varies from northern to southern Indiana due to variations in geology.

In general, the greater storage capacity of permeable outwash materials in northern Indiana valleys tend to reduce high stream flows. The release of stored water during dry periods augments low stream flows. The combination of these two factors produces a fairly flat duration curve, as represented by the Kankakee River curve in fig. 17. The particularly flat portion at the upper end of the curve in fig. 17 is primarily the result of the large amount of overbank storage available in the Kankakee valley.

In contrast to the Kankakee River's flat duration curve, the duration curve for Graham Creek is quite steep (fig. 17). This narrow channel in southeast Indiana flows across bedrock and thin till of low permeability. Because basin storage is limited, Graham Creek has sharp, rapid flood peaks during storm events, and often ceases to flow during dry periods.

Finally, the curve for the Whitewater River south of Brookville before the completion of Brookville Lake (fig. 17) characterizes a stream system with moderate variability of flow. The fairly high peak flows may be explained by the well-developed drainage system which in its lower reaches covers non-glaciated, highly dissected terrain. The presence of outwash deposits along the major river valleys probably accounts for the moderately sustained low flows.

Within the Whitewater Basin, unit curves for three gages on the Whitewater River (fig. 18) further illustrate the effects of surficial geology on water storage, and subsequently on stream-flow characteristics. The limited amount of ground-water inflow upstream of the Economy gage, as indicated by the steeper low-flow end of the duration curve, can probably be attributed to the small drainage basin and the predominance of till. The flatter duration curves for the Hagerstown and Alpine gages indicate a greater amount of ground-water contribution to these stream reaches, probably from outwash sands and gravels underlying the river valley. The Hagerstown duration curve may reflect a particularly high degree of ground-water discharge to stream reaches near Hagerstown from thick glacial drift filling a bedrock valley (fig. 8).

In contrast to differences in low-flow characteristics along the Whitewater River, higher stream flows per unit of drainage area exhibit close similarity (fig. 18). The similarity of duration curves at unit discharges having exceedance probabilities less than 20 mainly reflects the similarity of climate, land use, and vegetative cover near these three gage sites (see Searcy, 1959). The similarity of flow distribution between the Whitewater River and its east fork is also apparent in fig. 18, as shown by data points for the Abington gage.

Water-Level Correlation

In central Franklin County, the stream gaging station on the Whitewater River and the observation well Franklin-5 are located less than one-quarter mile apart and about 1 mile south of Brookville (fig. 14). Because the Whitewater River at this location and throughout most of its length is developed on outwash sands and gravels, a high degree of hydrologic connection is expected between the river and the ground-water system.

A plot of water-level *hydrographs* for the two monitoring sites near Brookville (fig. 19) provides a graphical comparison of water-level changes in the Whitewater River and the underlying outwash. The figure shows not only the close similarity of water-level changes but also the quick response of the surface-water and ground-water systems to precipitation (as measured in the town of Brookville).

Based on the close similarity of hydrographs, it appears that the Whitewater River is hydrologically connected to the underlying outwash aquifer. However, because a variety of geologic, geomorphic, and topographic factors influence hydrologic interactions between surface-water and ground-water systems, additional data are needed to better characterize these interconnections in the Whitewater River valley.

Hydrograph Separation

Hydrograph separation can be used to divide stream flow (total runoff) into its component parts: surface runoff, interflow, and *ground-water discharge* (base flow). *Surface runoff* is the combination of precipitation falling directly upon the stream and water flowing over the land surface toward the stream (*overland flow*). *Interflow* occurs when precipitation that has infiltrated into the soil moves laterally through the soil to the stream. For convenience, interflow and surface runoff are sometimes combined into one category, *direct runoff*. Base flow represents the portion of stream discharge that is contributed largely or entirely from the ground-water system.

The amount of base flow relative to direct runoff depends on a number of variables, including intensity of precipitation, soil moisture conditions, soil infiltration capacity, underlying geology, and areal basin characteristics. The amount of base flow is one measure of the degree to which stream flow is sustained

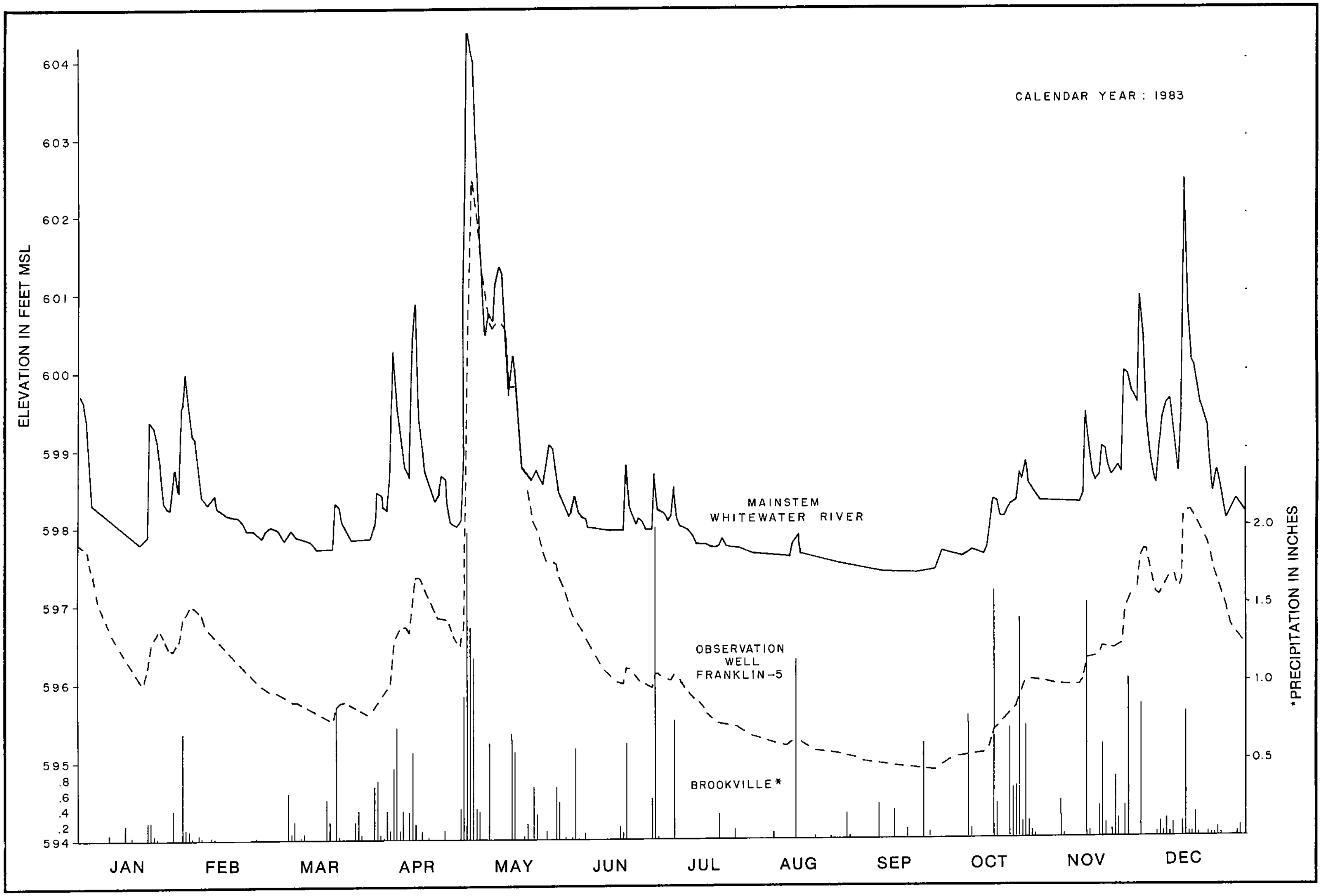

Figure 19. Water-level hydrographs and total daily precipitation near Brookville

Table 10. Ground-water contribution to stream flow based on hydrograph separation

