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.

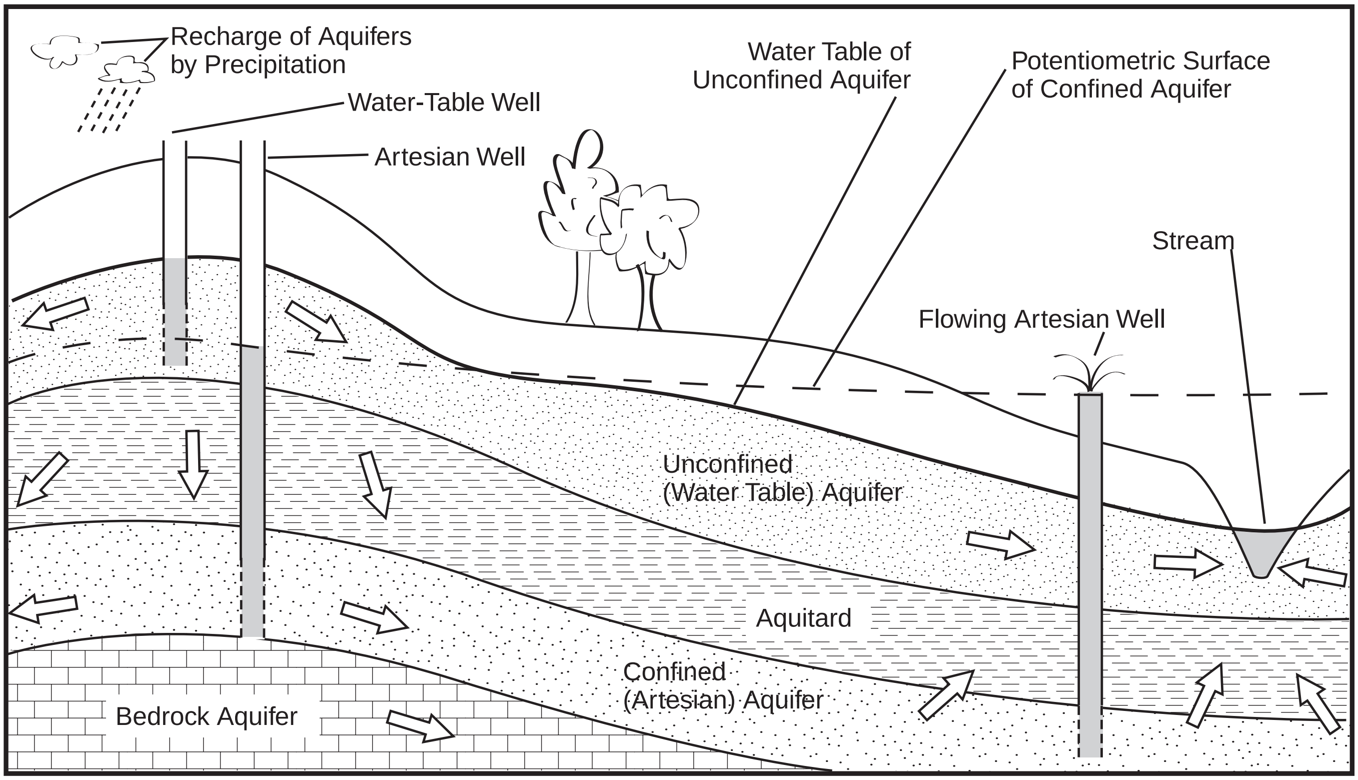


Figure 8: Aquifer types and ground-water movement

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

