Water Resources of the Upper White River Basin, East-Central Indiana

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1999-C

Prepared in cooperation with the Indiana Department of Natural Resources, Division of Water

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By L. W. CABLE, J. F. DANIEL, R. J. WOLF, *and* C. H. TATE

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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GLOSSARY

Base runoff. Sustained or fair-weather runoff. In streams, base runoff is composed largely of ground-water effluent (Langbein and Iseri, 1960).

Ground-water runoff. That part of runoff which has passed into the ground, become ground water, and been discharged into the stream channel (Langbein and Iseri, 1960).

Hydraulic conductivity. Replaces the term "field coefficient of permeability," which is defined by Ferris, Knowles, Brown, and Stallman (1962) as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at the prevailing water temperature.

Overland runoff. Runoff entering the stream promptly after rainfall or snowmelt by flow over the land surface directly toward the stream channel.

Potential yield. The amount of fresh water available for use without causing undesirable results such as excessively lowering ground-water levels or depleting streamflow during critical periods.

Storage coefficient. Replaces the term "coefficient of storage," which is defined by Ferris, Knowles, Brown, and Stallman (1962) as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

Transmissivity. Replaces the term "coefficient of transmissibility," which is defined by Ferris, Knowles, Brown, and Stallman (1962) as the rate of flow of water, in gallons per day, through a vertical strip of aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 1 foot per foot at the prevailing water temperature.

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

WATER RESOURCES OF THE UPPER WHITE RIVER BASIN, EAST-CENTRAL INDIANA

By L. W. CABLE, J. F. DANIEL, R. J. WOLF, and C. H. TATE

ABSTRACT

Ground-water discharge to the streams sustains year-round streamflow in the upper White River basin. This discharge, referred to as ground-water runoff or base runoff, is considered to be an index to the amount of ground water available for development. A comparison of the variations of ground-water runoff and aquifer distribution in the basin shows that the areas of best development potential are areas where thick sand and gravel aquifers are adjacent to the streams. The average ground-water runoff for these areas is between 400,000 and 500,000 gallons per day per square mile.

The most permeable aquifers in the basin are the sand and gravel deposits of Quaternary age. These aquifers occur mainly as relatively thick elongate bodies along bedrock valleys and as relatively thin sheetlike deposits at or near land surface. The representative hydraulic conductivity of these aquifers ranges from 1,500 to 2,500 gallons per day per square foot. The limestone and dolomite formations of the bedrock are a source of moderate quantities of water.

The long-term average streamflow in the basin is approximately 0.9 cubic feet per second per square mile. The yearly average discharge varies from about one-fourth to twice the long-term average. The 7-day 10-year low flow ranges from about 0.01 to 0.3 cubic feet per second per square mile; the main-stem flow ranges from 0.10 to 0.13 cubic feet per second per square mile.

The water in the aquifers is predominately a very hard calcium bicarbonate type; it is generally high in iron and contains a moderate amount of dissolved solids. Fresh water (1,000 milligrams per liter dissolved solids or less) is present to depths of approximately 400 feet below land surface. In the tributaries and in the headwaters region of the White River, the composition of surface water is very similar to that of ground water. The quality of the water in the White River deteriorates in the downstream direction owing to the cumulative effects of sewage effluent.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this study is to determine the potential yield of the water resources of the upper White River basin and to provide information to aid in resource development and management. This investigation is the first in a series of interdisciplinary basin studies planned for Indiana, and it is intended to establish criteria for future studies of this type.

The upper White River basin (fig. 1) was chosen as the first study area primarily because of present and potential water problems resulting from the concentration of population and industry. Indications are that localized pollution of streams by sewage effluent is the most immediate problem. However, if the current rate of population growth continues, water supply will become a problem in the foreseeable future. Flooding is always a great potential danger in humid areas of relatively low relief such as the upper White River basin. To deal more effectively with these and other water problems that may arise, management must have a comprehensive understanding of the hyrologic system, its potential, and its limitations. With this understanding, it may be possible to anticipate and prevent water problems rather than face the often costly and time-consuming alternative of correction.

In this report, the surface and subsurface hydrology and their interrelation are described and the chemical and physical properties of the water are listed. In regard to the subsurface, attention is given mainly to those aquifers that are sources of fresh ground water (1,000 milligrams per liter of dissolved solids or less) in moderate to large quantities. Estimates of the potential yield of ground water are made on the basis of the amount of ground water discharged to streams. The section on streamflow includes the determination of low-flow and flow-duration characteristics of the streams and regional draft-storage relations. No attempt is made, however, to evaluate specific reservoir sites. An analysis of flood frequency in the basin is adequately covered in previous publications and is not discussed in detail here. The section concerning water quality shows the general chemical and physical characteristics of water in different hydrologic environments. The concentration of significant chemical constituents is given for locations where data are available. Although an attempt is made to give some consideration to all phases of the total water resource, it must be stressed that this report is a general appraisal only; a more detailed study must be made before the water resources of the basin can be fully developed.

COOPERATION AND ACKNOWLEDGMENTS

The investigation of the water resources of the upper White River drainage basin was conducted by the U.S. Geological Survey in cooperation with the Indiana Department of Natural Resources,

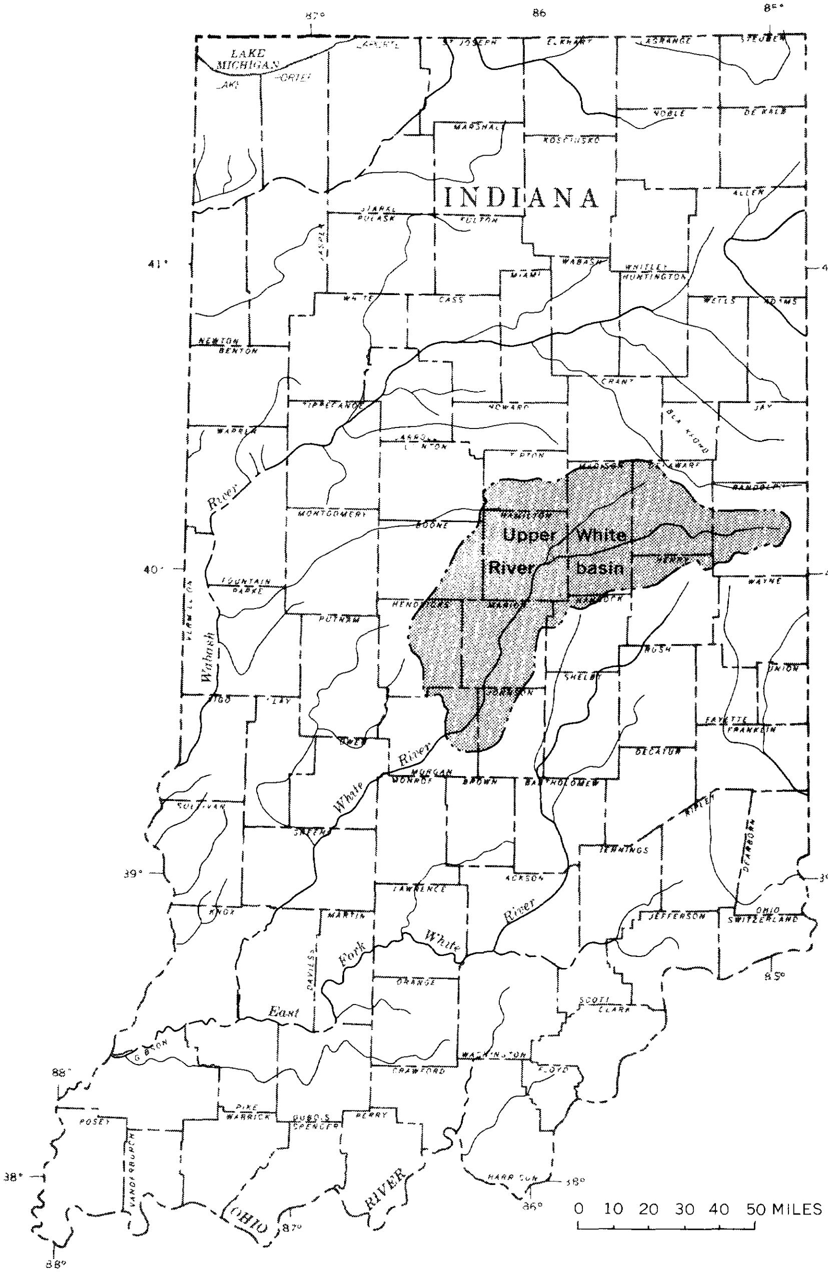


FIGURE 1.—Location of the upper White River basin.

Division of Water, as a part of the statewide investigation of the water resources of Indiana. The authors wish to express their sincere thanks to all who contributed time, information, and assistance during the collection, tabulation, and processing of data for the report. The authors are especially grateful to the Indiana Department of Natural Resources, Geological Survey and Division of Water.

UNITS

The units used throughout this report are those most commonly used in each discipline. No attempt has been made to convert to a single set of units. For example, precipitation is expressed in inches; ground water, in gallons per day; and surface water, in cubic feet per second. It is realized, however, that the significance of the data presented will be more readily recognized if it is in units with which the reader is familiar. Therefore, a table of conversion factors has been included (table 1) in order that units may be easily converted from one form to another.

SETTING

In areas of effluent drainage such as the upper White River basin, the surface-water divide and the ground-water divide are generally coincidental; thus the gradient of both the land surface and the water table is from the divides, or high points, toward the streams, or low points. Therefore, the principal stream and its tributaries compose a drainage system toward which most of the water in the basin tends to flow. With the exception of that part of precipitation which is removed by evapotranspiration or retained as soil moisture, precipitation that falls within a drainage basin makes its way either directly, as overland runoff, or indirectly, through the subsurface, to the streams. Thus, in the

TABLE 1.—*Conversion factors*

Cubic feet per second	Gallons per minute	Gallons per day	Million gallons per day	Acre-feet per day	Inches in 1 square mile per year
One	448.831	646,317	0.646317	1.9835	13.574
0.002228	One	1,440	0.001440	0.00442	0.03024
0.000001547	0.000694	One	0.000001	0.00000307	0.000021003
1.54723	694.444	1,000,000	One	3.0689	21.003
0.504167	226.286	325,851	0.325851	One	6.8438
0.073668	33.0646	47,613	0.047613	0.14612	One

Degrees Fahrenheit (°F) = 9/5°C + 32

drainage basin, ground water and surface water are interrelated to form a dynamic system that reacts as a unit to any change imposed on the system.

The hydrology of a drainage basin is controlled principally by the geology, physiography, and precipitation of the basin.

GEOLOGY

Sediments of Quaternary age mantle the bedrock and constitute the characteristic features of the present land surface. These sediments consist of thick deposits of unconsolidated glacial and alluvial sediment that were deposited chiefly during the Wisconsin Glaciation of the Pleistocene Epoch. They consist predominantly of glacial till but include some stratified beds of clay, silt, sand, and gravel. The stratified beds are outwash deposited from glacial melt water. The sorting action of stream transport and deposition tended to segregate the outwash into separate layers according to grain size. The layers of outwash sand and gravel are the best aquifers, and they occur uniformly throughout most of the basin. Outcrops of sand and gravel are not common; these deposits are, for the most part, buried beneath till or silt and clay of alluvial origin.

The bedrock is composed entirely of southwest-dipping marine sedimentary rocks of Paleozoic age. Although no major deformation has occurred, these rocks were subjected to much uplift and erosion prior to the advent of glaciation. Limestone and dolomite layers are the best aquifers in the bedrock formations.

PHYSIOGRAPHY

The upper White River basin comprises 2,444 square miles of the Till-Plains section of the Central Lowland physiographic province of Fenneman (1938). This province is characterized by a relatively flat to gently rolling till plain broken occasionally by stream valleys. For the most part, the physiography of the basin is typical of this province. However, in the extreme downstream part of the basin, the glacial deposits become thinner, and land-surface topography is a somewhat subdued reflection of the rugged bedrock surface beneath. Here, relatively steep sided knoblike bedrock hills protrude through the till and alluvial deposits of the plain.

In general, the physiography of the basin is conducive to a relatively uniform rate of ground-water recharge. The flatness of the topography retards surface runoff and thus allows more precipitation to soak into the ground. The uniform distribution of surficial glacial till contributes to a relatively slow but continuous percolation of water into the aquifers below.

PRECIPITATION

Precipitation is the ultimate source of all fresh water either on the surface or in the subsurface of the earth. The scarcity or abundance of fresh water in most areas depends on the amount of precipitation received and its mode of occurrence. When the climate of a region provides ample precipitation spread fairly evenly throughout the year, as in the upper White River basin (fig. 2), conditions are favorable for a year-round uniform supply of water. Based on the records for the period 1931–60, the normal annual precipitation in the basin is 39 inches.

RESOURCE AVAILABILITY

The hydrologic cycle for the upper White River basin is a system of circulation of a fixed volume of water that is composed of several parts. Mathematically, the parts can be expressed by the following generalized equation:

where

$$P = R + U + ET + \Delta M + \Delta GW_s + W, \quad (1)$$

P = Normal annual precipitation,
R = annual runoff,
U = underflow,
ET = evapotranspiration,
ΔM = change in soil moisture,
ΔGW_s = change in ground-water storage, and
W = consumptive use by man.

For the purpose of this study, however, most of these hydrologic components are not considered to be significant. For any one year, changes in soil moisture (ΔM) and changes in ground-water storage (ΔGW_s) are relatively small in this basin. The consumptive use by man (W) of both ground water and surface water is negligible because its amounts to less than 2 percent of runoff. Water which is not consumed is either discharged to the streams or infiltrated to the ground. Because the ground-water and surface-water divides generally coincide, underflow (U) occurs almost entirely at the basin outlet. On the basis of geology and water-level data, underflow which bypasses the gaging station is estimated to total less than 1 percent of runoff. Because this is a relatively small amount, it has been disregarded. Evapotranspiration (ET) accounts for loss of a large part of annual precipitation. However, there is no need to know the exact volume of water consumed by evapotranspiration, because any natural variation is

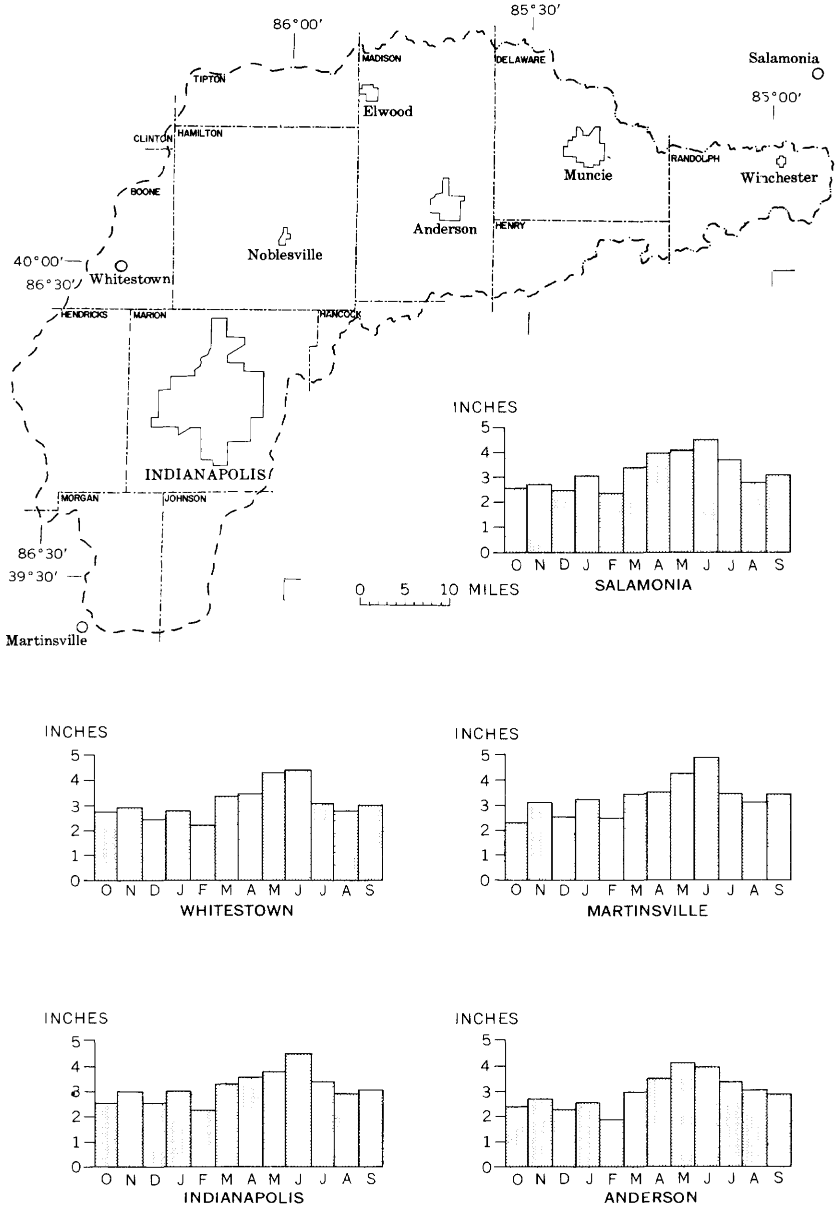


FIGURE 2.—Normal monthly precipitation for the period 1931–60 for selected sites.

automatically compensated for by a corresponding change in annual runoff. Under these simplifying assumptions, the hydrologic cycle in the upper White River basin becomes:

$$P = R + ET. \qquad (2)$$

If no significant manmade changes are imposed on the system, annual runoff (*R*) represents the water theoretically available for development. Stream-flow measurements at the basin outlet show the basinwide annual runoff to be 13 inches. Runoff is derived from two principal sources—ground-water discharge and overland runoff. (See fig. 3.) The part of runoff that is derived from ground-water discharge is referred to as ground-water runoff or base runoff and is available for development either as surface water or as ground water. Overland runoff is available for development as surface water only. Of course it is not possible to develop all the water available in either category. The questions are: How much water is available for development, and where are the best places to develop it? This report provides the data necessary for preliminary answers to these questions.

