GROUND-WATER RESOURCES OF THE GLACIAL OUTWASH ALONG THE WHITE RIVER, JOHNSON AND MORGAN COUNTIES, INDIANA

By Zelda Chapman Bailey and Thomas E. Imbrigiotta

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FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply inch-pound unit	By	To obtain SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.929	square meter per day (m^2/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
inch per year (in./yr)	2.54	centimeter per year (cm/a)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
gallon per day (gal/d)	3.785	liter per day (L/d)
gallon per minute (gal/min)	3.785	liter per minute (L/m)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/yr)	0.04381	cubic meter per year (m^3/a)
cubic foot per day per foot [$(ft^3/d)/ft$]	0.0929	cubic meter per day per meter [$(m^3/d)/m$]
gallon per day per square mile [$(gal/d)/mi^2$]	0.0982	cubic meter per day per square kilometer [$(m^3/d)/km^2$]
micromho per centimeter (µmho/cm)	1.0	microsiemen (µS)

To convert degree Fahrenheit (°F) to degree Celsius (°C)

$$(0.556)(°F - 32°) = °C$$

DATUM USED IN THIS REPORT

National Geodetic Vertical Datum of 1929 (NGVD of 1929):

A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

GROUND-WATER RESOURCES OF THE GLACIAL OUTWASH ALONG THE WHITE RIVER, JOHNSON AND MORGAN COUNTIES, INDIANA

By Zelda Chapman Bailey and Thomas E. Imbrigiotta

ABSTRACT

Test drilling and mapping of an 88-square-mile segment of outwash along the White River in Johnson and Morgan Counties revealed an unconfined sand and gravel aquifer ranging from 0 to 120 feet in saturated thickness. Average hydraulic conductivity is 340 feet per day, and transmissivity is as much as 35,000 square feet per day. Most recharge is directly from precipitation. The aquifer, primarily bounded by bedrock, is bounded in some areas by till interbedded with lenses of outwash. Some ground-water recharge infiltrates through the till, but the bedrock contributes virtually no water directly to the outwash. However, runoff from uplands recharges the outwash through losing streams. Domestic and municipal pumping has little impact on the aquifer at present. The ground-water system is generally balanced in inflow and outflow.

A two-dimensional digital model of the ground-water-flow system was constructed to test the conceptual model of the system and to study the effects of development on ground-water levels and flow in the White River. Three pumping plans were simulated by the model: Plan 1, 20-million gallons per day pumping of a well field; plan 2, enough pumping to reduce streamflow by 15 percent; and plan 3, enough pumping to reduce streamflow by 30 percent.

In plan 1, the maximum drawdown in the area of the simulated well field was 20 feet, and maximum drawdown in any of the 10 simulated 12-inch diameter wells was less than 30 percent of saturated thickness. The flow of the White River was reduced 5 percent.

In plan 2, 66-million gallons per day pumpage caused water-level declines of 13 feet and drawdowns of 33 percent or less of saturated thickness in the 33 simulated wells.

In plan 3, 122-million gallons per day pumpage caused declines of 25 feet and drawdowns of less than 40 percent of saturated thickness in 54 of the 61 simulated wells. Drawdowns in the remaining seven wells were between 40 and 50 percent of saturated thickness.

Sensitivity analyses of the calibrated model indicated that model variables could be adjusted within certain ranges without significantly changing simulated water levels and simulated rates of ground-water discharge to the White River. These variables and their ranges were: hydraulic conductivity (258 to 493 feet per day), streambed-leakance coefficient (less than 0.1 to 50 feet per day per foot), and areal recharge (7 to 17 inches per year). Ground-water discharge ranged from 80 to 120 cubic feet per second; calibrated seepage rate was 102 cubic feet per second.

Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan, and Owen Counties, Ind.--Continued

Well	Latitude	Longitude	Date	Depth of well (ft)	Temperature (°C)	pH	Specific conductance[a]	Dissolved oxygen	Redox potential	Hardness	Hardness, noncarbonate (as $CaCO_3$)	Dissolved solids[b]	Silica
MOR-44	392244	862403	11-1-79	45	12.5	7.2	430	2.1	114	---	---	---	----
			5-14-80	45	15.0	7.1	482	.8	131	220	0	265	18
			10-9-80	45	14.2	7.3	497	.1	---	200	0	305	18
MOR-47	392713	862616	11-2-79	24	14.0	7.1	679	2.4	409	---	---	---	----
			5-14-80	24	13.0	7.1	556	2.1	405	300	7	378	13
			10-7-80	24	16.1	7.1	605	.6	---	270	9	370	13
MOR-48	392509	862721	11-2-79	24	14.1	7.0	743	4.2	448	---	---	---	----
			5-15-80	24	12.0	6.9	689	2.6	380	330	62	420	12
			10-9-80	24	17.5	7.4	644	1.0	---	300	61	390	12
MOR-50	392417	862737	11-8-79	24	14.0	6.8	505	5.7	375	---	---	---	----
MOR-52	392340	862709	11-7-79	24	13.4	7.3	655	5.0	310	---	---	---	----
			5-14-80	24	13.1	7.2	670	5.2	405	320	107	433	10
			10-9-80	24	16.0	7.6	670	5.1	---	310	124	420	10
MOR-54	392439	862901	11-12-79	24	11.8	6.9	594	7.5	435	---	---	---	----
MOR-55	392518	862843	1-11-80	46	11.5	7.7	475	1.3	30	---	---	---	----
			5-15-80	46	13.9	7.4	448	1.6	257	250	15	306	12
			10-8-80	46	14.8	7.6	497	1.5	---	230	14	296	11
MOR-56	392228	862758	11-8-79	24	13.4	6.9	493	8.9	465	---	---	---	----
MOR-57	392228	862845	11-8-79	24	13.5	6.7	900	.7	170	---	---	---	----
MOR-59	392348	863010	11-12-79	24	12.5	6.8	657	4.5	330	---	---	---	----
MOR-61	392405	863129	11-9-79	24	13.2	6.9	405	4.9	515	---	---	---	----
MOR-62	392258	863117	11-12-79	45	12.4	6.7	585	1.0	445	---	---	---	----
MOR-64	392354	863208	11-9-79	24	13.0	7.0	480	3.2	475	---	---	---	----
MOR-65	392456	863228	1-11-80	25	12.8	7.5	490	.5	115	---	---	---	----
MOR-66	392416	863333	11-12-79	24	12.5	6.7	549	3.2	445	---	---	---	----
MOR-68	392355	863430	11-13-79	24	14.5	7.2	450	.3	425	---	---	---	----
			5-14-80	24	11.3	7.3	493	1.0	213	240	50	343	19
			10-8-80	24	15.5	7.4	459	<.05	---	200	43	281	20
MOR-69	392301	863351	11-9-79	24	14.5	6.9	496	.4	185	---	---	---	----
			5-13-80	24	14.5	7.3	474	.6	157	260	29	303	15
			10-8-80	24	15.4	7.2	500	<.05	---	240	24	307	14
MOR-70	392255	863557	11-13-79	24	14.0	7.2	358	4.3	320	---	---	---	----
MOR-71	392218	863654	11-13-79	24	13.5	7.1	498	1.2	460	---	---	---	----
MOR-72	392204	863257	11-8-79	28	12.8	6.7	710	7.3	455	---	---	---	----
			5-13-80	28	13.9	7.1	788	4.9	397	360	0	454	12
			10-6-80	28	13.4	6.9	731	3.7	---	320	0	430	12
MOR-73	392228	863331	11-9-79	24	14.0	6.7	645	.4	365	---	---	---	----
			5-13-80	24	13.6	7.3	609	.6	484	320	48	400	9.1
			10-8-80	24	13.8	7.1	613	<.05	---	280	38	377	9.0
MOR-74	392128	863427	1-11-80	30	11.5	8.1	416	3.2	210	---	---	---	----
MOR-76	392204	863725	11-13-79	24	12.8	7.0	411	2.5	495	---	---	---	----
OWN-1	392213	863759	11-13-79	34	12.8	7.0	426	5.3	535	---	---	---	----
			5-13-80	34	12.5	7.4	426	5.5	373	220	14	261	12
			10-8-80	34	15.3	7.6	516	8.0	---	240	47	313	12

Ground-water quality is generally uniform and typical of water in calcareous outwash deposits. Characteristics of the water include nearly neutral pH (median, 7.1); high alkalinity (mean, 240 milligrams per liter as calcium bicarbonate); very high hardness (mean, 280 milligrams per liter as calcium carbonate; an oxidizing redox environment (mean dissolved oxygen, 2.2 milligrams per liter; and mean redox potential, +347 millivolts); moderate dissolved-solids concentrations (mean, 366 milligrams per liter); and a calcium bicarbonate water type. The National Interim Primary Drinking Water Regulation for nitrate was exceeded in autumn 1980 in 3 of 42 water samples analyzed. National Secondary Drinking Water Regulations for iron and manganese were exceeded in 15 and 49 percent of 97 analyses, respectively.

Seasonal variations in water quality were statistically significant only for temperature and dissolved-organic-carbon concentration. Temperature was lower in spring than in autumn, but dissolved-organic-carbon concentration was lower in autumn than in spring. Mean concentrations of only two constituents, manganese and dissolved organic carbon, differed significantly in the till-bounded and bedrock-bounded areas. Mean concentrations of these constituents were higher in till-bounded than in bedrock-bounded areas.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Indiana Department of Natural Resources, began a series of studies of the glacial-drift aquifer systems in the upper reaches of the White River basin in 1972 (Meyer and others, 1975; Gillies, 1976; Lapham, 1981; W. W. Lapham, written commun., 1982; L. D. Arihood, written commun., 1982; L. D. Arihood and W. W. Lapham, 1982). This cooperation was continued in a study of an 88-mi^2 segment of outwash aquifer along the White River in Johnson and Morgan Counties (figs. 1 and 2) from 1978 to 1981. No detailed study of the aquifer has been done previously.

Purpose and Scope

The purpose of the study was to meet the needs of the Indiana Department of Natural Resources for ground-water information to be used in managing and planning water-supply development. The objectives were to (1) define the geometry, lithology, and hydraulic properties of the outwash aquifer; (2) study the hydraulic connection between the aquifer and the streams; (3) assess the overall potential for ground-water development and the feasibility of development plans; (4) study the effects of potential ground-water withdrawals on streamflow; (5) assess the general water quality of the aquifer; and (6) evaluate seasonal and areal variations in water quality.

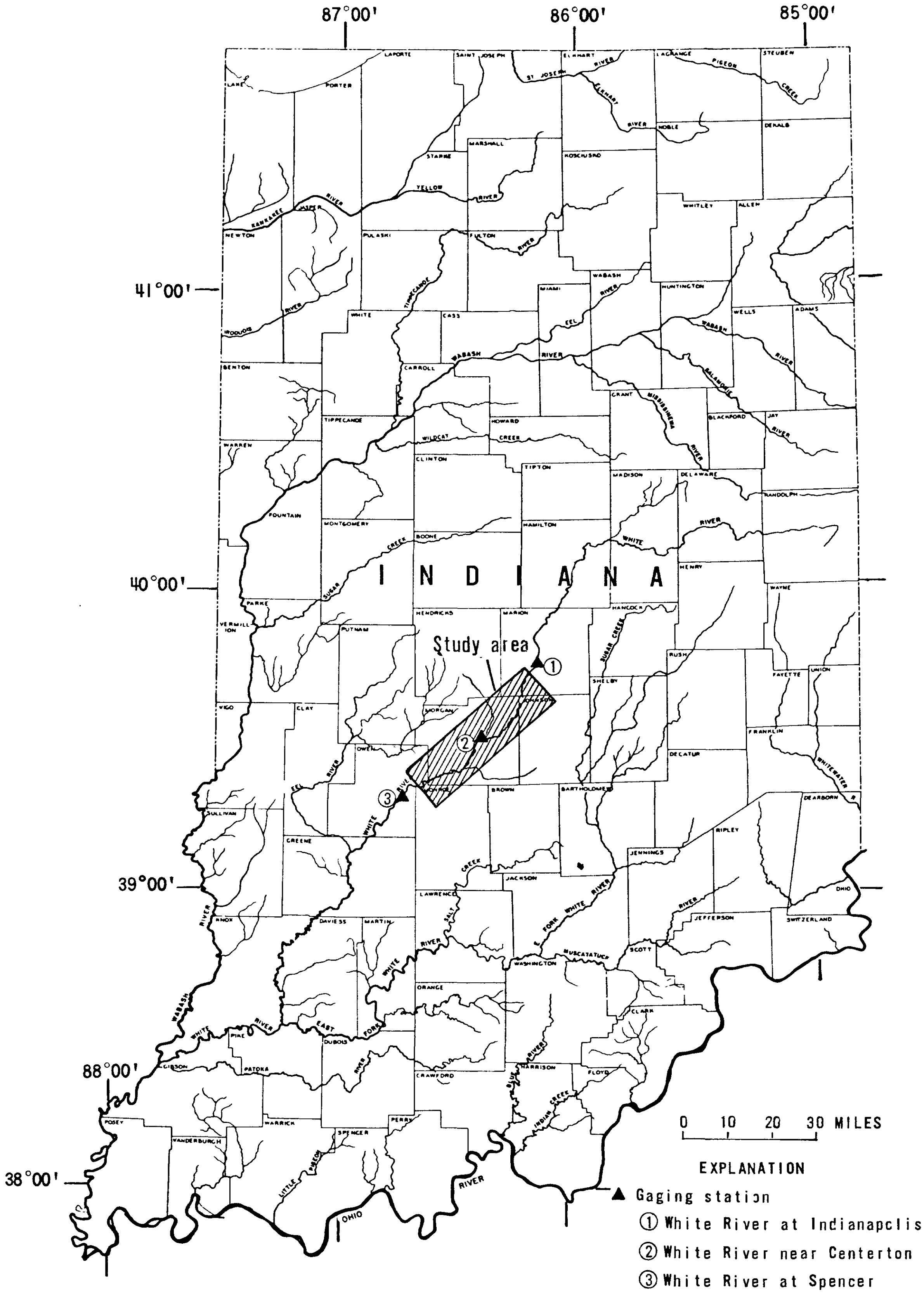


Figure 1.-- Location of study area.

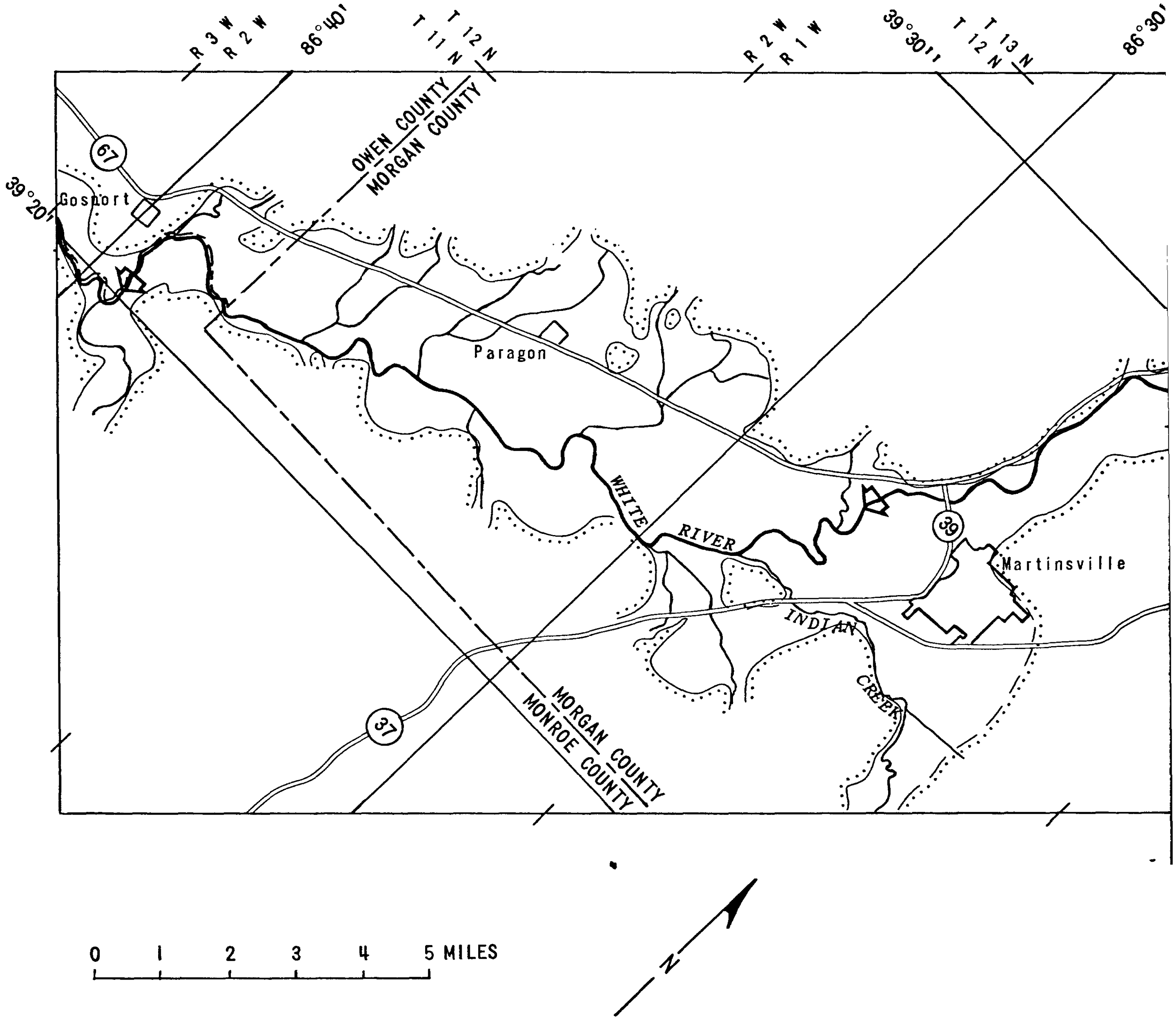
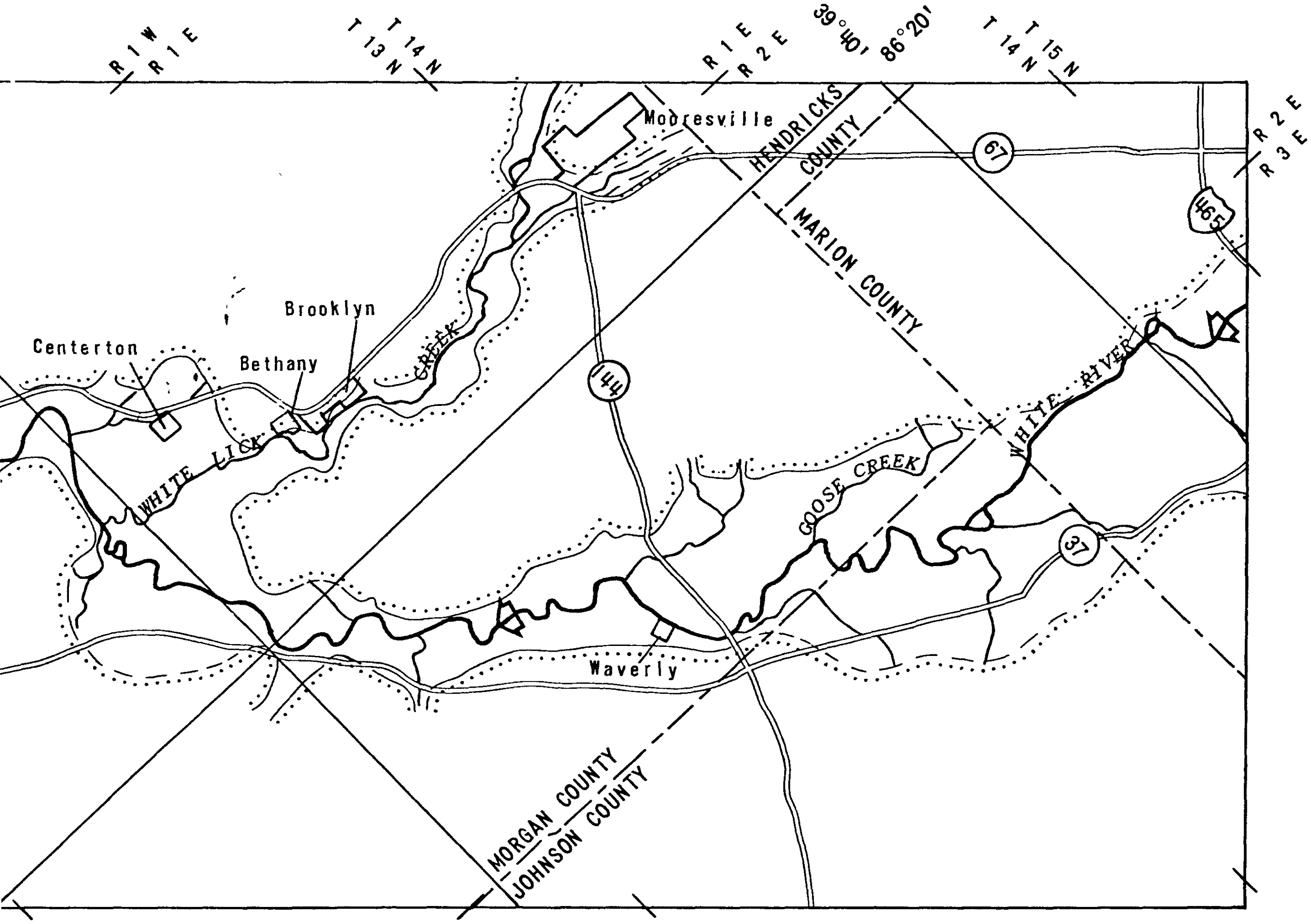


Figure 2.-- Study area.



EXPLANATION

Direction of flow

Outwash boundary. Dashed where approximate

Approach

Drillers' lithologic logs obtained from the Indiana Department of Natural Resources were used in preliminary subsurface mapping to define the geometry of the outwash aquifer. Because data on depth to bedrock were scarce, the Geological Survey drilled 88 test holes by auger to bedrock to obtain additional data.

Two-in.-diameter observation wells were installed in 70 of the 88 test holes and screened at depths of 20 to 45 ft. Water levels were monitored in these wells, in nine wells in Marion County, and in a continuous-record observation well in Morgan County. Specific-capacity tests on 43 of the wells were used to calculate the average hydraulic conductivity of the outwash. Water-level measurements, aquifer thickness, and the calculated hydraulic conductivity were used to calculate saturated thickness and transmissivity of the outwash. The hydraulic connection between the streams and aquifer was studied through the use of surface-water discharge measurements to calculate ground-water seepage rates and by measuring stream stage near observation wells. Seasonal fluctuations of the water table were monitored at the continuous-record well. Areal recharge to the aquifer was estimated from recharge rates used in studies of adjacent sections of the White River outwash system. Water samples taken from 55 observation wells were analyzed by methods described in Skougstad and others (1979) for major cations, anions, nutrients, and selected minor constituents.

A two-dimensional digital ground-water—flow model was constructed to simulate the flow system, test estimates of aquifer hydraulic properties, study the hydraulic connection between the aquifer and streams, demonstrate the effects of ground-water pumping on streamflow, assess the potential for ground-water development, and simulate specific development plans.

Chemical analyses of ground-water samples were statistically summarized and were compared with drinking-water standards and chemical analyses of White River water samples. Seasonal and areal variations of the data were evaluated by statistical comparison of mean seasonal and areal data and by areal mapping.

Acknowledgments

The authors acknowledge the Indiana Department of Natural Resources, Division of Water, who provided water-well records from their files, and the industries and municipal water suppliers, who provided pumpage records. Appreciation is also expressed to private property owners and the following organizations who granted access to properties for drilling and data collection: Indiana State Highway Commission; Commissioners of Johnson, Morgan, Monroe,

and Owen Counties; city of Martinsville; town of Brooklyn; Indianapolis Department of Parks and Recreation; and Indianapolis Power and Light Co. The company was also helpful in providing safe storage of Geological Survey drilling equipment and supplies.

STUDY AREA

Geography and Climate

Land use in the 88-mi^2 segment of outwash is mainly agricultural. Boundaries of the outwash valley are delineated in figure 2. Elevation in the flat to gently rolling area ranges from 550 ft at the downstream end to 675 ft at the upstream end. Most of the uplands surrounding the outwash valley are forested and are dissected by steep-sided stream valleys. Maximum elevation in the uplands is 900 ft. The streams draining the uplands are not shown on the base map (fig. 2) because that area was not investigated.

One city, Martinsville (population 11,311), and several small towns (populations totalling about 1,500) are within the study area (U.S. Department of Commerce, 1980, p. 16, 17). Mooresville, although shown in the figures, is outside the investigated area, and its population is not included in the total.

Mean temperature and average annual precipitation at Martinsville are 52.5° F and 40.81 in., respectively. Average annual precipitation at Indianapolis, 6 mi north of the study area, is 39.69 in. The period of record is 24 yr (1931-55) at Martinsville and 29 yr (1921-50) at Indianapolis (National Oceanic and Atmospheric Administration, 1974, p. 114). Monthly records at the Indianapolis Weather Service Forecast Office were used because monthly records were not available at Martinsville.

Drainage Features

The White River is the major stream in the study area. Average discharge (for 1930-31, and 1946-79) at the gaging station near Centerton (fig. 1) was 2,399 ft^3/s (U.S. Geological Survey, 1979, p. 181). The 7-day, 10-year annual low flow at this location is 208 ft^3/s (Rohne, 1972, p. 183). The lowest daily mean discharge was 138 ft^3/s in 1955, and the highest was 47,100 ft^3/s in 1964 (Horner, 1976, p. 285, 286).

Two major tributaries, White Lick and Indian Creeks, drain into the White River within the study area. Many small streams draining the uplands cross the outwash and flow into the White River. Many of these streams have been ditched and straightened to drain lowland fields.

Geology

Bedrock

The White River valley is cut into rocks of Mississipian age, the Borden Group, which consist of clayey siltstone and shale and interbedded limestone. Vertical and lateral variations in lithology are numerous, and lenses of sandstone may also be found (Shaver and others, 1970, p. 21). The valley is typically steep sided under the outwash fill (fig. 3). In some areas, a layer of thick clay underlies the outwash. In those areas, the top of the clay, instead of the bedrock, is mapped as the aquifer bottom. This mapping causes only a slight difference between bottom of the aquifer contours shown in figure 4 and those of the bedrock surface. Bedrock crops out in the upland areas that surround the valley, and a few bedrock erosional remnants also crop out in the outwash (fig. 5).

A secondary buried bedrock valley parallels the channel of the White River between Centerton and Martinsville (fig. 4). This valley is probably a former channel of the White River. The age of gravel in the channel, at least Illinoian, indicates that the channel was probably filled before or during the Wisconsinan (Oral commun., Henry Gray, Indiana Geological Survey, February 1979).

Glacial Deposits

Illinoian glacial deposits cover nearly the entire study area, but Wisconsinan deposits cover only the north half (fig. 5). However, the outwash filling the entire valley is a Wisconsinan fluvial deposit, and the windblown sand, including that south of the Wisconsinan boundary, is Wisconsinan (Gray and others, 1979). Illinoian and Wisconsinan tills are calcareous and coarsely silty to finely sandy (Harrison, 1963, p. 31). The till contains some sand and gravel lenses. Drillers' logs indicate that the till ranges from 3 to 170 ft in thickness.

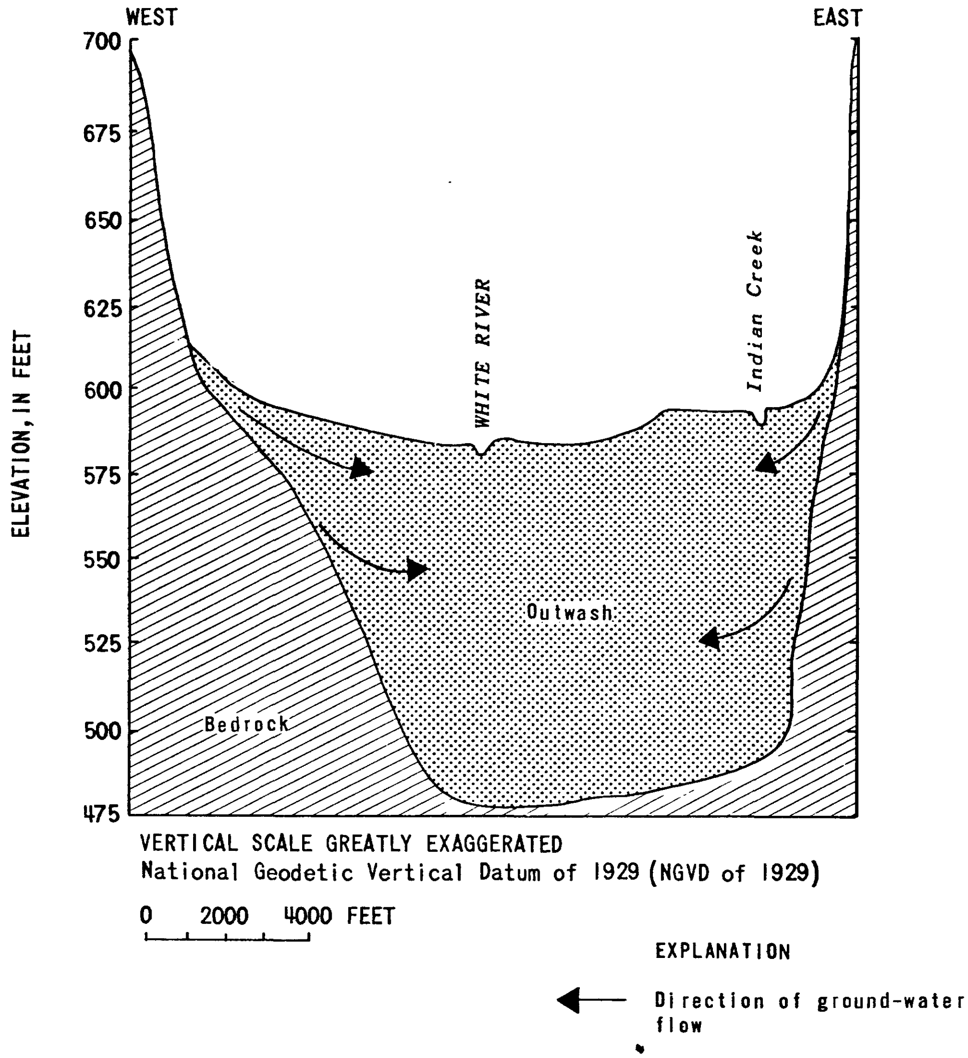


Figure 3.-- Generalized geologic section south of Martinsville, Morgan County, Ind.

In several areas, fine, windblown sand is deposited at the outwash edge and on top of the outwash or till, but glacial-lake deposits are scarce. The edges of the outwash along State Road 37 north of Martinsville are commonly bounded by till interbedded with lenses of outwash. A generalized geologic section across the valley shows this boundary condition (fig. 6). Ice-contact deposits (kames and eskers) cover some of the till at the valley edge within the area of Wisconsinan glaciation.

The sand and gravel outwash aquifer, as thick as 120 ft in places, ranges from 0.5 to 4 mi in width. Thin clay lenses of small areal extent are found in the outwash. The bedrock surface defines the bottom of the outwash in most of the study area, but in some areas a basal clay separates the outwash and the bedrock. The basal clay, where present, primarily in the south part of the study area, is the bottom of the aquifer.

