardness levels below 60 mg/L occur primarily in the Pennsylvanian bedrock aquifers in the southwest part of the basin.

Figure 16a and b display the spatial distribution of ground-water hardness levels for the unconsolidated and bedrock aquifers in the West Fork White River basin. In general, ground-water hardness levels are higher in the northeast portion of the West Fork White River basin relative to the southwest portion of the basin. The unconsolidated Tipton Till Plain Aquifer system and subsystem and the bedrock Silurian and Devonian Carbonates Aquifer system, all of which have high median hardness levels, cover a substantial part of the northeast portion of the basin.

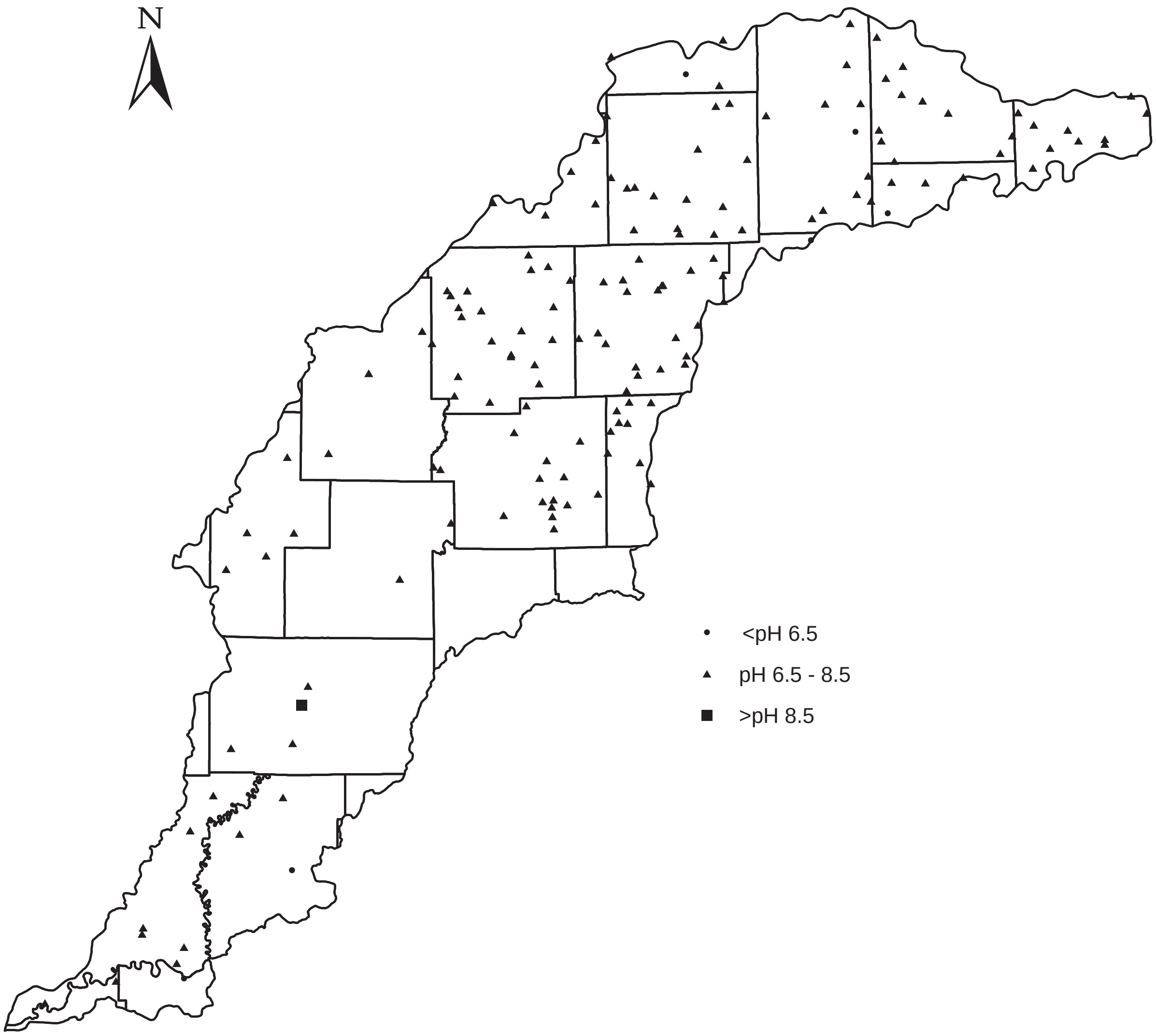


Figure 15a. Distribution of pH values for sampled wells - Unconsolidated aquifers

Box plots of calcium and magnesium concentrations in ground water are presented in appendix 4. Because calcium and magnesium are the major constituents responsible for hardness in water, the highest levels of these ions generally occur in ground water with high hardness levels. As expected, the unconsolidated Tipton Till Plain Aquifer system and subsystem and the bedrock Silurian and Devonian Carbonates Aquifer system have high median calcium and magnesium levels relative to most of the other aquifer systems. At the time of this publication, no enforceable or suggested standards have been established for calcium or magnesium.

Chloride, sodium and potassium

Chloride in ground water may originate from various sources including: the dissolution of halite and related minerals, marine water entrapped in sediments, and anthropogenic sources. Although chloride is often an important dissolved constituent in ground water, only three of the samples from the aquifer systems in the West Fork White River basin are classified as chloride dominated (appendix 3). Median chloride levels are less than 15 mg/L in all of the aquifer systems under consideration except the New Albany Shale (appendix 4). The highest median levels of all aquifer systems (approximately 40 mg/L) are in the Devonian and Mississippian New Albany Shale (appendix 4). The highest median values for unconsolidated aquifers occur in the White River and Tributaries Outwash subsystem and White River and Tributaries Outwash. Chloride concentrations at or above 250 mg/L, the SMCL for this ion, are detected in only six samples, all from bedrock aquifers.

Anthropogenic processes can locally affect chloride concentrations in ground water. Some anthropogenic factors commonly cited as influences on chloride levels in water include road salting during the winter, improper disposal of oil-field brines, contamination from sewage, and contamination from various types of industrial wastes (Hem, 1985, 1993). Five of the six wells with chloride levels at or above the SMCL occur in the southwestern part of the basin in the Pennsylvanian/Raccoon Creek Group Aquifer system. These wells have characteristics similar to the "soda water" wells

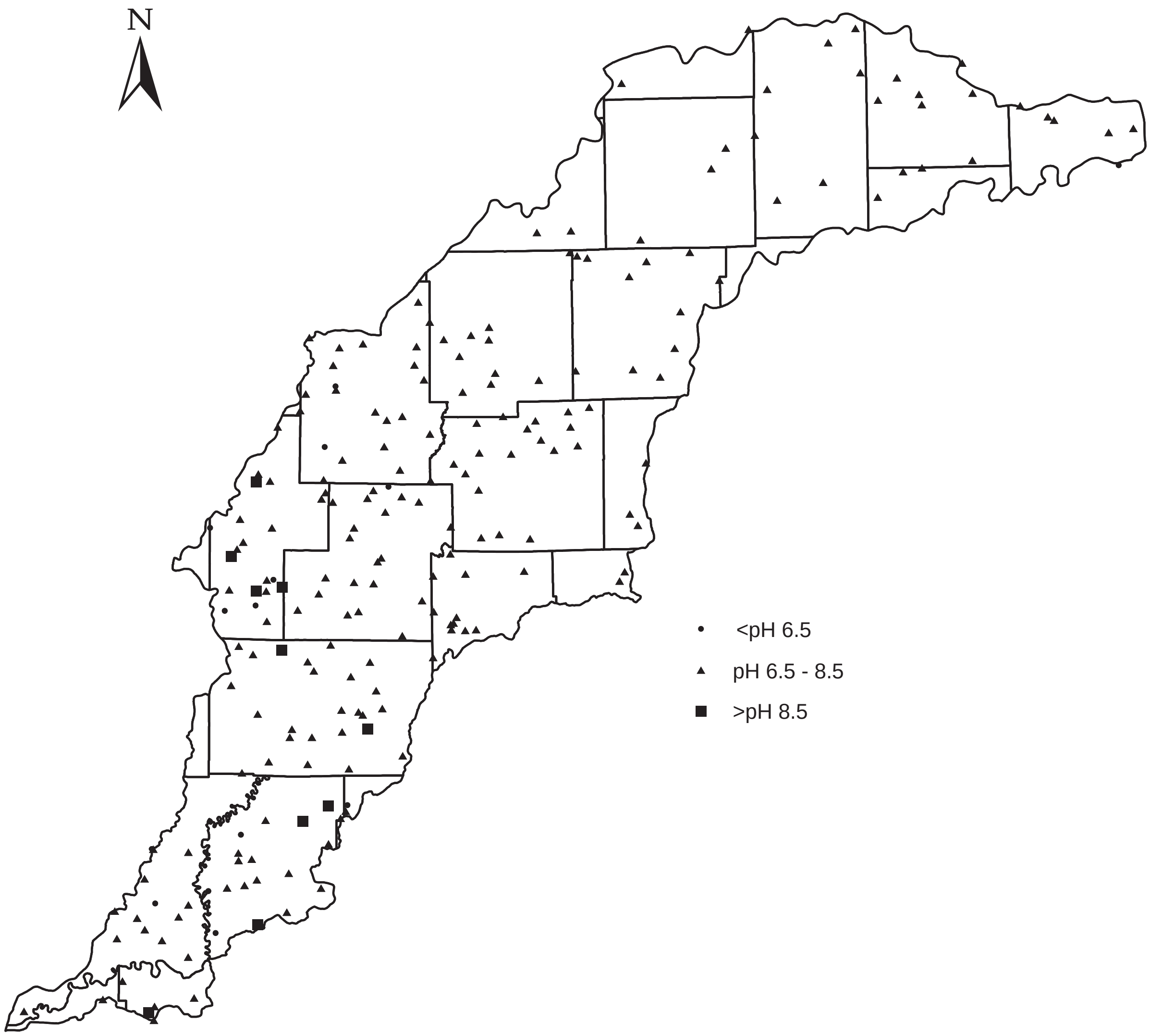


Figure 15b. Distribution of pH values for sampled wells - Bedrock aquifers

referenced in USGS WRI Report 97-4260 p. 35: bedrock wells greater than 100 feet deep in coal seams or sandstone aquifers that produce soft, sodium-chloride type water, with high TDS levels.

The dissolution of table salt or halite (NaCl) is sometimes cited as a source of both sodium and chloride in ground water. A qualitative technique to determine if halite dissolution is an influence on ground-water chemistry is to plot sodium concentrations relative to chloride concentrations. Because sodium and chloride ions enter solution in equal quantity during the dissolution of halite, an approximately linear relationship may be observed between these ions (Hem, 1985). If the concentrations are plotted in milliequivalents per liter, this linear relationship should be described by a line with a slope equal to one.

No clearly-defined linear relationship between concentrations of chloride and sodium is apparent in the ground-water samples under consideration (figure 17). This suggests that the concentrations of sodium and chloride in ground water of the West Fork White River basin are heavily influenced by factors other than to the dissolution of halite. Figure 17 and the box plots in appendix 4 indicate that sodium concentrations exceed chloride concentrations in many (70 percent) of the samples under consideration, suggesting that additional sources of sodium may be present. For example, calcium and magnesium in solution can be replaced by sodium on the surface of certain clays by *ion exchange*. Another possible source of sodium in ground water is the dissolution of silicate minerals in glacial deposits.

The highest sodium levels are found generally in the Pennsylvanian bedrock aquifer systems (figure 18), especially in the Carbondale and Raccoon Creek Groups. Trilinear analysis suggests that approximately 22 percent of bedrock samples are sodium and bicarbonate dominated.

Box plots of potassium concentrations in ground-water samples from the aquifer systems under consideration are displayed in appendix 4. In many natural waters, the concentration of potassium is commonly less than one-tenth the concentration of sodium (Davis and DeWiest, 1970). Almost 85 percent of the samples used for this report have potassium

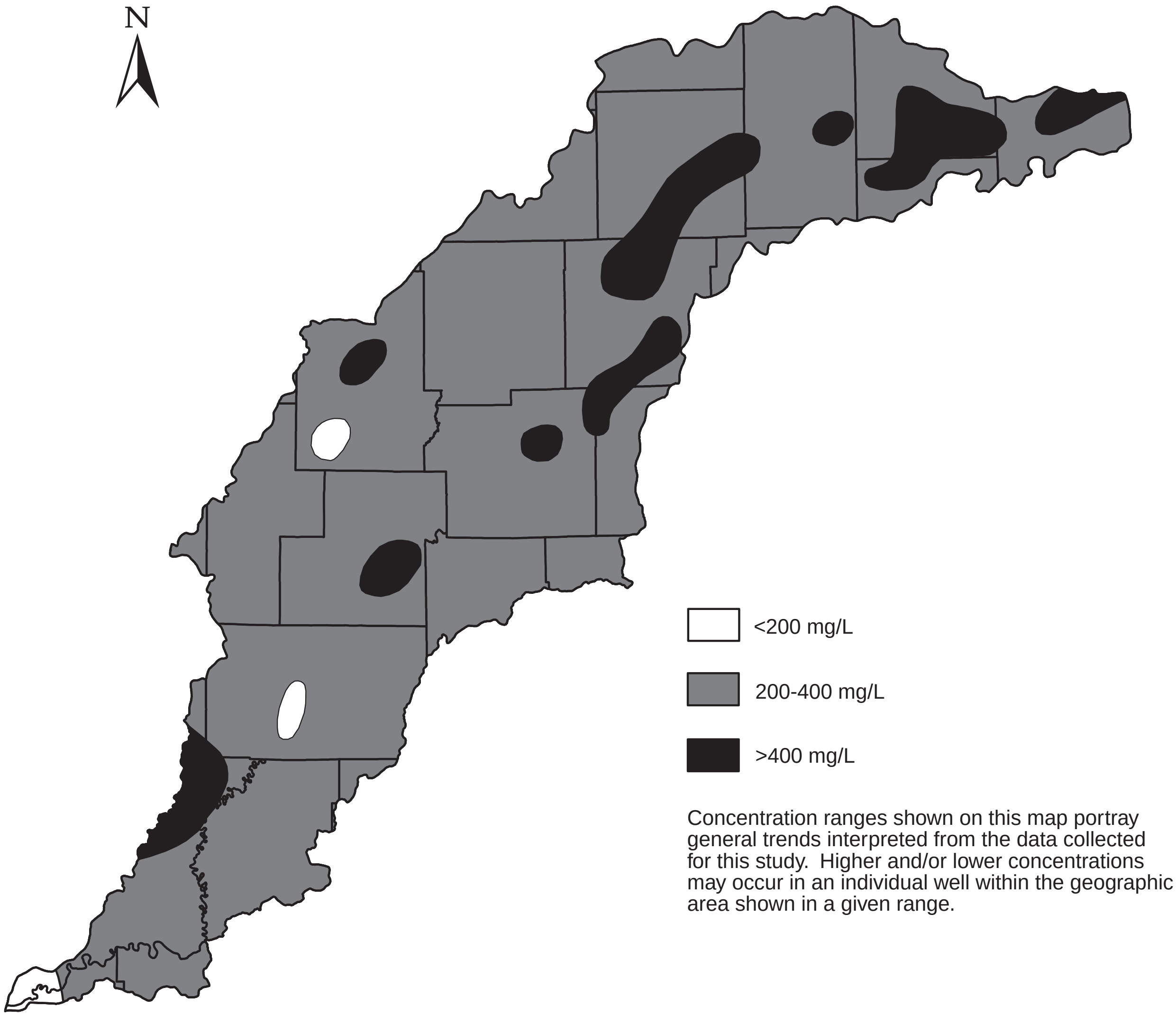


Figure 16a. Generalized areal distribution for Hardness - Unconsolidated aquifers

concentrations that are less than one-tenth the concentration of sodium.

Sulfate and sulfide

Sulfate (SO_4), an anion formed by oxidation of the element sulfur, is commonly observed in ground water. The established secondary maximum contaminant level (SMCL) for sulfate is 250 mg/L. Median sulfate levels for the samples from all aquifer systems in the West Fork White River are well below the SMCL. However, there are 8 ground-water samples that have sulfate concentrations above the SMCL, and another 16 samples have sulfate concentrations above 100 mg/L. The eight samples having sulfate values above the SMCL are all bedrock wells located in the southern part of Owen and Clay Counties and the northern part of Greene County. The other 16 are also located primarily in the southwest part of the basin with about half from unconsolidated aquifer systems. In general, sulfate levels are higher in the bedrock aquifer systems in the basin than in the unconsolidated systems. But, median sulfate concentrations vary considerably in both bedrock and unconsolidated aquifer systems.

Concentration ranges of sulfate in the unconsolidated aquifer systems are shown in figures 19a and b. Of the unconsolidated aquifer systems, the White River and Tributaries Outwash Aquifer system has the highest median levels. The aquifer system having the overall highest median levels is the Mississippian/Buffalo Wallow, Stephensport, and West Baden Group bedrock aquifer system; however, it must be remembered that the boundaries of each bedrock aquifer system are based on the boundaries of the subcrop of each major bedrock system. Therefore, wells located within this bedrock aquifer system may actually extend through the upper system into the underlying aquifer system (Blue River Group).

Various geochemical processes, sources, and time may influence the concentration of sulfate in ground water. One important source is the dissolution or weathering of sulfur-containing minerals. Two possible mineral sources of sulfate have been identified in the aquifers of the West Fork White River basin.

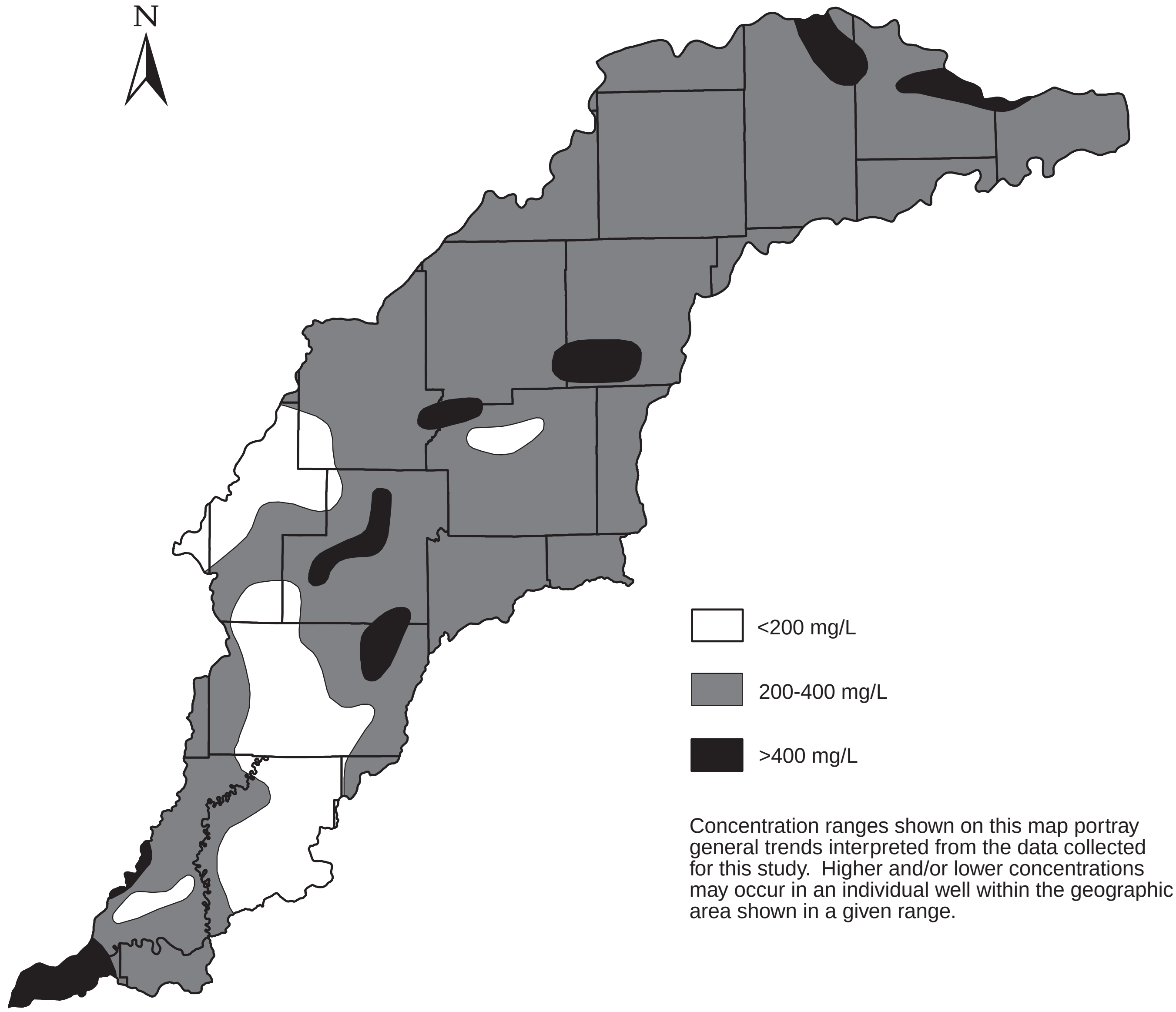


Figure 16b. Generalized areal distribution for Hardness - Bedrock aquifers

The first includes *evaporite* minerals, such as gypsum and anhydrite ($CaSO_4$). Gypsum and anhydrite are the two calcium sulphate minerals occurring in nature. Evaporite minerals are known to occur in both Mississippian and Devonian bedrock, and to a lesser extent, in Pennsylvanian and Silurian bedrock. Fragments of evaporite-bearing rocks may also have been incorporated into some unconsolidated units during glacial advances. There are rather extensive gypsum deposits in the lower part of the St. Louis limestone. The St. Louis evaporite unit accumulated in small basins within larger basins (intrasilled basins). Three major intrasilled basins exist in southwestern Indiana and are aligned in a northwest-southeast direction that corresponds to the trend of the rock formations. The maximum accumulation of the evaporites corresponds to the geographic locations of the intrasilled basins. One of these intrasilled basins lies within the West Fork White River basin in northern Greene County, southwestern Owen County, and southern Clay County.

The second possible mineral source of sulfate is pyrite (FeS_2), a mineral present in Silurian dolomite as highly localized nodules. Pyrite is also a common mineral in carbonaceous or black shales and Pennsylvanian coal beds. The oxidation of pyrite releases iron and sulfate into solution.

The high-sulfate ground-water samples taken from western Monroe, northeastern Greene, and southeastern Owen counties appear to be a result of dissolution of gypsum deposits related to the St. Louis limestone deposits. The high-sulfate ground-water samples taken from western Owen and Clay counties may be related to past coal-mining operations nearby. However, it is not apparent what the sources of other high-sulfate samples in the basin are.

Under *reducing*, low-oxygen conditions, sulfide (S^{-2}) may be the dominant species of sulfur in ground water. Some of the most important influences on the levels of sulfide in ground water are the metabolic processes of certain types of anaerobic bacteria. These bacteria use sulfate reduction in

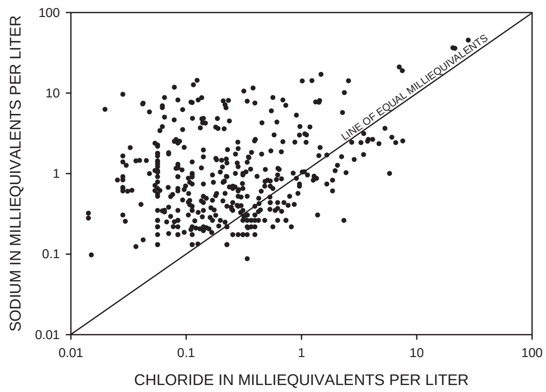


Figure 17. Sodium vs. Chloride in ground-water samples from the West Fork White River Basin

their metabolism of organic matter, which produces sulfide ions as a by-product (Freeze and Cherry, 1979; Hem, 1985).

A sulfide compound that is commonly considered undesirable in ground water is hydrogen sulfide (H_2S) gas. In sufficient quantities, hydrogen sulfide gas can give water an unpleasant odor, similar to that of rotten eggs. At present, there is no established SMCL for hydrogen sulfide in drinking water. Hem (1985) notes that most people can detect a few tenths of a milligram per liter of hydrogen sulfide in solution, and Freeze and Cherry (1979) state that concentrations greater than about 1 mg/L may render water unfit for drinking. Hydrogen sulfide is also corrosive to metals and, if oxidation to sulfuric acid occurs, concrete pipes. Possible results of hydrogen sulfide-induced corrosion include damage to plumbing, and the introduction of metals into water supplies (GeoTrans Inc., 1983)

Available data on the occurrence of hydrogen sulfide in the ground waters of the West Fork White River basin are qualitative. Well drillers may note the occurrence of "sulfur water" or "sulfur odor" on well records. This observation usually indicates the presence of noticeable levels of hydrogen sulfide gas in the well water. The occurrence of hydrogen sulfide is recorded on a few well records of those sampled in this study from Marion, Clay, and Putnam counties. Most of the recorded instances of detectable hydrogen sulfide levels examined for this report occur in wells completed in the Mississippian and Pennsylvanian bedrock aquifer systems.

Iron and Manganese

Because iron is the second most abundant metallic element in the Earth's outer crust (Hem, 1985), iron in ground water may originate from a variety of mineral sources; and several sources of iron may be present in a single aquifer system. Oxidation-reduction potentials, organic matter content, and the metabolic activity of bacteria can influence the concentration of iron in ground water. Because iron-bearing rocks were eroded, transported and deposited by glaciers, including igneous and metamorphic rocks from as far north as Canada, they have been incorporated into and are abundant in many unconsolidated deposits. Pyrite (FeS_2) oxidation may also contribute iron to unconsolidated aquifer systems. Iron is also present in organic wastes and in plant debris in soils. The presence of high iron concentrations in ground water with low sulfate levels may reflect siderite ($FeCO_3$) dissolution or the reduction of sulfate created by pyrite oxidation (Hem, 1985). Low concentrations in some of the bedrock systems may be explained by precipitation of iron minerals from activity of reducing bacteria (Hem, 1985) or by the loss of iron from cation-exchange processes occurring in confining clay, till or shale overlying the bedrock.

Iron levels equal to or below the SMCL are observed in less than 40 percent of all samples analyzed for this constituent. Iron concentrations commonly exceed the SMCL of 0.3 mg/L in water samples from both the unconsolidated and the bedrock aquifer systems (appendix 4). The SMCL for iron is less commonly exceeded in bedrock aquifer systems than in unconsolidated deposits. Forty-eight percent of the bedrock aquifer systems samples exceed the SMCL but 80 percent of the unconsolidated aquifer systems samples exceed the SMCL. Calculated median iron concentrations range between approximately 0.1mg/L and 1.2 mg/L in samples from the bedrock aquifer systems, and 0.75 mg/L and 2.4 mg/L in samples from the unconsolidated aquifer systems. Concentration ranges of iron in ground water of the unconsolidated and bedrock aquifer systems are mapped in figures 20a and b.

Water samples with iron levels above the SMCL are observed in all samples from wells completed in the unconsolidated Buried Valley aquifer system and 92 percent of the wells completed in the Tipton Till Plain Aquifer system. Water samples in bedrock aquifer system that have the highest percentage of ground-water samples with iron levels above the SMCL originate from wells completed in the Silurian and Devonian Carbonates.

In the West Fork White River basin the oxidation of pyrite fragments in glacial till deposits may produce the high iron concentrations in the Tipton Till Plain; the occurrence of high sulfate concentrations in many of the samples containing high iron concentrations is one indication that pyrite may be a source of dissolved iron. High iron concentrations are known to occur locally in the Silurian and Devonian carbonates; for example, the Liston Creek and upper Mississinewa formations in the northern part of the basin are known to contain pyrite and glauconite (another mineral that contains iron). In the southern part of the basin, the minerals pyrite and siderite are present in clay, shale, and coal units. Ferruginous shales and sandstones in some Pennsylvanian formations are also a source of other iron minerals.

Although the geochemistry of manganese is similar to that of iron, the manganese concentration in unpolluted waters is typically less than half the iron concentration (Davis and DeWiest, 1970). Manganese has a low SMCL (0.05 mg/L) relative to many other common constituents in ground water because even small quantities of manganese can cause objectionable taste and the deposition of black oxides. Because the *detection limit* for manganese in the DOW-IGS samples is twice the value of the SMCL, the number of times the SMCL

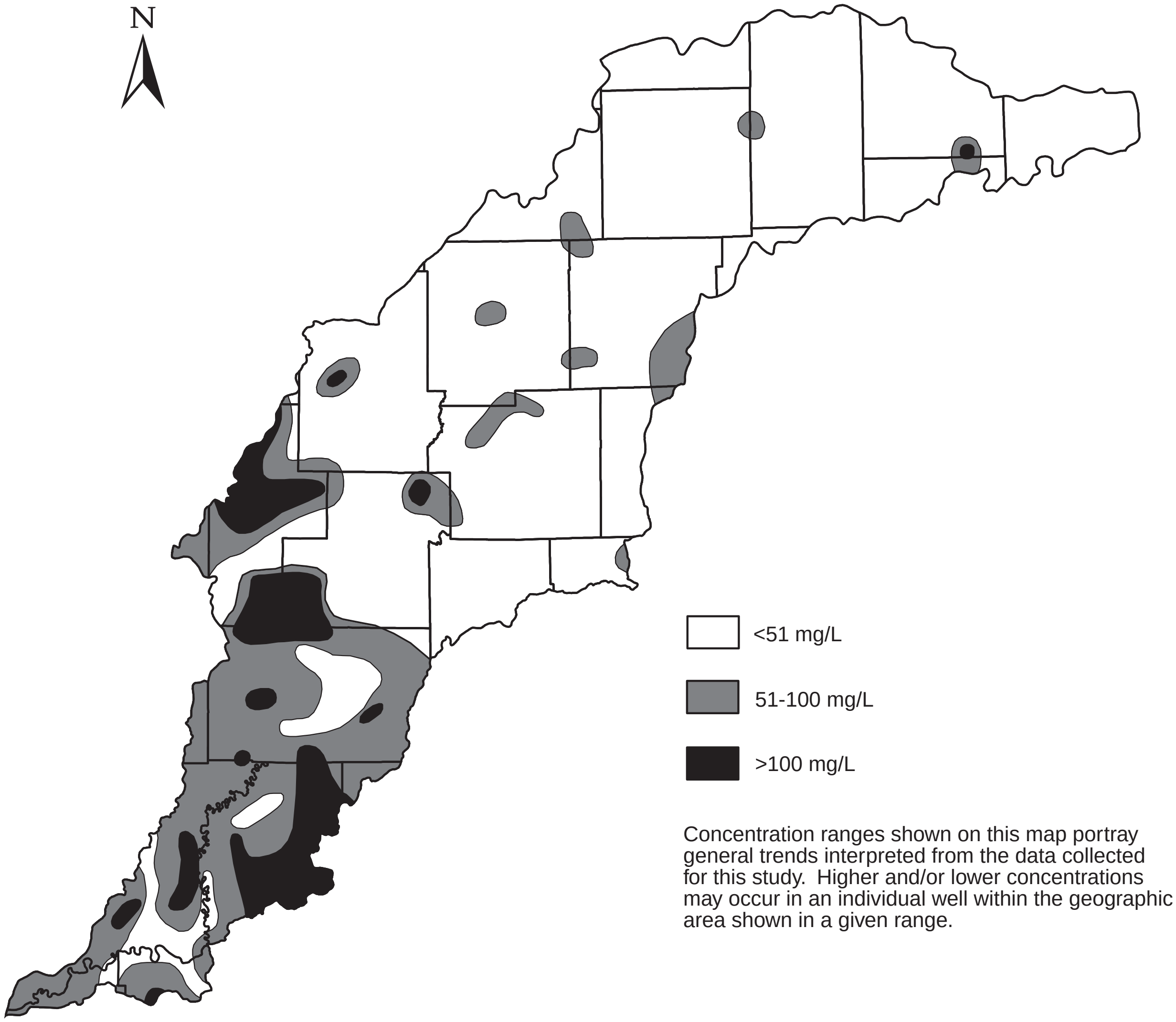


Figure 18. Generalized areal distribution for Sodium - Bedrock aquifers

is exceeded in this data set cannot be quantified. However, ground-water samples with manganese concentrations equal to or above the detection limit are observed in all of the aquifer systems in the West Fork White River basin (appendix 1).

Manganese in West Fork White River basin ground water originates from the weathering of rock fragments in the unconsolidated deposits and oxidation/dissolution of the underlying bedrock. Limestones and dolomites may be a minor source of manganese, because small amounts of manganese commonly substitute for calcium in the mineral structure of carbonate rocks (Hem, 1985). Manganese oxides have been found in siderite and limonite concretions in Mississippian rocks of the Borden Group and in concretions in the Mansfield iron ores of the Raccoon Creek Group. Manganese oxides have also been found in Indiana kaolin (halloysite) deposits, some of which occur at the contact of the Pennsylvanian Mansfield Formation with underlying Mississippian formations (Erd and Greenberg, 1960). Oxides of manganese can also accumulate in bog environments or as coatings on stream sediments (Hem, 1985). Therefore, it is possible that high manganese levels may occur in ground water from wetland environments or buried stream channels.

Fluoride

Many compounds of fluoride can be characterized as only slightly soluble in water. Concentrations of fluoride in most natural waters generally range between 0.1 mg/L and 10 mg/L (Davis and DeWiest, 1970). Hem (1985) noted that fluoride levels generally do not exceed 1 mg/L in most natural waters with TDS levels below 1000 mg/L. The beneficial and potentially detrimental health effects of fluoride in drinking water are outlined in the sidebar titled **National Drinking-Water Standards**.

Box plots of fluoride concentrations in ground-water samples from the aquifer systems under consideration are displayed in appendix 4. Seven of the well samples analyzed for fluoride contain levels at or above the 4.0 mg/L MCL. All of these occur in the Pennsylvanian/Raccoon Creek Group Aquifer system. Concentrations equal to or above the SMCL

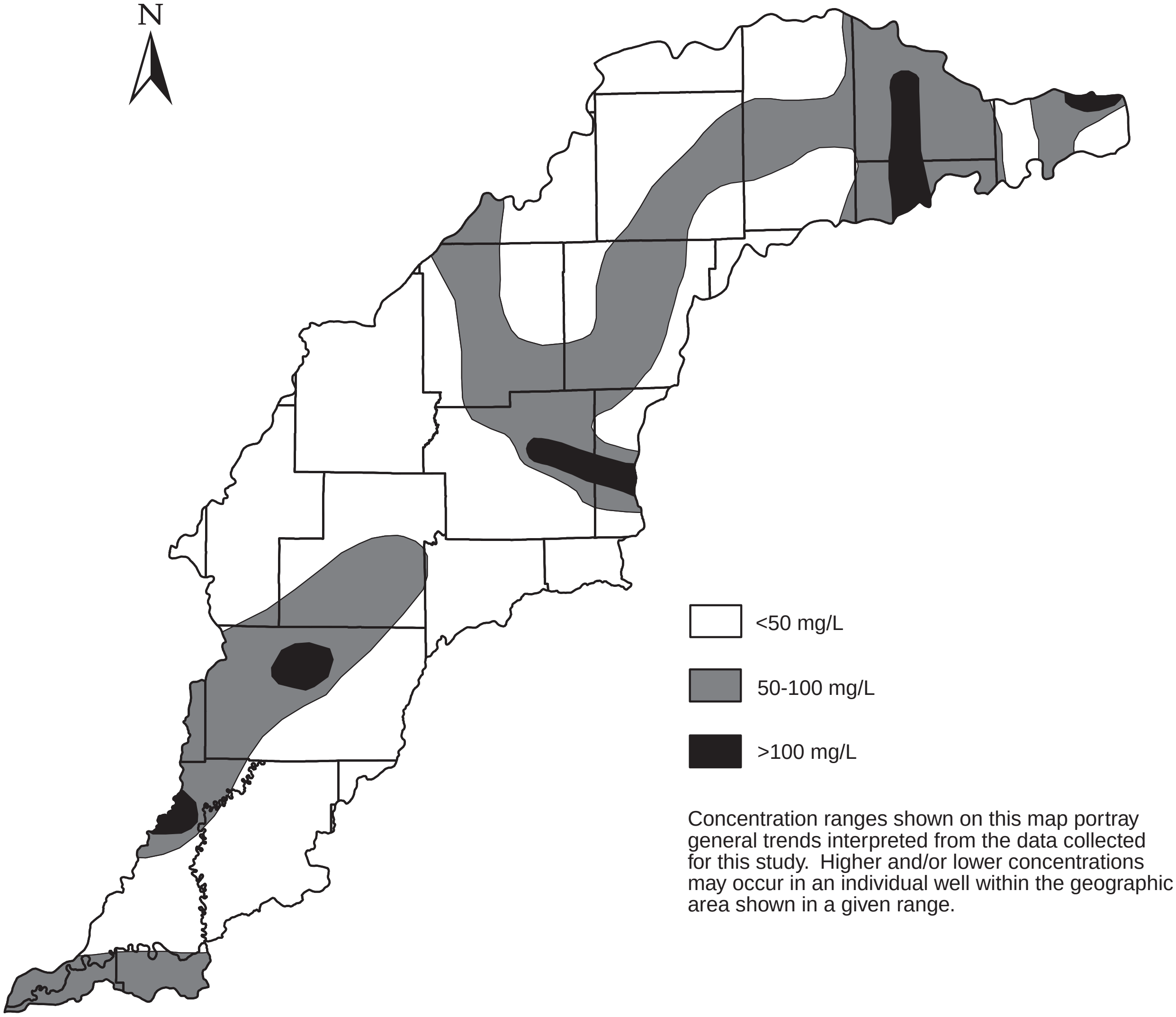


Figure 19a. Generalized areal distribution for Sulfate - Unconsolidated aquifers

for fluoride (2.0 mg/L) are detected in 33 samples and occur in all of the bedrock aquifer systems, but occur in only three samples from the unconsolidated aquifer systems (appendix 4 and figures 21a and b).