GROUND-WATER EVALUATION

AQUIFER IDENTIFICATION AND EVALUATION

GEOLOGIC CONTROLS

Knowledge of the geologic controls of the ground-water system of the upper White River basin is necessary to fulfill the purpose

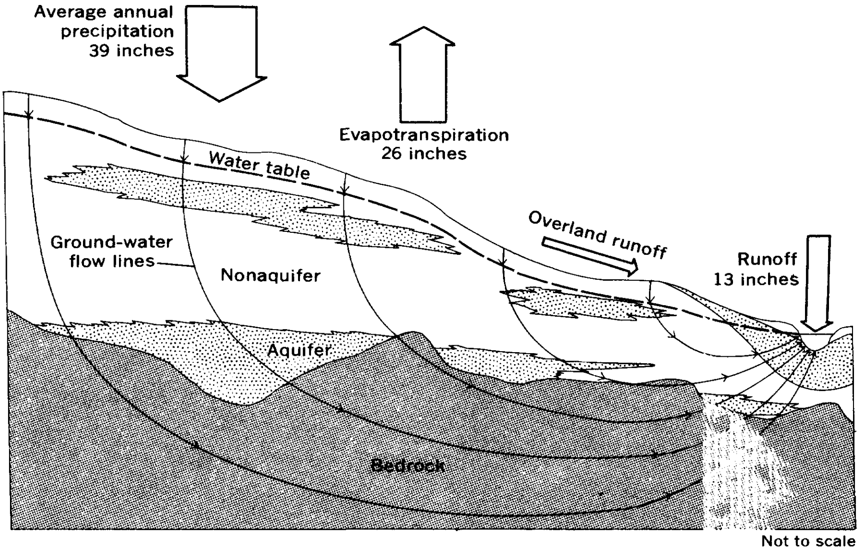


FIGURE 3.—Generalized diagram showing the hydrologic cycle for the upper White River basin.

of this project. Because this is a reconnaissance-type study, the use of all available geologic data was not feasible. Therefore, a grid system was used consisting of alternate township and range lines, and selected data were collected and hydrogeologic sections were drawn along these lines. From those logs of wells within 1 mile on either side of the grid lines that had information on lithology, the depths to bedrock or water levels were selected to draw the hydrogeologic sections. The resulting series of hydrogeologic sections, in conjunction with glacial and bedrock geologic maps, give a graphic view in three dimensions of the geologic units of the ground-water reservoir.

The hydrogeologic sections show a thick mantle of interbedded unconsolidated deposits above the bedrock surface. Successive advances and retreats of the glaciers during Pleistocene time caused repeated deposition and erosion of glacial till, outwash sand and gravel, lake sediment, and windblown silt. The sand and gravel layers of this sequence are the principal aquifers within the basin. The interbedded tills, clays, and silts are upper and lower confining layers of the aquifers. The thickest and most extensive aquifers are deep outwash sand and gravel bodies along the major bedrock valleys. Other aquifers are relatively shallow sheetlike bodies of significant areal extent. Both kinds of aquifers are commonly confined by glacial till; but in some areas they are not separated by till, and they coalesce to one thick sand and gravel body. Water-table conditions occur along the major streams where the uppermost clay and silt is thin or absent or where the water level is below the overlying clay. (See fig. 4.) Artesian conditions prevail where the sand and gravel aquifers are confined by till or clay. In the southern part of the basin, the sand and gravel aquifers occur only in the valleys.

The thickness of the unconsolidated deposits in the basin and the cumulative percentage of these deposits that are composed of sand and gravel is shown on plate 1. With this map, the general location of the thicker layers of sand and gravel can be determined. The data available for this study were not sufficient to define the thickness and areal extent of individual aquifers.

Aquifers of secondary importance occur in the bedrock directly beneath the unconsolidated sediments. The bedrock consists of dolomite, limestone, shale, and sandstone. Rocks of progressively younger age occur at the bedrock surface in the downstream direction in the basin because of the southwesterly regional dip. The bedrock ranges from limestone and shale of Ordovician age in the deep bedrock valleys in the northern part of the basin to

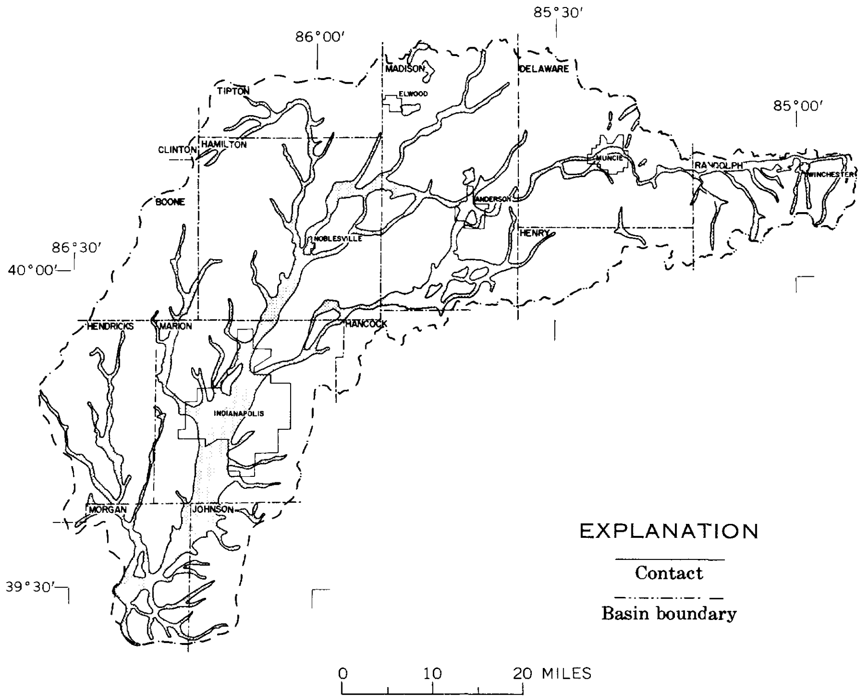


FIGURE 4.—Areas of surficial sand and gravel (shaded) where water-table conditions may occur.

shale and sandstone of Mississippian age in the southern part of the basin. (See fig. 5.) Figure 5 is a compilation from published (Wayne and others, 1966; Wier and Gray, 1961) and unpublished geologic maps of the Indiana Geological Survey.

The dolomite and limestone of Silurian and Devonian ages are the best and most widespread bedrock aquifers. Enlargement of the openings along fractures and bedding planes by the solvent action of percolating ground water formed permeable zones in these rocks. The depth to which effective solvent action has taken place is approximately 100 feet below the bedrock surface. Below this depth, the rocks have probably been little affected by solution, and they are not considered a significant part of the aquifer.

Many significant aquifers probably occur throughout the thick sequence of layered rock that composes the subsurface section of the upper White River basin. However, the uses for water from these aquifers are limited by the increasing concentration of dissolved chemical constituents with depth. Below depths of approximately 400 feet the water is saline, and at great depths it is brine. Although these aquifers are of little or no importance as sources

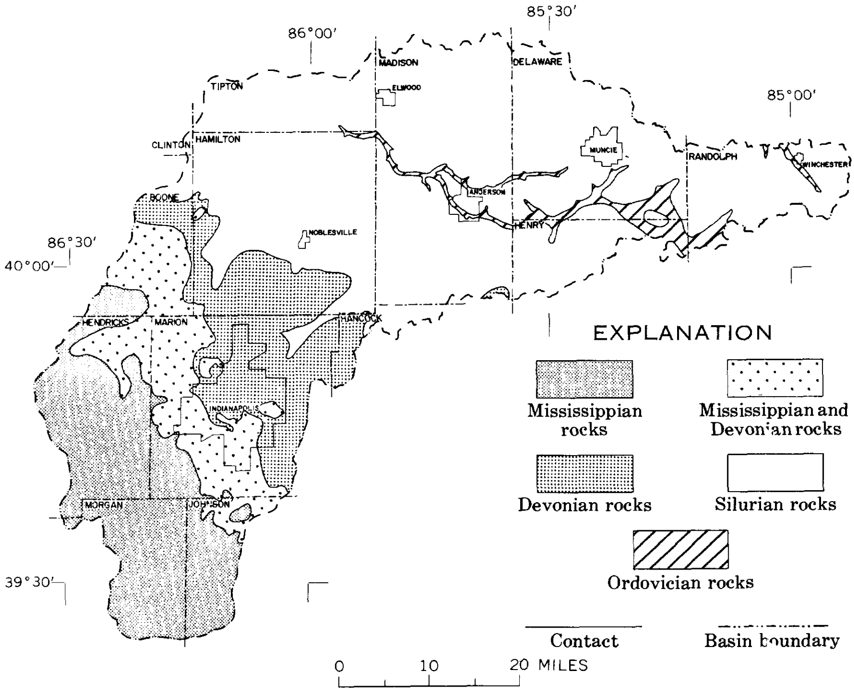


FIGURE 5.—Bedrock geology.

of fresh water supply, they could be economically important as sources of saline water and brine. Also, they may provide reservoir space for the disposal of industrial waste, for the storage of oil or natural gas, or perhaps for the storage of fresh water. More detailed mapping of the deep subsurface will be needed, however, before the feasibility of these uses can be determined.

AQUIFER COEFFICIENTS

Results of pumping tests and specific-capacity tests performed by consultants and drilling contractors are available for much of the basin, especially in the urban and industrial areas. Approximately 300 such tests from wells distributed over the basin were used to estimate the aquifer coefficients. An analysis of these results indicates that the representative hydraulic conductivity (K) for the confined sand and gravel aquifers is approximately 1,500 gpd per sq ft (gallons per day per square foot). However, where these aquifers occur at or very near land surface and adjacent to streams (fig. 4), indications are that the permeability is significantly greater. In these areas, the representative hydraulic conductivity is estimated to be 2,500 gpd per sq ft. The representative storage coefficient in the confined areas is estimated to be 0.0003. Where water-table conditions are present in these aquifers, the storage coefficient is estimated to be 0.1.

The bedrock data indicate that the top 100 feet of the limestone and dolomite is the best potential aquifer. Therefore, for all practical purposes, the bedrock aquifer can be considered to have a thickness of 100 feet. On the basis of analyses of specific-capacity tests of bedrock wells, the hydraulic conductivity is estimated to be 100 gpd per sq ft. From the formula $T=Km$, where T=transmissivity, in gallons per day per foot, and m=aquifer thickness, in feet, the regional value for transmissivity for the limestone and dolomite is estimated to be 10,000 gpd per ft (gallons per day per foot). Locally, the hydraulic conductivity and transmissivity can be much smaller or larger, depending on the geologic conditions.

INTERRELATION OF SURFACE AND SUBSURFACE FLOW SYSTEMS

As shown previously, the net interchange of water in this basin usually tends to be one way. That is, on a yearly basis, ground-water discharge sustains streamflow. There may be some areas or some time intervals of ground-water recharge from streamflow, but such areas are small and the time intervals short. The usual condition is ground-water discharge to streams. The more common term for this part of streamflow is base runoff.

Base runoff will also be referred to herein as ground-water runoff, because it is that quantity of infiltration or recharge remaining when evapotranspiration requirements have been met. It is the liquid residual of ground-water discharge. Base runoff can be evaluated using duration curves, ground-water-discharge rating curves, or stream-hydrograph analysis. The use of the duration curve has the drawback that no one can be sure what percent duration represents base runoff. Ground-water rating curves would require an observation-well network of an extent not available in this basin. Therefore, stream-hydrograph analysis was used.

MECHANICS OF GROUND-WATER-RUNOFF EVALUATION

The method of stream-hydrograph analysis used for this report was modified from that of Busby and Armentrout (1965). It seemed to be the most rational of several methods for separating base runoff from rainfall excess on the streamflow hydrograph. To facilitate explanation, figure 6 depicts a single-storm hydrograph. Base runoff is assumed to decrease, on the basis of the recession curve prior to the rise, until the time of the peak is reached. Base runoff then increases to merge with the recession after the

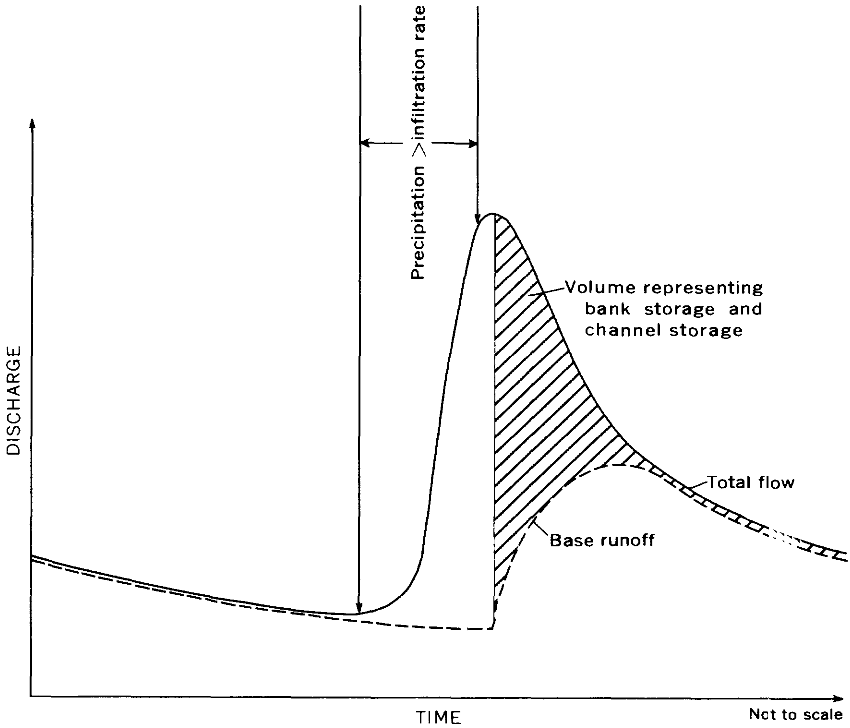


FIGURE 6.—Idealized separation of a single-storm hydrograph.

flood peak, at sufficient time lag for flows representing channel and bank storage to have passed.

Time of merging depends on basin characteristics such as drainage area, areal extent and hydraulic diffusivity of aquifers, soil characteristics, and vegetation. This time period varied generally from 4 to 7 days for streams in this basin. These time periods were chosen on the basis of visual inspection of several years' hydrograph record.

Separation was performed freehand. Multiple-storm peaks were assumed to obey the laws of superposition so that complete continuity of record was obtained. Recession curves for these peaks were drawn at the same slope as those for single-storm peaks at the same time of year. A generalized stream-discharge hydrograph for 1 complete water year (Oct. 1 through Sept. 30) with separated base runoff is shown in figure 7.

An investigation was made at a site in the basin to evaluate the accuracy of the hydrograph-separation method used in this study. The results provide important clues to the interrelation of

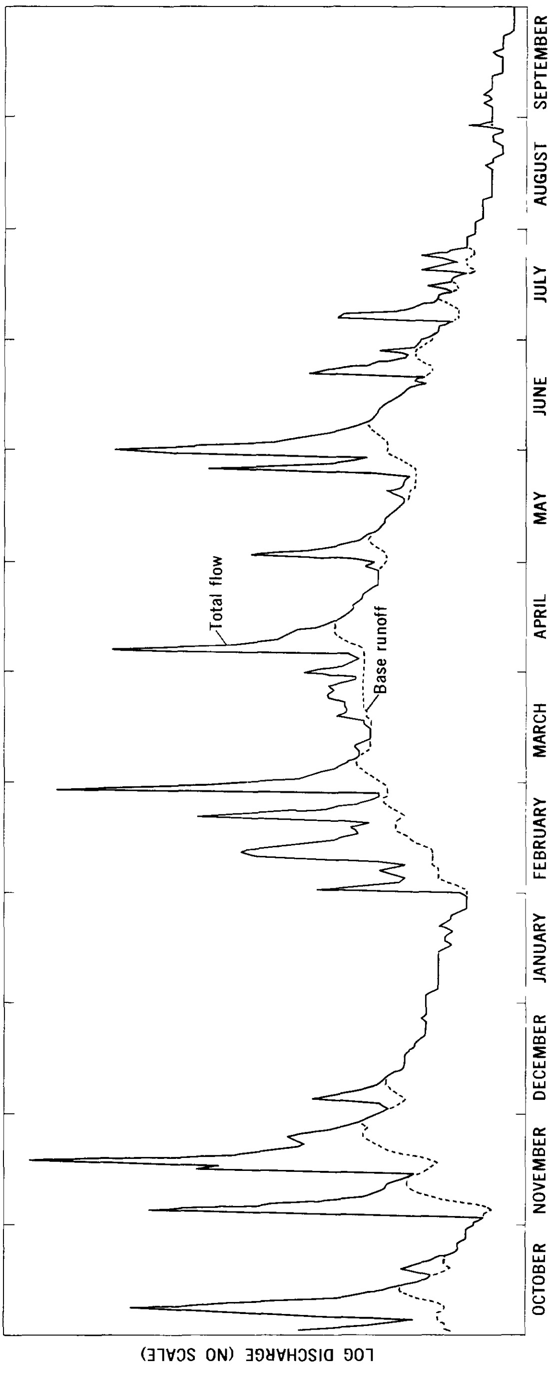


FIGURE 7.—Generalized stream hydrograph showing base-runoff separation.

ground water and surface water in the upper White River basin. The details of this site study are presented by Daniel, Cable, and Wolf (1970).