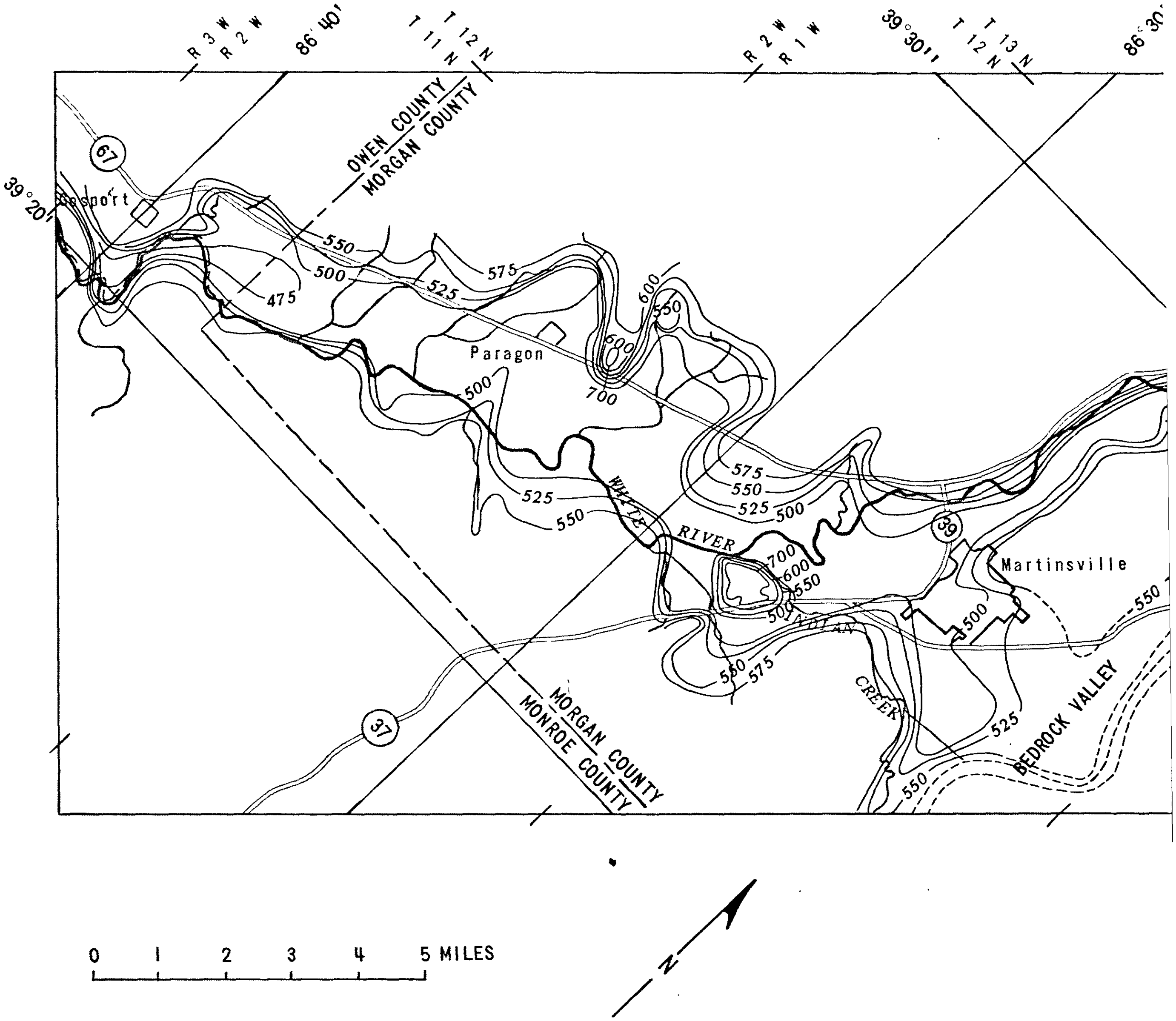
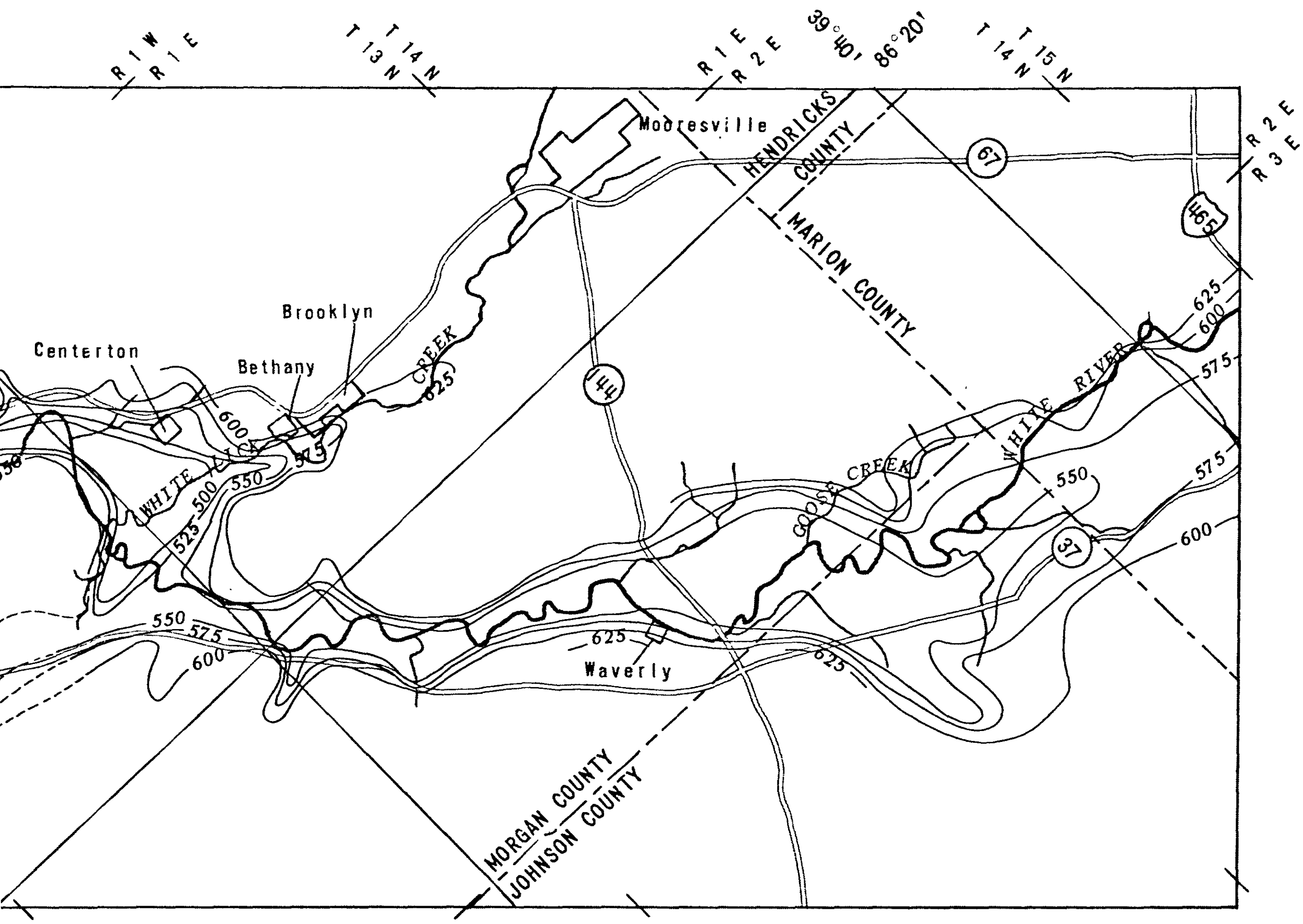


Figure 4.-- Elevation of bottom of the outwash.



EXPLANATION

——600 – – – Elevation of bottom of aquifer. Oashed where approximate. Interval 25 feet NGVD of 1929

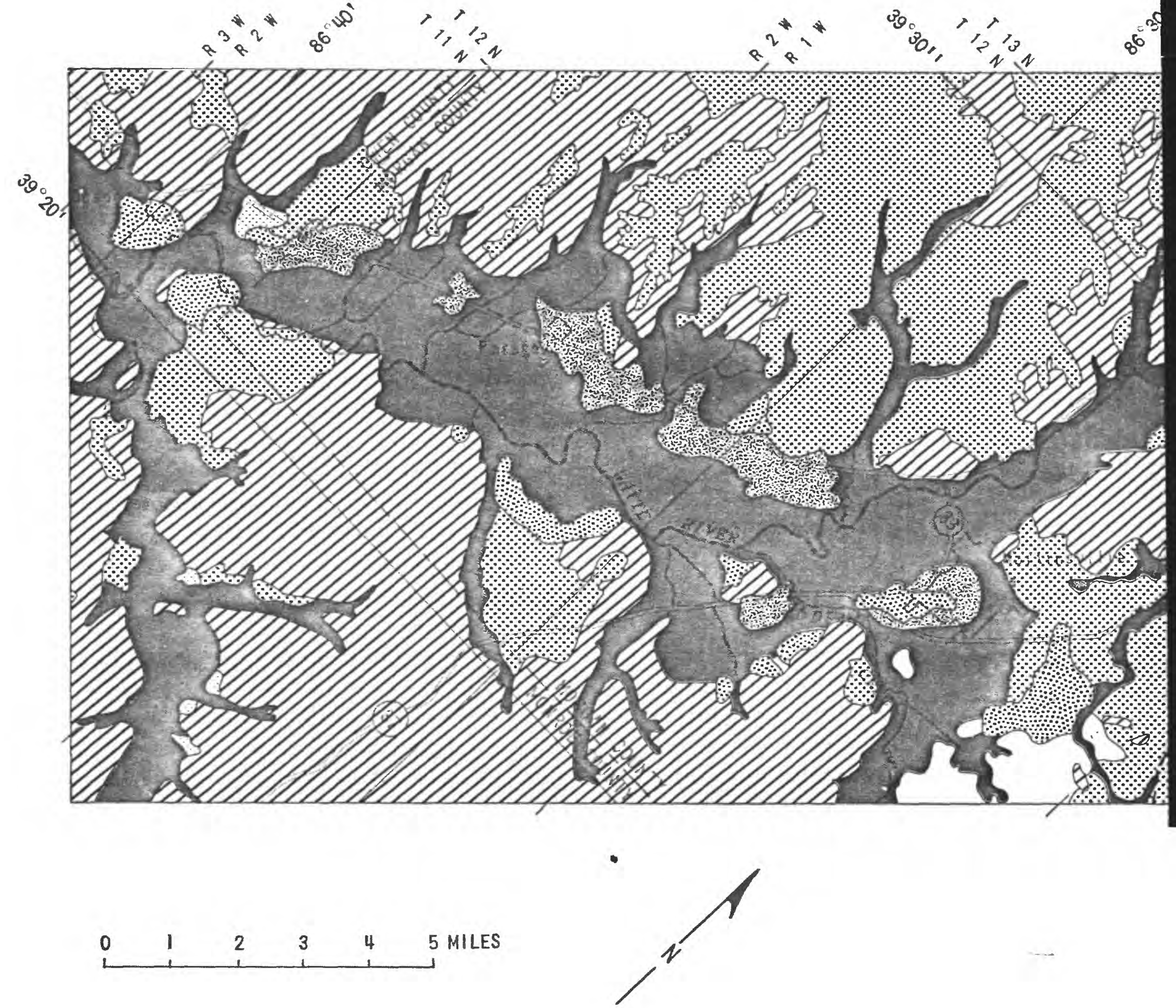
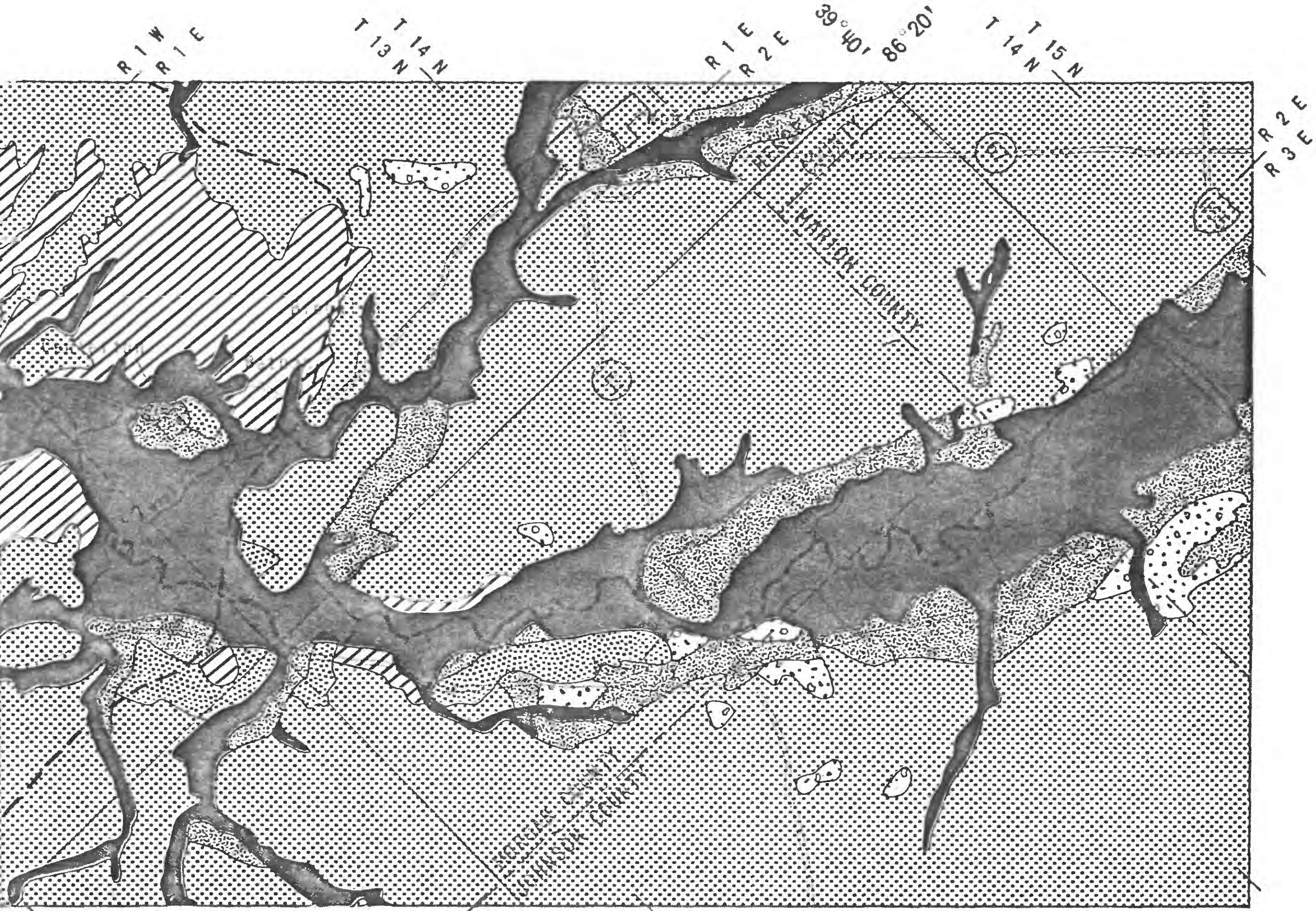


Figure 5,-- Generalized surficial geology of the study area.



Geology modified from H.H. Gray and others(1979)

EXPLANATION

QUATERNARY (PLEISTOCENE)

HOLOCENE — WISCONSINAN

- Recent alluvium covering outwash -- silt, sand, and gravel
- Windblown sand

WISCONSINAN

- Lake deposites -- clay, silt, and sand
- Outwash -- gravel, sand, and silt
- Ice-contact stratified deposits (kames, eskers) -- gravel, sand, and silt

ILLINOIAN

- Till -- sandy, loamy till; sand and gravel
- Outwash -- gravel and sand

MISSISSIPPIAN

- Bedrock

— — — Southern limit of Wisconsinan glaciation

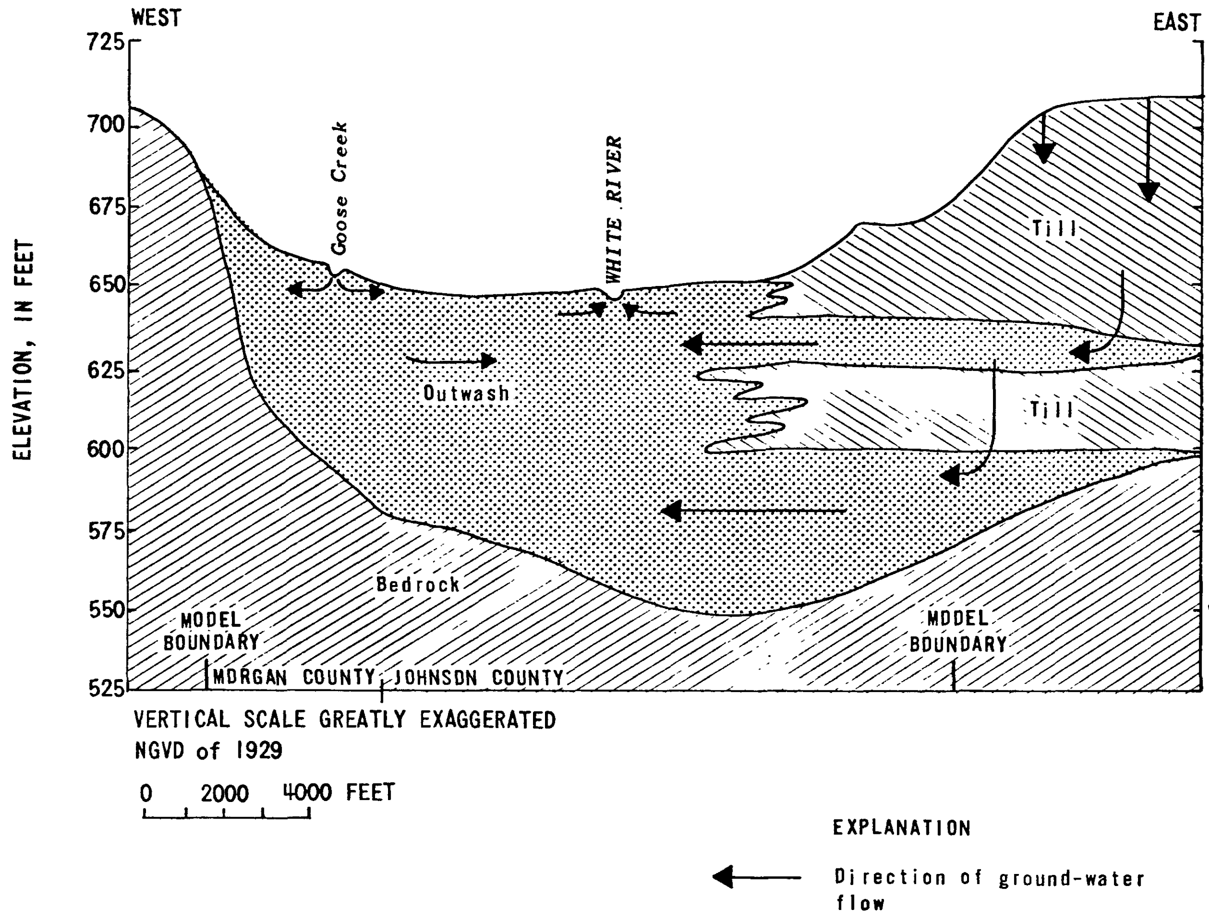


Figure 6.-- Generalized geologic section north of the Wisconsinan glacial boundary.

The secondary buried bedrock valley (fig. 4), is filled with a mixture of till and outwash overlain in some areas by dune sand (Gray and others, 1979). Test holes for defining the channel geometry and lithology could not be drilled by auger, because thickness of the valley fill exceeds 200 ft. Compared with the outwash in the main channel, the outwash deposits in the secondary channel are probably minor. Any flow through the secondary channel could be accounted for by simulating the boundary conditions in the digital flow model.

HYDROLOGIC SYSTEM

Potential of the Bedrock and the Outwash Aquifers

The Borden Group has a low effective porosity and is a poor source of water. Few wells in the Borden Group yield more than 5 gal/min, and many are dry. A small percentage of wells drilled in a fractured zone or in a more porous sand lens yield 10 to 15 gal/min (Heckard, 1964; Uhl, 1966). Some test holes near the valley walls were drilled into dry bedrock.

Wells in the outwash typically produce more than 250 gal/min, and some of them produce more than 2,000 gal/min (Heckard, 1964; Uhl, 1966).

Because yield from the bedrock is low compared with that from the outwash, the bedrock is considered to be impermeable and is not considered to be a direct source of recharge to the outwash.

Hydraulic Characteristics of the Outwash Aquifer

Average hydraulic conductivity of sand and gravel and of sand only, calculated from specific-capacity-test data (Theis, 1963), was 340 ft/d and 40 ft/d, respectively. Variation of hydraulic conductivity is shown in figure 7. Most of the area was assigned a conductivity of 340 ft/d, but parts containing fine sand or outwash containing large amounts of interbedded clay were assigned a conductivity of 40 ft/d. Meyer and others (1975, p. 17-18) calculated hydraulic conductivity of the outwash aquifer in Marion County from specific capacities of domestic wells: 415 ft/d for gravel, 240 ft/d for sand and gravel, and 40 ft/d for sand.

Numerous test-boring logs for an area of the outwash northeast of Paragon were available from the Indianapolis Power and Light Company. The logs indicate that this area contains more interbedded clay than the rest of the outwash. Because of the higher clay content, the outwash hydraulic conductivity

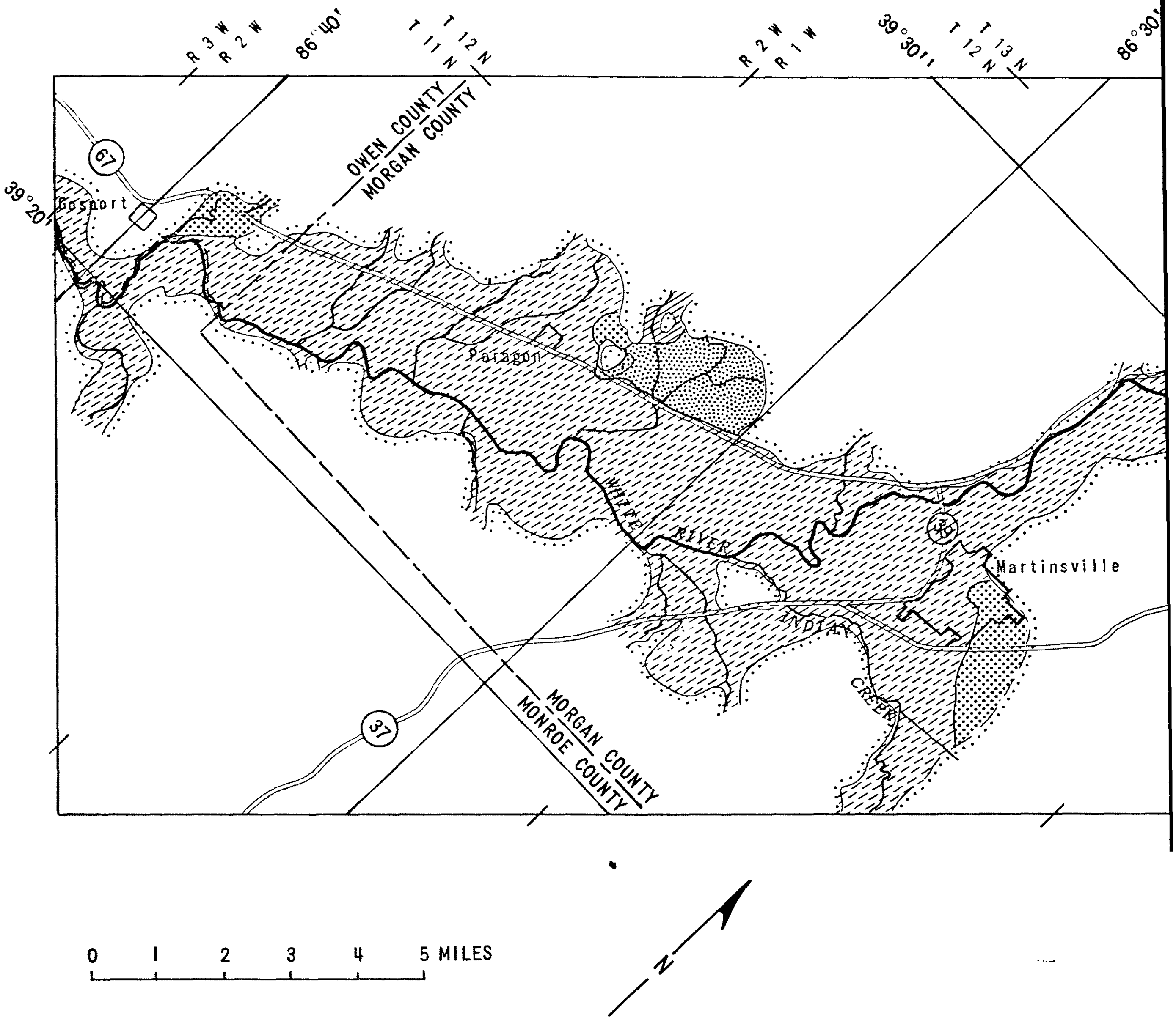
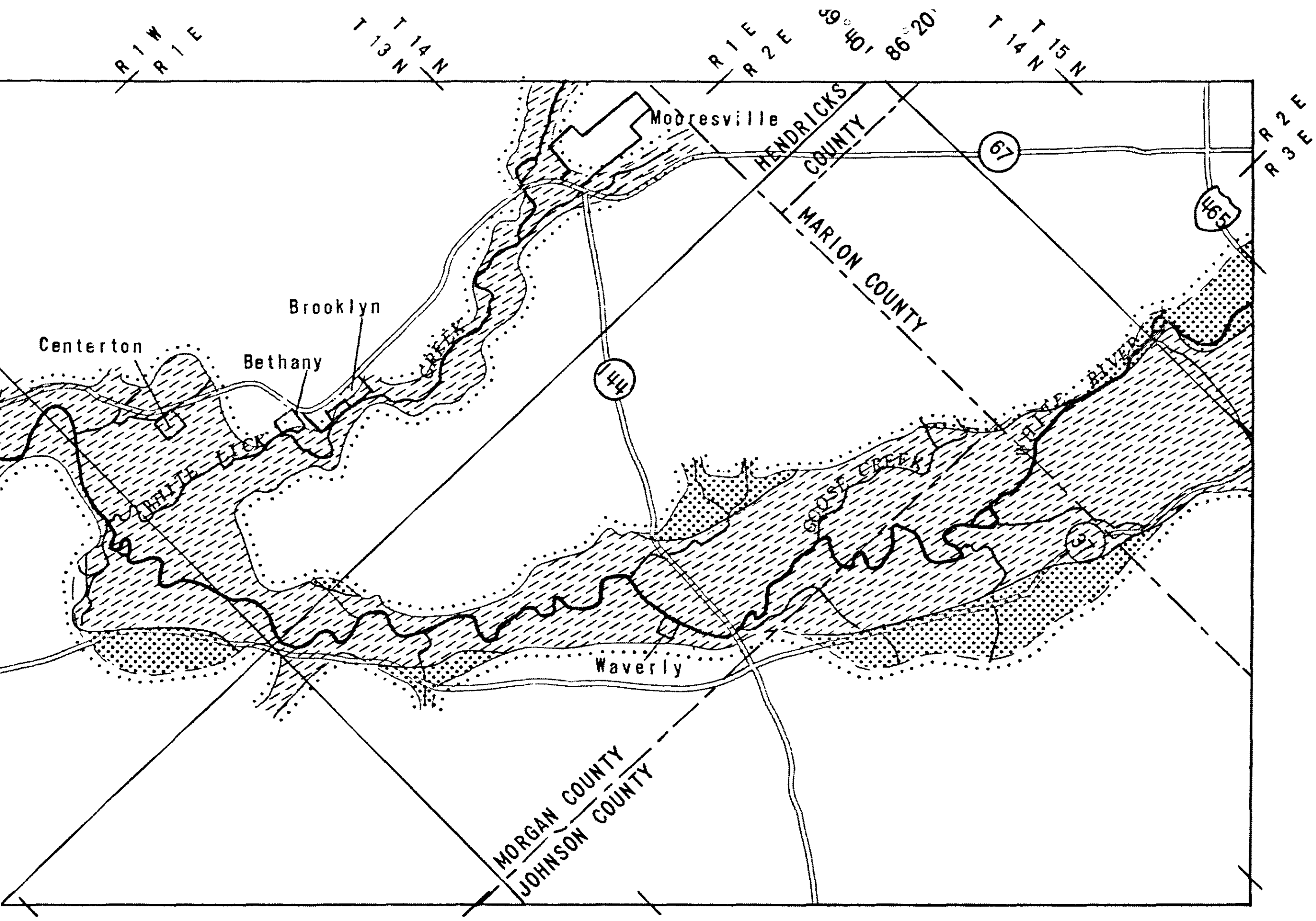


Figure 7.-- Hydraulic conductivity of the outwash.



EXPLANATION

FEET PER DAY

0	150-280
40	340
60	

Outwash boundary. Dashed where approximate

(340 ft/d) calculated from specific-capacity tests was not applied to the area. An average hydraulic conductivity for each test-hole site was calculated as follows: A hydraulic conductivity (from the specific-capacity tests) was assigned to each unit of the log (sand or sand and gravel). Then each conductivity was multiplied by the thickness of that unit to obtain a transmissivity. Finally, the sum of the transmissivities was divided by the total saturated thickness to obtain an average hydraulic conductivity. Hydraulic conductivity at the test-hole sites ranged from 60 to 280 ft/d (fig. 7).

The transmissivity of the rest of the aquifer was not determined at this stage of the study but was calculated by the model. Therefore, transmissivity is discussed in the "Calibration" section.

Saturated thickness of the aquifer was determined by subtracting the bottom elevation of the aquifer from water-level elevations in observation wells measured in the autumn 1980. Saturated thickness ranges from 0 to 120 ft (fig. 8).

The storage coefficient (or specific yield) of the outwash aquifer in Marion County was calculated and verified to be 0.11 by Meyer and others (1975, p. 19). The 0.11 would probably be valid in the section of outwash studied in Johnson and Morgan Counties. Only steady-state model simulations were done, so a storage coefficient was not required.

Stream-Aquifer Interaction

Water-level contours in figure 9 indicate that ground water discharges into the large streams: White River and White Lick and Indian Creeks. Some tributaries lose water to the ground-water system (observed during the discharge measurements in autumn 1980). However, this water loss may be seasonal. Losing streams are evident in flow-line construction, in measured ground-water levels that are lower than nearby stream stage, and by the complete loss of flow in some tributaries before they reach the White River. These streams are an additional source of recharge to the outwash aquifer.