Station number and name		Total drainage area (sq mi)	Water year[1]	Total runoff (inches)	Direct runoff		Ground water	
					inches	percent	inches	percent
03-274650	Whitewater River near Economy	10.4	1977-d	4.25	2.41	57	1.84	43
			1974-n	12.90	7.46	58	5.44	42
03-274750	Whitewater River near Hagerstown	58.7	1977-d	5.87	2.27	39	3.60	61
			1974-n	15.49	6.88	44	8.61	56
03-274950	Little Williams Creek at Connersville	9.16	1977-d	8.83	4.87	55	3.96	45
			1974-n	16.95	9.61	57	7.34	43
03-275000	Whitewater River near Alpine	522	1977-d	5.60	2.40	43	3.20	57
			1974-n	15.61	7.36	47	8.25	53
03-275500	E.F. Whitewater River at Richmond[2]	121	1977-d	4.82	1.95	40	2.87	60
			1974-n	12.20	5.41	44	6.79	56
03-275600	E.F. Whitewater River at Abington	200	1977-d	6.27	2.63	42	3.64	58
			1974-n	15.36	6.97	45	8.39	55
03-276500	Whitewater River at Brookville[3]	1224	1977-d	6.72	2.22	33	4.50	67
			1974-n	13.20	5.01	38	8.19	62

[1]Dry year (d) - 1977; normal year (n) - 1974.
[2]Upstream flow may be affected by municipal water supply diversion.
[3]Flow regulated by Brookville Lake dam since January 1974.

by ground-water contribution.

Graphical techniques exist to separate base flow from the stream-flow hydrograph. App. 6 illustrates a hydrograph separation for a one-year period (water year 1974) at the gage on East Fork Whitewater River at Abington. The base-flow hydrograph shown in app. 6 was used to compute the annual volume of base flow, which was then converted to inches by dividing the calculated volume by drainage area. The percent of base flow was then calculated by dividing the inches of base flow by inches of total runoff. The percent of direct runoff was calculated by dividing the inches of direct runoff by inches of total runoff.

This graphical technique was used to determine the amounts of base flow and direct runoff contributions at seven stream gaging sites in the Whitewater Basin. Hydrograph separations were made for a dry year (1977) and a normal year (1974) to determine if any significant difference exists in the percent of ground-water contribution.

As the results in table 10 show, ground water appears to constitute a slightly higher percentage of total runoff during the dry year analyzed than during the normal year analyzed. In addition, the ground-water contributions for both years are larger than the direct runoff contributions at all gages except Whitewater River near Economy and Little Williams Creek at Connersville. The larger ground-water contributions are on the main channels of the Whitewater drainage system where sand and gravel deposits are more abundant. Because the tributary valleys have less sand and gravel, the tributaries also have less potential *bank storage* and therefore flows are not as well sustained as in the main channels during dry periods.

Effects of Brookville Lake on Downstream Flows

Stream flows at two gaging stations downstream of Brookville Lake are modified by operations at the dam. At the *tailwater* gage on the East Fork Whitewater River (fig. 14, station 03-276000), daily mean flows are noticeably affected. For example, the daily discharge was zero on July 27, 1982 as a result of maintenance activities at the dam. On several other occasions during the post-reservoir period 1975-84, daily mean discharges near zero have been recorded. These unusually low flows typically were interspersed among discharges exceeding 300 cfs.

These extreme variations in daily stream flows are also apparent farther downstream on the mainstem Whitewater River (fig. 14, station 03-276500). At this station, the last 10 years of data reflect not only regulated outflow from the 382 sq. mi. watershed of the East Fork Whitewater River but also unaffected discharge from the 842 sq. mi. Whitewater River subbasin above the east fork. Therefore, reservoir-induced modifications of stream flow at the mainstem gage are somewhat masked. Despite this consideration, however, stream-flow records at the mainstem gage were utilized for the following discussion, primarily because 50 years of pre-reservoir data were available.

The reduction of flood discharges downstream of Brookville Lake can be illustrated by coordinated discharge-frequency values prepared by the Division of Water in cooperation with three federal agencies (Indiana Department of Natural Resources, 1986a). According to these determinations, the *100-year flood* on the Whitewater River at Brookville, as modified by the reservoir, is 59,000 cfs. This flood discharge is 30,000 cfs less than the estimated peak of 89,000 cfs which would have been expected in the absence of reservoir regulation. The 25-year flood is reduced from 68,000 cfs to 45,500 cfs, and the 10-year flood is reduced from 56,000 cfs to 40,000 cfs.

Flow duration curves can illustrate the decreased flood discharges for events of lesser magnitude (for example, discharges less than the 2-year, or average annual flood). A graphical relation for the pre-reservoir period 1929-73 was established between flow duration curves for the Alpine and Brookville stations on the Whitewater River. This graphical relation, assumed to remain valid for the period 1975-84, was then used to estimate the natural (unregulated) flow duration curve for the Brookville gage. The estimated curve for natural conditions was then compared to the actual curve derived from measured discharges during the same 10-year period.

As the resulting curves in fig. 20 show, the flood discharge being equaled or exceeded only 0.1 percent of the time is reduced from 26,000 cfs to 18,000 cfs due to flood control operations at the dam. The 1.0-percent duration discharge is reduced from 13,000 cfs to 8,600 cfs.

To estimate the effect of Brookville Lake on average discharge, the area under the affected duration curve in fig. 20, which represents the average discharge for the entire 10-year period of reservoir regulation, was compared to the area under the curve for unaffected conditions. The resulting values show that the 10-year average discharge for reservoir-affected conditions (1341 cfs) is 2.5 percent less than the unaffected average discharge (estimated to be 1375 cfs). Of this 34 cfs difference, approximately 23 cfs can be attributed to evaporative losses from the large reservoir surface.

Occasional maintenance activities and other infrequent operations at the Brookville Lake dam probably explain the decrease in extremely low stream flows, which is apparent from the lower end of the affected duration curve for the Whitewater River (fig. 20).