The records of 12 stream-gaging stations were used to evaluate ground-water runoff for the upper White River basin. Although more records were available, these were used because they are continuous records of sufficient length from stations located where streamflow is relatively unaffected by the activities of man. They give an adequate basinwide coverage of the flow in the White River and its major tributaries. For purposes of comparison, the basin was divided into seven major subbasins on the basis of areas gaged by these stations. The subbasins and the gaging stations are shown in figure 8. The periods of record for these gaging stations are shown in figure 9, and the average total flows are listed in table 2.

The average base runoff is also listed in table 2, but unless the variability of flow is known, the average is not very useful. Therefore, steps must be taken to determine the probability of exceeding or not exceeding specified base runoff for specified periods. This is the traditional way of analyzing streamflow records, and it should be a practical method for determining ground-water runoff.

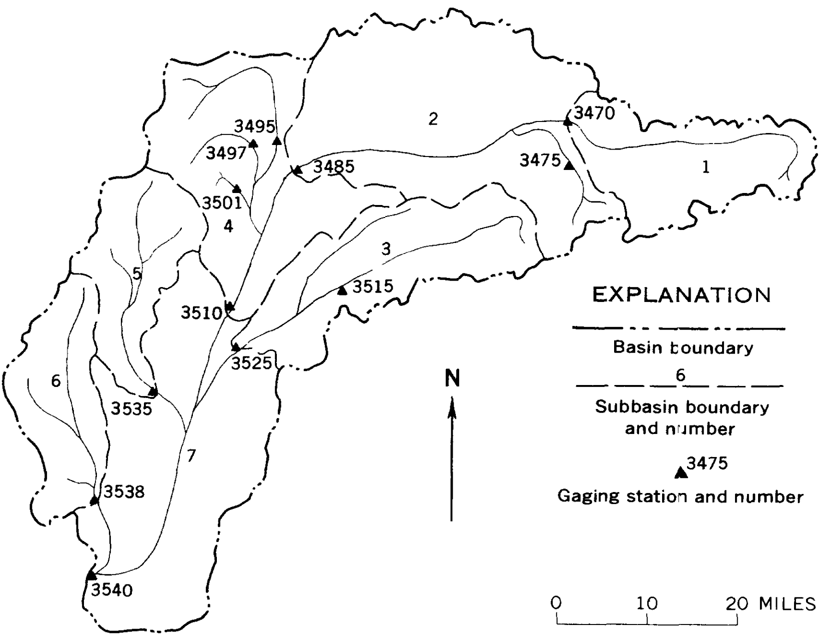
PROBABILITY ANALYSES

One way of expressing this variability is in terms of a recurrence interval, which is the average period between specified events. However, it is desirable to know multiyear averages for ground-water runoff. Therefore, a recurrence interval of 2 years for a 3-year average, or 3 years for a 2-year average, has little real meaning. It follows, then, that if we are to look at this variability with any statistical tool, we must resort to the probability concept. For instance, for what percentage of periods of a given length of time would we expect a certain average ground-water runoff to be exceeded or not exceeded?

For a single-year period, the theory and computations themselves are relatively simple. The plotting position (P) of an item in an array which approximates a normal distribution can be computed from the following equation:

$$P=\frac{m}{n+1}. \qquad (3)$$

In equation 3, m is the individual rank in the array, and n is the total number of occurrences. The ranking may be from low to high or vice versa. For this report, base runoff was ranked with



Subbasin No.	Subbasin area (sq mi)	Gaging-station No.	Gaging-station name
1	241	3-3470	White River at Muncie.
2	587	3485	White River near Noblesville.
		3475	Buck Creek near Muncie.
3	298	3525	Fall Creek at Millersville.
		3515	Fall Creek near Fortville.
4	391	3510	White River near Nora.
		3495	Cicero Creek near Arcadia.
		3497	Little Cicero Creek near Arcadia.
		3501	Hinkle Creek near Cicero.
5	174	3535	Eagle Creek at Indianapolis.
6	212	3538	White Lick Creek at Mooresville.
7	541	3540	White River near Centerton.

FIGURE 8.—Subbasins and gaging stations used to evaluate ground-water runoff.

the lowest, having m equal 1. The computations are not shown, but figure 10 is the probability distribution for Eagle Creek at Indianapolis, with the curve having been fitted by eye. The curve may be read as follows: A 10-percent chance exists that ground-water runoff will average less than 29 cfs (cubic feet per second) in any year. Conversely, there is a 90-percent chance that it will be exceeded. It must be stressed, however, that this flow is an integrated figure for the entire drainage area above the gage.

Multiyear ground-water-runoff rates should also be known, as well as single-year rates, so that long-term availability can be

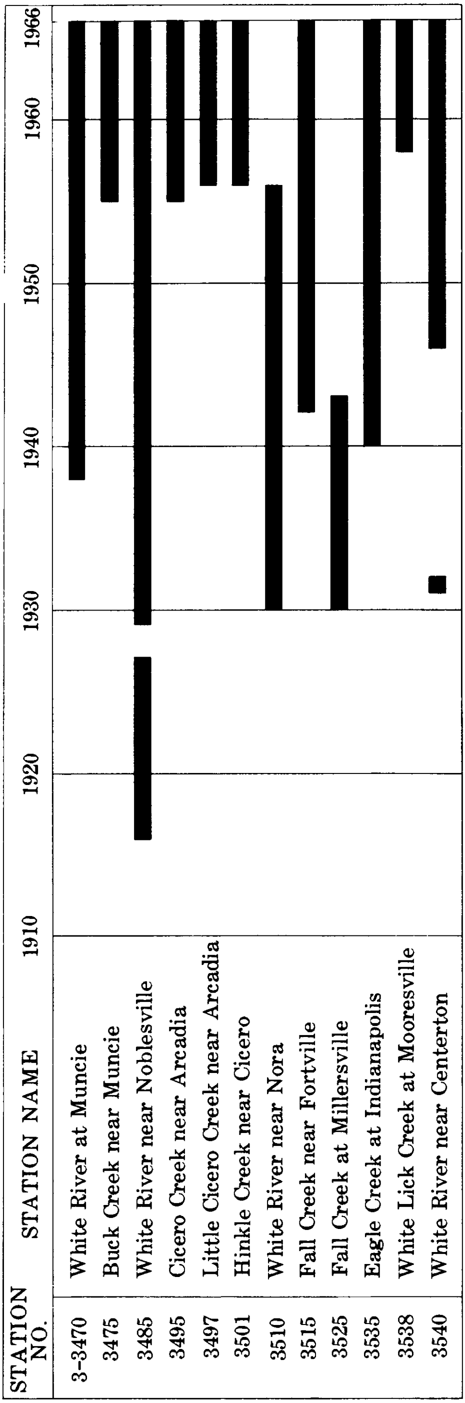


FIGURE 9.—Periods of base-runoff record at selected gaging stations.

TABLE 2.—*Average yearly discharge and average yearly base runoff at selected stations in the White River basin*

[Average discharge is discharge for comparable base-runoff record]

Station No. (pl. 3)	Station name	Average discharge		Average base runoff	
		Cubic feet per second	Inches per year	Cubic feet per second	Inches per year
3–3470	White River at Muncie	222	12.50	72.4	4.08
3475	Buck Creek near Muncie	34.3	13.11	20.4	7.80
3485	White River near Noblesville	796	13.04	341	5.59
3495	Cicero Creek near Arcadia	118	12.22	46.9	4.86
3497	Little Cicero Creek near Arcadia	39.4	13.22	12.4	4.16
3501	Hinkle Creek near Cicero	19.7	14.44	7.12	5.22
3510	White River near Nora	1,053	11.73	507	5.64
3515	Fall Creek near Fortville	166	13.32	91.5	7.35
3525	Fall Creek at Millersville	235	10.70	127	5.78
3535	Eagle Creek at Indianapolis	152	11.86	62.5	4.88
3538	White Lick Creek at Mooresville	198	12.68	85.0	5.44
3540	White River near Centerton	2,325	12.90	1,362	7.56

studied. Multiyear average rates require more advanced statistical tools. The methods used here were essentially those used by Leopold (1959).

Leopold was concerned with the variability of total streamflow.

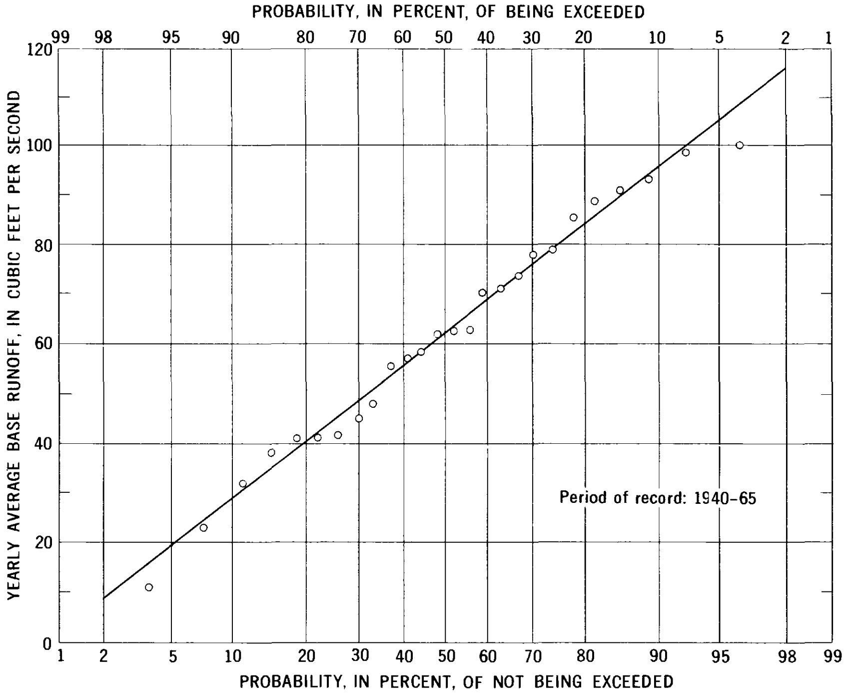


FIGURE 10.—Single-year base-runoff distribution for Eagle Creek at Indianapolis.

However, because ground-water runoff is subject to the same cyclic variability as total streamflow, the same methods should apply. Should streamflow be normally distributed, the variability of multiyear totals (or averages) could be determined statistically from the single-year distributions. But streamflow and ground-water runoff are not randomly distributed. Rather, they are subject to cyclic grouping into years of abundance and drought. This grouping effect has been termed "persistence."

Using all long-term records of streamflow in the United States and Europe, Leopold developed a curve of relation between the variability of mean values of streamflow and the length of period involved (fig. 11). The curve includes the effect of persistence so that standard statistical methods can be used. Because streamflow and ground-water runoff are subject to the same forcing function (precipitation), the effects of persistence should be the same on each, and the same methods should apply.

The ground-water runoff distributions for 2, 3, and 5 years were obtained using the dashed curve of figure 11. With these distributions, the probability or percentage chance that a particular length period will have ground-water runoff of a certain magnitude can be read.

A brief discussion of time lag between infiltration of precipitation and the emergence of ground water as base runoff follows. Although base runoff derives from the infiltration of precipitation during many previous years as well as during current periods,

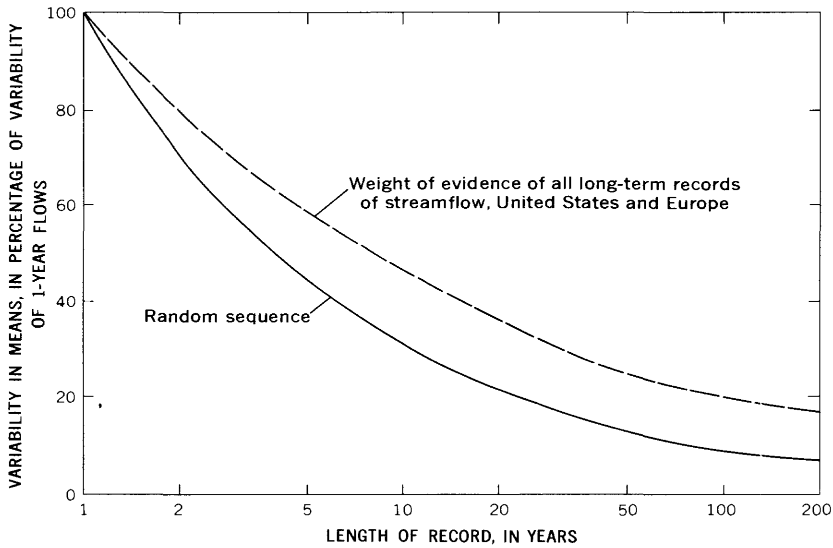


FIGURE 11.—Variability of mean values of streamflow for records of various lengths (after Leopold, 1959).

in the White River basin the bulk of base runoff for any year is derived from the infiltration of precipitation from that year and all or part of the previous year. Using data sets of 2 years, the relation between precipitation and base runoff has a correlation coefficient of about 0.7. Inclusion of precipitation data from antecedent years improves the relation somewhat but not to a great extent. Although a correlation coefficient of 0.7 does indicate that there are other factors influencing base runoff—one of which is probably areal extent of aquifers—those factors are relatively constant and should add nothing to the persistence effect. Therefore, ground-water runoff is directly related to precipitation in recent years, but with a time lag. Even with the time lag, however, ground-water runoff is still subject to the same cyclic grouping of wet and dry years. These relations are not presented here but were used to verify that the described method is applicable. In some cases these correlations were used to determine the magnitude of yearly figures for computation of plotting and positions. However, only the actual data were used in the curve-fitting process for probability.

GROUND-WATER-RUNOFF DISTRIBUTION

Maps showing the distribution of ground-water runoff, in gallons per day per square mile, for selected probabilities and time periods were drawn using the techniques described above. In order to forestall any confusion with duration, the probabilities are expressed in terms of not being exceeded. The distributions of ground-water runoff for 1-, 2-, 3-, and 5-year periods for 10-, 30-, and 50-percent probabilities are shown on plate 2. In each of these categories, subbasins of similar ground-water runoff are grouped together for ease of comparison.

A comparison of plate 1 with plate 2 shows that there is greater ground-water runoff where there are large percentages of sand and gravel in conjunction with a large thickness of drift. In areas with small sand and gravel percentages in conjunction with a small thickness of drift, the ground-water runoff is low.

With ground-water runoff as an index, the potential yields of ground water for the major subbasins can easily be compared. The larger the ground-water-runoff rate, in conjunction with thick sand and gravel aquifers, the higher the potential yield. Again, it should be emphasized that these rates are integrals for the entire subbasin. There are certainly high-yield areas and low-yield areas within each subbasin. Consider, for example, subbasins 2 and 4. For all of subbasin 2, the average (plate 2, 50-percent probability) ground-water-runoff rate is 297,000 gpd per sq mi (gallons per day per square mile). This rate would be approximately the same with or without subbasin 2a, whose average rate is 372,000 gpd per sq mi. The much higher potential of subbasin 2a is masked by the integrated rate for the entire subbasin. The opposite results occur in subbasin 4. There, the integrated average rate is 316,000 gpd per sq mi. This figure masks the much lower ground-water-runoff rate of subbasin 4a, which is only 198,000 gpd per sq mi. These variations occur also at the 10- and 30-percent probabilities. Significant intrasubbasin variations exist throughout the entire basin, and a more detailed study will be required to locate and evaluate them. For most subbasins, however, the integrated rate of ground-water runoff can be considered the minimum rate for high-yield areas and the maximum rate for the low-yield areas within the subbasin. The ground-water-runoff rates for high-yield areas should always be at least equal to, and possibly much greater than, the integrated rate.

Although the ground-water-runoff rates theoretically constitute the potential yield of the ground-water resource, not all the ground-water runoff can be recovered. The physical settings and economic factors of each subbasin will dictate what percentage of the ground-water runoff can be recovered. Also, rates of withdrawal must be determined so that no adverse effects on natural streamflow occur. If enough ground water is pumped and the wells intercept base runoff, runoff will eventually be reduced. However, with a more detailed study, rates and sites of withdrawal can be judiciously chosen so that these decreases will not occur during natural lowflow periods.

SURFACE-WATER EVALUATION

STREAMFLOW CHARACTERISTICS

Records of streamflow in the upper White River basin have been collected on an expanding scale since the late 1920's. Meager data were collected in the first two decades of this century. The data-collection sites and the period of record for each site are shown on plate 3. Continuous records of daily flows have been collected at 25 sites. Periodic discharge measurements have been obtained at nine partial-record sites, with at least one measurement obtained in each year of record. In addition, many miscellaneous measurements have been obtained at other sites. The periodic and miscellaneous measurements are useful in correlation with continuous records to estimate flow characteristics of the partial-record of miscellaneous sites.

AVERAGE DISCHARGE

An analysis of the records of streamflow in the upper White River basin indicates that the average flow is uniform over the basin and is directly proportional to the size of the drainage area.

There are 18 stations in the basin with essentially unregulated flow having periods of record including the 8-year period ending in 1966. The average flow for this period ranged from 0.715 to 0.840 cfs per sq mi (cubic feet per second per square mile), with an average of 0.775 cfs per sq mi. The variations appear to be random in respect to both location and drainage size. To determine the long-term average discharge, the longer records were analyzed. Eleven of the stations have records of 15 years or more. The average discharge for the period of record of these stations ranged from 0.838 to 0.953 cfs per sq mi, with an average of 0.894 cfs per sq mi. This figure, rounded to 0.9 cfs per sq mi, is a reliable estimate of the long-term average flow in the basin.

VARIABILITY

The yearly average discharge varies from about one-fourth to twice the long-term average. A marked variation occurs in daily discharge. This variation of flow is classically depicted by the duration curve. The curve indicates the precentage of time that a given flow has been exceeded during the preiod of record.

Duration curves, adjusted to a common period of 35 years (1931–65 water years), were prepared for all continuous-record gaging stations with essentially unregulated flow. A composite curve (fig. 12) is presented for the main stem of the White River from below Muncie to Centerton. The composite curve is within about 15 percent of the curve for any of the stations and is reliable, except where extensive diversions take place.

