# AVAILABILITY OF WATER FROM THE OUTWASH AQUIFER, MARION COUNTY, INDIANA

By Barry S. Smith

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

| Multiply inch-pound units | By | To obtain SI units |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meters (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 ($m^2/d$) |
| gallons per day per square foot [$(gal/d)/ft^2$] | 0.041 | meters per day (m/d) |
| mile (mi) | 1.609 | kilometer (km) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| inch per year (in/yr) | 25.4 | millimeter per year (cm/yr) |
| cubic foot per second ($ft^3/s$) | 0.0283 | cubic meter per second ($m^3/s$) |
| gallon per day (gal/d) | $4.38 \times 10^{-8}$ | cubic meter per second ($m^3/s$) |
| 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 ($m^3/yr$) |
| 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 [$(gal/d)/mi^2$] | $9.82 \times 10^{-2}$ | cubic meter per day per square kilometer [$(m^3/d)/km^2$] |

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

$$(5/9)\ (°F - 32°) = °C$$

## TRADE NAMES DISCLAIMER

Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

## DATUM

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

# AVAILABILITY OF WATER FROM THE OUTWASH AQUIFER, MARION COUNTY, INDIANA

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## ABSTRACT

The outwash aquifer is a continuous, unconfined, sand and gravel deposit containing isolated boulders, silt, and clay deposits along the White River, Fall Creek, and Eagle Creek. The direction of flow in the aquifer is from the adjacent Tipton till plain toward the streams and major pumping centers. Pumpage and water-level data indicate that the outwash aquifer was in virtual steady state from 1974 through 1980.

A two-dimensional, finite-difference model of the outwash aquifer, calibrated to water levels of October 6 to 10, 1980, indicated that 48 percent of the water received by the aquifer was effective recharge from precipitation, 41 percent was from the boundaries representing flow from the confined aquifers of the till plain, and 11 percent was leakage through the streambeds of White River, Fall Creek, and Eagle Creek, induced by pumping. Twenty-nine percent of the total discharges from the aquifer was pumpage; 68 percent was natural seepage to White River, Fall Creek, and Eagle Creek; and 3 percent was subsurface outflow.

The digital model was slightly more sensitive to changes in hydraulic conductivity than to changes in effective recharge rates or hydraulic conductivity of the streambed. The model, however, was insensitive to increases in the hydraulic conductivity of the streambed.

The calibrated digital model was used to estimate the amount of water that could be pumped from the outwash aquifer. A drawdown limit of 50-percent saturated thickness applied to 78 fully penetrating pumping wells assumed to be 1 foot in diameter produced 97 cubic feet per second from the outwash aquifer. Reductions in streamflows caused by a simulated pumpage of 97 cubic feet per second and constant-flux boundaries were 85 cubic feet per second in the White River and 12 cubic feet per second in Fall Creek. In comparison, the 7-day, 10-year low flows were 83 cubic feet per second in the White River near Nora and 39 cubic feet per second in Fall Creek at Millersville. Therefore, 97 cubic feet per second is considered to be the limit of water available from the outwash aquifer in Marion County. Simulated pumpage of 115 cubic feet per second and constant-flux boundaries produced streamflow reductions of 101 cubic feet per second in the White River, which exceeds the 7-day, 10-year lowflow near Nora, and 13 cubic feet per second in Fall Creek. Therefore, a pumpage of 115 cubic feet per second is considered to be beyond the limit of water available from the aquifer.

# INTRODUCTION

In July 1975, the U.S. Geological Survey released a report on the availability of ground water in Marion County (Indianapolis) by Meyer and others (1975). The ground-water flow system in the county, an electric-analog model for simulating ground-water flow, and the results of pumping simulated with the analog model are described in the report. The pumping simulations indicated that the unconfined outwash aquifer adjacent to the White River was a valuable source of water from which at least 57.5 Mgal/d (89.0 $ft^3/s$) could be pumped in addition to that already developed in 1973 (Meyer and others, 1975, p. 84).

In November 1978, the Indianapolis Water Company, the principal water utility serving Marion County, canceled plans to participate in constructing a major reservoir (Highland) in central Indiana and began to consider the outwash aquifer for additional water supply.

In 1979, the Indiana Department of Natural Resources, concerned about further development of ground water in central Indiana, began a cooperative agreement with the U.S. Geological Survey to do a digitial-model analysis of the outwash aquifer (fig. 1). The purpose of the study was to estimate the availability of water in the aquifer and to compare the results with those of the analog-model analysis by Meyer and others (1975). The digital model would then be available to the cooperator for examining future ground-water development.

By October 1980, the Indianapolis Water Co. had completed the first phases of an extensive development project in the outwash aquifer in southern Marion County. In an unrelated project in central Marion County, a private company completed tests in the outwash aquifer for a water heat-pump system that would heat and cool a 38-story office building. These projects indicated a renewed interest in development of the outwash aquifer.