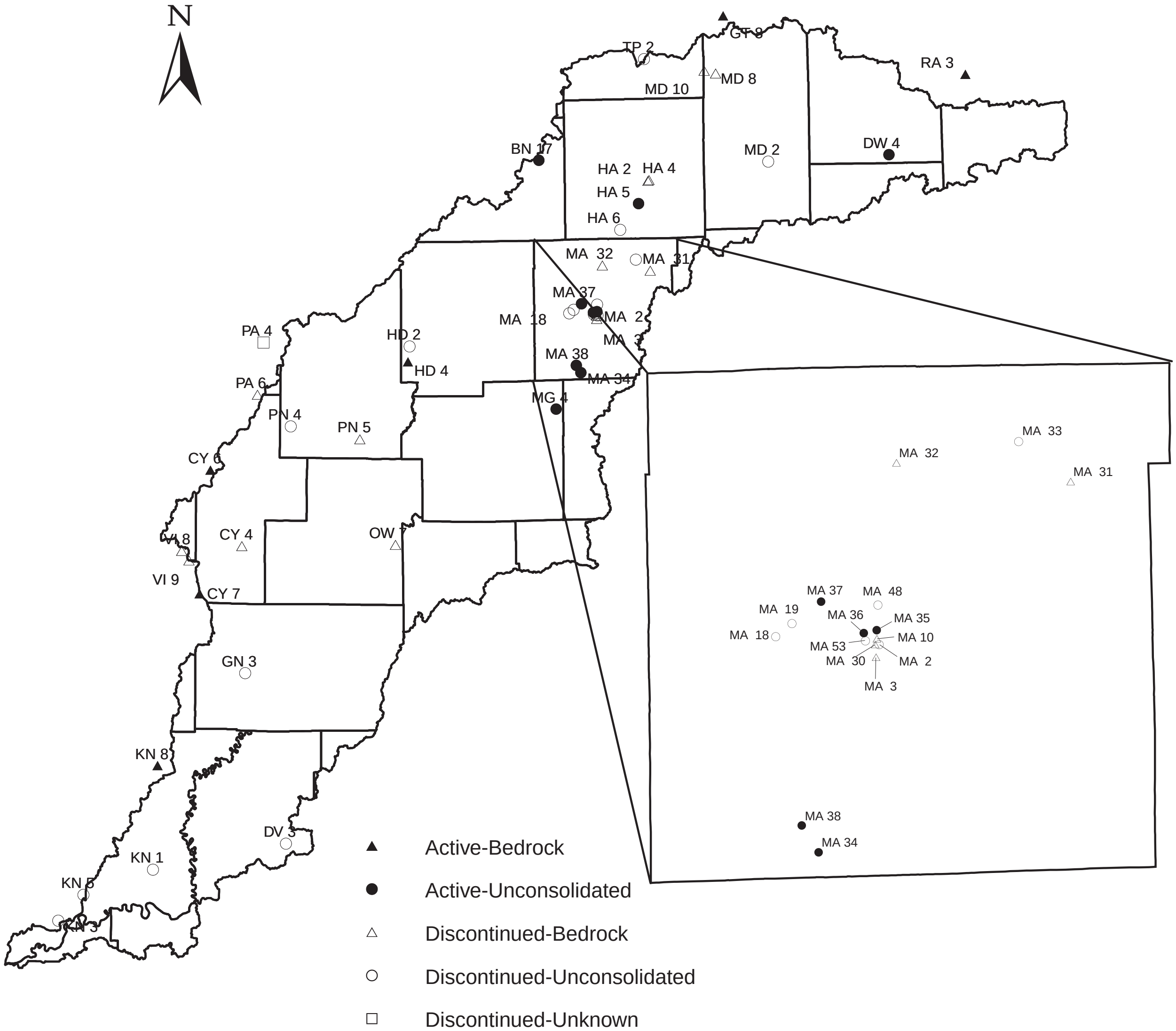


Figure 9. Locations of observation wells in the West Fork White River basin

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.