The effect of seasonal reservoir operations (fig. 15) on stream flows of the Whitewater River was illustrated by an analysis of monthly mean flows. Regression equations derived from monthly mean flows for March, April, October, and November at Alpine and Brookville were used to estimate monthly means which would have occurred at Brookville each year during

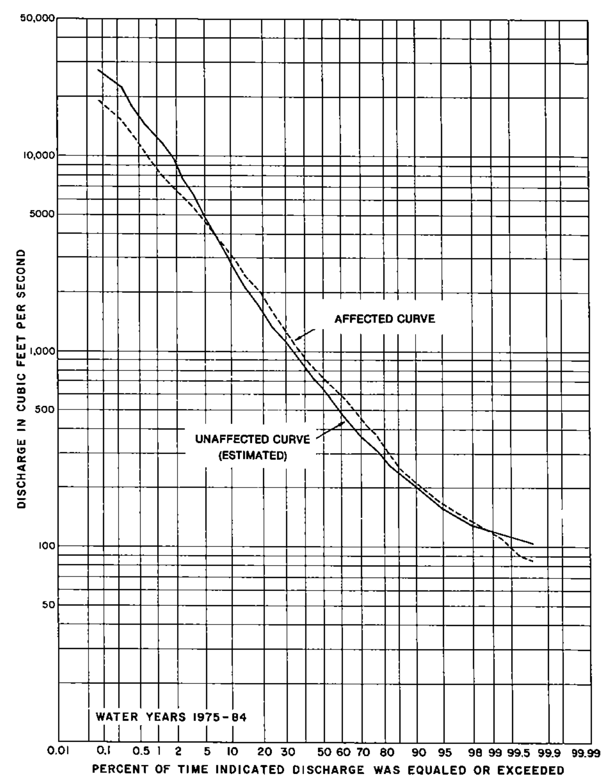

Figure 20. Flow duration curves for Whitewater River at Brookville showing the effects of Brookville Lake

the period 1975-84. These estimated means were then compared to values derived from Brookville's post-reservoir discharge records. This analysis showed that during reservoir filling in March and April, monthly mean stream flows at the Brookville gage are less than flows which would have been expected under natural conditions. Conversely, monthly means during reservoir *drawdown* in October and November are greater than means that would normally have been expected.

Surface-Water Quality

Water quality standards for several designated uses have been adopted by the former Indiana Stream Pollution Control Board (1985) and the former Indiana Environmental Management Board (1979). At the time of this report, these standards are being revised by the Indiana Water Pollution Control Board (1987). App. 7 summarizes state and federal standards current as of early 1987 for public water supply, as well as recommended criteria for aquatic life, irrigation, and livestock watering.

Standards for recreation are intended to maintain the aesthetics of a body of water and to protect the public from possible health risks. Concentrations of *fecal coliform* are used to monitor the suitability of surface water for body-contact recreation. More stringent limits for fecal coliform have been established for *whole-body contact* recreation (swimming— a single sample maximum of 400 cells per 100 ml) than for *partial-body contact* (wading—2000 cells per 100 ml).

In the Whitewater Basin, all lakes and reservoirs, as well as the Whitewater River below its east fork are designated for whole-body contact recreation from April through October (the recreation season), and for partial-body contact recreation from November through March. The remainder of streams in the basin are presently designated for partial-body contact recreation year-round. However, these recreational use designations and standards will be modified to include all waters for whole-body contact if proposed water quality revisions are adopted by the Indiana Water Pollution Control Board (1987).

Two streams in Franklin County are designated for "limited use." The amount of flow and habitat in Richland Creek and its unnamed tributary are insufficient to support diverse communities of fish and other aquatic life. During dry periods, treated effluent from a rubber manufacturing plant provides the only flow in the two streams. The only viable uses for Richland Creek are wading and livestock watering. The unnamed tributary to Richland Creek has no potential for recreational or agricultural uses (Indiana State Board of Health, 1982).

"Exceptional use" streams are high-quality waters which provide exceptional aquatic habitat, support unique assemblages of aquatic organisms, or are integral features of protected or particularly scenic areas. Although no exceptional use streams have been designated in the Whitewater River Basin, a 28-mile segment of the Whitewater River in Franklin County has been recommended for inclusion in Indiana's Natural, Scenic, and Recreational Rivers System (Indiana Department of Natural Resources, 1986b). Inclusion in this system would at least partially protect the river segment from detrimental human impacts.

Surface-Water Quality Data

Surface-water quality data in the Whitewater River Basin can be grouped into two categories, streams and reservoirs. Since 1980, stream quality data have been collected quarterly as near-surface *grab samples* by the Indiana Department of Environmental Management at two stations, the East Fork Whitewater River at Abington and the Whitewater River at Brookville. (Prior to 1980, samples were generally collected on a monthly basis.) Until 1987, the stations at Abington and Brookville were located at the U.S. Geological Survey's stream-flow gaging sites (fig. 14). Recently, however, the stream quality station at Brookville was moved downstream to Cedar Grove.

The stream quality stations at Abington and Brookville (Cedar Grove) are operated as part of a statewide surface-water quality monitoring network established in 1957 by the Indiana State Board of Health. Water quality data for the entire state are published in reports prepared annually by the Department of Environmental Management (and formerly prepared by the Board of Health). App. 8 summarizes water quality constituents at the Abington and Brookville stations having at least 15 values published over a selected 10-year period, 1976-85.

The U.S. Geological Survey collected data for sediment and selected chemical constituents at their Abington stream-flow gage from 1969-76, and some sediment data at the Hagerstown and Alpine gages (fig. 14), primarily during the same period. From 1974-86, the Whitewater River gaging station at Brookville was part of the National Stream Quality Accounting Network (NASQUAN), a nationwide program established in 1972 by the U.S. Geological Survey to statistically test for long-term regional trends in the quality of the nation's surface waters. The NASQUAN site was moved to the station near Alpine in late 1986.

App. 9 is taken from a more comprehensive statistical summary for the NASQUAN gage at Brookville for the 7-year period, 1974-81 (Smith and Alexander, 1983). The appendix lists mean concentrations of 22 common water quality constituents, as well as estimated medians of trace metals for which the detection limit was exceeded in at least half the samples analyzed.

Water quality data for Silver Creek downstream of Whitewater Lake, the East Fork Whitewater River near Liberty, and the East Fork Whitewater River below Brookville Lake dam (fig. 14) are periodically collected by the U.S. Army Corps of Engineers. App. 10 summarizes selected river quality constituents having at least 15 concentration values and for which the detection limit was exceeded in at least half the samples analyzed over the period of record, 1972-86. Fig. 21 illustrates mean concentrations of selected constituents at the three Corps stations and at the U.S. Geological Survey's NASQUAN gage.

Water quality data for Brookville Lake are periodically collected by the U.S. Army Corps of Engineers, primarily at three sites (fig. 14). App. 11 summarizes selected constituents having at least 15 concentration values and for which the detection limit was exceeded in at least half the samples analyzed over the period of record, 1974-86.

Water quality data for Whitewater Lake have been collected primarily as part of special studies by the U.S. Environmental Protection Agency (1976a) and the Indiana State Board of Health (data unpublished). In addition, bacterial counts at the swimming beach are monitored weekly by the Board of Health during the recreation season.

The Indiana-American Water Company's Richmond District withdraws approximately 60 percent of its water from Middle Fork Reservoir, and 40 percent from ground water. Water quality parameters affecting water treatment and public health are monitored daily by the utility. Measured parameters for reservoir water include turbidity, iron, manganese, pH, hardness, alkalinity, odor, bacteria, and chlorine residual. Additional samples from the reservoir are collected twice a year for determination of major inorganic ions, trace metals, and organic pollutants.