Fluoride-containing minerals such as fluorite, apatite and fluorapatite commonly occur in clastic sediments (Hem, 1985). The weathering of these minerals may thus contribute fluoride to ground water in sand and gravel units. The mineral fluorite may also occur in limestones or dolomites. Fluoride may also substitute for hydroxide (OH^-) in some minerals because the charge and ionic radius of these two ions are similar (Manahan, 1975; Hem, 1985).

Nitrate

Nitrate (NO_3^-) is the most frequently detected drinking-water contaminant in the state (Indiana Department of Environmental Management, [1995]) as well as the most common form of nitrogen in ground water (Freeze and Cherry, 1979). Madison and Brunett (1984) developed concentration criteria to qualitatively determine if nitrate levels (as an equivalent amount of nitrogen) in ground water may be influenced by anthropogenic sources. Using these criteria, nitrate levels of less than 0.2 mg/L are considered to represent natural or background levels. Concentrations ranging from 0.21 to 3.0 mg/L are considered transitional, and may or may not represent human influences. Concentrations between 3.1 and 10 mg/L may represent elevated concentrations due to human activities.

High concentrations of nitrate are undesirable in drinking waters because of possible health effects. In particular, excessive nitrate levels can cause *methemoglobinemia* primarily in infants. The maximum contaminant level, MCL, for nitrate (measured as N) is 10 mg/L.

Ranges of nitrate levels (measured as N) in ground-water samples from the West Fork White River basin are plotted in figures 22a and b. Because most samples were below the DOW-IGS detection limit, the occurrence of "background" levels as defined by Madison and Brunett (1984) cannot be quantified. However, figures 22a and b indicate that most of the samples contain nitrate concentrations below the level

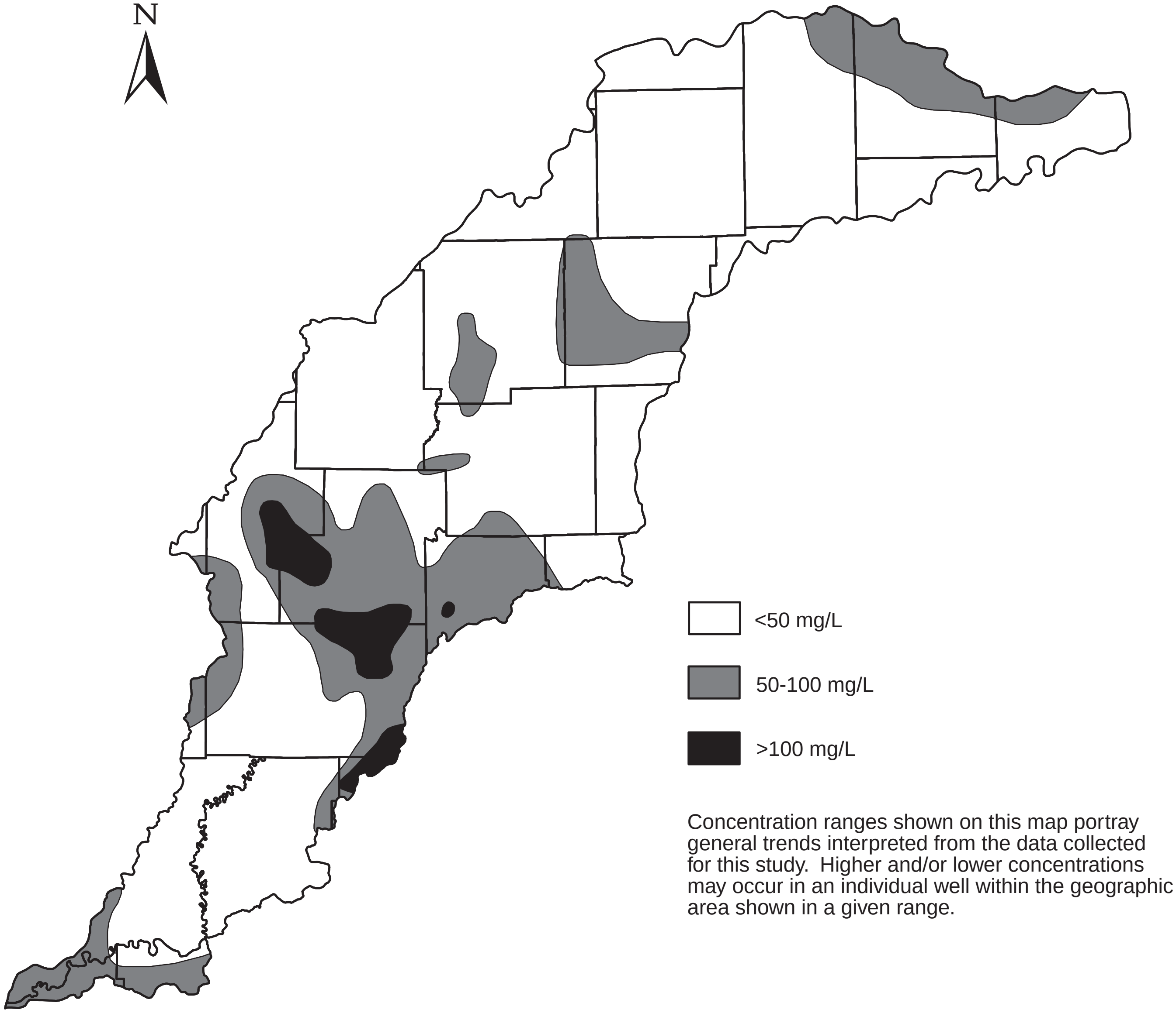


Figure 19b. Generalized areal distribution for Sulfate - Bedrock aquifers

interpreted by Madison and Brunett (1984) to indicate possible human influences.

Only six samples with nitrate levels exceeding the MCL were recovered from wells in the basin (figures 22a and b). Four of these were from the White River and Tributaries Outwash Aquifer system in Knox and Daviess Counties. Nitrate levels from other sampled wells that are nearby, however, are below the detection limit. Overall, the distribution of nitrate concentrations in ground water of the West Fork White River basin appears to indicate that levels generally do not exceed 1.0 mg/L, as almost 90 percent of the samples are below that level. High concentrations of nitrate, which may suggest human influences, appear to occur in isolated wells or limited areas.

Two other studies also provide perspective on nitrate in ground water in the West Fork White River basin, one conducted by the Indiana Farm Bureau and another by the U.S. Geological Survey. A brief discussion of these studies and their findings follow.

In 1987, the Indiana Farm Bureau, in cooperation with various county and local agencies, began the Indiana Private Well Testing Program. The purpose of this program is to assess ground-water quality in rural areas, and to develop a statewide database containing chemical analysis of well samples. By the end of 1993 samples from over 9000 wells, distributed over 68 counties, had been collected and analyzed as a part of the program (Wallrabenstein and others, 1994). Most of the ground-water samples collected during this study were analyzed for inorganic nitrogen and some specific pesticides. The results of the pesticide sampling are presented in the section entitled **Pesticides in West Fork White River basin ground waters**.

The techniques used to analyze the samples collected for the Farm Bureau study actually measured the combined concentrations of nitrate and nitrite (nitrate+nitrite). However, the researchers noted that nitrite concentrations were general-

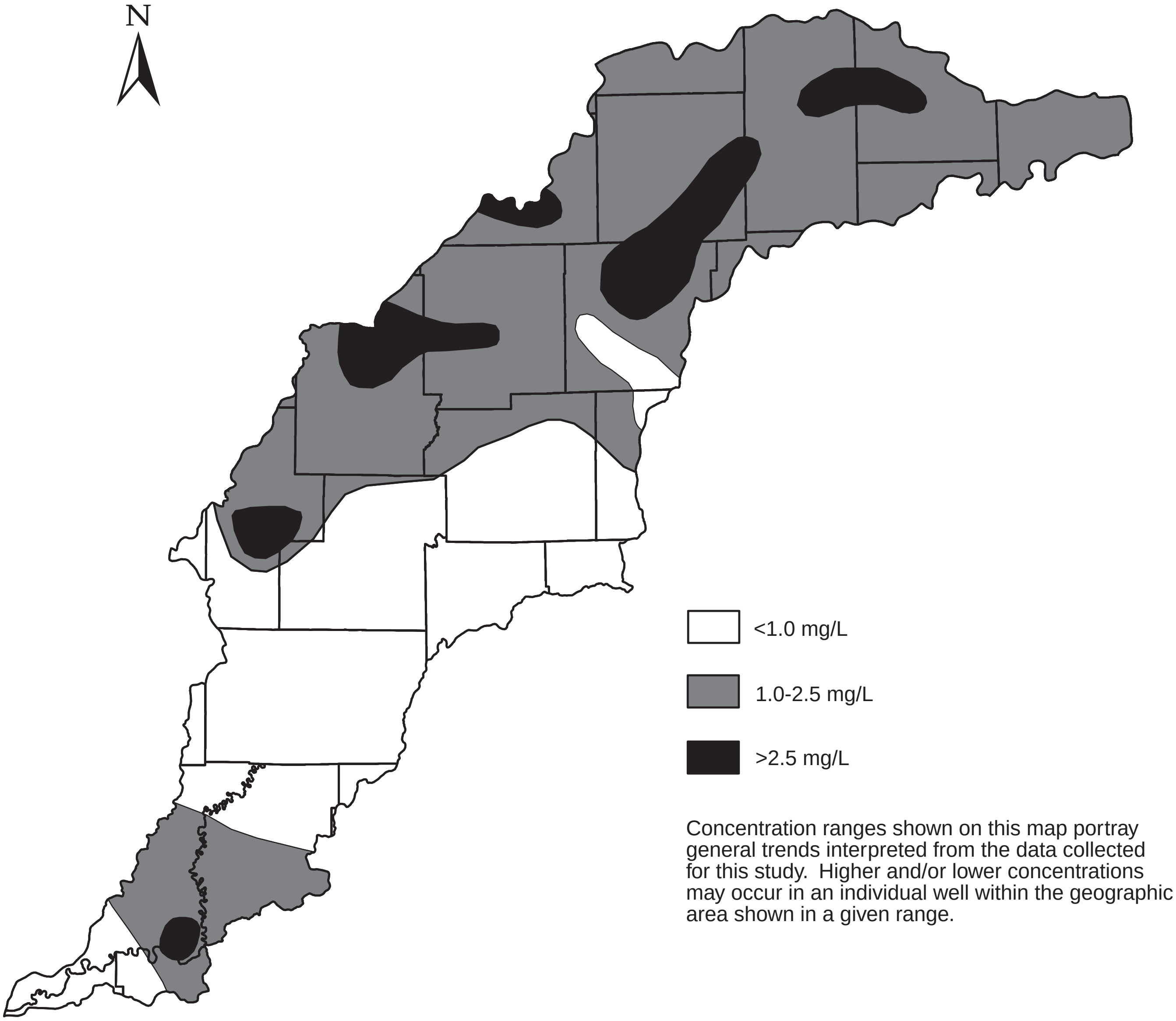


Figure 20a. Generalized areal distribution for Iron - Unconsolidated aquifers

ly low. Thus the nitrate+nitrite concentrations were approximately equal to the concentrations of nitrate in the sample (Wallrabenstein and others, 1994). The MCL for nitrate+nitrite (as equivalent elemental nitrogen) is 10 mg/L.

Greene, Pike, and Randolph are the only counties of the 29 counties (table 1) that lie partially or wholly within the West Fork White River basin that did not participate in the Farm Bureau study. For this discussion, however, only the statistics for the counties that have more than 50 percent of their area encompassed within the basin were closely examined: Clay, Daviess, Delaware, Hamilton, Hendricks, Knox, Madison, Marion, Morgan, Owen, and Putnam. Statistics for Boone, Johnson, Monroe, and Tipton counties were also briefly examined because these counties have more than 35 percent of their area in the basin. Data on the owners and exact locations of the wells sampled for the Farm Bureau study were not provided in the report. Although the exact locations of the samples cannot be determined, the data do provide a general sense for nitrate conditions in the basin.

Approximately 80 percent of all samples in the counties of the basin had nitrate+nitrite concentrations below the reporting limit of 0.3 mg/L. Nitrate+nitrite concentrations above the MCL were observed in approximately 3 percent of the wells sampled.

Although most of the samples had concentrations below reporting limits, samples from each county contained nitrate+nitrite levels over the reporting limit (0.3 mg/L). The largest number of samples having nitrate+nitrite concentrations above the reporting limit were in Hendricks, Putnam, Johnson, Morgan, and Daviess Counties. The smallest number of samples and smallest percentage of samples having nitrate+nitrite concentrations above the reporting limit were reported for Tipton, Boone, and Madison Counties.

However, sheer numbers do not necessarily represent the complete picture of the nitrate situation in a county. Differences in sample size in the counties tend to distort the

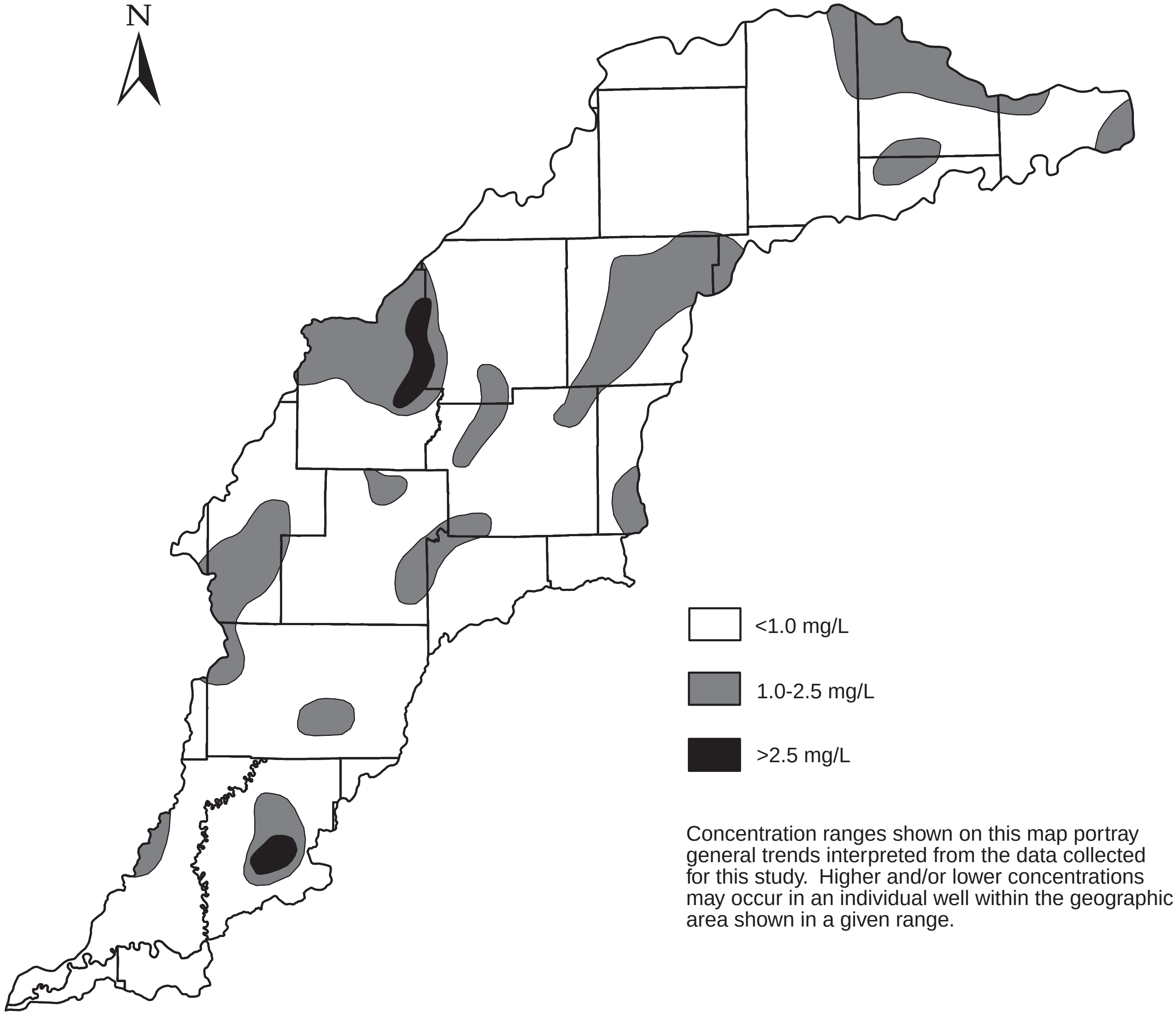


Figure 20b. Generalized areal distribution for Iron - Bedrock aquifers

magnitude of the nitrate issue in a county. For example, although Hendricks County reported 94 samples above reporting limits, the large sample size of 873 make the percentage of samples having reportable levels at less than 11 percent. Whereas, the small sample size of 31 for Knox County produce approximately 71 percent result for samples having reportable values. In spite of the small sample size there are obviously nitrate issues in Knox County, because approximately 50 percent of the samples taken in the county had reported values greater than 3.0 mg/L, including 29 percent with nitrate values greater than the MCL.

A variety of anthropogenic activities can contribute nitrate to ground waters, and may increase nitrate concentrations above the MCL. Because nitrate is an important plant nutrient, nitrate fertilizers are often added to cultivated soils. Under certain conditions, however, these fertilizers may enter the ground water through normal infiltration or through a poorly-constructed water well. Nitrate is commonly present in domestic wastewater, and high levels of this constituent are often associated with septic systems. Animal manure can also be a source of nitrate in ground-water systems, and high nitrate levels are sometimes detected in ground waters down-gradient from barnyards or feedlots. Because many sources of nitrate are associated with agriculture, rural areas may be especially susceptible to nitrate pollution of ground water. To help farmers and other rural-area residents assess and minimize the risk of ground-water contamination by nitrate and other agricultural chemicals, the American Farm Bureau Federation has developed a water quality self-help checklist specifically for agricultural operations (American Farm Bureau Federation, 1987).

In 1991, the U.S. Geological Survey (USGS) began the National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface and ground water and to provide a sound scientific understanding

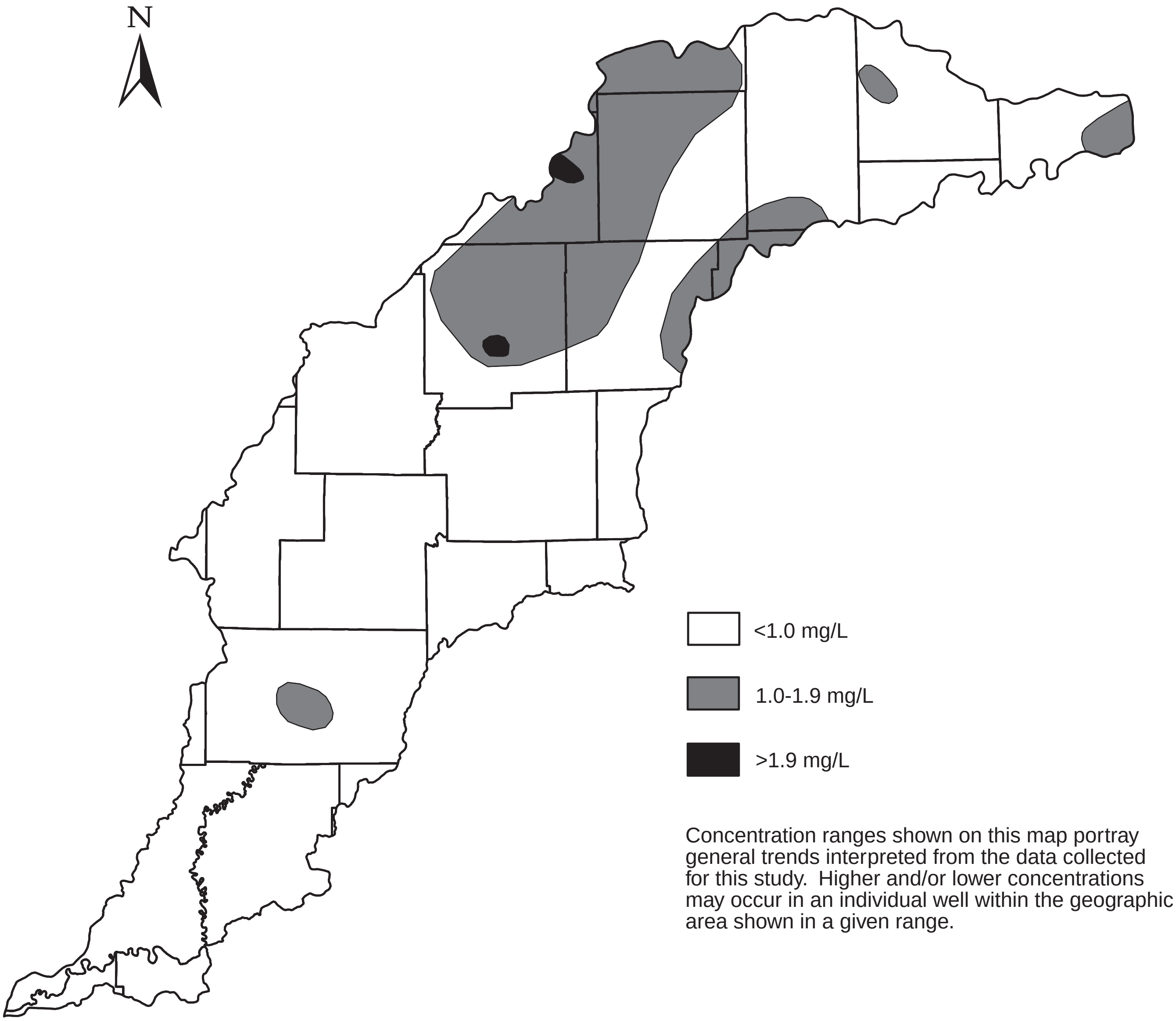


Figure 21a. Generalized areal distribution for Fluoride - Unconsolidated aquifers

of the primary natural and human factors affecting the quality of these resources (Hirsch and others, 1988).

The White River Basin in Indiana was among the first 20 river basins to be studied as part of the NAWQA program. A component of the White River Basin study is to determine the occurrence of nitrate in the shallow ground water of the basin. Moore and Fenelon (1996) describe nitrate data collected from 103 monitoring wells from June 1994 through August 1995. The study included both the West Fork and the East Fork White River Water Management basins of Indiana.

Findings of the study:

• Nitrate concentrations in water samples from the 94 shallow wells in the White River Basin ranged from less than 0.05 mg/L to a high of 21 mg/L.

• Water from 6 of the 94 shallow wells (6.4 percent) contained nitrate concentrations higher than 10 mg/L. Nitrate was not detected, at a detection limit of 0.05 mg/L, in 43 percent of the shallow wells.

• In contrast to the wells with no detectable nitrate, samples from 29 percent of the shallow wells had nitrate concentrations higher than 3.0 mg/L.

• The paired wells in the fluvial deposits show stratification of nitrate concentration with depth. The largest percentage of shallow wells with a nitrate concentration between 3.1 and 10 mg/L (42 percent) and the largest percentage of shallow wells with a nitrate concentration higher than 10 mg/L (17 percent) were in fluvial deposits underlying agricultural land.

• Nitrate concentrations in samples from three-fourths of the shallow wells in fluvial deposits underlying urban land were above the detection limit; however, the nitrate concentration did not exceed 10 mg/L in any of the samples.

• Water samples from more than one third of the wells in the glacial lowland had nitrate concentrations higher than 3.0 mg/L.

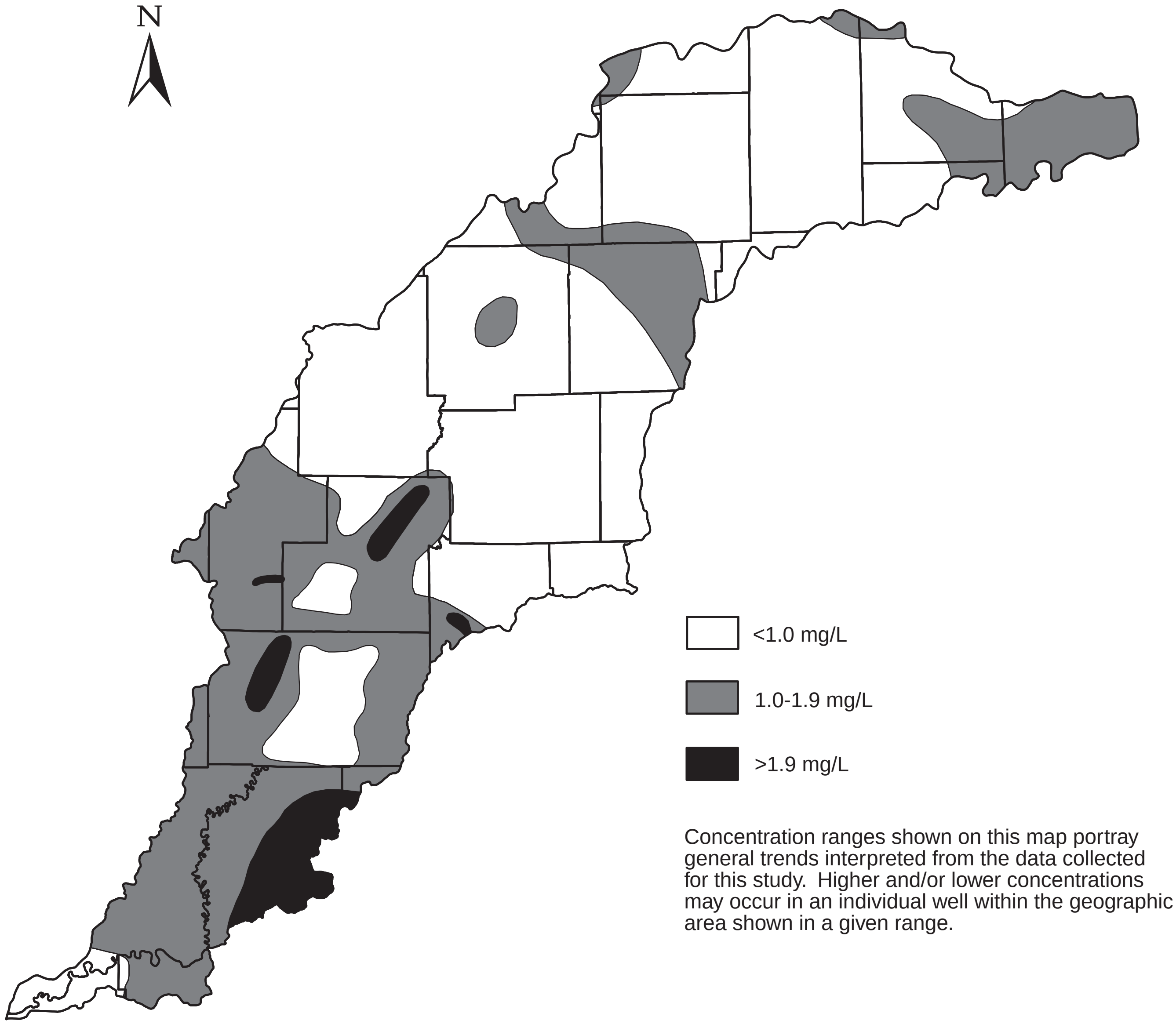


Figure 21b. Generalized areal distribution for Fluoride - Bedrock aquifers

• Nitrate concentrations were below the detection limit in samples from approximately 65 percent of the wells in the till plain and 41 percent of the wells in the glacial lowland.

Strontium

Ground water in the West Fork White River basin may be characterized as containing "relatively high" concentrations of strontium compared to ground water in other regions. For example, Skougstad and Horr (1963) analyzed 175 ground-water samples from throughout the United States and noted that 60 percent contained less than 0.2 mg/L of strontium. Davis and DeWiest (1970) report that concentrations of strontium in most ground water generally range between 0.01 and 1.0 mg/L. Of the 372 ground-water samples analyzed for strontium in this report, however, only about 22 percent contained strontium concentrations less than 0.2 mg/L. Almost 25 percent of the wells sampled in the West Fork White River basin contained strontium concentrations greater than 1.0 mg/L. Figures 23a and b display the spatial distribution of ground-water strontium levels for the unconsolidated and bedrock aquifer systems in the West Fork White River basin.

The unconsolidated aquifer systems generally have lower median strontium concentrations than the bedrock aquifer systems. The lowest median strontium concentrations of all the aquifer systems are observed in the ground-water samples from the unconsolidated White River and Tributaries Outwash Aquifer system and subsystem. The unconsolidated aquifer systems with the highest median strontium concentrations are the Tipton Till Plain Aquifer system and subsystem. The lowest median strontium concentrations in the bedrock aquifer systems are observed in samples from the Pennsylvanian bedrock systems. The Mississippian/Buffalo Wallow, Stephensport, and West Baden Group Aquifer system has the highest median strontium concentration of all the

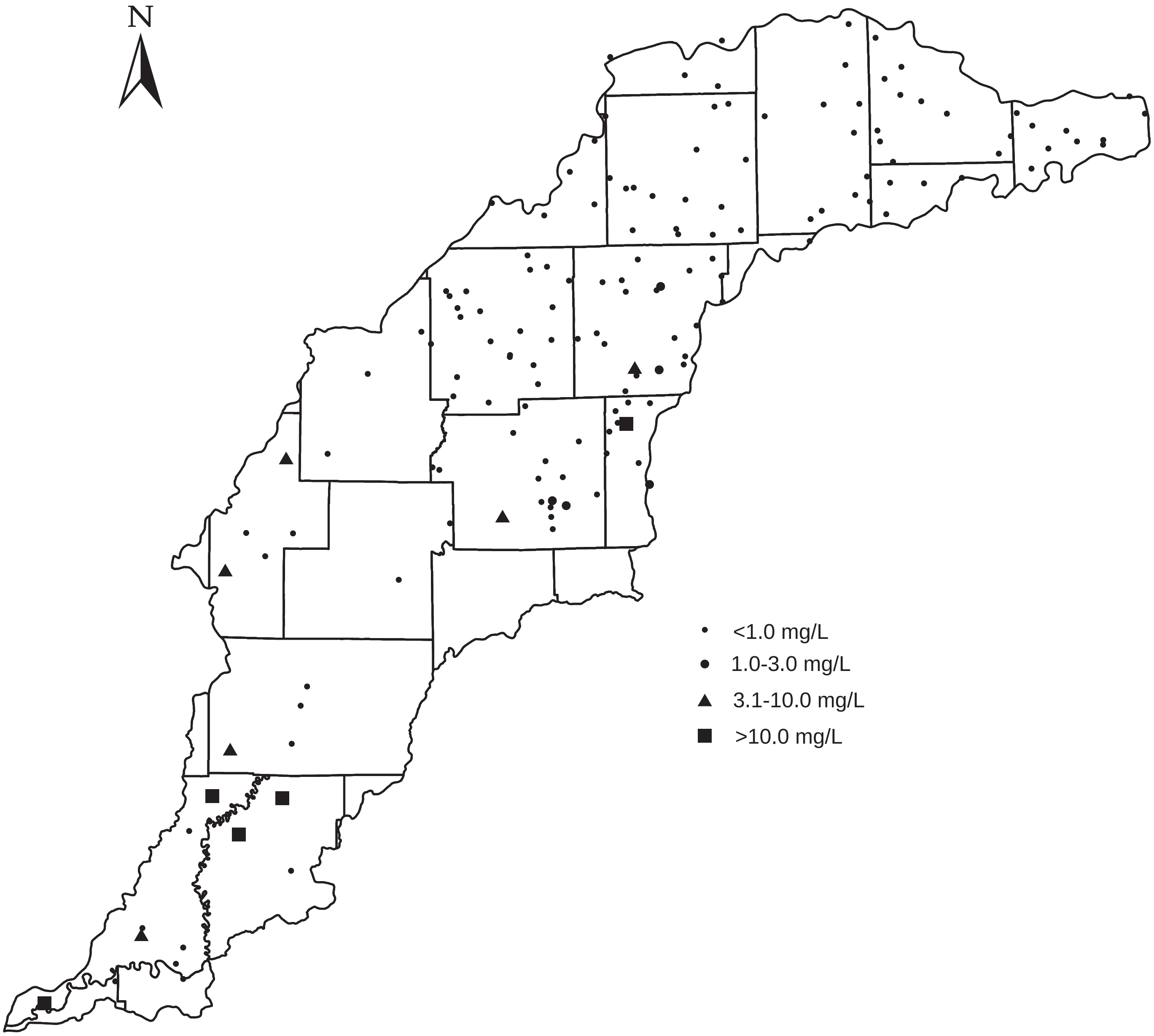


Figure 22a. Distribution of Nitrate-Nitrogen concentrations for sampled wells - Unconsolidated aquifers

aquifer systems (appendix 4).

Elevated concentrations of strontium are apparent in the bedrock aquifers in some areas of Monroe, Greene, and Owen Counties, and in the unconsolidated and bedrock aquifers of Randolph County. At the time of this report, no enforceable drinking-water standards have been established for strontium. However, the non-enforceable lifetime *health advisory* for strontium is set at 17.0 mg/L. Four samples from wells completed in the Mississippian/Blue River and Sanders Group Aquifer system in Monroe County and one sample from the Tipton Till Plain Aquifer subsystem in Randolph County contain strontium concentrations in excess of the health advisory (see appendix 4). In addition to these 5 wells, fifteen others have strontium concentrations greater than 5 mg/L. Seven of these were in Randolph County and all but one of the rest were in Greene, Owen and Monroe Counties.

Sources of strontium in ground water are generally the trace amounts of strontium present in rocks. The strontium-bearing minerals celestite ($SrSO_4$) and strontianite ($SrCO_3$) may be disseminated in limestone and dolomite. Also, celestite is associated with gypsum deposits, which occur in the rocks of the Blue River and Sanders Group. These rocks are located in Greene, Owen, and Monroe Counties. Silurian rocks of several different lithologies may be the source of high strontium and concentrations in Randolph County.

Because strontium and calcium are chemically similar, strontium atoms may also be adsorbed on clay particles by ion exchange (Skougstad and Horr, 1963). Ion-exchange processes may thus reduce strontium concentrations in ground water found in clay-rich sediments.

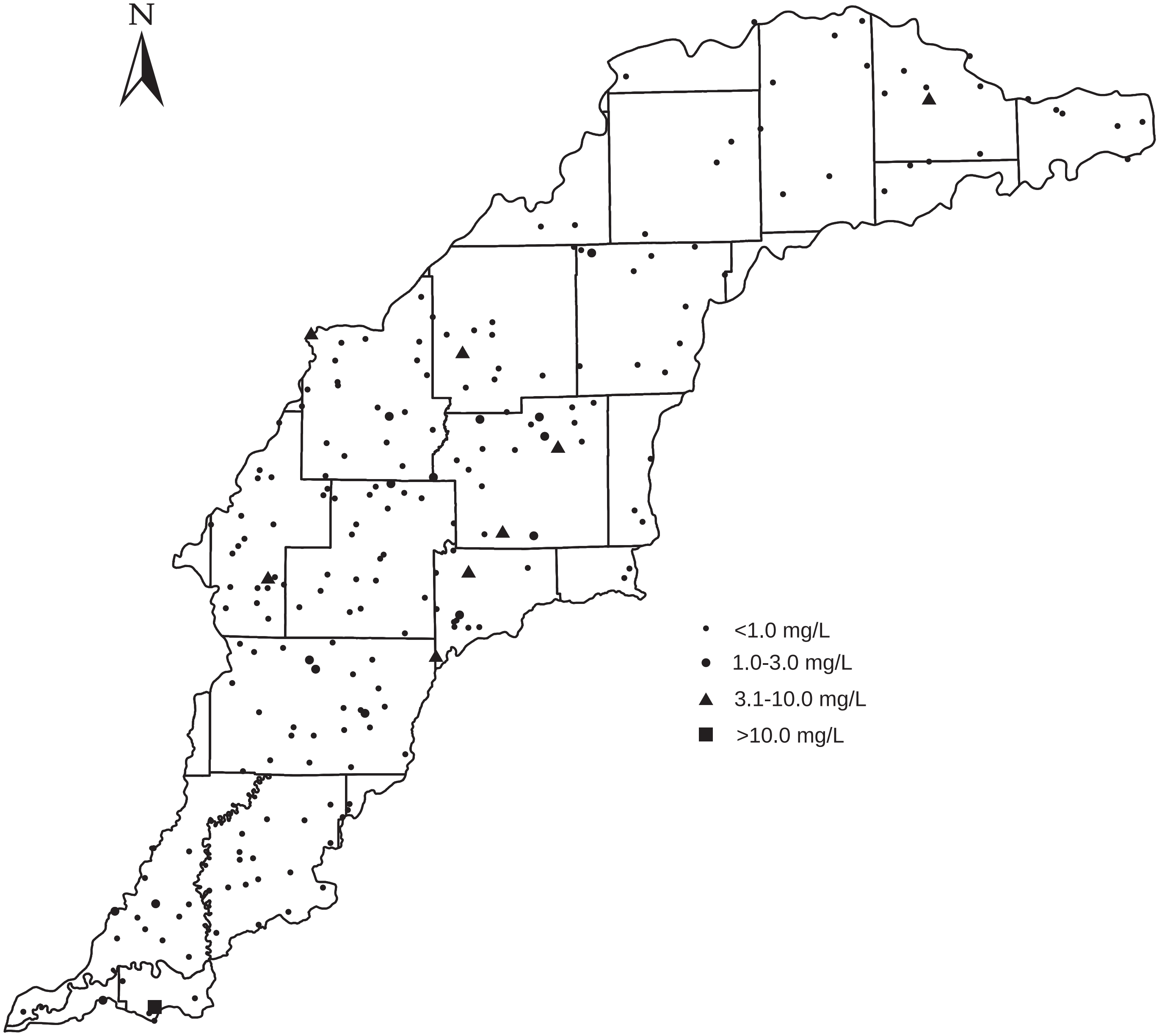


Figure 22b. Distribution of Nitrate-Nitrogen concentrations for sampled wells - Bedrock aquifers

Zinc

Generally, significant dissolved quantities of the metal zinc occur only in low pH or high-temperature ground water (Davis and DeWiest, 1970). Concentrations of zinc in ground-water samples from the West Fork White River basin are plotted in figures 24a and b. Three hundred eleven of the ground-water samples analyzed (approximately 84 percent) contain levels below the detection limit of 0.1 mg/L for zinc. None of the samples analyzed contain zinc in concentrations above the 5 mg/L SMCL established for this constituent (appendix 2).