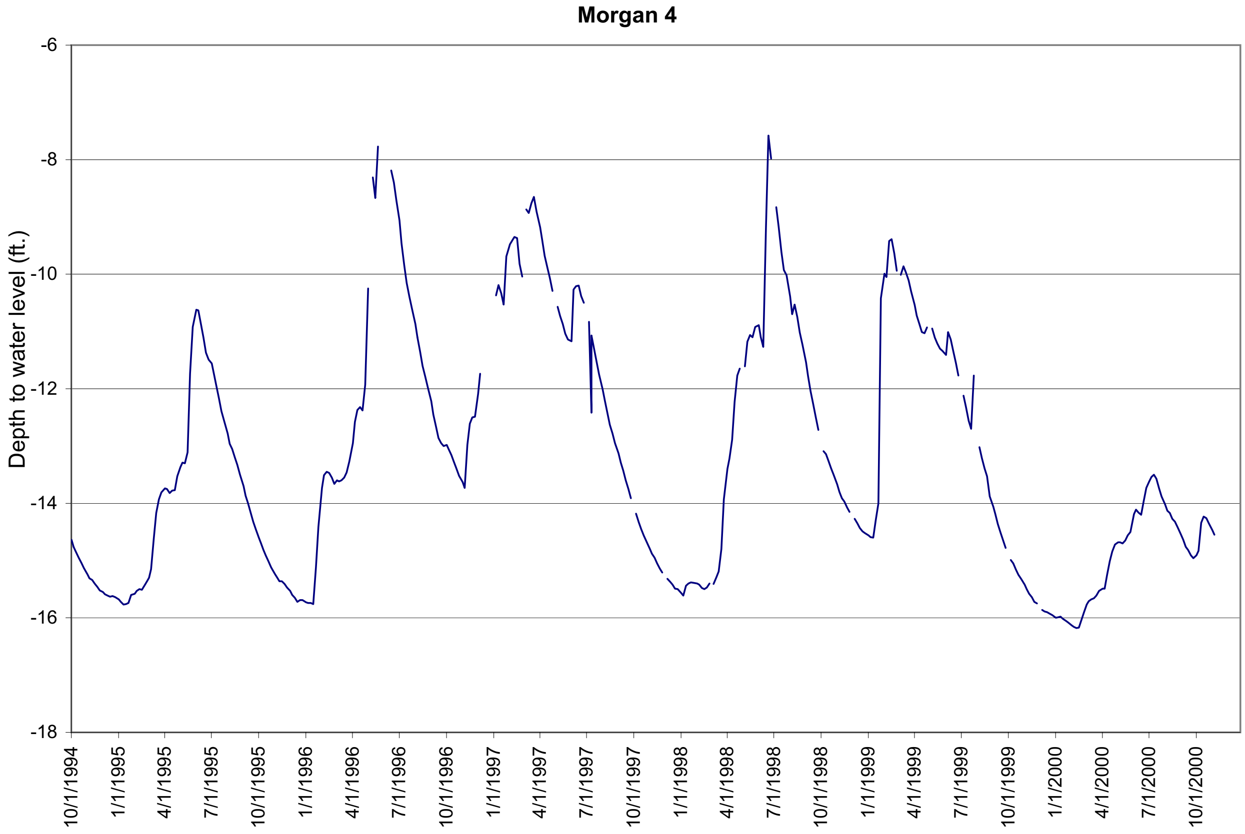
The following discussion of unconsolidated aquifer systems begins in the northern portion of the West Fork White River basin. The locations of the aquifer systems are shown in plate 5. In the northern part of the West Fork White River basin, unconsolidated aquifer systems are the primary source of ground 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

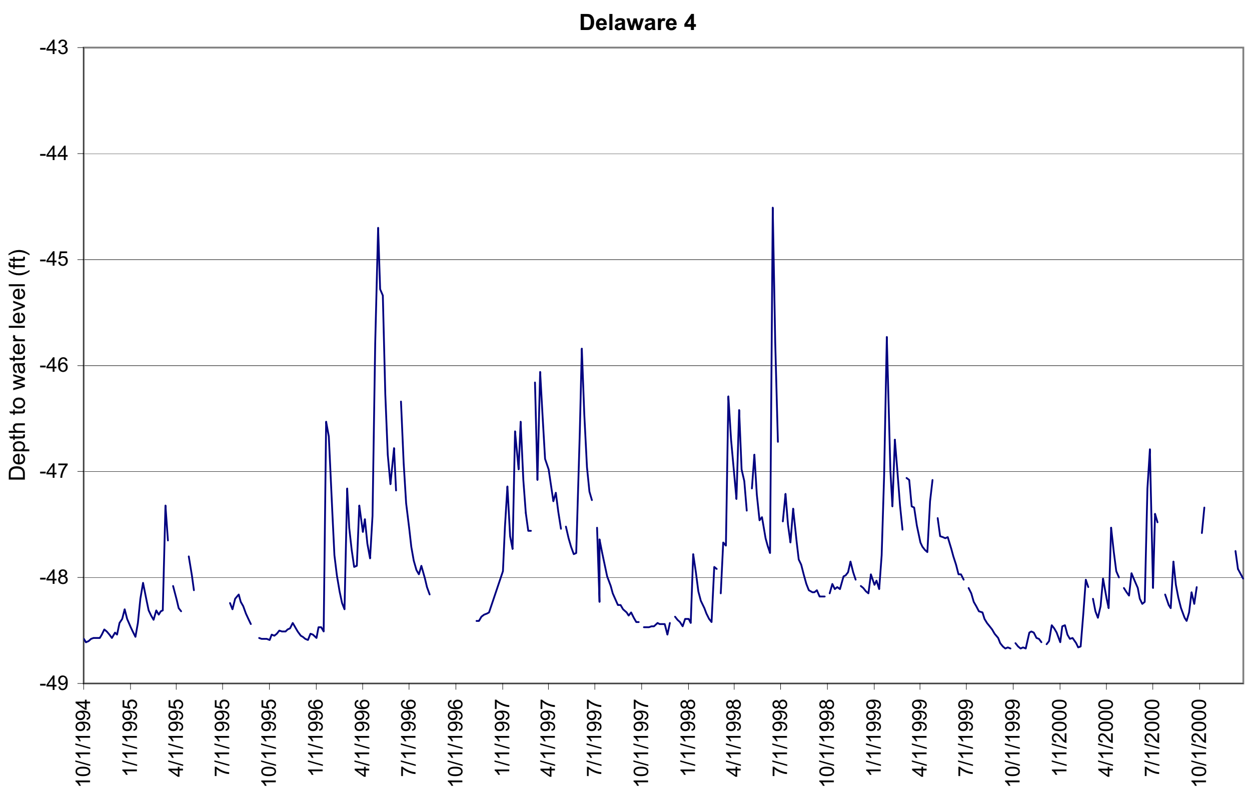
(Equivalent to the Wayne-Henry Aquifer System in the Whitewater River Basin)