Streams

Based upon available data, water quality is generally considered good in the Whitewater River and its east fork. Standards for public water supply and aquatic life have not been exceeded in samples collected by the In-

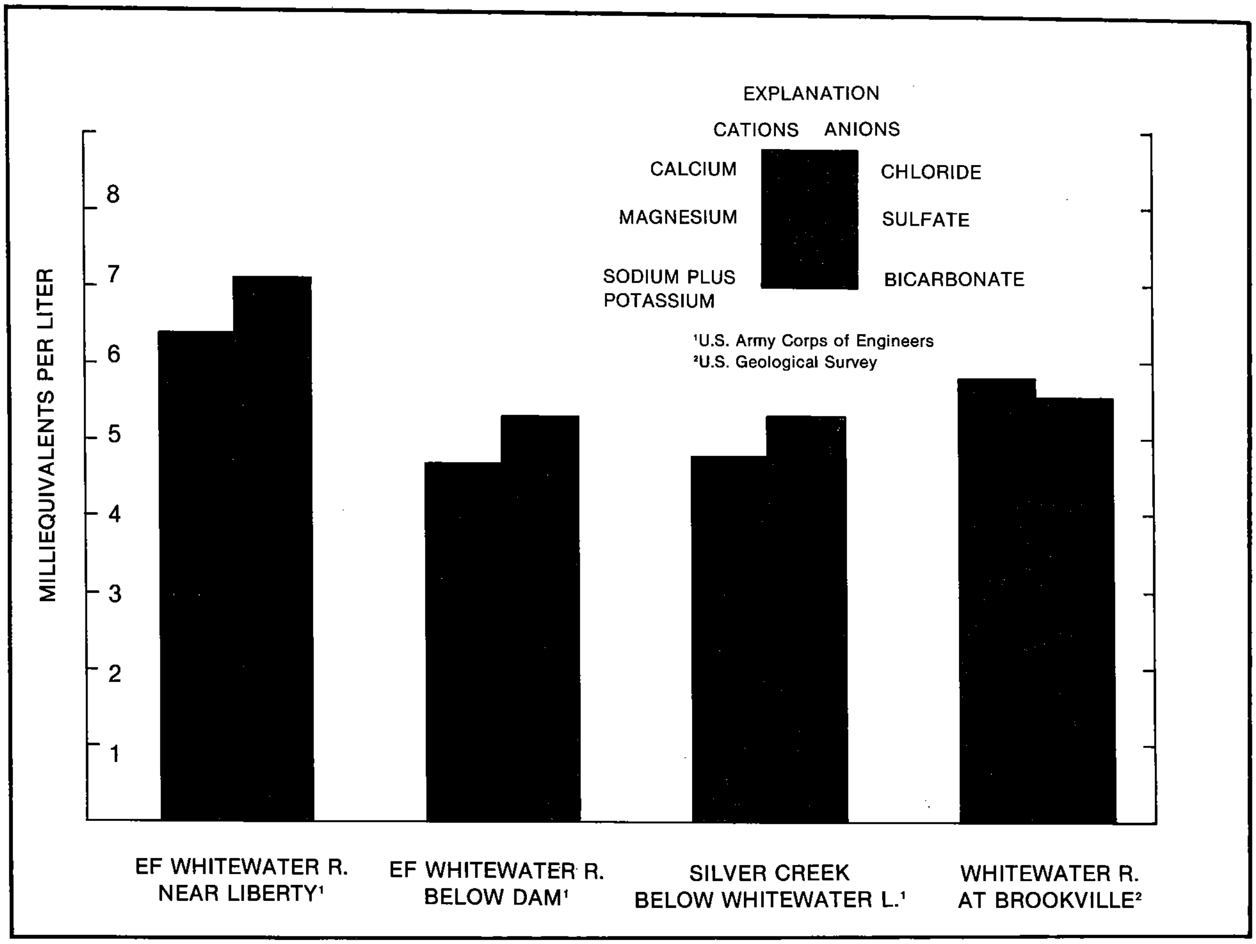

Figure 21. Comparison of major chemical constituents at selected stream quality stations

diana Department of Environmental Management at their Abington and Brookville stations during the past 10 years (1976-85). Nutrients (phosphorus and inorganic nitrogen) have sometimes been present in concentrations greater than those recommended for the prevention of nuisance algal growth in flowing waters, but excessive *phytoplankton* populations have not been recorded, and mean nutrient values are fairly low. High fecal coliform concentrations occasionally found in the Whitewater River and its east fork, however, indicate the presence of point and/or non-point sources of pollution. High fecal coliform counts often are associated with municipal discharges, *combined sewer overflows*, and/or agricultural runoff.

On the Whitewater River at Brookville, fecal coliform concentrations from April through November sometimes exceed the standard for whole-body contact recreation (400 cells per 100 ml). Violations recorded by the Indiana Department of Environmental Management (IDEM) at their former monitoring site ranged from 610 to 110,000 cells per 100 ml during the 10-year period, 1976-85. These and other excessive values, although interspersed among much lower concentrations, produce a skewed mean, as app. 8 shows.

At the Brookville monitoring station, located about 0.4 mile downstream of the Brookville sewage treatment plant, nearly two-thirds of the samples collected by the IDEM from 1976-79 during the recreation season violated the whole-body contact standard. About half of the quarterly samples collected from 1980-85 during the recreation season violated the standard. In contrast, only 6 percent of the samples collected from November to March for the period 1976-79 violated the standard for partial-body contact recreation (2000 cells per 100 ml), while one-third violated the standard from 1980-85.

Only occasional fecal coliform violations of the partial-body contact standard have been recorded downstream of the Connersville wastewater treatment plant, the largest point-source discharge on the Whitewater River. Dissolved oxygen and ammonia violations downstream of Connersville seldom occur (Indiana Department of Environmental Management, [1986]).

On the East Fork Whitewater River downstream of Richmond, fecal coliform standards for partial-body contact recreation (2000 cells per 100 ml) have been violated in only 10 to 20 percent of the samples collected by the IDEM during the period 1976-85. The average frequency of occurrence during the past 10 years has remained about the same (approximately one violation per year per sample set). Although the river reach near Abington is not designated for whole-body contact recreation, nearly 60 percent of the samples collected from 1976-85 had fecal coliform values less than 400 cells per 100 ml, the maximum permissible concentration in other waters which are used for whole-body contact recreation.

Reservoirs

Middle Fork Reservoir, Whitewater Lake, and Brookville Lake represent three moderately *eutrophic* lakes of either large acreage (Brookville Lake) or shallow mean depth. According to the lake classification system used by the Indiana Department of Environmental Management (1986), water quality problems in these lakes are infrequent, and designated aquatic life and recreational uses are rarely if ever impaired. To help maintain the good conditions in these lakes, the IDEM has recommended the control of nutrient input via phosphorus removal at wastewater treatment facilities, landuse management, and the control of septic tank seepage.

The IDEM uses 10 trophic parameters to derive a composite numerical index scaled from 0 to 75, which defines a generic four-tiered classification of lakes throughout Indiana. An index of 75 and a Class 4 designation would represent the most eutrophic conditions, for example. According to this classification scheme, Middle Fork Reservoir has a Eutrophication Index of 18 and is designated as a Class 1 lake (Indiana Department of Environmental Management, 1986).

Compared with the other two lakes of record in the basin, Middle Fork Reservoir is considered by the IDEM to be the least eutrophic. The reservoir is characterized by low nutrient concentrations, low turbitity, and small, diverse populations of phytoplankton and *macrophytes*. With respect to primary and secondary drinking-water regulations (app. 7), only concentrations of iron and manganese in raw water samples occasionally exceed the secondary levels for finished drinking water. Other inorganic parameters have been within acceptable limits, and no organic pollutants have been detected (K. Cooper, Indiana-American Water Company, personal communication, 1987).