Duration curves for the tributary streams vary considerably; therefore, a composite curve would be misleading. Figure 13 includes curves for the gaged tributary streams. The shaded band includes all gaged tributaries except Fall Creek and Buck Creek, which have higher sustained flows than the other gaged tributaries. Ungaged streams may depart from the indicated band. A few discharge measurements during periods of base runoff would make possible a more reliable estimate of the low end of the duration curve.

LOW-FLOW FREQUENCY

A drawback of the duration curve is that it does not indicate the length of low-flow periods. This is overcome by a frequency analysis of the mean flow for consecutive periods of various lengths.

Low-flow frequency curves were prepared for all stations with essentially unregulated flow and were estimated for several other

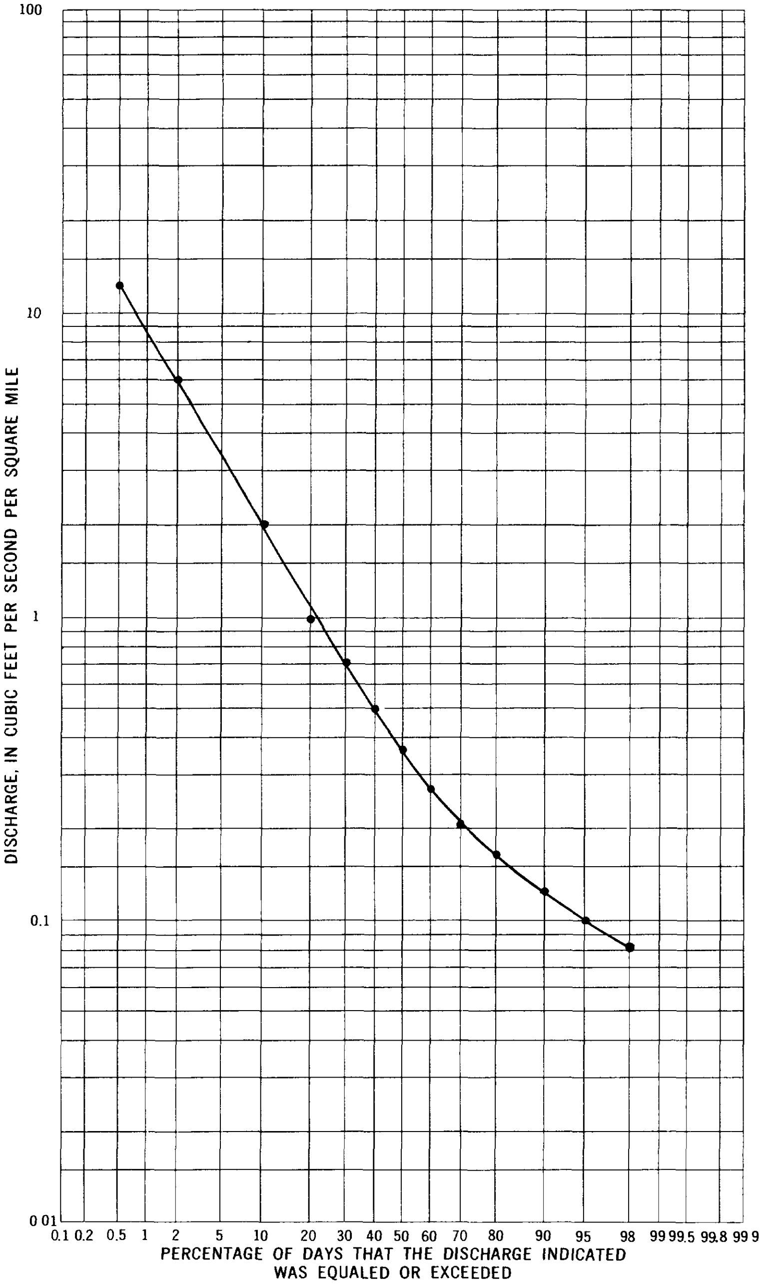


FIGURE 12.—Duration curve for the White River main stem from below Muncie to Centerton.

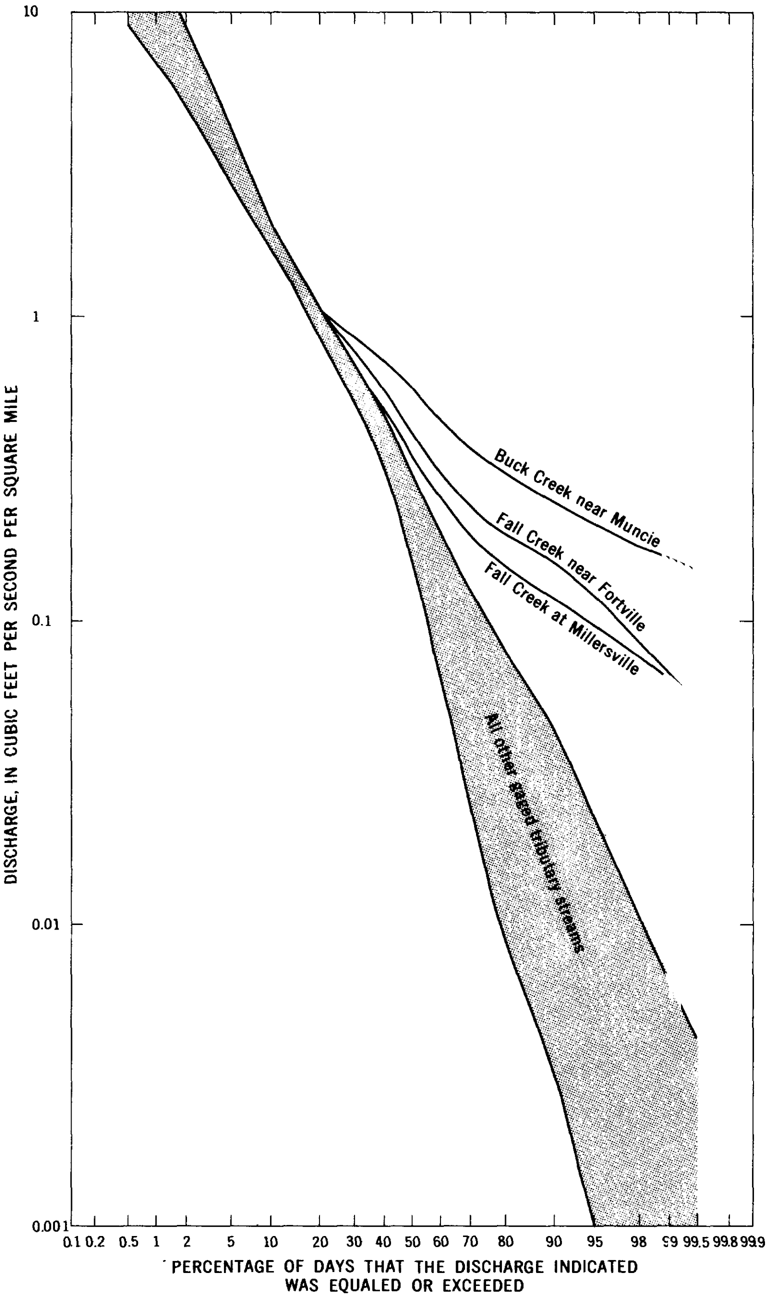


FIGURE 13.—Duration curves for gaged tributaries to the White River.

points by correlation of discharge measurements with the flow at gaging stations. No regionalization of the low-flow frequency curve is possible owing to the lack of sufficient knowledge of the effect of geology. The commonly used index of the low-flow frequency curve, the 7-day 10-year low flow, was estimated where data were available. (See pl. 3.) Local influences may cause significant departure from the indicated value, but generally the value is reliable. Low-flow measurements at selected sites could strengthen or modify the estimate.

FLOOD FLOWS

Speer and Gamble (1965) presented a means of determining the probable magnitude and frequency of flood peaks in the Ohio River basin, which includes the upper White River basin. Green and Hoggatt (1960) did the same for the State of Indiana. No analysis of flood volume and frequency has been published. Although flood water is part of the water resources, flood volume and frequency analysis is beyond the scope of this project.

There is a seasonal pattern to floods. To evaluate this pattern, the distribution of peaks by months was determined for White River near Noblesville and Fall Creek near Fortville. The peaks used in the analysis are those exceeding the base established for each station. The base is defined as that rate of discharge which will be exceeded on the average of three times per year. For White River near Noblesville, the base is 5,500 cfs; and for Fall Creek near Fortville, it is 1,300 cfs. Tabulation by month of the distribution of peaks above the base is given in table 3 for these two stations.

Although floods can occur throughout the year, approximately three-fourths of them occur during the 6-month period November through March. During the summer, however, the smaller streams are more likely to experience flooding than are the larger streams.

The two major types of flood protection are reservoirs and levees. Reservoirs reduce the magnitude of flood flows; levees restrict flood flows. Neither of these measures is utilized extensively in this basin at present (1968).

One flood-control reservoir is nearing completion on Eagle Creek. The drainage area above the dam is 168 square miles, and the flood-control capacity of the reservoir is 42,400 acre-feet. Three water-supply reservoirs—Morse, Geist, and Prairie Creek—may at times provide a small amount of flood protection. Local protection by levees is provided on a limited extent at Muncie and

TABLE 3.—*Distribution of flood peaks by months for White River near Noblesville and Fall Creek near Fortville*

Month	White River near Noblesville, 1916–61		Fall Creek near Fortville, 1942–61	
	Percentage of peaks in month	Percentage of months having peaks	Percentage of peaks in month	Percentage of months having peaks
November	4.3	11	2.9	10
December	9.4	22	5.8	15
January	19.5	35	16.0	30
February	12.9	35	14.5	45
March	18.7	48	18.9	45
April	18.0	37	14.5	35
Total	82.8	----	72.6	----
May	6.5	15	7.2	20
June	5.0	15	14.5	35
July	.7	2	2.9	10
August	2.2	7	1.4	5
September	1.4	2	0	0
October	1.4	4	1.4	5
Total	17.2	----	27.4	----

Indianapolis, and additional levee projects are authorized for Anderson and Indianapolis.

TIME OF TRAVEL

Traveltime in a stream has two main concepts. One has to do with particle travel, as typified by the movement of an accidental spill of organic or chemical pollutants. The other concept is the traveltime of a flood peak or flood wave, which is needed in flood forecasting.

The U.S. Geological Survey has, since 1965, been collecting data on traveltime of particles for most of the major streams in Indiana. These data were collected by tracing the movement of clouds of a harmless dye and by relating these movements to time and discharge. The peak concentration of these clouds always lags the leading edge and decreases downstream as dispersion and channel storage dilute the clouds. Plate 4 relates traveltimes of the leading edge to peak concentration on the main stem of the White River from the headwaters through the project area. Three discharge conditions are represented; they are low, medium, and high flows. Plate 4*A* represents traveltime of the leading edge of the dye cloud, and plate 4*B* represents traveltime of the peak concentration. Traveltime between any two locations can be estimated by (1) connecting two of the points representing two of the discharge conditions at each location with a straight line, (2) interpolating along this line at each location to the discharge for which traveltime is desired, and (3) reading the time for each interpolated point from the bottom scale. The traveltime between the locations is the difference between the two time values. An example is illustrated on plate 4*A*. The rate of travel, in miles per hour, can be estimated from the type curves shown as insets on plate 4. More detailed information will be presented in a report on the time of travel of Indiana streams to be issued at a later date.

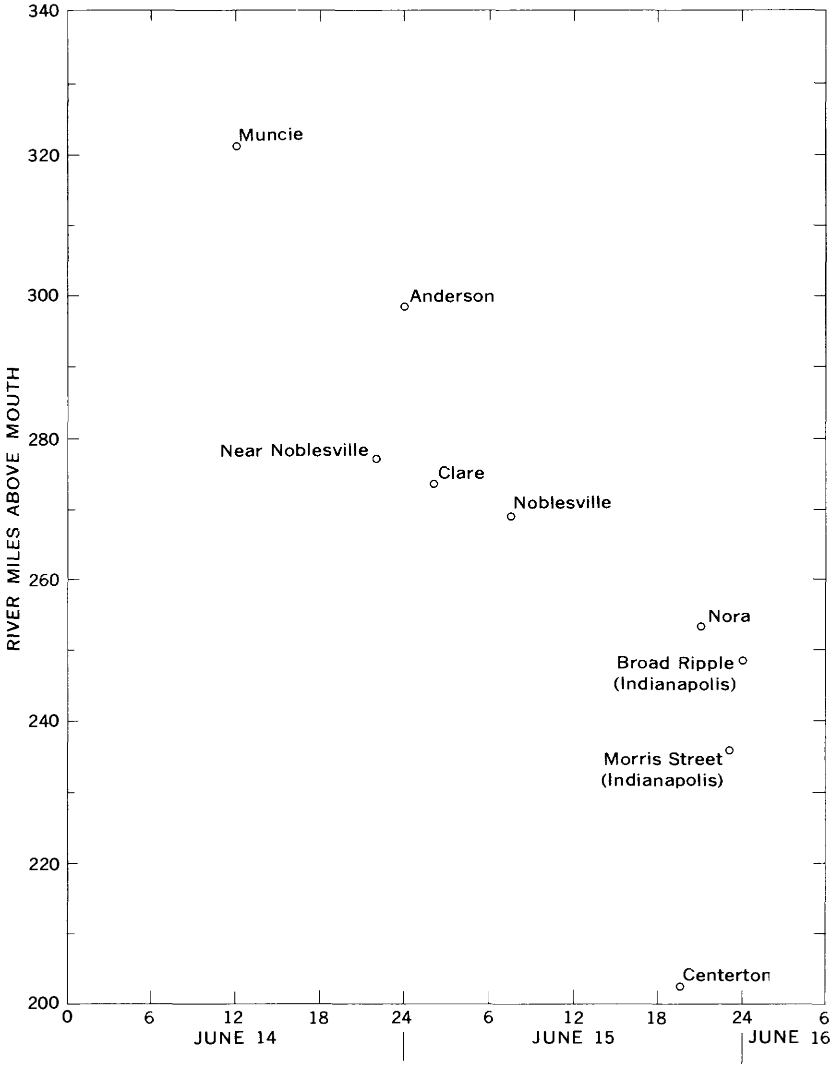


FIGURE 14.—Time of peak for the June 1958 flood.

The other concept of traveltime—flood-peak travel—is shown in figure 14. Illustrated are the times of peak occurrence at stations from Muncie to Centerton on the main stem for the June 1958 peak. This peak was chosen because it was well defined at all points. Because of the timing of tributary inflows and concentration time for the basin as a whole, there was no peak timing which occurred consistently. In the case illustrated, the lower part of the basin contributed inflow at such a time as to make the peak at Centerton occur before the peaks at Nora and at the Indianapolis stations. This has occurred more than once, but still there is no typical pattern for the whole basin. Headwater tributaries may contribute a large amount of the peak at Centerton, or they may not. In summary, the use of flood-peak timing provides questionable results. This method should not be used unless a typical pattern can be established. Therefore, figure 14 is only an example.

STORAGE TO AUGMENT FLOW

The 7-day 10-year low flow is a measure of the flow available with virtually no storage. With storage, a higher dependable flow is available.

Draft-storage analyses have been made using the low-flow frequency curves. Hardison (1966) developed regionalized relations between draft and storage, mean flow, and median 7-day low flow. His relations were computed using the records of 72 stream-gaging stations in the Eastern United States. This method was utilized to develop the draft-storage relation in the upper White River basin. The relation is shown for two levels of chance of deficiency: 5-percent chance (fig. 15) and 10-percent chance (fig. 16). The median 7-day low flow cannot be regionalized, however. Median 7-day low-flow data are available at gaging stations (Hoggatt, 1962), and low flow can be determined at other sites where some streamflow data are available. In the upper White River basin, the median 7-day low flow ranges from approximately 0.01 to 0.3 cfs per sq mi, with that of the main stem ranging from 0.10 to 0.13 cfs per sq mi.

As example of the use of the regional draft-storage curves, assume that a proposed reservoir site has a drainage area of 100 square miles. Sufficient low-flow measurements are available to allow the median annual 7-day low flow (Q) to be estimated as 10 cfs. The estimate of the mean flow ($\overline{Q}$) is 90 cfs, or 33,000 cfs-days per year. The computed ratio $Q/\overline{Q}=10/90=0.11$ If a 5-percent chance of failure is deemed acceptable, use that graph.