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

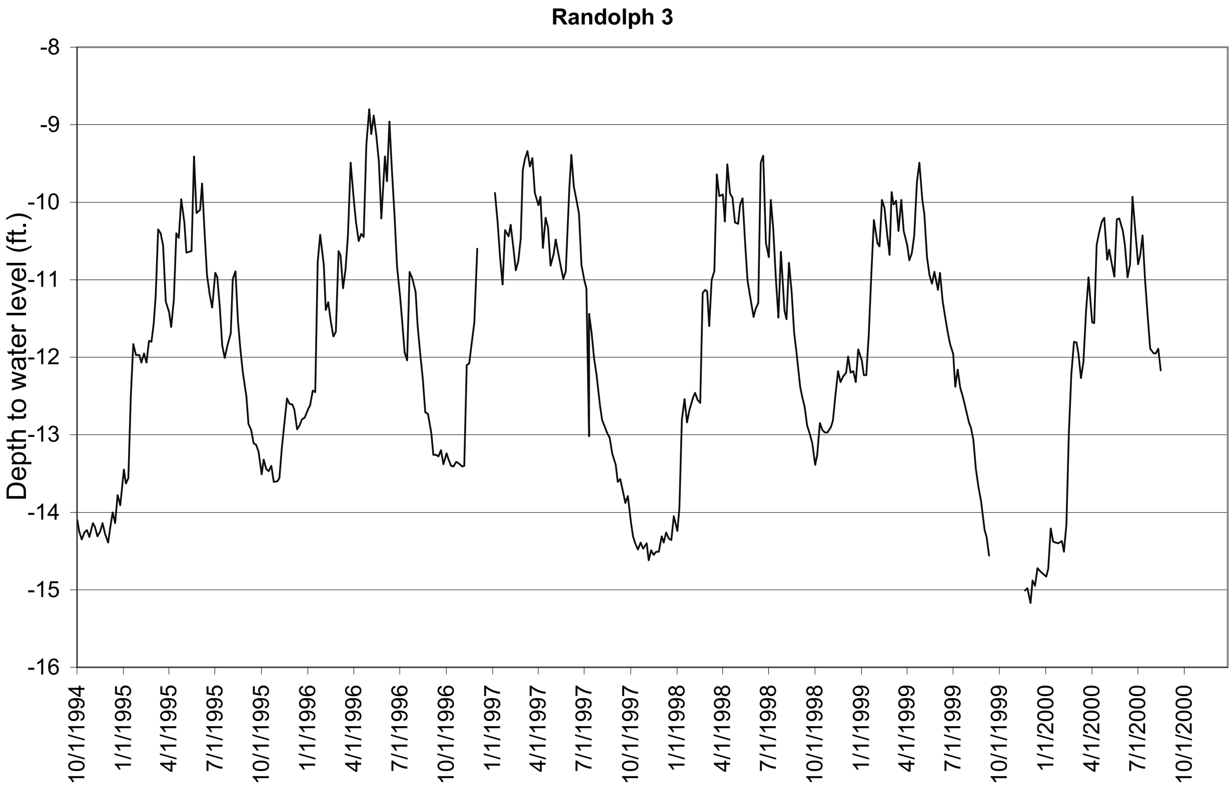


a. Unconfined outwash sand and gravel



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

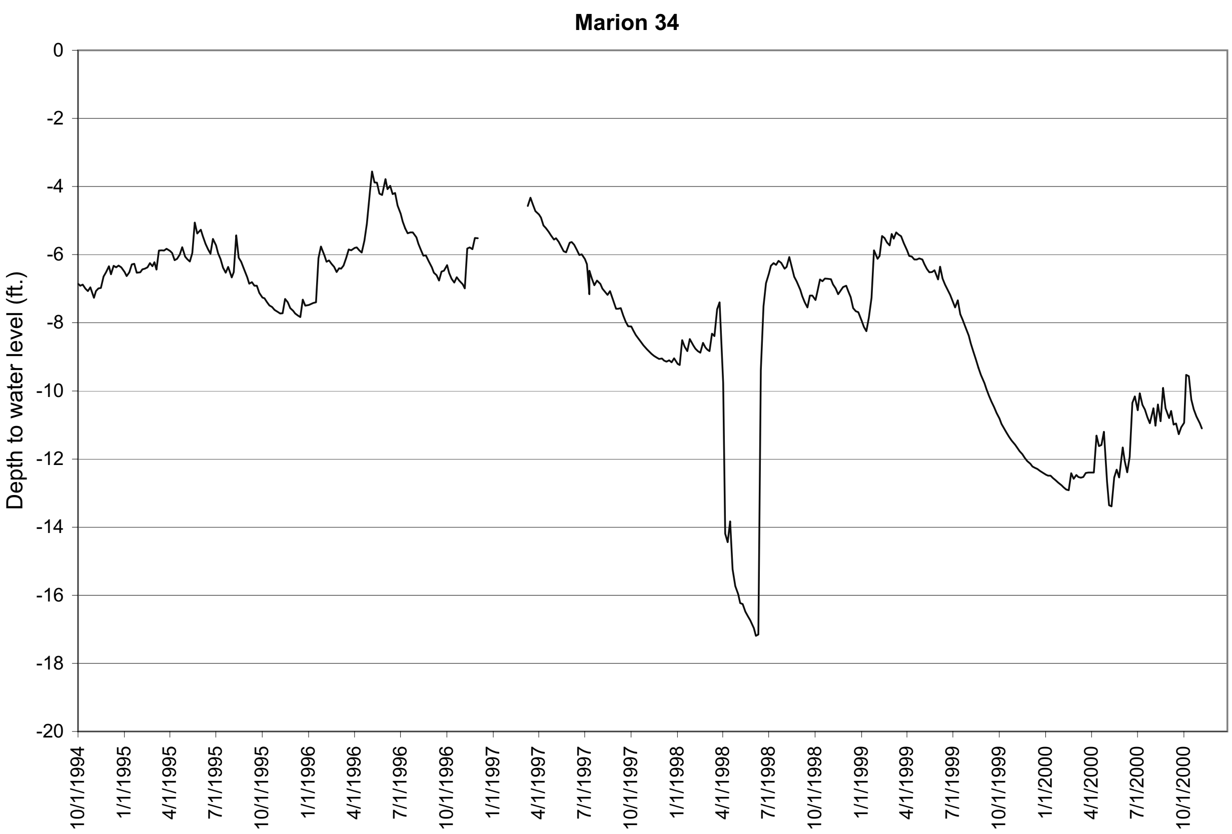