Whitewater Lake, the most eutrophic of the three basin lakes, is an Index 29, Class 2 lake. When the U.S. Environmental Protection Agency sampled 27 Indiana lakes in 1973 for a combination of six parameters, Whitewater Lake ranked 24th in overall trophic quality (U.S. Environmental Protection Agency, 1976a).

Subsequent sampling by the Indiana State Board of Health in 1975 and 1976 showed an improvement in Whitewater Lake's trophic condition, as evidenced by a decrease in nutrient concentrations, phytoplankton counts, and turbidity. Although the lake is still considered eutrophic, recreational uses at the beach have rarely been impaired due to excessive algal or macrophyte development or high coliform counts (W. McInerny, IDNR Division of Engineering, personal communication, 1987). However, because of a recurring problem with siltation, the lake has been dredged periodically since 1978 (M. Gentry, IDNR Division of State Parks, personal communication, 1987).

Brookville Lake, Indiana's second deepest manmade reservoir, is a large, moderately eutrophic lake of good water quality (Index 21, Class 1). The eutrophication index computed by the IDEM in 1985 is only two eutrophy points less than the index calculated in 1979, which indicates a stability of the lake's overall water quality.

Epilimnetic total phosphorus in Brookville Lake was the lowest of 12 Indiana lakes and reservoirs recently sampled by the IDEM, and phosphorus levels were less than the detection level of 0.03 mg/l in all three sections of the lake that were tested. (The maximum total phosphorus concentration recommended for prevention of nuisance algal production in non-flowing waters is 0.05 mg/l; Hardy, 1984). Fish and sediment samples collected in 1985 contained no *toxic* substances such as metals, *polychlorinated biphenyls*, and pesticides in amounts great enough to be of concern (Indiana Department of Environmental Management, [1986]).

Both beneficial and detrimental effects on water quality can result from impounding water. Some beneficial effects of Brookville Lake on the water quality of East Fork Whitewater River include reductions in turbidity, alkalinity, hardness, and biochemical oxygen demand, primarily due to the decreased turbulence and longer residence time of reservoir water. The reduction in bicarbonate, the major component of alkalinity, is apparent from fig. 21 for the two stations on the East Fork Whitewater River upstream and downstream of Brookville Lake. The figure also shows the reduction of calcium and magnesium, the principal components of hardness.

A major detrimental effect due to impounding river water results from thermal stratification and the consequent degradation of water quality in the lower layer of the reservoir, or *hypolimnion*. Summer stratification of Brookville Lake, which occurs when surficial waters are heated by the sun, can be illustrated by depth profiles of selected constituents in the lake's deepest basin (fig. 22).

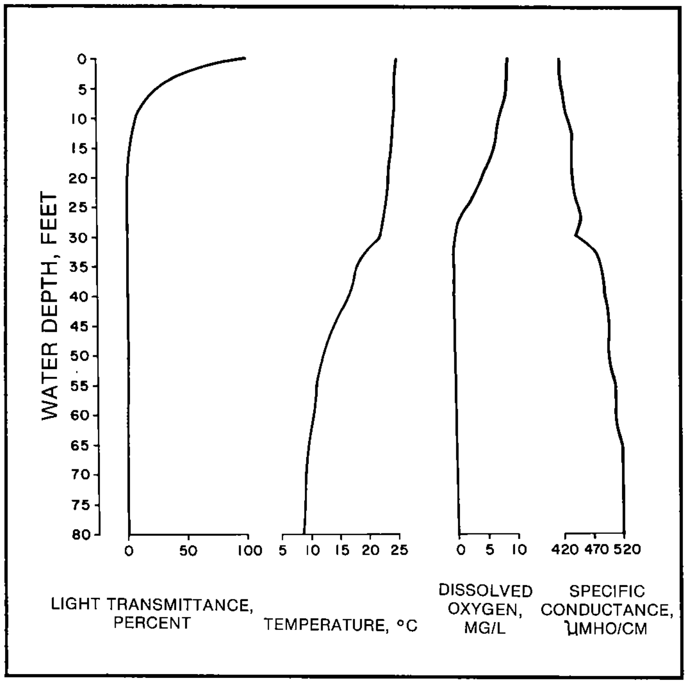

Figure 22. Depth profiles of selected physical parameters at Brookville Lake near dam

(Data from the Indiana Department of Environmental Management, August 1985)

As is typical in a thermally stratified lake, the abundance of suspended matter limits the penetration of sunlight to the hypolimnion; consequently, oxygen-producing photosynthesis does not occur and the hypolimnion becomes anoxic (fig. 22). Although the anoxic conditions can impact downstream water quality if hypolimnetic lake water is released, no detrimental impacts have been documented. An anoxic hypolimnion also limits the usefulness of bottom waters as fish habitat, but no significant decrease in the quality of fisheries has been observed (D. Kingsley, IDNR Division of Fish and Wildlife, personal communication, 1987). Other effects and potential effects of impoundment on water quality and biota are discussed in an environmental impact statement by the U.S. Army Corps of Engineers (1974).

GROUND-WATER HYDROLOGY

Ground-Water Data

Ground-water data for the Whitewater River Basin come from several sources, including water-well records, the observation well network, lithologic logs, seismic information, and localized project data (for example, pumping tests and other analytical and mathematical models).

Since 1959, water-well drilling contractors have been required to submit a complete record to the IDNR of every water well that is drilled. More than 3000 water-well records maintained in the IDNR, Division of Water files for the Whitewater River Basin were reviewed and screened for the ground-water assessment portion of this study. Most of the records are for wells less than 150 feet in depth.

Water-level data in the Whitewater River Basin have been collected from observation wells by the U.S. Geological Survey in cooperation with the IDNR (formerly the Department of Conservation) since 1946. In northwestern Fayette County (fig. 14), observation well Fayette-2 monitored ground-water levels from 1946 to 1970. In central Union County, observation well Union-6 began recording in 1966, but was discontinued in 1974. Fayette-2 was used to record water-level changes within till and Union-6 monitored the ground water in limestone bedrock.

From 1966 to present, water-level data have been collected from observation well Wayne-6 located in southwestern Wayne County (fig. 14). In central Franklin County, observation well Franklin-5 has recorded ground-water level data for the periods of 1968 to 1971 and 1974 to present. The two wells monitor natural fluctuations in water levels within Pleistocene outwash deposits.

The water-level fluctuations for Wayne-6 and Franklin-5 (fig. 23) are typical of the changes expected for outwash *aquifers*. During the wet seasons of winter and spring, the water level plots show a rise in the *piezometric surface*. In the summer and autumn, the water levels fall in response to decreased aquifer *recharge*. Data for all of the years plotted in fig. 23 show this same pattern. Also, the extremes of ground-water levels during the 5-year period plotted in fig. 23 only cover a range of 7.5 feet. This relatively small amount of fluctuation is an indicator of the large volume of ground water held in storage.

Based upon a Division of Water review, the two observation wells in the Whitewater Basin are adequate for monitoring water-level fluctuations in outwash valley-train deposits commonly used for water supply. Because the potential for high-capacity pumpage elsewhere in the basin is quite small, no additional observation wells are needed at this time.