Ground-water seepage to the White River was estimated by measuring stream discharges in the autumn of 1980 at about 70-percent flow duration. That flow was equal to the rate that is exceeded 70-percent of the time (Horner, 1976, p. 263). On a large stream such as the White River, seepage is commonly difficult to measure. Generally, the lower the flow the more accurate the measurements. However, flow rate during the study was rarely lower than 70-percent flow duration. Seven sites along the White River within the study area (fig. 10) and one site outside the area at the Indianapolis gage (fig. 1) were measured. Inflow to the White River from each tributary was also measured. Metered flow into the river from sewage-treatment plants was recorded. Ground-water seepage to the river, calculated from these measurements, averaged 90 (ft^3/d)/ft (cubic foot per day per linear foot of stream channel) or about 286 ft^3/s through the entire study area. This rate was much higher than rates reported by Meyer and

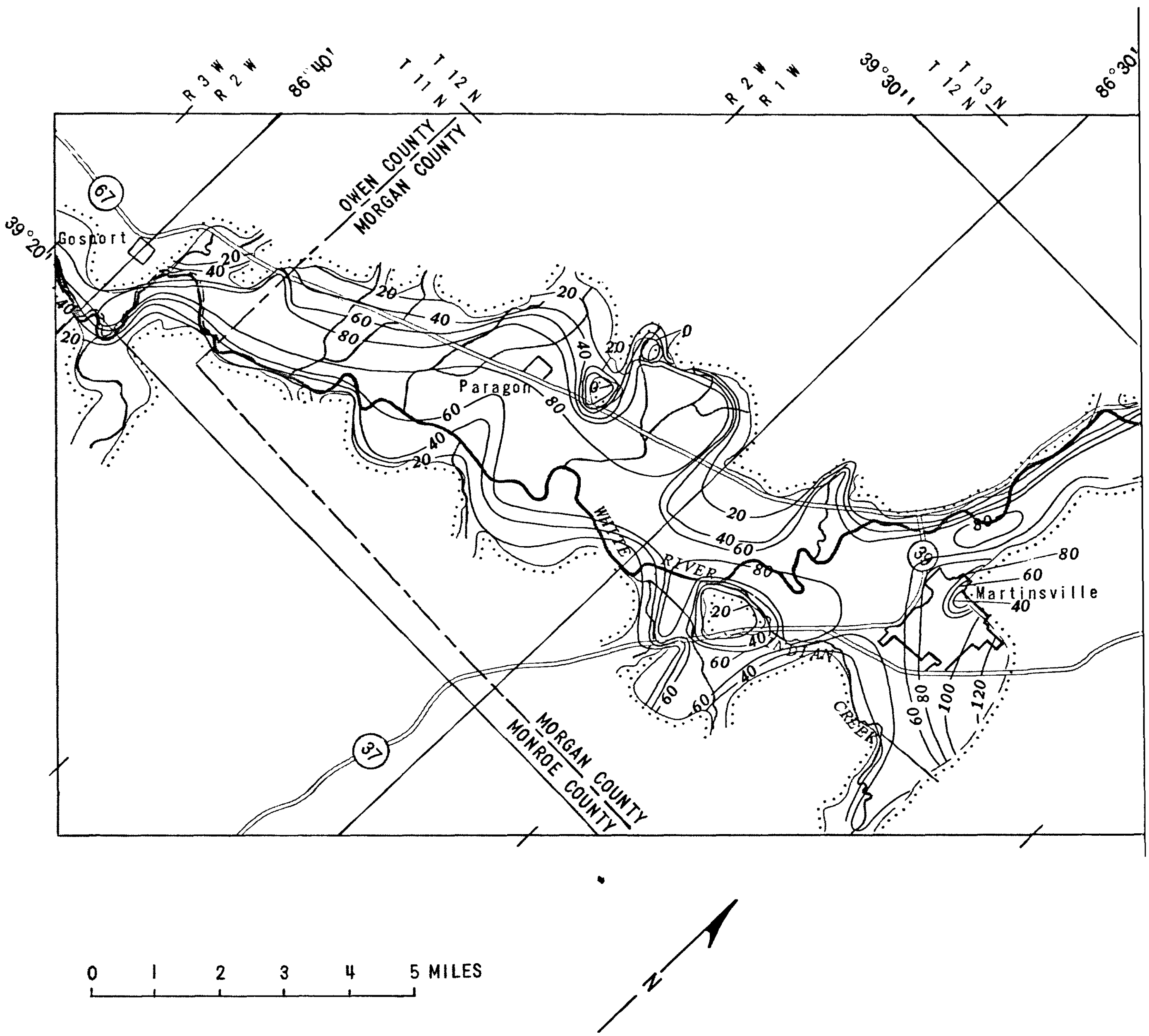
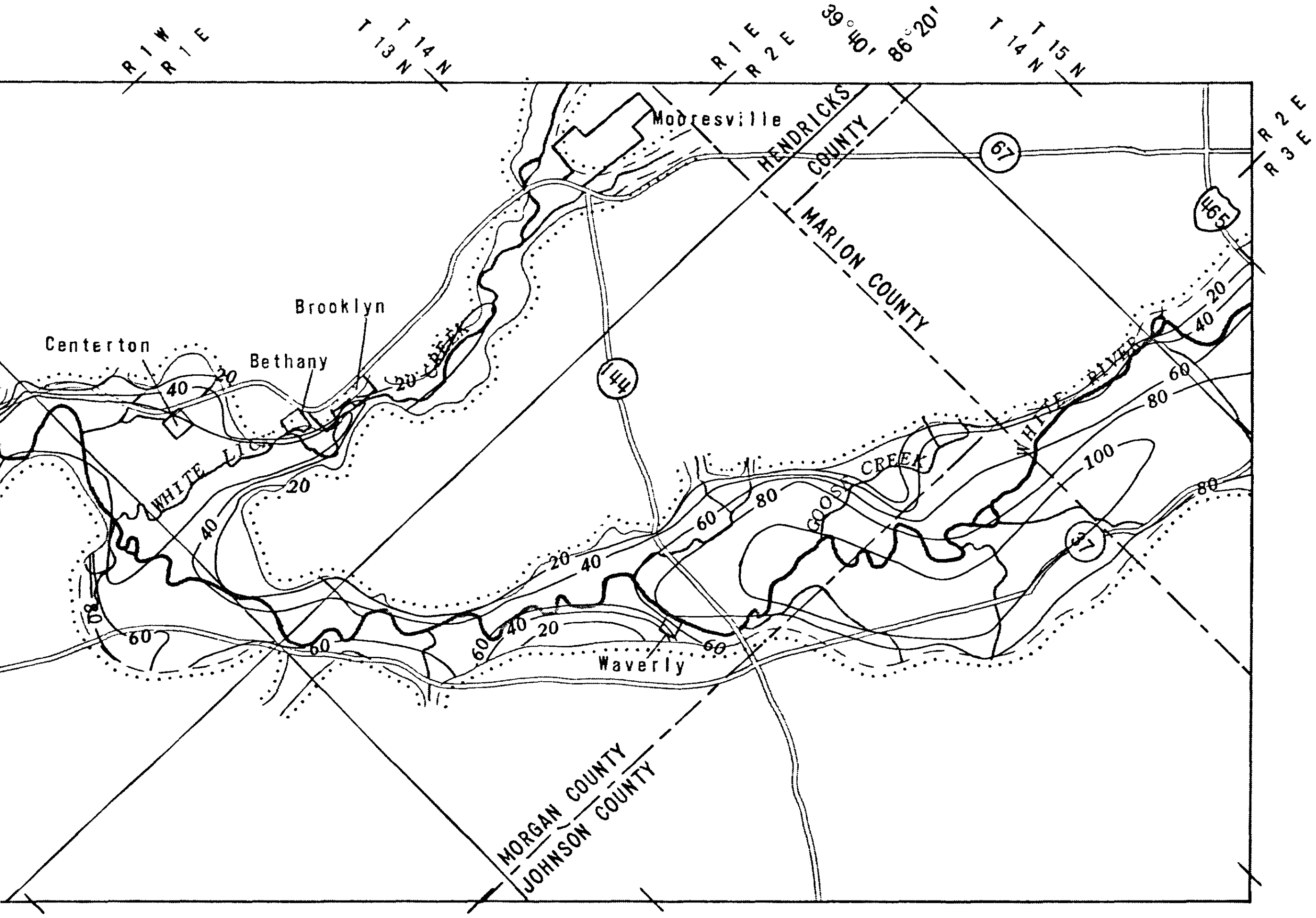


Figure 8.-- Saturated thickness of the outwash, autumn 1980.



EXPLANATION

—— 40 —— Line of equal saturated thickness. Interval 20 feet

Outwash boundary. Dashed where approximate

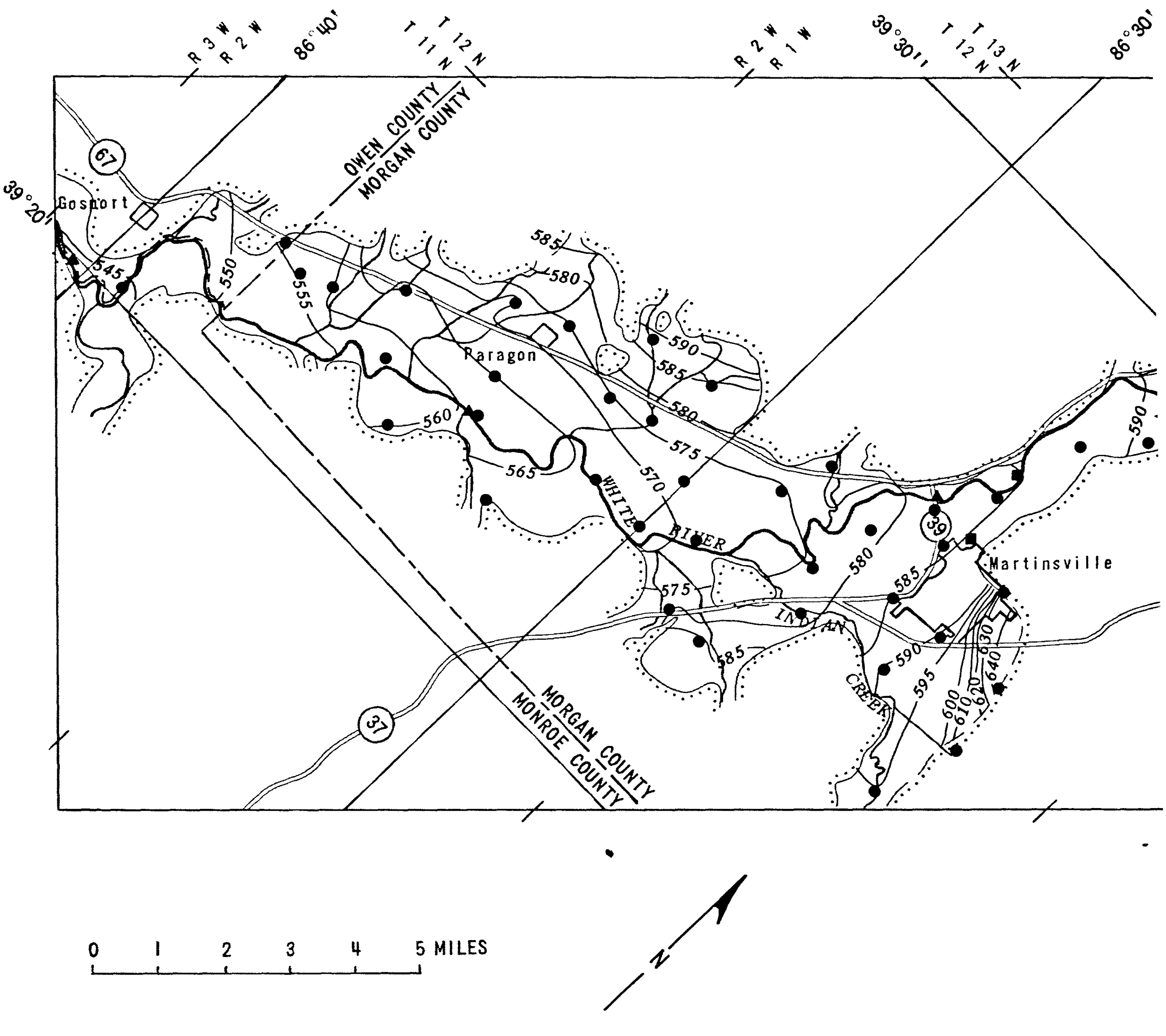
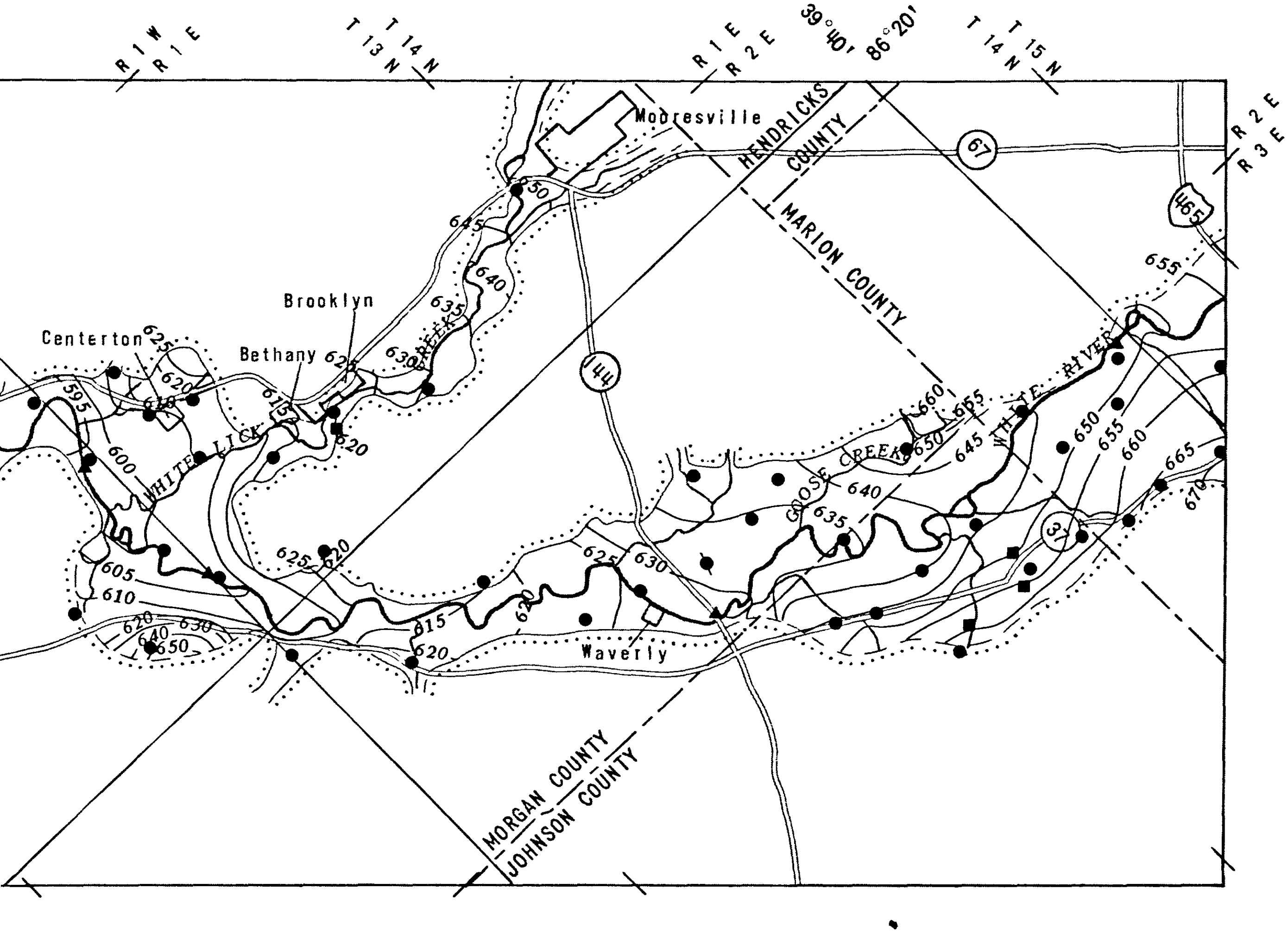


Figure 9.-- Water levels in the outwash, autumn 1980.



EXPLANATION

—620—	Line of equal water level. Interval 5 feet. NGVD of 1929
●	Observation well
■	Municipal well field
▲	Discharge-measurement site
	Continuous-record observation well Morgan 4
	Outwash boundary. Dashed where approximate

others (1975, p. 28) and Gillies (1976, p. 13). Their seepage rates of 42 and 40 $(ft^3/d)/ft$, respectively, were calculated for sections of the White River upstream from the study area. Even the additional recharge added to the ground-water system by losing streams would not account for an average seepage as high as the measured rate.

The hydrograph (fig. 10) for the Centerton gage (fig. 1) indicates that the White River was not at base flow when the discharge measurements were made, so the measured seepage rate, probably unrepresentative of base flow, was not accepted. Because flow during the study period was usually above 70-percent flow duration, the discharge measurements were not repeated.

Seepage to the White River was also calculated from statistical summaries of streamflow data based on discharge at about 70-percent flow duration between the gages at Indianapolis and Spencer (Horner, 1976, p. 263, 294). The locations of these gages are shown in figure 1. Use of statistical summaries in calculating ground-water seepage is more valid than the one-time seepage measurements because the calculations are based on statistical summaries of almost 50 yr of record. Measurements of surface inflow from tributaries during autumn 1980 included 5- to 8-percent measurement errors. Flow from sewage-treatment plants was averaged. Measured tributary and sewage-treatment plant inflows were then subtracted from the difference in discharge at the gages. The calculated seepage to the White River ranges from 28 to 34 $(ft^3/d)/ft$ (90 to 107 ft^3/s in the entire study area). This range was used in the calibration of the digital ground-water flow model.

Water-Level Fluctuation, Evapotranspiration, and Recharge

Seasonal fluctuations in the water table are related to seasonal changes in precipitation and evapotranspiration rate. Fluctuations in water levels have been continuously recorded at the Morgan-4 observation well (fig. 9) since May 1978. The hydrograph for Morgan-4 is shown in figure 11. Seasonal fluctuation is as much as 5 ft. Ground-water levels are normally high during March and April and low during October and November. These fluctuations reflect seasonal changes in recharge. The highs during the summer on the hydrograph are not typical but are caused by above average precipitation (fig. 12). The cycle of seasonal fluctuation should be less variable during years of average rainfall distribution. Regular seasonal fluctuations within a range of about the same water-level elevations each year indicate that the ground-water system is in a near-steady condition. The Morgan-4 hydrograph represents a short period of record having above average precipitation concentrated in July and August, so this hydrograph is probably inadequate for determining whether the ground-water system is at steady state. However, other hydrographs of outwash water levels north of the study area cover a longer period of record and indicate near steady state (Meyer and others, 1975, p. 37). Therefore, the system can probably be simulated by a steady-state model.

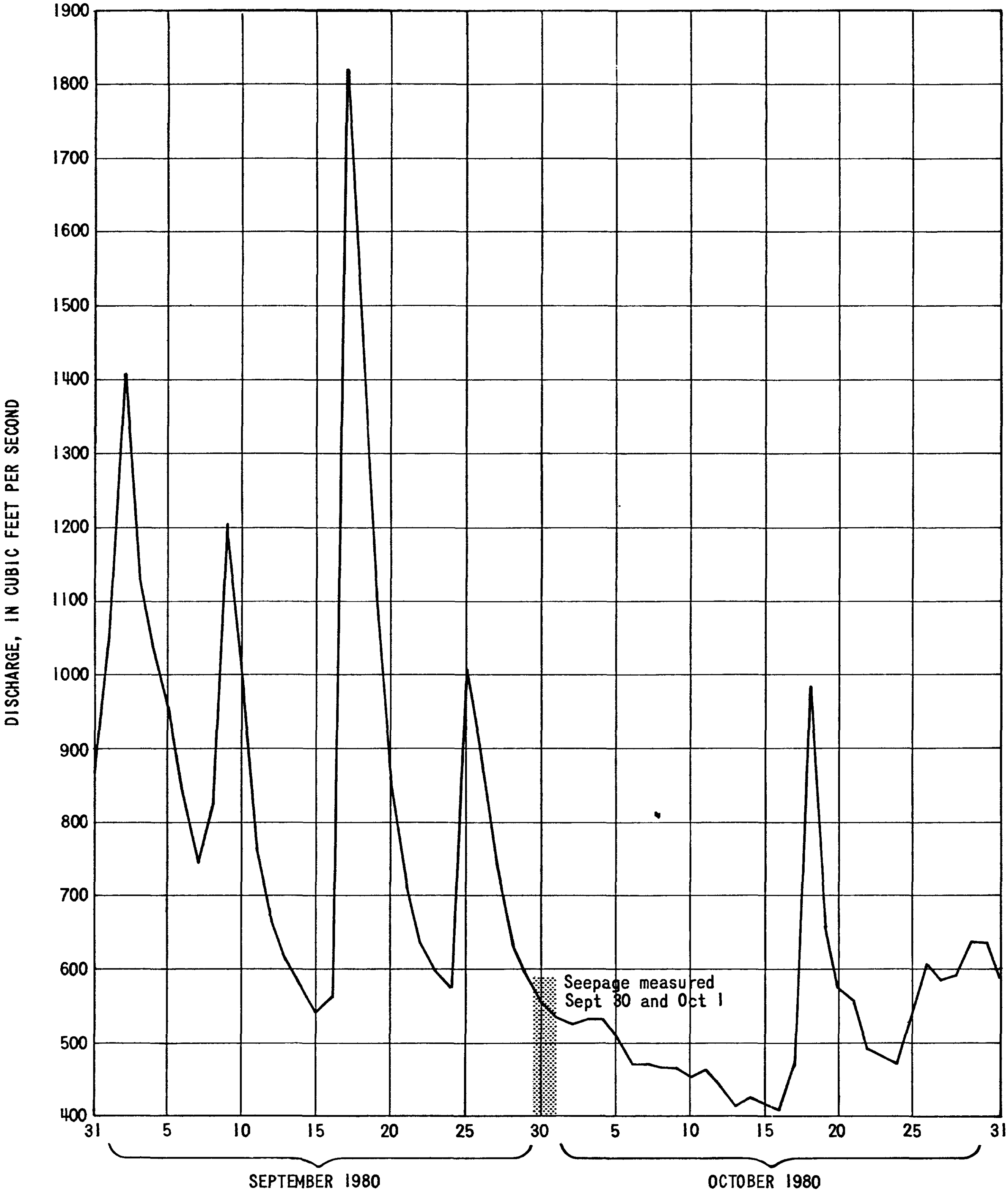


Figure 10.-- Discharge of the White River near Centerton, Morgan County, Ind.

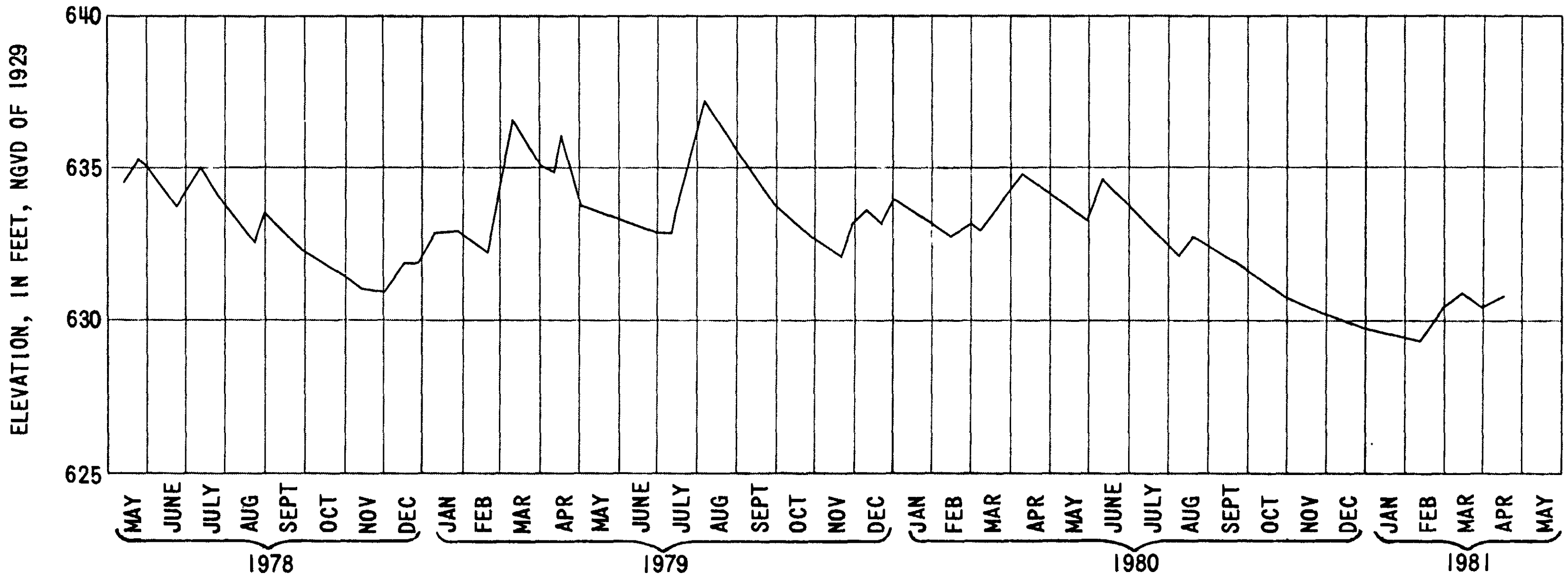
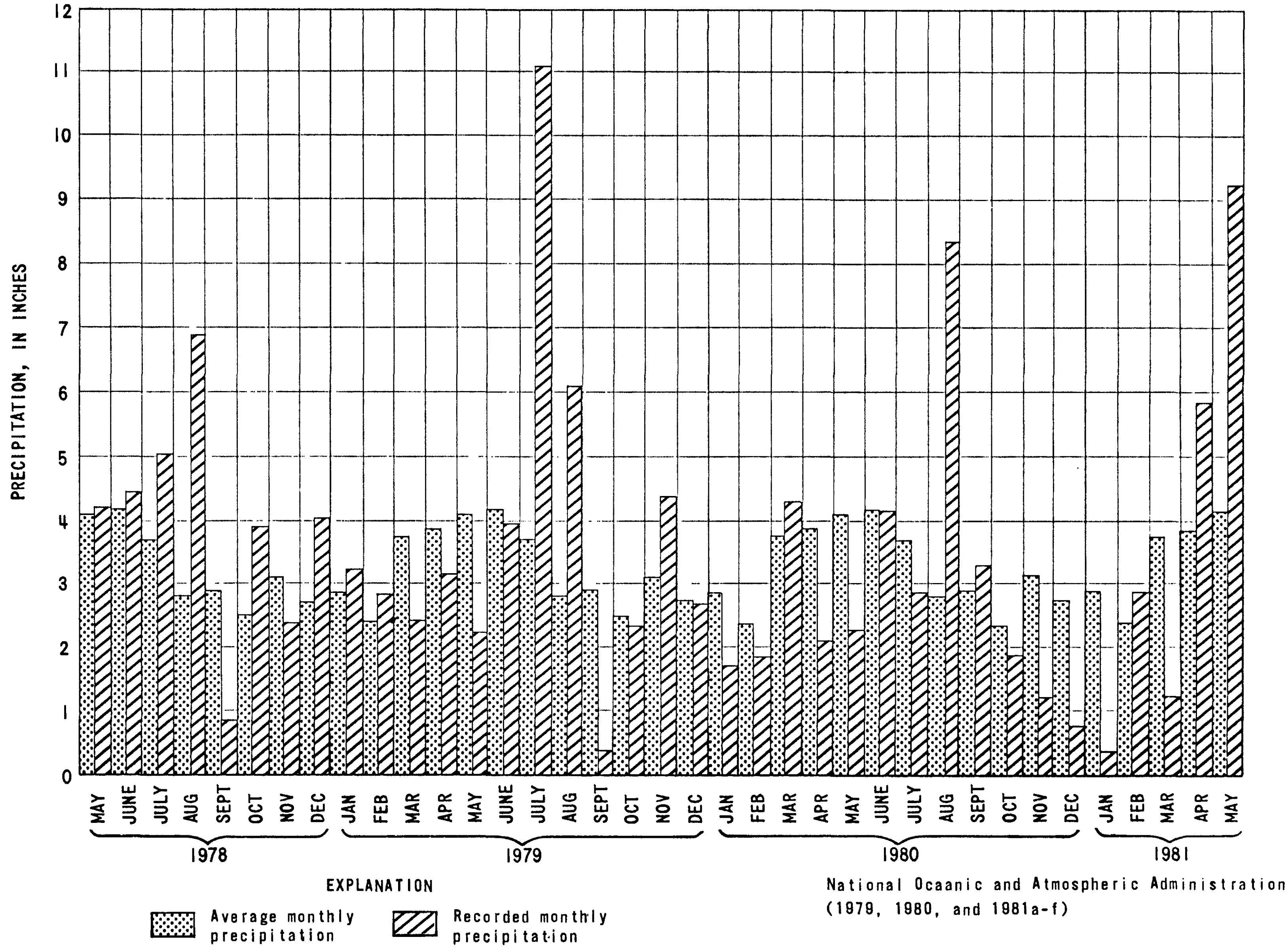


Figure 11.-- Water levels at the Morgan-4 observation well.



National Ocaanic and Atmospheric Administration (1979, 1980, and 1981a-f)

Figure 12.-- Average monthly and recorded monthly precipitation at the Indianapolis Weather Service Forecast Office.

Shallow domestic wells and municipal well fields (fig. 9) pump about 1,880 Mgal/yr. These withdrawals have not noticeably affected the balance of the system, and their local effects are minimal. No effect can be seen at 5-ft contour intervals (fig. 9).

The water table is generally too deep to be directly affected by evapotranspiration. Depth to water ranges from 5 to 31 ft and averages 13 ft. However, low hydrograph readings generally relate to the growing season and high readings to colder months of minimal plant growth. The probable effect of evapotranspiration is not direct removal of water from the water table but interception of precipitation in the unsaturated zone, which effectively reduces recharge.

Average areal recharge to the outwash aquifer was assumed to be 12.0 in./yr. Average areal recharge to the outwash aquifer upstream from the study area was estimated by model simulations to be 11.9 in./yr (Gillies, 1976, p. 19), and 13.5 in./yr (Meyer and others, 1975, p. 48). By flow-net analysis and comparison to geologically similar areas, Herring (1976, p. 35) calculated a recharge rate of 600,000 (gal/d)/mi^2 or 12.6 in./yr to the outwash aquifer in Marion County. Herring's recharge rate was calculated indirectly. Meyer's recharge rate was estimated by the model to match high spring water levels, and Gillies' rate was estimated to match low autumn water levels. The water levels used in the model of the study area in Johnson and Morgan Counties were also low autumn levels. Consequently, a recharge rate of 12 in./yr, close to Gillies' estimate, was chosen as the average recharge rate. Sensitivity analyses, discussed in the "Sensitivity Analysis" section, done on model-simulated recharge indicated that the rate could be adjusted between 7 and 17 in./yr in the digital model without significantly changing the match between measured and modeled water levels.

Ground-Water Flow

The outwash aquifer is unconfined in most of the study area. The aquifer is recharged by direct infiltration of precipitation and by inflow from outwash interbedded with till layers along the valley boundaries (fig. 6). The aquifer is also recharged by seepage from streams that drain the adjacent uplands. The aquifer is discharged by seepage into the major streams and by pumping.

Water-level contours (fig. 9) indicate that flow is generally parallel to the outwash boundary and toward the White River. This is shown by the water-level contours that are perpendicular to the outwash boundary. Contours that are parallel to the outwash boundary indicate that ground water crosses the boundary into the outwash.

In cross section, most of the ground-water flow within the system is assumed to be lateral (figs. 3 and 6). Some vertical flow is downward at the outwash edge and upward to discharge into major streams. These vertical components are assumed to be localized and negligible in the overall flow system. Areas where vertical flow is probably predominant are indicated by closely spaced contours showing tens of feet of water-level changes over a short distance (fig. 9).

DIGITAL-MODEL ANALYSIS OF THE AQUIFER

Model Assumptions

The finite-difference model of Trescott and others (1976) was used to simulate a two-dimensional flow system in the outwash aquifer. The following assumptions, which are consistent with the real hydrologic system, were made to simplify the model analysis.