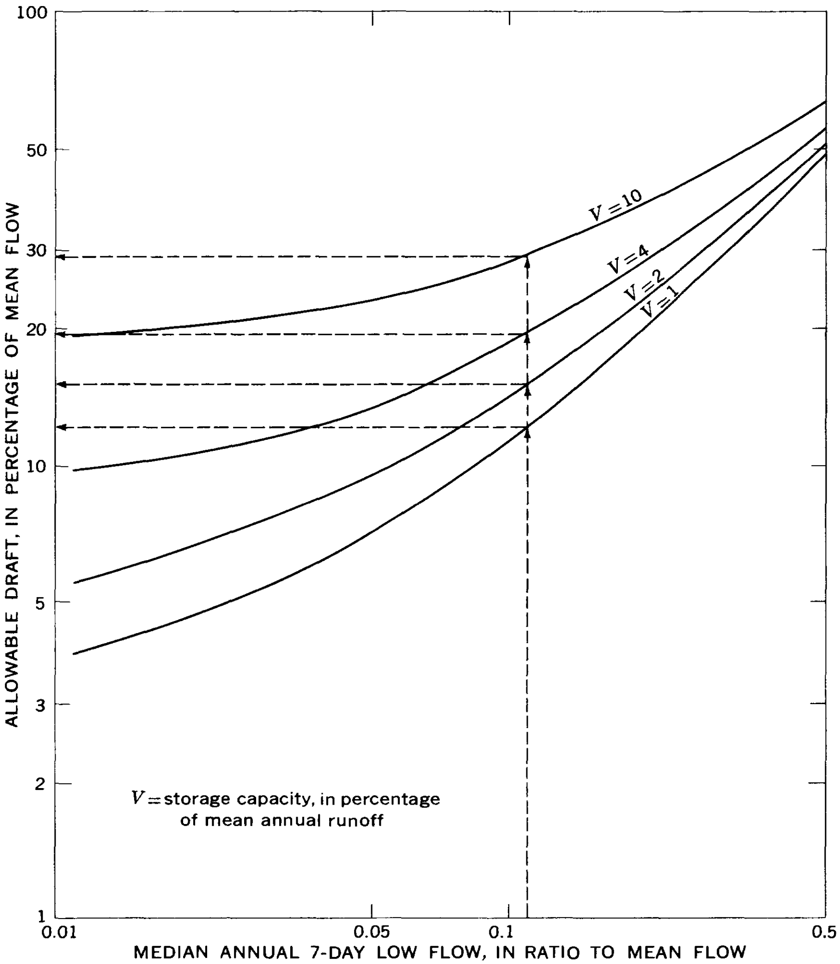


FIGURE 15.—Areal draft-storage relationship for a 5-percent chance of deficiency. Parameter is storage capacity, in percent of mean annual runoff.

From the scale, follow vertically 0.11 to intersect each of the curves. (See dashed lines in fig. 15.) Draft rates for storage volumes of 1, 2, 4, and 10 percent of the mean annual runoff are 12, 15, 20, and 29 percent of the mean flow, or 11, 14, 18, and 26 cfs, respectively. The storage volumes are 330, 660, 1,320, and 3,300 cfs-days, respectively, or 650, 1,300, 2,600, and 6,500 acre-feet. A draft-storage curve (fig. 17) can then be constructed for the proposed site by plotting draft rates against required storage.

The design of any reservoir intended to store water for low-flow augmentation must take into account evaporation and sedi-

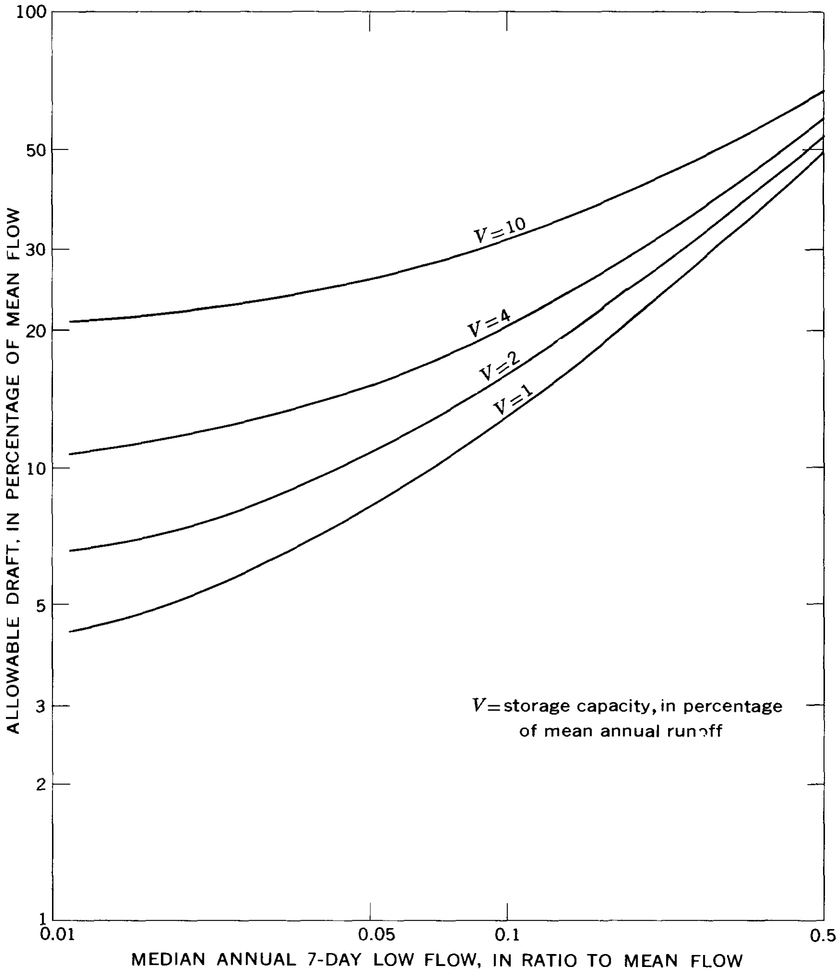


FIGURE 16.—Areal draft-storage relationship for a 10-percent chance of deficiency. Parameter is storage capacity, in percent of mean annual runoff.

mentation. Based on the period 1946–55, the average evaporation rate for lakes in the upper White River basin is 33 inches per year (Kohler and others, 1959, pl. 2). Thus, to offset this loss, more storage space should be provided than is actually needed to store just the amount of water destined for low-flow augmentation.

CHEMICAL AND PHYSICAL PROPERTIES OF THE WATER

Water in the upper White River basin has chemical and physical properties that make it generally acceptable for most uses. On the average, the natural concentrations of most dissolved

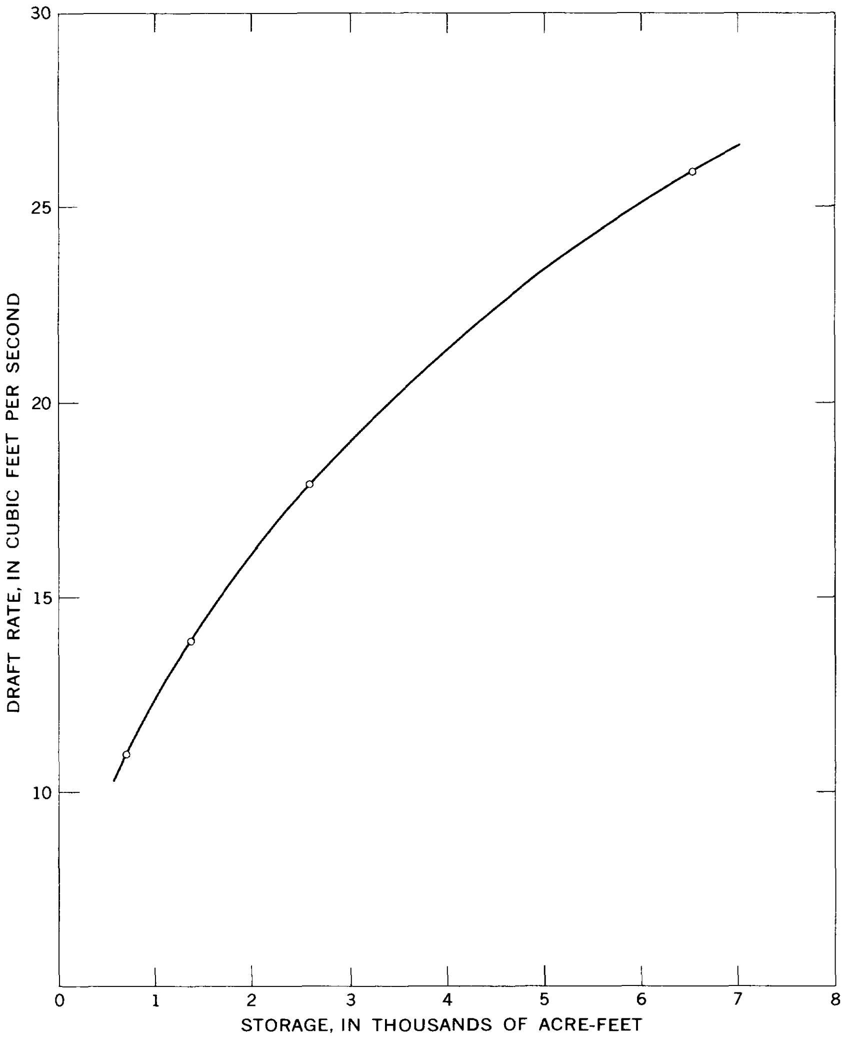


FIGURE 17.—Draft-storage curve for a proposed reservoir site.

chemical constituents are within the limits recommended by the U.S. Public Health Service (1962, p. 7) for drinking-water standards on interstate carriers.

GROUND WATER

The quality of ground water was determined from the evaluation of chemical analyses of water from 60 wells in or near the basin. (See fig. 18.) These analyses indicate that the water from the sand and gravel, as well as that from the bedrock aquifers,

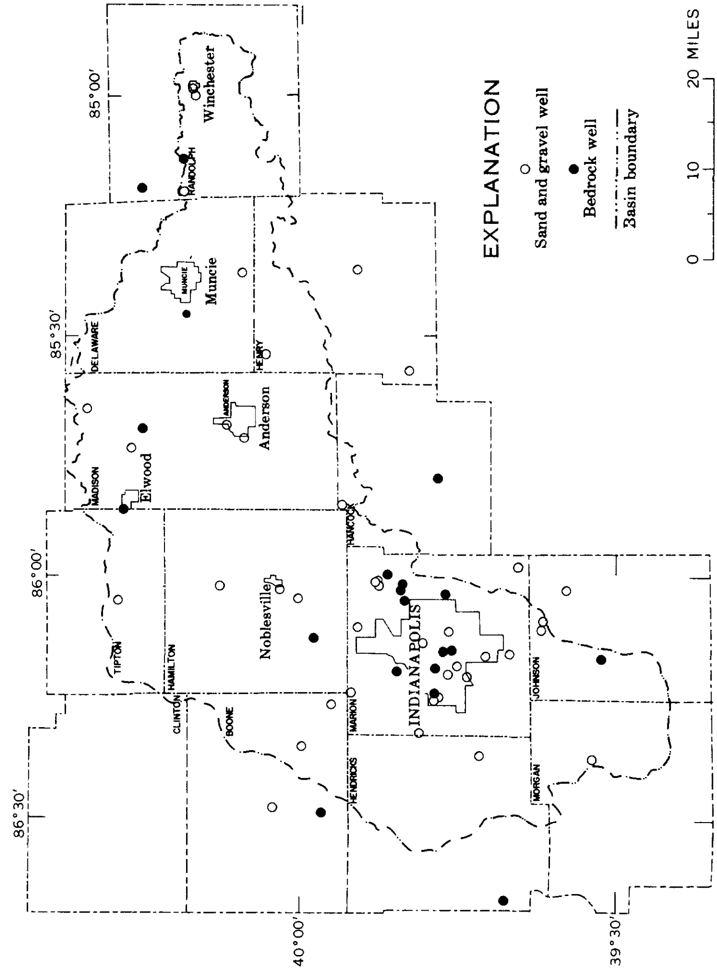


FIGURE 18.—Location of ground-water sampling sites.

TABLE 4.—*Range and average of chemical parameters of ground water*

[Results in milligrams per liter, except as indicated]

Parameters	Sources of water			
	Sand and gravel		Bedrock	
	Average	Range	Average	Range
Silica (SiO_2)	15	7.3–24	15	2.3–32
Iron (Fe)	1.5	.0–5.0	1.6	.63–4.5
Manganese (Mn)	.07	.00–.61	.03	.00–.35
Calcium (Ca)	96	61–178	88	56–186
Magnesium (Mg)	30	2.4–44	35	3.2–65
Sodium (Na)	19	3.4–71	27	6.8–150
Potassium (K)	2.0	.2–9.1	1.9	.6–4.4
Bicarbonate (hcO_3)	391	260–528	414	272–597
Carbonate (CO_3)	.0	---------	.0	---------
Sulfate (SO_4)	66	.0–268	60	.8–319
Chloride (Cl)	9.8	1.4–33	12	1.8–51
Fluoride (F)	.4	.0–1.4	.6	.2–1.0
Nitrate (NO_3)	1.4	.0–9.7	2.2	.1–8.5
Dissolved solids (calculated)	434	296–749	443	285–914
Hardness as $CaCO_3$	361	256–624	367	233–705
Specific conductance (micromhos at 25°C)	726	507–1,090	705	451–1,320
Temperature (°C)	13	11–14	13	12–16
H^+ concentration expressed as pH	7.4	6.9–8.0	7.5	7.2–8.3

is predominantly a very hard calcium bicarbonate type; it is generally high in iron and has a moderate amount of dissolved solids. (See table 4.) No chemical analyses of water from deep bedrock wells were available. On the basis of data from wells in other areas in the State, however, it is reasonable to expect that throughout the basin fresh water can be obtained to depths of about 400 feet below land surface.

SURFACE WATER

On the basis of prospective needs for an availability of information about the quality of streamflow in the basin, the following parameters were considered: specific conductance, hardness, alkalinity, chlorides, dissolved oxygen, suspended sediment, pH, and temperature. Because at low flow the headwaters of the various tributaries exhibit a chemical composition similar to that of ground water, the information presented here pertains essentially to the main stem of the White River.

The specific conductance, hardness, and alkalinity at upper, middle, and lower points on the main stem correlate with flow, in cubic feet per second per square mile. (See fig. 19.) The resulting relation can be used to predict values of these parameters at any point on the White River. The hardness and alkalinity curves are relatively well defined, but there can be large devia-

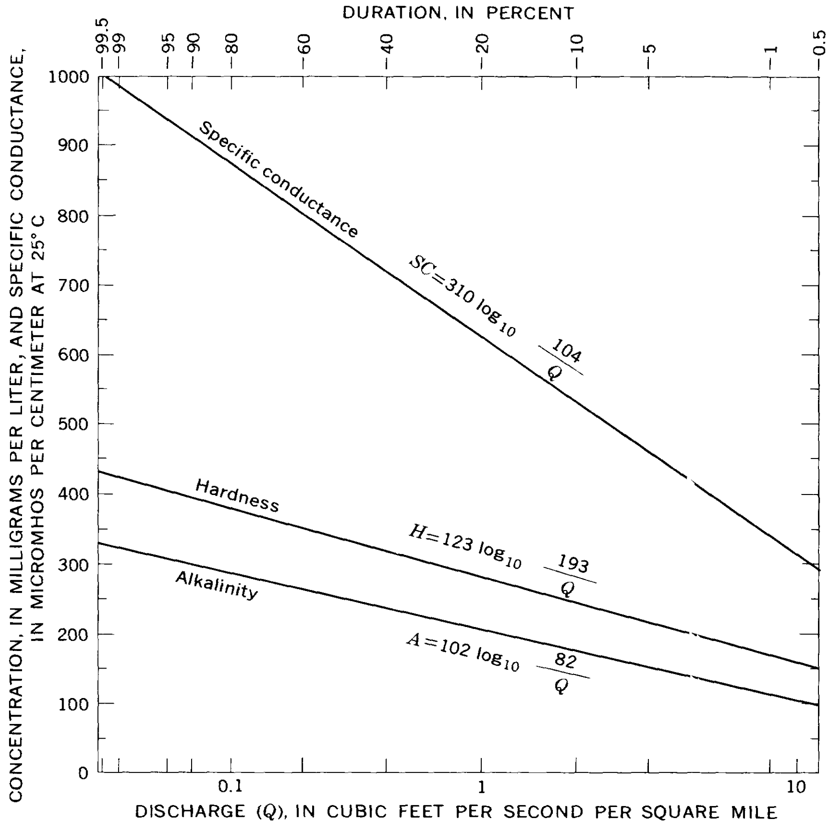


FIGURE 19.—Main-stem White River quality parameters.

tions to the high side of the specific-conductance curve immediately downstream from sewage-treatment outfalls during low-flow periods.

Figure 20 shows the relationship of chloride concentration to discharge at upper, middle, and lower points in the basin. It indicates that, although chloride is not present in excessive concentrations, the chloride does increase in the downstream direction.

Dissolved-oxygen tests indicate that the assimilative capacity of the stream upstream from Indianapolis is sufficient to handle the waste loads imposed upon it and still maintain oxygen levels above the minimum limits. However, in the more sluggish reach of the river downstream from Indianapolis, the oxygen demand of the treated sewage effluent discharged to the stream is high enough to cause the dissolved oxygen content of the water to fall below the minimum level of 4.0 milligrams per liter. The stream

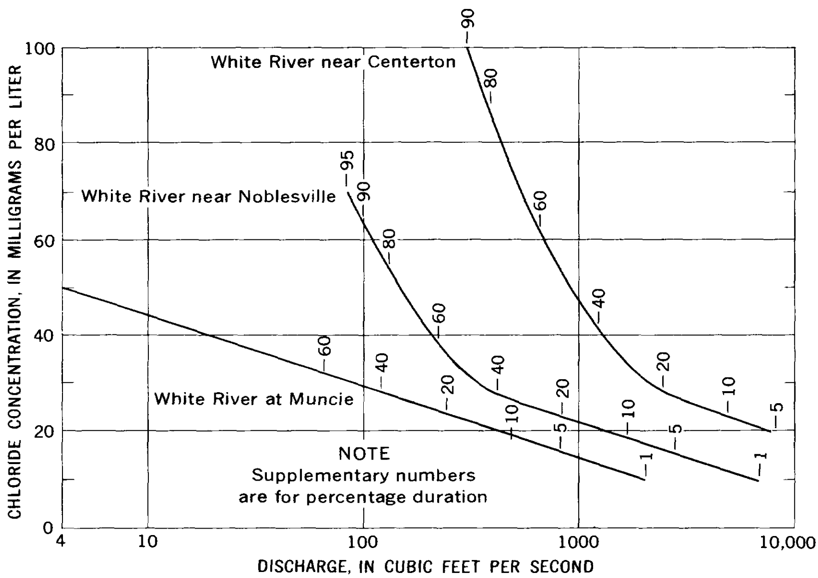


FIGURE 20.—Chloride concentration at selected points.

has not completely recovered at the gage near Centerton. At high flow, however, the decline in dissolved-oxygen concentration would not be so drastic nor last so far downstream.