Piezometric Surface

The ground-water level within an aquifer constantly fluctuates in response to rainfall events, evapotranspiration, ground-water movement (including recharge and discharge), and ground-water pumpage. Maximum fluctuations recorded at four observation wells in the Whitewater Basin average 8 feet. Because the natural fluctuations are small, static water levels from wells can be used to approximate regional ground-water flow direction.

Static water levels used to develop the piezometric surface map for the Whitewater River Basin (pl. 2) include data for aquifers at various depths. The map represents a composite of water levels of the major aquifer systems, and it may or may not be a true representation of water levels in very shallow or very deep aquifers.

The piezometric surface map (pl. 2) can be used to define the probable flow path of contaminants and to identify significant areas of ground-water recharge and discharge. In a general way, the piezometric surface approximates overlying topography and intersects the land surface at major streams. The map can also be used to calculate expected depths to water in a well, but not to determine recommended depths of wells. At any specific site, the appropriate well depth can only be determined by an understanding of the local geologic conditions.

In the Whitewater River Basin, ground-water levels range from an elevation of 1165 feet m.s.l. in Randolph County to a low of about 500 feet m.s.l. where the Whitewater River enters the state of Ohio. Regional ground-water flow, which generally reflects regional topographic drainage, is toward the Whitewater River and its major tributaries (pl. 2).

Whitewater River Basin Aquifer Systems

The aquifer systems of the Whitewater River Basin can be broadly divided into two classes, unconsolidated aquifer systems and the underlying bedrock aquifer systems. The unconsolidated systems include the *intratill* Wayne-Henry, Fayette-Union, and Dearborn Aquifer Systems and the Whitewater Valley Aquifer System (pl. 3). These unconsolidated systems, sub-

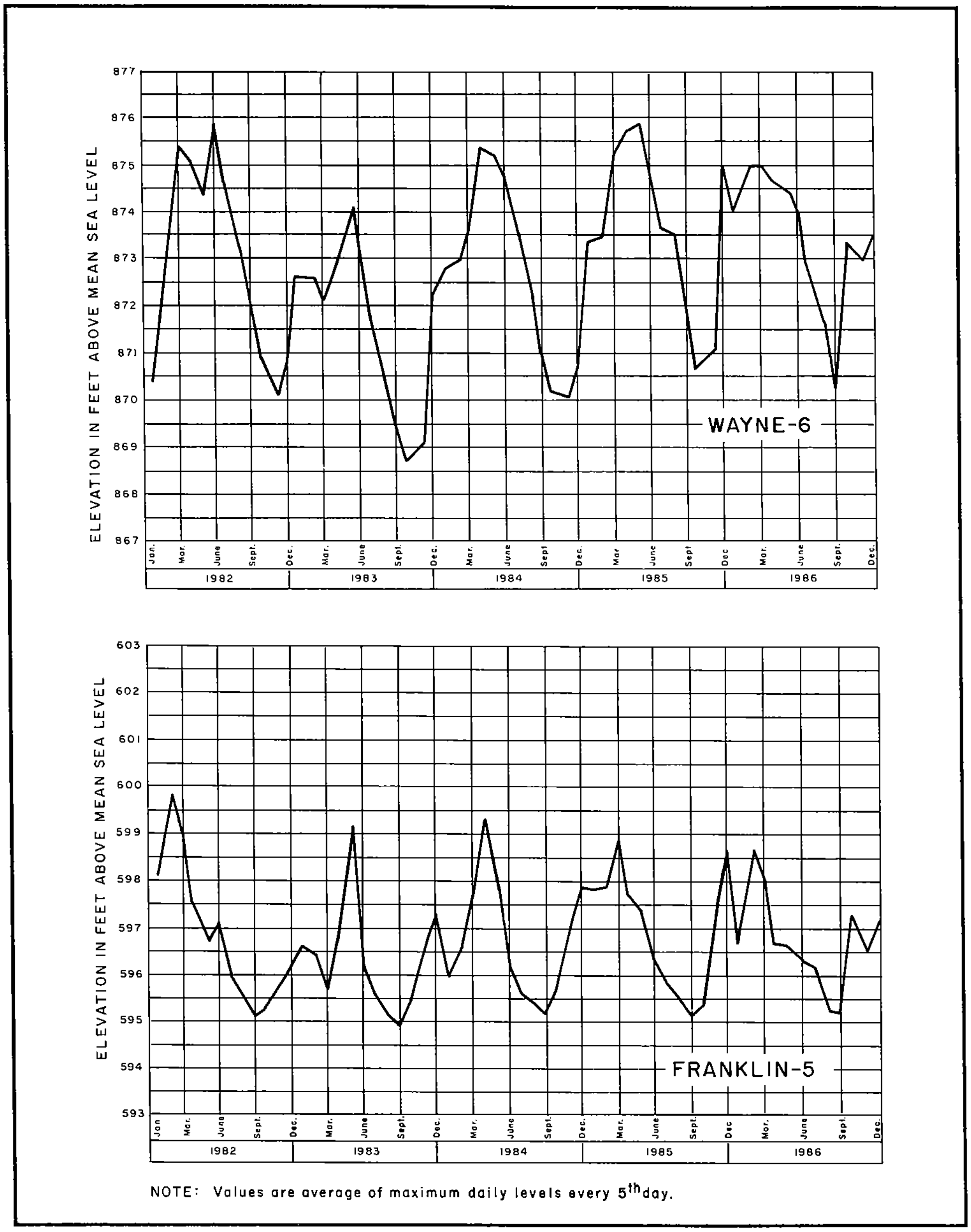

Figure 23. Monthly water levels in observation wells Wayne-6 and Franklin-5

divided on the basis of similar aquifer and geologic conditions, are mainly composed of glacially derived tills, lacustrine clays, and sands and gravels of perhaps pre-Illinoian to Wisconsinan age. The bedrock systems, subdivided on the basis of water-producing rock strata, are the Ordovician Aquifer System and the Silurian Aquifer System. These systems are composed primarily of sequences of limestones, dolomites, and shales. Table 11 summarizes selected characteristics of the unconsolidated and bedrock systems within the Whitewater Basin.

Wayne-Henry Aquifer System

The Wayne-Henry Aquifer System is approximately bounded to the north by the Knightstown Moraine (fig. 11). The surficial deposits in this area are Wisconsinan tills identified by Burger and others (1971) and Gray and others (1972) as ground moraine or end moraine. Aquifer characteristics are not distinctly different between areas mapped as end moraine (the Knightstown Moraine) and areas mapped as ground moraine.

The dominant aquifers within the Wayne-Henry 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 sand or muddy sand to coarse gravel. Individual aquifers within this system are usually not traceable beyond small, limited areas. One exception occurs west and southwest of Richmond, where well data show a fairly extensive, definable aquifer (see Centerville Subsystem in pl. 3).

The thickness of the Wayne-Henry System ranges from 30 feet or less over areas of high bedrock to 300 feet or more in buried bedrock valleys. The thickness of aquifer materials within the system ranges from 0 feet (all clay, often a *dry hole*) to 40 feet. Common thicknesses are less than 10 feet.

The Wayne-Henry Aquifer System contrasts sharply with the Whitewater Valley Aquifer System, which transects it (pl. 3). The intratill Wayne-Henry aquifers are generally deeper than the Whitewater aquifers and are confined within till sequences dominated by clays. Water-bearing units of the Whitewater Aquifer System are *unconfined*, usually fairly shallow, and are characterized by thick sequences of sand and gravel with little clay.