1. The bedrock in contact with the sides and the bottom of the outwash aquifer is impermeable and neither contributes water to the outwash nor receives water from it. This assumption is supported by water-level contours virtually perpendicular to the bedrock boundaries. Drilling and drillers' logs indicate dry holes and low-production wells in the bedrock and provide additional support for this assumption.

2. On a regional scale, the outwash aquifer is homogeneous and isotropic; therefore, a single hydraulic conductivity was used for the outwash. In areas containing material in addition to outwash, a hydraulic conductivity lower than that for the outwash was used.

3. Areal recharge to the aquifer is uniform because areal precipitation and land use (affecting evapotranspiration) is assumed to be uniform and because the outwash material is regionally homogeneous.

4. The flow system is two dimensional because the primary component of flow is horizontal. Except for some areas near the outwash boundaries, the water-level contours indicate a uniform horizontal flow of slight shallow gradient.

5. The flow system is at or near steady state. Long-term water-level fluctuations are about the same as small seasonal water-level fluctuations. The water level that is modeled is considered to be representative of average conditions.

Construction of Model

The model grid (fig. 13) is a 7.8 by 33.9 mi rectangle. Its area is 264 mi^2, but the area of simulated ground-water flow is only 85.6 mi^2. The large number of inactive grid blocks was necessary to accommodate the irregular shape of the outwash aquifer. The grid blocks, having a node centered in each block, are commonly referred to as nodes. Most nodes in the grid represent 1,000-ft squares. In areas where less resolution was required, nodes represent 1,000-by 2,000-ft rectangles.

A streambed thickness of 1 ft was used to simplify calculating the vertical-streambed-leakance coefficient. The coefficient is calculated in the model by dividing the streambed hydraulic conductivity by the 1-ft streambed thickness. Adjustments in streambed hydraulic conductivity are actually adjustments of the streambed-leakance coefficient.

Streams were simulated as accurately as possible within the constraints of the grid (fig. 13). Because no river node was completely filled by the area of the stream, the leakance coefficient was reduced in each node according to the percentage of area the stream occupied. For example, if the leakance coefficient is 1 (ft/d)/ft and the area of the stream is 25 percent of the node, then the coefficient for that node is 0.25 (ft/d)/ft. Initially, 2 (ft/d)/ft was assigned to each river node. This rate was chosen as a reasonable starting value for streams in an outwash system, on the basis of ranges of leakance coefficients used in other White River basin studies (Meyer, 1975, p. 53; Gillies, 1976, p. 18; Lapham, 1981, p. 49).

River stage was calculated for each river node on the basis of measured elevations of certain points and an assumed uniform gradient between those points. Stream locations and gradients were simulated as closely as possible to actual conditions. Initial hydraulic conductivities used in the model were the ones shown in figure 7. Elevations of aquifer bottom for each node were determined from the map in figure 4. Initial water levels are from the contour map of autumn 1980 water levels (fig. 9).

A uniform average recharge rate of 12 in./yr was used in the entire area. Evapotranspiration was not simulated in the model because its effects are accounted for in the recharge rate.

Annual municipal pumpage was averaged for each well field and was entered into the model as closely as possible to each well's location. Pumpage had to be divided into more than one node, where the well was on a grid-block perimeter.

Boundary Conditions

Impermeable boundaries are simulated around most of the model perimeter and the bedrock hills in the outwash because the bedrock is assumed to contribute no water to the ground-water flow system. The bottom of the outwash aquifer, in contact with bedrock or clay, is also considered to be an impermeable boundary. Because the aquifer is simulated as unconfined, the top boundary is the water table and is free to fluctuate. However, under the streambeds, the aquifer is simulated as being confined.

The north and south boundaries across the outwash are arbitrary limits of the study area. The outwash extends past these boundaries, and water-level contours indicate that some ground water crosses the boundaries. The boundaries are simulated as constant-head nodes (fig. 13). The remaining constant-head nodes simulate outwash bounded by till or dune sand. Water-level contours parallel to the boundaries in these areas indicate flow across those boundaries. Flow across the constant-head boundaries could not be measured. Net flux for each constant-head node was calculated in the model.

Calibration of Model

The ground-water flow model was calibrated to autumn 1980 water levels assumed to be at steady state. Aquifer hydraulic conductivity was adjusted to match measured water levels. Most of these adjustments were in areas of low conductivity, and values were lowered further during calibration. The model-simulated hydraulic conductivity after calibration is shown in figure 14. The very low hydraulic conductivity in some isolated areas may not represent the true conductivity, only the one that best simulates the steep gradient of the water table (fig. 9). In these areas, the vertical component, which is not represented in the two-dimensional model, probably dominates the flow system.

Where adjustments of aquifer hydraulic conductivity within a realistic range did not match water levels, especially near streams, the streambed-leakance coefficient was adjusted. Adjustments of the coefficient for small tributaries were very effective in matching water levels in nearby observation wells. Model streambed-leakance coefficients after calibration are shown in figure 15.

Water levels in the model were matched as closely as possible to measured water levels. All the measured water levels were matched within 4 ft. Sixty-seven percent were matched within 1 ft, and 32 percent, within 3 ft. Contours of model-simulated water levels are shown in figure 16.

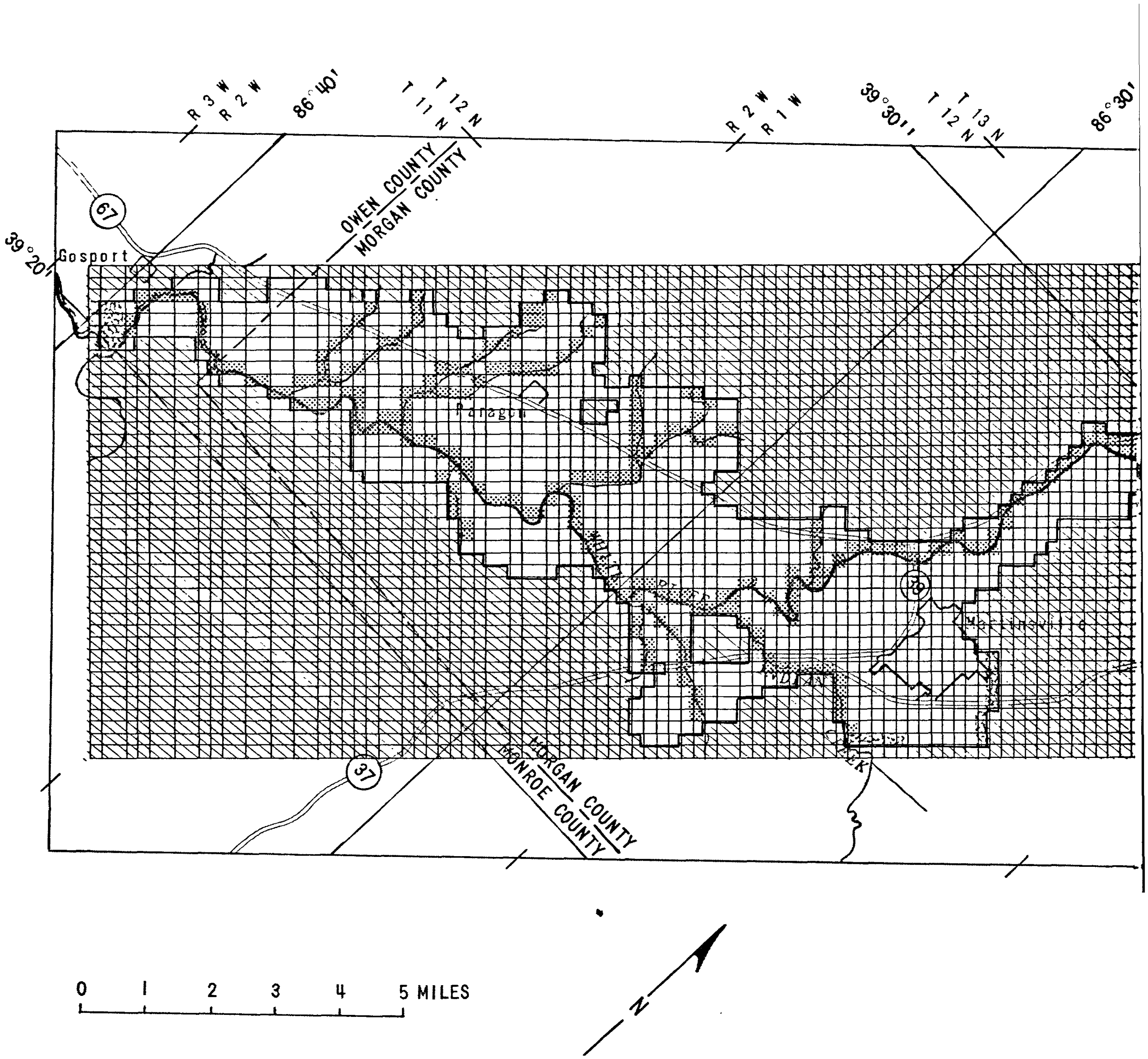
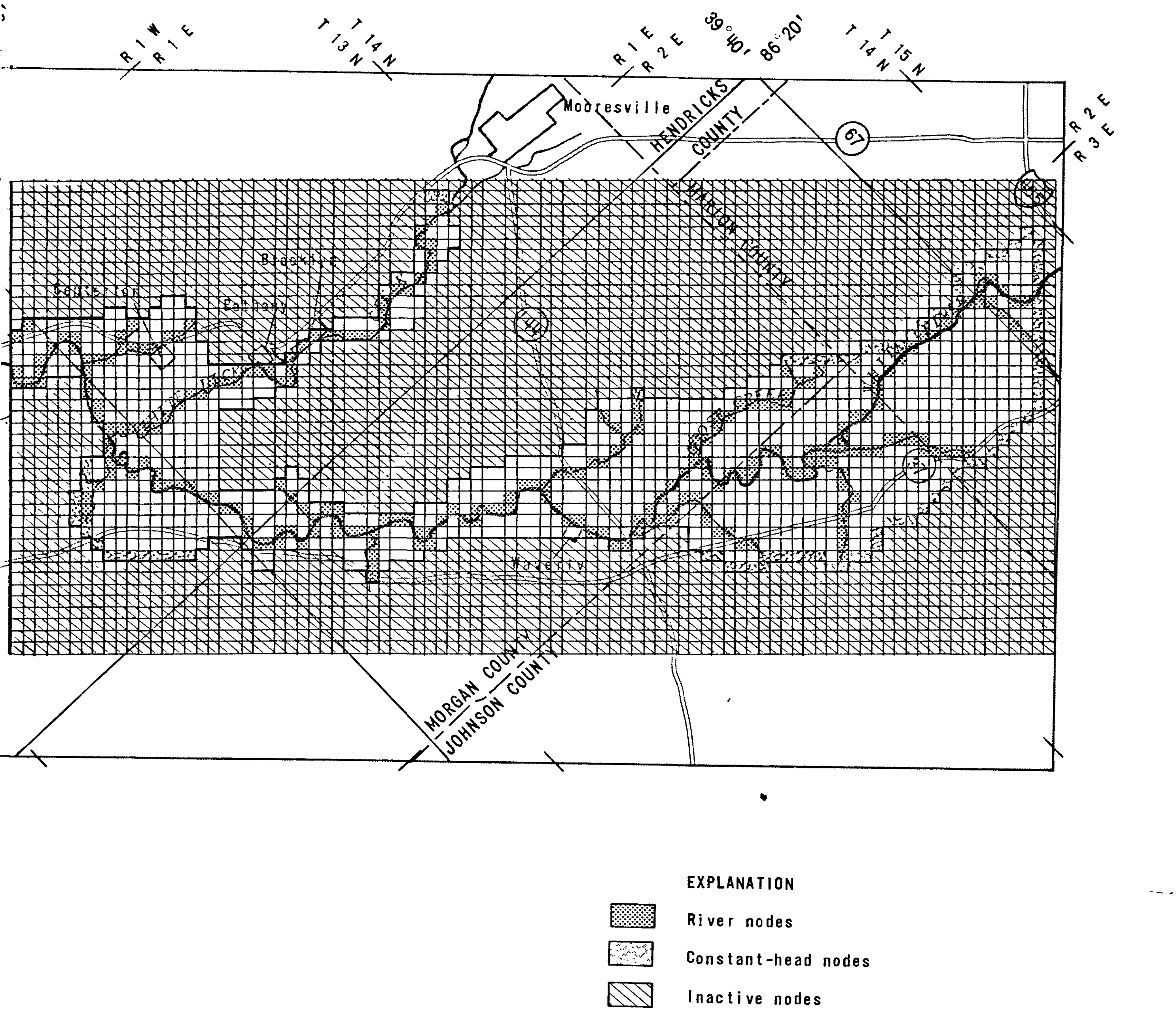


Figure 13.-- Finite-difference grid for the digital flow model.


R 1 W
R 1 E
T 14 N
T 13 N
R 1 E
R 2 E
39°40'
86°20'
T 15 N
T 14 N
R 2 E
R 3 E
Mooresville
HENDRICKS COUNTY
MARION COUNTY
67
MORGAN COUNTY
JOHNSON COUNTY
EXPLANATION
River nodes
Constant-head nodes
Inactive nodes

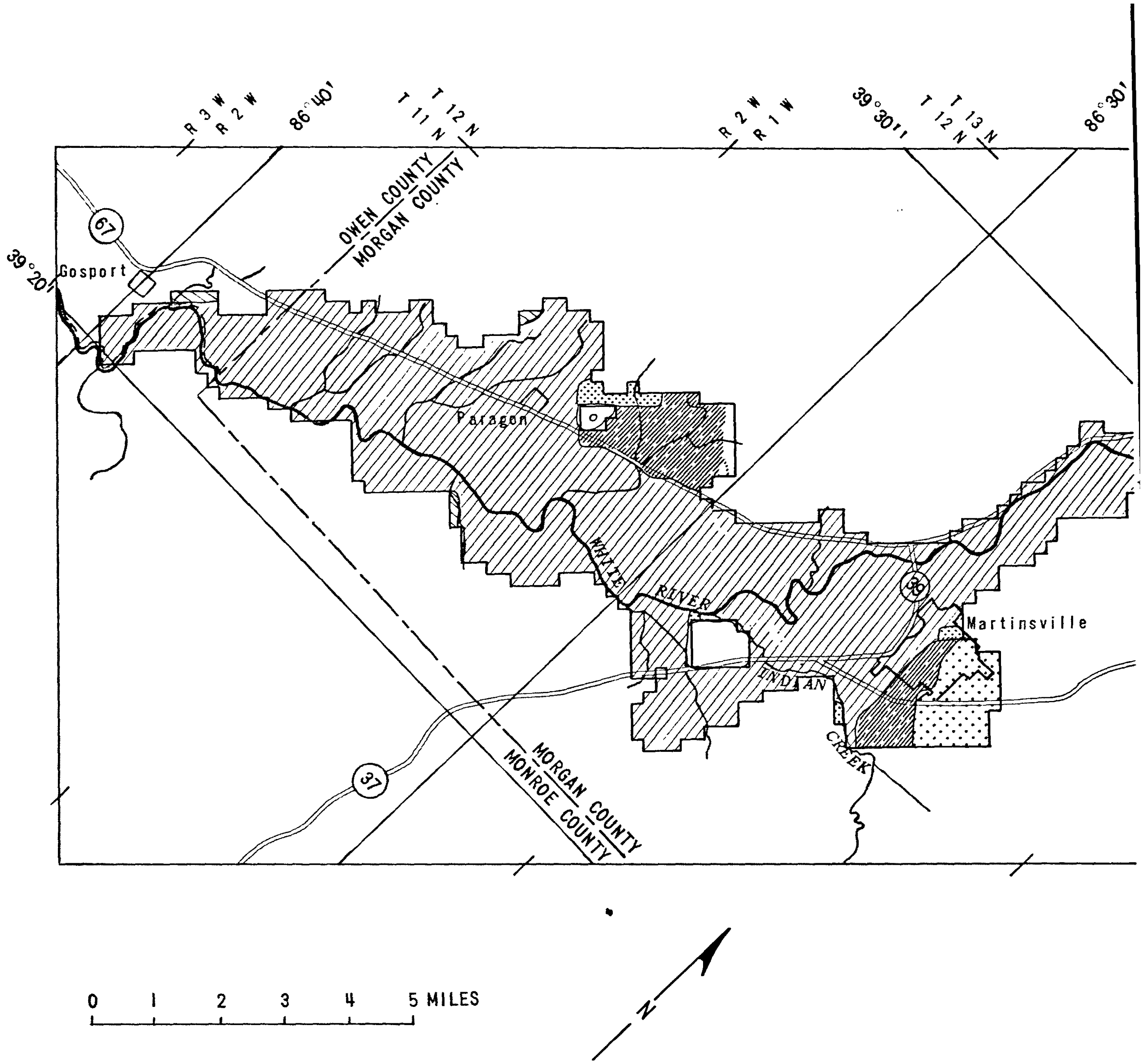
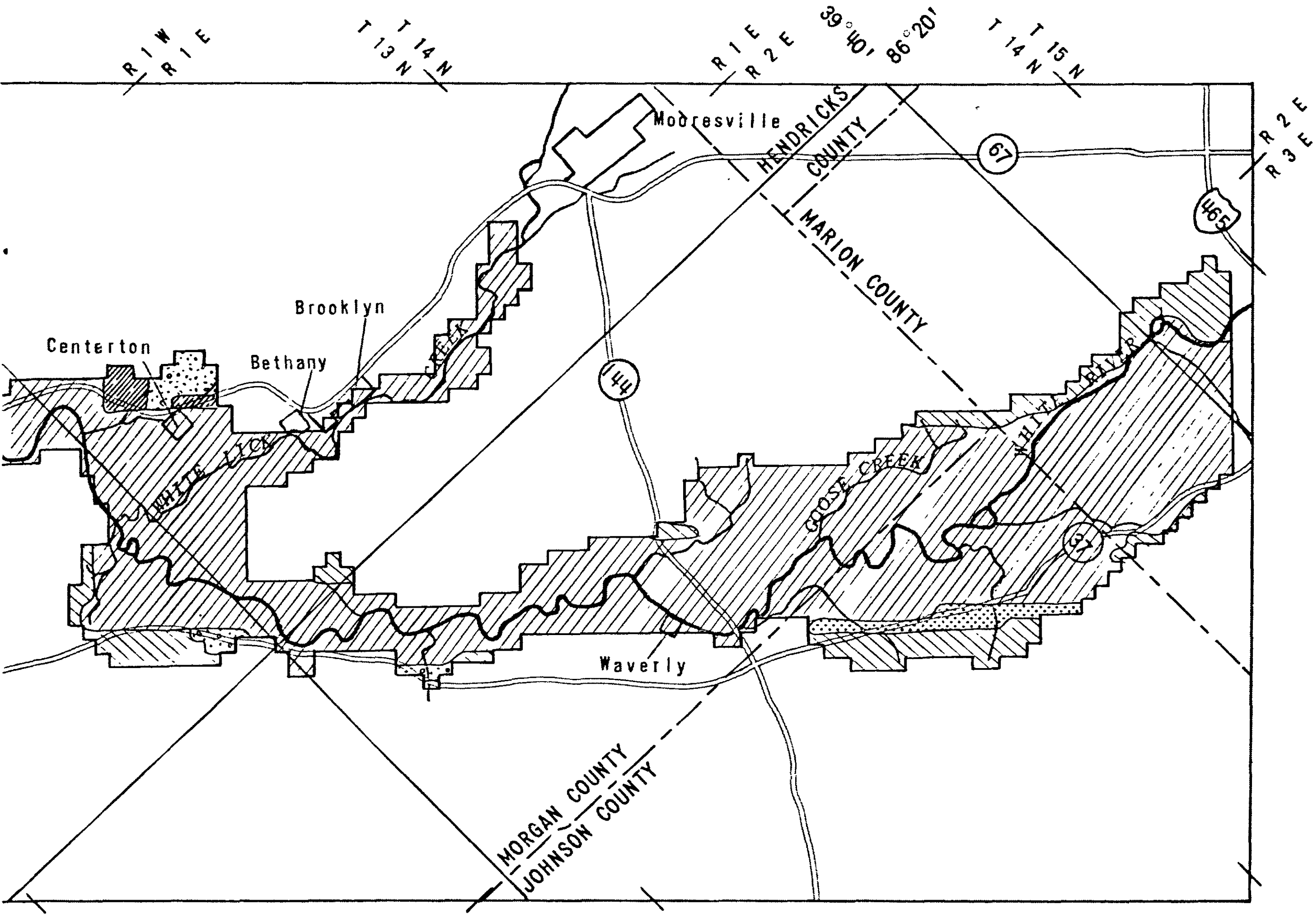


Figure 14.-- Model-simulated hydraulic conductivity of the outwash.



EXPLANATION

FEET PER DAY

0	100-150
5	150-300
10-20	340
40	

Active-node boundary

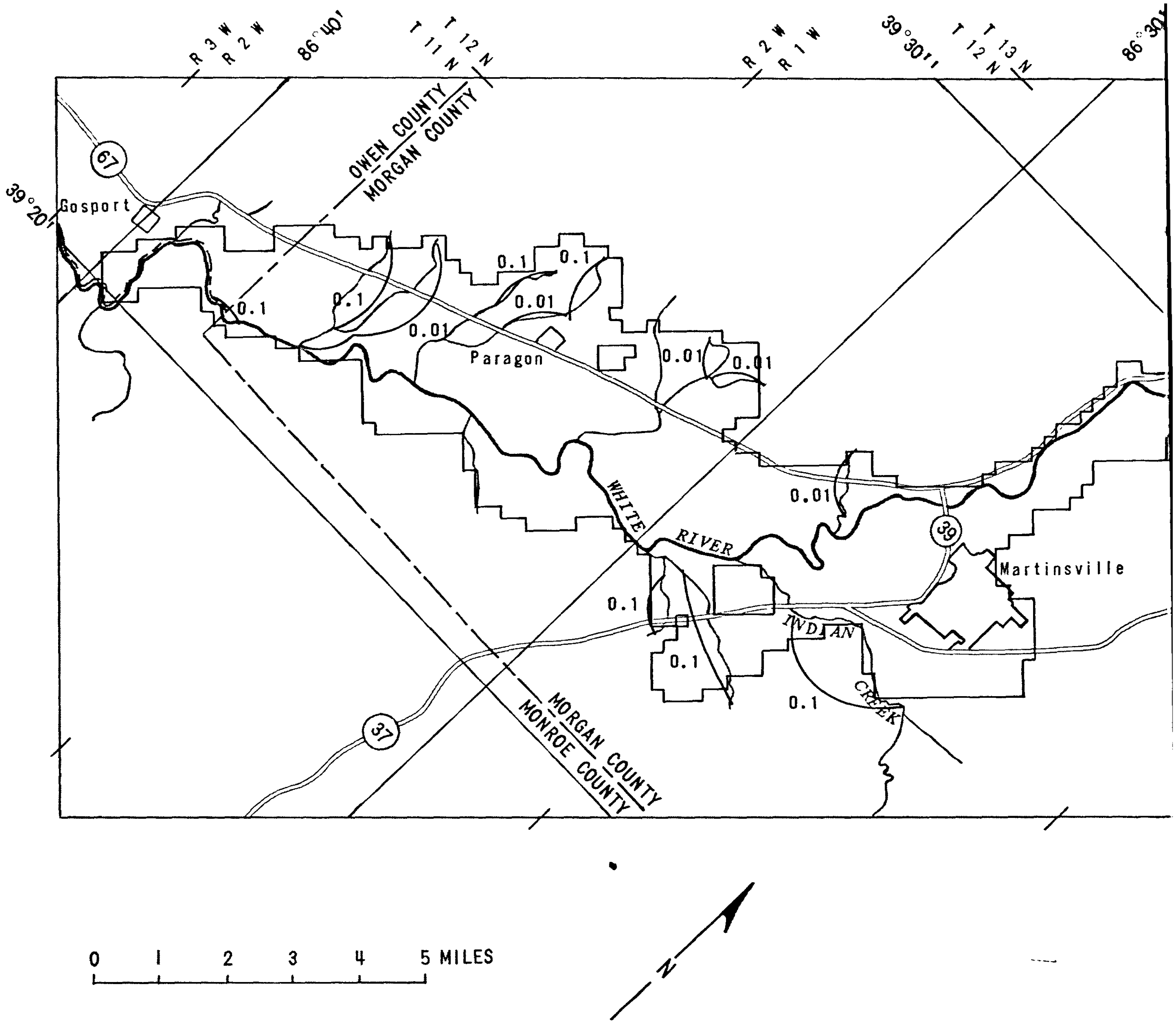
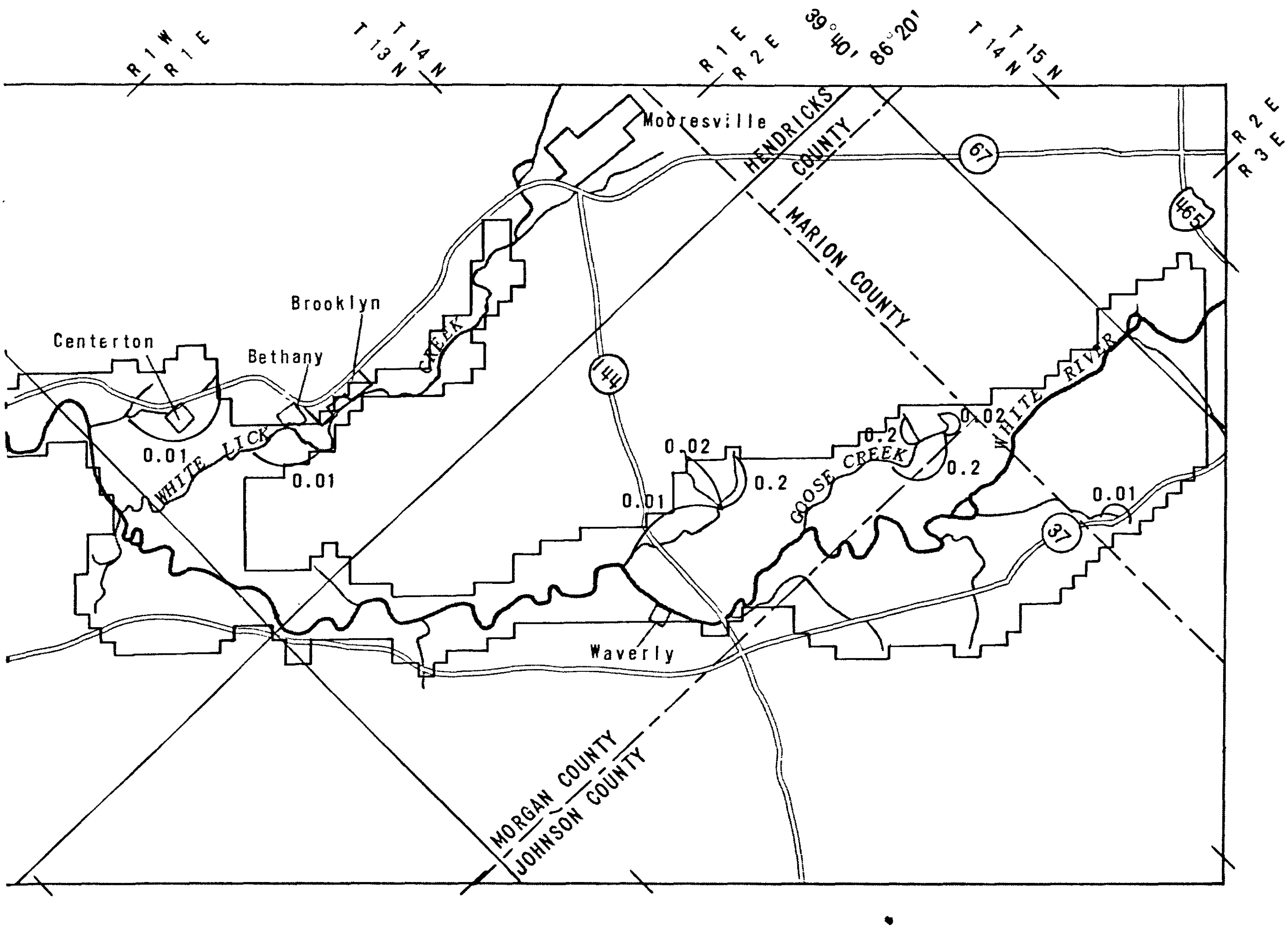


Figure 15.-- Model-simulated streambed-leakance coefficients.