Figure 11: Water-level decline in observation well affected by nearby pumpage

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-

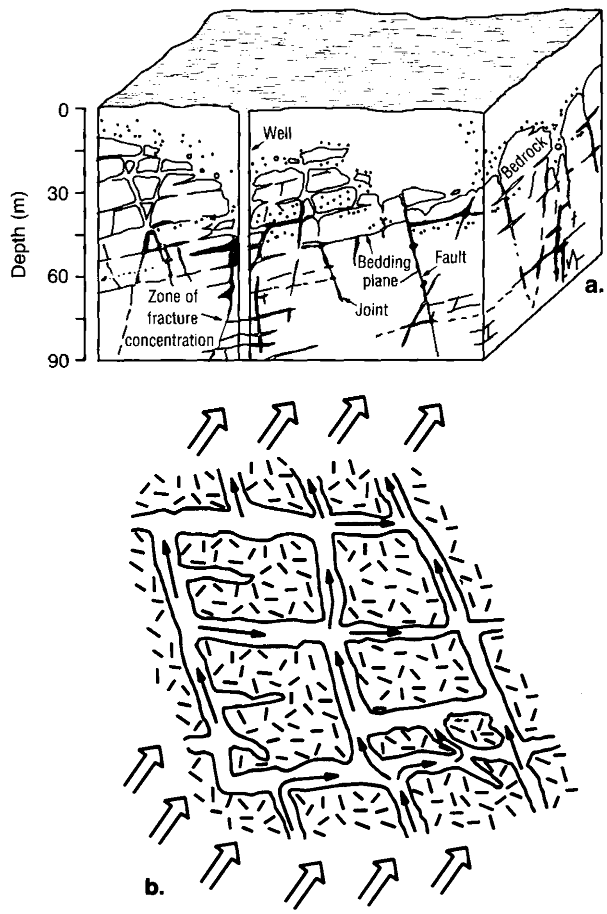
Ground-water flow and the dissolution of carbonate rocks