The boundary between the Wayne-Henry Aquifer System and the Fayette-Union Aquifer System which borders it to the south is not distinct. Although both are intratill systems, the Wayne-Henry System has thicker, more numerous, and more productive sand and gravel zones than the Fayette-Union System.

Well depths in the Wayne-Henry System are highly variable and are influenced by the bedrock elevation and the depth to productive sand and gravel zones within the tills. Although well depths in this system vary from 14 to 254 feet, most wells range from 70 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 usually *bucket-rig wells* drawing water from thin sand and gravel layers or from clays overlying bedrock highs.

The elevations of water-bearing zones in the Wayne-Henry 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 900 to 1150 feet m.s.l. but are usually in the range of 1030 to 1120 feet m.s.l. Along the southern boundary of the system, aquifer elevations range from 790 to 1065 feet m.s.l., but most wells produce from aquifers of elevation 850 feet m.s.l. or higher.

The confined intratill aquifers within the Wayne-Henry System often have only slight hydrologic connections; therefore, static water levels may differ significantly within a small area. Static water levels throughout the Wayne-Henry System range from 0 feet (land surface or above) to 105 feet. Most static water

Table 11. Summary of unconsolidated and bedrock aquifer systems

Aquifer system	Area (sq mi)	System type	Avg. aquifer thicknesses (ft)	Range of well yields (gpm)	Expected well yields (gpm)	Static water levels (ft)
Wayne-Henry	448	Intratill	10	0 - 150	6 - 15	20 - 50
Fayette-Union	362[1]	Intratill	2 - 4	0 - 60	2 - 10	20 - 40
Dearborn	464	Intratill	0 - 2	0 - 20	0 - 2	3 - 40
Whitewater	103	Valley train	25 - 75	50 - 1200	500	0 - 30
Ordovician	1034[1]	Bedrock	10 - 100	0 - 50	0 - 8	15 - 50
Silurian	342[1]	Bedrock	10 - 100	0 - 60	10	<50

[1]Includes area of the county to the Ohio border outside the basin boundary.

levels, however, range from 20 to 50 feet below land surface. *Flowing wells*, although quite rare, occur sporadically throughout the system.

Well yields in the Wayne-Henry Aquifer System are usually adequate for domestic supply purposes; however, low-yield wells and dry holes have sometimes been reported. Most wells yield 15 gpm (gallons per minute) or less, but reported yields range from 0 to 150 gpm. High-capacity wells (70 gpm or greater) are fairly uncommon.

In the area west and southwest of Richmond, a fairly consistent intratill sand and gravel zone has been delineated (see Centerville Subsystem in pl. 3). This zone ranges from 1 to 25 feet in thickness but is usually about 5 feet thick. Wells range from 50 to 120 feet deep. The elevation of the top of the subsystem is between 960 and 990 feet m.s.l. Static water levels range from 13 to 80 feet but are usually between 25 and 50 feet. Wells yield from 6 to 30 gpm, and most wells produce at least 10 gpm.

Fayette-Union Aquifer System

The Fayette-Union Aquifer System is bounded to the north by the gradational contact with the Wayne-Henry Aquifer System (pl. 3). The southern boundary is also gradational but approximately coincides with the Hartwell Moraine (fig. 11), which marks the southern limit of Wisconsinan glaciation in the Whitewater Basin.

The Fayette-Union Aquifer System is mainly composed of glacial tills which 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 ranges from 0 to 30 feet throughout the Fayette-Union Aquifer system, but generally is about 2 to 4 feet. Thicker layers occasionally are found in areas near the Whitewater Valley Aquifer System, which occupies the Whitewater River Valley.

The boundary between the Fayette-Union and Whitewater Valley Aquifer Systems is distinct (pl. 3). The thick outwash sands and gravels of the Whitewater System contrast sharply with the clay-rich composition of the Fayette-Union System. To the south, the boundary between the Fayette-Union Aquifer System and Dearborn Aquifer System is gradational and not clearly defined (pl. 3). Both systems have clay-rich till sequences overlying bedrock; however, the Fayette-Union System has thicker deposits of Wisconsinan till, whereas the Dearborn System has thinner deposits of predominantly pre-Wisconsinan age. In general, sand and gravel zones in the Fayette-Union Aquifer System are thicker, more numerous, and more productive than those in the Dearborn Aquifer System.

Well depths in the Fayette-Union Aquifer System are influenced by bedrock elevation and the depth to productive sand and gravel layers within the thicker tills. Well depths range from 11 to 260 feet, but most wells are 30 to 70 feet deep. The shallowest wells are usually found in thin tills overlying bedrock highs or in thin, shallow outwash deposits in minor tributary valleys of the Whitewater River. The deeper wells are in areas where thick till occurs within buried bedrock valleys.

Intratill aquifer elevations range from 780 to 1078 feet m.s.l. Aquifer elevations are highest along the basin's western topographic boundary in western Fayette County, along the eastern boundary in eastern Union County, and on the drainage divide between the east and west forks of the Whitewater River. The lowest aquifer elevations occur in areas adjacent to the Whitewater Valley Aquifer System. Aquifers most commonly occur between 900 and 1030 feet m.s.l. in upland areas and between 780 and 900 feet m.s.l. in lowland areas.

Most wells of the Fayette-Union Aquifer System produce from intratill sand and gravel deposits and are therefore confined by some thickness of clay or till. Static water levels range from 0 to 90 feet but are usually between 20 and 40 feet. Flowing wells are extremely rare.

Well yields in the Fayette-Union Aquifer System are variable, but generally only fair to poor yields may be expected. Wells drilled in this system produce from 0 to 60 gpm; however, most wells average only 2 to 3 gpm, and supplemental storage is often required in order to meet peak demands for domestic needs. Although ground-water conditions in the Fayette-Union Aquifer System are limited, dry holes are uncommon. Most wells can produce at least the minimum amount necessary for small household domestic purposes (1 to 2 gpm). Because significant sand and gravel aquifer zones are commonly absent in much of the Fayette-Union Aquifer System, bucket-rig wells are frequently used. These wells draw water from thin sand zones or from seepage from fractures within the till. Few high-capacity wells are present, nor can they be reasonably expected, in this aquifer system.

A small area of the Fayette-Union System in northeast Union County has been subdivided because of the more frequent occurrence of notable sand and gravel deposits (see Liberty Subsystem in pl. 3). Sand and gravel aquifers in the Liberty Subsystem average about 4 feet in thickness, and aquifer elevations are usually between 950 and 1050 feet m.s.l. Drilled wells, which range from 33 to 130 feet deep, have yields ranging from 4 to 40 gpm. Most wells yield about 10 gpm, a sufficient amount for a typical domestic supply. Bucket-rig wells are less common due to the presence of thicker, more productive sand and gravel layers.

Dearborn Aquifer System

The Dearborn Aquifer System, which covers the southern portion of the Whitewater Basin, has the most limited ground-water resources of the unconsolidated aquifer systems (pl. 3). Unconsolidated materials of the Dearborn Aquifer System consist of thin, eroded residuum and predominantly pre-Wisconsinan tills.