EXPLANATION

0.01 — Calibrated streambed leakance for reach indicated, in foot per day per foot

Unlabeled stream segments are 1 foot per day per foot

— Active-node boundary

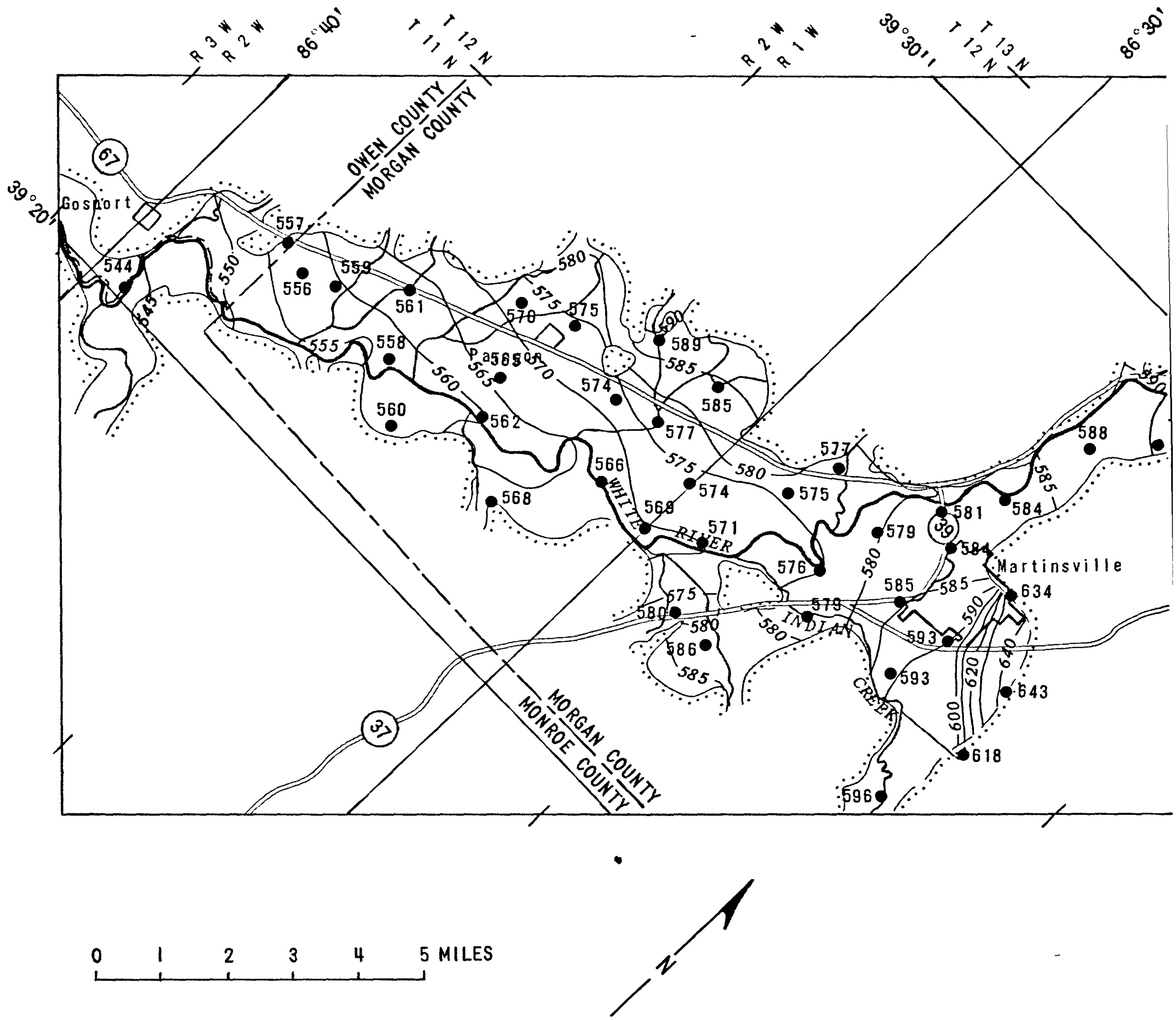
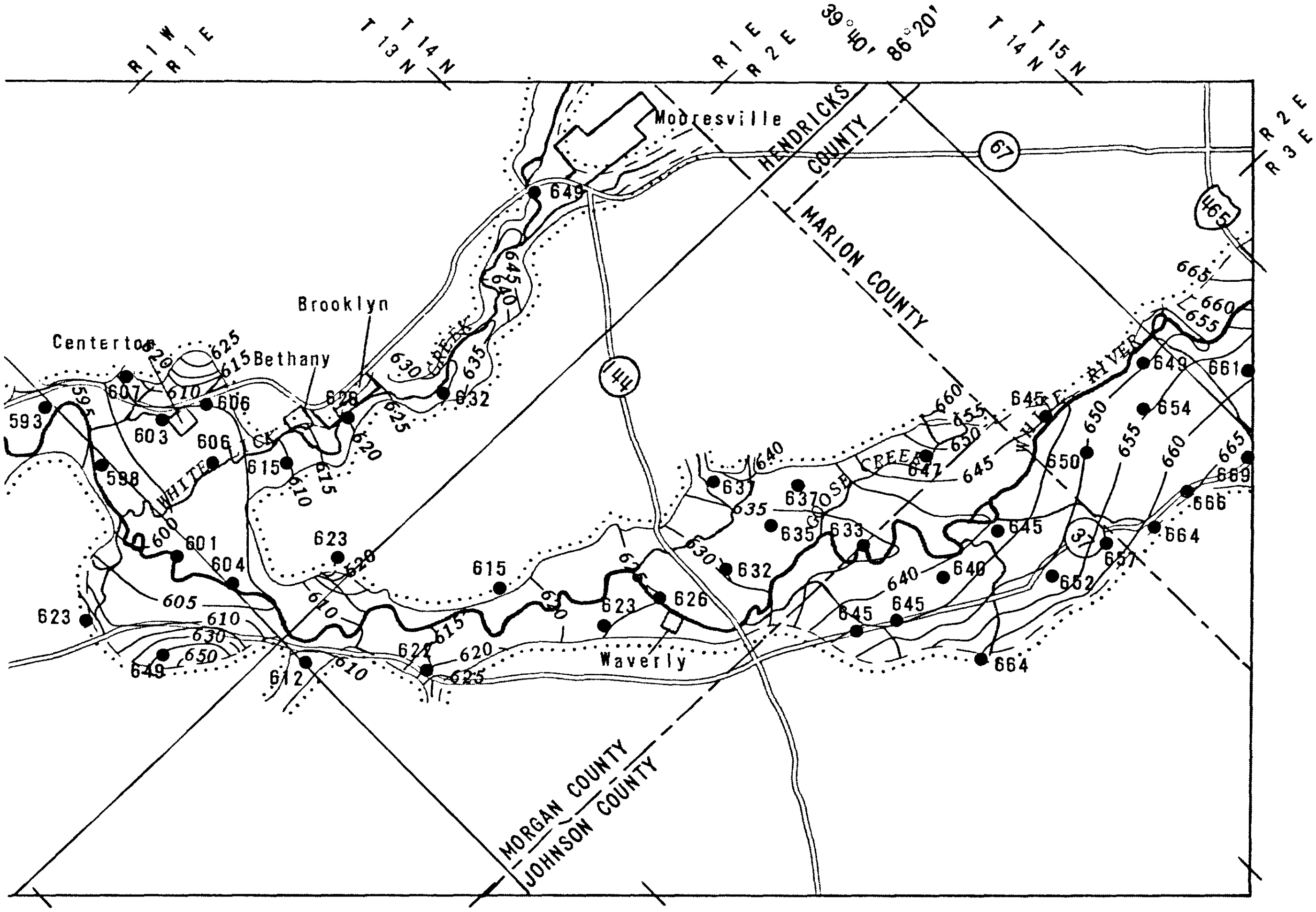


Figure 16.-- Model-simulated water levels in the outwash.



EXPLANATION

— 650 — Line of equal water level. Interval 5 feet. NGVD of 1929

● 649 Observation well and measured water level

Continuous-record observation well Morgan 4

Outwash boundary. Dashed where approximate

Transmissivity of the aquifer (fig. 17), calculated from model-adjusted water levels and hydraulic conductivity, ranges from 5,000 to 35,000 ft^2/d. In some areas, a low hydraulic conductivity, used to match the steep gradient of the water table, results in a transmissivity that may be lower than the true one.

The steady-state water budget for the modeled area is given in table 1. The model calculated a net flux for each constant-head node. These constant-head nodes were replaced in the calibrated model by the net flux. Flux from outside the modeled area represents 16 percent of the recharge to the outwash aquifer. Leakage from the losing streams is 27 percent of the recharge to the aquifer. Fifty-seven percent of the recharge is infiltration from precipitation.

Ground-water seepage to the White River, calculated by the model, is about 32 $(ft^3/d)/ft$. This seepage is within the 28- to 34-$(ft^3/d)/ft$ range calculated for the study area at the 70-percent flow duration at Indianapolis and Spencer gages. Model-simulated seepage to the White River from the total modeled area was 8.8×10^6 ft^3/d (102 ft^3/s). Model-simulated ground-water seepage to all the streams was 120 ft^3/s, or 93 percent of the discharge in the model. The remaining 7 percent was removed by simulation of actual municipal well-field pumpage.

Table 1.--Steady-state ground-water budget of the model for autumn 1980 conditions in the outwash

	Flow		Percent of total
	(ft^3/s)	(Mgal/d)	
Sources			
Constant flux	21	33	16
Areal recharge	73	113	57
Leakage from streambeds	35	54	27
Total	129	200	100
Discharges			
Ground-water seepage to streams	120	187	93
Pumpage	9	13	7
Total	129	200	100

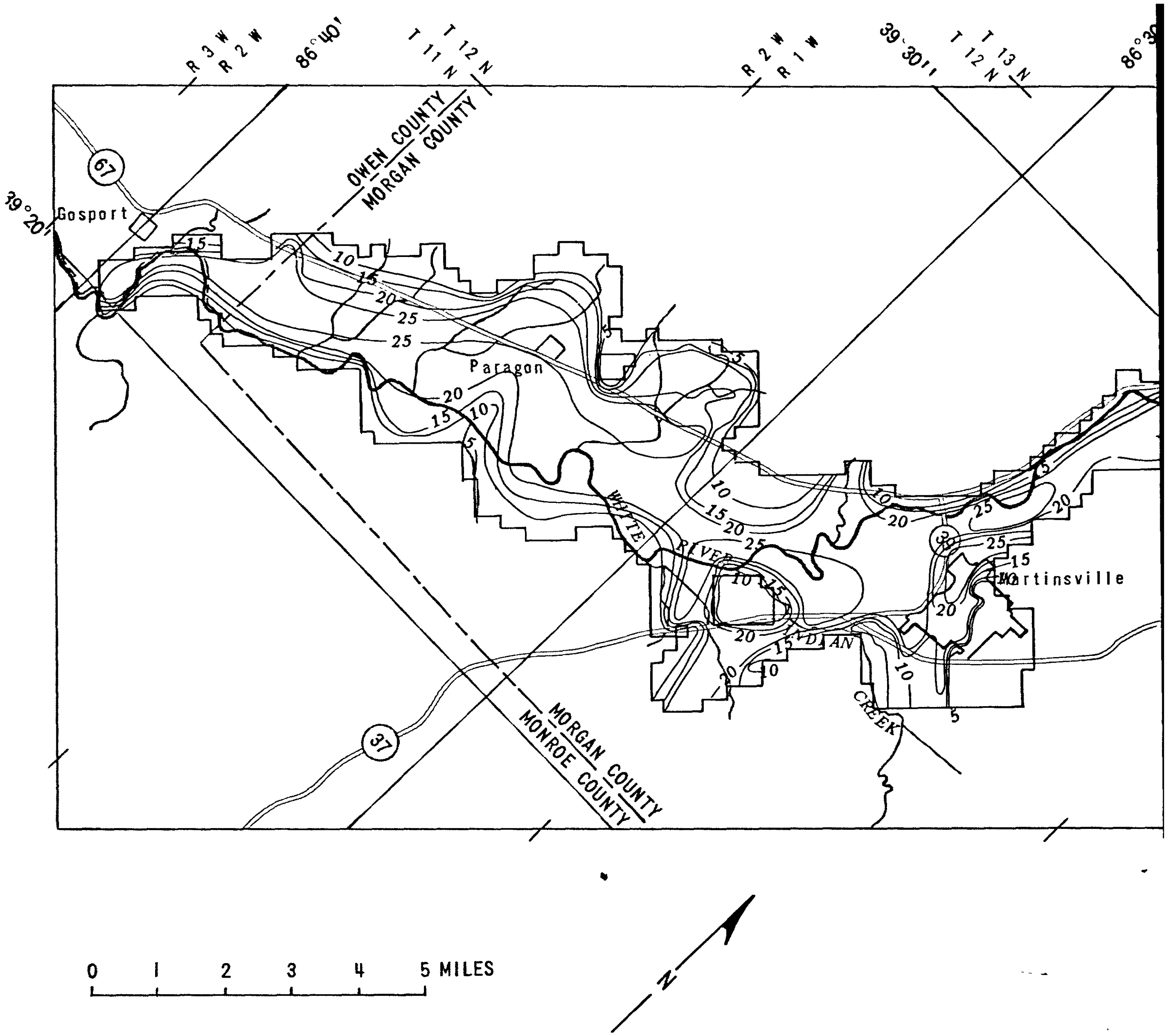
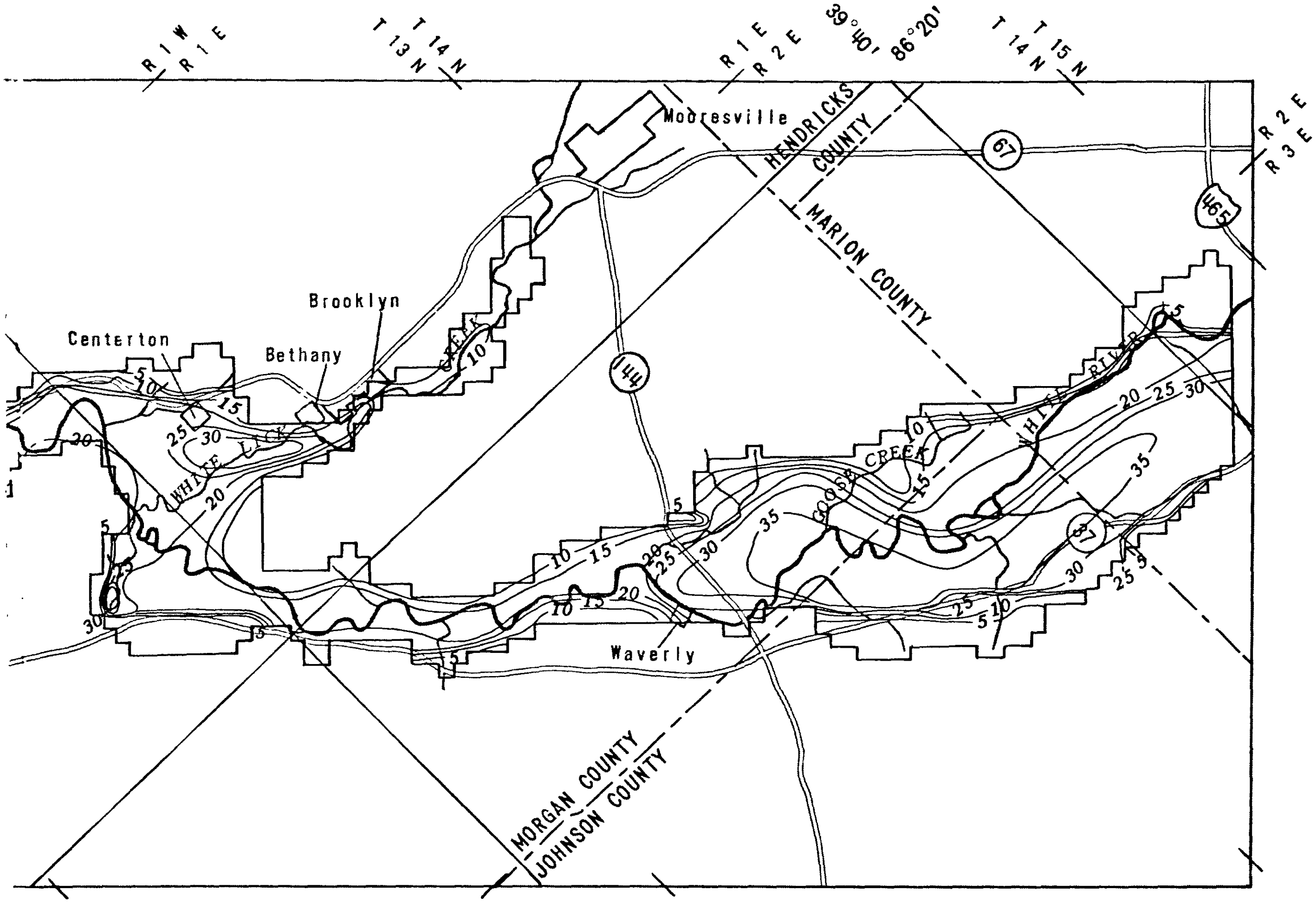


Figure 17.-- Model-simulated transmissivity of the outwash.



EXPLANATION

——*10*—— Line of equal transmissivity, in thousands of square feet per day. Interval 5,000 square feet per day

———— Active-node boundary

Sensitivity Analyses

The response of the model to adjustments of streambed leakance, aquifer hydraulic conductivity, and areal recharge was evaluated by sensitivity analyses. The ranges of adjustments for the three variables were from 0.1 to 50 times the calibrated streambed leakance; from 0.5 to 5 times the aquifer hydraulic conductivity; and from 0.2 to 2 times the calibrated recharge rate. For each adjustment, a sensitivity test was done on the calibrated model for constant-head and constant-flux boundaries.

A statistical procedure programmed by D. B. Sapik (written and oral commun., 1981) and added as a subroutine to the digital model program simplified error calculations. The root mean square error (RMSE) was calculated for measured and calculated water levels by the equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_i^m - h_i^c)^2}{N}}$$

where

N is number of observations (75),

h_i^m is measured water level, in feet,

and

h_i^c the calculated water level, in feet.

The RMSE was plotted for each adjustment in a variable to display the range of sensitivity.

The RMSE for all variables at the values used in the calibrated model is 1.55 ft because not all measured water levels were matched exactly during calibration. If all heads had been exactly matched, the RMSE would be zero. An acceptable range in which the model was considered to be insensitive to changes in a variable was set at 2 ft of additional error or from 1.55 to 3.55 ft.

Sensitivity analyses done with constant-flux boundaries more accurately represent the response of the real system than analyses with constant-head boundaries. Generally, with constant-head boundaries, the variables are insensitive in a wide range of adjustments, whereas with constant-flux boundaries, the same variables are much more sensitive and produce a narrow range in which the model is insensitive to the adjustments. This insensitivity results from the ability of the constant-head nodes to add as much water to the system as is necessary to maintain a balance. But, because the amount of water entering the system is fixed for constant-flux boundaries, adjustments in the variables cause an imbalanced water budget.

Aquifer hydraulic conductivity was adjusted from 0.5 to 5 times the calibrated value, or from 170 to 1,700 ft/d for most of the aquifer. The resulting curves are shown in figure 18. The curve for constant-head boundaries shows that the model is not sensitive within the tested range. Constant-flux boundaries cause a higher degree of sensitivity to changes in hydraulic conductivity than constant-head boundaries cause. The model is not sensitive from 0.76 to 1.45 times the calibrated values, or from 258 to 493 ft/d. Multiples of the parameter outside this range, either higher or lower, cause a RMSE larger than the acceptable error.

Streambed-leakance adjustments ranging from 0.1 to 50 times the calibrated values resulted in almost identical curves for both types of boundaries. This variable was insensitive at values less than 50 times the calibrated value. Differences between measured and calculated water levels near small tributaries having very low calibrated leakances contributed more to RMSE value than differences between measured and calculated water levels near the White River. The model was originally considered to be calibrated for a streambed-leakance coefficient of 2 (ft/d)/ft; however, 1 (ft/d)/ft produced a lower RMSE value. Subsequently, the model was recalibrated with the leakance shown in figure 15, and the sensitivity analyses were repeated for the recalibrated model (fig. 19).

Recharge was set at 12 in./yr for the entire modeled area and was not adjusted during calibration. But for the sensitivity analyses, recharge was adjusted within the range from 3.6 to 24.0 in./yr (fig. 20). Recharge was not sensitive in this range for constant-head boundaries nor in the range from 0.58 to 1.45 times (7.0 to 17.4 in./yr) for constant-flux boundaries.

The sensitivity analyses resulted in an improved calibrated model. The most significant aspect of the analyses was that a streambed leakance of 1 (ft/d)/ft produced a closer match to measured water levels than the original calibrated model. Recharge could be adjusted by 5 in./yr from the calibrated 12 in./yr and still produce virtually the same match to measured water levels. The aquifer hydraulic conductivity derived from specific-capacity tests (340 ft/d for sand and gravel) was within the acceptable RMSE range from 258 to 493 ft/d. Seepage to the White River, 102 ft /s in the calibrated model, ranged from 80 to 120 ft /s within the insensitive range for each tested variable. This range represents reasonable seepage values for the modeled system.

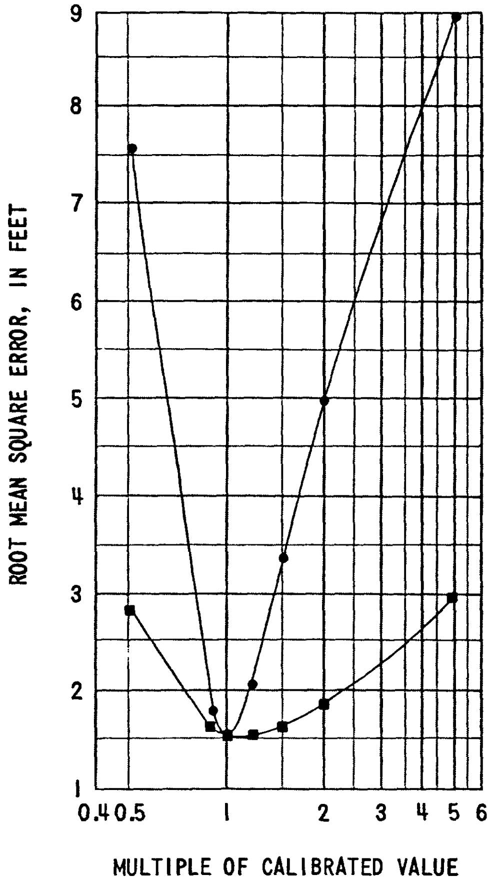


Figure 18.-- Sensitivity of the digital flow model to adjustments in hydraulic conductivity of the outwash.

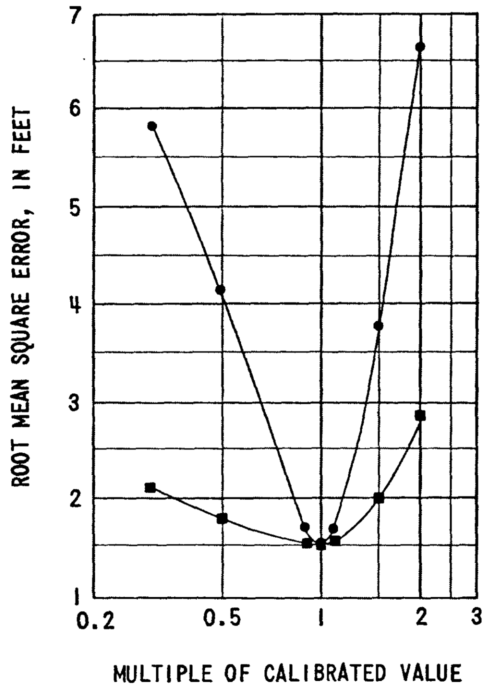


Figure 20.-- Sensitivity of the digital flow model to adjustments in recharge.

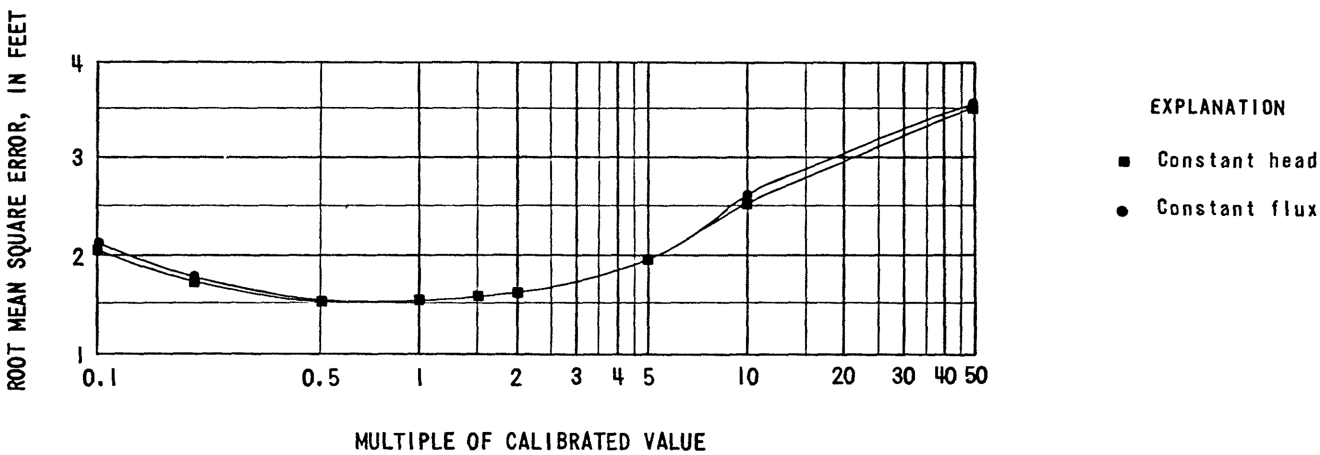


Figure 19.-- Sensitivity of the digital flow model to adjustments in streambed leakance.

Pumping Simulations

The calibrated model was used to assess the potential of the outwash aquifer and the effects of pumping on water levels and streamflow. Only steady-state conditions were simulated because the main consideration was the determination of a final water-level distribution under simulated stress, not the time to reach that point.

Three pumping simulations, based on suggestions from Indiana Department of Natural Resources were used: Plan 1, 20-Mgal/d pumping in a well field; and general pumping plans 2 and 3 that reduce streamflow in the White River by 15 percent and 30 percent, respectively. Two Mgal/d was pumped from each simulated 12-in. diameter well. Wells were at least 1,000 ft apart and 1,000 ft from the river. The wells were arranged parallel to the White River and placed in areas of greatest saturated thickness. The drawdown limit in the pumping wells was 66 percent of saturated thickness. No pumping was simulated in the central one-third of the study area because, according to Indiana Department of Natural Resources, the area is unlikely to be extensively developed.

In each plan, pumping was simulated for constant-head and constant-flux boundaries to establish a range of simulated drawdowns and to identify the areal extent of that drawdown. Constant-head boundaries produce less drawdown and areal extent of drawdown than constant-flux boundaries produce because water levels at the boundary are held constant and additional water is provided to the system under stress. For constant-flux boundaries, water enters the system through the nodes at a fixed rate. Only the results of pumping simulated with constant-flux boundaries are shown in the figures because in most areas the drawdown contours for constant-head and constant-flux boundaries differed minimally.

Reduction of streamflow due to pumping of ground water that would have discharged into the White River is a major concern. Total streamflow is not a variable in the model, but loss of ground-water flow to the river by pumping can be calculated. Ground-water seepage to the river is calculated in the calibrated model, and the difference in seepage after pumping can be compared with the original steady-state seepage. The near 70-percent flow duration at Centerton, 540 ft^3/s (Horner, 1976, p. 285), was used to calculate the percentage reduction of streamflow.

Losing streams that add recharge to the ground-water system present a problem during pumping simulations. Almost all flow in these streams seeped into the aquifer at autumn 1980 flow rates, to which the model is calibrated. During pumping simulations, the losing streams were removed from the model to prevent additional simulated loss from them. The constant-head river nodes at affected locations were replaced by a model-calculated flux that represents actual loss (and the calibrated stream condition). Gaining segments were adjusted to minimize infiltration to the aquifer during simulated pumping.

In pumping plan 1, the simulation consisted of 10 wells pumping 2 Mgal/d each. The wells were placed 1,000 ft apart in two rows paralleling the White River (fig. 21). The simulation with constant-head boundaries resulted in a

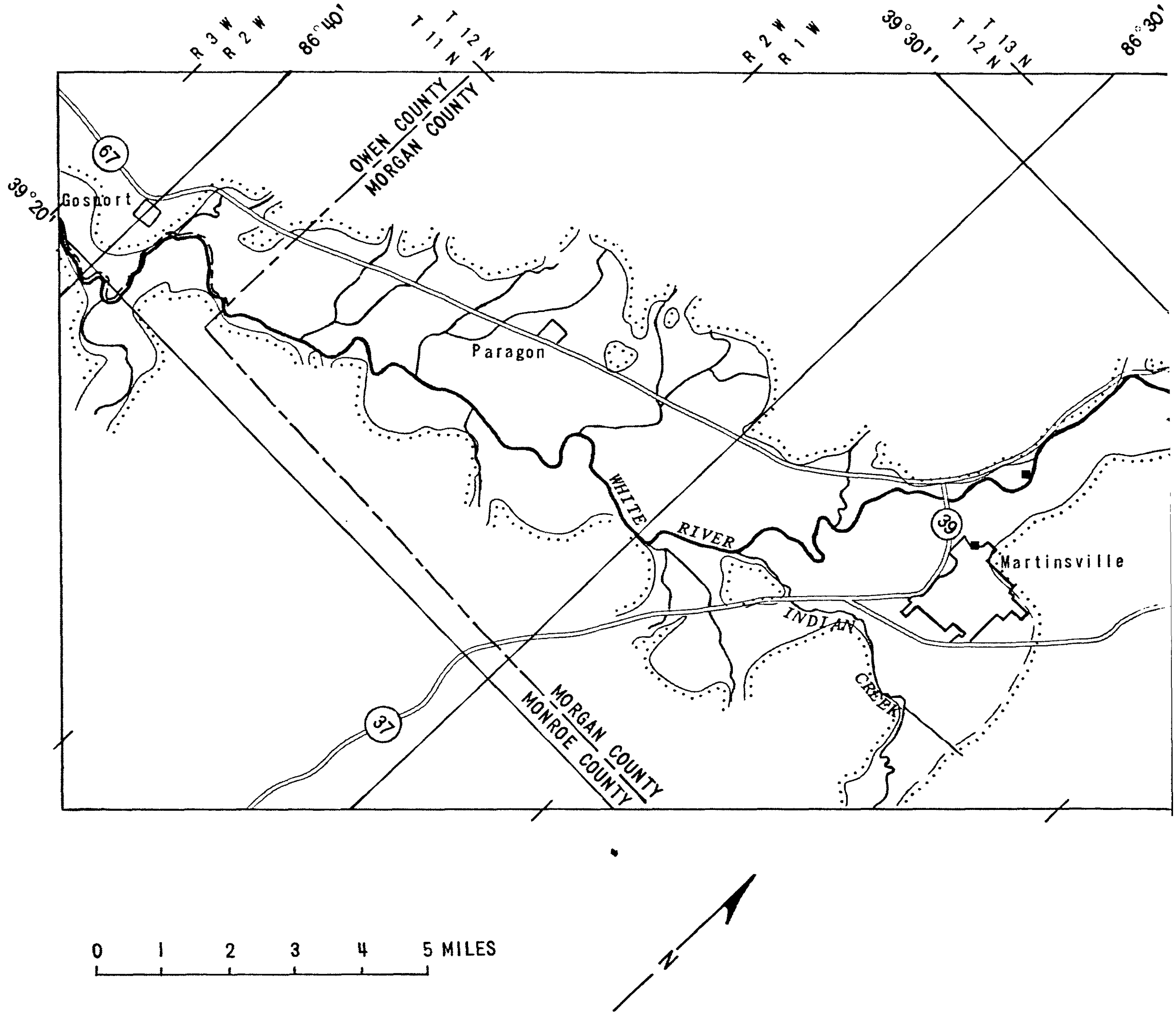
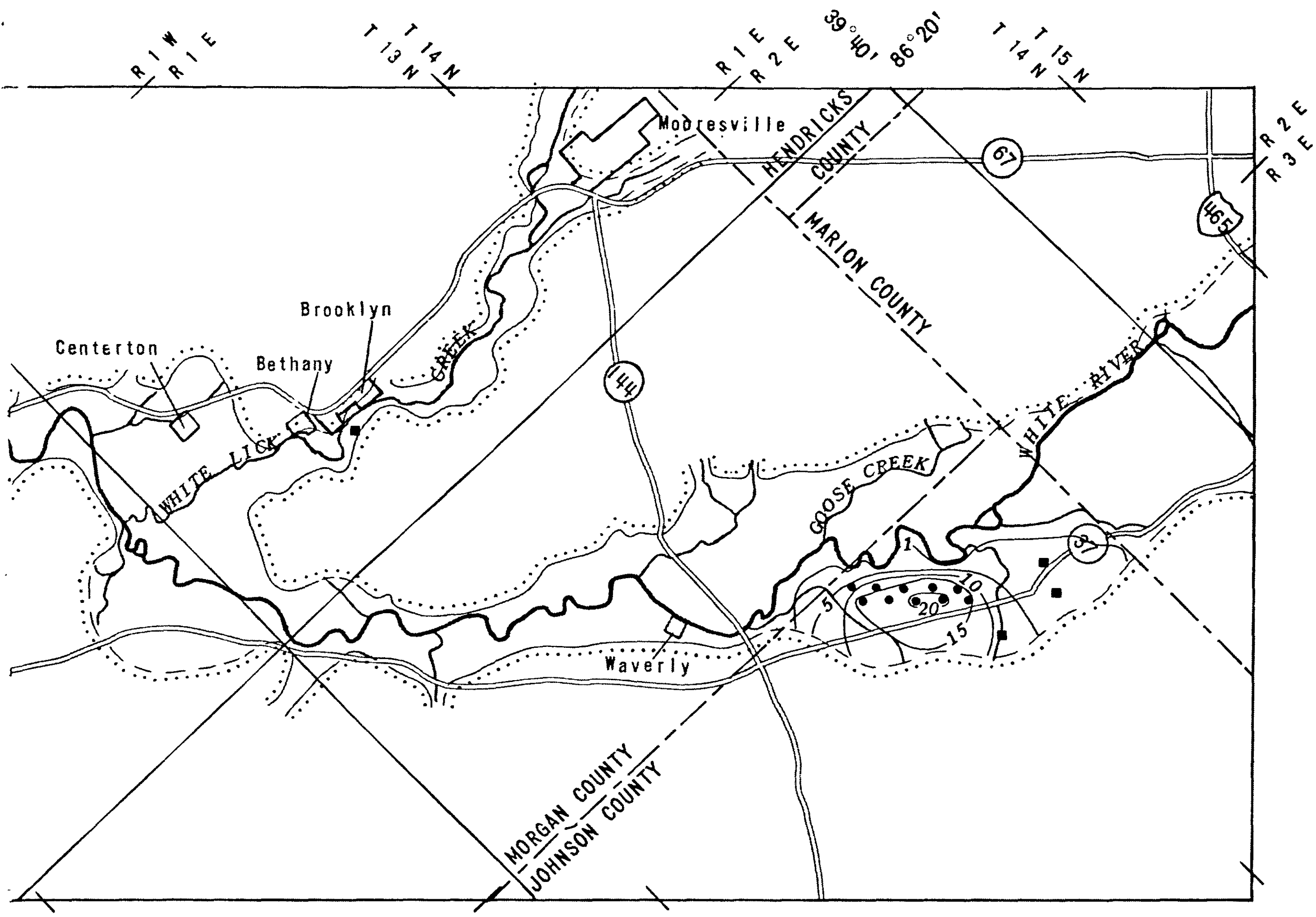


Figure 21.-- Drawdown in the outwash for simulated 20-million gallons per day pumping, with constant-flux boundaries.