Lead

Naturally occurring minerals that contain lead are widely dispersed, but have low solubility in most natural ground water. The co-precipitation of lead with manganese oxide and the adsorption of lead on organic and inorganic sediment surfaces help to maintain low lead concentration levels in ground water (Hem, 1985). Much of the lead present in tap water may come from anthropogenic sources, particularly lead solder used in older plumbing systems. Because natural concentrations of lead are normally low and because there are so many uncertainties involved in collecting and analyzing samples, lead was not analyzed in this study.

Total dissolved solids

Total dissolved solids (TDS) are a measure of the total amount of dissolved minerals in water. Essentially, TDS rep-

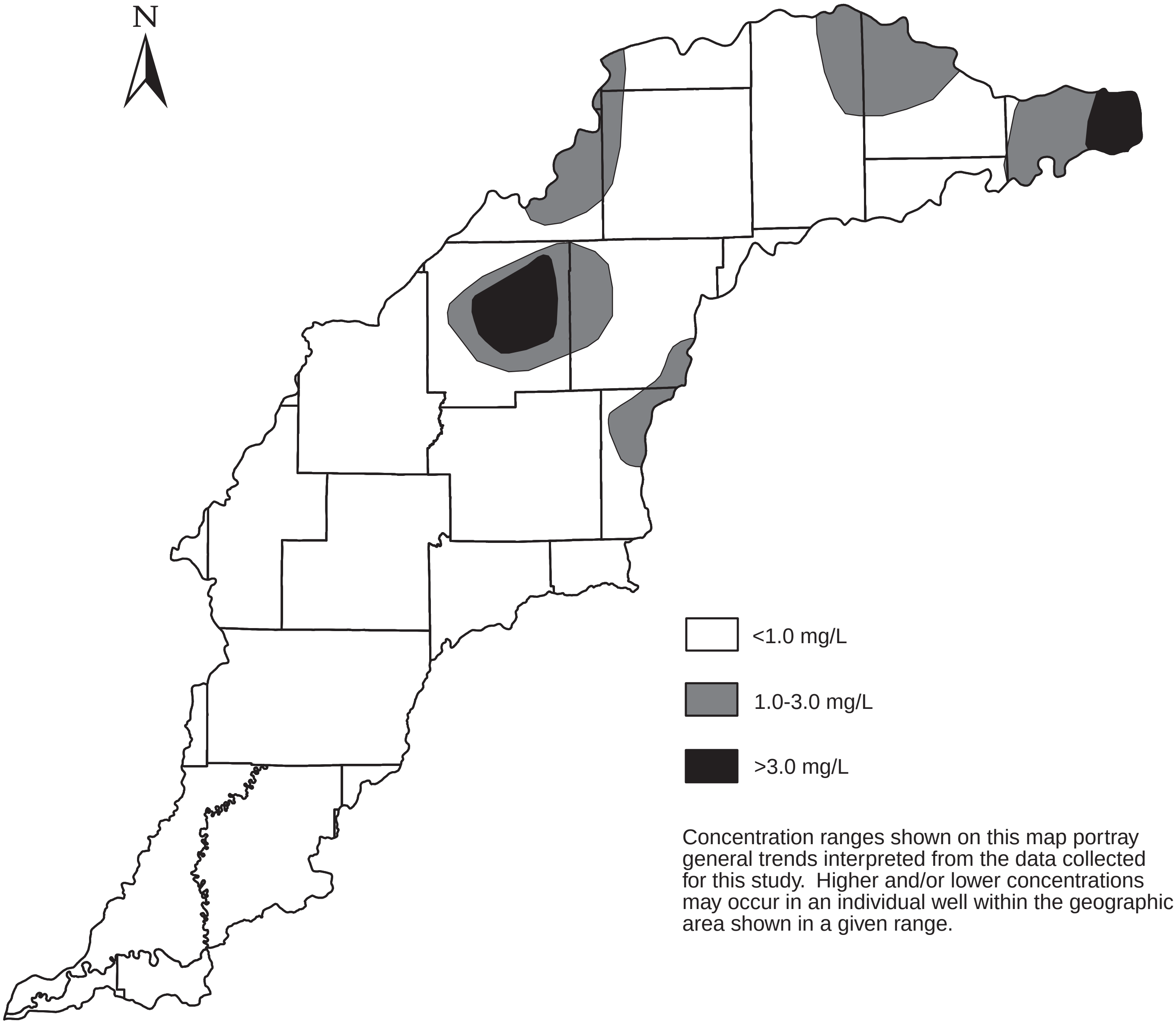


Figure 23a. Generalized areal distribution for Strontium - Unconsolidated aquifers

resents the sum of concentrations of all dissolved constituents in a water sample. In general, if a ground-water sample has a high TDS level, high concentrations of major constituents will also be present in that sample. The secondary maximum contaminant level (SMCL) for TDS is established at 500 mg/L. Drever (1988), however, defines fresh water (water sufficiently dilute to be potable) as water containing TDS of less than 1000 mg/L.

More than 81 percent of the samples collected from wells in the West Fork White River basin contain TDS levels that exceed the SMCL. The lowest median TDS level is observed in samples from the Mississippian/Buffalo Wallow, Stephensport and West Baden Groups Aquifer system, which is the only aquifer system having a median TDS level below the SMCL (appendix 4); however, this system also displays the greatest variability in TDS levels. The lowest median TDS level in the unconsolidated aquifer systems is slightly above the SMCL and is observed in samples from the White River and Tributaries Outwash Aquifer system (appendix 4).

Although the lowest median values for TDS occur in a bedrock aquifer system, in general TDS values are higher in the bedrock aquifer systems in the basin than in the unconsolidated deposits. Median TDS levels are more variable in the bedrock aquifer systems than in the unconsolidated systems, as both the highest and lowest median TDS levels occur in the bedrock systems. Three of the bedrock aquifer systems, the Devonian and Mississippian/New Albany Shale, the Pennsylvanian/Carbondale Group, and the Pennsylvanian/McLeansboro Group, have the highest median TDS levels of all aquifer systems, which are approximately 700 mg/L. Some of the highest TDS levels are observed in the Pennsylvanian/Raccoon Creek Group Aquifer system. Of the 16 bedrock well samples exceeding 1000 mg/L, eleven occur in this aquifer system. In contrast, only one of the unconsolidated aquifer systems has a median TDS level above 600 mg/L, which is the White River and Tributaries Outwash

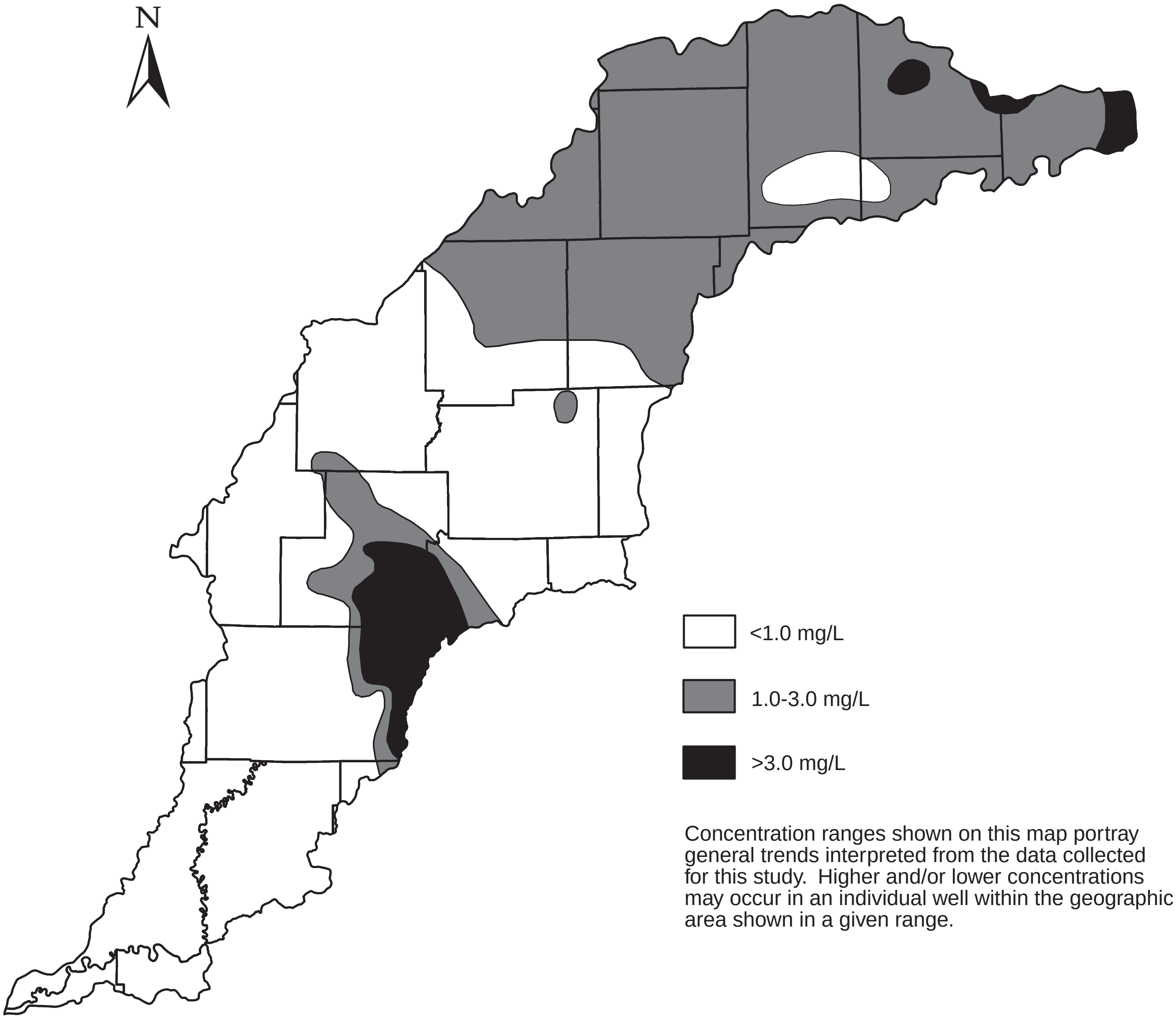


Figure 23b. Generalized areal distribution for Strontium - Bedrock aquifers

Subsystem at 635 mg/L. Figures 25a and b display the spatial distribution of ground-water TDS levels for the unconsolidated and bedrock aquifer systems in the West Fork White River Basin.

Because of the wide range in solubility of different minerals, one of the principal influences on TDS levels in ground water is the minerals that come into contact with the water. Water in contact with highly soluble minerals will probably contain higher TDS levels than water in contact with less soluble minerals. Amount of carbonate materials and ground-water residence time also exert substantial control over the levels of chemical constituents in ground water.

In an aquifer where ground-water flow is very sluggish and flushing of the aquifer is minimal, ground water can reach a state of chemical saturation with respect to dissolved solutes. Areas of active ground-water flushing generally have lower TDS values.

Ion-exchange processes in clays can also increase TDS because, in order to maintain electrical charge balance, two *monovalent* sodium or potassium ions must enter solution for each *divalent* ion absorbed. Clay minerals can have high cation-exchange capacities and may exert a considerable influence on the proportionate concentration of the different cations in water associated with them (Hem, 1985). The exchange of calcium for sodium results in high sodium levels, and total dissolved solids increase in ground water when calcium ions are exchanged for sodium ions (Freeze and Cherry, 1979).

Shale and other fine-grained sedimentary rocks (referred to as hydrolyzates) are composed, in large part of clay minerals and other fine-grained particulate matter that has formed by chemical reactions between water and silicates. Shale and similar rocks may be porous but do not transmit water readily because openings are very small and are poorly interconnected. Many such rocks were originally deposited in saltwater, and some of the solutes may remain in the pore space and

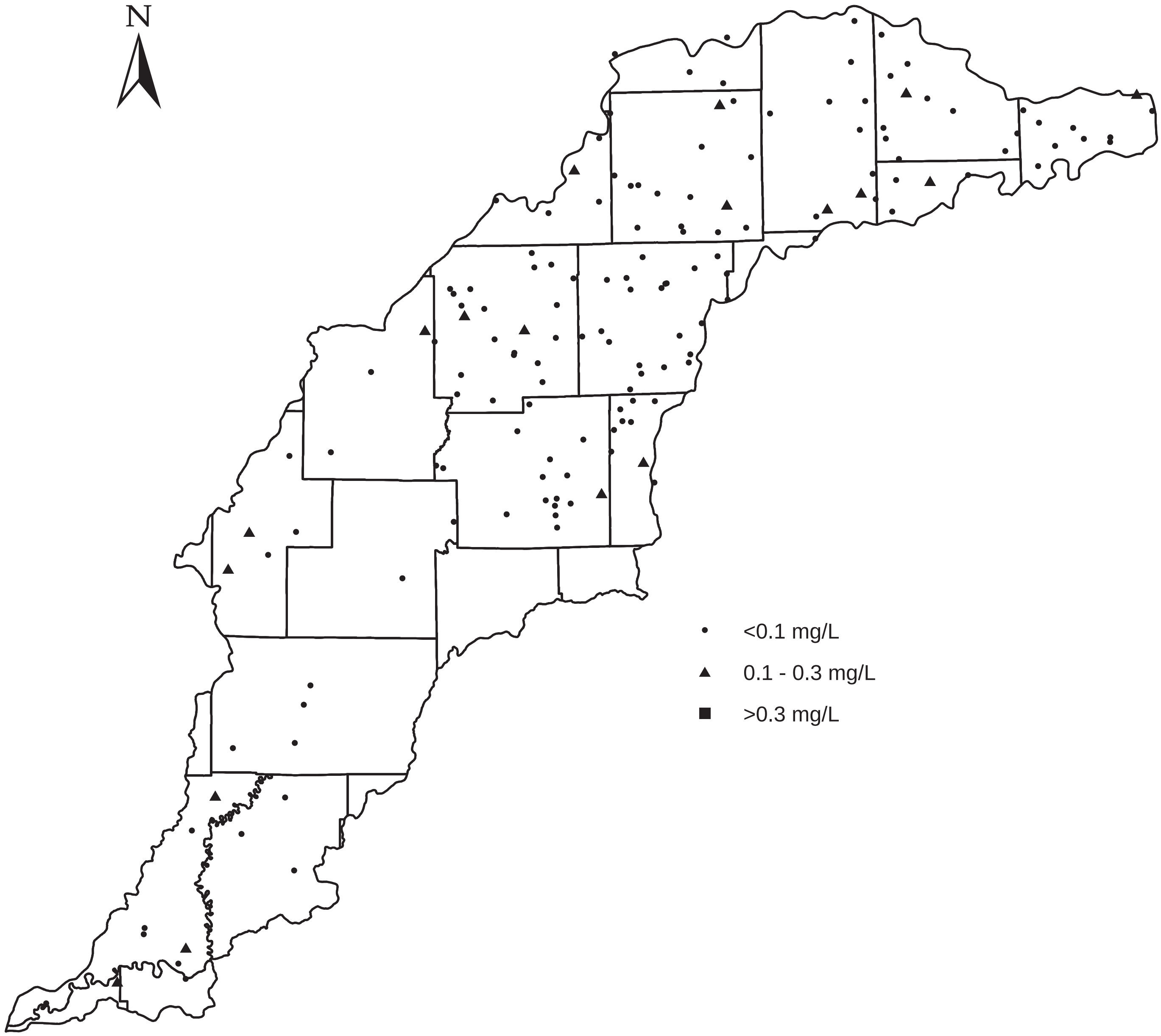


Figure 24a. Distribution of Zinc concentrations for sampled wells - Unconsolidated aquifers

attached to the particles for long periods after the rock has been formed. As a result, the water obtained from a hydrolyzate rock may contain rather high concentrations of dissolved solids. If they are interbedded with rocks that are more permeable, there can be migration of water and solutes from the hydroyzates into the aquifers with which they are interbedded. Although it is not necessarily true for all waters associated with hydrolyzates, such waters commonly share one dominant characteristic; sodium is their principal cation.

The high TDS levels in the Pennsylvanian bedrock aquifer systems could reflect long residence times and cation exchange in bedrock systems that contain a high percentage of shale. The high TDS level is a factor that prevents deep bedrock formations from being considered practical sources of potable ground water in the West Fork White River basin.

Total dissolved solids levels may also be influenced by ground-water pollution. Road salting, waste disposal, mining, landfills, and runoff from urban or agricultural areas are some human factors that may add dissolved constituents to ground water. Coal mining in the Pennsylvanian bedrock may also play an important role in the high TDS values in those aquifer systems within and adjacent to the mines.

Radon

Radon is a radioactive noble gas produced by the decay of radium. Uranium minerals in rocks are the source of radium. The primary source of the radon gas in ground water is the radium in the aquifer material (Hem, 1985). Radon subsequently undergoes decay by emitting an alpha particle (positively charged helium nucleus). When ingested or inhaled over an extended period of time, radon and some of its decay products can cause cancer. Radon levels are measured in pic-

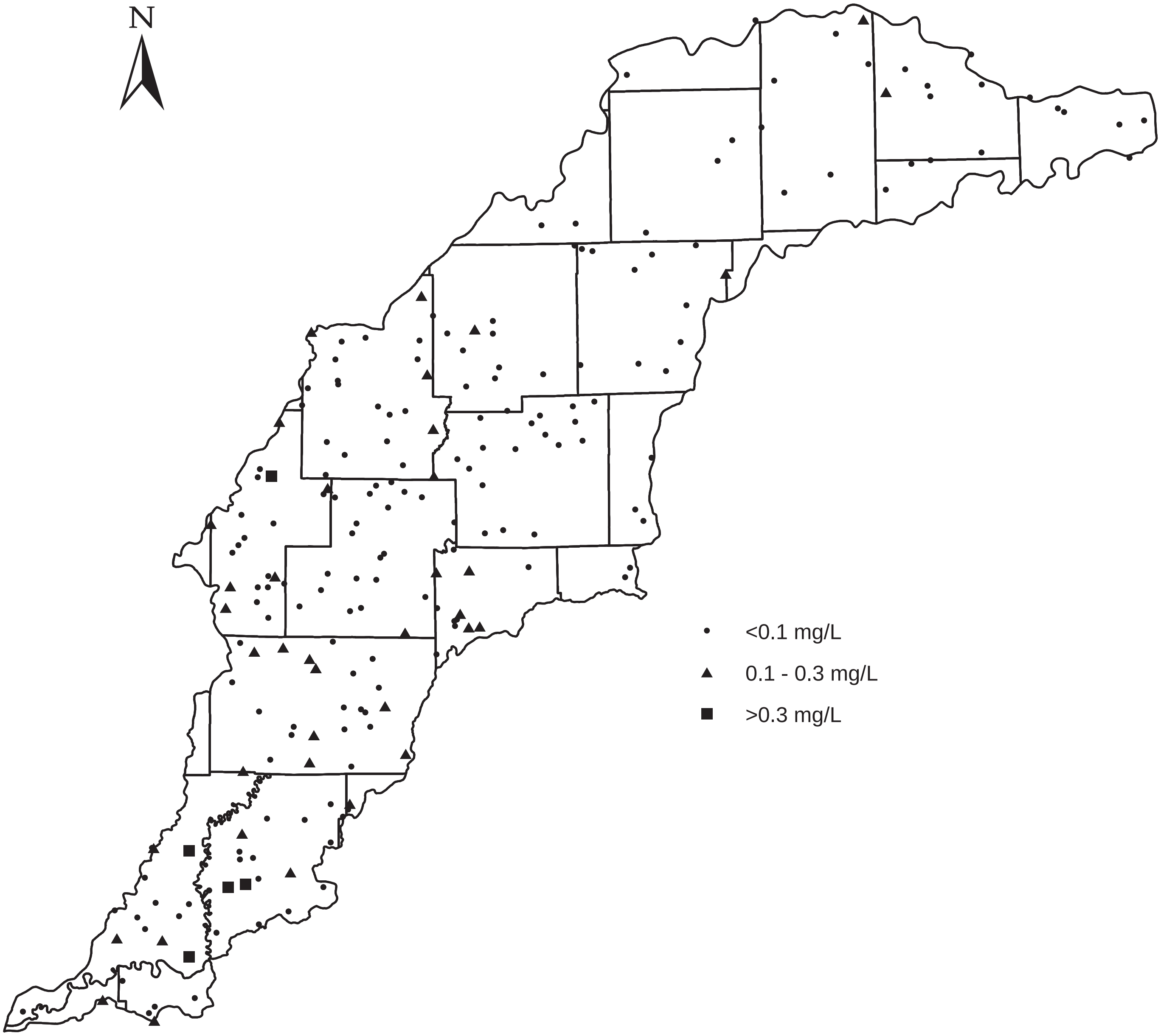


Figure 24b. Distribution of Zinc concentrations for sampled wells - Bedrock aquifers

ocuries per liter (pCi/L). An activity of one pCi/L is approximately equal to the decay of two atoms of radon per minute in a liter of air or water. At present, no Maximum Contaminant Level (MCL) has been established for radon in drinking water; however, the Environmental Protection Agency has proposed an MCL of 300 pCi/L

One hundred seventy-six of the 372 ground-water samples taken for this study were analyzed for radon. The bedrock aquifers generally exhibit greater variability in median radon activity than the unconsolidated aquifers (appendix 4). The Mississippian/Borden Group and the Blue River and Sanders Groups have the highest median activity in the bedrock aquifer systems. In the unconsolidated aquifer systems, the Dissected Till and Residuum aquifer system has the highest median radon activity. Fourteen samples have activity greater than 1000 pCi/L. All but one of these are from bedrock aquifers. Ten are from the Mississippian aquifer systems. Four aquifer systems: (Buried Valley, Lacustrine and Backwater Deposits, Devonian and Mississippian/New Albany Shale, and Mississippian/Buffalo Wallow, Stephensport, and West Baden Group) have fewer than 4 samples, so they are not included in the median comparison.

Pesticides

Because agriculture is an important form of land use in Indiana, pesticides are widely used in the state to control weeds and insects. In 1990, for example, a reported 28 million pounds of corn and soybean pesticides were used throughout the state (Risch, 1994). The widespread use of pesticides has created concerns about possible adverse affects that these chemicals may have on the environment. Among these concerns is the possibility that pesticides may contami-

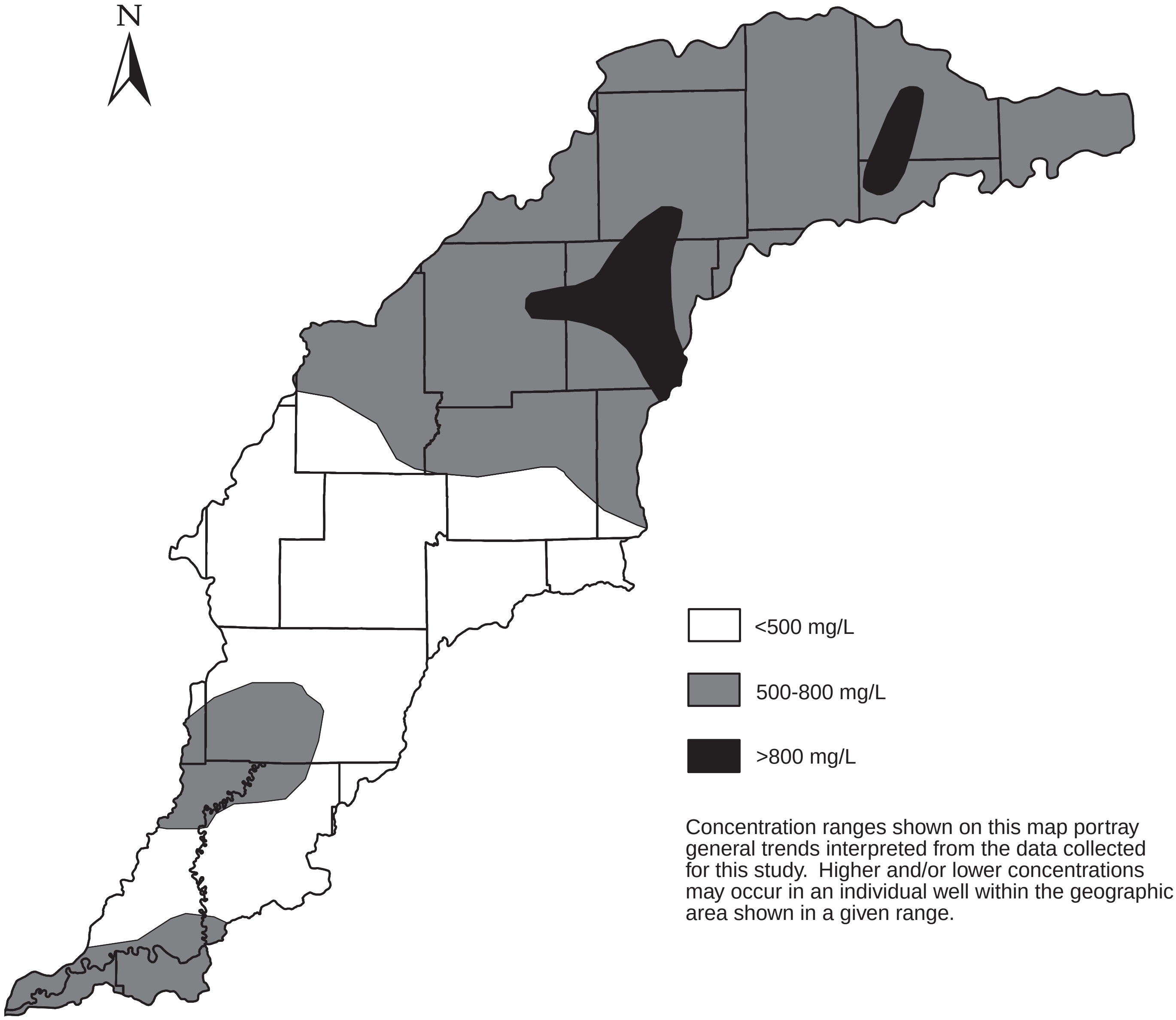


Figure 25a. Generalized areal distribution for Total Dissolved Solids - Unconsolidated aquifers

nate ground-water supplies.

Through a cooperative effort, the U.S. Geological Survey and the Indiana Department of Environmental Management have developed a statewide-computerized database containing analyses of pesticides in ground-water samples. This database contains the results of 725 ground-water samples collected during 6 statewide and 15 localized studies between December 1985 and April 1991. Sources of data consist of the U.S. Geological Survey, the Indiana Department of Environmental Management, the Indiana Department of Natural Resources, and the U.S. Environmental Protection Agency. A comprehensive summary of the pesticide database was written by Risch (1994).

The pesticide database includes 47 water sample analyses from 28 different wells in the West Fork White River basin that were sampled in August 1989 through February 1990 as a part of a cooperative effort between the Indiana Department of Environmental Management (IDEM) and the Indiana Department of Natural Resources (IDNR). The 28 wells are a subset of 372 wells sampled for inorganics by the DOW-IGS as part of the West Fork White River basin water resource assessment that were selected by Department of Environmental Management staff for pesticide analysis (figure 26). The inorganic chemical analyses for the 28 samples are included in appendix 1.

The 28 wells were sampled for 53 pesticides and 4 *metabolites*. Fifteen of the wells were developed in bedrock; thirteen in unconsolidated materials. No pesticides or Volatile Organic Compounds (VOCs) were detected in the samples (Indiana Department of Environmental Management, [1990]).

A major focus of a private well-water testing program in Indiana (Wallrabenstein and others, 1994) is to collect information on the presence of *triazine* herbicide and alachlor (Lasso) in rural water supplies. The private testing program, which is sponsored by the Indiana Farm Bureau, Soil and Water Conservation Districts, County Health Departments,

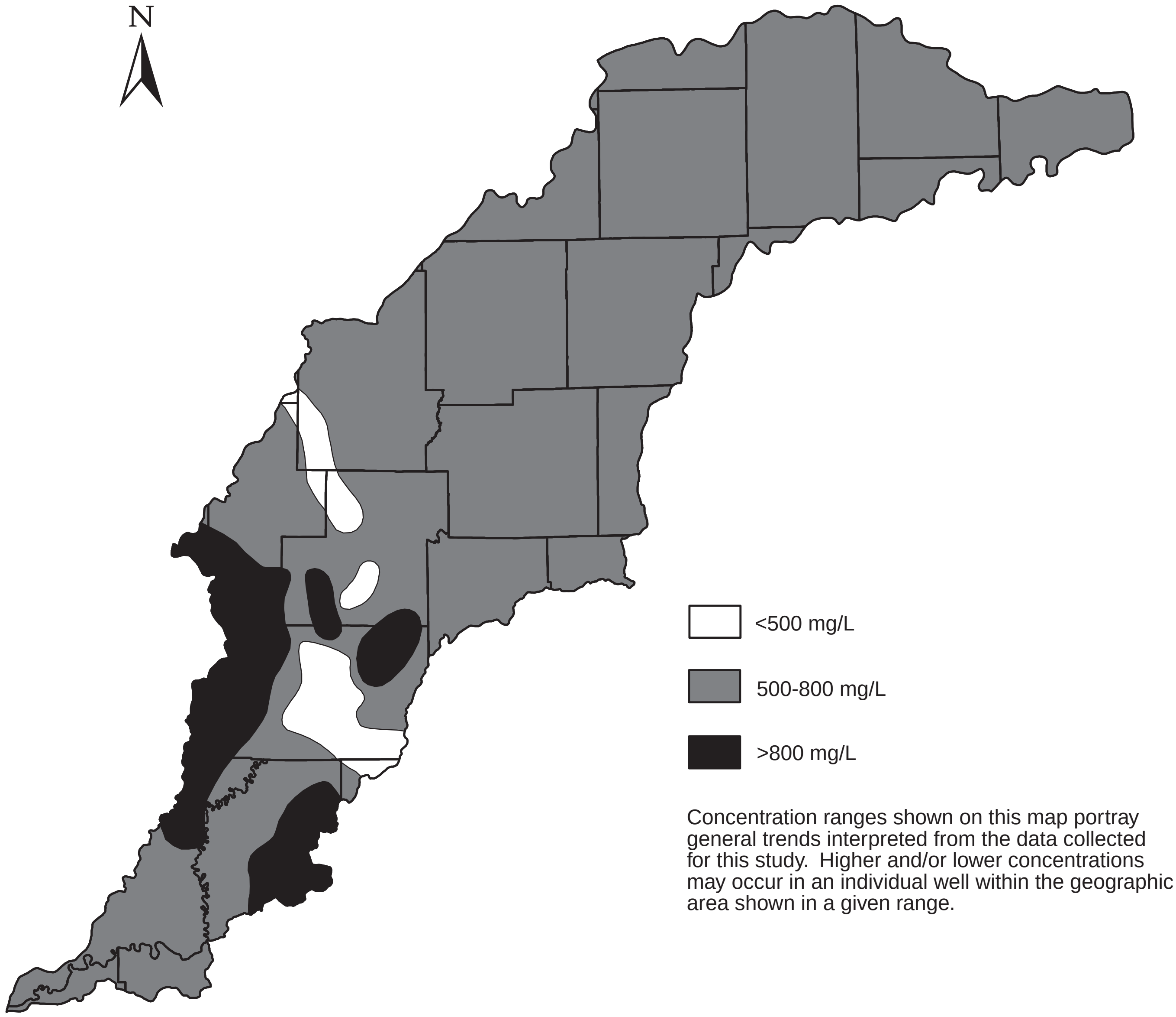


Figure 25b. Generalized areal distribution for Total Dissolved Solids - Bedrock aquifers

Resource Conservation and Development Districts, County Extension Offices, and other local entities, uses *immunoassay* analyses to screen for triazine herbicides and alachlor. Nitrate levels in rural water supplies are also examined, as discussed on the previous pages of this chapter under the heading of **Nitrate**.

The *triazine* immunoassay screen indicates the presence of one or more of the common triazine herbicides including atrazine (AAtrex), cyanazine (Bladex), and simazine (Princep), and some triazine *metabolites*. The alachlor screen indicates the presence of alachlor (Lasso), metolachlor (Dual), metalaxyl (Ridomil) or one of the related *acetanilide* herbicides. The alachlor screen may also react to various alachlor metabolites. The immunoassay procedures, thus do not indicate which specific pesticide(s) is (are) present, but will confirm the absence of triazine- or acetanilide-pesticides at concentrations above the method detection limit (MDL). In the assessment of data collected during the private-well screening program, the researchers used the term "triazine" to refer to triazine herbicides and their metabolites, and used the term "acetanilide" in reference to alachlor, metolachlor and related metabolites (Wallrabenstein and others, 1994).

The results of the triazine and alachlor screening were assessed in terms of two standards; the *detection limit* (DL) and the maximum contaminant level (MCL). The MCLs used for this study were those for atrazine (3.0 µg/L) and alachlor (2.0 µg/L). Samples were categorized into one of the following four groups: 1) no triazine or acetanilide detected; 2) concentrations above DL, but less than one-half MCL; 3) concentrations above one-half MCL up to the MCL; 4) concentrations above the MCL. The detection limits for triazine and acetanilide for this study are reported as 0.05 micrograms per liter (µg/L) or parts per billion (ppb) and 0.2 µg/L, respectively. Because of the ambiguity in the analysis, well owners whose samples contained levels of triazine in the range of 3.0 µg/L or acetanilide in the range of 2.0 µg/L were encouraged

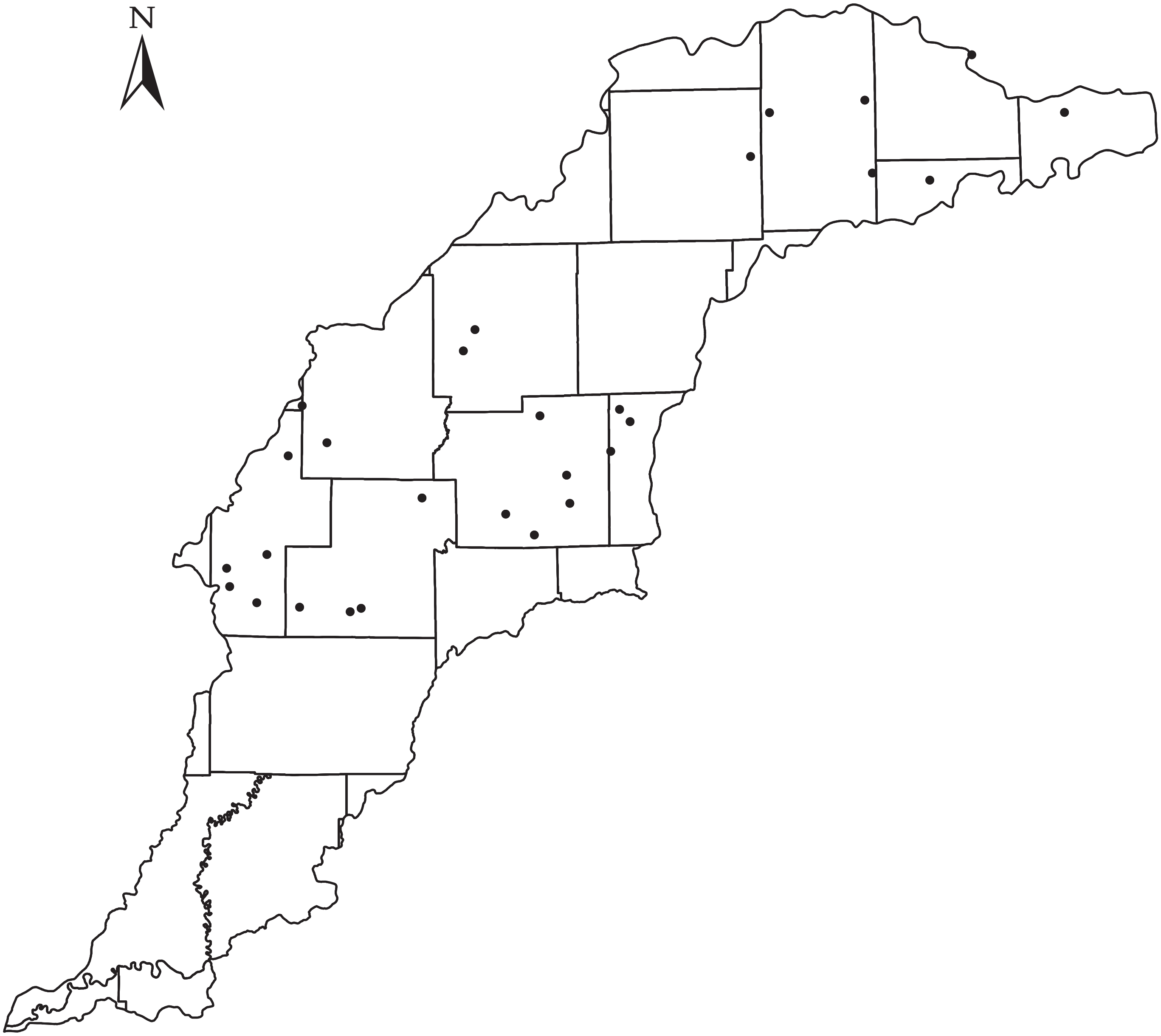


Figure 26. Location of pesticide samples for West Fork White Study (Cooperative effort between Indiana Department of Natural Resources - Division of Water and Indiana Depatment of Environmental Management - Ground Water Section)

to have another sample analyzed with gas chromatographic methods (Wallrabenstein and others, 1994).

All but three of the 29 counties (table 1) that lie partially within the West Fork White River basin participated in the Farm Bureau study: Greene, Pike, and Randolph. However, only the statistics for the counties that have more than 50 percent of their area encompassed within the West Fork White River basin were closely examined for inclusion in this discussion: Clay, Daviess, Delaware, Hamilton, Hendricks, Knox, Madison, Marion, Morgan, Owen, and Putnam. Statistics for counties that have less than 50 percent, but more than 35 percent of their area in the basin (Boone, Johnson, Monroe, and Tipton) were also briefly examined to provide a comprehensive picture of triazine and alachlor values in the basin.

Ninety-six percent of the samples analyzed for the major counties in the basin had concentrations of acetanilide below the detection limit of 0.2 mg/L. However, some samples from all but 3 of the counties (Marion, Monroe, and Tipton) contained acetanilide concentration levels above detection. Nine samples, or approximately 0.3 percent of samples taken, reported concentrations greater than 2.0 mg/L. Hendricks, Clay, and Johnson Counties had the highest number of samples at the higher levels. However, Knox and Clay Counties, both counties having small sample sizes, had the highest percentage of detectable levels of acetanilide.