Thin layers of intratill sand and gravel occasionally occur, but most often only clay is encountered above bedrock. Sand and gravel lenses can approach 15 feet in total thickness but are more commonly only 1 to 2 feet thick. Bucket-rig wells may produce water from thin sands, gravels, or clay or till units in this system.

The Whitewater Valley Aquifer System cuts through the Dearborn System (pl. 3). The boundary between these two systems is sharply defined by geologic materials, aquifer elevations, and water availability.

The depths of wells in the Dearborn System range from 25 to 70 feet, although most wells are less than 50 feet deep. Aquifer elevations are typically at or above 900 feet m.s.l. Static water levels range from 3 to 40 feet. Well yields range from 0 to 20 gpm, although most wells produce only a few gpm. Dry holes are fairly common. No flowing wells have been reported.

Whitewater Valley Aquifer System

The Whitewater Valley Aquifer System occupies the valleys of the Whitewater River and its major tributaries. This system has long, narrow, north-south trending branches which cut through the other unconsolidated aquifer systems in the basin (pl. 3).

The system contains large volumes of sand and gravel which were deposited by glaciers and now fill the major stream valleys. As the glaciers melted, 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 Whitewater River and its tributaries.

The sand and gravel deposits of the Whitewater Valley Aquifer System range from less than 10 feet to more than 100 feet in thickness. In most areas of the system, outwash deposits are between 25 and 75 feet thick. Throughout the basin, the thick sands and gravels of the Whitewater Valley Aquifer System abruptly contrast with the clay-rich or bedrock environments of the surrounding aquifer systems.

Well depths in the Whitewater System range from 10 to 120 feet, but most wells are between 30 and 60 feet deep. The elevation of the aquifer system varies uniformly from north to south. Along the basin boundary in Randolph County, the aquifer system elevation is about 1110 feet m.s.l. Where the system leaves the state in Dearborn County, the elevation is approximately 600 feet m.s.l. for the upper terraces and approximately 500 feet m.s.l. for the modern valley outwash.

Because the system is largely unconfined, static water levels are more consistent than in the surrounding aquifer systems and are generally shallower. Average static water levels of 30 feet or less are common throughout the system.

The Whitewater Valley Aquifer System is by far the most productive aquifer system in the basin, and is the only system with the potential to consistently meet the needs of high-capacity users. Well yields of 500 gpm can be expected throughout most of the system. Presently there are a few wells which have the capacity to produce up to 1200 gpm.

In some areas of the Whitewater Valley Aquifer System, thick zones of sand and gravel have been covered by a layer of clay or till (see cross-hatched area on pl. 3). These areas are surficially similar to the adjacent Wayne-Henry Aquifer System, but the sand and gravel aquifer zones are depositionally related to the Whitewater System.

Thickness of the sand and gravel zones in these areas ranges from 12 to 54 feet. Most well logs show 20 to 30 feet of sand and gravel, although the upper portions are often unsaturated. Well depths range from 34 to 87 feet. The elevation of the top of the sand and gravel zone ranges from about 900 to 940 feet m.s.l. Static water levels are between 10 and 46 feet. Domestic wells in this area yield from 10 to 18 gpm, and one high-capacity well producing 140 gpm was reported.

Ordovician Bedrock Aquifer System

Ordovician bedrock aquifers, which occur in the central portion of the Whitewater River Basin, underlie a much larger portion of the basin than the Silurian bedrock aquifers. Most of Wayne, Fayette, Union, Ripley, and Dearborn Counties are underlain by the Ordovician Bedrock Aquifer System (pl. 3).

Although the Ordovician bedrock is only marginally productive, it nonetheless is used as a water source, especially in the southern portions of the basin where other potential aquifers are often absent. Records for wells penetrating Ordovician rocks in the Whitewater Basin usually indicate multiple layers of limestone and shale, occasionally only shale, and rarely only limestone.

Wells completed in the Ordovician Bedrock Aquifer System range from 40 to 350 feet deep. Well depths are highly variable throughout the basin but generally decrease from north to south. Well depth depends on bedrock elevation and drift thickness. The amount of penetration into the bedrock is also highly variable, and ranges from about 10 to more than 100 feet. Well productivity does not appear to be significantly correlated with the amount of bedrock penetration. Elevation of the top of the bedrock surface is shown on pl. 1. Static water levels range from 0 to 140 feet but are usually between 15 and 50 feet.

Wells in the Ordovician Bedrock Aquifer System generally produce from 0 to 8 gpm. A well yielding 50 gpm was recorded, although wells producing significantly more than 10 gpm are rare. Dry holes are fairly common. *Drawdowns* associated with wells in the Ordovician Bedrock Aquifer system are often extreme. Even with low pumping rates, wells will often pump dry and drawdowns of more than 50 feet are commonly reported.

Silurian Bedrock Aquifer System

Silurian bedrock aquifers are found along the north, northeast, and west margins of the Whitewater Basin (pl. 3). Records for wells in the Silurian System usually indicate fairly thick sequences of limestone. Some shale is occasionally reported, most commonly near the Silurian-Ordovician contact. Depths of wells vary from about 100 to 330 feet, but most wells are 150 to 200 feet deep. Some wells penetrate 15 to 60 feet into the limestone, although 30 feet or less is usual. Static water levels range from 20 to 70 feet but are typically 50 feet or less.

Well yields in the Silurian Bedrock Aquifer System range from 0 to 60 gpm. The best Silurian bedrock production is in Randolph County along the northern edge of the basin. Although one dry hole was reported in this area, nearly all wells produce more than 10 gpm, and wells producing 30 to 60 gpm are common. Farther south in the basin, the capacity of the Silurian Bedrock Aquifer System decreases. In areas within a few miles of the Silurian-Ordovician contact, wells usually produce 10 gpm or less and dry holes are occasionally reported. Drawdown values are high in these areas and wells may pump dry.

Ground-Water Quality

Chemical data on water samples from a total of 153 wells were used to characterize the ground-water quality of the unconsolidated and bedrock aquifer systems defined in the Whitewater River Basin (fig. 24). Major sources of information included: 1) 114 ground-water samples collected from domestic, stock, industrial, municipal, and public supply wells in a cooperative effort between the Division of Water and the Indiana Geological Survey (fall 1985); 2) Indiana State Board of Health analyses of municipal, public supply, and test wells; and 3) U.S. Geological Survey analyses of observation and municipal wells. Most data summarized in this report were collected between 1974 and 1985; however, older data were occasionally utilized. Data for individual wells are tabulated in app. 12.

The distribution of sample sites reflects water availability in the basin. For example, only nine wells were sampled in the Dearborn Aquifer System. In this area, ground-water resources are limited and fewer wells, which are predominantly bucket-rig wells, were available for sampling.

Data from wells in the Whitewater Basin are treated as point values; however, the data actually represent the average concentration of a certain unknown volume of the aquifer. The extent of aquifer representation primarily depends on the depth of the well in question, the *hydraulic conductivity* of the aquifer, and the rate of pumping (Sasman and others, 1981). In addition, water collected from deep bedrock wells can be a mixture of water from different production zones.

A number of factors may cause the alteration of original aquifer water before and after sampling, such as contact with plumbing, residence time in a pressure tank, method of sampling, and time elapsed between sampling and laboratory analysis. In addition, bucket-rig wells were not completely flushed of well water that had been exposed to the atmosphere. Because the