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

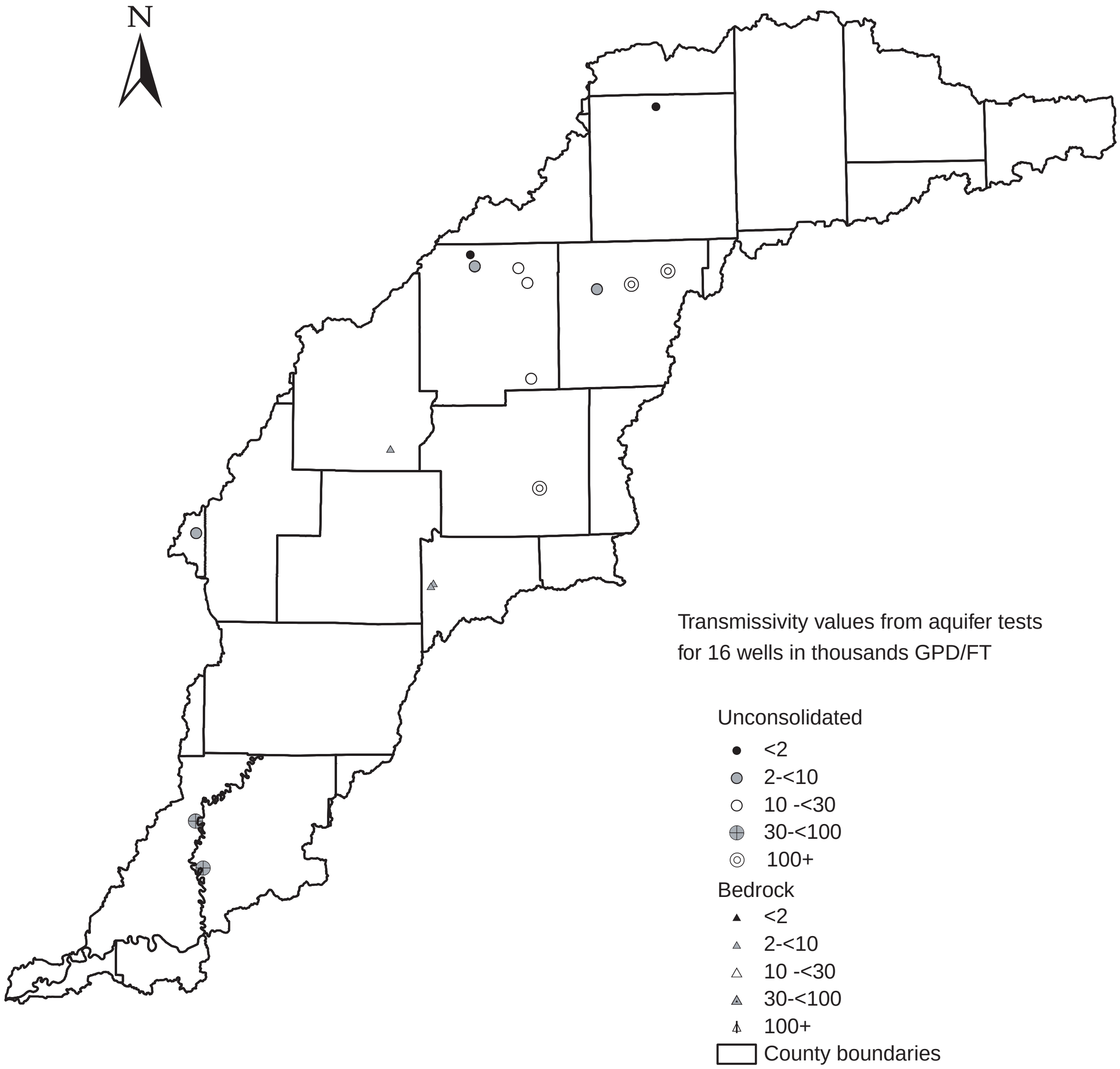


Figure 12. Transmissivity estimates from aquifer tests