Suspended-sediment discharge at the Centerton gage averages 223 tons per square mile per year and that of Fall Creek averages only 85 tons per square mile per year.

Throughout most of the basin, pH values range between 7.0 and 8.5.

The temperature of surface water follows seasonal and diurnal cycles in response to changes in air temperature. Thermographs for the stations near Noblesville and near Centerton show the mean monthly temperature to be lowest in January and highest in July. (See fig. 21.) The total annual fluctuation of the mean temperature is approximately 22°C (degrees Celsius). Generally the mean monthly temperature is 3°C higher near Centerton than near Noblesville.

SUMMARY OF CONCLUSIONS

The general nature of the hydrosystem in the upper White River basin can be summarized briefly as follows:

1. The surface drainage divides and the watertable divides coincide. The surface divides are reflected also in the potentio-

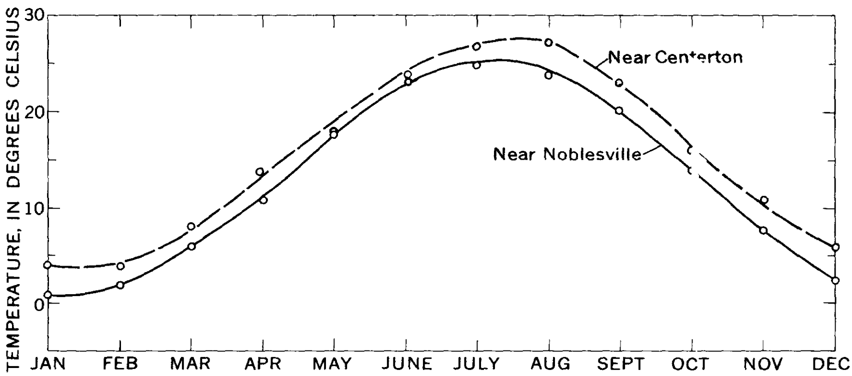


FIGURE 21.—Mean monthly temperature of the White River near Noblesville and near Centerton.

metric surface of the deeper sand and gravel aquifers and the bedrock.

2. The sole source of fresh-water replenishment is the precipitation that falls directly on the basin.
3. The regional hydraulic gradient of the water table is approximately 10 feet per mile, and ground water movement is predominately from the divides toward the streams.
4. Ground-water recharge occurs relatively uniformly over the basin as vertical percolation.
5. The principal avenues of ground-water discharge in the basin are evapotranspiration and ground-water runoff.
6. On the average, base runoff accounts for approximately 55 percent of annual runoff, and overland runoff accounts for about 45 percent.

The ground-water–surface-water relationship in the basin is such that ground water sustains streamflow during periods of no precipitation. The sustaining mechanism is the natural discharge of ground water into the stream. The commonly used term for this discharge is "ground-water runoff." Ground-water runoff represents that part of recharge which remains after evapotranspiration requirements have been met. It provides an index to the amount of ground water available for development. No lasting undesirable effects upon the system will result as long as ground-water withdrawals do not greatly exceed ground-water runoff for long periods of time.

The water year can be conveniently used as the smallest basic unit for estimating potential yield. Annual base runoff, determined by means of stream-discharge hydrograph separation, is equivalent to ground-water runoff, which is the liquid phase of ground-water discharge. Annual base runoff is an index of the integrated ground-water potential for the gaged area. Overland runoff for the gaged area equals total runoff minus base runoff.

A comparison of the base-runoff variation with aquifer distribution shows the ground-water runoff to be greatest in those areas where thick aquifers are present adjacent to the streams. Where aquifers are thin or absent, ground-water runoff is least. Probability analyses show the average ground-water runoff for the high-yield areas in the basin to be between 400,000 and 500,000 gpd per sq mi.

Sand and gravel of glacial origin are the best aquifers in the upper White River basin. Although numerous small lenses and pockets are present, two main bodies of sand and gravel occur fairly consistently throughout the Quaternary section. One of these is a relatively thick elongate body concentrated along bedrock valleys. In most places, this aquifer is in direct contact with the bedrock. The other principal sand and gravel body is a shallow and relatively thin sheetlike deposit. These are the chief sources of ground water in the basin, although the limestone and dolomite formations of the top 100 feet of the bedrock show fair aquifer potential. The representative hydraulic conductivity of the sand and gravel aquifers ranges from 1,500 gpd per sq ft under confined conditions to 2,500 gpd per sq ft under unconfined conditions.

Continuous records of daily discharge are available for 25 gaging stations in the upper White River basin. An analysis of gaging-station records shows the long-term average discharge of the basin to be approximately 0.9 cfs per sq mi. The yearly average discharge varies from about one-fourth to twice the long-term average. The 7-day 10-year low flow, a commonly used index of low-flow frequency, ranges from about 0.01 to 0.3 cfs per sq mi; the main stem alone ranges from 0.10 to 0.13 cfs per sq mi.

The chemical and physical properties of the water available for development in the upper White River basin make it acceptable for most uses. Water in the sand and gravel aquifers, as well as in the bedrock aquifers, is predominantly a very hard calcium bicarbonate type; it is generally high in iron and contains a moderate amount of dissolved solids. Fresh water (1,000 milligrams per liter or less) is present to depths of approximately 400 feet below land surface.

In the tributaries and in the headwaters region of the main stem of the White River, the chemical and physical composition of surface water is very similar to that of ground water, especially at periods of low flow. In the main stem, however, the quality of the water tends to deteriorate downstream as a result of the cumulative effect of sewage effluent. The extent of quality deterioration is inversely related to the flow in the stream.

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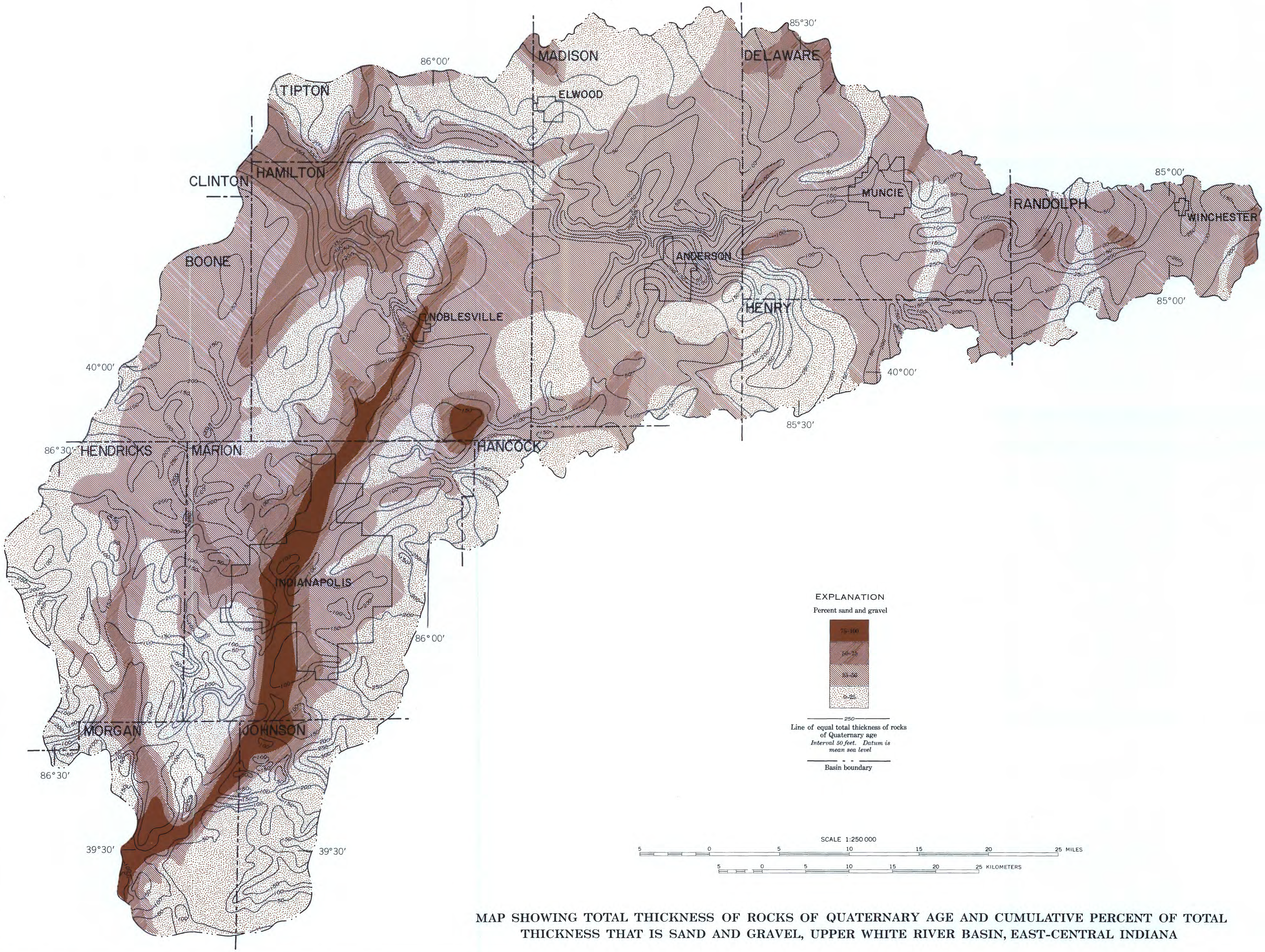
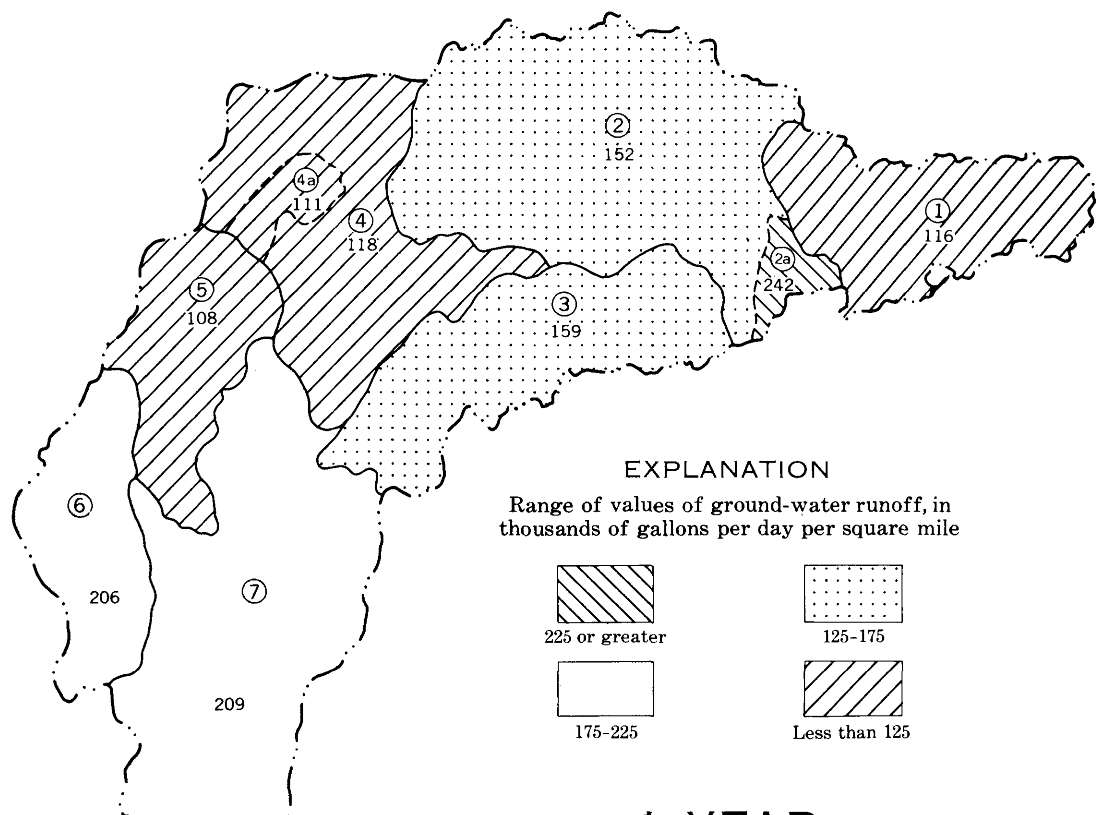
☆ U.S. GOVERNMENT PRINTING OFFICE: 1971 O—437-656

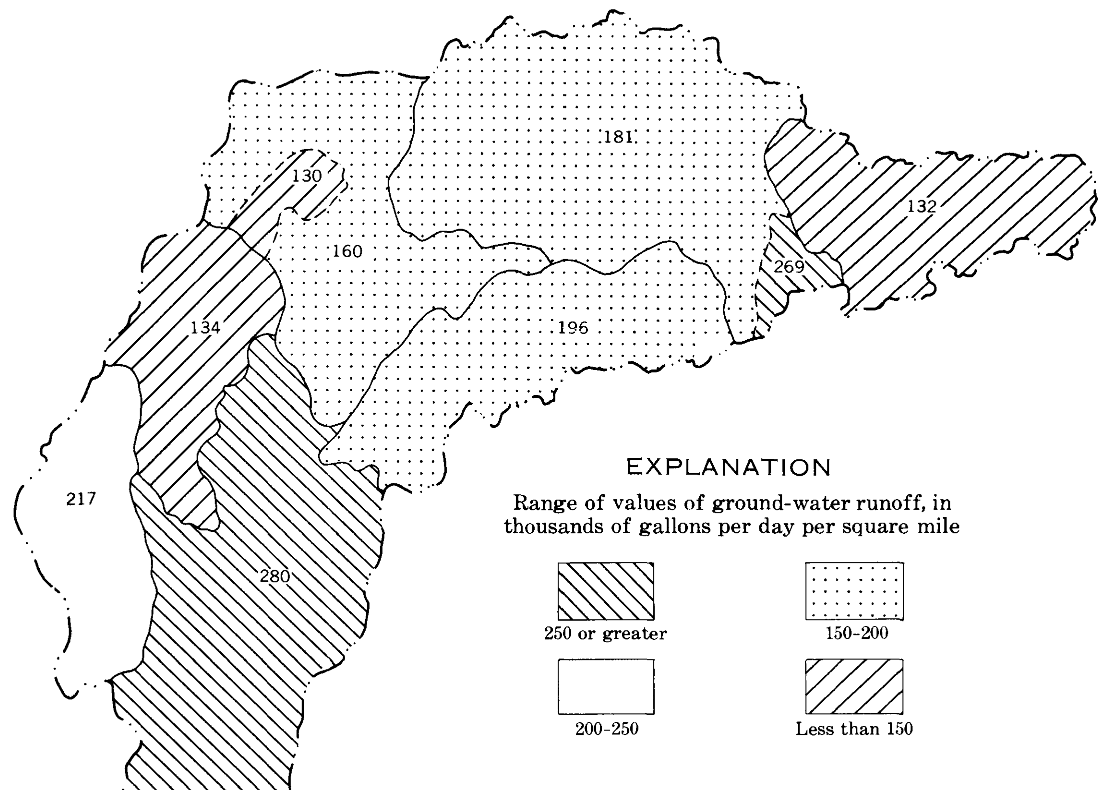


MAP SHOWING TOTAL THICKNESS OF ROCKS OF QUATERNARY AGE AND CUMULATIVE PERCENT OF TOTAL THICKNESS THAT IS SAND AND GRAVEL, UPPER WHITE RIVER BASIN, EAST-CENTRAL INDIANA