Ninety-four percent of the samples analyzed had concentrations of Triazine below the detection limit of 0.05 mg/L. However, samples from each county under consideration contained triazine concentration levels above detection limits.

Only two counties, Davies and Putnam, had samples exceeding 3 mg/L.

Throughout the state, over 90 percent of the water samples analyzed for the Indiana Farm Bureau pesticide study contained no detectable amounts of triazine or acetanilide. The MCL for triazine was exceeded in only 0.1 percent of all samples. Approximately 1.6 percent of all samples contained acetanilide levels above 2.0 µg/L, however, the majority of acetanilide detects were believed to be caused by a soil metabolite of alachlor (Wallrabenstein and others, 1994). In general, triazine and acetanilide were most frequently detected in shallow (less than 50 feet deep) wells. Furthermore, samples collected from dug or driven wells (generally shallow) contained a higher percentage of detects than samples collected from drilled wells. The occurrence of detectable concentrations of triazine and acetanilide in ground water suggests that shallow, poorly-constructed (not well-sealed) wells may be especially susceptible to pesticide contamination.

In 1991, the U.S. Geological Survey (USGS) began the National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface and ground water and to provide a sound scientific understanding of the primary natural and human factors affecting the quality of these resources (Hirsch and others, 1988). The White River basin in Indiana was one of the basins chosen for study. The study includes both the West Fork and the East Fork White River Water Management basins of Indiana.

Synthesizing data analysis was a major component of the NAWQA program. One of the first topics addressed in the program was pesticides. Carter and others (1995) presented a retrospective analysis of available pesticide data, 1972-92, for the White River Basin (West Fork and East Fork). It included data on the occurrence of pesticides in streams, stream-bottom sediments, fish, and ground waters. Of 101 wells sampled throughout the White River Basin for a variety of pesticides, detectable concentrations of pesticides were found at only 4 wells. Water from three of the four wells was contaminated with atrazine. The metabolite-to-parent compound ratio for atrazine is higher in ground water than in surface water. Based on limited amounts of data, atrazine concentrations in ground water at wells appear to fluctuate seasonally; atrazine concentrations are found to be more elevated later in the year in ground water than in surface waters. This time lag may be because the travel time of atrazine through the unsaturated zone to the aquifers is relatively long, or because the aquifers are storing contaminated water from nearby surface-water sources during the spring flush of herbicides. All of the wells where detectable amounts of atrazine were found are in outwash aquifers, indicating that this aquifer type may be particularly susceptible to water-soluble pesticide contamination.

Overall, shallow ground water in regions of high hydraulic conductivity have higher water-soluble pesticide concentrations in shallow ground water than ground water in regions of low hydraulic conductivity. The physical properties of overlying material seem to be the main factors determining the concentrations of pesticides in shallow aquifers and ground-water wells, although a variety of other factors, such as land use and farming practices, also can affect observed concentrations.

From June 1994 through August 1995, additional data were collected in the White River basin for the NAWQA program to determine the occurrence of pesticides in the shallow ground water of the basin (Fenelon and Moore, 1996a).

Findings of the study:

- Most of the pesticides that were analyzed for, including all 11 insecticides, were not detected above the reporting limit in any well.
- Seven herbicides and one atrazine metabolite (desethyl atraziane, a breakdown product of atrazine) were detected at least once. Of these eight compounds, only four-atrazine, desethyl atrazine, metolachlor, and metribuzin-were detected more than twice. The highest measured concentration of any compound detected was 0.19 mg/L(micrograms per liter) of alachlor, whereas the most frequently detected compound was desethyl atrazine (14 of 94 samples).
- No pesticide [sampled for] was present in a concentration that exceeded a U.S. Environmental Protection Agency (USEPA) national drinking-water standard or guideline.
- The occurrence of pesticides in shallow ground water in the White River Basin contrasts with conditions observed in the White River at a site near the mouth of the river at Hazleton, Indiana (Crawford, 1995). A significantly greater frequency of detections and much higher concentrations of atrazine and metolachlor were observed in the river than in the ground water.
- The greatest percentage of wells (42 percent) where at least one pesticide was detected are on agricultural land overlying fluvial deposits.
- Pesticides in ground water underlying agricultural areas of the till plain and glacial lowland were uncommon.
- The lowest percentage (12 percent) of wells where at least one pesticide was detected are on urban land overlying fluvial deposits.

Other recent ground-water sampling studies

Other primary topics addressed by the National Water-Quality Assessment (NAWQA) Program besides pesticides are: nutrients, volatile organic compounds and aquatic biology. The following is a summary of the findings of the White River study regarding nutrients and volatile organic compounds in ground water.

Martin and others (1996) assessed water-quality in the White River Basin by examining analysis of selected information on nutrients, 1980-92. Ground-water-quality data from 101 wells were used to determine the effect of aquifer type, well depth, well type, and season on nutrient concentrations in ground water. Median concentrations of ammonia were highest (0.25 mg/L) in till aquifers composed of buried sand and gravel lenses, probably because of biochemical reduction of nitrate to ammonia. Concentrations of nitrate in till aquifers were low, probably because till reduced the downward percolation of soil water and because reducing conditions enabled denitrification and biochemical reduction of nitrate to ammonia. Median concentrations of nitrate were highest in karst aquifers, probably because macropore, sinkholes, and other *solution* features provided a direct connection of surface and ground water through preferential flow paths from the clayey mantle to the karst aquifer. Concentrations of ammonia generally were higher in deep wells, whereas concentrations of nitrate generally were higher in shallow wells. High ammonia concentrations at depth may have been caused by nitrate by the downward percolation of nitrogen-containing soil water from the land surface. Refer to the **Nitrate** section of this report for additional details.

Another component of the White River Basin study is to determine the occurrence of volatile organic compounds (VOCs) in the shallow ground water of the basin. VOCs are of national concern because some of the compounds are *toxic* and (or) *carcinogenic*. Fenelon and Moore (1996b) present the findings from VOC data collected from 100 monitoring wells from June 1994 through August 1995. The study includes both the West Fork and the East Fork White River Water Management basins of Indiana.

Findings of the study:

• Twelve of the 58 VOCs that were analyzed for in ground water samples were detected at or above the reporting limit in at least 1 of the 91 shallow wells.

• Chloroform (trichloromethane) was the most commonly detected VOC, whereas the highest measured VOC concentration was 39 mg/L (microgram per liter) of 1,1-dichloroethene.

• No VOC had a measured concentration in ground water that exceeded a national drinking-water standard or guideline for public water supplies.

• Samples from shallow wells in the nine pairs of shallow and deep wells had a greater frequency of detections and higher concentrations of VOCs than samples from the deep wells.

• VOCs were detected in only 4 of the 66 wells in agricultural settings.

• Most of the ground water with detectable VOCs in the White River Basin underlies urban land. Slightly more than half of the shallow wells in urban settings, as compared to six percent of the shallow wells in agricultural settings, had at least one VOC detected above the reporting limit.

• Chloroform was the most frequently detected VOC (40 percent of wells) in ground water underlying urban land. The median detected concentration of chloroform in urban settings was 0.5 mg/L; all of the chloroform detections were in Indianapolis.

• A likely source of the low concentrations of chloroform in ground water underlying urban land in the White River Basin is chlorinated public-supply water.

• Atmospheric deposition is probably a minor source of chloroform in ground water.

Ground-water contamination

A ground-water supply, that under natural conditions would be acceptable for a variety of uses, can be adversely affected by contamination from human activities. Contamination, as defined by the Indiana Department of Environmental Management, occurs when levels of contaminants are in excess of public drinking-water standards, or health protection guidance levels promulgated by the USEPA.

Over the past 100 years industrial and agricultural practices that accompany development have created ample opportunity for ground-water contamination in the West Fork White River basin. Numerous potential sources for ground-water contamination exist in the West Fork White River basin, including sanitary landfills, sewage treatment plants, industrial facilities, agricultural operations, septic and underground storage tanks, and road-salt storage facilities.

Some cases of actual ground-water contamination have been identified in the basin. The Indiana Department of Environmental Management (IDEM), Ground-Water Section, maintains a database of Indiana sites having 'confirmed' ground-water contamination. The 1998 and 2000 Indiana Water Quality Reports produced by the Indiana Department of Environmental Management, Office of Water Management, Planning Branch provide an overview of the ten highest priority sources of ground-water contamination in Indiana and the associated contaminants impacting ground-water quality; a summary of Indiana ground-water protection efforts is also included. In these reports, IDEM summarizes the ground water contamination sites in ground water in the White, West Fork White, and Patoka River basins by hydrogeologic settings developed by Fleming and others, 1995. Nitrates were identified by IDEM as the contaminant most often encountered in ground water.

Susceptibility of aquifers to surface contamination

Because contaminants can be transmitted to the ground-water system by infiltration from the surface, the susceptibility of an aquifer system to contamination from surface sources depends in part on the type of material that forms the surface layer above the aquifer. In general, sandy surficial sediments can easily transmit water from the surface, but provide negligible filtering of contaminants. Clay-rich surficial deposits, such as glacial till, generally have lower vertical *hydraulic conductivity* than sand and gravel deposits, thereby limiting the movement of contaminated water. However, the presence of fractures can locally decrease the effectiveness of a till in protecting ground water. The differences in basic hydrologic properties of sands and clays make it possible to use surficial geology to estimate the potential for ground-water contamination.

The highly complex relationships of the various glacial deposits in the West Fork White River basin preclude site-specific comments about susceptibility of the regional aquifer systems to contamination. However, a few gross generalizations can be made here. Additional detail on susceptibility of hydrogeologic settings in the state are available in Fleming and others, 1995.

The **Tipton Till Plain** aquifer system consists chiefly of intratill lenses of outwash sand and gravel that are highly variable in depth and lateral extent and are confined by variably thick clay or till sequences. It generally is considered to have low susceptibility to surface contamination.

The **Tipton Till Plain Subsystem** aquifer system is composed primarily of glacial tills that contain intratill sand and gravel of limited thickness and extent. It is similar to the Tipton Till Plain aquifer system but is generally considered moderately vulnerable to surface contamination. This system is located in many areas where the bedrock is shallow and till cover overlying the sand and gravel is thin.

The **Dissected Till and Residuum** aquifer system, consisting of thin, eroded residuum and predominantly pre-Wisconsin till overlying bedrock dominates the southern portions of the basin. Because of the low permeability of the surface materials, this system is not very susceptible to contamination from surface sources.

The water-bearing units of the **White River and Tributaries Outwash** aquifer system are unconfined, usually fairly shallow, and are characterized by thick sequences of sand and gravel with little clay. This aquifer system is highly susceptible to contamination due to its lack of clay layers and shallow water levels.

White River and Tributaries Outwash Subsystem aquifer system, adjacent to the White River and Tributaries Outwash Aquifer system, consists of thick zones of sand and gravel that have been covered by a layer of clay or till. In general, this system is highly susceptible to surface contamination. Although the overlying clay or till may provide some protection to the confined portions of the White River and Tributaries Outwash Subsystem Aquifer system, in many places surficial valley train deposits coalesce with the deeper outwash deposits making them more vulnerable. Two small areas of this system in Gibson and Knox Counties have thick layers of clay overlying the sand and gravel making them moderately susceptible to surface contamination.

The **Lacustrine and Backwater Deposits** aquifer system that is made up of discontinuous bodies of deposits extending along areas of outwash close to the West Fork White River Valley. These bodies are marked by thick deposits of soft silt and clay that have low susceptibility to surface contamination

The **Buried Valley** aquifer system has a low susceptibility to surface contamination because outwash sediments within the bedrock valleys are generally overlain by tills. Although lenses of outwash sand and gravel may occur within the tills, the predominance of fine-grained sediments above the bedrock valleys limits the migration of contaminants from surface sources to the deep aquifers.

The susceptibility of bedrock aquifer systems to surface contamination is dependant on the nature of the overlying sediments, because the bedrock throughout the basin is overlain by unconsolidated deposits. Just as recharge for bedrock aquifers cannot exceed that of overlying unconsolidated deposits, susceptibility to surface contamination will not exceed that of overlying deposits. However, because the bedrock aquifer systems have complex fracturing systems, once a contaminant has been introduced into a basin bedrock aquifer system, it will be difficult to track. The outcrop/subcrop area of the **Blue River and Sanders Groups** is well known for significant karst development. Because of the shallow rock, open joints, and *solution* channels the aquifer system is quite susceptible to contaminants introduced at and near land surface. In the outcrop/subcrop area of the **Buffalo Wallow, Stephensport, and West Baden Groups** the rock is predominantly shallow and contains numerous, irregular joints. In limited areas some karst has developed in the limestone beds. These conditions warrant considering the aquifer system as a whole to be somewhat susceptible to contaminants introduced at and near land surface. In areas where the **Silurian and Devonian Carbonates** are overlain directly by unconfined sand and gravel outwash, the bedrock is highly susceptible to surface contamination. In general, the Pennsylvanian bedrock aquifer systems are not very susceptible to contamination from the land surface.

Regional estimates of aquifer susceptibility can differ considerably from local reality. Variations within geologic environments can cause variation in susceptibility to surface contamination. Also, man-made structures such as poorly-constructed water wells, unplugged or improperly-abandoned wells, and open excavations, can provide contaminant pathways which bypass the naturally-protective clays. In contrast, man-made structures can also provide ground-water protection that would not normally be furnished by the natural environment. For example, large containment structures can inhibit infiltration of both surface water and contaminants. Current regulations administered by the Indiana Department of Environmental Management (IDEM) contain provisions for containment structures, thereby permitting many operations to occur that would otherwise provide an increased contamination risk to soils and the ground water. Other regulations administered by the IDNR regulate the proper construction of new wells and sealing (plugging) of abandoned wells, whether related to petroleum or water production.

Protection and management of ground-water resources

Major ground-water management and protection activities in Indiana are administered by the Indiana Department of Environmental Management (IDEM), Indiana Department of Natural Resources (IDNR), and the Indiana State Department of Health (ISDH). An expanded cooperative effort in the form of the Inter-Agency Ground-Water Task Force involves representatives of these three agencies as well as the State Chemist, State Fire Marshal, and members of local government, labor, and the business, environmental and agricultural communities. The Task Force was first formed in 1986 to develop a state ground-water quality protection and management strategy and is mandated by the 1989 Ground Water Protection Act (IC 13-7-26) to coordinate the implementation of this strategy. The strategy is an agenda of state action to prevent, detect, and correct contamination and depletion of ground water in Indiana (Indiana Department of Environmental Management, 1986). The 1989 act also requires the IDEM to maintain a registry of contamination sites, operate a clearinghouse for complaints and reports of ground-water pollution, and investigate incidents of contamination that affect private supply wells.

The 1998 and 2000 Indiana Water Quality Reports produced by the Indiana Department of Environmental Management, Office of Water Management, Planning Branch provide a summary of Indiana ground-water protection efforts.

GLOSSARY

ablation-the melting of a glacier and associated depositional processes. An ablation complex is a heterogeneous assemblage of till-like sediment, sand and gravel, and lake deposits formed during the disintegration of a glacier

accretionary-in this usage, describes the gradual addition of new land to old by the deposition of sediment carried by stream flow

acetanilide-a white, crystalline organic powder (CH3CONHC6H5) used chiefly in organic synthesis and in medicine for the treatment of headache, fever and rheumatism

alluvial-pertaining to or composed of alluvium

alluvium-fine- to coarse-grained sediment deposited in or adjacent to modern streams and derived from erosion of surface sediments elsewhere in the watershed or from valley walls

anhydrite-a mineral consisting of anhydrous calcium sulfate: CaSO4; it represents gypsum without its water of crystallization, and it alters readily to gypsum. It usually occurs in white or slightly colored, granular to compact masses

anion-an atom or molecule that has gained one or more electrons and possess a negative electrical charge

anthropogenic-relating to the impact or influence of humans or human activities on nature

aquifer-a saturated geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients

aquifer system-a heterogeneous body of permeable and poorly permeable materials that functions regionally as a water-yielding unit; it consists of two or more aquifers separated at least locally by confining units that impede ground-water movement, but do not affect the overall hydraulic continuity of the system

aquitard-a confining layer that retards but does not prevent the flow of water to or from an adjacent aquifer

arenaceous-said of a sediment or sedimentary rock consisting wholly or in part of sand-size fragments, or having a sandy texture or the appearance of sand

argillaceous-pertaining to, largely composed of, or containing clay-sized particles or clay minerals

artesian-see confined

backwater-water held or forced back, as by a dam, flood, tide, etc.

basal tills-refers to tills originating from the zone of the glacier near the bed

base flow-the portion of stream flow derived largely or entirely from ground-water discharge

basement rocks-the crust of the Earth below sedimentary deposits

bioclastic vuggy dolomite-a calcium magnesium carbonate rock which consists primarily of fragments or broken remains of organisms (such as shells) and which contains small cavities usually lined with crystals of a different mineral composition from the enclosing rock

calcareous-describes a rock or sediment that contains calcium carbonate

carbonate-in this usage, a rock consisting chiefly of carbonate minerals which were formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g. limestone and dolomite

carcinogenic-capable of producing a cancer

cation-an atom or molecule that has lost one or more electrons and possesses a positive charge

clastic-pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin; also said of the texture of such a rock

colluvial-pertaining to colluvium

colluvium-loose rock debris at the foot of a slope or cliff deposited by rock falls, landslides and slumpage

cone of depression-a depression in the ground water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of influence of a well

confined-describes an aquifer which lies between impermeable formations; confined ground-water is generally under pressure greater than atmospheric; also referred to as artesian

contact-a plane or irregular surface between two types or ages of rock

contaminant (drinking water)-as defined by the U.S. Environmental Protection Agency, any physical, chemical, biological, or radiological substance in water, including constituents which may not be harmful

contemporaneous-formed or existing at the same time

cuesta-a hill or ridge with a gentle slope on one side and a steep slope on the other

cyclothem-a cycle applied to sedimentary rocks to describe a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian Period. Cyclothems are typically associated with unstable shelf or interior basin conditions in which alternate marine transgressions and regressions occur; nonmarine sediments usually occur in the lower half of a cyclothem, marine sediments in the upper half

debris-flow-body of sediment that has moved downslope under the influence of gravity; may be derived from a wide variety of pre-existing sediments that are generally saturated and may be deposited on or against unstable substrates, such as glacial ice; flowage occurs when the sediments lose their cohesive strength and liquify. Mud flows are a variety of debris flow composed primarily of fine-grained sediment such as silt and clay. Historically, debris flows formed by flowage of soft till have been referred to as flow till. Because ancient mudflows frequently resemble glacial till they are sometimes referred to as till-like sediment

detection limit-is the amount of constituent that produces a signal sufficiently large that 99 percent of the trials with the amount will produce a detectable signal 5X the instrumental detection limit

differential erosion-erosion that occurs at irregular or varying rates, caused by the differences in the resistance and hardness of surface materials: softer and weaker rocks are rapidly worn away; whereas harder and more resistant rocks remain to form ridges, hills, or mountains

disconformity-term used to refer to rock formations that exhibit parallel bedding but have between them a time break in deposition

discharge-see discharge area

discharge area-region where ground water is moving toward, and generally appearing at the land surface or in a surface water body

divalent-having a valence of two, the capacity to unite chemically with two atoms of hydrogen or its equivalent

dolomitic-dolomite-bearing, or containing dolomite; esp. said of a rock that contains 5 to 50 percent of the mineral dolomite in the form of cement and/or grains or crystals; containing magnesium

down-dip-a direction that is downwards and parallel to the dip (angle from the horizontal) of a structure or surface

drainage basin-the land area drained by a river and its tributaries; also called watershed or drainage area

drawdown (ground water)-the difference between the water level in a well before and during pumping

end moraine-see moraine, end

epicontinental-situated on the continental shelf or on the continental interior

escarpment-a long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the continuity of the land by separating two level or gently sloping surfaces, and produced by erosion or by faulting

esker-narrow, elongate ridge of ice-contact stratified drift believed to form in channels under a glacier

evapotranspiration-a collective term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration

evaporite-see evaporitic deposits

evaporitic deposits-of or pertaining to sedimentary salts precipitated from aqueous solutions and concentrated by evaporation

exposure-in this usage, (geology) an area of a rock formation or geologic structure that is visible, either naturally or artificially, i.e. is unobscured by soil, vegetation, water, or the works of man; also, the condition of being exposed to view at the earth's surface

facies-features, such as bedding characteristics or fossil content, which characterize a sediment as having been deposited in a unique environment

fan-body of outwash having a fan shape and an overall semi-conical profile; generally deposited where a constricted meltwater channel emerges from an ice margin into a large valley or open plain. The fan head represents the highest and most ice-proximal part of the fan and commonly emanates from an end moraine or similar ice marginal feature. Ice-contact fans were deposited up against or atop ice and are commonly collapsed and pitted. Meltwater along the toe of the fan commonly occupies fan-marginal channels

fault-(structural geology) a fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture

flow till-see debris flow

flowing well-a well completed in a confined aquifer in which the hydrostatic pressure is greater than atmospheric pressure, and the water rises naturally to an elevation above land surface

fluvial-of or pertaining to rivers

fossiliferous-containing fossils, which are preserved plant or animal imprints or remains

gamma-ray logs-the radioactivity log curve of the intensity of natural gamma radiation emitted from rocks in a cased or uncased borehole. It is used for correlation, and for distinguishing shales and till (which are usually richer in naturally radioactive elements) from sand, gravel, sandstone, carbonates, and evaporites

geode-a hollow or partly hollow and globular or subspherical body, from 2.5 cm to 30 cm or more in diameter, found in certain limestone beds and rarely in shales

glacial lobe-segment of a continental ice sheet having a distinctive flow path and lobate shape that formed in response to the development of regional-scale basins (e.g., Lake Erie) on the surface that the ice flowed across. The shapes and flow paths of most of the individual glacial lobes in this part of the upper Midwest were largely related to the forms of the Great Lake basins. Each lobe was tens of thousands of square miles in size and had flow patterns and histories that were distinct from one another

glacial terrain-geographic region or landscape characterized by a genetic relationship between landforms and the underlying sequences of sediments

glaciolacustrine-pertaining to, produced by, or formed in a lake or lakes associated with glaciers

ground-water discharge-in this usage, the part of total runoff which has passed into the ground and has subsequently been discharged into a stream channel

gypsum-a widely distributed mineral consisting of hydrous calcium sulfate

health advisories (HAs)-provide the level of a contaminant in drinking water at which adverse non-carcinogenic health effect would not be anticipated with a margin of safety

hummocky-describes glacial deposits arranged in mounds with intervening depressions

hydraulic conductivity-a parameter that describes the conductive properties of a porous medium; often expressed in gallons per day per square foot; more specifically, rate of flow in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature

hydraulic gradient-the rate of change in total head per unit of distance of flow in a given direction

hydrostatic pressure-the pressure exerted by the water at any given point in a body of water at rest. The hydrostatic pressure of ground water is generally due to the weight of water at higher levels in the zone of saturation

ice-contact fans-see fan

ice-contact stratified drift-glacial sediment composed primarily of sand and gravel that was deposited on, against, or within glacier ice. These deposits typically have highly irregular surface form due to the collapse of the adjacent ice

igneous-describes rocks that solidified from molten or partly molten material

immunoassay-is a quantitative or qualitative method of analysis for a substance which relies on an antibody or mixture of antibodies as the analytical reagent. Antibodies are produced in animals in response to a foreign substance called an antigen. The highly sensitive and specific reaction between antigens and antibodies is the basis for immunoassay technology

incised-describes the result of the process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley

infiltration-the process (rate) by which water enters the soil surface and which is controlled by surface conditions

ion exchange-the process of reciprocal transfer of ions

kame-irregular ridge or roughly conical mound of sand and gravel with a hummocky surface; usually formed in contact with disintegrating ice

karst-topography characterized by closed depressions or sinkholes, caves, and underground drainage formed by dissolution of limestone, dolomite, or gypsum

lacustrine-pertaining to, produced by, or formed in a lake or lakes

lacustrine sediment-sediment deposited in lakes; usually composed of fine sand, silt, and clay in various combinations

lithologic-describes the physical character of a rock; includes features such as composition, grain size, color, and type of bedding

lithology-the description of rocks, esp. in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition, and grain size

loam-describes a soil composed of a mixture of clay, silt, sand, and organic matter

mass movement-a unit movement of a portion of the land surface; gravitative transfer of material down a slope

maximum contaminant level-the maximum permissible level of a contaminant in water which is delivered to the free-flowing outlet of the user of a public water system

median-middle value of a set of observations arranged in order of magnitude

meltwater-water resulting from the melting of snow or glacial ice

metabolite-a product of metabolic action

methemoglobinemia-a disease, primarily in infants, caused by the conversion of nitrate to nitrite in the intestines, and which limits the blood's ability to transport oxygen

monovalent-having a valence of one, the capacity to unite chemically with one atom of hydrogen or its equivalent

moraine-unsorted, unstratified glacial drift deposited chiefly by the direct action of glacial ice

moraine, end-a ridgelike accumulation of drift built along any part of the outer margin of an active glacier; often arcuate in shape, end moraines mark places along which the terminus of a glacier remained for relatively long periods. Terminal moraines mark the ultimate extent of a particular glacier, whereas recessional moraines are deposited where the ice-margin stabilized for a period of time during the retreat of the glacier

moraine, ground-material (primarily till) deposited from a glacier on the ground surface over which the glacier moved, and generally forming a region of low relief

muck-a highly organic dark or black soil less than 50 percent combustible

mud flow-see debris flow

outwash-sediment deposited by meltwater out in front of an ice margin; usually composed of sand and/or gravel. An outwash plain is a broad tract of low relief covered by outwash deposits, whereas an outwash terrace is a relatively small flat or gently sloping tract that lies above the valley of a modern stream

outwash plain-see outwash

outwash terrace-see outwash

overconsolidated-refers to the consistency of unconsolidated sediment that is much harder than would be expected from its present depth of burial; fine-grained glacial sediments such as till are commonly overconsolidated due to such processes as burial by ice or younger sediments, frequent wetting and drying, and freezing and thawing

paraconformably-this type of unconformity is a kind of disconformity in which no erosion surface is discernible or in which the contact is a simple bedding plane, and in which the beds above and below the break are parallel

paired wells-in this usage, refers to multiple closely spaced observations wells each set at a different depth for the purpose of determining the hydrostatic pressure on different aquifers at the same location

percolate (geology)-to seep downward from an unsaturated zone to a saturated zone

periglacial-said of the processes, conditions, areas, climates, and topographic features at the immediate margins of former and existing glaciers and ice sheets, and influenced by the cold temperature of the ice

permeability-the capacity of a porous medium to transmit a fluid; highly dependent upon the size and shape of the pores and their interconnections

physiographic region-an area of characteristic soils, landforms, and drainage that have been developed on geologically similar materials

physiography-in this usage, a description of the physical nature (form, substance, arrangement, changes) of objects, esp. of natural features

pinnacle reefs-a term used in the Michigan Basin to apply to an isolated stromatoporoid-algal reef mound, now dolomitized, in the Middle Silurian rocks of the subsurface

piezometric surface-an imaginary surface representing the level to which water from a given aquifer will rise under the hydrostatic pressure of the aquifer

Pleistocene-geologic epoch corresponding to the most recent ice age; beginning about 2 million years ago and ending approximately 10,000 years ago

porosity-the amount of pore space; specifically, the ratio of the total volume of voids to the total volume of a porous medium

postdepositional-occurring after materials had been deposited

potable-water which is palatable and safe to drink: ie., fit for human consumption

potentiometric surface-an imaginary surface representing the total head of ground water in a confined aquifer that is defined by the level to which water will rise in a well

pre Wisconsin-general term that refers to the part of the Ice Age prior to about 75,000 years ago, during which many other glacial episodes at least as extensive as those of the Wisconsin Age took place

prodeltaic-the part of a delta that is below the effective depth of wave erosion, lying beyond the delta front, and sloping gently down to the floor of the basin into which the delta is advancing and where clastic river sediment ceases to be a significant part of the basin-floor deposits

proglacial-occurring or being deposited directly in front of a glacier

provenance-a place of origin; specifically the area from which the constituent materials of a sedimentary rock or facies are derived; also, the rocks of which this area is composed

pumping test-a test conducted by pumping a well at a constant rate for a period of time, and monitoring the change in hydraulic head in the aquifer

recharge (ground water)-the process by which water is absorbed and added to the zone of saturation

reducing-describes the process of removing oxygen from a compound

reef-a ridgelike or moundlike structure, layered or massive, built by sedentary calcareous organisms, esp. corals, and consisting mostly of their remains

regression-(stratigraphy) the retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal

relict-said of a topographic feature that remains after other parts of the feature have been removed or have disappeared

residuum-(weathering) residue

runoff, (total)-the part of precipitation that appears in surface-water bodies; it is the same as stream flow unaffected by artificial manipulation

saline-describes water that contains a high concentration of dissolved solids, typically greater than 10,000 milligrams per liter

sandstone-a medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material

secondary maximum contaminant level-recommended, nonenforceable standards established to protect aesthetic properties of drinking water, such as taste and odor

sedimentary rock-formed by the deposition of sediment

seismic-pertaining to an earthquake or earth vibration, including those that are artificially induced

shale-a fine-grained detrital sedimentary rock, formed by the consolidation (esp. by compression) of clay, silt, or mud

skewed-describes the state of asymmetry of a statistical frequency distribution, which results from a lack of coincidence of the mode, median, and arithmetic mean of the distribution

slack water-a quiet part of, or a still body of water

sluiceway-valley or channel that conducted large amounts of glacial meltwater through and/or away from a glacier; may or may not be occupied by a modern stream; commonly associated with one or more former ice margins

solution-(geology) a process of chemical weathering by which mineral and rock materials passes into solution; e.g. removal of the calcium carbonate in limestone by carbonic acid derived from rain-water containing carbon dioxide acquired during its passage through the atmosphere

source area-general geographic region that furnished the sediment supply for a particular deposit. Sediments deposited by different rivers or glaciers can often be distinguished because their respective source areas differ in terms of the composition of bedrock and other sediments they contain; see provenance

static water level-the level of water in a well that is not being affected by withdrawal of ground water

stratigraphy-the geologic study of the formation, composition, sequence and correlation of unconsolidated or rock layers

storage coefficient-the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head

subcrop-a "subsurface outcrop" that describes the areal limits of a truncated rock unit at the buried surface of an unconformity

subjacent-being lower, but not necessarily lying directly below

swale-a slight depression, sometimes swampy, in the midst of generally level land

tectonic-said of or pertaining to the forces involved in, or the resulting structures or features of, tectonics or earth movements

terminal moraine-see moraine, end

till-unsorted sediment deposited directly from glacier ice with little or no reworking by meltwater or mass movement; usually contains particles ranging in size from clay to boulders

till-like sediment-see till and debris flow

till plain-an extensive area with a flat to undulating surface, underlain by till and commonly covered by ground moraines and subordinate end moraines

topography-the relief and contour of a surface, especially land surface

toxic-describes materials which are or may become harmful to plants or animals when present in sufficient concentrations

transgression-the spread or extension of the sea over the land areas

transmissivity-the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient

triazine-any of a group of chemicals containing three nitrogen and three carbon atoms arranged in a six member ring and having the formula C3H3N3; also any of various derivative of these compounds including several used as herbicides

tunnel valley-wide, linear channel oriented perpendicular to an ice margin and eroded into the substrate below the ice sheet. A tunnel valley typically represents a major route for meltwater draining part of an ice sheet, and exiting the front of that ice sheet

unconfined-describes an aquifer whose upper surface is the water table which is free to fluctuate under atmospheric pressure

unconformably-not succeeding the underlying rocks in immediate order of age or not fitting together with them as parts of a continuous whole

unconformity-a substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession

valley train-large, elongated body of outwash localized within the confines of a topographic valley

water table-the upper surface of the zone of saturation below which all voids in rock and soil are saturated with water

watershed-see drainage basin

Wisconsin Age-the most recent period of major glacial activity during the ongoing ice age, perhaps beginning as long as 75,000 years ago and continuing until about 10,000 years ago

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Appendix 1. Results of chemical analysis

{All values in milligrams per liter except as noted}

{Well locations displayed in Plate 9}

Aquifer systems: Unconsolidated--BV - Buried Valley Aquifer System; DTR - Dissected Till and Residuum Aquifer System; LB - Lacustrine and Backwater Deposits Aquifer System; TTP - Tipton Till Plain Aquifer System;
TTPS - Tipton Till Plain Aquifer Subsystem; WR - White River and Tributaries Outwash Aquifer System; WRS - White River and Tributaries Outwash Aquifer Subsystem
Bedrock--DM - Devonian and Mississippian—New Albany Shale Aquifer System; M-B - Mississippian—Borden Group Aquifer System; M-BRS - Mississippian—Blue River and Sanders Groups Aquifer System;
M-BSW - Mississippian—Buffalo Wallow, Stephensport, and West Baden Groups Aquifer System; P-RC - Pennsylvanian—Raccoon Creek Group Aquifer System; P-C - Pennsylvanian—Carbondale Group Aquifer System;
P-M - Pennsylvanian—McLeansboro Group Aquifer System

Date sampled: month/year

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
BOONE COUNTY																					
51	85857	20N	2E	13	132	TTP	7/89	*7.81*	205	49.5	19.8	41.4	0.7	2.2	<0.1	293.0	2	<1	1.9	<0.7	483
52	85805	18N	2E	14	170	TTP	7/89	*7.80*	232	53.2	24.2	44.7	0.9	2.1	<0.1	338.5	5	<1	0.8	<0.7	550
53	85790	19N	2E	20	132	TTP	7/89	*7.63*	227	53.6	22.6	40.6	0.9	1.5	<0.1	333.0	2	<1	2.3	<0.7	542
54	85795	19N	2E	2	167	TTP	7/89	*7.52*	231	58.9	20.4	38.2	0.9	2.2	<0.1	335.3	2	<1	1.2	<0.7	544
55	85788	18N	2E	32	200	M-B	7/89	*7.88*	126	26.9	14.3	84.6	2.6	0.2	<0.1	311.8	5	4	0.9	<0.7	526
56	86310	18N	1E	22	148	TTP	7/89	*7.14*	374	88.8	37.1	69.3	1.8	8.4	<0.1	498.3	34	<1	0.9	<0.7	862
57	85810	18N	1E	33	110	M-B	7/89	*7.77*	266	60.7	27.9	26.7	1.1	0.4	0.4	331.3	3	6	1.6	<0.7	542
67	85800	18N	1W	16	54	TTP	8/89	*7.58*	384	104.7	29.9	4.9	0.4	3.9	0.2	277.9	12	78	0.3	<0.7	583
BROWN COUNTY																					
133	85859	10N	3E	28	54	M-B	8/89	*7.43*	315	83.1	26.3	40.1	0.9	<0.2	0.1	354.1	10	22	0.2	<0.7	623
134	86822	10N	3E	16	75	M-B	8/89	*7.67*	103	24.8	9.9	100.1	1.9	<0.2	<0.1	271.1	22	16	1.1	<0.7	512
CLAY COUNTY																					
131	85794	12N	5W	27	100	P-RC	8/89	*7.76*	234	65.2	17.4	14.1	1.2	0.5	0.8	235.7	2	6	0.3	<0.7	403
143	86295	13N	6W	35	60	DTR	8/89	*7.36*	241	58.1	23.3	9.8	0.4	<0.2	<0.1	185.2	19	6	0.2	9.51	395
144	198671	13N	6W	9	160	P-RC	8/89	*7.83*	57	14.4	5.1	150.9	3.1	<0.2	<0.1	380.7	2	3	0.5	<0.7	653
166	85869	9N	6W	7	100	P-RC	8/89	*6.21*	113	26.5	11.5	5.8	0.2	1.0	0.2	105.3	2	11	0.1	<0.7	201
169	3882	9N	7W	16	200	P-C	8/89	*6.36*	964	178.7	126.2	36.8	1.1	1.7	1.6	232.3	12	717	0.3	<0.7	1374
170	86807	10N	7W	33	75	P-RC	8/89	*6.60*	312	85.6	23.9	38.3	1.2	7.3	1.1	248.8	50	74	0.2	<0.7	597
171	85823	10N	7W	21	34	WR	8/89	*6.51*	318	78.8	29.6	9.1	0.3	<0.2	0.8	248.8	14	32	0.3	4.88	499
172	85868	11N	7W	35	108	P-RC	8/89	*7.86*	84	20.0	8.3	115.1	1.6	0.2	<0.1	321.2	2	<1	1.0	<0.7	546
173	85818	10N	6W	21	100	P-RC	8/89	*6.37*	320	76.2	31.7	45.6	0.8	4.3	1.4	182.8	8	207	0.1	<0.7	612
174	85813	10N	6W	8	55	WR	8/89	*6.86*	267	83.9	13.9	8.5	0.4	4.7	<0.1	229.8	10	25	0.2	<0.7	437
175	212172	11N	7W	26	69	WR	8/89	*7.31*	270	69.2	23.7	36.7	0.6	2.7	<0.1	326.3	5	<1	0.5	<0.7	544
176	85863	11N	7W	11	280	P-RC	8/89	*8.18*	13	3.2	1.3	187.8	1.1	<0.2	<0.1	403.7	3	<1	0.9	<0.7	695
189	86747	12N	6W	16	120	P-RC	9/89	*7.00*	188	48.4	16.4	54.6	1.2	<0.2	<0.1	314.3	2	<1	0.6	<0.7	513
238	82119	11N	6W	26	46	WR	6/90	*6.93*	258	76.5	16.2	11.6	<1	6.9	0.1	218.7	10	36	<1	<0.7	434
239	82118	11N	6W	16	106	P-RC	6/90	*6.81*	436	93.2	49.4	106.5	4.1	2.1	0.3	317.2	3	335	<1	<0.7	987