EXPLANATION

—— 5 ——	Line of equal drawdown. Intervals 4 and 5 feet
●	Simulated well
■	Municipal well field
.... — —	Outwash boundary. Dashed where approximate

maximum drawdown of 18 ft, and that with constant-flux boundaries resulted in a drawdown of 20 ft or less. The area affected by drawdown is slightly larger for constant-flux boundaries than for constant-head boundaries (fig. 21). Drawdown in the pumping wells for both boundary conditions was less than 30 percent of saturated thickness. Streamflow reduction in the White River was about 5 percent for each simulation: 26 ft^3/s with constant-head boundaries and 29 ft^3/s with constant-flux boundaries.

In plan 2, the simulation consisted of 33 wells pumping a total of 66 Mgal/d. Maximum drawdown, for both constant-head and constant-flux boundaries was 13 ft, but the areal extent of drawdown was greater for constant flux (fig. 22) than for constant head. Streamflow reduction with constant-head boundaries was 79 ft^3/s, and that with constant-flux boundaries was 84 ft^3/s. Drawdown in the pumping wells was 33 percent or less of saturated thickness.

In plan 3, the simulation consisted of 61 wells pumping a total of 122 Mgal/d. Locations of these wells, which include the wells in the previous simulation, are shown in figure 23. Maximum drawdown with constant-head boundaries was 24 ft, and that with constant-flux boundaries was 25 ft. Areal extent of drawdown for the constant-flux boundaries is shown in figure 23. Streamflow was reduced by 156 ft^3/s with constant-head boundaries and 164 ft^3/s with constant-flux boundaries. In the simulations, water was intercepted before reaching the White River. In all areas of pumping, the gradient was reversed, and water was drawn from the river. The drawdown in two wells was 50 percent of saturated thickness; in five, between 40 and 50 percent; and in the remaining 54, 40 percent or less of saturated thickness.

These pumping simulations are not intended to be predictive but to indicate the response of the system to various pumping plans. The well-field simulation shows the system's response to concentrated pumping. The two general pumping plans indicate the overall potential yield of the aquifer and the effects of that yield on streamflow. Pumpage and reduction of flow in the White River are summarized in table 2.

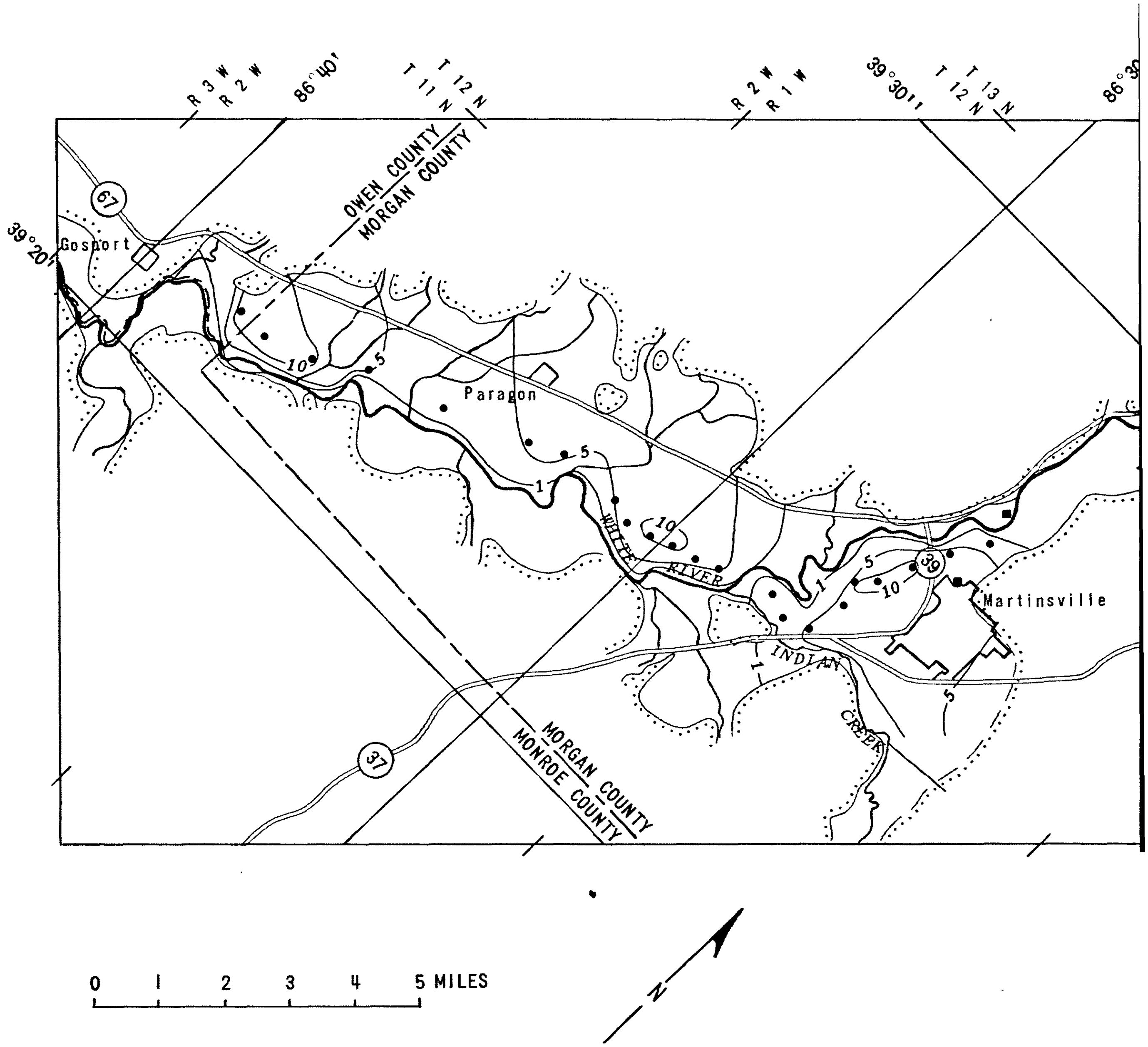
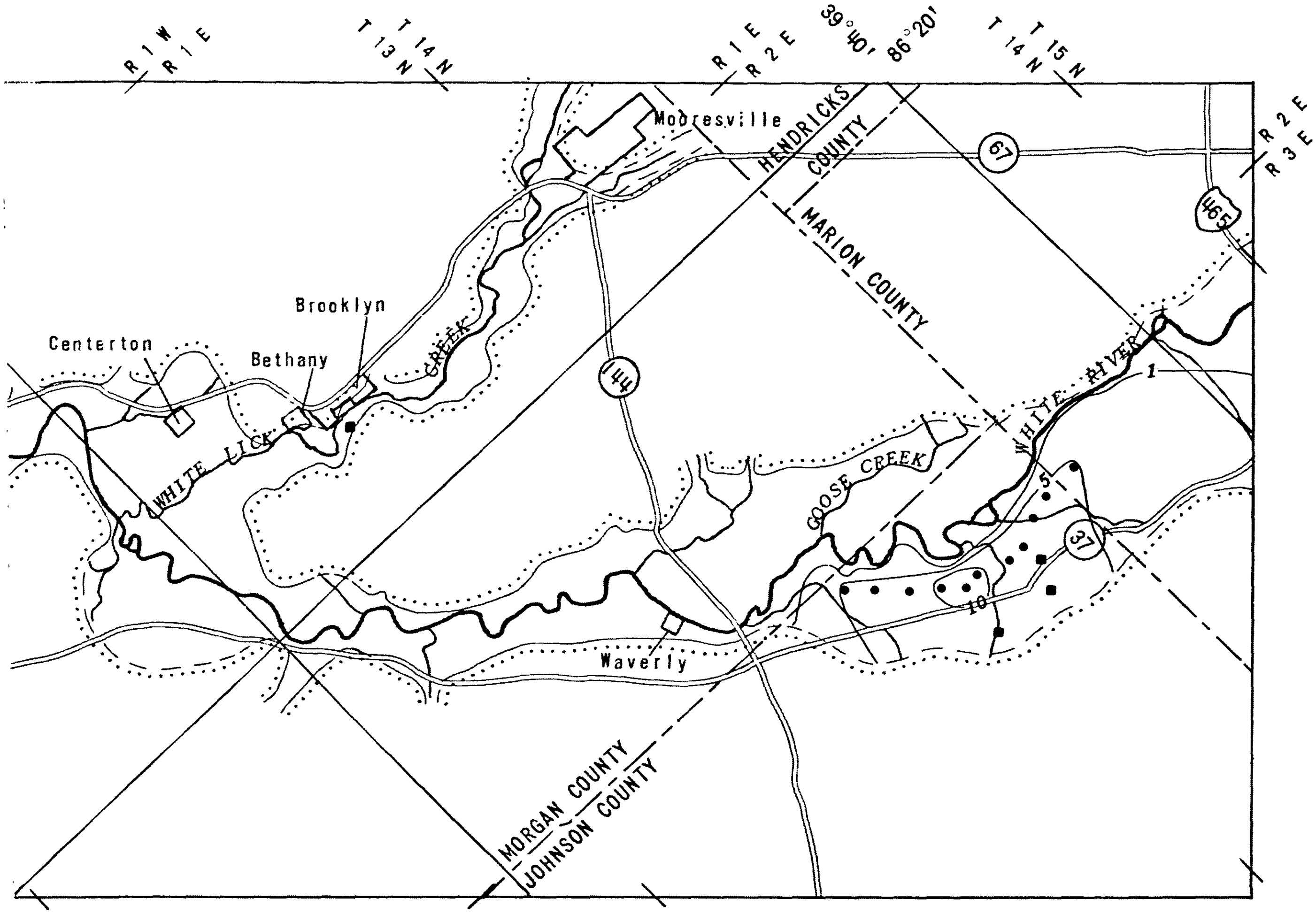


Figure 22.-- Drawdown in the outwash for simulated 66-million gallons per day pumping, with constant-flux boundaries.



EXPLANATION

— 5 —	Line of equal drawdown. Intervals 4 and 5 feet
●	Simulated well
■	Municipal well field
―― — — ⋯⋯	Outwash boundary. Dashed where approximate

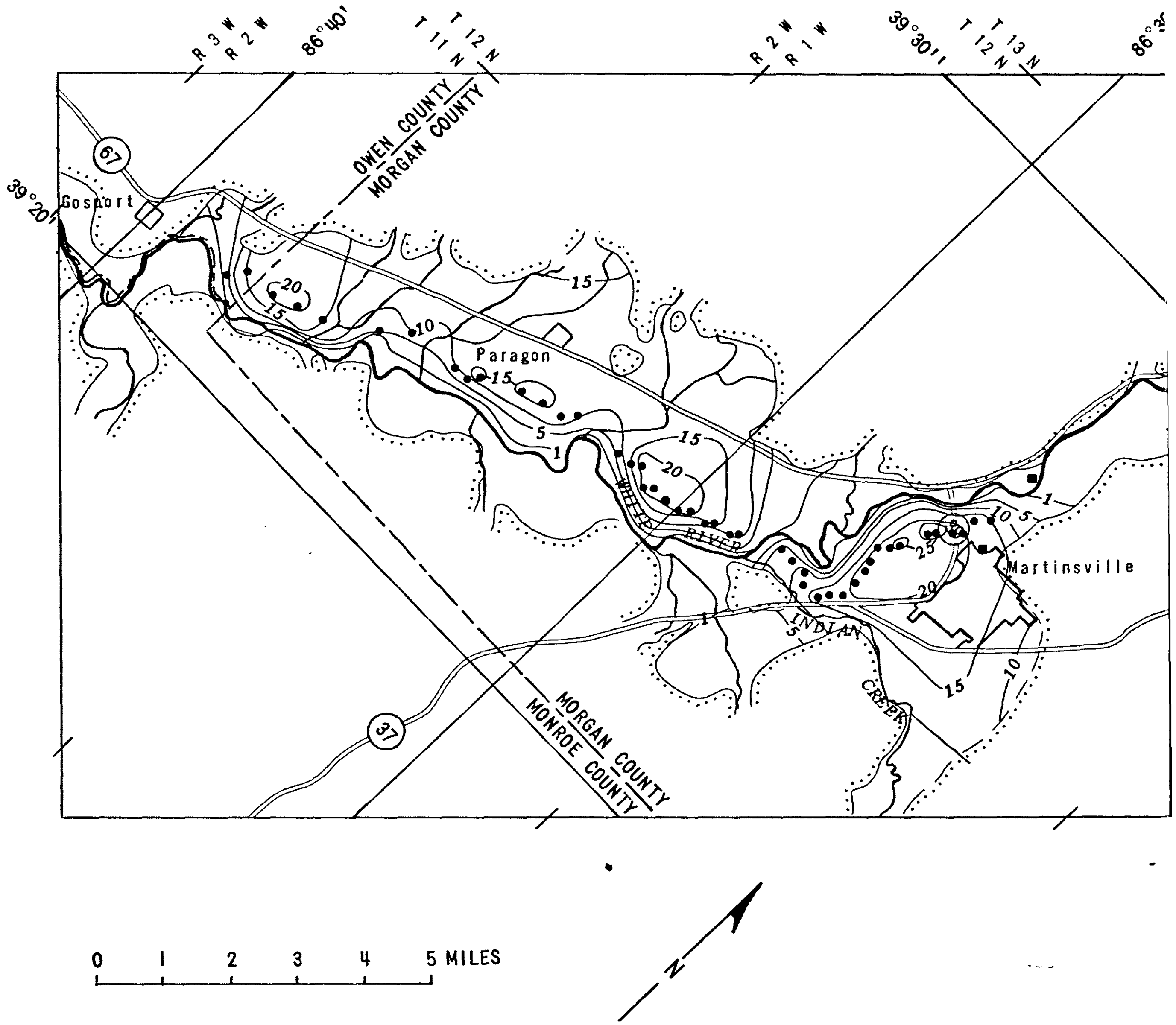
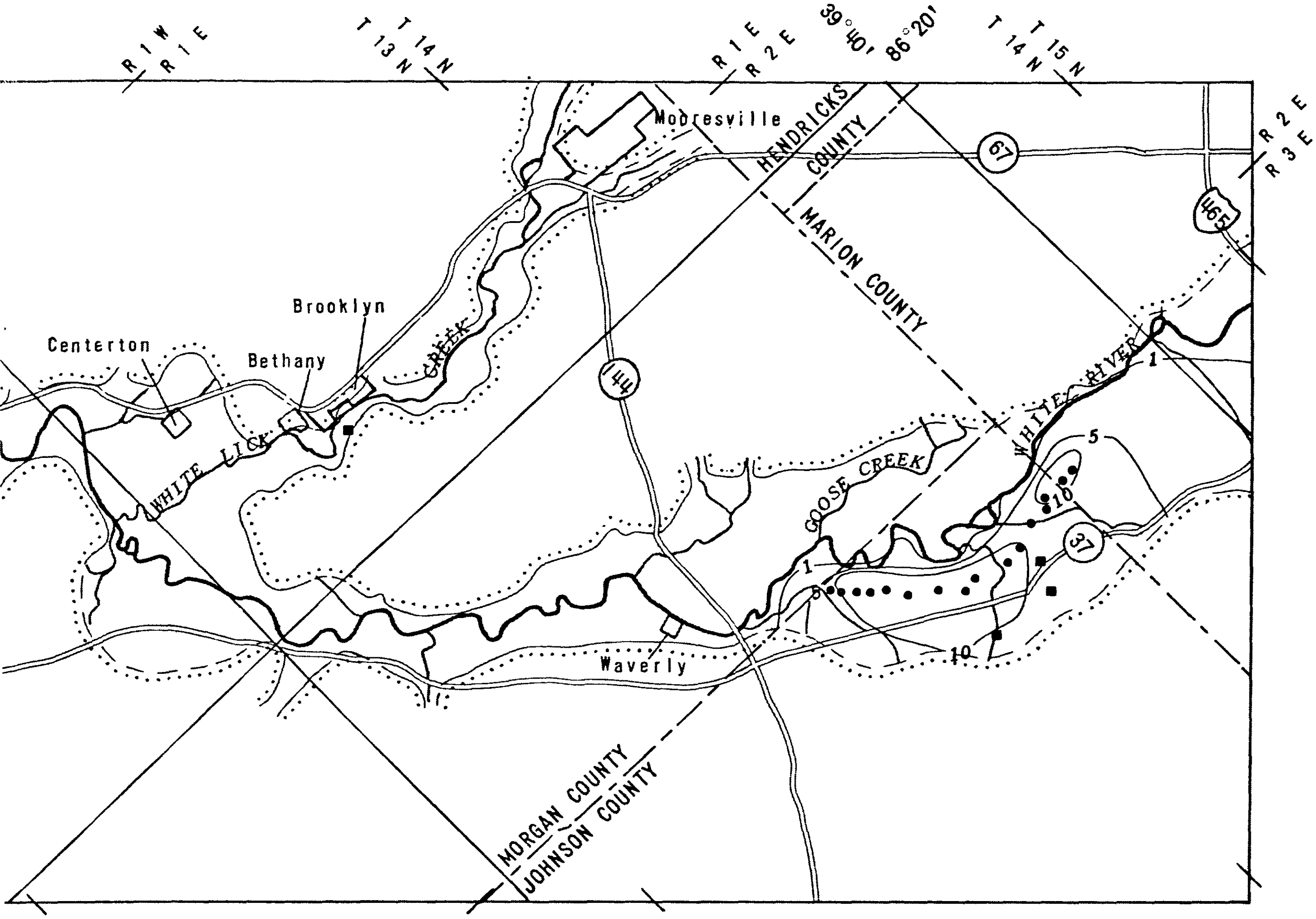


Figure 23.-- Drawdown in the outwash for simulated 122-million gallons per day pumping, with constant-flux boundaries.



EXPLANATION

—— 5 ——	Line of equal drawdown. Intervals 4 and 5 feet
●	Simulated well
■	Municipal well field
——— - - - ········	Outwash boundary. Oashed where approximate

Table 2.--Streamflow reduction resulting from simulated ground-water pumping (constant-flux boundaries)

Pumping plan	Number of wells	Pumpage (Mgal/d)	Streamflow[1] reduction (Mgal/d)	(ft^3/s)	Streamflow reduction (percent)
1	10 (well field)	20	17	29	5
2	33 (general pumpage)	66	54	84	15
3	61 (general pumpage)	122	106	164	30

[1]Reduction of flow in the White River. The remaining water infiltrates from tributaries.

GROUND-WATER QUALITY

Two of the six objectives of the investigation were to assess the water quality of the outwash aquifer and to evaluate seasonal and areal variations in water quality.

Methods

Well Network and Sampling Frequency

Water samples were collected from 55 of the 70 observation wells installed for the study. All 55 wells were sampled in the initial survey in November 1979 and January 1980. On the basis of areal distribution, 21 of these wells were chosen for more detailed sampling in May and October 1980. The locations of the 55 wells are shown in figure 24.

The wells, constructed of 2-in.-diameter galvanized-steel casings and screens, are screened in the aquifer at depths of 20 to 45 ft. Each is identified by a three-letter prefix corresponding to the county name and a sequential site number for that county. For example, MOR-15 is well 15 in Morgan County (MAR, Marion; MOR, Morgan; JON, Johnson; OWN, Owen).

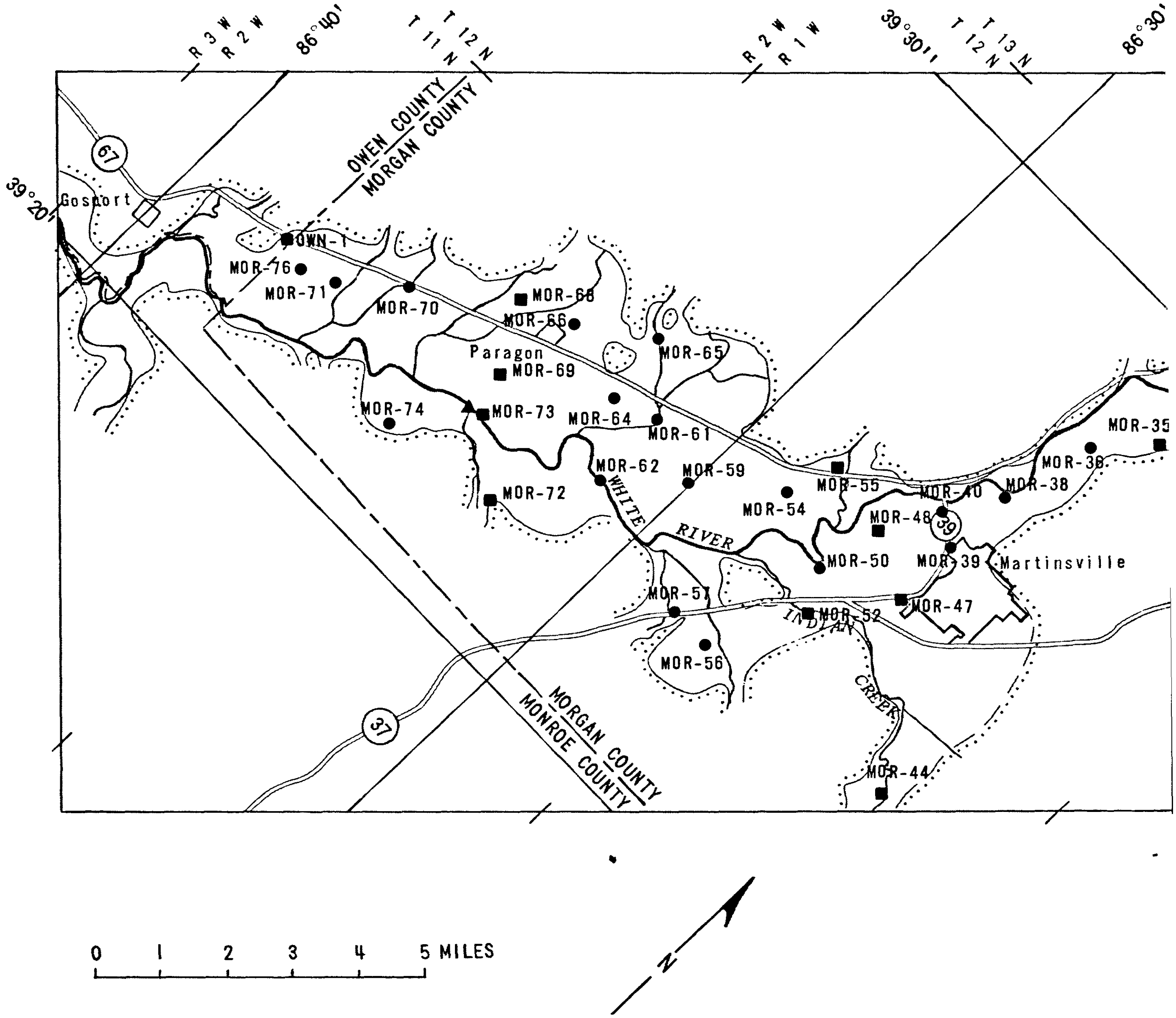
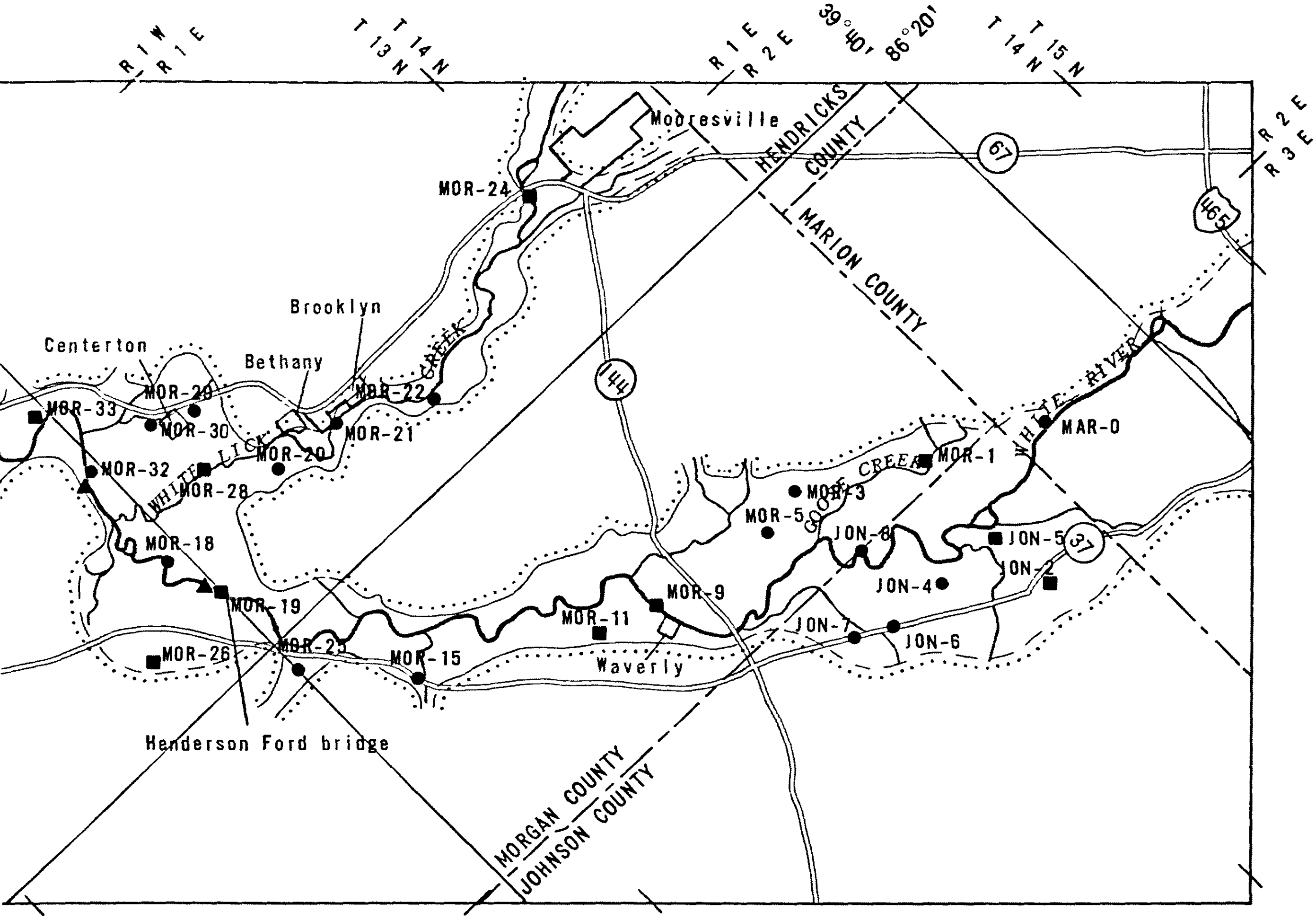


Figure 24.-- Wells and surface-water sites sampled for water-quality analysis.



EXPLANATION

●	Well sampled one time
■	Well sampled three times
▲	Indiana State Board of Health surface-water monitoring site
MOR-5	Well-site designation
═══ ┄┄┄	Outwash boundary. Dashed where approximate

Sample Collection and Analysis

Observation wells were sampled by modifications of techniques described in Wood (1976). A centrifugal pump was used to flush wells thoroughly before sampling. Field properties and constituents (temperature, pH, specific conductance, dissolved oxygen, and redox potential) of the flushing water were measured until temperature, pH, and specific conductance stabilized. Samples were then taken with a peristaltic pump that minimized contamination, aeration, and degassing of the sample because no pump parts contacted the sampled water. Samples were pressure filtered through 0.45-μ membranes, collected in sample containers, and preserved by procedures described in Skougstad and others (1979). Dissolved-organic-carbon samples were collected by the technique described in Malcolm and Leenheer (1973). Alkalinities were determined by electrometric titration in the field.

Samples were analyzed by the Geological Survey Central Laboratory, Doraville, Ga., by procedures described in Skougstad and others (1979) and Goerlitz and Brown (1972). Samples were analyzed for the constituents and properties listed in table 3.

Table 3.--Water-quality constituents and properties determined in analysis of ground-water samples

Major constituents and properties	Minor constituents	Nutrients	Miscellaneous
Calcium	Iron	Ammonia	Dissolved solids
Magnesium	Manganese	Nitrite	Dissolved organic carbon
Sodium	Aluminum	Nitrate	
Potassium		Organic nitrogen	
Alkalinity		Orthophosphate	
Fluoride			
Chloride			
Sulfate			
Silica			

Statistics

Water-quality data were interpreted by parametric statistics. A basic assumption in the use of these statistics is that the data are normally distributed. The data distributions were tested for normality and were transformed where necessary to improve their normality, by the following equation:

$$Y = \ln (x + 1)$$

where

Y is the transformed value,

x the untransformed value,

and

ln the natural logarithm, base e.

The digit 1 was added to all values in the transformation because the natural log of zero cannot be computed. Standard measures of central tendency (mean and median), dispersion (standard deviation and coefficient of variation), and range (minimum and maximum) were calculated for all constituents and properties. Means calculated from natural log-transformed values approximated the geometric mean. Seasonal averages for all wells and areal averages for selected well groups were calculated for all constituents and properties. A student's t-test was used to determine the significance of differences between seasonal and areal means. Additionally, correlations between redox potentials and concentrations of iron, manganese, and dissolved oxygen were calculated. A computer software package called SAS or Statistical Analysis System (SAS Institute, Inc., 1979) was used in all the statistical calculations.

Results

Chemical Quality of Ground Water

Chemical analyses of the ground-water samples collected in this study are given in table 10. A statistical summary that includes means, ranges, and coefficients of variation for these data is presented in table 4. The coefficients of variation indicate that the means calculated for many of the constituents have a low variability. The coefficient of variation for some constituents and properties exceeded 50 percent, probably because the concentration or measurement of the parameter was at or below the detection limit of the analytical procedure used.