10–PERCENT PROBABILITY



1 YEAR



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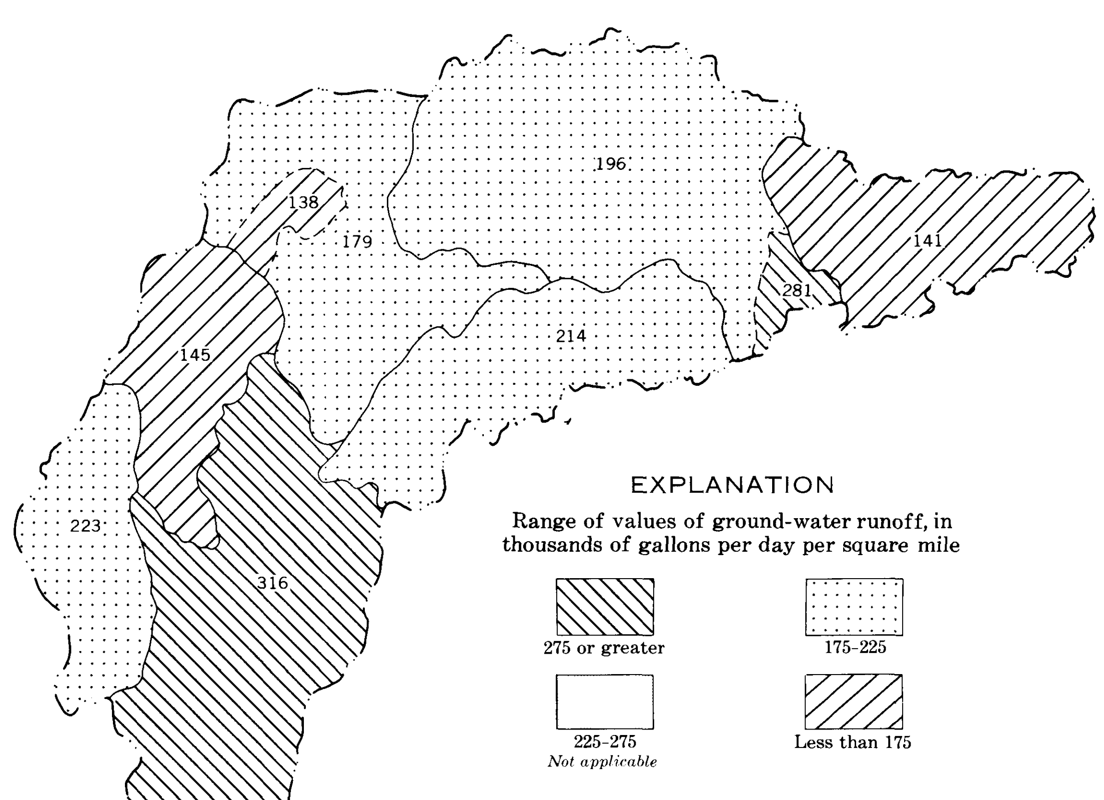
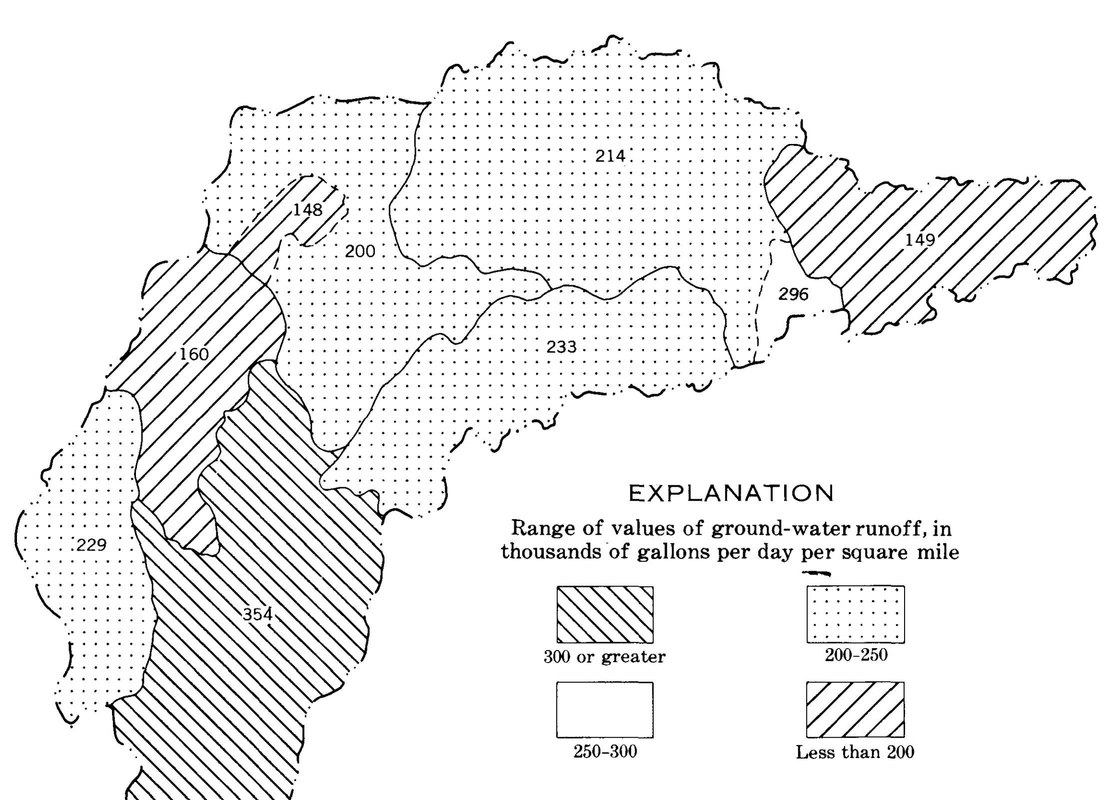
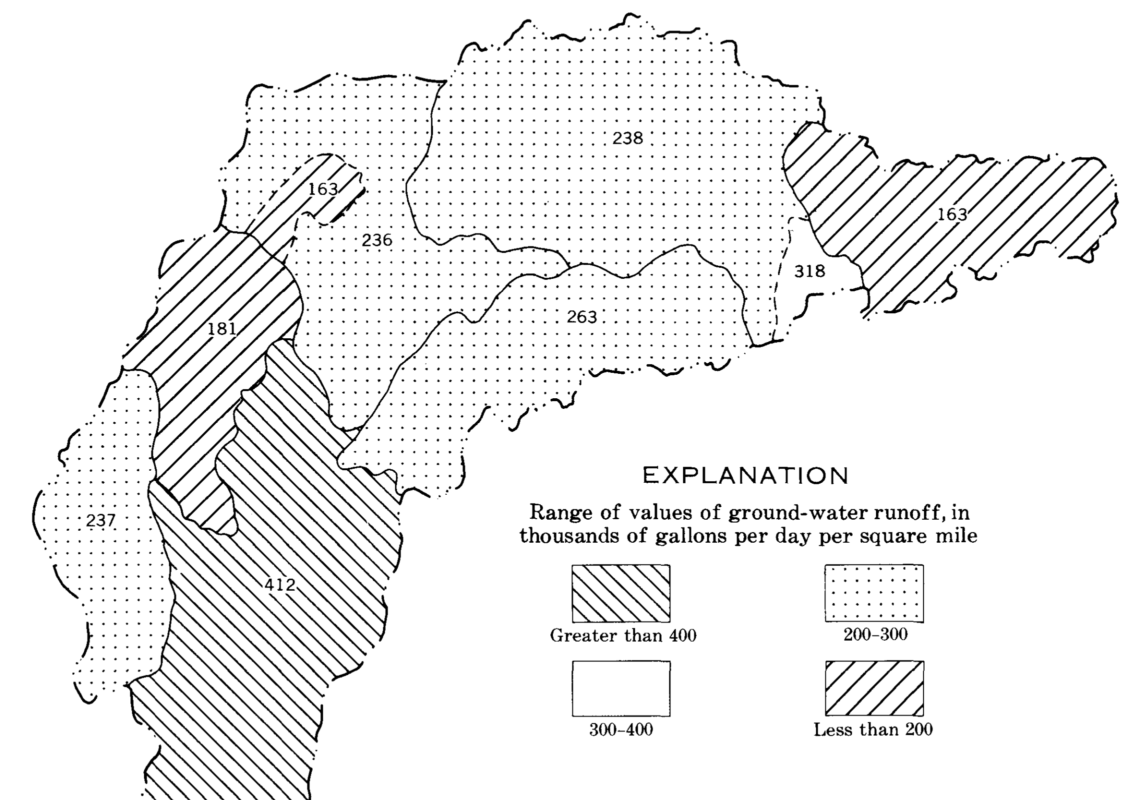


3 YEARS



5 YEARS

30–PERCENT PROBABILITY



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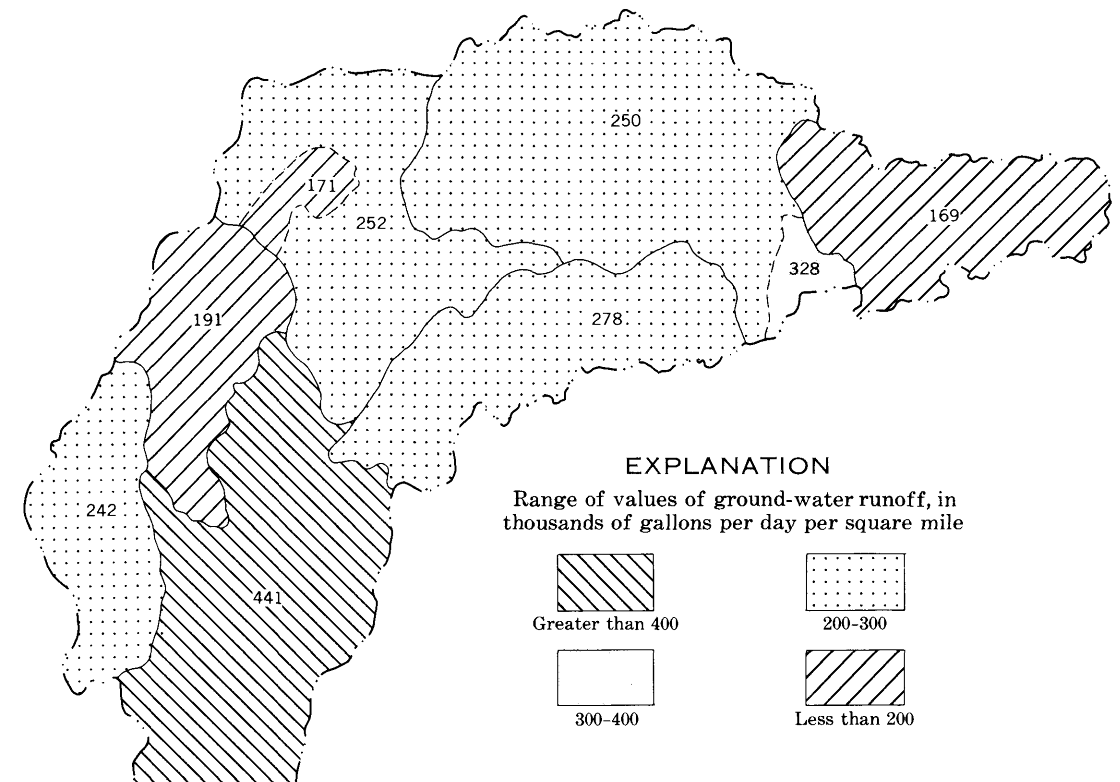

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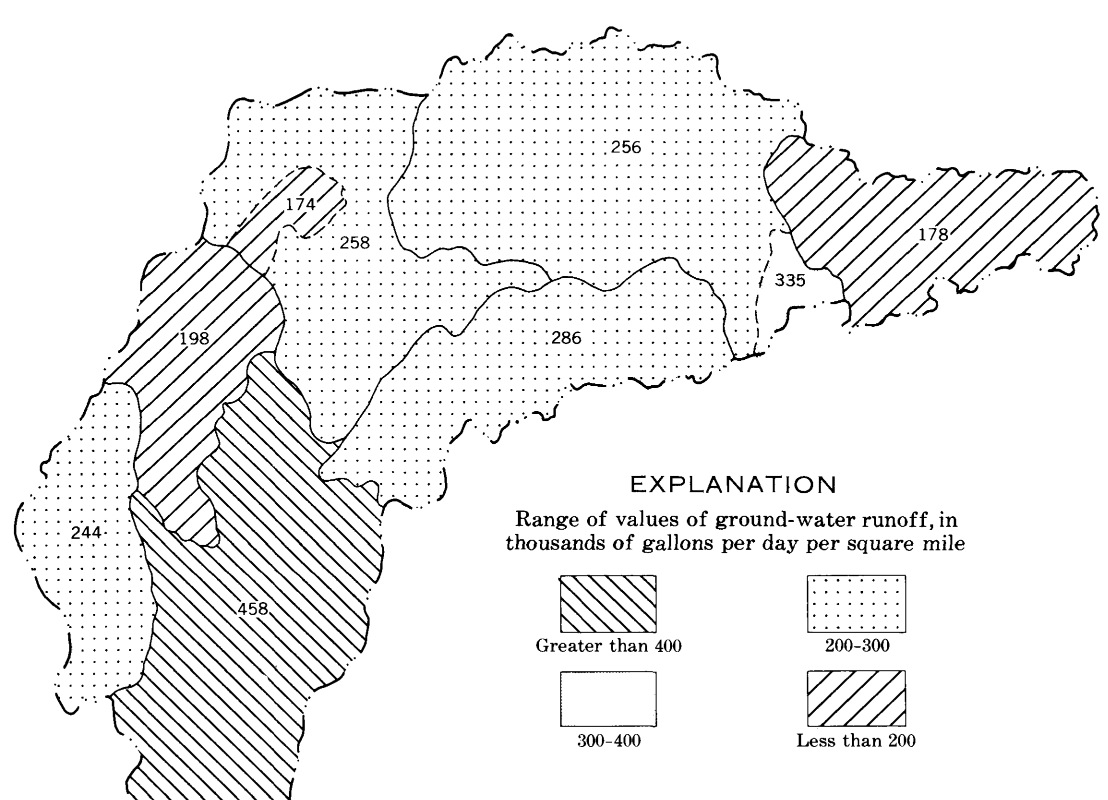

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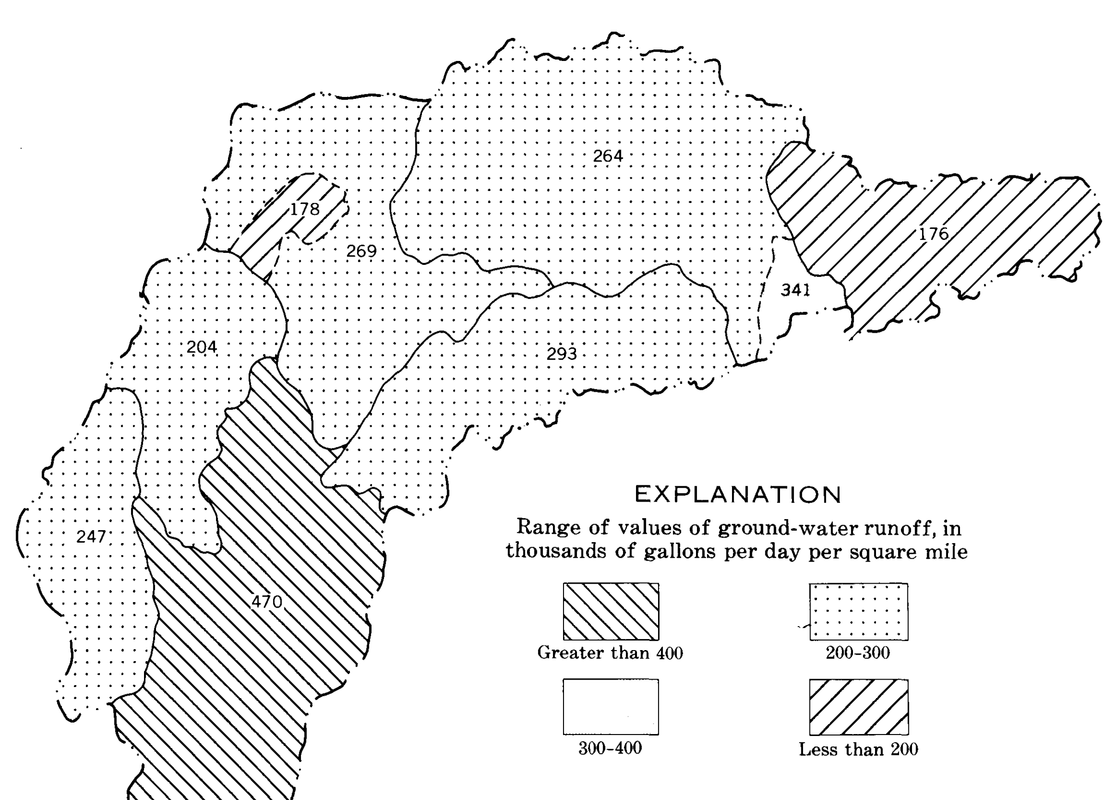
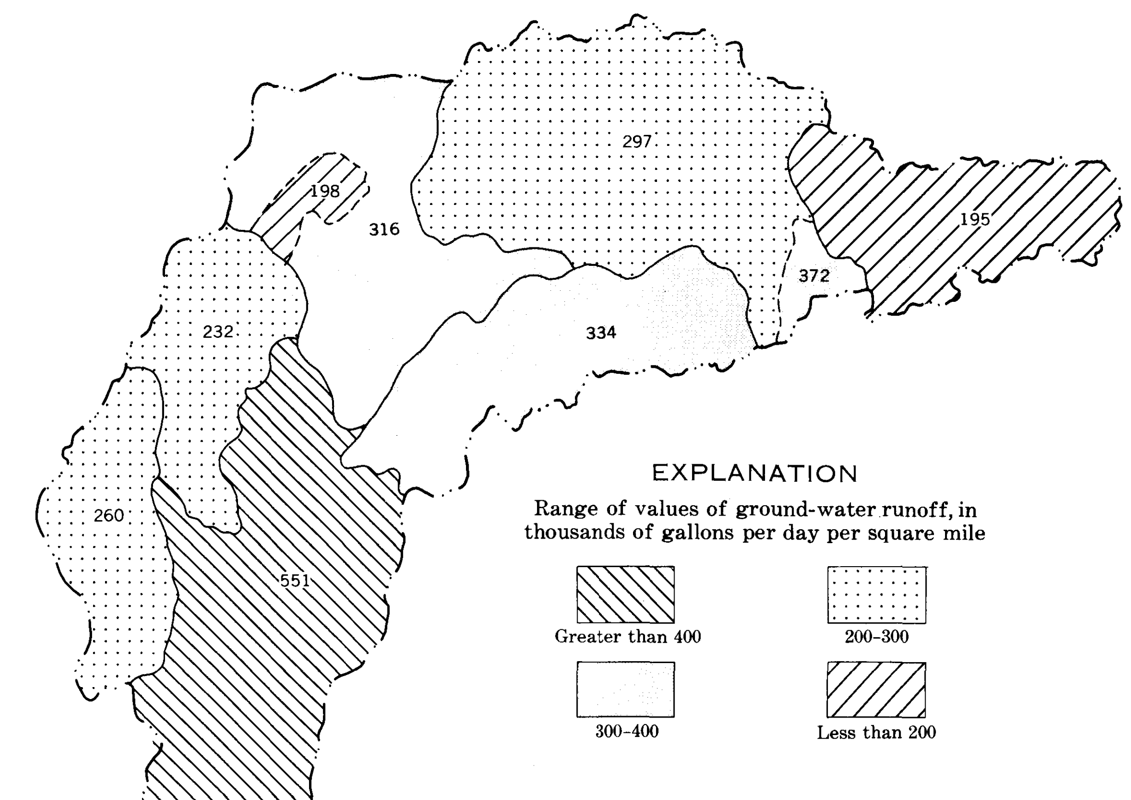
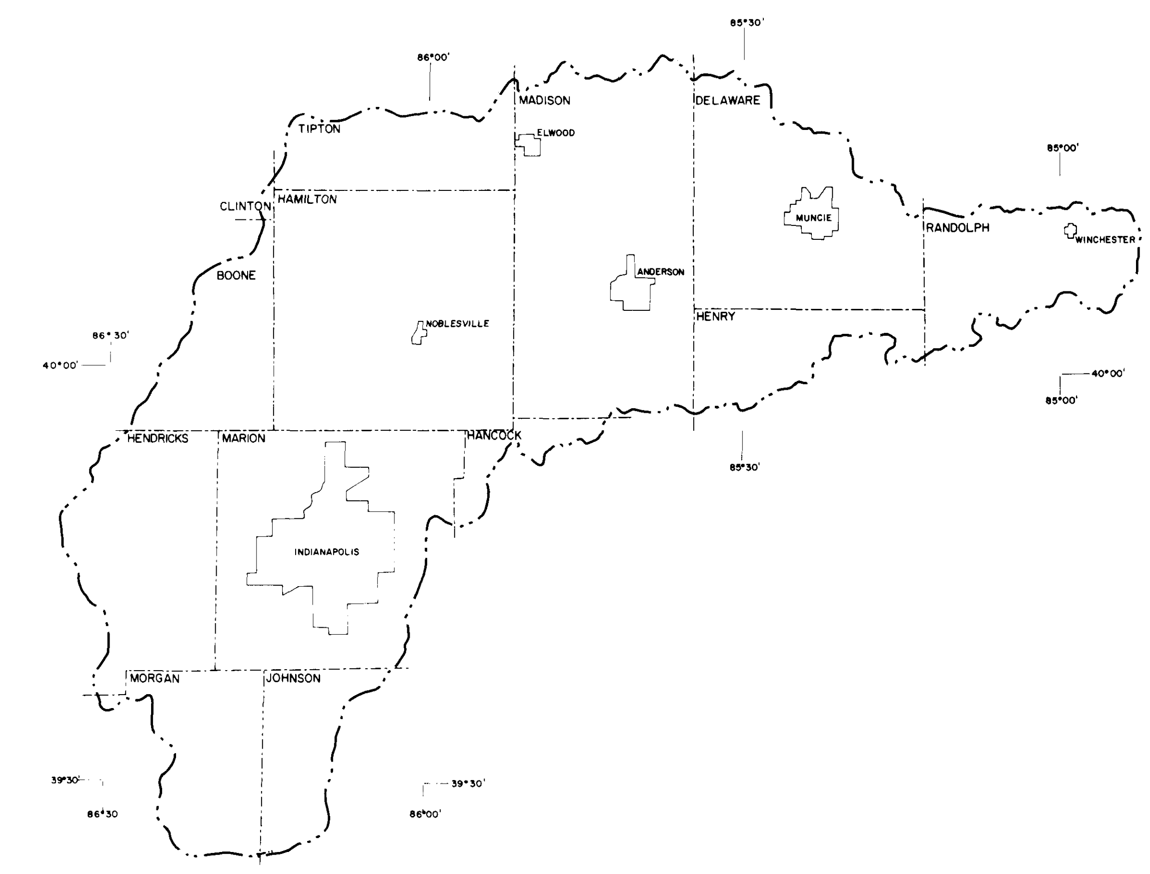