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$ [2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
CLAY COUNTY continued																					
240	82124	12N	6W	7	260	P-RC	6/90	*7.80*	55	13.9	4.9	176.5	1.9	<0.2	<0.1	379.5	50	3	1.2	<0.7	717
241	82125	9N	7W	18	140	P-RC	6/90	*8.88*	15	3.4	1.6	168.1	1.5	<0.2	<0.1	416.9	1	<1	2.2	<0.7	671
242	82126	12N	5W	34	176	P-RC	6/90	*7.97*	35	8.8	3.1	111.0	1.8	<0.2	<0.1	263.4	4	5	<1	<0.7	458
244	82117	11N	7W	34	172	P-RC	6/90	*7.48*	146	32.2	16.0	82.5	1.3	0.3	<0.1	305.1	8	4	<1	<0.7	522
245	82103	10N	7W	4	255	P-RC	6/90	*8.58*	15	2.8	2.0	435.6	1.8	1.1	<0.1	544.3	266	28	4.2	<0.7	1400
246	82104	10N	6W	20	120	P-RC	6/90	*6.70*	96	22.6	9.6	44.0	<1	<0.2	<0.1	88.8	19	36	<1	7.68	286
247	82105	10N	6W	27	225	P-RC	6/90	*8.97*	2	<2	<1	392.0	1.2	<0.2	<0.1	797.2	52	<1	4.7	<0.7	1380
248	82106	10N	6W	32	80	P-RC	6/90	*6.72*	317	73.1	32.8	42.1	1.5	0.8	0.3	362.6	13	19	<1	<0.7	632
249	82107	10N	6W	31	320	P-RC	6/90	*9.22*	1	<2	<1	484.1	1.2	0.2	<0.1	735.5	250	5	3.8	<0.7	1580
253	82099	9N	6W	20	185	P-RC	6/90	*8.22*	14	3.8	1.1	186.3	0.8	<0.2	<0.1	408.6	8	<1	1.0	<0.7	699
351	82116	11N	7W	19	180	P-C	7/90	*5.55*	147	29.6	17.7	83.3	1.5	<0.2	<0.1	328.6	7	1	<1	<0.7	551
DAVIESS COUNTY																					
302	82071	3N	7W	16	205	P-C	7/90	*7.15*	97	24.8	8.4	97.9	1.9	0.2	<0.1	299.6	16	<1	<1	<0.7	521
303	82063	2N	7W	19	125	P-C	7/90	*6.27*	365	89.2	34.5	19.0	0.9	0.4	<0.1	403.6	<1	3	<1	<0.7	660
304	82065	2N	6W	7	235	P-C	7/90	*8.87*	6	<2	0.7	264.8	1.0	<0.2	<0.1	566.8	14	<1	2.5	<0.7	954
305	82064	2N	6W	2	225	P-RC	7/90	*6.97*	64	12.7	7.9	142.9	2.9	0.8	<0.1	369.5	3	<1	1.6	<0.7	628
306	82088	5N	5W	31	265	P-RC	7/90	*8.84*	3	<2	<1	290.1	1.0	<0.2	<0.1	645.8	4	<1	3.6	<0.7	1060
307	82089	5N	5W	22	285	P-RC	7/90	*8.89*	12	2.8	1.2	327.7	1.4	<0.2	<0.1	694.9	44	<1	3.2	<0.7	1200
310	82090	5N	5W	36	340	P-RC	7/90	*8.14*	3	<2	0.5	329.9	1.0	<0.2	<0.1	720.1	4	6	5.2	<0.7	1220
311	82084	4N	5W	22	185	P-RC	7/90	*7.97*	2	<2	<1	159.3	0.6	<0.2	<0.1	283.8	2	67	<1	<0.7	579
312	82087	5N	6W	22	125	WR	7/90	*6.86*	339	89.4	28.1	6.3	<1	<0.2	<0.1	223.5	17	23	<1	14.68	514
313	82086	5N	6W	32	260	P-RC	7/90	*7.04*	211	57.0	16.8	33.7	0.5	1.8	<0.1	266.8	7	<1	<1	<0.7	450
314	82079	4N	7W	26	275	P-C	7/90	*7.58*	110	30.6	8.1	172.0	1.8	<0.2	<0.1	486.4	2	4	1.0	<0.7	822
315	82075	3N	5W	21	265	P-RC	7/90	*8.01*	18	3.9	2.0	177.1	1.3	<0.2	<0.1	388.7	4	<1	2.7	<0.7	667
316	82072	3N	6W	2	315	P-RC	7/90	*8.33*	23	3.6	3.4	827.1	3.0	3.2	<0.1	863.2	760	5	3.4	<0.7	2660
317	82073	3N	6W	1	65	LB	7/90	*6.41*	255	72.1	18.2	24.9	<1	2.5	<0.1	285.5	2	6	<1	<0.7	484
318	82074	3N	6W	7	180	P-RC	7/90	*7.95*	24	3.8	3.6	1040.0	3.7	3.4	<0.1	993.7	992	<1	2.2	<0.7	3260
319	82080	4N	7W	35	260	P-C	7/90	*7.01*	79	18.7	7.9	161.5	1.8	<0.2	<0.1	412.6	26	3	1.3	<0.7	729
320	82081	4N	7W	36	145	P-C	7/90	*6.66*	164	45.6	12.3	78.5	1.2	<0.2	<0.1	308.3	2	8	<1	<0.7	536
321	82070	3N	7W	14	225	P-C	7/90	*7.34*	140	33.0	14.0	134.0	2.3	0.7	<0.1	433.9	2	<1	<1	<0.7	726
322	82069	3N	8W	24	114	P-C	7/90	*6.40*	334	96.0	23.0	4.0	<1	3.6	0.3	245.9	12	54	<1	<0.7	502
324	82083	4N	7W	11	175	P-C	7/90	*6.07*	251	68.1	19.6	5.9	<1	<0.2	<0.1	223.4	1	26	<1	<0.7	405
325	82082	4N	7E	14	44	WR	7/90	*7.14*	222	60.9	17.0	4.4	2.1	<0.2	<0.1	127.9	11	44	<1	12.88	361
DELAWARE COUNTY																					
1	3082	21N	10E	31	238	SD	7/89	*7.20*	409	103.0	36.9	10.1	1.0	1.3	<0.1	344.0	4	41	0.4	<0.7	629
2	1302	20N	10E	7	76	TTP	7/89	*7.01*	558	136.0	53.2	10.4	1.1	2.7	<0.1	389.1	22	123	0.2	<0.7	835
3	1551	20N	10E	22	37	TTPS	7/89	*7.10*	508	127.3	46.2	17.0	1.1	2.2	<0.1	358.3	34	97	0.1	<0.7	770
4	18508	19N	11E	1	62	TTP	7/89	*7.17*	446	110.5	41.3	5.3	0.9	0.8	0.1	303.6	29	80	0.1	0.84	648
11	2752	21N	10E	12	121	SD	7/89	*7.17*	369	95.0	32.0	4.3	0.7	1.6	<0.1	343.5	6	22	0.1	<0.7	588

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
DELAWARE COUNTY continued																					
13	22887	21N	11E	32	101	SD	7/89	*7.20*	476	105.7	51.8	14.4	1.1	1.7	<0.1	377.6	10	119	0.3	<0.7	776
14	2577	21N	9E	22	96	SD	7/89	*7.14*	386	97.5	34.7	5.7	0.8	1.4	<0.1	332.0	8	50	0.2	<0.7	612
19	21868	19N	9E	6	45	TTP	7/89	*7.24*	370	93.6	33.1	19.2	0.9	0.9	<0.1	286.9	45	76	0.2	<0.7	627
24	85	20N	9E	6	165	SD	7/89	*7.37*	311	80.0	27.1	8.7	0.6	1.6	<0.1	336.4	3	8	0.3	<0.7	548
27	34565	22N	9E	30	111	TTP	7/89	*7.17*	365	92.2	32.7	8.4	0.7	2.0	<0.1	342.4	5	60	0.4	<0.7	630
33	2888	21N	9E	15	69	TTPS	7/89	*7.29*	391	96.3	36.7	6.9	0.7	2.3	<0.1	345.9	14	63	0.3	<0.7	651
326	82194	20N	9E	3	140	TTP	7/90	*6.84*	323	84.0	27.6	10.8	0.7	0.7	<0.1	347.3	<1	9	<1	<0.7	568
327	82195	20N	10E	7	108	SD	7/90	*6.73*	291	75.1	25.1	7.8	1.3	<0.2	<0.1	193.5	24	57	1.1	5.87	458
335	82189	19N	11E	14	65	TTP	7/90	*6.54*	404	107.5	33.1	3.7	0.7	2.3	<0.1	314.7	14	52	<1	<0.7	605
336	82190	19N	11E	19	181	SD	7/90	*6.65*	14	3.5	1.2	144.3	<1	<0.2	<0.1	339.3	<1	15	<1	<0.7	587
340	82188	19N	9E	20	96	TTP	7/90	*7.16*	377	96.9	32.9	2.3	0.6	2.2	<0.1	273.0	12	91	<1	<0.7	577
342	82193	20N	9E	31	109	TTP	7/90	*6.59*	360	92.7	31.4	5.7	0.7	1.8	<0.1	357.8	11	2	<1	<0.7	591
343	82204	21N	9E	29	38	TTP	7/90	*7.04*	371	98.6	30.4	5.7	0.8	2.6	<0.1	330.6	7	36	<1	<0.7	593
GIBSON COUNTY																					
276	82047	1N	10W	34	115	P-M	7/90	*6.55*	407	92.9	42.6	34.3	0.6	<0.2	<0.1	220.0	102	87	<1	2.48	654
277	82046	1N	10W	24	51	DTR	7/90	*6.89*	342	92.3	27.1	12.4	0.5	0.8	0.6	359.7	2	<1	<1	<0.7	586
GREENE COUNTY																					
120	34698	7N	4W	2	250	M-BSW	8/89	*7.46*	1384	368.6	112.8	25.9	1.2	1.8	<0.1	179.6	23	1106	1.1	<0.7	1879
121	34656	7N	4W	28	100	P-RC	8/89	*7.79*	222	49.2	24.2	7.6	0.4	<0.2	<0.1	190.9	5	27	0.1	1.76	360
122	34668	7N	4W	21	61	M-BSW	8/89	*7.84*	260	55.1	29.9	16.4	0.6	0.3	0.2	247.8	2	19	0.2	<0.7	435
123	34645	7N	5W	24	83	M-BSW	8/89	*7.67*	293	74.2	26.3	18.3	0.6	0.7	0.4	245.3	8	58	0.2	<0.7	495
124	40934	6N	5W	1	184	P-RC	8/89	*7.98*	193	44.7	19.8	41.7	0.9	2.2	<0.1	273.1	3	2	0.5	<0.7	453
125	40650	6N	5W	29	235	P-RC	8/89	*7.22*	23	5.5	2.3	188.5	1.0	<0.2	<0.1	416.3	5	7	0.5	<0.7	593
126	40602	6N	5W	5	165	P-RC	8/89	*7.91*	253	66.1	21.4	22.3	0.5	3.8	0.1	279.5	4	<1	0.4	<0.7	464
127	34673	7N	4W	24	185	M-BSW	8/89	*7.99*	187	40.6	20.7	97.1	0.7	<0.2	<0.1	306.0	5	66	0.4	<0.7	609
161	30636	8N	5W	2	290	P-RC	8/89	*8.30*	40	11.0	3.1	271.0	1.5	<0.2	<0.1	361.8	3	255	1.3	<0.7	993
163	28602	8N	5W	29	165	P-RC	8/89	*7.70*	184	47.2	16.1	10.5	0.6	<0.2	0.1	153.1	5	27	0.2	1.22	305
164	28642	8N	5W	17	60	P-RC	8/89	*6.57*	242	49.8	28.5	17.3	0.6	<0.2	<0.1	199.3	11	35	0.3	2.44	404
167	28761	8N	6W	10	245	P-RC	8/89	*8.85*	17	3.4	2.0	836.3	1.9	<0.2	<0.1	737.9	730	<1	2.9	<0.7	2475
168	28729	8N	7W	13	105	P-RC	8/89	*7.34*	74	17.1	7.7	164.5	1.4	<0.2	<0.1	399.9	8	12	0.7	<0.7	709
192	30630	8N	4W	27	243	P-RC	9/89	*7.61*	210	48.9	21.4	33.5	1.0	<0.2	<0.1	260.3	1	19	0.3	<0.7	451
193	86723	7N	6W	36	155	P-RC	9/89	*7.94*	54	13.6	4.9	88.3	0.9	<0.2	<0.1	201.4	34	2	0.3	<0.7	397
194	40930	6N	6W	2	144	P-RC	9/89	*7.16*	198	54.1	15.3	12.7	0.3	0.6	<0.1	219.8	2	<1	0.2	<0.7	361
195	34808	6N	6W	12	60	WR	9/89	*7.58*	173	48.4	12.6	2.8	0.2	1.1	<0.1	142.3	4	27	0.1	<0.7	278
196	40573	6N	6W	29	130	P-RC	9/89	*7.26*	107	29.5	8.2	87.6	0.8	<0.2	<0.1	298.0	2	3	0.2	<0.7	501
197	34816	11N	7W	16	36	DTR	9/89	*7.32*	324	91.0	23.6	16.3	0.5	<0.2	0.3	234.2	17	86	0.3	5.53	560
198	40940	6N	4W	31	285	P-RC	9/89	*7.42*	68	16.6	6.6	57.7	0.8	<0.2	<0.1	195.0	3	<1	0.4	<0.7	329
199	34655	7N	4W	34	345	P-RC	9/89	*8.92*	3	0.6	0.4	221.1	0.7	<0.2	<0.1	516.2	1	5	2.0	<0.7	836
200	40776	6N	3W	20	280	M-BSW	9/89	*6.86*	210	37.0	28.8	33.0	0.7	<0.2	<0.1	178.2	1	122	1.2	<0.7	453

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
GREENE COUNTY continued																					
202	30625	8N	4W	15	305	P-RC	9/89	*6.98*	453	120.0	37.3	60.7	0.8	0.4	<0.1	167.3	3	432	0.2	<0.7	875
204	85808	10N	2W	19	165	M-BRS	9/89	*6.65*	319	79.6	29.4	4.6	0.3	<0.2	<0.1	301.4	4	16	0.5	0.77	515
254	82098	8N	7W	3	142	P-C	6/90	*8.36*	65	14.5	7.0	200.8	2.0	<0.2	<0.1	513.9	5	<1	1.5	<0.7	854
255	82094	7N	7W	4	285	P-C	6/90	*6.53*	922	246.0	74.9	97.9	2.1	1.6	0.2	432.2	5	688	1.3	<0.7	1660
256	82095	7N	6W	19	205	P-RC	6/90	*8.04*	10	1.9	1.4	326.1	1.6	0.3	<0.1	593.3	91	<1	3.8	<0.7	1150
257	82097	7N	7W	19	38	WRS	6/90	*8.62*	2	<2	<1	324.5	1.6	<0.2	<0.1	757.2	36	<1	2.9	<0.7	1270
258	82096	7N	5W	5	25	WR	6/90	*6.51*	286	80.0	20.9	16.0	4.2	0.5	0.6	153.0	34	108	<1	<0.7	460
301	82093	6N	7W	35	140	P-C	7/90	*6.83*	71	15.2	8.0	183.4	2.4	<0.2	<0.1	460.7	7	13	<1	<0.7	798
HAMILTON COUNTY																					
35	85867	19N	6E	18	90	TTPS	7/89	*7.32*	419	108.0	36.4	11.9	0.7	2.7	<0.1	333.3	28	87	0.4	<0.7	690
39	85862	19N	5E	21	300	SD	7/89	*7.51*	247	49.6	30.0	48.4	2.7	0.8	<0.1	296.0	52	5	0.6	<0.7	555
45	85768	18N	3E	4	172	TTP	7/89	*7.58*	281	74.9	23.0	8.0	0.6	1.1	<0.1	268.3	4	27	0.6	<0.7	476
46	86305	17N	5E	1	110	TTP	7/89	*7.72*	311	81.7	26.0	3.2	0.5	1.1	<0.1	278.7	4	38	0.3	<0.7	502
47	86557	20N	5E	11	96	TTP	7/89	*7.41*	311	74.7	30.2	20.6	0.9	1.3	<0.1	334.0	3	7	1.2	<0.7	562
48	86562	20N	5E	9	91	TTP	7/89	*7.30*	386	100.3	33.0	14.6	0.7	2.3	<0.1	375.0	20	42	0.4	<0.7	682
205	82177	18N	3E	3	163.5	TTP	6/90	*7.40*	243	60.5	22.4	31.8	0.7	0.4	<0.1	301.5	1	11	<1	<0.7	506
206	82185	19N	3E	30	121	TTP	6/90	*7.63*	262	62.5	25.8	38.1	0.6	1.9	0.1	348.9	1	<1	1.4	<0.7	566
207	82178	18N	4E	7	84	TTP	6/90	*7.82*	288	71.1	26.9	18.3	0.7	2.1	<0.1	324.5	2	<1	<1	<0.7	526
208	82170	17N	3E	3	105	TTP	6/90	*7.68*	266	67.4	23.7	27.1	0.7	1.7	<0.1	319.3	3	<1	<1	<0.7	522
209	82169	17N	3E	2	136	SD	6/90	*7.54*	323	77.7	31.4	19.4	0.7	0.5	<0.1	332.3	21	3	<1	<0.7	570
211	82180	18N	4E	34	50	WR	6/90	*7.13*	442	119.2	35.3	61.3	1.6	3.6	<0.1	332.4	135	94	<1	<0.7	862
215	82187	19N	5E	2	65	SD	6/90	*7.52*	396	100.6	35.2	6.9	0.9	0.4	<0.1	357.7	6	38	<1	<0.7	632
216	82186	19N	4E	12	108	TTP	6/90	*8.03*	301	78.9	25.3	4.0	0.5	1.4	<0.1	267.5	3	28	<1	<0.7	475
217	82179	18N	4E	14	69	WR	6/90	*7.41*	405	111.7	30.6	5.8	0.8	1.5	<0.1	303.8	12	83	<1	<0.7	623
218	82181	18N	5E	22	45	TTP	6/90	*7.83*	365	95.3	31.0	8.1	0.6	3.6	<0.1	315.3	9	32	<1	<0.7	574
219	82175	17N	5E	4	70	TTP	6/90	*6.88*	334	88.0	27.8	2.9	0.5	0.5	0.1	283.0	2	48	<1	<0.7	520
220	82173	17N	4E	3	85	WR	6/90	*8.00*	341	86.5	30.5	9.2	0.7	1.4	<0.1	296.0	4	46	<1	<0.7	545
HANCOCK COUNTY																					
101	86746	16N	5E	23	150	TTP	8/89	*7.65*	350	81.5	35.7	28.4	0.9	1.6	<0.1	369.4	2	17	1.0	<0.7	630
350	82176	17N	7E	16	84	TTP	7/90	*6.03*	336	87.7	28.4	5.8	<1	1.3	<0.1	322.1	3	9	<1	<0.7	540
HENDRICKS COUNTY																					
64	86731	17N	2E	17	178	DM	8/89	*7.85*	295	66.6	31.3	33.3	0.7	2.2	<0.1	351.0	2	<1	1.8	<0.7	576
65	85803	17N	1E	27	96	TTP	8/89	*7.78*	311	78.1	28.3	8.0	0.5	2.2	<0.1	276.6	2	30	0.9	<0.7	501
66	86726	17N	1E	29	137	TTP	8/89	*7.78*	273	65.7	26.6	50.2	0.7	0.9	<0.1	368.4	2	<1	0.7	<0.7	606
68	86721	16N	2W	11	50	TTPS	8/89	*7.66*	378	101.4	30.4	3.7	0.4	<0.2	<0.1	281.6	4	62	0.3	<0.7	553
69	85824	16N	2W	16	90	TTPS	8/89	*7.78*	290	72.0	26.9	21.0	0.5	1.2	<0.1	308.4	8	<1	0.6	<0.7	516
70	86290	15N	1E	7	143	TTPS	8/89	*7.62*	349	89.3	30.6	23.9	0.7	1.8	<0.1	377.1	2	<1	0.7	<0.7	621
71	85829	16N	1W	33	115	M-B	8/89	*7.87*	157	33.9	17.6	80.8	2.6	0.2	<0.1	315.3	3	<1	2.9	<0.7	533
72	86265	15N	2W	12	82	M-B	8/89	*7.16*	505	130.0	43.8	29.0	0.9	<0.2	<0.1	362.4	73	66	0.1	<0.7	795

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
HENDRICKS COUNTY continued																					
73	86260	15N	2W	23	66	M-B	8/89	*7.88*	322	84.2	27.1	8.2	0.4	<0.2	<0.1	215.8	19	45	0.2	7.14	486
74	86270	15N	2W	8	78	M-B	8/89	*7.73*	354	93.2	29.5	13.0	0.8	0.5	<0.1	314.1	7	31	0.3	<0.7	569
75	85793	16N	2W	31	106	M-B	8/89	*7.76*	379	97.5	33.0	9.2	0.6	4.8	0.4	329.9	27	8	0.6	<0.7	593
76	86657	15N	1E	33	60	TTPS	8/89	*7.66*	354	87.5	33.0	8.4	0.6	2.4	<0.1	322.5	4	16	0.6	<0.7	557
77	108760	15N	1W	26	38	DTR	8/89	*7.75*	322	87.1	25.5	10.4	1.1	0.6	0.2	232.9	19	58	0.2	<0.7	489
78	86275	14N	1W	3	80	M-B	8/89	*7.39*	367	94.8	31.8	9.1	0.9	<0.2	<0.1	284.3	11	57	0.2	<0.7	560
79	86766	14N	1W	9	107	M-B	8/89	*7.79*	341	86.2	30.7	27.6	0.8	1.4	<0.1	371.9	7	<1	0.8	<0.7	619
80	86776	14N	2W	10	51	LB	8/89	*7.81*	1	0.2	0.1	181.8	0.2	<0.2	<0.1	331.9	12	28	0.4	<0.7	637
81	86637	14N	2W	22	95	LB	8/89	*7.68*	359	95.5	29.2	5.6	0.4	1.6	0.2	328.2	6	11	0.3	<0.7	561
82	86632	14N	1W	35	85	M-B	8/89	*7.67*	319	83.6	26.8	58.5	1.1	1.5	<0.1	403.6	14	7	0.5	<0.7	695
83	86757	15N	1E	14	108	TTPS	8/89	*7.88*	318	78.0	30.1	23.5	0.8	1.2	<0.1	332.2	4	7	1.1	<0.7	563
137	86771	14N	1W	29	66	BV	8/89	*7.20*	375	97.2	32.1	3.7	0.5	1.4	<0.1	284.9	10	64	0.2	<0.7	564
213	82166	17N	1E	20	268	TTP	6/90	*7.80*	292	67.2	30.2	51.7	1.3	1.9	<0.1	406.0	2	<1	<1	<0.7	655
214	82163	16N	2E	5	64	TTP	6/90	*7.88*	299	75.3	27.0	21.1	0.7	1.2	<0.1	322.7	1	4	1.1	<0.7	535
222	82149	15N	2W	18	95	DTR	6/90	*7.13*	319	81.9	27.9	15.2	0.5	1.2	<0.1	355.1	1	1	<1	<0.7	572
224	82140	14N	2W	14	88	M-B	6/90	*6.90*	350	90.4	30.3	11.3	0.8	0.4	0.2	283.0	15	62	<1	<0.7	563
259	82158	16N	2W	9	160	BV	7/90	*6.89*	266	65.1	25.2	40.4	0.8	1.4	<0.1	361.6	16	<1	<1	<0.7	600
260	82159	16N	2W	22	127	TTPS	7/90	*7.23*	271	70.9	23.0	24.3	0.5	1.9	<0.1	341.4	7	<1	<1	<0.7	553
261	82160	16N	2W	35	77	TTPS	7/90	*7.15*	294	65.6	31.8	31.1	0.7	1.3	<0.1	386.7	8	<1	<1	<0.7	617
262	82161	16N	1W	29	115	TTPS	7/90	*7.16*	321	76.5	31.7	15.2	0.7	1.8	<0.1	323.8	11	22	1.1	<0.7	567
263	82150	15N	1W	9	110	M-B	7/90	*6.95*	347	84.5	33.0	26.0	1.2	0.5	<0.1	383.3	13	23	<1	<0.7	660
264	82151	15N	1W	16	51	DTR	7/90	*6.87*	404	100.5	37.3	10.5	0.7	3.2	<0.1	331.0	25	56	<1	<0.7	647
265	82152	15N	1W	26	120	TTPS	7/90	*7.54*	163	32.0	20.1	86.5	1.8	0.7	<0.1	311.1	42	<1	2.4	<0.7	572
269	82162	16N	1E	24	156	TTPS	7/90	*7.28*	194	44.7	20.0	175.5	3.5	0.8	<0.1	616.6	4	<1	<1	<0.7	1010
356	82141	14N	1E	15	49	WR	7/90	*7.13*	335	89.7	27.0	4.6	0.6	1.7	<0.1	260.8	13	58	<1	<0.7	521
357	82142	14N	1E	10	82	M-B	7/90	*6.94*	335	88.6	27.6	15.7	0.8	0.6	<0.1	361.2	8	4	<1	<0.7	596
HENRY COUNTY																					
16	85852	18N	10E	6	41	TTP	7/89	*7.01*	422	106.0	38.3	5.7	0.8	0.7	0.1	319.7	26	109	0.1	<0.7	682
17	21769	19N	10E	30	135	SD	7/89	*7.11*	340	83.7	31.8	6.7	0.6	1.2	<0.1	336.6	3	20	0.3	<0.7	567
18	22084	19N	9E	27	225	SD	7/89	*7.30*	294	67.0	30.8	21.2	0.7	1.2	<0.1	332.9	8	6	0.4	<0.7	548
22	85847	18N	9E	7	258	SD	7/89	*7.45*	269	61.6	28.0	27.0	0.8	0.9	<0.1	308.5	5	14	0.4	<0.7	520
32	21809	19N	10E	36	93.5	TTP	7/89	*7.19*	384	98.3	33.7	3.2	0.6	0.3	<0.1	314.0	8	70	0.1	<0.7	604
337	82183	18N	9E	29	42.5	TTP	7/90	*6.28*	362	92.3	32.1	4.8	0.7	2.0	<0.1	310.4	8	45	<1	<0.7	571
339	82184	18N	9E	5	66	TTP	7/90	*6.78*	500	139.1	37.1	53.9	2.2	0.3	0.5	315.7	167	59	<1	<0.7	852
JOHNSON COUNTY																					
92	86826	13N	3E	18	42	DTR	8/89	*7.68*	416	106.4	36.5	9.9	0.6	2.4	0.1	367.9	5	33	0.6	<0.7	655
93	86732	13N	3E	8	86	TTP	8/89	*7.82*	287	72.6	25.7	32.1	1.3	3.6	<0.1	334.6	4	6	0.4	<0.7	563
94	86786	14N	3E	32	54	WR	8/89	*7.68*	456	120.9	37.6	19.1	0.9	2.4	<0.1	311.0	66	57	0.2	<0.7	691
102	86280	14N	3E	27	55	TTP	8/89	*7.88*	409	110.6	32.3	13.1	0.8	<0.2	<0.1	284.3	33	74	0.2	0.86	622

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
JOHNSON COUNTY continued																					
103	86325	13N	3E	9	62	DTR	8/89	*7.81*	302	78.5	25.7	3.3	0.4	<0.2	<0.1	197.7	8	36	0.2	11.07	447
104	86320	13N	3E	31	49	DTR	8/89	*7.74*	382	92.6	36.6	17.3	0.8	0.5	0.1	380.5	4	19	0.3	<0.7	646
110	85814	12N	3E	224	40	DTR	8/89	*7.63*	679	155.4	70.8	21.9	1.8	<0.2	<0.1	399.6	40	246	0.2	1.90	1041
111	85843	11N	3E	14	90	M-B	8/89	*7.63*	443	114.8	38.2	10.7	0.8	1.0	0.4	386.9	6	24	0.2	<0.7	679
112	85838	11N	3E	10	88	M-B	8/89	*7.88*	310	80.0	26.7	48.6	0.7	1.1	<0.1	385.7	3	<1	0.4	<0.7	640
359	82132	12N	3E	1	45	M-B	8/90	*6.79*	348	88.2	31.0	9.7	0.7	<0.2	0.4	312.2	15	29	<1	<0.7	565
360	82133	12N	3E	11	44	DTR	8/90	*6.78*	309	78.8	27.3	28.5	0.8	1.1	0.2	359.7	10	3	1.1	<0.7	602
361	82148	14N	4E	31	55	TTP	8/90	*6.80*	350	89.0	31.0	8.0	<1	0.3	0.2	356.7	11	32	<1	<0.7	618
KNOX COUNTY																					
274	82041	1S	12W	12	85	P-M	7/90	*6.82*	452	113.2	41.2	6.7	0.6	3.0	0.2	383.8	11	56	<1	<0.7	710
275	82042	1S	11W	4	51	WR	7/90	*7.27*	2	<2	<1	202.1	0.1	<0.2	<0.1	316.3	20	59	<1	13.33	736
283	82050	1N	8W	8	179	WRS	7/90	*7.01*	338	83.4	31.5	14.9	0.6	2.9	<0.1	409.2	9	<1	<1	<0.7	652
284	82049	1N	8W	3	200	P-C	7/90	*7.22*	377	91.6	36.2	23.1	0.6	1.0	<0.1	429.4	9	<1	<1	<0.7	697
285	82062	2N	8W	28	107	WRS	7/90	*7.05*	328	81.6	30.1	23.0	0.7	3.2	<0.1	391.6	11	<1	<1	<0.7	635
286	82078	4N	8W	10	74	LB	7/90	*6.80*	480	133.3	35.7	6.4	0.6	4.8	0.2	229.6	15	222	<1	<0.7	707
287	82077	4N	8W	27	103.5	P-M	7/90	*6.65*	316	61.9	39.3	131.3	2.2	0.7	0.3	454.7	81	71	1.2	<0.7	952
288	82076	4N	9W	25	108	P-M	7/90	*6.65*	63	12.6	7.6	13.0	<1	5.4	0.5	77.9	8	16	<1	<0.7	175
289	82067	3N	4W	10	70	P-M	7/90	*6.75*	419	101.4	40.2	23.3	0.8	2.1	0.2	366.2	30	47	<1	<0.7	704
290	82053	2N	10W	1	100	P-M	7/90	*6.95*	438	99.1	46.4	19.8	0.7	<0.2	<0.1	361.3	24	59	<1	1.81	709
291	82066	3N	9W	35	105	P-M	7/90	*6.24*	263	57.4	29.1	26.6	<1	<0.2	<0.1	249.8	22	40	<1	1.36	501
292	82068	3N	8W	34	235	P-C	7/90	*6.85*	109	27.4	9.8	109.8	1.2	<0.2	<0.1	339.8	5	<1	<1	<0.7	579
293	82061	2N	8W	5	245	P-C	7/90	*7.06*	100	24.0	9.7	232.4	1.3	<0.2	<0.1	491.5	84	<1	2.1	<0.7	959
294	82058	2N	9W	25	205	P-M	7/90	*6.80*	216	59.8	16.3	15.5	0.7	0.4	<0.1	243.8	1	4	<1	<0.7	411
295	82057	2N	9W	15	140	P-M	7/90	*7.48*	185	44.0	18.3	48.1	0.9	<0.2	<0.1	308.5	1	<1	<1	<0.7	500
296	82056	2N	9W	15	97	WRS	7/90	*7.65*	197	54.0	15.0	4.2	<1	1.1	0.1	180.9	2	13	<1	<0.7	321
297	82059	2N	9W	22	95	WRS	7/90	*7.32*	261	72.7	19.4	5.7	<1	<0.2	<0.1	206.3	26	4	<1	8.81	431
298	82054	2N	10W	24	50	P-M	7/90	*7.42*	132	31.1	13.3	138.0	1.6	<0.2	0.1	403.2	19	31	<1	<0.7	734
299	82060	2N	9W	9	165	P-M	7/90	*8.03*	15	4.0	1.3	150.8	0.7	0.3	<0.1	347.8	8	<1	<1	<0.7	593
300	82085	5N	7W	18	43	WR	7/90	*6.69*	402	106.5	33.0	12.3	<1	<0.2	<0.1	250.1	12	16	<1	32.53	638
MADISON COUNTY																					
15	85763	19N	8E	35	71	TTP	7/89	*7.21*	326	83.8	28.4	5.0	0.5	2.1	<0.1	336.4	2	14	0.2	<0.7	556
20	85785	20N	7E	11	120	TTP	7/89	*7.21*	323	82.4	28.7	6.2	0.6	3.3	<0.1	348.8	2	<1	0.2	<0.7	558
21	86497	21N	8E	17	76	TTP	7/89	*7.02*	371	96.8	31.4	6.2	0.7	2.2	<0.1	379.7	3	16	0.3	<0.7	630
23	85783	18N	8E	14	50	TTP	7/89	*7.12*	371	93.7	33.5	6.1	0.6	3.7	0.1	303.1	22	72	0.2	<0.7	608
25	85877	20N	8E	10	71	TTP	7/89	*7.33*	368	92.4	33.4	5.9	1.1	1.4	<0.1	318.0	13	50	0.2	<0.7	593
26	86492	21N	8E	14	200	SD	7/89	*7.17*	414	101.4	39.2	11.8	1.0	1.7	<0.1	392.4	3	63	0.3	<0.7	711
28	86507	22N	8E	21	116	TTP	7/89	*7.26*	366	94.4	31.6	9.7	0.7	1.7	<0.1	339.1	9	37	0.3	<0.7	609
29	86512	22N	8E	30	142	SD	7/89	*7.02*	448	109.6	42.4	23.5	2.0	<0.2	<0.1	363.8	87	58	0.4	<0.7	775
34	85872	19N	7E	36	112	SD	7/89	*7.43*	272	57.7	31.3	14.2	1.0	0.6	<0.1	314.5	1	<1	0.3	<0.7	497

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
MADISON COUNTY continued																					
36	144989	20N	6E	22	85	TTP	7/89	*7.60*	349	90.3	30.2	3.5	0.7	0.9	<0.1	269.3	11	73	0.2	<0.7	544
37	86517	21N	6E	34	222	SD	7/89	*7.50*	332	83.2	30.3	8.3	0.8	0.4	<0.1	311.1	9	29	0.7	<0.7	550
38	86552	20N	6E	33	220	SD	7/89	*7.48*	364	76.5	42.0	83.9	7.6	0.3	<0.1	309.8	188	17	0.8	<0.7	801
40	85778	18N	6E	11	82	SD	7/89	*7.46*	342	81.9	33.4	8.1	0.7	1.4	<0.1	324.6	16	32	0.6	<0.7	578
41	85773	18N	7E	26	71	TTP	7/89	*7.57*	317	79.8	28.7	5.3	0.6	1.0	0.2	341.2	3	2	0.3	<0.7	547
338	82182	18N	8E	16	93	TTP	7/90	*6.77*	351	90.3	30.6	7.0	0.8	0.9	0.2	309.7	12	28	<1	<0.7	555
341	142321	20N	8E	33	43	TTP	7/90	*6.30*	456	116.7	39.9	5.7	0.8	2.3	<0.1	291.7	83	55	<1	<0.7	667
348	82206	22N	8E	22	220	SD	7/90	*7.29*	313	76.7	29.6	15.5	0.7	1.3	<0.1	361.5	2	7	1.1	<0.7	584
349	155320	18N	7E	34	229	TTP	7/90	*6.94*	325	82.5	28.9	16.4	0.8	1.0	<0.1	330.1	19	2	<1	<0.7	563
MARION COUNTY																					
42	66797	17N	5E	20	125	TTP	7/89	*7.59*	356	88.9	32.7	5.5	0.6	0.8	<0.1	306.1	20	49	0.6	<0.7	580
43	66692	17N	4E	35	140	TTP	7/89	*7.38*	397	105.9	32.1	17.3	0.8	3.3	<0.1	309.3	59	50	0.2	<0.7	652
44	65292	17N	3E	24	195	SD	7/89	*7.12*	381	97.7	33.5	37.2	1.0	<0.2	<0.1	311.1	79	47	0.4	<0.7	685
58	61544	16N	2E	1	78	TTP	7/89	*7.84*	300	69.3	30.9	21.2	0.7	1.6	<0.1	325.0	2	<1	1.0	<0.7	534
59	86736	16N	3E	4	57	TTP	7/89	*7.45*	497	132.4	40.5	71.9	1.5	3.1	0.2	380.8	123	78	0.2	<0.7	923
60	64109	16N	4E	8	82	WR	7/89	*7.47*	494	125.5	44.1	61.1	1.1	2.3	0.2	332.9	147	47	0.4	<0.7	844
61	86741	16N	4E	8	60	WR	7/89	*7.51*	424	112.4	34.8	56.1	1.0	<0.2	<0.1	317.8	97	44	0.2	1.90	748
62	64242	16N	5E	3	215	SD	7/89	*7.94*	374	89.4	36.8	20.1	0.8	1.6	<0.1	372.1	4	18	0.8	<0.7	637
63	63863	16N	5E	3	172	TTP	7/89	*7.82*	342	70.6	40.4	32.2	0.8	0.9	<0.1	351.0	2	36	1.0	<0.7	622
95	41612	14N	4E	5	43	TTP	8/89	*7.43*	483	127.5	39.9	39.1	0.9	<0.2	<0.1	371.9	59	65	0.2	2.12	803
96	232296	14N	4E	8	250	DM	8/89	*8.10*	213	42.2	26.4	69.3	2.0	<0.2	<0.1	309.5	21	19	0.6	<0.7	564
97	86791	14N	4E	2	97	TTP	8/89	*7.82*	390	97.3	35.9	55.4	0.9	1.4	<0.1	505.1	3	<1	0.8	<0.7	824
98	59138	15N	4E	26	47	TTP	8/89	*7.78*	422	97.5	43.4	13.8	0.9	1.4	<0.1	382.7	10	28	1.3	<0.7	675
99	86761	15N	4E	22	212	SD	8/89	*7.67*	310	63.7	36.8	56.3	2.3	<0.2	<0.1	295.2	31	62	2.7	<0.7	620
100	58664	15N	4E	15	50	TTP	8/89	*7.62*	663	171.7	57.1	65.3	1.5	5.5	<0.1	390.3	216	78	0.4	<0.7	1082
210	82171	17N	3E	23	50	WRS	6/90	*6.74*	428	104.8	40.6	20.4	0.9	1.2	<0.1	330.0	48	62	<1	<0.7	691
212	82174	17N	4E	13	143	SD	6/90	*7.50*	341	86.9	30.2	9.5	0.8	1.8	<0.1	340.2	1	13	<1	<0.7	569
270	82167	17N	2E	16	339	DM	7/90	*7.30*	306	61.6	37.0	69.1	3.8	<0.2	<0.1	346.5	39	57	1.5	<0.7	696
271	82168	17N	2E	22	55	DM	7/90	*7.11*	455	122.5	36.4	55.6	1.1	<0.2	<0.1	325.6	117	57	<1	2.94	807
272	82153	15N	2E	16	55	TTPS	7/90	*7.20*	314	78.9	28.4	13.5	0.5	1.2	<0.1	299.7	3	29	<1	<0.7	532
273	82143	14N	2E	4	56	M-B	7/90	*7.06*	674	175.7	57.1	58.2	0.9	<0.2	0.1	360.0	268	58	<1	<0.7	1070
362	82510	14N	3E	2	178	DM	8/90	*6.67*	408	108.5	33.4	39.5	1.1	1.3	<0.1	284.3	123	56	<1	<0.7	716
363	82145	14N	3E	2	47	WR	8/90	*7.14*	1	<1	<1	185.1	<1	<0.2	<0.1	269.8	51	53	<1	9.26	665
364	82146	14N	3E	21	71	WR	8/90	*6.79*	411	113.2	31.2	14.1	0.9	3.0	0.1	285.8	66	88	<1	<0.7	672
365	82147	14N	3E	11	81	TTP	8/90	*6.91*	338	90.8	27.2	3.7	<1	<0.2	0.6	330.7	9	7	<1	<0.7	550
366	82154	15N	2E	12	89	TTPS	8/90	*7.11*	291	72.1	27.0	15.8	0.7	0.9	<0.1	319.7	9	<1	<1	<0.7	525
367	82164	16N	3E	15	46	TTP	8/90	*7.02*	586	155.9	47.9	23.2	1.1	3.2	0.1	303.2	206	63	<1	<0.7	880
368	82172	17N	3E	34	116	SD	8/90	*6.97*	262	63.5	25.1	24.1	0.8	1.4	<0.1	315.2	12	<1	<1	<0.7	520
369	162210	16N	4E	26	190	SD	8/90	*6.86*	286	56.9	35.1	31.0	0.9	1.1	<0.1	337.2	10	23	<1	<0.7	577