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

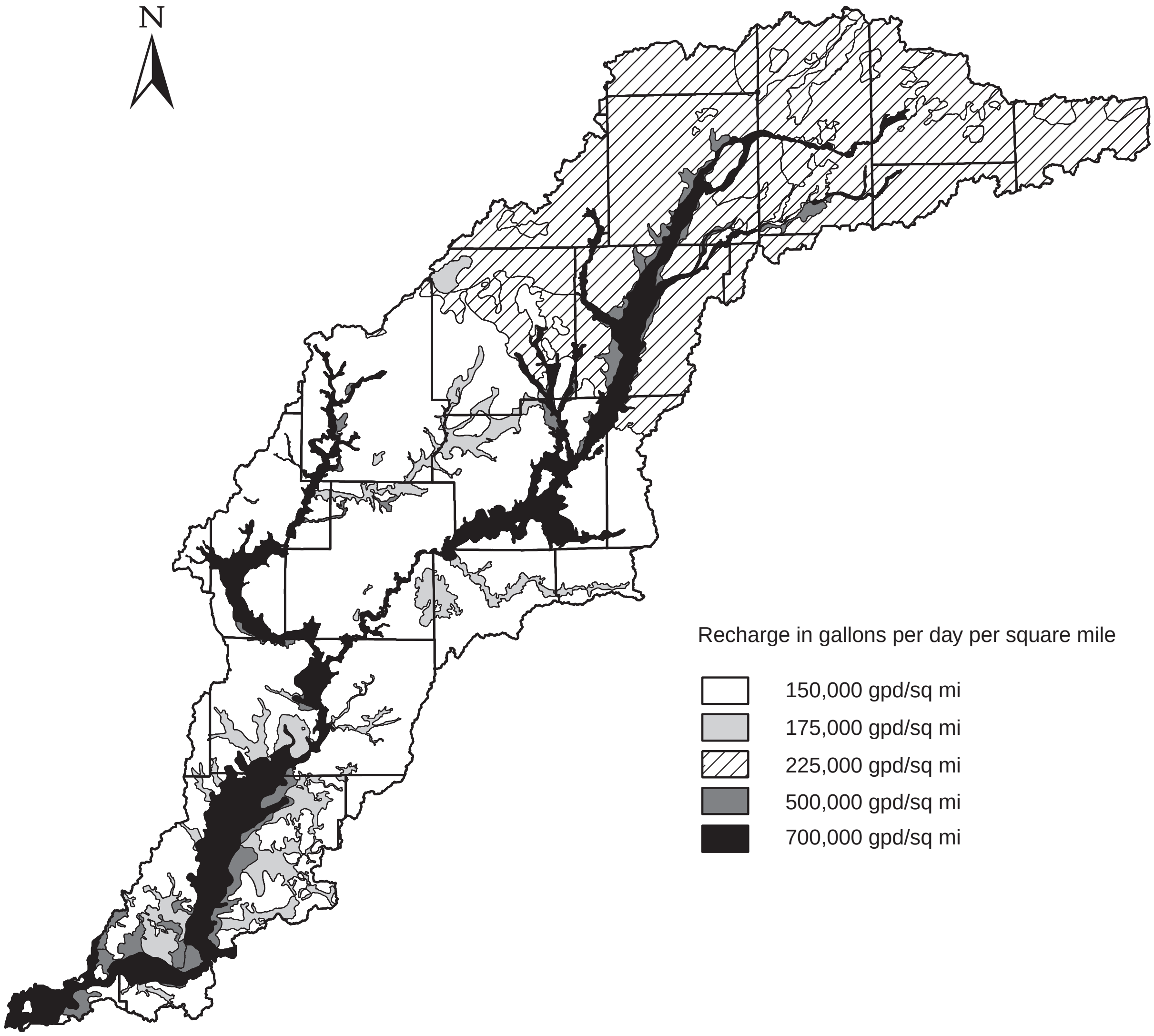


Figure 13a. Estimated recharge rates of unconsolidated aquifer systems

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