Table 4.--Statistical summary of chemical quality of ground-water samples, 1979-80

[All units of measure in milligrams per liter, except pH or as indicated; --, not determined; C, Celsius; mV, millivolt; N, nitrogen; P, phosphorus]

Constituents and properties	Number of analyses	Mean	Coefficient of variation (percent)	Minimum	Maximum
Temperature (°C)	97	[a]13.4	14	7.5	20.3
pH	97	[b]7.1	---	6.0	8.1
Specific conductance (μmho/cm at 25° C)	97	570	4	340	915
Dissolved oxygen	97	[a]2.2	59	<0.05	9.5
Redox potential (mV)	76	[a]+347	39	-190	+535
Hardness (as $CaCO_3$)	42	[a]280	18	170	410
Hardness, noncarbonate (as $CaCO_3$)	42	[a]38	83	0	130
Dissolved solids[c]	42	[a]366	19	250	524
Silica	42	11	12	4	20
Alkalinity (as $CaCO_3$)	97	240	4	160	400
Chloride	42	13	21	3.1	43
Fluoride	42	0.1	32	0.1	0.2
Sulfate	42	[a]32	38	0.6	63
Calcium	42	75	4	49	120
Magnesium	42	[a]22	16	14	27
Sodium	42	6.2	24	2.9	26
Potassium	42	1.1	34	0.4	3.7
Iron	97	0.03	56	<0.005	6.5
Manganese	97	0.050	45	<0.0005	0.81
Aluminum	42	0.02	27	<0.005	0.10
Dissolved organic carbon	42	2.9	44	0.5	10
Ammonia as N	42	0.07	251	<0.005	1.2
Nitrite as N	42	0.01	147	<0.005	0.11
Nitrate as N	42	2.6	65	<0.005	24
Organic nitrogen as N	42	0.04	118	<0.005	0.18
Orthophosphate as P	41	0.01	150	<0.005	0.10

[a] Arithmetic means, all others geometric means.
[b] Median.
[c] Residue on evaporation at 180° C.

Ground water has a near neutral pH (median, 7.1), high alkalinity [mean, 240 mg/L (milligrams per liter) as $CaCO_3$], very high hardness (mean, 280 mg/L as $CaCO_3$), and an oxidizing-redox environment [mean dissolved-oxygen concentration, 2.2 mg/L; and mean redox potential, +347 mV (millivolts)]. Mean dissolved-solids concentration and specific conductance were 366 mg/L and 570 μmho/cm at 25° C (micromho per centimeter at 25 degrees Celsius). In all samples, calcium and bicarbonate are the dominant cation-anion pair.

Concentrations of the major ions at the 21 sites sampled in both the spring and autumn of 1980 are plotted in figure 25. Most of the analyses are clustered on all three parts of the trilinear plot (Piper, 1944). This demonstrates that most of the samples have a similar water type and, consequently, that the general water quality does not vary much in the study area. Cable and others (1971), in a study of the water resources of the entire upper White River basin, and Shampine, in Meyer and others (1975), in a study of the outwash in Marion County, obtained water-quality results similar to those in the current study. Freeze and Cherry (1979, p. 284) noted that these general water-quality characteristics are typical of ground water flowing through calcareous glacial outwash in the Midwest.

Ground-Water Quality and Drinking-Water Standards

If water is to be used for a municipally treated drinking-water supply, the concentrations of certain dissolved constituents must not exceed specified limits. These limits are given in the National Interim Primary Drinking Water Regulations (NIPDWR) and the National Secondary Drinking Water Regulations (NSDWR) of the U.S. Environmental Protection Agency (1975 and 1979). (Recommended limits discussed in the rest of this section pertain to these two references). The limits for selected inorganic chemicals are given in table 5. The NIPDWR limits define the concentrations of toxic inorganic constituents that might adversely affect public health. The NSDWR limits are concentrations of additional inorganic chemicals that might affect the esthetic quality (taste, color, or odor) of drinking water.

Of the water-quality constituents determined, only two, fluoride and nitrate, have NIPDWR limits. The mean concentration of fluoride was 0.1 mg/L, and the maximum was 0.2 mg/L. The mean concentration of nitrate was 2.6 mg/L (as nitrogen). The recommended 10-mg/L limit for this constituent, was exceeded in three water samples taken from wells MOR-52 (24 mg/L), OWN-1 (13 mg/L), and MOR-48 (12 mg/L) in October 1980. Water from these wells, previously sampled in May 1980, had low nitrate concentrations at that time. The high nitrate concentrations in October were apparently due to the proximity of these wells to farm fields fertilized after autumn harvest or to lower recharge in autumn, which does not dilute the nitrate concentrations as much as higher spring recharge.

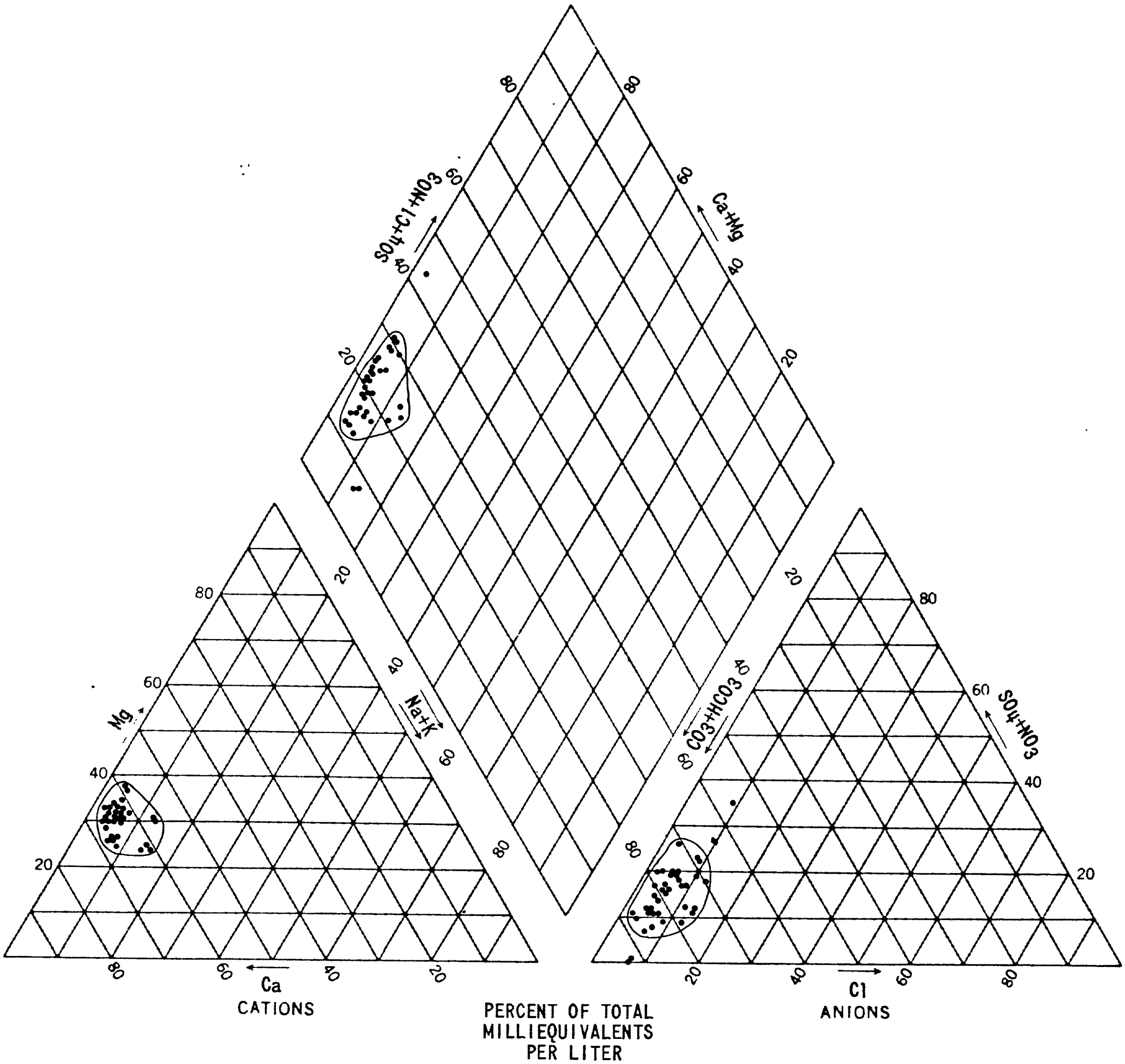


Figure 25.-- Trilinear diagram representing analysis of water samples collected in May and October 1980.

Table 5.--Drinking-water standards for selected properties of water and inorganic constituents dissolved in water

[Source, U.S. Environmental Protection Agency (1975 and 1979), Primary and Secondary Regulations]

National Interim Primary Drinking-Water Regulations		National Secondary Drinking-Water Regulations	
Constituent	Concentration (mg/L)	Constituent or property	Concentration (mg/L)
Arsenic	0.05	Chloride	250
Barium	1.0	Copper	1.0
Cadmium	.010	Iron	.3
Chromium	.05	Manganese	.05
Fluoride	[a]1.4-2.4	pH[b]	[c]6.5-8.5
Lead	.05	Sulfate	250
Mercury	.002	Dissolved solids[e]	500
Nitrate	[d]10	Zinc	5
Selenium	.01		
Silver	.05		

[a]Concentration is temperature dependent.
[b]Negative logarithm of the hydrogen ion concentration.
[c]Not milligrams per liter.
[d]As nitrogen.
[e]Residue on evaporation at 180° C.

Of the constituents and properties having NSDWR limits, only pH and concentrations of chloride, sulfate, iron, manganese, and dissolved solids were determined. Concentrations of chloride and sulfate were less than their respective 250-mg/L recommended limits in all the samples analyzed. In two samples, pH was less than the 6.5 to 8.5 recommended range. In January 1980, pH at MOR-40 was 6.3 and at MOR-36 pH was 6.0. Neither well has been sampled again, so these results have not been confirmed.

Dissolved-solids concentration exceeded the 500-mg/L recommended limit only at MOR-24 (524 mg/L) in October 1980. The dissolved-solids concentration at this site in May 1980, 489 mg/L, indicates that the high concentration was not an anomaly. Runoff containing road salt from State Highway 67 adjacent to MOR-24 is probably the source of these high dissolved-solids concentrations because the water samples having the highest sodium and chloride concentrations measured in the study were from this well.

Iron and manganese concentrations exceeded recommended limits in 15 and 49 percent of all analyses. The wells from which these high-concentration samples were obtained were in all parts of the study area. Cable and others (1971) noted high iron and manganese concentrations in the ground water of the upper White River basin. Therefore, treatment for these two metals may be necessary if municipal ground-water supplies are developed.

The explanation for the frequency of the high concentrations of iron and manganese is apparently a wide distribution of iron and manganese minerals in the outwash. Because both metals readily participate in redox reactions, their high concentrations are most often linked to dissolved-oxygen depletion and reducing redox environments in ground-water systems (Stumm and Morgan, 1970, p. 545). The correlations in table 6 are indicative of these conditions. Correlations of iron and manganese with both the dissolved-oxygen concentrations and the redox potentials were found to be negative at the 0.0001 significance level. Thus, where iron and manganese concentrations were high, the dissolved-oxygen concentration and the redox potential of the sample were usually low.

Hem (1970, p. 130) stated that ground water having manganese concentrations that exceed iron concentrations is unusual. Manganese concentrations were greater than or equal to iron concentrations in 59 percent of all samples analyzed in Johnson and Morgan Counties. The differential solubility of iron and manganese compounds at the redox conditions in the ground-water system may be one possible explanation for this finding. Manganese compounds dissolve more readily than iron compounds as the redox environment changes from oxidizing to reducing. Apparently, the redox environment in many of the samples was reducing enough to cause a high concentration of dissolved manganese but not reducing enough to dissolve most of the iron minerals.

Table 6.--Correlation of iron and manganese concentrations with dissolved-oxygen concentrations and redox potentials

[N, number of observations; r, correlation coefficient; P, significance level of correlation]

Correlated pairs	N	r	P
Iron and redox potential	76	-0.79	0.0001
Iron and dissolved oxygen	97	-.45	.0001
Manganese and redox potential	76	-.52	.0001
Manganese and dissolved oxygen	97	-.57	.0001

Although limits are mandated for several organic compounds in drinking water, no limit is given for the concentration of dissolved organic carbon. However, Leenheer and others (1974) have cited an average dissolved-organic-carbon concentration of 5 mg/L as the threshold for organic contamination of ground water. The average concentration measured in samples for this study was 2.9 mg/L, but at four sites the average concentrations were greater than 5 mg/L: JON-5 (7.9 mg/L), MOR-26 (7.9 mg/L), JON-2 (6.2 mg/L), and MOR-24 (5.6 mg/L). Runoff and infiltration from nearby farm fields, residential septic systems, and urban drainage are probably the causes for these high dissolved-organic-carbon concentrations.

Ammonia nitrogen is another constituent that does not have a mandated standard. However, the National Academy of Sciences and National Academy of Engineering (1972) have recommended that ammonia nitrogen concentrations in water-supply sources not exceed 0.5 mg/L. Ammonia nitrogen concentration of water from well MOR-44 exceeded this limit in two different samplings. High concentrations of this constituent are most frequently associated with landfill leachate or septic-system effluent. However, none of these sources were at or near well MOR-44, so the cause of the elevated ammonia nitrogen concentrations is not known.

Ground-Water and White River Water Quality

The White River is sampled monthly at three sites by the Indiana State Board of Health: (1) near Centerton at Henderson Ford bridge, (2) near Centerton at the Indianapolis Power and Light Company generating station, and (3) at Paragon. (See fig. 24 for site locations.) The annual mean measurements of properties and concentrations of dissolved constituents of surface water at the three sites for 1980 are shown in table 7, (Indiana State Board of Health, 1981, p. 113-115). Only parameters measured by both the ISBH and for this study are included. Mean concentrations for corresponding ground-water properties and constituents (median of pH) from table 4 are included for comparison.

Specific conductance, and concentrations of dissolved oxygen, chloride, sulfate, sodium, and potassium are significantly higher in the White River than in the ground water. The higher dissolved-oxygen concentrations are caused by diffusion of atmospheric oxygen into the surface water at the air-water interface, reaeration by turbulent flow, and oxygen-producing plants and algae in the river. The higher specific conductance of the river is due to its higher concentrations of chloride, sulfate, sodium, and potassium. Shampine (1975), in a study of the water quality of the upper White River, found that concentrations of chloride, sulfate, and sodium are increased greatly by runoff from urban areas and effluent from wastewater-treatment plants. Although no specific analyses of runoff or effluent for major dissolved ions are available for the current study area, analyses of water samples in the White River immediately upstream and downstream from the Indianapolis wastewater-treatment facility in

Table 7.--Ground-water and surface-water quality, Johnson and Morgan Counties, 1980

[Measurements in milligrams per liter except pH or as otherwise noted; --, not determined; IPALCO, Indianapolis Power and Light Co.]

Site	N[a]	Temp. (°C)	pH	Dis-solved oxygen	Specific conductance (µmho/cm at 25° C)	Alkalinity (as $CaCO_3$)	Hardness	Sodium	Potassium	Chloride	Sulfate
Annual mean data, 1980 (Indiana State Board of Health, 1981)											
White River at Centerton, Henderson Ford bridge (River mile 202.6)	12	15	[b]7.4	7.1	857	244	318	----	---	64	75
White River at Centerton IPALCO generating station (River mile 199.3)	12	15	[b]7.4	7.8	827	242	316	----	---	61	73
White River at Paragon (River mile 181.5)	12	15	[b]7.5	8.5	778	233	305	36	4.2	56	68
Mean data for USGS observation wells, from table 4											
		13.4	[b]7.1	2.2	570	240	280	6.2	1.1	13	32

[a] Number of analyses.
[b] Median.

October 1981 showed that specific conductance increased from approximately 600 µmho/cm at 25° C upstream to more than 900 µmho/cm at 25° C downstream (U.S. Geological Survey, unpublished data, 1982). Thus, concentrations of the major dissolved constituents of the White River are probably also increased by runoff from the Indianapolis area and by effluents from wastewater-treatment plants in Indianapolis and Martinsville. However, even with the increased concentrations the surface water remains a calcium and magnesium bicarbonate type similar to the ground water.

Alkalinity, chloride, and sulfate concentrations of the White River, as well as specific conductance and hardness of the river, decrease with distance downstream from Centerton to Paragon. Although the decreases in concentrations of a few constituents are very small, they indicate that the river is being diluted. Dilution by ground water, which has a lower concentration of most constituents than the White River has, is possible because the river is gaining ground water within the study area. Tributaries or other runoff having low dissolved-solids concentrations could also dilute the river. This theory is supported by analyses of water samples collected from the tributaries in October 1981. Specific conductance averaged only 300-400 µmho/cm then (U.S. Geological Survey, unpublished data, 1982).

Variation in Water Quality

Seasonal variations were investigated statistically by comparing the water-quality results obtained in spring with those obtained in autumn. Areal variations were examined by statistically testing and mapping the data from two groups of wells influenced by either of two types of aquifer boundary materials, till or bedrock.

The statistical comparisons were done by the t-test. (See section "Statistics.") The result of the t-test is a probability that the means compared are from the same population. Consequently, low probabilities indicate that the means are significantly different. In this study a probability of less than 0.05, a significance level of 95 percent or greater, was used as the limit in determining significant differences.

Seasonal Variations.--The seasonal means of only two measurements, temperature and dissolved organic carbon, differed significantly. These means are presented in table 8.

Although the difference between seasonal mean temperatures is less than 1° C, the ground-water temperatures in spring were consistently lower than those in autumn. The ambient air temperature was also lower in spring than in autumn, and the shallow aquifer was affected by and reflected this same trend.

Table 8.--Mean temperatures and mean dissolved-organic-carbon concentrations for spring and autumn, 1979-80

Constituent	Units of measure	Spring			Autumn			P^b
		Number of analyses	Mean	C.V.[a] (percent)	Number of analyses	Mean	C.V.[a] (percent)	
Temperature	°C	21	12.7	10	76	13.6	15	0.0155
Dissolved organic carbon	mg/L	21	[c]4.0	33	21	[c]2.1	53	.0084

[a]Coefficient of variation.
[b]Significance level of the t-test.
[c]Geometric mean.

The mean concentration of dissolved organic carbon in spring was almost twice that in autumn (table 8). Infiltrating melt water may be a source of organic compounds to the ground-water system in spring. Decaying fallen branches, leaves, and crop remnants produced in autumn and winter may accumulate and enter the hydrologic system only when discharge and ground-water levels are high during the spring melt.

Areal Variations.--Areal variations in ground-water quality most often result from the influence of different hydrologic units, geologic formations, or land-use activities. However, all wells sampled were screened in one homogenous hydrologic and geologic unit, the outwash aquifer, and nearly all wells were in areas where land use is mainly agricultural. The only areal difference identified was that the outwash aquifer was bounded by two types of geologic materials in different parts of the study area. Till, interbedded with lenses of outwash, bounds the aquifer in the north, whereas bedrock, in some areas capped by thin till, bounds the rest of the aquifer (figs. 3, 5, and 6). Concentrations of water-quality constituents from wells in the areas affected by these two types of boundary materials were grouped and then were compared statistically. Those concentrations that differed statistically were also mapped.

Mean concentrations of only two constituents, dissolved organic carbon and manganese, differed significantly in the till-bounded and bedrock-bounded areas (table 9). The areal distribution of the mean concentrations of the two constituents are shown in figures 26 and 27. Locations of wells where mean concentrations of the two constituents exceeded drinking-water limits are shown in bold-faced type.

Table 9.--Mean concentrations of dissolved organic carbon and manganese in areas having till and bedrock boundaries, 1979-80

Constituent	Units of measure	Till			Bedrock			P[c]
		Number of analyses	Mean[a]	C.V.[b] (percent)	Number of analyses	Mean[a]	C.V.[b] (percent)	
Manganese	mg/L	20	0.130	20	77	0.035	50	0.0001
Dissolved organic carbon	mg/L	10	5.5	27	32	2.3	45	.0013

[a]Geometric mean.
[b]Coefficient of variation.
[c]Significance level of the t-test.

Well water whose mean manganese concentration exceeded the 0.05-mg/L limit is widely distributed throughout the study area (fig. 26). However, a higher percentage of the till-bounded wells (70 percent) than of the bedrock-bounded wells (42 percent) contained water that exceeded the limit. Mean manganese concentrations of water in the till-bounded wells were 3.7 times those in the bedrock-bounded wells (table 9). These higher manganese concentrations may be due to a higher manganese content in the till than in the bedrock. The till is younger and less weathered than the bedrock. Clays that make up the till have excellent sorption and substitution sites for metals such as manganese (Hem, 1970, p. 147). Unfortunately, no analysis of the composition of the till is available (Ned K. Bleuer, Indiana Geological Survey, oral commun., 1982). Another potential explanation is the greater permeability of the till compared with that of the bedrock. The more permeable till allows some water to percolate to the outwash aquifer. The water may dissolve manganese from the till and transport it to the outwash. Percolation and dissolution would not be as likely in the virtually impermeable bedrock.

Three of the four wells whose water had average dissolved-organic-carbon concentrations greater than 5 mg/L, the threshold that Leenheer and others (1974) suggested to indicate ground-water contamination, are in the till-bounded area (fig. 27). The mean dissolved-organic-carbon concentration of water in the till-bounded wells was 2.4 times that in the bedrock-bounded wells. The reason that dissolved-organic-carbon concentrations of water are higher in the till-bounded wells than in the bedrock-bounded wells may be that organic deposits associated with the till are being leached out into the outwash.

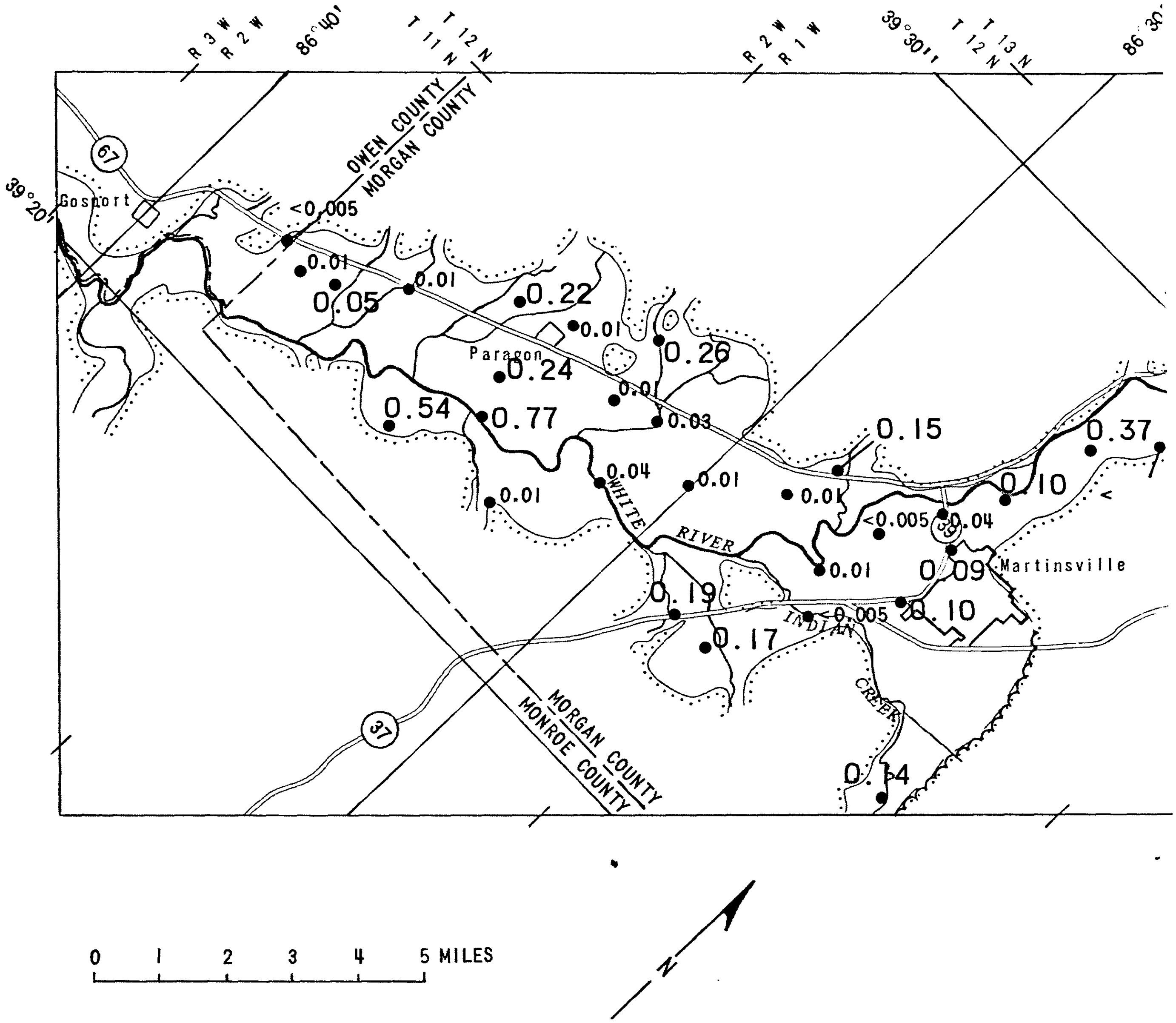
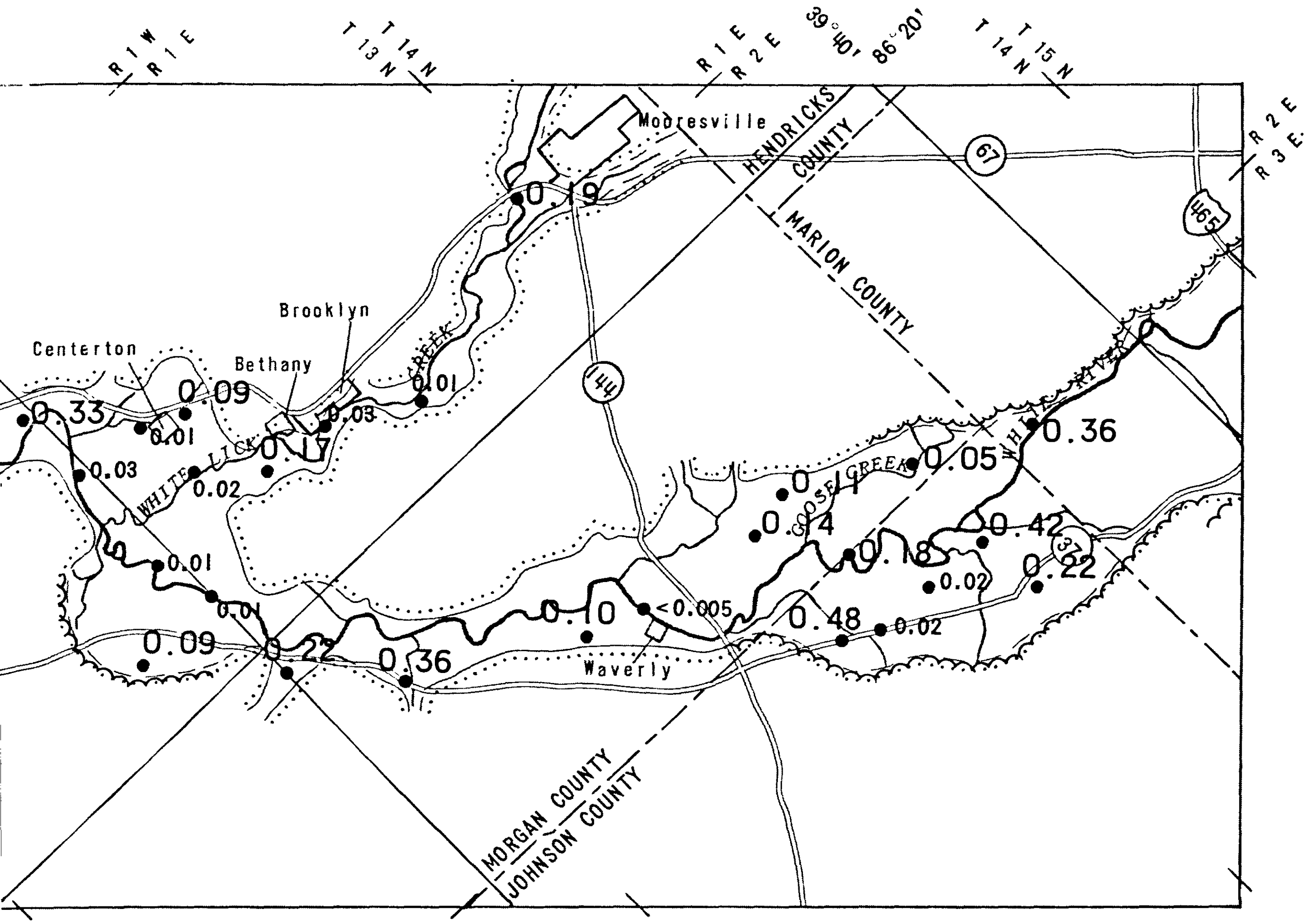


Figure 26.-- Manganese concentrations in the outwash.