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
MARION COUNTY continued																					
370	82155	15N	5E	6	174	TTP	8/90	*7.20*	267	51.2	33.8	47.1	0.9	0.8	<0.1	364.7	10	4	<1	<0.7	599
371	82165	16N	4E	17	62	WR	8/90	*6.88*	426	112.7	35.1	57.7	1.6	3.1	0.3	309.7	133	78	<1	<0.7	806
372	82156	15N	2E	14	67	TTPS	8/90	*7.06*	341	85.6	30.9	18.7	0.8	0.9	<0.1	354.7	18	14	<1	<0.7	612
MARTIN COUNTY																					
308	82092	5N	4W	19	315	P-RC	7/90	*6.12*	267	56.0	31.0	58.0	1.1	<0.2	1.4	138.0	3	203	<1	<0.7	528
309	82091	5N	4W	30	345	P-RC	7/90	*8.19*	8	1.7	0.8	202.2	0.8	<0.2	<0.1	434.2	2	8	3.9	<0.7	748
MONROE COUNTY																					
119	86832	9N	1W	30	80	M-BRS	8/89	*7.62*	309	84.1	24.1	7.5	0.4	<0.2	<0.1	258.0	11	33	0.8	<0.7	484
135	86837	9N	2W	15	43	M-BRS	8/89	*7.41*	268	50.6	34.6	36.2	1.1	<0.2	<0.1	281.5	12	37	0.9	1.11	535
136	222297	9N	2W	22	205	M-BRS	8/89	*7.66*	337	73.4	37.4	3.4	0.7	0.6	<0.1	256.7	2	135	1.9	<0.7	621
158	222303	9N	2W	18	225	M-BSW	8/89	*8.06*	347	76.8	37.9	2.8	0.7	<0.2	<0.1	241.0	1	82	1.7	<0.7	507
162	86827	8N	2W	18	65	M-BRS	8/89	*8.37*	303	76.8	27.0	11.7	0.6	<0.2	<0.1	255.7	11	34	1.2	3.21	508
225	82115	10N	1W	17	145	M-B	6/90	*7.17*	389	106.0	30.2	13.0	0.6	<0.2	<0.1	353.2	4	52	<1	<0.7	643
236	82113	10N	2W	4	145	M-B	6/90	*7.43*	269	70.0	23.0	34.8	0.6	2.5	<0.1	337.0	8	4	<1	<0.7	561
237	82114	10N	2W	14	120	M-B	6/90	*6.75*	478	155.8	21.6	21.2	<1	<0.2	<0.1	333.1	15	136	<1	7.23	796
266	82100	9N	2W	28	65	M-BRS	7/90	*7.16*	320	78.5	30.3	4.7	1.2	<0.2	<0.1	234.5	6	112	1.5	<0.7	553
267	82102	9N	2W	21	95	M-BRS	7/90	*7.22*	298	70.4	29.7	3.0	0.6	0.2	<0.1	245.9	4	90	1.9	<0.7	540
268	82101	9N	2W	26	105	M-BRS	7/90	*7.14*	301	73.0	28.8	4.7	0.5	<0.2	<0.1	252.9	5	76	1.8	<0.7	534
MORGAN COUNTY																					
84	86285	14N	1E	29	80	BV	8/89	*7.77*	363	93.7	31.4	5.0	0.6	3.1	<0.1	358.1	2	<1	0.6	<0.7	584
85	85809	13N	1E	8	90	M-B	8/89	*7.65*	366	95.2	31.2	4.1	0.5	<0.2	<0.1	317.5	3	31	0.3	<0.7	562
86	86836	13N	1W	13	84	BV	8/89	*7.67*	311	81.1	26.3	32.9	0.8	2.4	<0.1	364.4	2	<1	0.4	<0.7	599
87	86315	13N	1W	25	222	M-B	8/89	*7.42*	59	14.1	5.9	17.8	0.3	<0.2	<0.1	56.2	4	25	0.2	0.88	150
88	86777	12N	1E	3	60	WR	8/89	*7.62*	469	125.5	37.8	7.6	1.1	0.7	0.2	299.4	21	110	0.2	<0.7	676
89	86722	13N	1E	22	180	M-B	8/89	*7.43*	124	29.7	12.1	15.6	0.3	<0.2	<0.1	80.7	9	40	0.2	1.94	228
90	85775	13N	2E	8	105	M-B	8/89	*7.76*	372	95.0	32.8	16.1	0.7	1.1	<0.1	389.5	4	4	0.6	<0.7	639
91	86806	14N	2E	26	58	M-B	8/89	*7.75*	366	93.3	32.3	12.2	0.7	1.1	0.4	351.3	6	14	0.5	<0.7	600
105	86330	13N	2E	21	95	WRS	8/89	*7.68*	7	1.6	0.7	172.9	0.2	<0.2	<0.1	294.1	14	72	0.2	<0.7	629
106	85819	12N	1E	15	110	WR	8/89	*7.88*	254	66.9	21.3	8.9	0.4	<0.2	<0.1	194.4	8	40	0.2	0.75	393
107	86752	12N	1E	34	115	WR	8/89	*7.78*	282	75.6	22.7	5.5	0.4	0.8	0.2	263.5	2	6	0.2	<0.7	444
108	85833	11N	2E	6	48	DTR	8/89	*7.85*	188	50.9	14.9	11.7	0.3	<0.2	<0.1	163.9	5	18	0.3	1.20	316
109	85873	12N	2E	18	51	WR	8/89	*7.83*	306	79.6	26.2	6.4	0.4	<0.2	0.3	285.8	3	3	0.2	<0.7	478
113	86787	11N	1E	28	59	M-B	8/89	*7.50*	300	86.3	20.6	7.0	0.5	<0.2	<0.1	233.9	4	41	0.2	1.72	462
114	86782	11N	1E	23	160	WR	8/89	*7.71*	277	73.6	22.6	21.9	0.5	0.7	<0.1	297.2	11	<1	0.1	<0.7	502
118	86737	12N	2W	18	85	M-BRS	8/89	*7.28*	386	121.5	20.1	7.7	0.8	<0.2	<0.1	288.3	15	68	0.2	2.30	602
138	86831	13N	1W	6	110	M-B	8/89	*7.04*	499	127.5	43.9	11.7	0.6	<0.2	<0.1	377.4	19	77	0.2	3.00	764
139	86300	13N	1W	30	142	M-B	8/89	*7.88*	186	43.0	19.2	86.4	1.3	2.3	<0.1	372.5	6	<1	0.9	<0.7	621
140	85764	12N	2W	11	80	M-B	8/89	*7.61*	260	63.0	25.0	18.5	0.5	1.0	0.2	194.7	19	59	0.3	<0.7	434
141	86762	12N	2W	3	107	M-B	8/89	*7.53*	353	94.9	28.3	17.9	0.6	0.8	0.4	343.1	7	11	0.2	<0.7	592

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
MORGAN COUNTY continued																					
179	86727	13N	2E	28	60	M-B	9/89	7.01	314	83.8	25.5	4.9	0.3	<0.2	0.9	285.4	5	18	0.6	<0.7	498
180	86781	14N	2E	32	87	M-B	9/89	6.63	395	96.9	37.3	9.5	0.6	<0.2	<0.1	336.0	31	41	0.8	<0.7	638
181	85804	13N	1E	4	70	M-B	9/89	6.52	452	115.9	39.5	55.6	0.5	<0.2	<0.1	243.3	233	47	0.2	2.08	806
182	85828	11N	1E	11	100	WR	9/89	7.68	258	69.3	20.6	21.9	0.5	1.2	<0.1	269.6	22	<1	0.2	<0.7	473
183	85848	11N	1W	10	45	WR	9/89	7.79	283	77.1	22.1	5.8	0.5	<0.2	<0.1	218.5	14	26	0.2	8.63	457
184	85878	12N	1W	19	79	M-BRS	9/89	8.36	367	85.0	37.7	8.1	0.6	<0.2	<0.1	316.6	6	43	0.2	<0.7	576
226	82131	12N	2W	26	44	DTR	6/90	7.14	368	95.4	31.6	7.4	0.6	2.3	<0.1	302.4	12	51	<1	<0.7	577
227	82130	12N	1W	35	210	WR	6/90	7.44	248	69.6	18.0	3.5	<1	<0.2	<0.1	219.8	3	15	<1	1.13	390
228	82123	11N	1W	2	180	WR	6/90	7.18	1	<2	<1	111.1	<1	<0.2	<0.1	245.7	5	8	<1	<0.7	432
229	82121	11N	1W	22	60	M-B	6/90	6.83	435	116.5	35.0	13.8	0.6	<0.2	<0.1	355.7	16	64	<1	3.39	703
230	82122	11N	1W	30	125	M-B	6/90	7.34	298	76.0	26.3	35.3	1.0	3.6	<0.1	376.2	6	<1	<1	<0.7	616
231	82128	12N	2W	8	92	DTR	6/90	7.09	348	88.9	30.6	16.6	<1	1.7	0.3	386.5	5	7	<1	<0.7	632
232	82129	12N	2W	7	188	BV	6/90	7.20	288	73.8	25.2	56.4	0.9	3.1	<0.1	369.5	39	<1	<1	<0.7	657
358	82136	13N	1E	25	102	M-B	8/90	7.10	312	83.5	25.2	4.9	<1	<0.2	<0.1	261.3	12	40	<1	4.07	508
OWEN COUNTY																					
115	86767	11N	2W	16	94	DTR	8/89	7.80	312	74.5	30.8	8.1	0.5	0.3	<0.1	290.8	3	15	0.2	<0.7	495
116	86792	11N	2W	16	125	M-B	8/89	7.69	251	67.2	20.4	57.1	1.0	<0.2	0.2	322.4	24	4	0.3	<0.7	576
117	85774	12N	3W	35	185	M-BRS	8/89	8.41	47	8.9	6.0	177.8	4.1	<0.2	<0.1	356.6	47	14	3.0	<0.7	700
128	85784	12N	4W	27	130	M-BRS	8/89	7.86	193	40.2	22.6	13.9	0.9	<0.2	<0.1	201.3	1	7	0.6	<0.7	339
129	85779	12N	4W	23	160	M-BRS	8/89	7.75	378	105.7	27.9	9.4	0.5	1.6	<0.1	335.6	4	25	0.2	<0.7	593
130	85799	12N	5W	35	152	P-RC	8/89	7.80	145	28.5	18.0	71.6	2.5	0.3	<0.1	235.2	38	1	1.0	<0.7	455
159	176187	9N	4W	16	265	M-BSW	8/89	8.05	192	36.6	24.5	19.2	0.9	0.2	<0.1	202.1	1	15	1.7	<0.7	358
160	85874	9N	4W	18	84	M-BSW	8/89	7.37	250	59.8	24.4	14.5	0.2	3.5	0.1	266.6	3	2	0.4	<0.7	440
165	85864	9N	6W	12	100	P-RC	8/89	7.82	139	35.7	12.2	110.9	1.0	0.2	<0.1	338.0	7	15	0.6	<0.7	600
177	86802	10N	5W	33	100	P-RC	8/89	6.78	543	134.7	50.2	103.2	3.1	0.4	<0.1	383.4	8	364	0.2	<0.7	1140
178	86797	10N	4W	29	225	P-RC	8/89	7.31	361	46.9	59.4	12.6	1.1	<0.2	<0.1	282.7	3	85	0.2	<0.7	561
187	85769	12N	3W	28	125	M-BRS	9/89	6.89	308	80.2	26.2	25.8	0.6	2.4	<0.1	341.7	17	4	0.3	<0.7	582
190	85853	11N	4W	1	120	M-BSW	9/89	7.52	421	104.2	39.2	34.0	0.7	2.3	<0.1	420.2	7	72	0.4	<0.7	779
191	85858	11N	4W	30	185	P-RC	9/89	6.92	137	35.3	11.8	40.2	1.1	<0.2	<0.1	205.1	3	13	0.3	<0.7	363
201	85879	9N	3W	32	245	M-BSW	9/89	6.86	743	188.2	66.5	5.8	0.9	0.8	<0.1	195.0	3	580	2.0	<0.7	1100
203	85770	9N	3W	2	145	M-BRS	9/89	6.94	374	97.2	32.0	10.6	0.4	3.5	0.1	394.6	4	16	0.2	<0.7	651
233	82127	12N	3W	19	80	M-BRS	6/90	6.47	165	48.0	10.9	10.5	<1	<0.2	<0.1	136.0	7	30	<1	1.81	290
234	82109	10N	4W	11	80	M-BRS	6/90	7.24	475	106.4	51.0	7.4	0.9	2.1	<0.1	233.1	<1	241	1.6	<0.7	704
235	82110	10N	4W	26	217	M-BSW	6/90	7.44	214	48.5	22.7	2.2	0.6	<0.2	<0.1	156.3	<1	59	1.2	<0.7	334
243	82120	11N	4W	17	247	P-RC	6/90	7.34	232	61.9	18.8	25.5	1.5	<0.2	<0.1	234.3	3	29	<1	<0.7	432
250	82108	10N	5W	22	95	P-RC	6/90	6.80	424	108.7	37.2	31.8	1.4	0.6	0.2	349.2	12	111	<1	<0.7	736
251	215241	10N	3W	29	77	WR	6/90	6.95	419	115.2	32.0	19.8	1.1	<0.2	<0.1	334.2	32	53	<1	0.90	674
252	82111	10N	4W	1	125	M-BRS	6/90	7.25	279	62.6	29.9	6.4	0.6	0.6	<0.1	233.1	<1	40	1.9	<0.7	434

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
PARKE COUNTY																					
145	86652	14N	6W	36	80	P-RC	8/89	*7.19*	216	52.5	20.6	10.8	0.4	0.8	<0.1	218.5	3	6	0.2	<0.7	370
PIKE COUNTY																					
278	82048	1N	9W	19	58	P-M	7/90	*7.42*	306	72.8	30.2	29.1	0.9	0.7	<0.1	350.2	1	3	<1	<0.7	576
279	82045	1S	9W	11	360	P-M	7/90	*8.84*	5	<2	0.5	243.5	0.9	<0.2	<0.1	538.6	11	7	1.4	<0.7	903
280	82044	1S	9W	14	70	P-M	7/90	*6.60*	309	68.6	33.4	56.4	1.0	<0.2	0.1	406.9	10	12	2.0	<0.7	690
281	82043	1S	9W	2	50	P-M	7/90	*7.65*	6	<2	0.6	187.9	0.6	<0.2	<0.1	278.2	24	52	<1	19.88	701
282	82051	1N	8W	35	50	P-C	7/90	*6.63*	301	71.9	29.6	21.3	0.7	0.7	0.5	186.6	46	82	<1	<0.7	493
323	82052	1N	8W	21	97	WR	7/90	*5.87*	355	97.5	27.1	4.8	0.7	1.3	0.3	257.1	14	57	<1	<0.7	523
PUTNAM COUNTY																					
132	85789	12N	5W	15	140	P-RC	8/89	*7.94*	155	35.5	16.2	61.1	2.8	0.2	0.1	259.2	14	<1	0.8	<0.7	453
142	86811	13N	2W	18	65	M-B	8/89	*7.42*	433	111.2	37.8	8.7	0.6	0.8	0.3	388.6	9	20	0.3	<0.7	674
146	86647	14N	5W	19	190	P-RC	8/89	*7.63*	321	82.9	27.8	7.6	0.5	1.5	<0.1	302.0	2	9	0.2	<0.7	512
147	85834	15N	5W	35	94	M-BRS	8/89	*7.65*	374	94.7	33.4	5.9	0.6	1.1	<0.1	345.4	4	24	0.3	<0.7	594
148	85839	15N	5W	13	125	M-BRS	8/89	*7.75*	362	88.3	34.5	6.6	0.5	3.3	<0.1	331.4	5	12	0.3	<0.7	561
149	85844	15N	5W	8	70	P-RC	8/89	*7.46*	465	121.4	39.4	24.2	0.7	<0.2	<0.1	352.6	38	73	0.2	5.56	761
150	85849	15N	4W	16	83	M-BRS	8/89	*7.75*	339	80.7	33.6	4.5	0.7	0.4	<0.1	304.6	5	18	0.3	<0.7	522
151	85854	15N	3W	2	106	DTR	8/89	*7.71*	331	81.5	31.2	15.1	0.8	3.2	<0.1	361.0	2	<1	0.6	<0.7	586
152	85798	16N	3W	14	90	M-B	8/89	*7.65*	400	94.8	39.8	11.3	0.7	1.7	<0.1	393.7	5	1	0.8	<0.7	647
153	175254	15N	3W	14	161	M-B	8/89	*7.79*	355	91.8	30.6	22.9	0.7	3.8	<0.1	393.5	2	<1	0.7	<0.7	642
154	86751	14N	3W	1	65	M-B	8/89	*7.76*	376	96.0	33.2	8.6	0.5	4.7	0.2	368.2	6	6	0.4	<0.7	614
155	86756	14N	3W	33	65	M-BRS	8/89	*7.72*	397	100.0	36.0	8.5	0.5	2.9	0.2	362.3	22	13	0.4	<0.7	633
156	86642	14N	4W	35	90	M-BRS	8/89	*7.59*	370	92.6	33.8	7.9	0.4	2.1	<0.1	359.0	2	11	0.3	<0.7	596
157	86816	13N	4W	24	92	M-BRS	8/89	*7.76*	263	63.7	25.4	8.0	0.4	0.9	<0.1	254.0	2	8	0.3	<0.7	424
185	86796	13N	5W	36	103	M-BRS	9/89	*6.79*	363	98.6	28.4	18.5	0.4	0.5	<0.1	339.1	8	44	0.2	<0.7	621
186	86742	12N	3W	8	110	M-BRS	9/89	*6.98*	333	77.5	33.8	18.4	0.4	0.6	<0.1	351.2	17	<1	0.3	<0.7	584
188	86821	13N	5W	27	90	P-RC	9/89	*5.29*	45	11.0	4.3	4.8	0.4	<0.2	0.3	2.6	4	44	0.1	0.86	87
221	82135	13N	4W	1	50	M-BRS	6/90	*7.34*	312	84.2	24.8	5.1	<1	<0.2	<0.1	285.8	7	27	<1	1.13	507
223	82157	15N	3W	34	40	M-B	6/90	*6.80*	344	92.8	27.4	5.0	<1	0.6	0.4	336.1	3	10	<1	<0.7	559
352	82134	13N	5W	34	180	WR	7/90	*6.73*	112	30.7	8.6	2.7	<1	1.0	<0.1	113.9	2	<1	<1	<0.7	188
353	82138	14N	5W	14	145	M-BRS	7/90	*7.31*	87	14.7	12.2	121.7	4.5	<0.2	<0.1	315.2	32	10	<1	<0.7	584
354	82137	14N	5W	14	103	M-BRS	7/90	*6.19*	285	61.6	31.9	17.8	0.6	2.2	<0.1	319.7	6	10	<1	<0.7	527
355	82139	14N	4W	3	145	DTR	7/90	*7.00*	447	113.2	40.0	23.8	0.8	4.0	<0.1	424.6	36	55	<1	<0.7	799
RANDOLPH COUNTY																					
5	86582	19N	12E	27	66	TTP	7/89	*7.32*	345	73.8	39.1	15.0	1.0	2.2	<0.1	391.4	3	22	0.5	<0.7	658
6	86547	20N	12E	9	139	SD	7/89	*7.23*	430	102.3	42.5	9.2	1.0	2.0	<0.1	405.7	10	28	0.4	<0.7	705
7	86542	20N	12E	20	84	TTP	7/89	*7.08*	392	99.5	35.1	4.7	0.8	1.9	<0.1	350.8	5	48	0.2	<0.7	633
8	86572	19N	13E	18	45	TTP	7/89	*7.21*	356	89.3	32.3	5.1	0.7	1.4	<0.1	330.7	4	29	0.2	<0.7	575
9	86577	19N	13E	10	50	TTP	7/89	*7.15*	392	95.5	37.4	5.0	0.7	2.2	<0.1	333.7	8	53	0.3	<0.7	619

Location Number	IDNR/DOW Well ID Number	Township	Range	Section	Well Depth (feet)	Aquifer System	Date Sampled	pH[1]	Total Hardness	Calcium	Magnesium	Sodium	Potassium	Iron	Manganese	Alkalinity as $CaCO_3$[2]	Chloride	Sulfate	Fluoride	NO_3 as N	Total Dissolved Solids[3]
RANDOLPH COUNTY continued																					
10	86567	19N	14E	17	83	TTP	7/89	*7.48*	340	75.5	36.9	18.7	1.0	2.0	<0.1	386.4	<1	10	0.5	<0.7	635
12	86537	20N	13E	29	101	SD	7/89	*7.13*	396	97.0	37.4	25.0	0.9	<0.2	<0.1	311.7	70	68	0.1	0.70	687
30	86527	20N	15E	31	160	SD	7/89	*7.48*	310	72.7	31.3	14.1	0.9	2.2	<0.1	368.5	2	<1	0.7	<0.7	588
31	86532	20N	14E	12	45	TTPS	7/89	*6.98*	470	87.8	61.0	22.2	1.7	<0.2	<0.1	459.6	6	103	0.7	<0.7	870
328	82200	20N	15E	20	98	TTP	7/90	*6.58*	288	66.8	29.5	13.9	0.8	1.5	<0.1	354.3	<!	<1	1.4	<0.7	560
329	82199	20N	14E	33	306	SD	7/90	*7.31*	249	40.1	36.2	42.8	1.1	0.6	<0.1	299.0	24	8	1.1	<0.7	523
330	82191	19N	14E	27	221	SD	7/90	*6.47*	348	87.1	31.8	20.8	1.0	1.2	<0.1	389.2	4	24	1.3	<0.7	659
331	82192	19N	14E	8	204	TTP	7/90	*6.88*	308	68.2	33.4	30.2	0.9	1.9	<0.1	357.8	3	9	1.1	<0.7	593
332	82197	20N	13E	33	39	TTP	7/90	*6.86*	462	120.1	39.5	7.0	1.0	1.2	0.1	301.0	49	92	<1	<0.7	683
333	82198	20N	13E	19	91	SD	7/90	*6.68*	355	86.9	33.7	4.3	0.6	1.6	<0.1	313.2	3	53	<1	<0.7	574
334	82196	20N	12E	34	118	TTP	7/90	*7.01*	357	88.3	33.3	6.7	0.7	1.3	<0.1	345.6	<1	17	<1	<0.7	581
TIPTON COUNTY																					
49	86502	22N	5E	27	92	TTP	7/89	*7.61*	336	98.8	21.8	24.0	1.0	1.5	<0.1	408.7	2	14	0.5	<0.7	673
50	86522	21N	3E	21	243	SD	7/89	*7.66*	287	71.6	26.3	25.0	0.8	1.1	<0.1	359.7	2	<1	1.1	<0.7	578
344	82201	21N	3E	6	182	TTP	7/90	*6.56*	262	63.4	25.2	30.0	0.8	0.9	<0.1	321.8	2	<1	1.4	<0.7	528
345	82202	21N	4E	23	135	TTP	7/90	*6.21*	314	83.0	26.0	21.0	<1	1.1	<0.1	391.5	3	9	<1	<0.7	632
346	82203	21N	5E	33	98	TTP	7/90	*6.98*	237	49.0	28.0	28.0	1.9	3.2	<0.1	359.0	3	<1	<1	<0.7	558
347	82205	22N	6E	17	100	SD	7/90	*7.10*	330	82.9	30.0	6.5	0.8	2.0	<0.1	348.1	6	5	1.2	<0.7	568

[1] Results in standard pH units.

[2] Laboratory analysis.

[3] TDS values are the sum of major constituents expected in an anhydrous residue of a ground-water sample with bicarbonate converted to carbonate in the solid phase.

Appendix 2. Results of chemical analysis for strontium and zinc. (All values in milligrams per liter)

Location number	Strontium	Zinc
BOONE COUNTY		
51	1.6	<0.1
52	0.7	<0.1
53	3.8	0.1
54	1.5	<0.1
55	0.6	<0.1
56	2.1	<0.1
57	3.8	<0.1
67	0.4	<0.1
BROWN COUNTY		
133	0.3	<0.1
134	0.4	<0.1
CLAY COUNTY		
131	0.3	0.2
143	<0.1	<0.1
144	0.2	0.1
166	<0.1	<0.1
169	0.4	0.1
170	0.4	0.1
171	0.2	0.1
172	0.5	<0.1
173	0.2	0.2
174	0.1	<0.1
175	0.4	0.1
176	0.1	<0.1
189	0.3	0.6
238	0.1	<0.1
239	0.7	<0.1
240	0.2	<0.1
241	0.1	<0.1
242	0.1	<0.1
244	0.5	<0.1
245	0.3	<0.1
246	<0.1	<0.1
247	<0.1	<0.1
248	0.4	<0.1
249	<0.1	<0.1
253	<0.1	<0.1
351	0.5	0.1
DAVIESS COUNTY		
302	0.6	0.6
303	0.3	<0.1
304	<0.1	<0.1
305	0.3	<0.1
306	<0.1	<0.1
307	0.1	<0.1
310	<0.1	<0.1
311	<0.1	<0.1
312	0.1	<0.1
313	0.2	<0.1
314	0.3	<0.1
315	0.2	<0.1
316	0.4	0.1
317	0.1	<0.1
318	0.5	<0.1
319	0.4	<0.1
320	0.1	<0.1
321	0.6	0.4
322	0.1	<0.1
324	0.1	0.1
325	0.1	<0.1
DELAWARE COUNTY		
1	4.5	<0.1
2	1.1	<0.1
3	0.2	<0.1
4	0.1	<0.1
11	0.7	<0.1
13	3	<0.1
14	1.2	<0.1
19	0.2	<0.1
24	1.5	0.1
27	1.9	<0.1
33	0.5	<0.1
326	2.7	0.3
327	0.5	<0.1
335	0.3	<0.1
336	<0.1	<0.1
340	0.2	<0.1
342	0.5	<0.1
343	1	<0.1
GIBSON COUNTY		
276	0.2	0.3
277	0.2	0.1
GREENE COUNTY		
120	14.9	<0.1
121	0.1	<0.1
122	0.2	<0.1
123	0.3	<0.1
124	0.3	<0.1
125	0.1	0.1
126	0.3	0.1
127	0.1	0.1
161	0.2	<0.1
163	0.1	0.1
164	0.1	0.2
167	0.5	0.1
168	0.2	0.1
192	0.3	<0.1
193	0.2	<0.1
194	0.1	<0.1
195	0.1	<0.1
196	0.4	<0.1
197	0.1	<0.1
198	0.2	<0.1
199	<0.1	<0.1

Appendix 2. Results of chemical analysis for strontium and zinc continued.

Location number	Strontium	Zinc
GREENE COUNTY continued		
200	8.1	0.1
202	11.6	<0.1
204	3.6	0.1
254	0.4	<0.1
255	0.7	<0.1
256	0.2	<0.1
257	<0.1	<0.1
258	0.2	<0.1
301	0.4	0.1
HAMILTON COUNTY		
35	0.4	<0.1
39	1.1	<0.1
45	0.4	<0.1
46	0.3	<0.1
47	6.3	<0.1
48	0.6	0.2
205	0.8	<0.1
206	1.4	<0.1
207	1	<0.1
208	0.9	<0.1
209	2.1	<0.1
211	0.2	<0.1
215	0.7	<0.1
216	0.2	<0.1
217	0.2	<0.1
218	1.5	0.1
219	0.2	<0.1
220	0.8	<0.1
HANCOCK COUNTY		
101	0.7	<0.1
350	0.6	<0.1
HENDRICKS COUNTY		
64	2.3	<0.1
65	3.1	<0.1
66	0.8	<0.1
68	0.3	<0.1
69	0.6	<0.1
70	0.9	0.3
71	1.6	<0.1
72	0.1	0.1
73	0.1	<0.1
74	0.3	<0.1
75	0.5	<0.1
76	1.9	<0.1
77	0.2	<0.1
78	0.4	<0.1
79	1.7	<0.1
80	<0.1	<0.1
81	0.2	<0.1
82	0.9	<0.1
83	3.5	<0.1
137	0.3	<0.1
213	0.8	<0.1
214	2.3	<0.1
222	0.4	<0.1
224	0.7	<0.1
259	0.9	<0.1
260	0.9	<0.1
261	1	0.1
262	3.9	<0.1
263	2.3	<0.1
264	1	<0.1
265	4.2	<0.1
269	0.9	<0.1
356	0.2	<0.1
357	0.4	<0.1
HENRY COUNTY		
16	0.2	0.1
17	1	<0.1
18	1.2	<0.1
22	0.9	<0.1
32	0.1	<0.1
337	0.4	<0.1
339	0.8	<0.1
JOHNSON COUNTY		
92	0.9	<0.1
93	1.1	<0.1
94	0.2	<0.1
102	0.2	<0.1
103	0.1	<0.1
104	0.6	<0.1
110	0.3	<0.1
111	0.3	<0.1
112	0.4	<0.1
359	1.4	<0.1
360	3.6	0.3
361	1.3	<0.1
KNOX COUNTY		
274	0.1	<0.1
275	<0.1	<0.1
283	0.2	<0.1
284	0.3	0.7
285	0.4	0.1
286	0.2	<0.1
287	0.9	0.8
288	<0.1	0.1
289	0.3	<0.1
290	0.1	<0.1
291	0.1	<0.1
292	0.3	<0.1
293	0.2	<0.1
294	0.3	0.1
295	0.3	<0.1
296	<0.1	<0.1

Appendix 2. Results of chemical analysis for strontium and zinc continued.

Location number	Strontium	Zinc
KNOX COUNTY continued		
297	0.1	<0.1
298	0.3	0.1
299	0.1	<0.1
300	0.1	0.1
MADISON COUNTY		
15	0.6	<0.1
20	0.3	<0.1
21	1	<0.1
23	0.3	<0.1
25	1.6	<0.1
26	2.7	<0.1
28	1.5	<0.1
29	2.7	<0.1
34	0.6	<0.1
36	0.1	<0.1
37	2.1	<0.1
38	2.3	<0.1
40	0.3	<0.1
41	0.3	0.1
338	1	0.1
341	0.1	<0.1
348	1.4	0.1
349	0.7	<0.1
MARION COUNTY		
42	0.9	<0.1
43	0.4	<0.1
44	0.9	<0.1
58	2.1	<0.1
59	0.3	<0.1
60	0.8	<0.1
61	0.2	<0.1
62	2.8	0.3
63	1.2	<0.1
95	0.2	<0.1

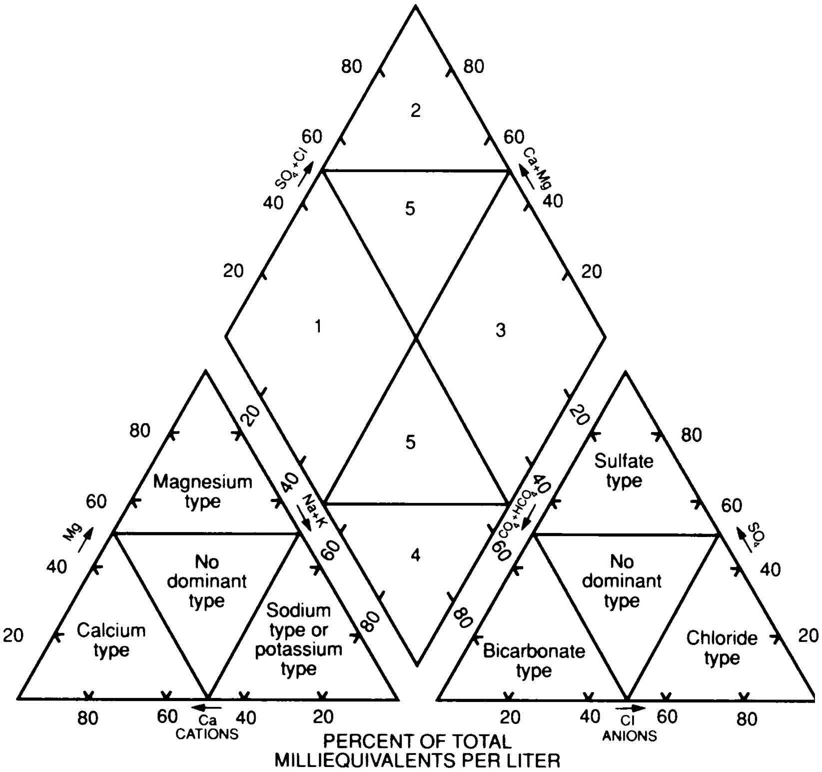
Location number	Strontium	Zinc
96	1	<0.1
97	1.5	<0.1
98	1.8	<0.1
99	0.9	<0.1
100	0.4	<0.1
210	2.4	<0.1
212	1.2	<0.1
270	1	<0.1
271	0.4	<0.1
272	1.6	<0.1
273	0.3	<0.1
362	0.3	<0.1
363	<0.1	<0.1
364	0.2	<0.1
365	0.2	<0.1
366	1.1	<0.1
367	0.3	<0.1
368	1.4	<0.1
369	1.3	<0.1
370	0.8	<0.1
371	0.4	<0.1
372	0.6	<0.1
MARTIN COUNTY		
308	0.1	0.1
309	<0.1	<0.1
MONROE COUNTY		
119	2.8	0.1
135	8.4	0.1
136	49.8	<0.1
158	5.4	<0.1
162	15.3	<0.1
225	0.4	<0.1
236	0.4	<0.1
237	0.1	0.2
266	26.1	<0.1

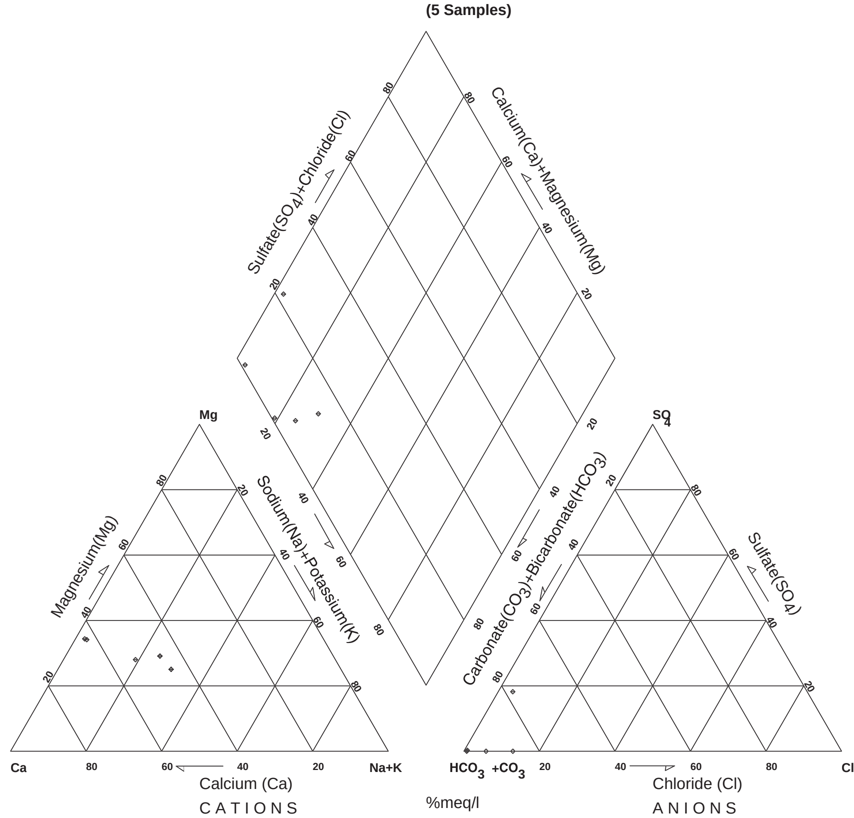
Location number	Strontium	Zinc
267	35.6	<0.1
268	30	0.2
MORGAN COUNTY		
84	0.8	<0.1
85	0.3	<0.1
86	0.5	<0.1
87	<0.1	<0.1
88	0.2	<0.1
89	<0.1	<0.1
90	1.1	<0.1
91	0.8	<0.1
105	<0.1	<0.1
106	0.1	<0.1
107	0.1	<0.1
108	0.1	<0.1
109	0.1	<0.1
113	0.1	<0.1
114	0.4	<0.1
118	0.2	0.2
138	0.2	<0.1
139	1.8	<0.1
140	0.1	<0.1
141	0.2	<0.1
179	0.4	<0.1
180	1.1	<0.1
181	0.1	<0.1
182	0.2	<0.1
183	0.1	<0.1
184	0.1	<0.1
226	0.2	0.1
227	0.1	<0.1
228	<0.1	<0.1
229	0.2	<0.1
230	1	<0.1
231	0.2	<0.1

Appendix 2. Results of chemical analysis for strontium and zinc continued.