5 YEARS

50–PERCENT PROBABILITY



1 YEAR



GEOGRAPHIC LOCATION

EXPLANATION

242
Values of ground-water runoff for subbasins, in thousands of gallons per day per square mile

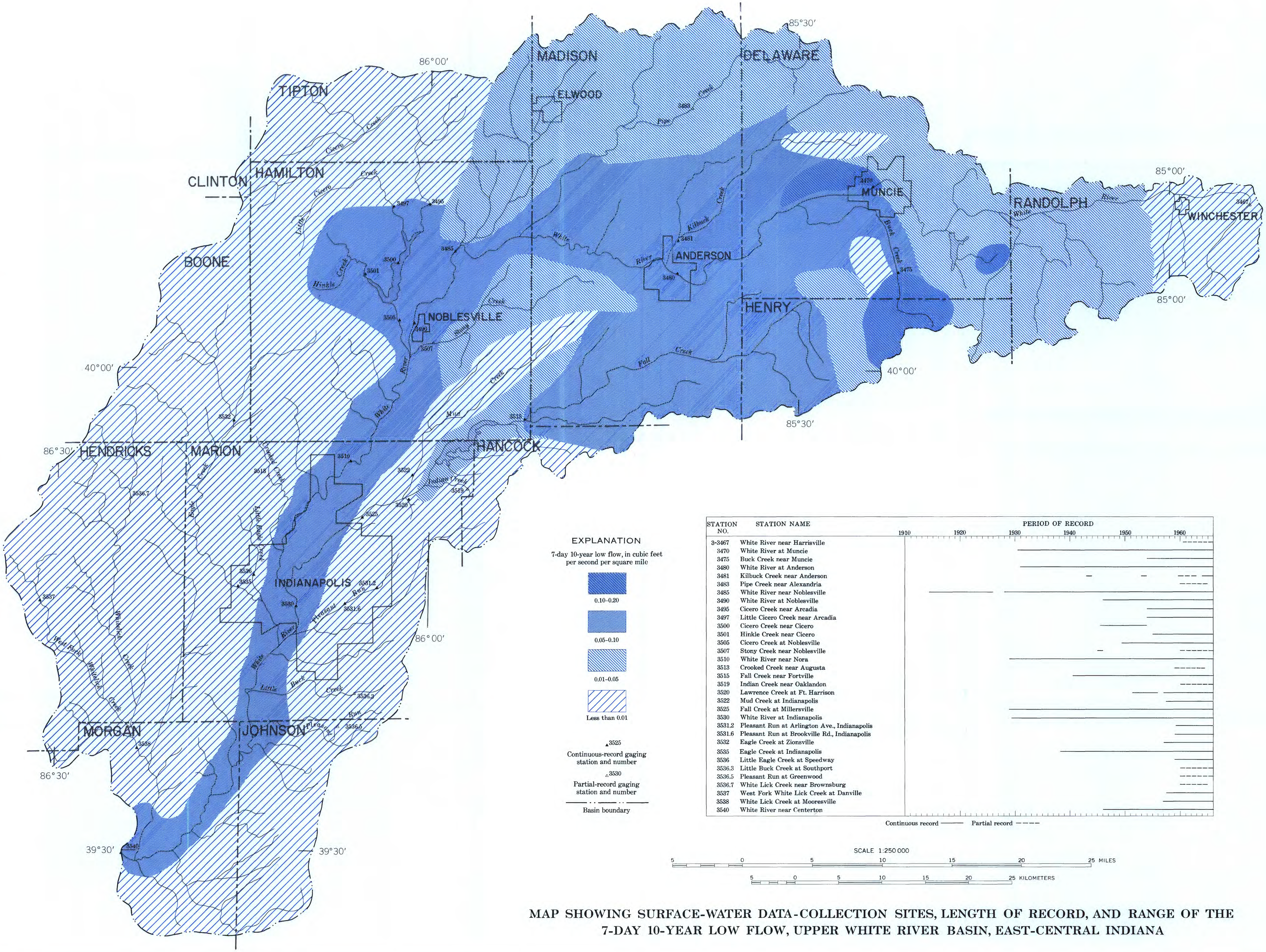
⑥
Subbasin boundary and number

Boundary of areas used in example in text

Basin boundary

MAPS SHOWING GROUND-WATER RUNOFF FOR THE 10-, 30-, AND 50-PERCENT PROBABILITY OF NOT BEING EXCEEDED, UPPER WHITE RIVER BASIN, EAST-CENTRAL INDIANA

PREPARED IN COOPERATION WITH THE
INDIANA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATER



EXPLANATION

7-day 10-year low flow, in cubic feet per second per square mile

0.10–0.20

0.05–0.10

0.01–0.05

Less than 0.01

▲3525 Continuous-record gaging station and number

△3530 Partial-record gaging station and number

—·—·— Basin boundary

STATION NO.	STATION NAME	PERIOD OF RECORD (1910, 1920, 1930, 1940, 1950, 1960)
3-3467	White River near Harrisville	
3470	White River at Muncie	
3475	Buck Creek near Muncie	
3480	White River at Anderson	
3481	Kilbuck Creek near Anderson	
3483	Pipe Creek near Alexandria	
3485	White River near Noblesville	
3490	White River at Noblesville	
3495	Cicero Creek near Arcadia	
3497	Little Cicero Creek near Arcadia	
3500	Cicero Creek near Cicero	
3501	Hinkle Creek near Cicero	
3505	Cicero Creek at Noblesville	
3507	Stony Creek near Noblesville	
3510	White River near Nora	
3513	Crooked Creek near Augusta	
3515	Fall Creek near Fortville	
3519	Indian Creek near Oaklandon	
3520	Lawrence Creek at Ft. Harrison	
3522	Mud Creek at Indianapolis	
3525	Fall Creek at Millersville	
3530	White River at Indianapolis	
3531.2	Pleasant Run at Arlington Ave., Indianapolis	
3531.6	Pleasant Run at Brookville Rd., Indianapolis	
3532	Eagle Creek at Zionsville	
3535	Eagle Creek at Indianapolis	
3536	Little Eagle Creek at Speedway	
3536.3	Little Buck Creek at Southport	
3536.5	Pleasant Run at Greenwood	
3536.7	White Lick Creek near Brownsburg	
3537	West Fork White Lick Creek at Danville	
3538	White Lick Creek at Mooresville	
3540	White River near Centerton	

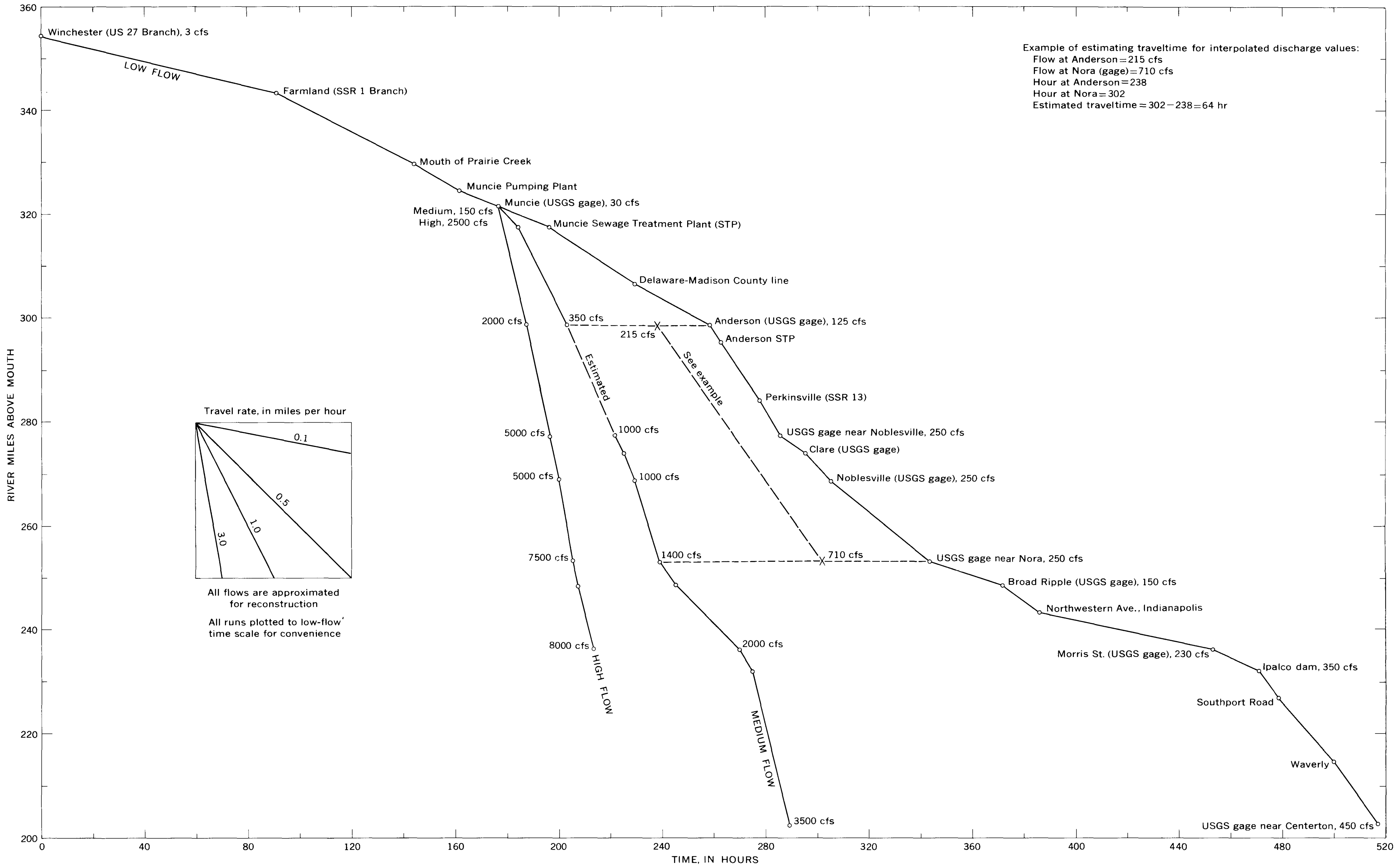
Continuous record ——— Partial record - - - -

SCALE 1:250 000

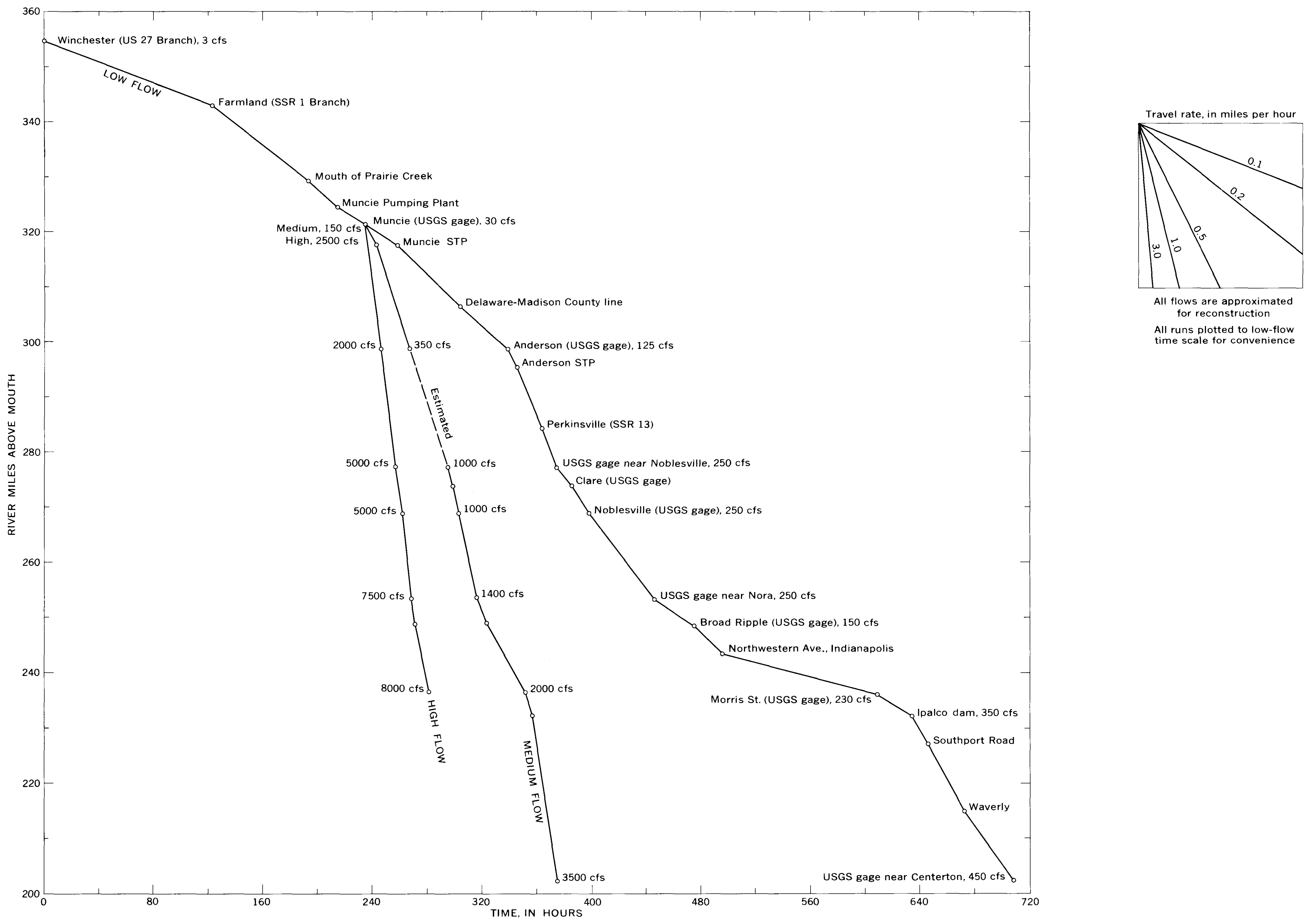
5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

MAP SHOWING SURFACE-WATER DATA-COLLECTION SITES, LENGTH OF RECORD, AND RANGE OF THE 7-DAY 10-YEAR LOW FLOW, UPPER WHITE RIVER BASIN, EAST-CENTRAL INDIANA



A. TRAVELTIME OF LEADING EDGE OF DYE CLOUD



B. TRAVELTIME OF PEAK CONCENTRATION OF DYE CLOUD

PROFILES SHOWING RESULTS OF TIME-OF-TRAVEL STUDY ON WHITE RIVER, UPPER WHITE RIVER BASIN, EAST-CENTRAL INDIANA