EXPLANATION

●	Well-site
0.01	Mean manganese concentration less than 0.05 milligram per liter
0.48	Mean manganese concentration greater than or equal to 0.05 milligram per liter
········	Outwash bounded by bedrock
⌒⌒⌒	Outwash bounded by till

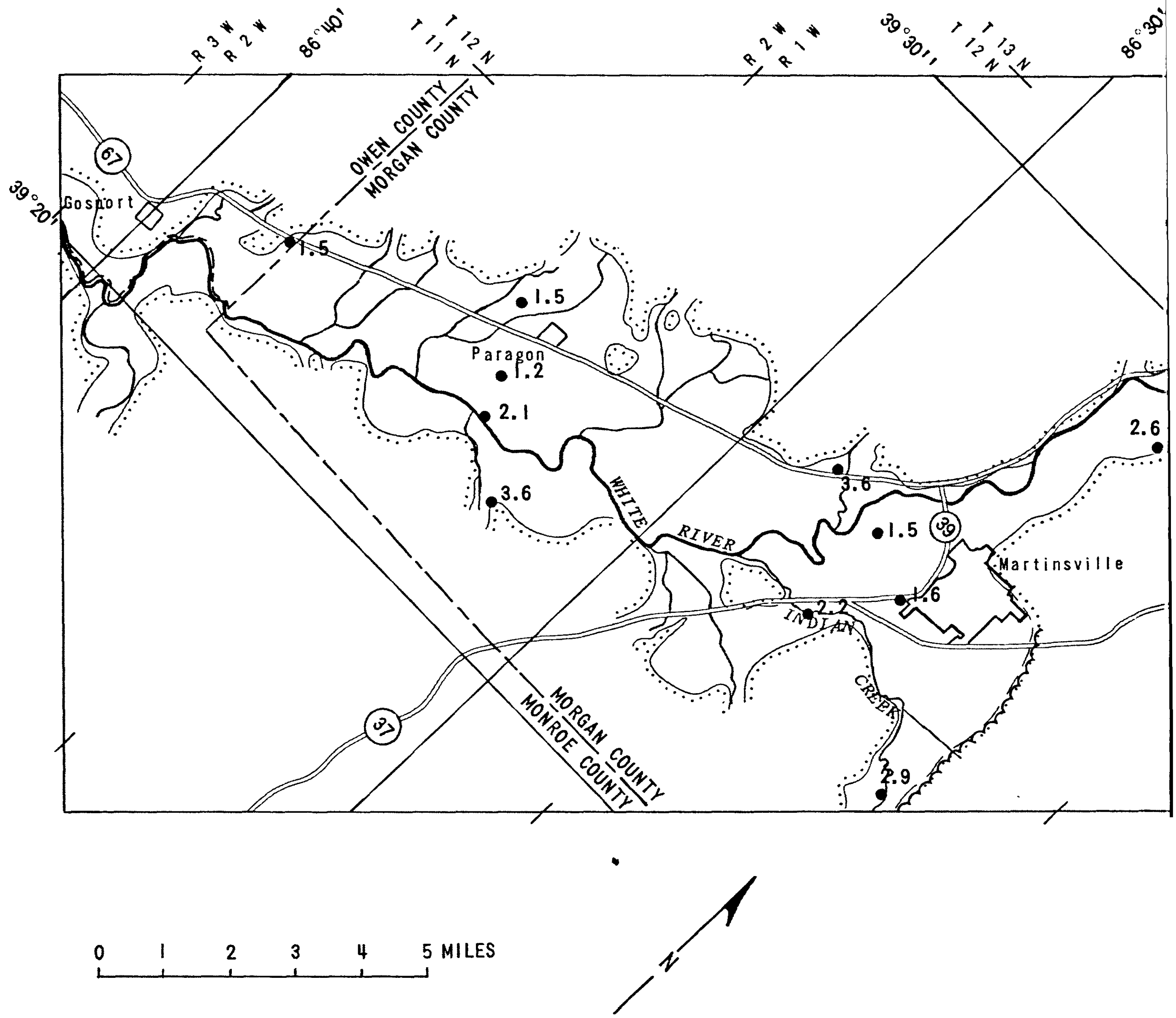
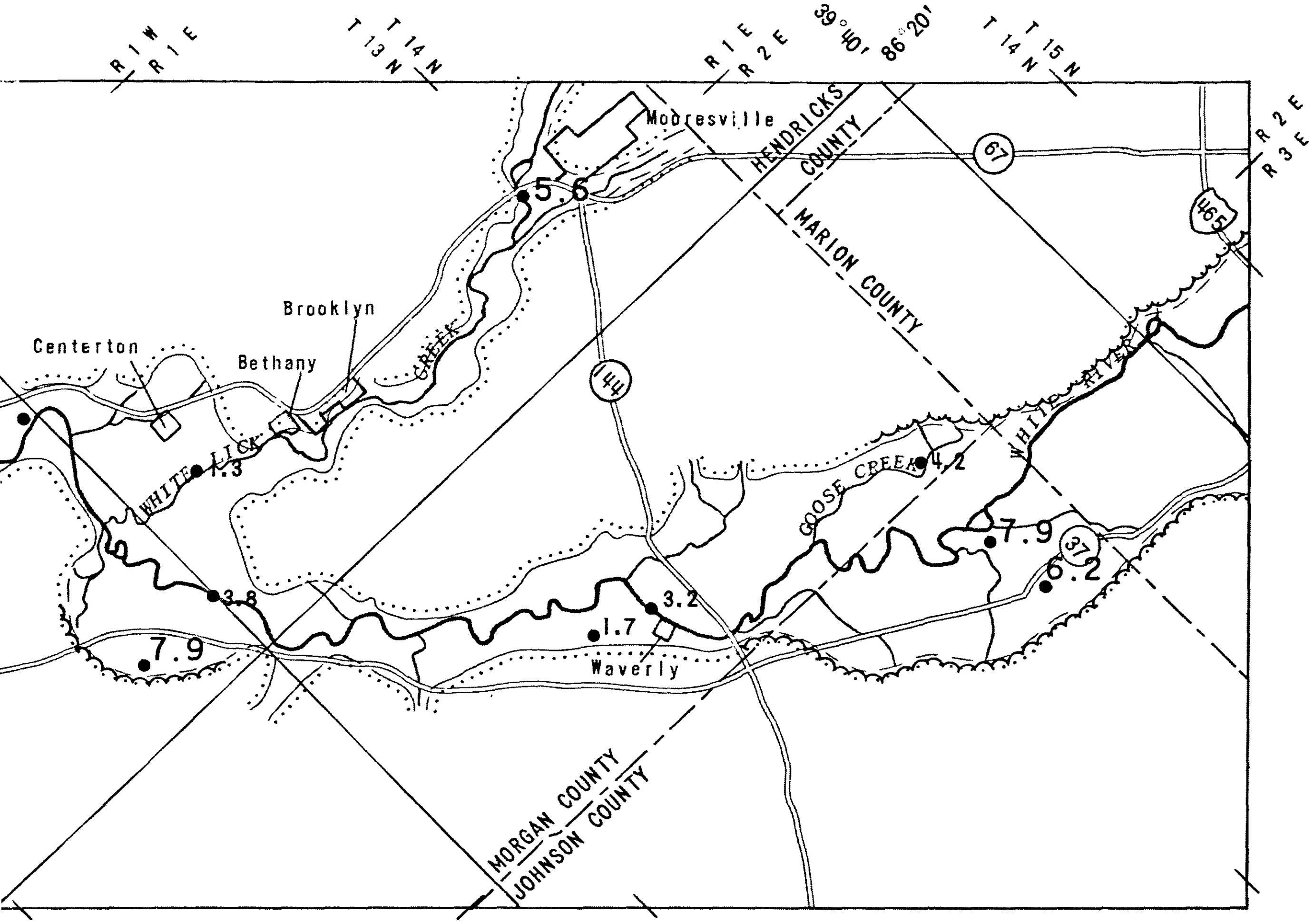


Figure 27.-- Dissolved-organic-carbon concentrations in the outwash.



EXPLANATION

●	Well-site
3.6	Mean dissolved-organic-carbon concentration less than 5.0 milligrams per liter
7.9	Mean dissolved-organic-carbon concentration greater than 5.0 milligrams per liter
········	Outwash bounded by bedrock
⌄⌄⌄⌄	Outwash bounded by till

SUMMARY AND CONCLUSIONS

The unconfined glacial outwash along the White River in Johnson and Morgan Counties consists of saturated sand and gravel as thick as 120 ft in a bedrock valley. Average hydraulic conductivity of the outwash is 340 ft/d, and the general range in tranmissivity is from 5,000 to 35,000 ft^2/d. Most of the recharge to the outwash is from precipitation. Small tributaries, draining surrounding bedrock and till uplands, also recharge the aquifer as they cross the outwash. Most of the aquifer is bounded by bedrock that contributes virtually no other recharge to the system. Some recharge enters the outwash through areas where till interbeds with thinning outwash. The White River and its large tributaries, White Lick and Indian Creeks, gain water from the ground-water system so that inflow and outflow to the ground-water system is generally balanced.

The potential for ground-water development and the effects of development on water levels in the aquifer and on flow in the White River were assessed by simulating the potential stress on the system in a digital ground-water-flow model. The effects of concentrated stress were analyzed by simulating a 20-Mgal/d well field. Overall potential of the aquifer was assessed by simulating two general pumping plans, one pumping 66 Mgal/d and reducing streamflow by 15 percent and another pumping 122 Mgal/d and reducing streamflow by 30 percent. Drawdowns in the 12-in. diameter simulated wells were generally 30 percent or less of saturated thickness. Worst-case pumping simulations produce water-level declines of less than 25 ft.

The ground-water quality is generally uniform and typical of water flowing through calcareous glacial deposits. Characteristics of the water include slightly basic pH (median, 7.1), high alkalinity (mean, 240 mg/L as $CaCO_3$), very high hardness (mean, 280 mg/L as $CaCO_3$), an oxidizing redox environment (mean dissolved-oxygen concentration, 2.2 mg/L; mean redox potential, +347 mV), moderate dissolved-solids concentrations (mean, 366 mg/L), and a calcium bicarbonate water type. The National Interim Primary Drinking Water Regulations limit for nitrate was exceeded in 3 of 42 samples. National Secondary Drinking Water Regulations limits for iron and manganese were exceeded in 15 and 49 percent of 97 analyses. The White River has significantly higher specific conductance and concentrations of dissolved oxygen, chloride, sulfate, sodium, and potassium than the ground water.

Seasonal variations in water quality were statistically significant only for temperature and concentration of dissolved organic carbon. Temperature was lower in spring than in autumn, but dissolved-organic-carbon concentration was lower in autumn than in spring. Mean concentrations of only two constituents, dissolved organic carbon and manganese, differed significantly in the till-bounded and bedrock-bounded areas. Mean concentrations of these constituents were higher in till-bounded than in bedrock-bounded areas.

Mapping the aquifer and studying the ground-water flow system by a digital model indicates that the outwash aquifer has considerable potential for development. Because most of the area has virtually impermeable boundaries, ground-water development will deplete the remaining flow in nearby small tributaries and will reduce seepage to the White River. Even in areas where some water enters the outwash through sand or till and interbedded outwash boundaries, pumping will not induce much more water from these areas. Ground-water quality is generally uniform, and treatment of iron and manganese will probably be necessary if municipal supplies are developed.

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Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan and Owen Counties, Ind.

[Well--JON, Johnson; MAR, Marion; MOR, Morgan; and OWN, Owen, Counties; latitude (north) and longitude (west) in degrees, minutes, and seconds; all units of measure in milligrams per liter, except for pH or as indicated; C, Celsius; mV, millivolts; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; --, not determined]

Well	Latitude	Longitude	Date	Depth of well (ft)	Temperature (°C)	pH	Specific conductance[a]	Dissolved oxygen	Redox potential	Hardness	Hardness, noncarbonate (as $CaCO_3$)	Dissolved solids[b]	Silica
MAR-0	393828	861422	10-23-79	24	12.5	7.4	625	0.2	175	---	--	---	----
JON-2	393712	861232	10-23-79	31	11.1	7.5	609	.6	228	---	--	---	----
			5-20-80	31	13.1	7.1	611	.6	241	320	36	385	12
			10-3-80	31	12.1	7.1	608	<.05	----	300	48	378	13
JON-4	393616	861345	10-24-79	35	12.1	7.5	528	4.9	360	---	--	---	----
JON-5	393709	861339	10-23-79	24	13.1	7.3	730	3.0	355	---	--	---	----
			5-20-80	24	11.0	7.0	733	3.3	401	360	29	463	9.4
			10-3-80	24	12.5	7.0	707	<.05	----	330	56	437	9.6
JON-6	393528	861343	10-24-79	24	12.8	7.5	568	2.0	368	---	--	---	----
JON-7	393502	861405	10-25-79	24	12.9	6.8	641	.3	267	---	--	---	----
JON-8	393549	861457	10-25-79	24	13.4	7.2	693	.6	281	---	--	---	----
MOR-1	393708	861518	10-25-79	24	13.1	7.2	575	7.6	384	---	--	---	----
			5-19-80	24	11.0	7.4	623	6.8	458	310	40	382	8.2
			10-3-80	24	12.3	7.1	647	6.6	----	300	45	390	9.0
MOR-3	393548	861626	1-8-80	33	12.0	7.0	380	4.8	460	---	--	---	----
MOR-5	393514	861610	10-26-79	35	12.6	7.0	672	2.1	335	---	--	---	----
MOR-9	393339	861633	10-26-79	24	20.3	7.3	460	.3	285	---	--	---	----
			5-19-80	24	12.0	7.6	496	9.4	451	250	40	294	4.0
			10-3-80	24	16.0	7.2	469	<.05	----	230	38	272	5.0
MOR-11	393256	861650	1-8-80	21	12.0	7.0	810	9.5	370	---	--	---	----
			5-19-80	21	10.2	7.3	713	5.8	440	320	21	439	9.1
			10-10-80	21	15.8	7.3	771	2.1	----	320	4	462	10
MOR-15	393100	861813	1-9-80	32	7.5	7.0	340	2.0	340	---	--	---	----
MOR-18	392947	862213	10-31-79	24	16.4	7.1	638	3.9	496	---	--	---	----
MOR-19	393002	862120	10-31-79	24	15.0	7.3	489	5.2	455	---	--	---	----
			5-16-80	24	11.3	7.0	623	4.8	450	290	24	361	7.8
			10-7-80	24	15.7	7.1	624	6.8	----	290	15	376	8.5
MOR-20	393134	862256	1-9-80	24	12.4	6.9	670	6.2	330	---	--	---	----
MOR-21	393227	862155	10-30-79	24	14.9	7.3	495	6.2	467	---	--	---	----
MOR-22	393331	862109	10-30-79	24	16.4	7.0	655	3.2	464	---	--	---	----
MOR-24	393601	862229	10-30-79	24	13.8	7.1	830	1.5	216	---	--	---	----
			5-16-80	24	12.7	6.6	915	.6	245	410	11	489	10
			10-2-80	24	16.5	7.2	875	<.05	----	350	5	524	9.7
MOR-25	393001	861938	1-9-80	56	10.6	7.4	480	.5	-190	---	--	---	----
MOR-26	392848	862112	10-31-79	24	15.5	7.4	341	3.4	493	---	--	---	----
			5-15-80	24	13.0	7.3	395	2.8	435	220	33	250	13
			10-7-80	24	16.0	7.5	408	4.6	----	190	33	252	15
MOR-28	393052	862256	10-30-79	24	14.7	7.2	500	7.3	489	---	--	---	----
			5-15-80	24	12.5	7.1	568	3.9	467	270	28	350	7.2
			10-9-80	24	16.4	7.6	599	3.8	----	280	53	361	7.5
MOR-29	393117	862337	1-9-80	46	8.0	7.4	400	2.6	172	---	--	---	----
MOR-30	393047	862358	10-31-79	40	14.7	7.1	694	2.0	438	---	--	---	----
MOR-32	392953	862403	11-1-79	24	13.1	7.2	585	5.2	414	---	--	---	----
MOR-33	392958	862516	11-1-79	45	10.9	7.3	510	1.4	137	---	--	---	----
			5-15-80	45	12.5	7.0	641	.3	135	290	10	402	8.3
			10-10-80	45	11.1	7.1	574	<.05	----	260	0	347	8.0
MOR-35	392841	862506	10-31-79	45	14.7	7.4	484	4.4	474	---	--	---	----
			5-15-80	45	14.0	7.1	572	3.5	485	280	53	356	13
			10-10-80	45	14.4	7.3	545	3.2	----	250	50	333	13
MOR-36	392759	862554	1-10-80	26	11.9	6.0	890	.8	305	---	--	---	----
MOR-38	392644	862612	1-10-80	33	11.5	6.6	630	1.7	405	---	--	---	----
MOR-39	392543	862617	11-1-79	24	13.8	7.1	725	2.2	362	---	--	---	----
MOR-40	392655	862558	1-10-80	43	11.4	6.3	900	.6	305	---	--	---	----

Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan and Owen Counties, Ind.--Continued

Well	Latitude	Longitude	Date	Alkalinity (as $CaCO_3$)	Chloride	Fluoride	Sulfate	Calcium	Magnesium	Sodium	Potassium	Iron (µg/L)	Manganese (µg/L)
MOR-52	392340	862709	11-7-79	190	----	--	--	---	--	----	---	20	10
			5-14-80	213	22	0.1	27	85	26	3.7	1.3	<5	2
			10-9-80	186	22	.1	26	81	25	3.7	1.5	<5	<.5
MOR-54	392439	862901	11-12-79	216	----	--	--	---	--	----	---	10	10
MOR-55	392518	862843	1-11-80	180	----	--	--	---	--	----	---	210	180
			5-15-80	235	8.5	.1	26	66	20	4.8	1.7	40	130
			10-8-80	216	8.3	.1	27	61	20	4.6	1.9	70	140
MOR-56	392228	862758	11-8-79	231	----	--	--	---	--	----	---	20	170
MOR-57	392228	862845	11-8-79	298	----	--	--	---	--	----	---	2,700	190
MOR-59	392348	863010	11-12-79	226	----	--	--	---	--	----	---	20	10
MOR-61	392405	863129	11-9-79	196	----	--	--	---	--	----	---	20	30
MOR-62	392258	863117	11-12-79	234	----	--	--	---	--	----	---	20	40
MOR-64	392354	863208	11-9-79	176	----	--	--	---	--	----	---	<5	10
MOR-65	392456	863228	1-11-80	240	----	--	--	---	--	----	---	1,200	260
MOR-66	392416	863333	11-12-79	191	----	--	--	---	--	----	---	10	10
MOR-68	392355	863430	11-13-79	159	----	--	--	---	--	----	---	<5	240
			5-14-80	190	18	.2	30	64	20	5.5	.4	<5	220
			10-8-80	157	19	.2	27	53	17	6.5	.4	<5	210
MOR-69	392301	863351	11-9-79	223	----	--	--	---	--	----	---	890	320
			5-13-80	231	11	.1	36	71	20	4.9	1.3	1,000	170
			10-8-80	216	7.3	.1	38	63	19	4.0	1.5	1,000	240
MOR-70	392255	863557	11-13-79	164	----	--	--	---	--	----	---	<5	10
MOR-71	392218	863654	11-13-79	209	----	--	--	---	--	----	---	10	50
MOR-72	392204	863257	11-8-79	294	----	--	--	---	--	----	---	20	10
			5-13-80	380	22	.1	22	100	26	6.9	.5	10	8
			10-6-80	332	17	.1	20	88	25	10	.6	30	10
MOR-73	392228	863331	11-9-79	248	----	--	--	---	--	----	---	10	810
			5-13-80	272	12	.2	43	85	25	4.1	.7	<5	740
			10-8-80	242	12	.1	44	76	23	4.1	.9	<5	760
MOR-74	392128	863427	1-11-80	168	----	--	--	---	--	----	---	110	540
MOR-76	392204	863725	11-13-79	189	----	--	--	---	--	----	---	20	10
OWN-1	392213	863759	11-13-79	228	----	--	--	---	--	----	---	20	10
			5-13-80	206	3.1	.1	16	59	17	3.6	.8	<5	2
			10-8-80	193	5.2	.1	22	64	19	3.5	1.0	<5	1

Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan and Owen Counties, Ind.--Continued

Well	Latitude	Longitude	Date	Alkalinity (as $CaCO_3$)	Chloride	Fluoride	Sulfate	Calcium	Magnesium	Sodium	Potassium	Iron (µg/L)	Manganese (µg/L)
MAR-0	393828	861422	10-23-79	253	----	---	----	---	--	----	---	1,400	360
JON-2	393712	861232	10-23-79	261	----	---	----	---	--	----	---	190	310
			5-20-80	284	6.7	0.2	61	84	26	5.0	1.0	120	180
			10-3-80	252	7.3	.2	63	77	25	5.5	1.3	40	180
JON-4	393616	861345	10-24-79	243	----	---	----	---	--	----	---	20	20
JON-5	393709	861339	10-23-79	329	----	---	----	---	--	----	---	20	410
			5-20-80	331	15	.1	48	100	27	4.2	1.0	10	400
			10-3-80	274	16	.1	51	89	25	4.2	1.3	<5	450
JON-6	393528	861343	10-24-79	251	----	---	----	---	--	----	---	<5	20
JON-7	393502	861405	10-25-79	286	----	---	----	---	--	----	---	60	480
JON-8	393549	861457	10-25-79	289	----	---	----	---	--	----	---	30	180
MOR-1	393708	861518	10-25-79	254	----	---	----	---	--	----	---	40	60
			5-19-80	270	15	.1	33	85	24	4.3	1.3	<5	40
			10-3-80	255	15	.1	39	82	24	5.7	2.1	<5	40
MOR-3	393548	861626	1-8-80	262	----	---	----	---	--	----	---	60	110
MOR-5	393514	861610	10-26-79	300	----	---	----	---	--	----	---	<5	140
MOR-9	393339	861633	10-26-79	198	----	---	----	---	--	----	---	10	10
			5-19-80	210	10	.1	38	62	24	2.9	1.0	10	8
			10-3-80	192	9.7	.1	37	56	21	3.4	1.4	30	1
MOR-11	393256	861650	1-8-80	269	----	---	----	---	--	----	---	20	30
			5-19-80	299	36	.1	33	84	27	21	2.3	<5	1
			10-10-80	316	33	.1	34	82	27	18	3.7	20	5
MOR-15	393100	861813	1-9-80	218	----	---	----	---	--	----	---	40	360
MOR-18	392947	862213	10-31-79	271	----	---	----	---	--	----	---	<5	10
MOR-19	393002	862120	10-31-79	248	----	---	----	---	--	----	---	10	10
			5-16-80	266	11	.1	22	79	22	5.9	1.0	<5	2
			10-7-80	275	12	.1	25	80	22	5.7	1.7	110	6
MOR-20	393134	862256	1-9-80	294	----	---	----	---	--	----	---	410	170
MOR-21	393227	862155	10-30-79	231	----	---	----	---	--	----	---	10	30
MOR-22	393331	862109	10-30-79	294	----	---	----	---	--	----	---	10	10
MOR-24	393601	862229	10-30-79	335	----	---	----	---	--	----	---	150	170
			5-16-80	399	31	.1	38	120	27	17	1.2	210	190
			10-2-80	345	43	.1	42	100	24	26	1.5	220	220
MOR-25	393001	861938	1-9-80	242	----	---	----	---	--	----	---	1,400	220
MOR-26	392848	862112	10-31-79	162	----	---	----	---	--	----	---	<5	140
			5-15-80	187	3.5	.2	24	55	19	3.8	.6	<5	50
			10-7-80	157	4.6	.1	22	49	17	3.6	.7	<5	90
MOR-28	393052	862256	10-30-79	216	----	---	----	---	--	----	---	10	10
			5-15-80	242	12	.2	26	77	18	6.7	1.3	<5	30
			10-9-80	227	20	.2	33	79	19	6.9	1.7	<5	20
MOR-29	393117	862337	1-9-80	216	----	---	----	---	--	----	---	80	90
MOR-30	393047	862358	10-31-79	302	----	---	----	---	--	----	---	20	10
MOR-32	392953	862403	11-1-79	259	----	---	----	---	--	----	---	20	30
MOR-33	392958	862516	11-1-79	270	----	---	----	---	--	----	---	2,700	330
			5-15-80	280	16	.1	38	85	20	8.7	2.0	2,800	330
			10-10-80	266	13	.1	36	74	18	8.1	2.3	2,700	340
MOR-35	392841	862506	10-31-79	207	----	---	----	---	--	----	---	20	10
			5-15-80	227	18	.1	34	74	22	6.6	.8	<5	<.5
			10-10-80	200	20	.1	35	68	20	5.9	1.0	<5	2
MOR-36	392759	862554	1-10-80	351	----	---	----	---	--	----	---	110	370
MOR-38	392644	862612	1-10-80	202	----	---	----	---	--	----	---	70	100
MOR-39	392543	862617	11-1-79	344	----	---	----	---	--	----	---	20	70
MOR-40	392655	862558	1-10-80	318	----	---	----	---	--	----	---	70	40
MOR-44	392244	862403	11-1-79	264	----	---	----	---	--	----	---	6,500	170
			5-14-80	271	14	.2	.9	65	15	15	.8	5,800	130
			10-9-80	247	14	.2	.6	57	14	15	.9	5,900	130
MOR-47	392713	862616	11-2-79	268	----	---	----	---	--	----	---	<5	200
			5-14-80	293	6.4	.1	31	84	23	6.6	.7	10	140
			10-7-80	261	6.6	.1	34	73	22	6.2	1.2	<5	40
MOR-48	392509	862721	11-2-79	266	----	---	----	---	--	----	---	20	10
			5-15-80	268	19	.1	38	88	27	4.9	.5	<5	2
			10-9-80	239	19	.1	38	77	25	5.1	.6	<5	1
MOR-50	392417	862737	11-8-79	229	----	---	----	---	--	----	---	10	10

Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan and Owen Counties, Ind.--Continued

Well	Latitude	Longitude	Date	Aluminum	Dissolved organic carbon	Ammonia as N	Nitrite as N	Nitrate as N	Organic nitrogen as N	Orthophosphate as P
MOR-48	392509	862721	11-2-79	--	---	-----	-----	-----	-----	-----
			5-15-80	10	3.0	0.06	<0.005	7.1	<0.005	0.02
			10-9-80	10	.6	.01	<.005	12	<.005	<.005
MOR-50	392417	862737	11-8-79	--	---	-----	-----	-----	-----	-----
MOR-52	392340	862709	11-7-79	--	---	-----	-----	-----	-----	-----
			5-14-80	10	4.2	.07	.01	1.1	<.005	.01
			10-9-80	10	1.0	<.005	<.005	24	.01	<.005
MOR-54	392439	862901	11-12-79	--	---	-----	-----	-----	-----	-----
MOR-55	392518	862843	1-11-80	--	---	-----	-----	-----	-----	-----
			5-15-80	10	7.3	<.005	.01	1.5	<.005	<.005
			10-8-80	10	1.5	<.005	.01	1.2	.05	<.005
MOR-56	392228	862758	11-8-79	--	---	-----	-----	-----	-----	-----
MOR-57	392228	862845	11-8-79	--	---	-----	-----	-----	-----	-----
MOR-59	392348	863010	11-12-79	--	---	-----	-----	-----	-----	-----
MOR-61	392405	863129	11-9-79	--	---	-----	-----	-----	-----	-----
MOR-62	392258	863117	11-12-79	--	---	-----	-----	-----	-----	-----
MOR-64	392354	863208	11-9-79	--	---	-----	-----	-----	-----	-----
MOR-65	392456	863228	1-11-80	--	---	-----	-----	-----	-----	-----
MOR-66	392416	863333	11-12-79	--	---	-----	-----	-----	-----	-----
MOR-68	392355	863430	11-13-79	--	---	-----	-----	-----	-----	-----
			5-14-80	10	1.8	.03	.04	7.7	<.005	<.005
			10-8-80	50	1.3	<.005	.11	3.5	.03	.01
MOR-69	392301	863351	11-9-79	--	---	-----	-----	-----	-----	-----
			5-13-80	10	1.2	.08	<.005	.03	<.005	.03
			10-8-80	20	1.3	.01	<.005	.43	.01	<.005
MOR-70	392255	863557	11-13-79	--	---	-----	-----	-----	-----	-----
MOR-71	392218	863654	11-13-79	--	---	-----	-----	-----	-----	-----
MOR-72	392204	863257	11-8-79	--	---	-----	-----	-----	-----	-----
			5-13-80	80	1.4	.05	<.005	3.5	.12	<.005
			10-6-80	40	8.0	.04	.01	1.5	.01	.01
MOR-73	392228	863331	11-9-79	--	---	-----	-----	-----	-----	-----
			5-13-80	10	1.8	.03	.01	4.0	<.005	<.005
			10-8-80	20	2.5	<.005	.01	4.5	.08	<.005
MOR-74	392128	863427	1-11-80	--	---	-----	-----	-----	-----	-----
MOR-76	392204	863725	11-13-79	--	---	-----	-----	-----	-----	-----
OWN-1	392213	863759	11-13-79	--	---	-----	-----	-----	-----	-----
			5-13-80	20	3.2	.08	<.005	2.9	<.005	.02
			10-8-80	10	.5	.01	<.005	13	.01	<.005

[a]In micromho per centimeter at 25° C.
[b]Residue on evaporation at 180° C.

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Table 10.--Chemical analyses of water from wells in Johnson, Marion, Morgan and Owen Counties, Ind.--Continued

Well	Lati-tude	Longi-tude	Date	Alumi-num	Dis-solved organic carbon	Ammonia as N	Nitrite as N	Nitrate as N	Organic nitrogen as N	Ortho-phos-phate as P
MAR-0	393828	861422	10-23-79	---	----	-----	------	------	------	------
JON-2	393712	861232	10-23-79	---	----	-----	------	------	------	------
			5-20-80	10	8.0	0.04	<0.005	<0.005	<0.005	<0.005
			10-3-80	40	4.7	<.005	<.005	.11	.07	<.005
JON-4	393616	861345	10-24-79	---	----	-----	------	------	------	------
JON-5	393709	861339	10-23-79	---	----	-----	------	------	------	------
			5-20-80	10	7.0	.03	.01	4.8	.10	<.005
			10-3-80	50	9.0	.01	.01	5.1	.14	<.005
JON-6	393528	861343	10-24-79	---	----	-----	------	------	------	------
JON-7	393502	861405	10-25-79	---	----	-----	------	------	------	------
JON-8	393549	861457	10-25-79	---	----	-----	------	------	------	------
MOR-1	393708	861518	10-25-79	---	----	-----	------	------	------	------
			5-19-80	20	10	.05	.01	5.1	.09	<.005
			10-3-80	10	1.5	.02	.01	6.8	.12	<.005
MOR-3	393548	861626	1-8-80	---	----	-----	------	------	------	------
MOR-5	393514	861610	10-26-79	---	----	-----	------	------	------	------
MOR-9	393339	861633	10-26-79	---	----	-----	------	------	------	------
			5-19-80	<5	5.5	.04	<.005	3.9	.08	<.005
			10-3-80	10	1.7	<.005	<.005	.63	.01	<.005
MOR-11	393256	861650	1-8-80	---	----	-----	------	------	------	------
			5-19-80	<5	1.4	<.005	<.005	3.9	.13	.01
			10-10-80	10	2.0	.01	.01	.30	<.005	.01
MOR-15	393100	861813	1-9-80	---	----	-----	------	------	------	------
MOR-18	392947	862213	10-31-79	---	----	-----	------	------	------	------
MOR-19	393002	862120	10-31-79	---	----	-----	------	------	------	------
			5-16-80	20	9.1	.03	.01	3.5	<.005	<.005
			10-7-80	10	1.3	.01	<.005	3.6	<.005	<.005
MOR-20	393134	862256	1-9-80	---	----	-----	------	------	------	------
MOR-21	393227	862155	10-30-79	---	----	-----	------	------	------	------
MOR-22	393331	862109	10-30-79	---	----	-----	------	------	------	------
MOR-24	393601	862229	10-30-79	---	----	-----	------	------	------	------
			5-16-80	<5	8.5	.04	.01	1.5	.05	<.005
			10-2-80	50	3.6	.05	<.005	1.9	.08	<.005
MOR-25	393001	861938	1-9-80	---	----	-----	------	------	------	------
MOR-26	392848	862112	10-31-79	---	----	-----	------	------	------	------
			5-15-80	10	6.3	<.005	<.005	6.7	<.005	------
			10-7-80	40	9.9	<.005	.01	5.2	.03	.020
MOR-28	393052	862256	10-30-79	---	----	-----	------	------	------	------
			5-15-80	<5	1.7	.02	<.005	5.3	<.005	<.005
			10-9-80	10	1.0	.01	<.005	5.3	<.005	<.005
MOR-29	393117	862337	1-9-80	---	----	-----	------	------	------	------
MOR-30	393047	862358	10-31-79	---	----	-----	------	------	------	------
MOR-32	392953	862403	11-1-79	---	----	-----	------	------	------	------
MOR-33	392958	862516	11-1-79	---	----	-----	------	------	------	------
			5-15-80	10	4.2	.10	.04	.05	.06	<.005
			10-10-80	10	1.6	.14	<.005	.02	.03	<.005
MOR-35	392841	862506	10-31-79	---	----	-----	------	------	------	------
			5-15-80	20	5.9	.01	<.005	4.5	<.005	<.005
			10-10-80	50	.9	<.005	<.005	4.3	.18	<.005
MOR-36	392759	862554	1-10-80	---	----	-----	------	------	------	------
MOR-38	392644	862612	1-10-80	---	----	-----	------	------	------	------
MOR-39	392543	862617	11-1-79	---	----	-----	------	------	------	------
MOR-40	392655	862558	1-10-80	---	----	-----	------	------	------	------
MOR-44	392244	862403	11-1-79	---	----	-----	------	------	------	------
			5-14-80	100	3.3	1.1	.05	.02	<.005	.03
			10-9-80	100	2.6	1.2	<.005	<.005	<.005	.10
MOR-47	392713	862616	11-2-79	---	----	-----	------	------	------	------
			5-14-80	10	2.8	.05	.01	.51	.10	<.005
			10-7-80	10	.8	.02	.01	5.8	<.005	<.005