Location number	Strontium	Zinc
MORGAN COUNTY continued		
232	0.3	<0.1
358	0.1	<0.1
OWEN COUNTY		
115	0.2	<0.1
116	0.2	<0.1
117	0.3	<0.1
128	1.2	<0.1
129	0.2	<0.1
130	1.6	<0.1
159	6.6	<0.1
160	0.4	<0.1
165	0.2	<0.1
177	1.1	<0.1
178	1.4	<0.1
187	0.3	<0.1
190	0.5	<0.1
191	0.6	<0.1
201	10.5	0.1
203	0.5	<0.1
233	0.1	<0.1
234	4.5	<0.1
235	2.4	<0.1
243	1.2	<0.1
250	0.5	<0.1
251	0.3	<0.1
252	2.4	<0.1
PARKE COUNTY		
145	0.1	<0.1
PIKE COUNTY		
278	0.3	<0.1
279	<0.1	<0.1
280	0.5	0.1
281	<0.1	<0.1
282	0.1	<0.1
323	0.1	<0.1
PUTNAM COUNTY		
132	1.4	<0.1
142	0.3	0.1
146	0.1	<0.1
147	0.2	<0.1
148	0.4	<0.1
149	0.1	0.1
150	0.3	<0.1
151	1	0.2
152	0.4	0.2
153	1.3	<0.1
154	0.3	0.1
155	0.5	<0.1
156	0.3	<0.1
157	0.3	<0.1
185	0.3	<0.1
186	0.2	<0.1
188	<0.1	<0.1
221	0.1	<0.1
223	0.1	<0.1
352	0.1	<0.1
353	0.6	<0.1
354	0.9	<0.1
355	0.3	<0.1
RANDOLPH COUNTY		
5	14.5	<0.1
6	5.4	<0.1
7	0.9	<0.1
8	0.9	<0.1
9	0.4	<0.1
10	9.7	<0.1
12	0.5	<0.1
30	6.6	<0.1
31	17.9	0.2
328	5.5	<0.1
329	1.3	<0.1
330	6.8	<0.1
331	1.2	<0.1
332	1.2	<0.1
333	0.9	<0.1
334	2.1	<0.1
TIPTON COUNTY		
49	0.4	<0.1
50	2	<0.1
344	1.4	<0.1
345	0.4	<0.1
346	0.8	<0.1
347	1.3	<0.1

For additional data, including location information, see Appendix 1

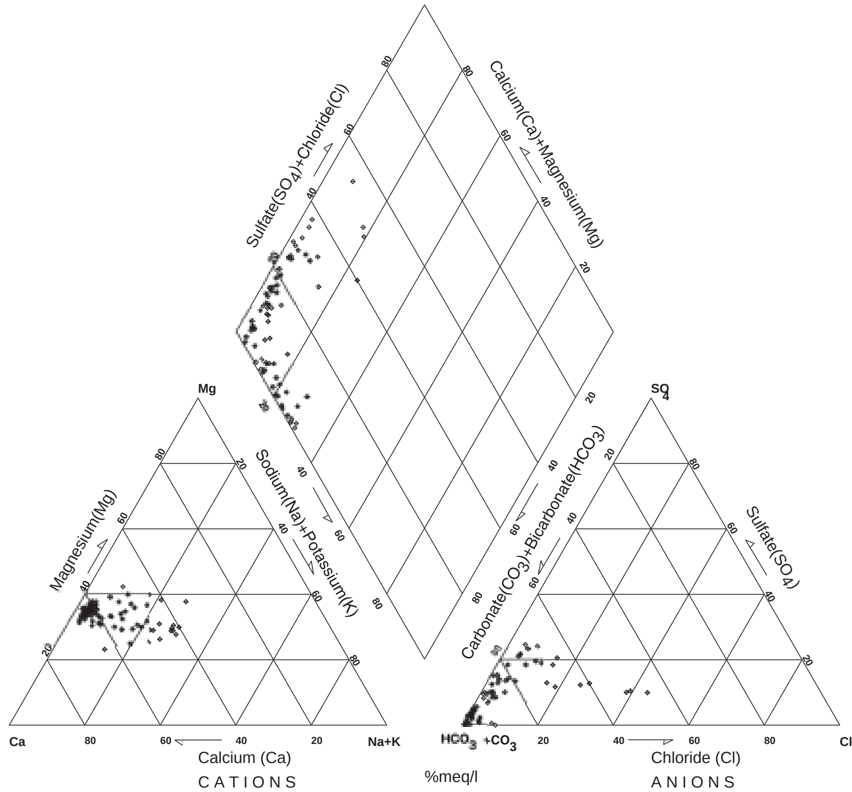




Appendix 3a. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

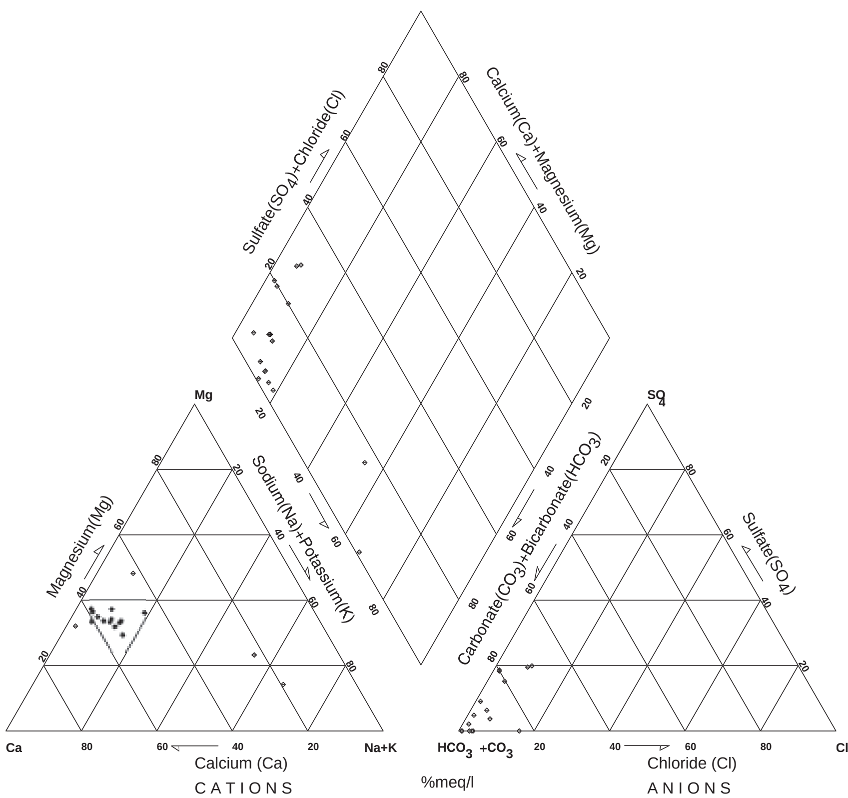
Tipton Tillplain Aquifer System

(75 Samples)



Tipton Tillplain Aquifer Subsystem

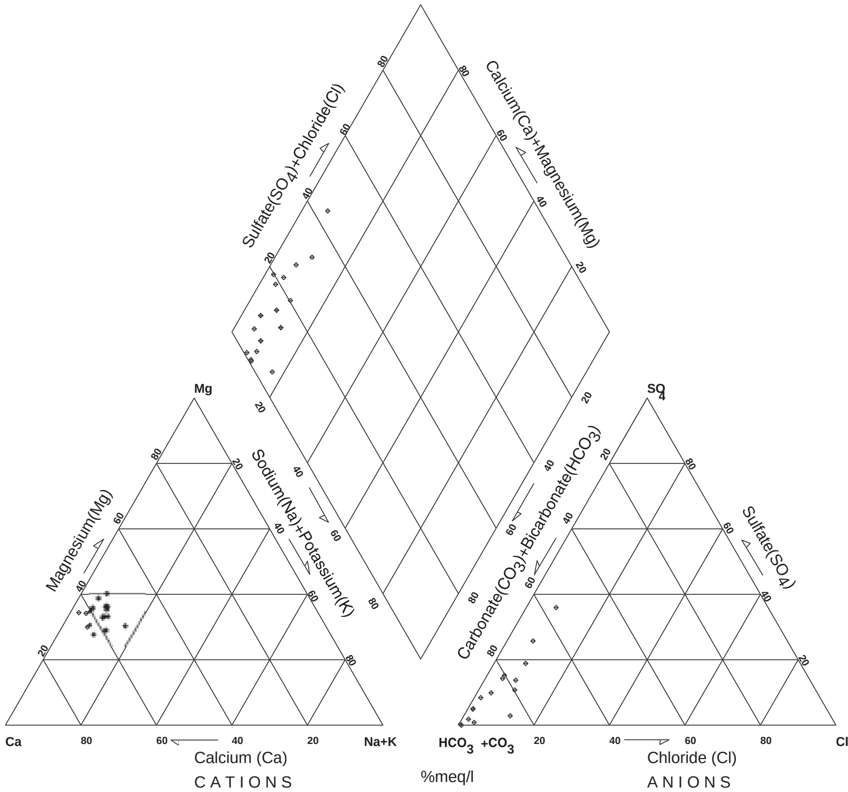
(17 Samples)



Appendix 3b. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

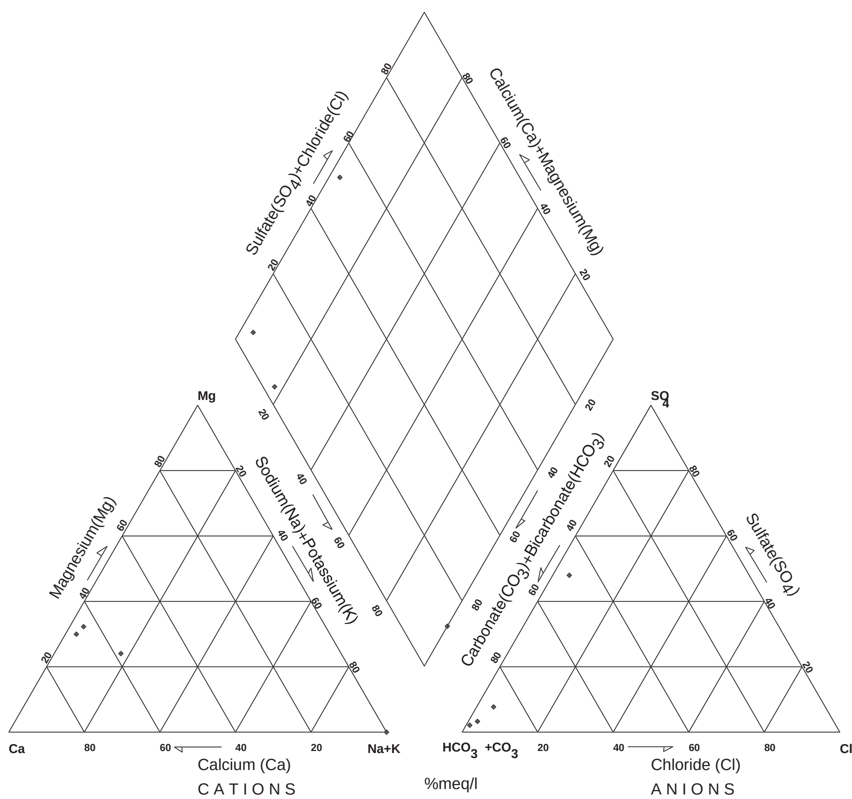
Dissected Till and Residuum Aquifer System

(17 Samples)



Lacustrine and Backwater Deposits Aquifer System

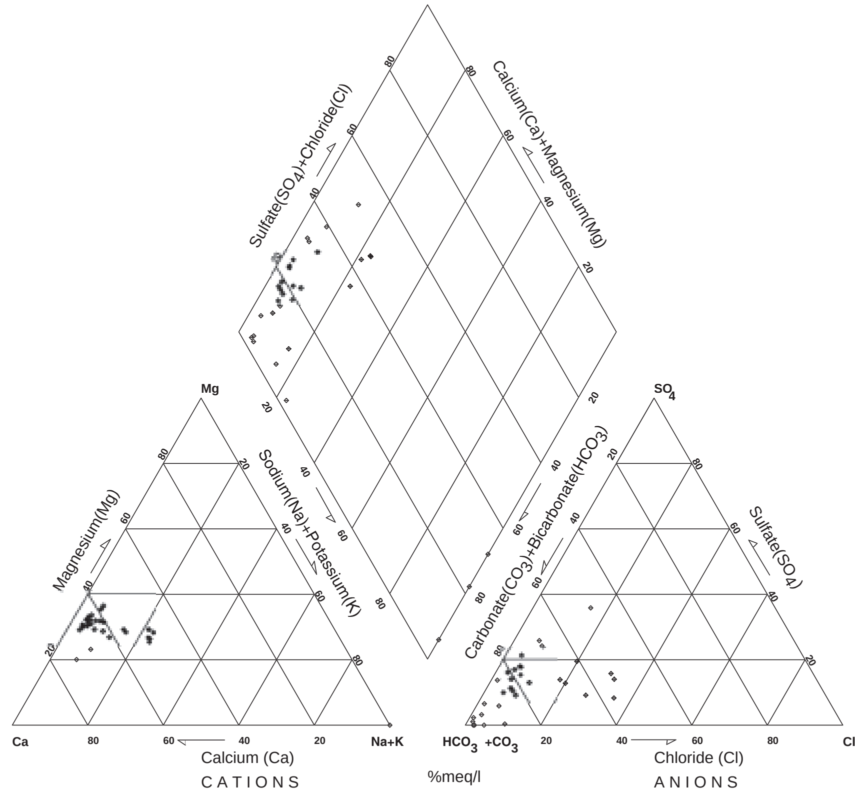
(4 Samples)



Appendix 3c. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

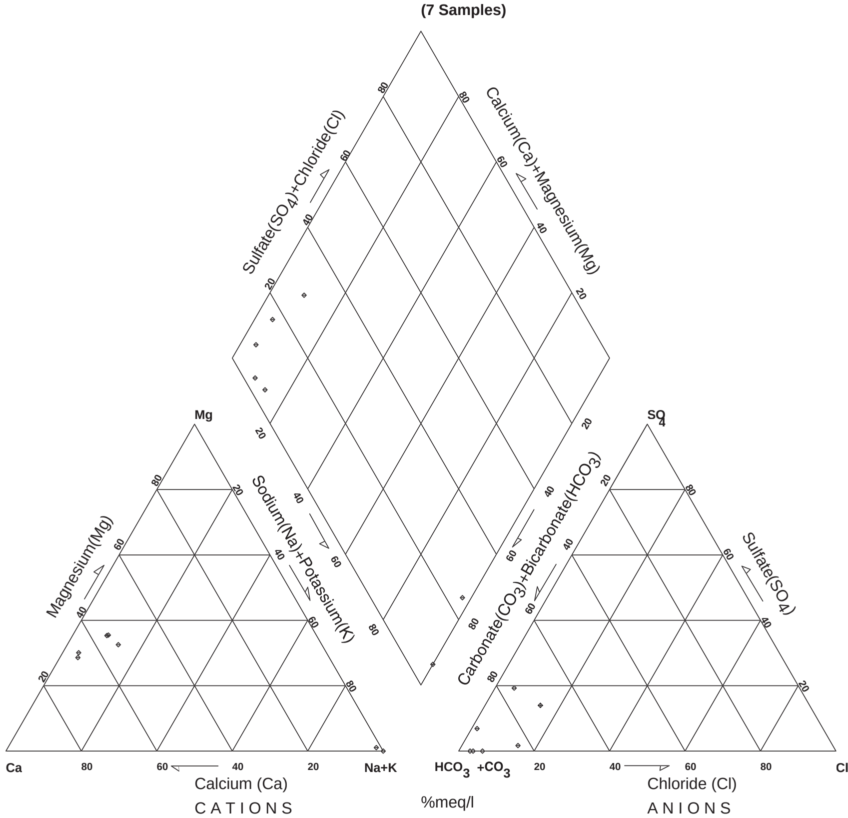
White River and Tributaries Outwash Aquifer System

(32 Samples)



White River and Tributaries Outwash Aquifer Subsystem

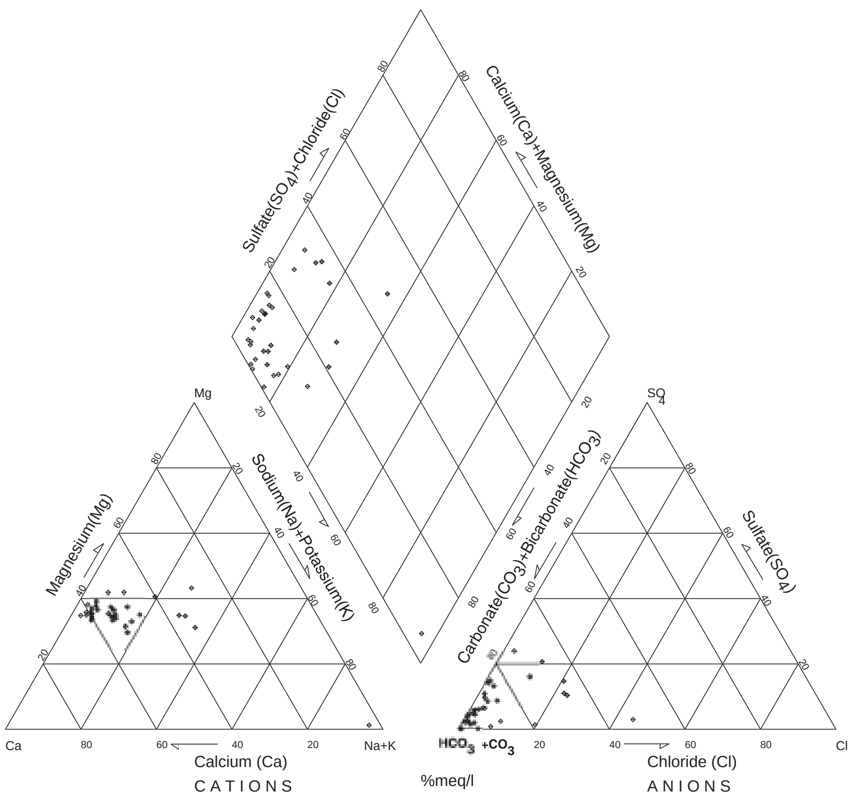
(7 Samples)



Appendix 3d. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

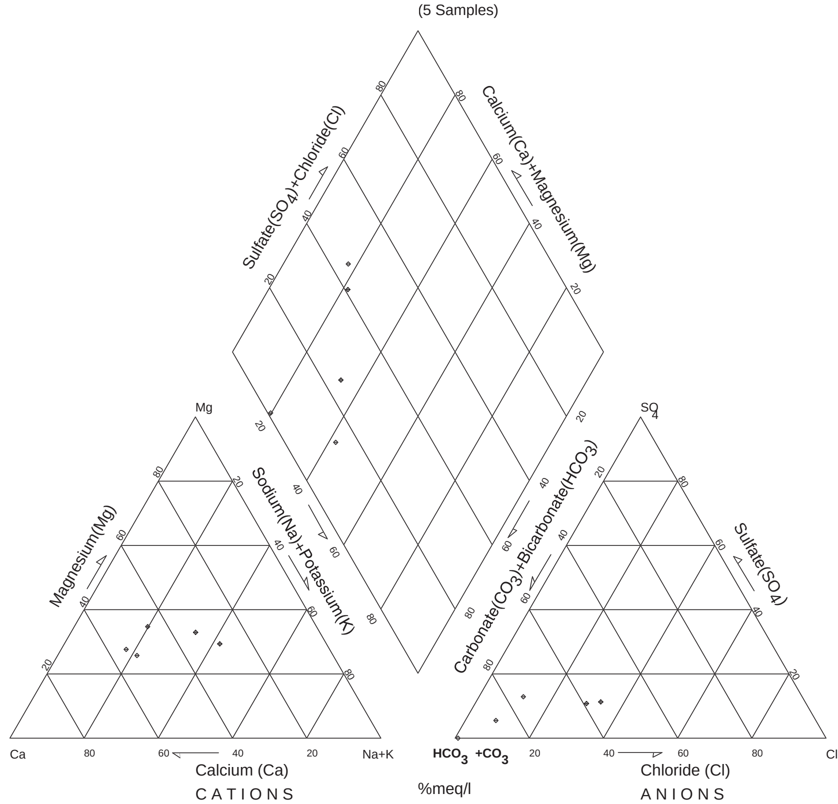
Silurian and Devonian Carbonates Aquifer System

(34 Samples)



Devonian & Mississippian--New Albany Shale Aquifer System

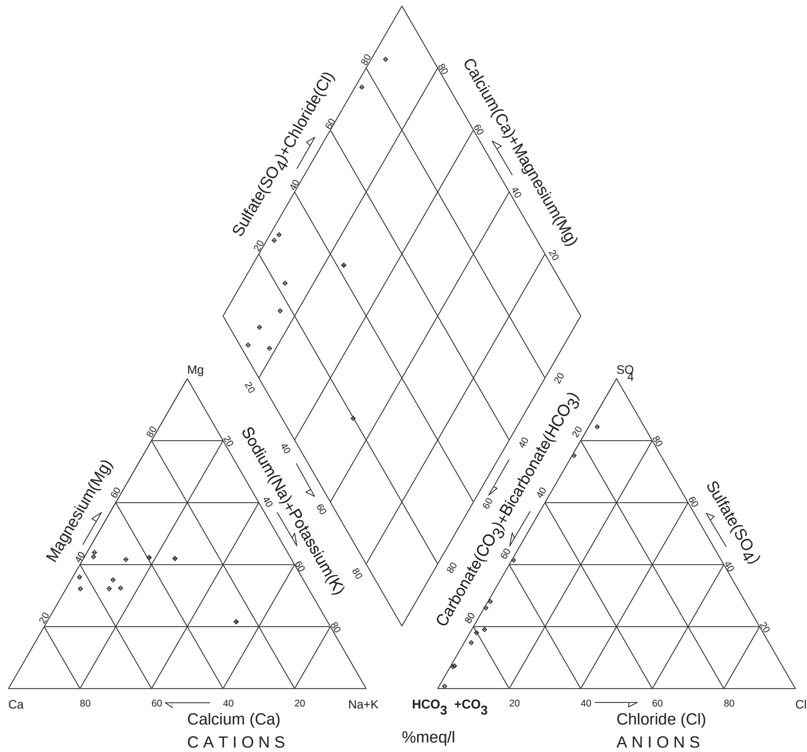
(5 Samples)



Appendix 3e. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

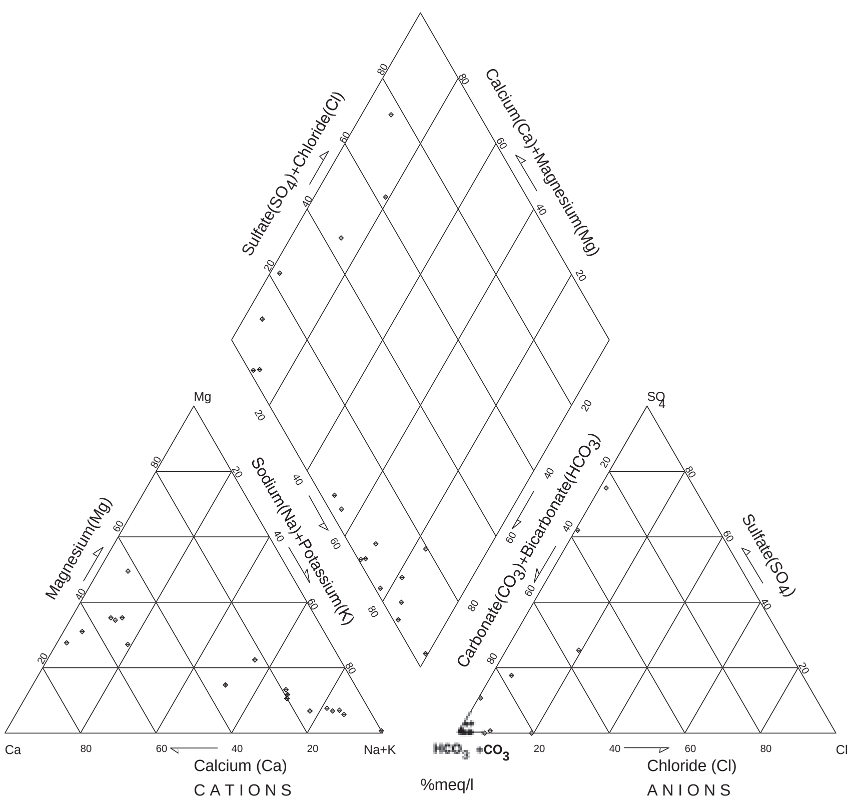
Mississippian--Buffalo Wallow, Stephensport, & W Baden Group Aquifer System

(11 Samples)



Pennsylvanian--Carbondale Group Aquifer System

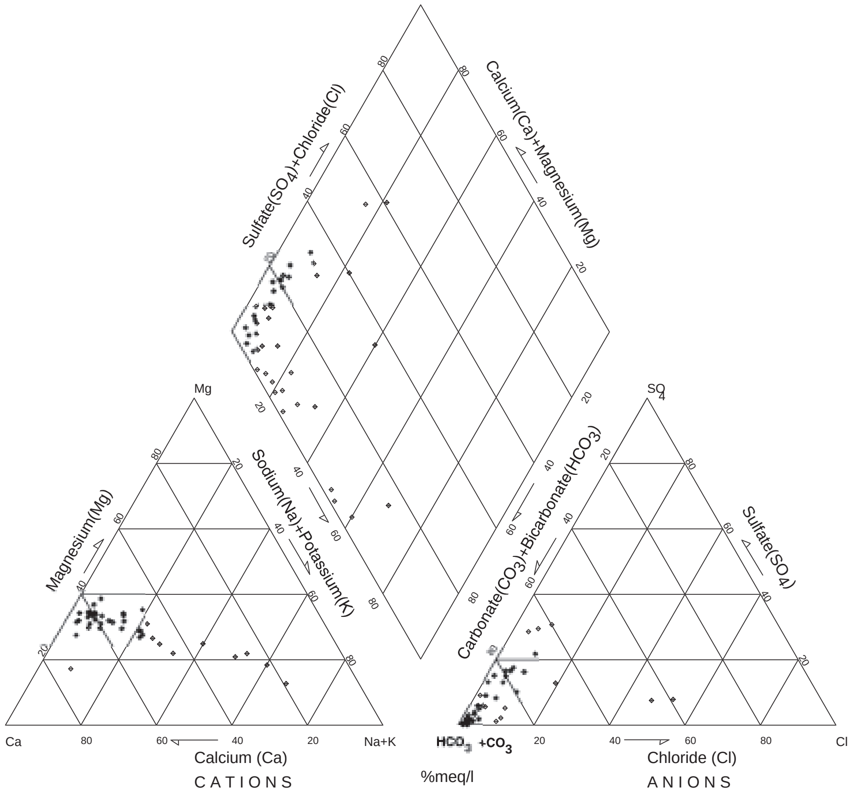
(18 Samples)



Appendix 3f. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

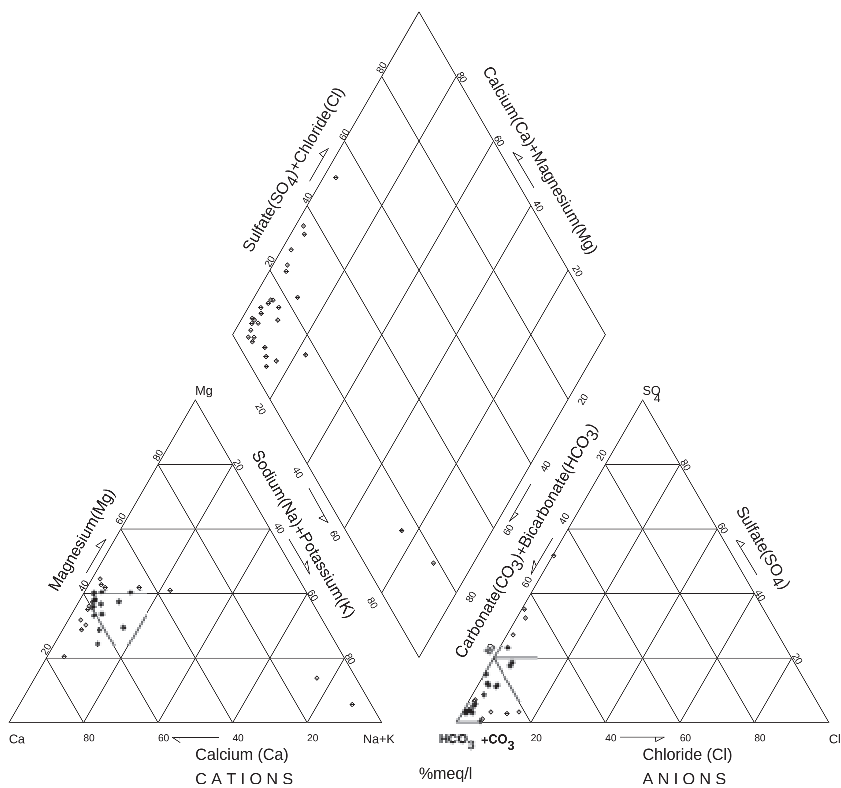
Mississippian--Borden Group Aquifer System

(44 Samples)



Mississippian--Blue River and Sanders Group Aquifer System

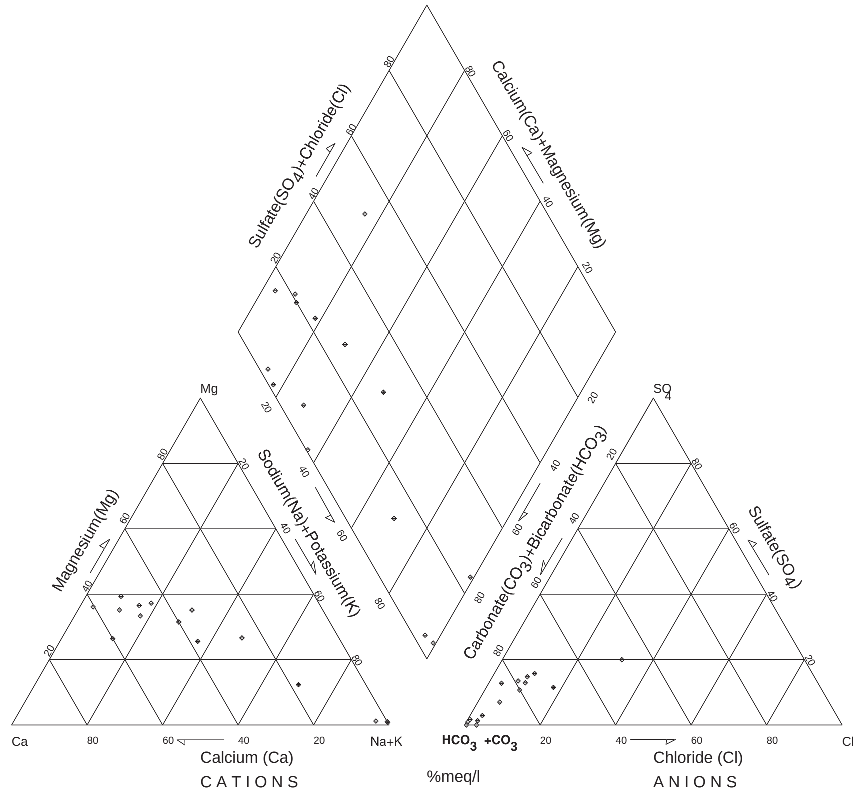
(29 Samples)



Appendix 3g. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems

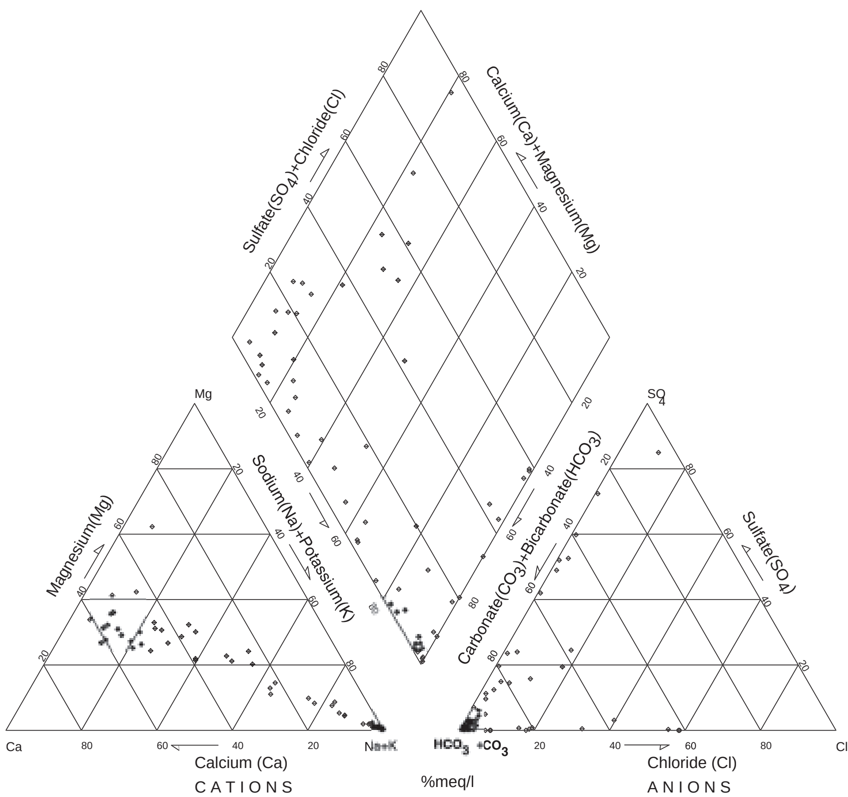
Pennsylvanian--McLeansboro Group Aquifer System

(15 Samples)

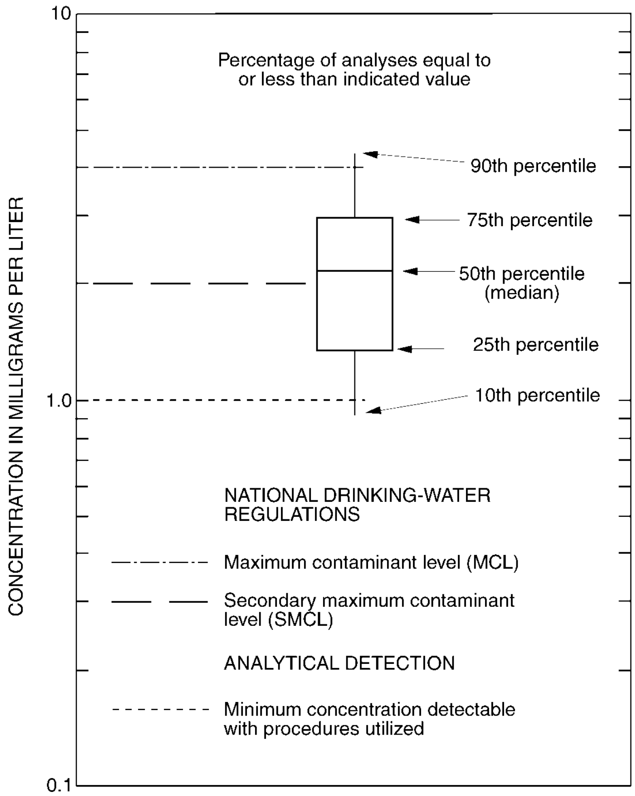


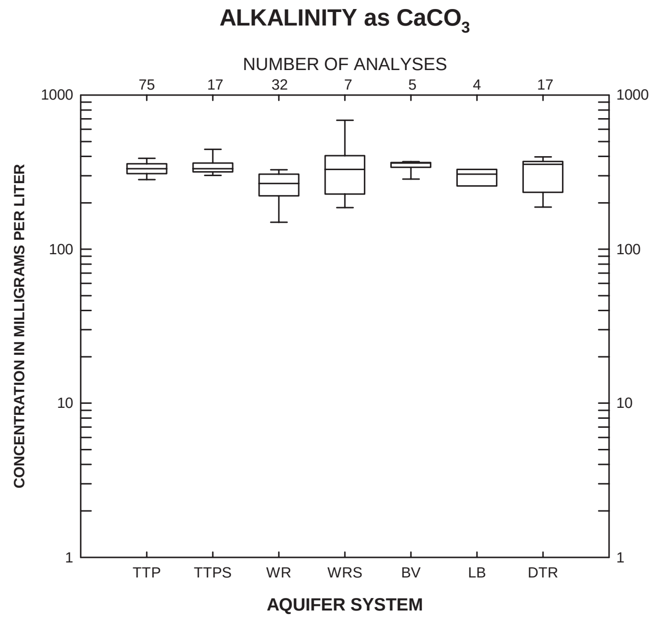
Pennsylvanian--Raccoon Creek Group Aquifer System

(59 Samples)