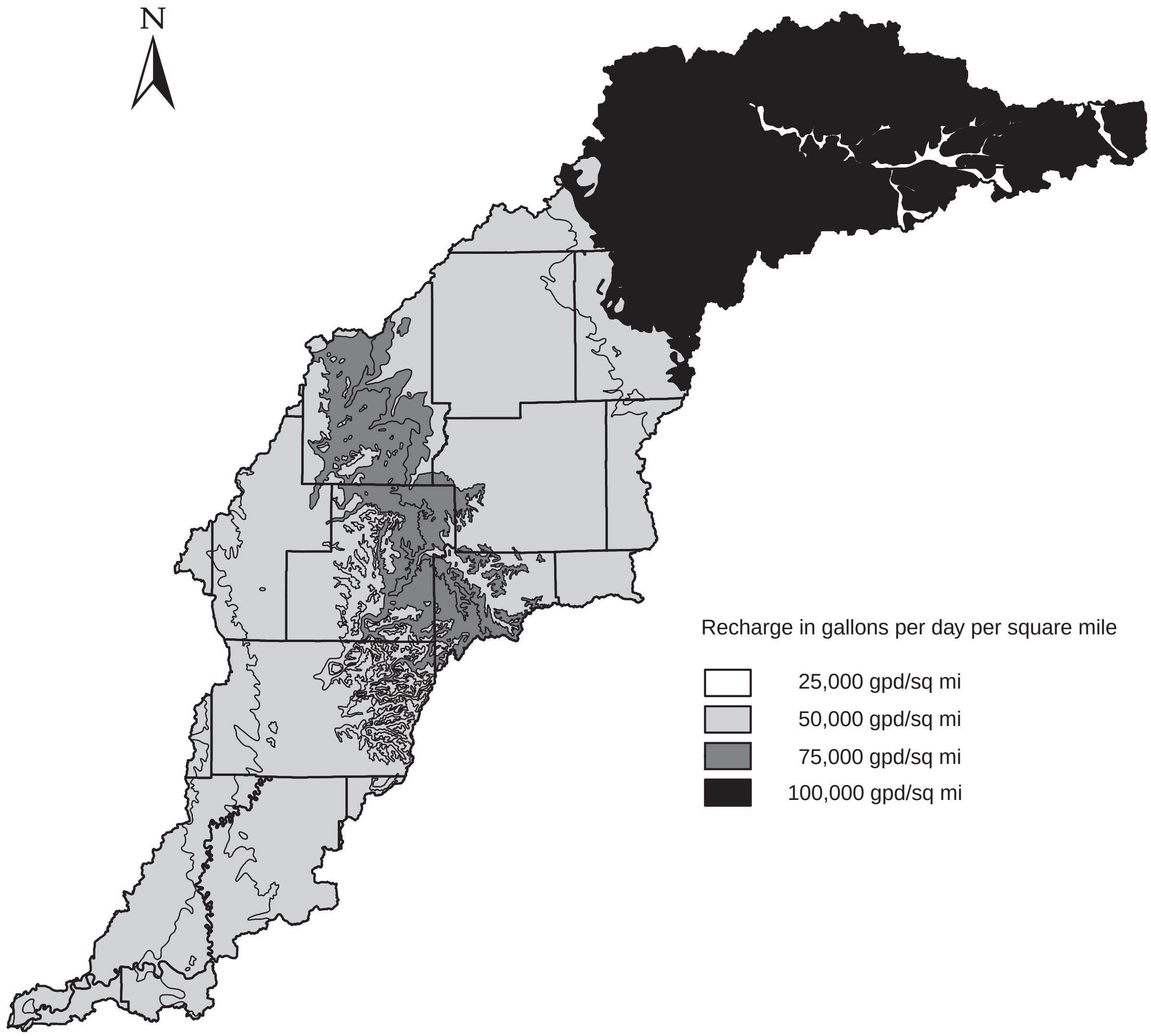


Figure 13b. Estimated recharge rates of bedrock aquifer systems

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