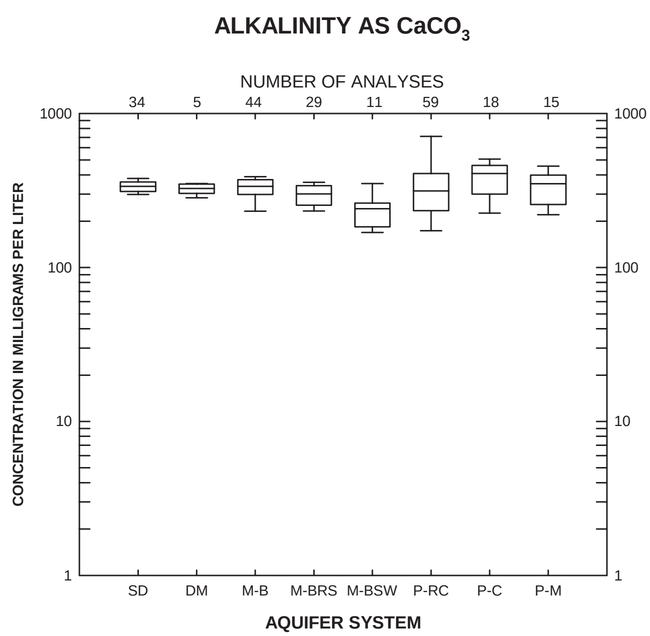
Appendix 3h. Piper trilinear diagrams of ground-water quality data for major unconsolidated aquifer systems



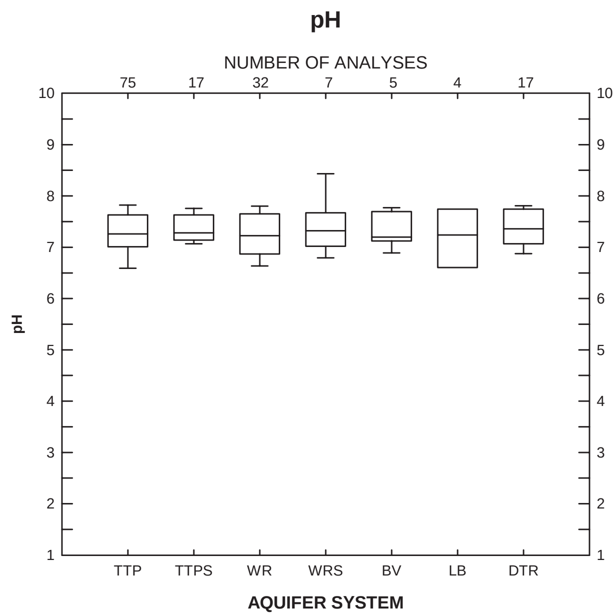


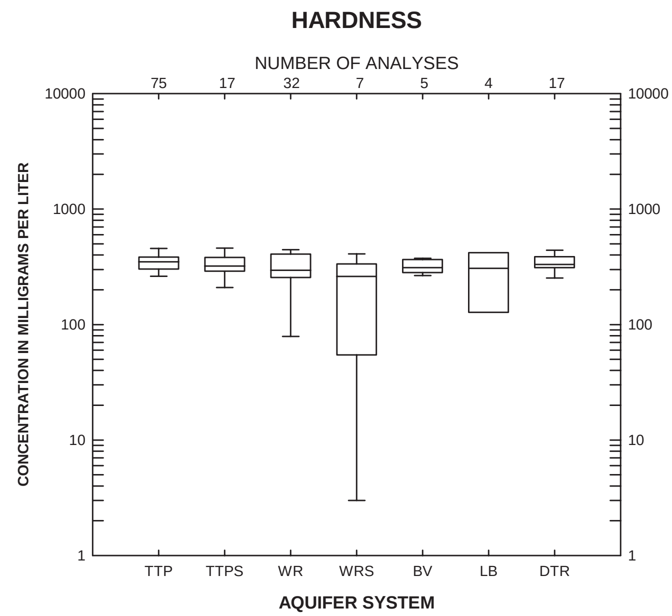
TTP	Tipton Till Plain
TTPS	Tipton Till Plain Subsystem
WR	White River Outwash
WRS	White River Subsystem
BV	Buried Valley
LB	Lacustrine and Backwater Deposits
DTR	Dissected Till and Residuum

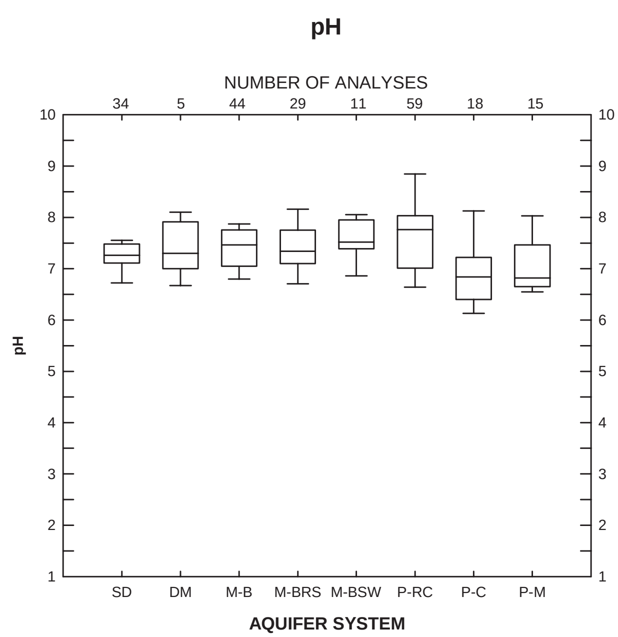
SD	Silurian and Devonian Carbonates
DM	Devonian and Mississippian/New Albany Shale
M-B	Mississippian/Borden Group
M-BRS	Mississippian/Blue River and Sanders Groups
M-BSW	Mississippian/Buffalo Wallow, Stephensport, and West Baden Groups
P-RC	Pennsylvanian/Raccoon Creek Group
P-C	Pennsylvanian/Carbondale Group
P-M	Pennsylvanian/McLeansboro Group

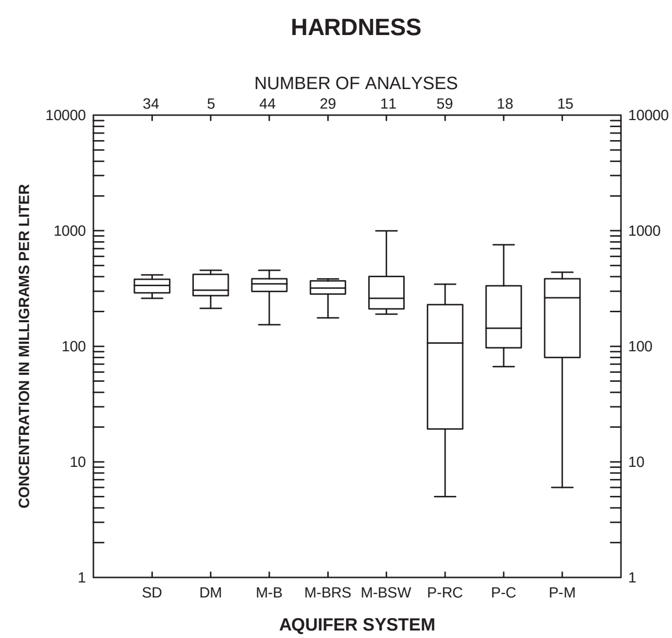


Appendix 4a. Statistical summary of selected water-quality constituents for aquifer systems

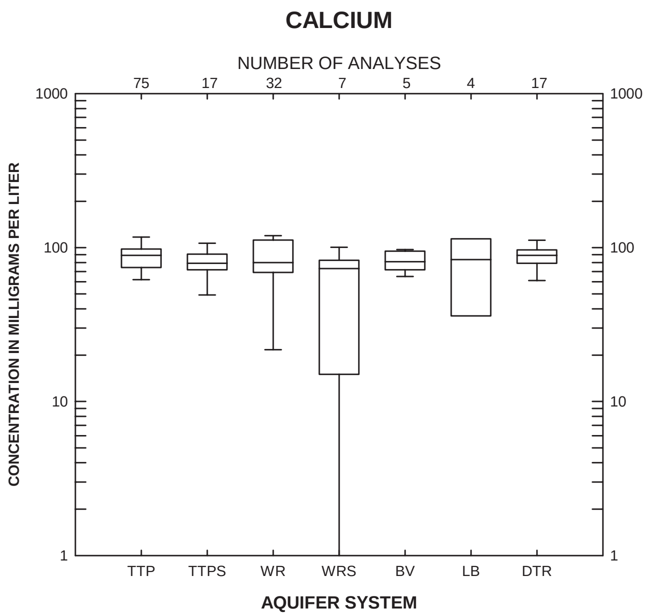


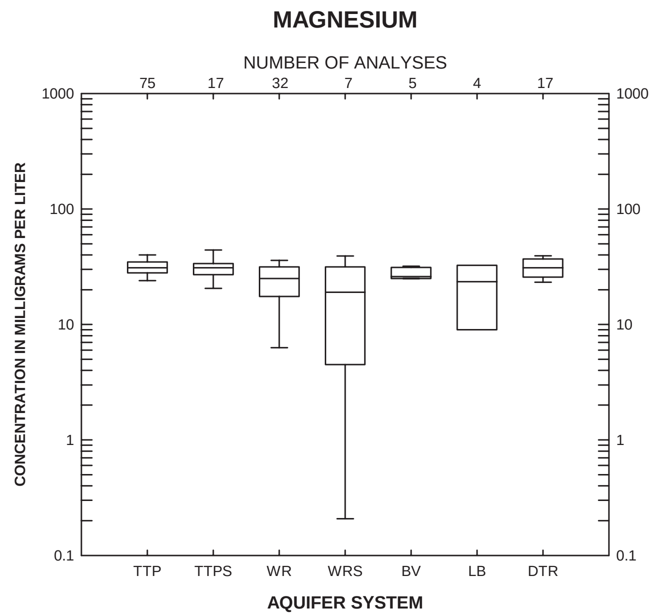


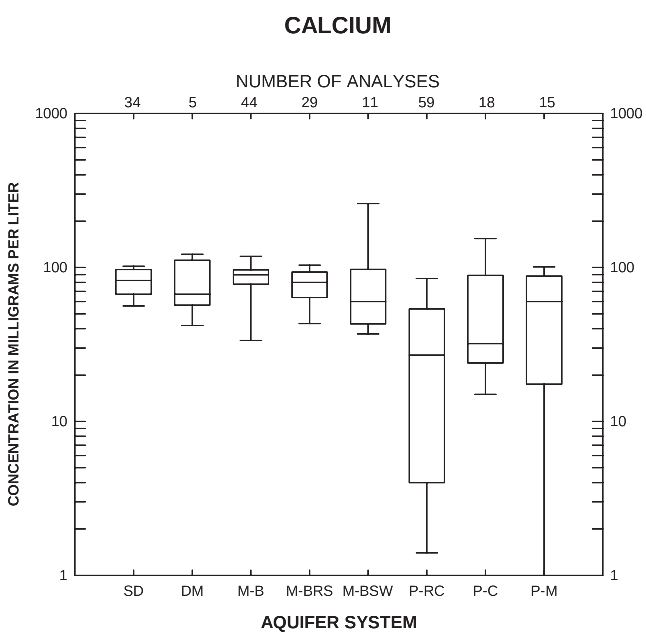


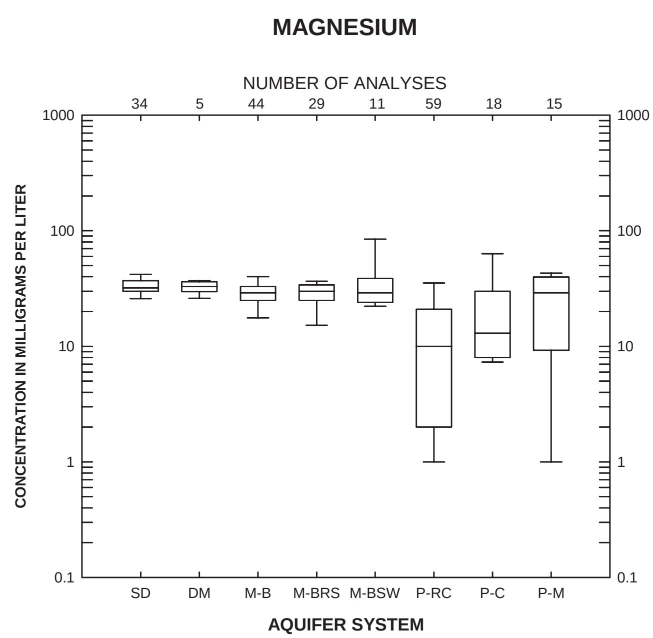


Appendix 4b. Statistical summary of selected water-quality constituents for aquifer systems

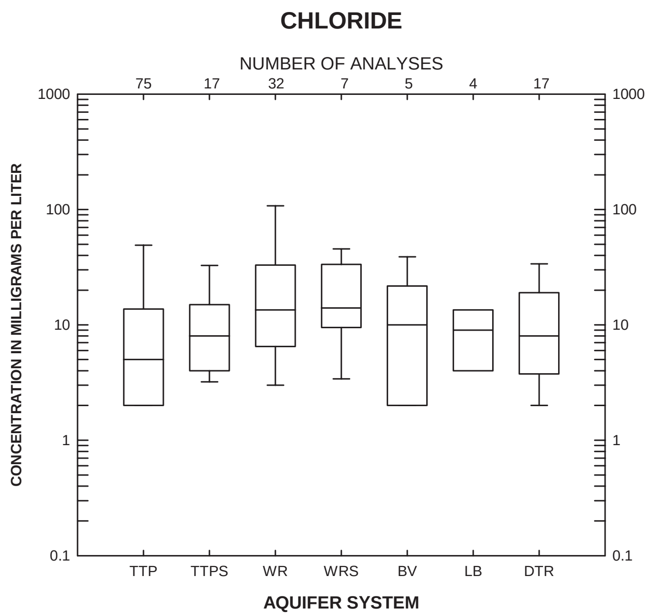


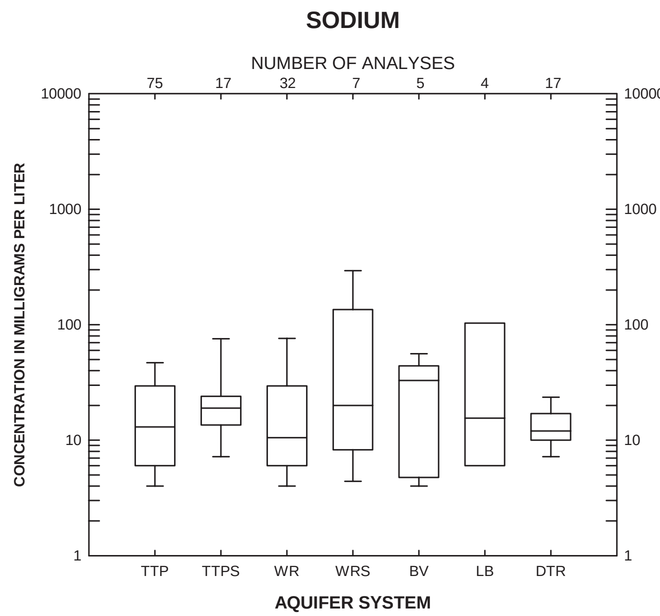


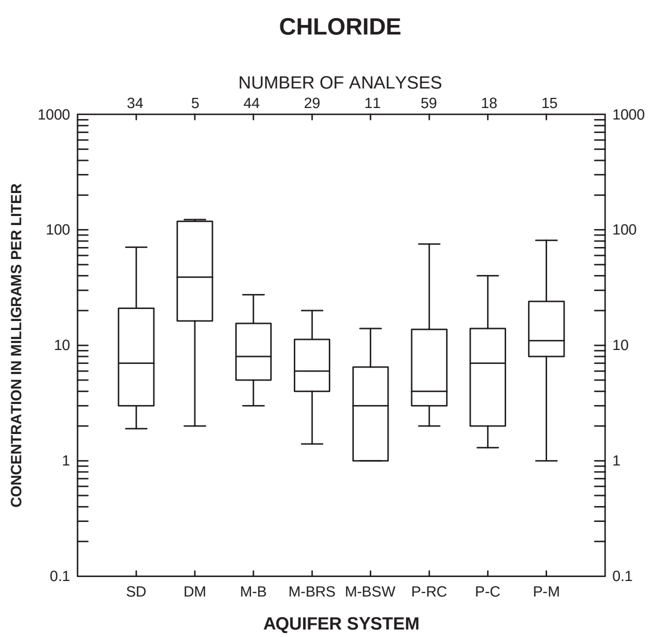


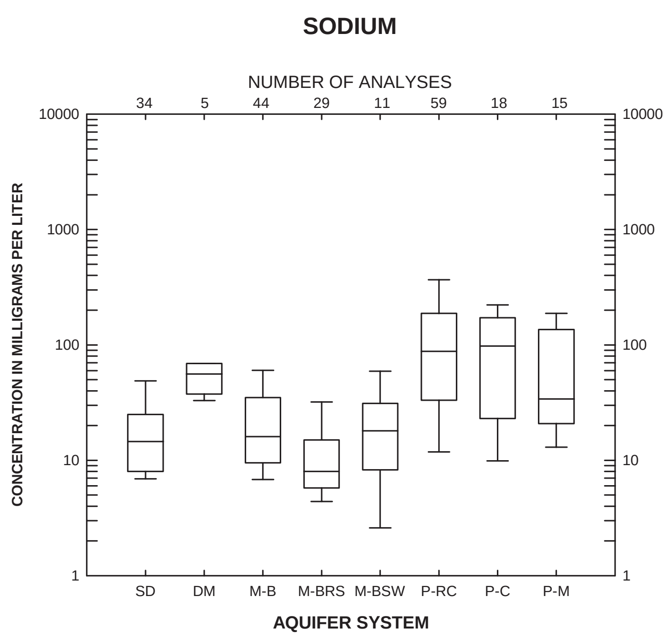


Appendix 4c. Statistical summary of selected water-quality constituents for aquifer systems

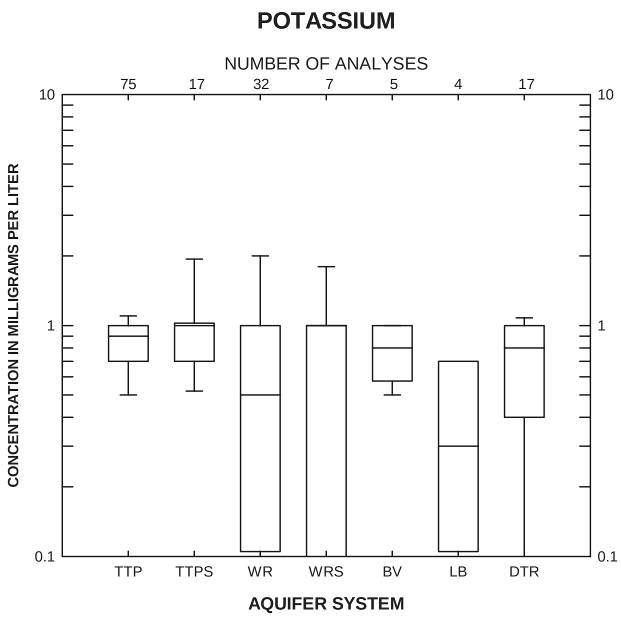


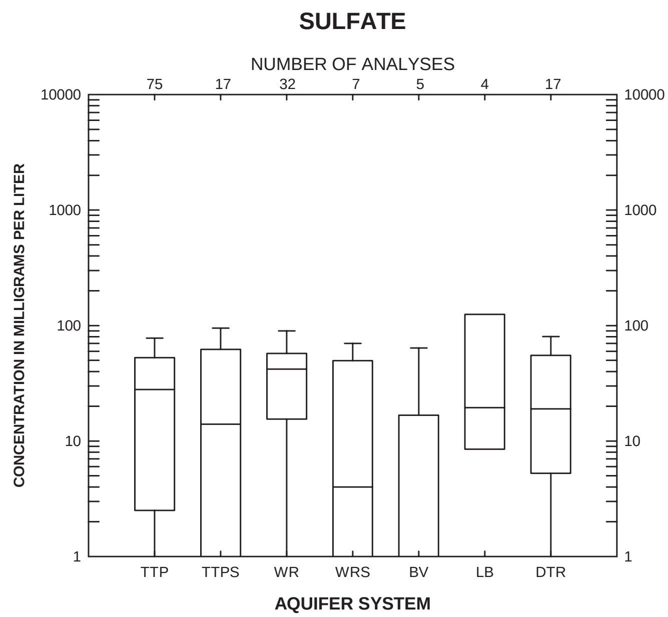


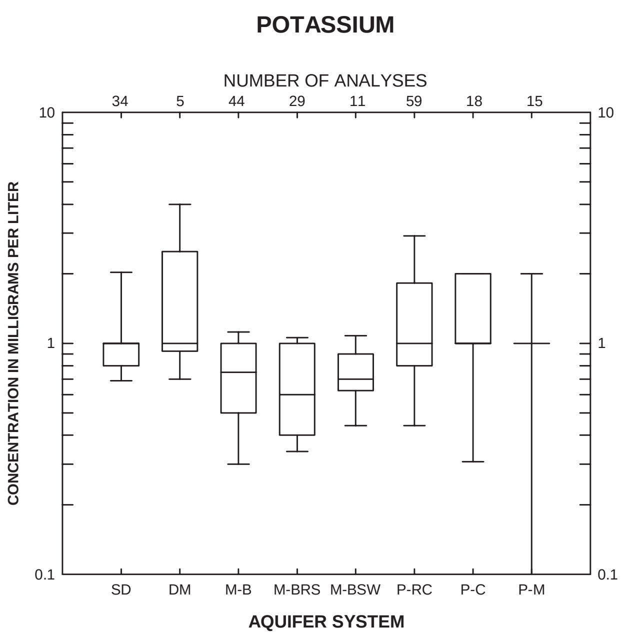


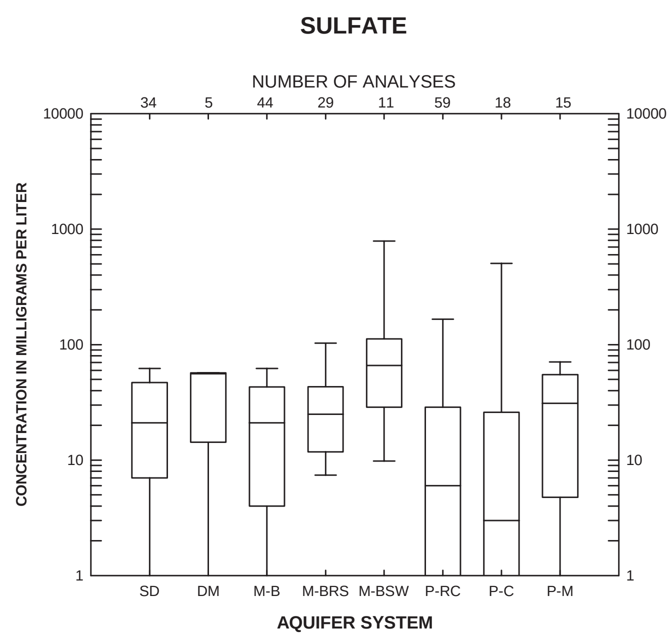


Appendix 4d. Statistical summary of selected water-quality constituents for aquifer systems

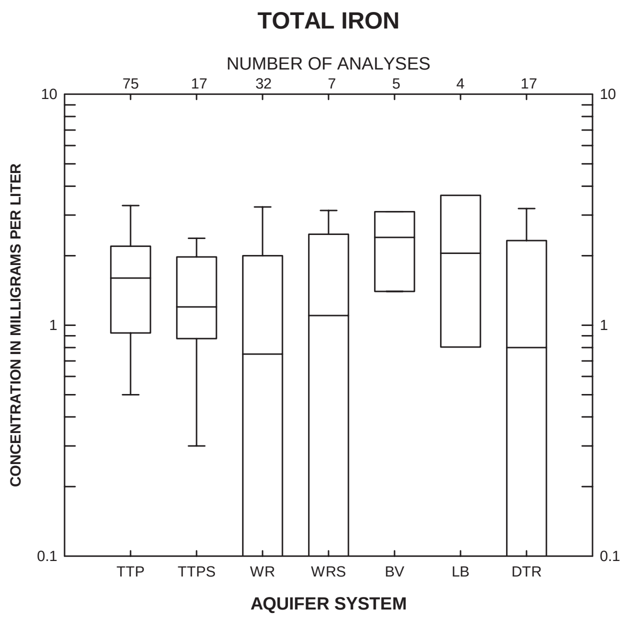


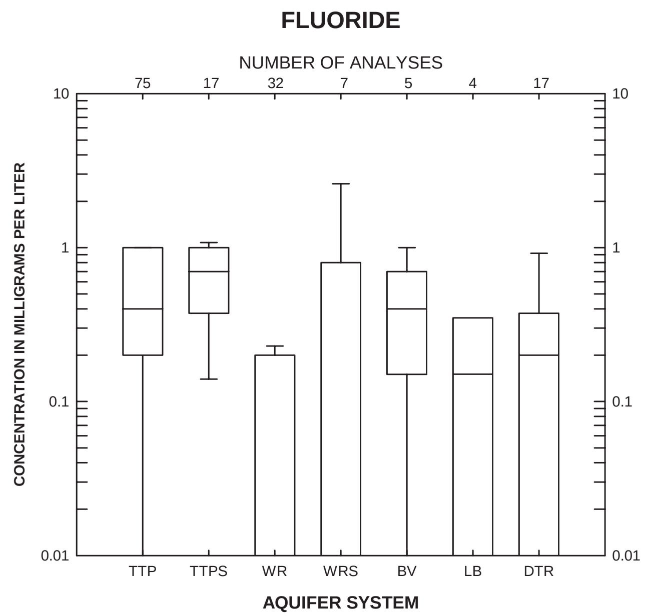


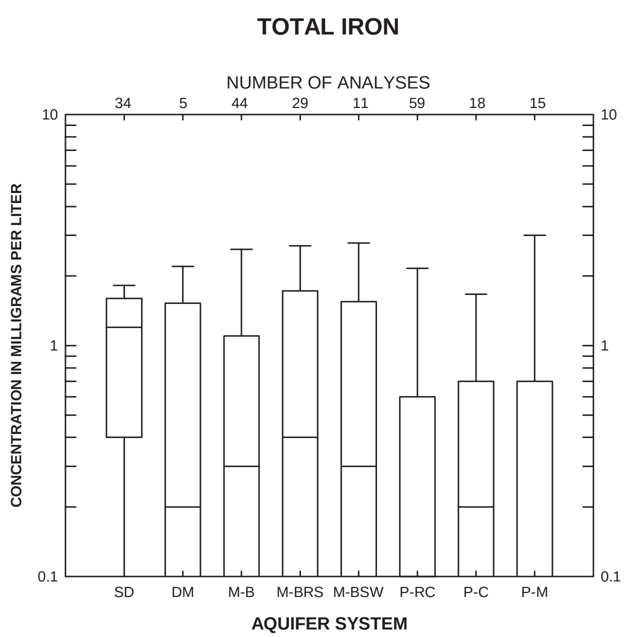


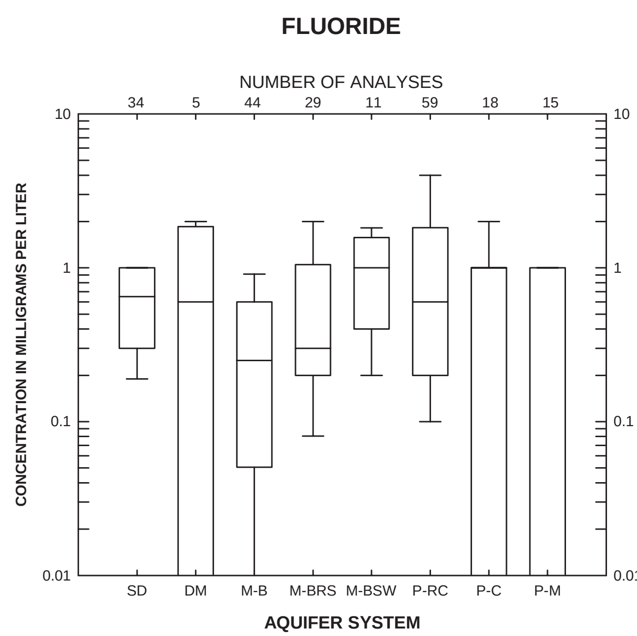


Appendix 4e. Statistical summary of selected water-quality constituents for aquifer systems

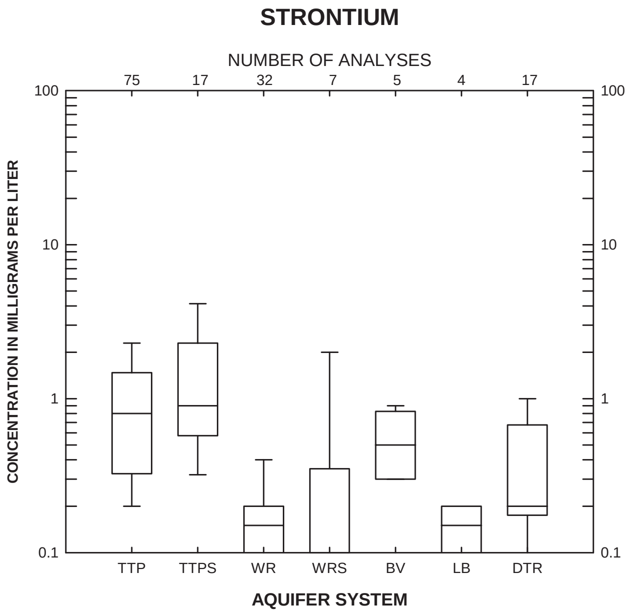


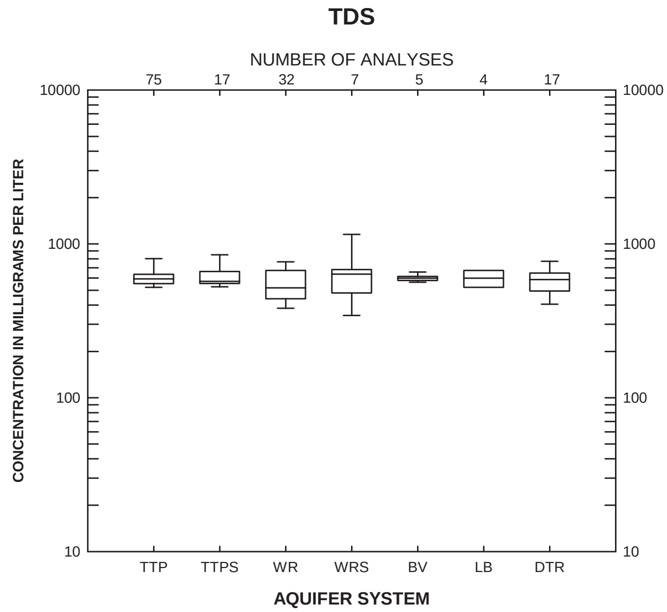


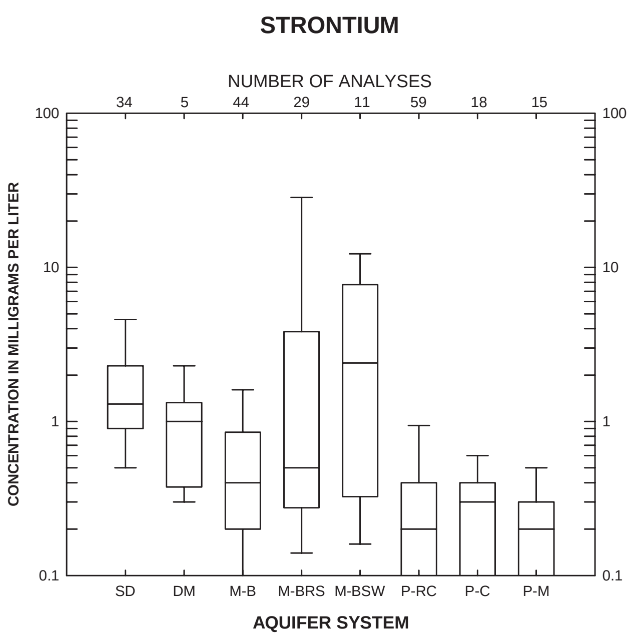


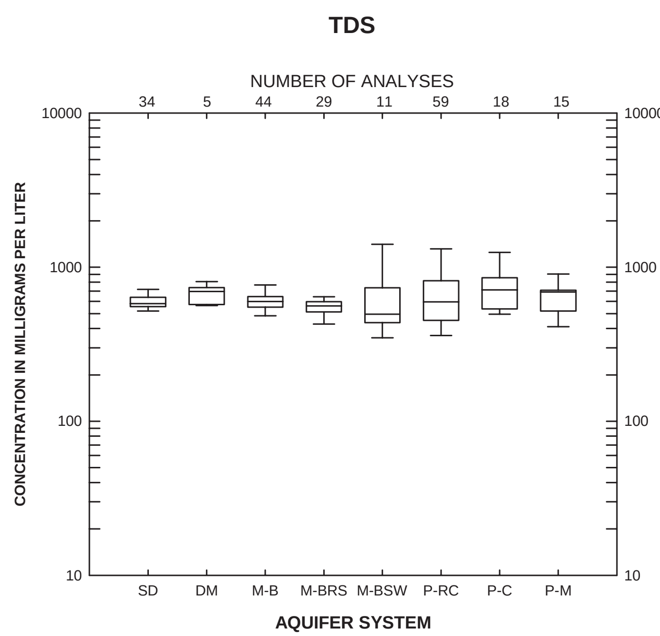


Appendix 4f. Statistical summary of selected water-quality constituents for aquifer systems

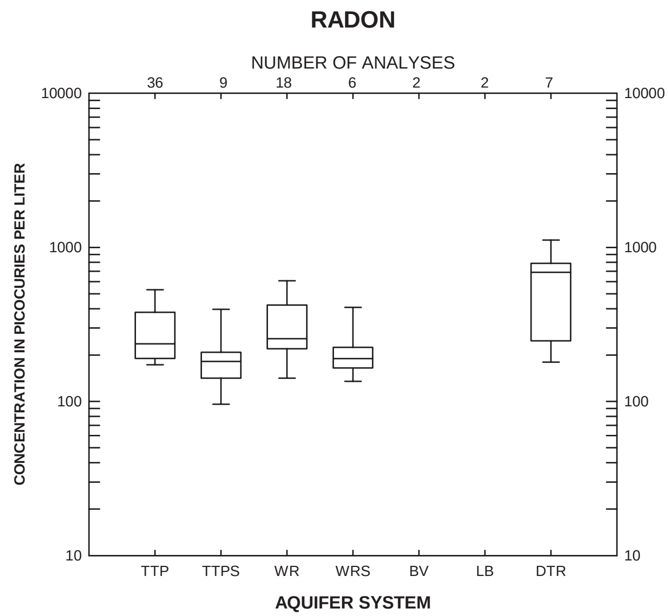


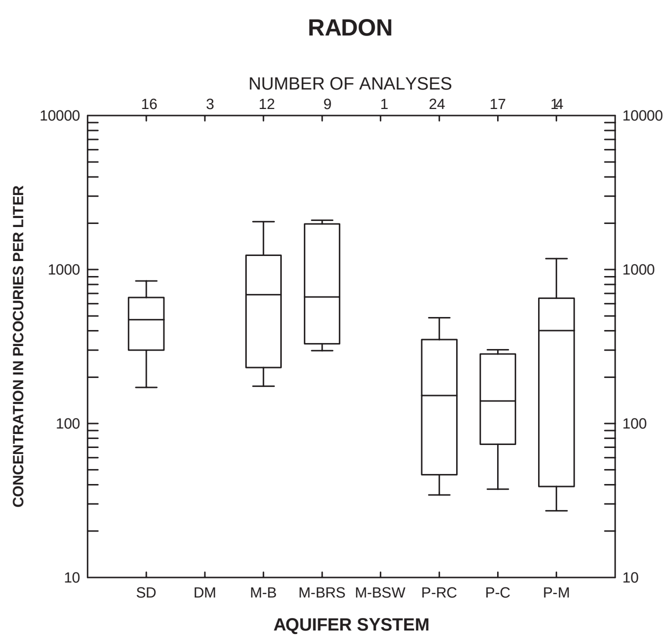






Appendix 4g. Statistical summary of selected water-quality constituents for aquifer systems





Appendix 4h. Statistical summary of selected water-quality constituents for aquifer systems

Appendix 5. Standards and suggested limits for selected inorganic constituents

(All values except pH and are in milligrams per liter. If multiple uses have been designated, the most protective standard applies. Dash indicates no available criterion).

Aquatic life: Values for all constituents except iron, pH, selenium, and silver are 4-day average concentrations; selenium value is the 24-hour average; silver criterion is not to be exceeded at any time. All values are chronic aquatic criteria which apply outside the mixing zone, except for silver which is the acute aquatic criterion. Where applicable, trace metal standards were calculated using a hardness value of 325 milligrams per liter. Except where indicated, all values are from the Indiana Water Pollution Control Board, 1992, IAC 327 2-1-6.

Public supply: Unless otherwise noted, values represent maximum permissible level of contaminant in water at the tap. National secondary regulations (denoted sec) are not enforceable. All values are from the U.S. Environmental Protection Agency, 2001.

Irrigation and livestock: All values are from the U.S. Environmental Protection Agency, 1973.

Constituent	Aquatic life	Public supply	Irrigation	Livestock
Arsenic (trivalent)	0.190	0.01	0.10	0.2
Barium	-	2.0	-	-
Cadmium	0.003	0.005	0.01	0.05
Chloride	230	250 sec	-	-
Chlorine	0.011	-	-	-
Chromium (total)	0.05[a]	0.1	0.1	1.0
Copper	0.032	1.0 sec	0.20	0.5
Cyanide	0.005	0.2	-	-
Fluoride	-	4.0	1.0	2.0
	-	2.0 sec		
Iron	1.00[b]	0.3 sec	5.0	-
Lead	0.014	0.015**	5.0	0.1
Manganese	-	0.05 sec	0.20	-
Mercury (inorganic)	0.012*	0.002	-	0.01
Nickel	0.427	-	0.20	-
Nitrate (asnitrogen)	-	10.0	-	-
pH (standard unit)	6.0-9.0	6.5-8.5 sec	4.5-9.0	-
Selenium	0.035	0.05	0.02	0.05
Silver	0.015	0.1 sec	-	-
Sulfate	-	250 sec	-	-
Total dissolved solids	-	500 sec	500-1000	3000
Zinc	0.288	5 sec	2.0	25.0

* Value is in micrograms per liter
[a] U.S. Environmental Protection Agency, 1973
[b] _____1976
** Action Level