## Purpose and Scope

Objectives of the study were to analyze the water budget of the outwash aquifer, estimate the amount of water that could be pumped from the aquifer, and determine the effect of pumping on water levels and streamflow. The objectives were met by (1) collecting and interpreting hydrologic and lithologic data and reviewing data from previous reports; (2) updating ground-water pumpage data; (3) measuring water levels and streamflows; (4) constructing or revising aquifer-boundary, water-level, saturated-thickness, and hydraulic-conductivity maps; (5) constructing and calibrating a two-dimensional digital ground-water flow model; (6) simulating pumping in the digital model; and (7) testing the sensitivity of the model.


Figure 1.-- Location of the study area.

In this report, the hydrology of the outwash aquifer, the digital model used to simulate flow in the aquifer in October 1980, and the results of pumping simulations used to evaluate the availability of water from the aquifer are described. Pumping simulations used to estimate the availability of ground water were based solely on hydrologic considerations.

## Study Area

The study area includes approximately 90 $mi^2$ of the unconfined outwash aquifer along the White River in Marion County and northern Johnson and Morgan Counties (fig. 2). The northern one-third of the area is residential, the southern one-third is agricultural, and the middle one-third is within the commercial and industrial center of Indianapolis. The outwash aquifer extends beyond the area north and south along the White River.

Indianapolis is incorporated with Marion County in a combined city-county government. The population of Marion County was 765,233 in 1980 (U.S. Department of Commerce, 1982, p. 16-8). The climate is temperate. Mean annual temperature was 52.6° F from 1941 to 1980, and average annual precipitation was 39.93 in/yr from 1941 to 1980 (National Oceanic and Atmospheric Administration, 1980). Average annual discharge on the White River at Indianapolis was 11.6 in/yr from 1931 to 1981 (U.S. Geological Survey, 1982, p. 177).

## Previous Studies

Various aspects of the ground-water resources of Marion County have been described in the literature. In addition to the electric-analog model study of Marion County (Meyer and others, 1975), McGuinness (1943) described the amount and the effects of ground-water pumpage; Roberts and others (1955) described water use, pumpage, surface-water resources, and water quality; Herring (1976) described availability and general water quality; and Pettijohn (1977) described flow and water quality in and near seven landfills in the county.

The following reports for areas near Marion County are of interest: Gillies (1976) reported the availability of ground water in the outwash aquifer in Hamilton County, immediately north of Marion County, and Bailey (1982) reported the ground-water resources of the outwash aquifer in Johnson and Morgan Counties immediately south of Marion County. Other reports on ground water resources in the White River basin include: Arihood (1982) in Hamilton and Tipton Counties, Lapham (1981) in Madison County, and Arihood and Lapham (1982) in Delaware County. Cable and others (1971) reported the water resources of the entire upper White River basin.

## Acknowledgments

The author is indebted to 23 commercial, municipal, and industrial users, who provided ground-water pumpage data, and to the Indianapolis Water Co., who provided surface-water use data as well. Thanks are given to Detroit Diesel Allison Division of General Motors Corp. for permission to maintain several observation wells on their property and to the many other private and public landowners who permitted access to and maintenance of observation wells.

Special recognition is given to the Indiana Department of Natural Resources, Division of Water, for numerous drillers' well logs and for providing a hydrograph for observation well 53. Thanks is also given to Stremmel and Hill, Inc., and the Indianapolis Water Co., for preliminary data from a test drilling and aquifer test project in southern Marion County; and to Atec Associates, Inc., for preliminary data from an aquifer test project in central Marion County.

# HYDROGEOLOGY

## Geologic Setting

The geology of Marion County has been described by Harrison (1963). A brief description of the geologic setting based on a review of drillers' well logs and previous studies follows.

The outwash aquifer is a continuous sand and gravel deposit containing isolated boulder, silt, and clay deposits along the White River, Fall Creek, and Eagle Creek (fig. 3). The outwash was deposited and reworked by melt-water streams flowing from the Wisconsinan ice sheet. Clay, and silt deposits are numerous in the outwash but are generally discontinuous.

At the edges of the valleys of the White River and the upstream reaches of Fall Creek and Eagle Creek, the outwash deposits intergrade with deposits of the Tipton till plain. Till layers are predominant, and sand and gravel deposits are discontinuous in the till plain.

Part of the till plain has been isolated between the White River and Fall Creek in T. 16 N., R. 3 E. (Harrison, 1963, pl. 1). At its highest point marked by a small kame, the deposit stands 155 ft above the White River.

A large kame stands 150 ft above the outwash east of the White River in T. 14 N., R. 3 E., in southern Marion County. Well logs showing depths to 175 ft below land surface in the kame indicate thick sequences of sand grading

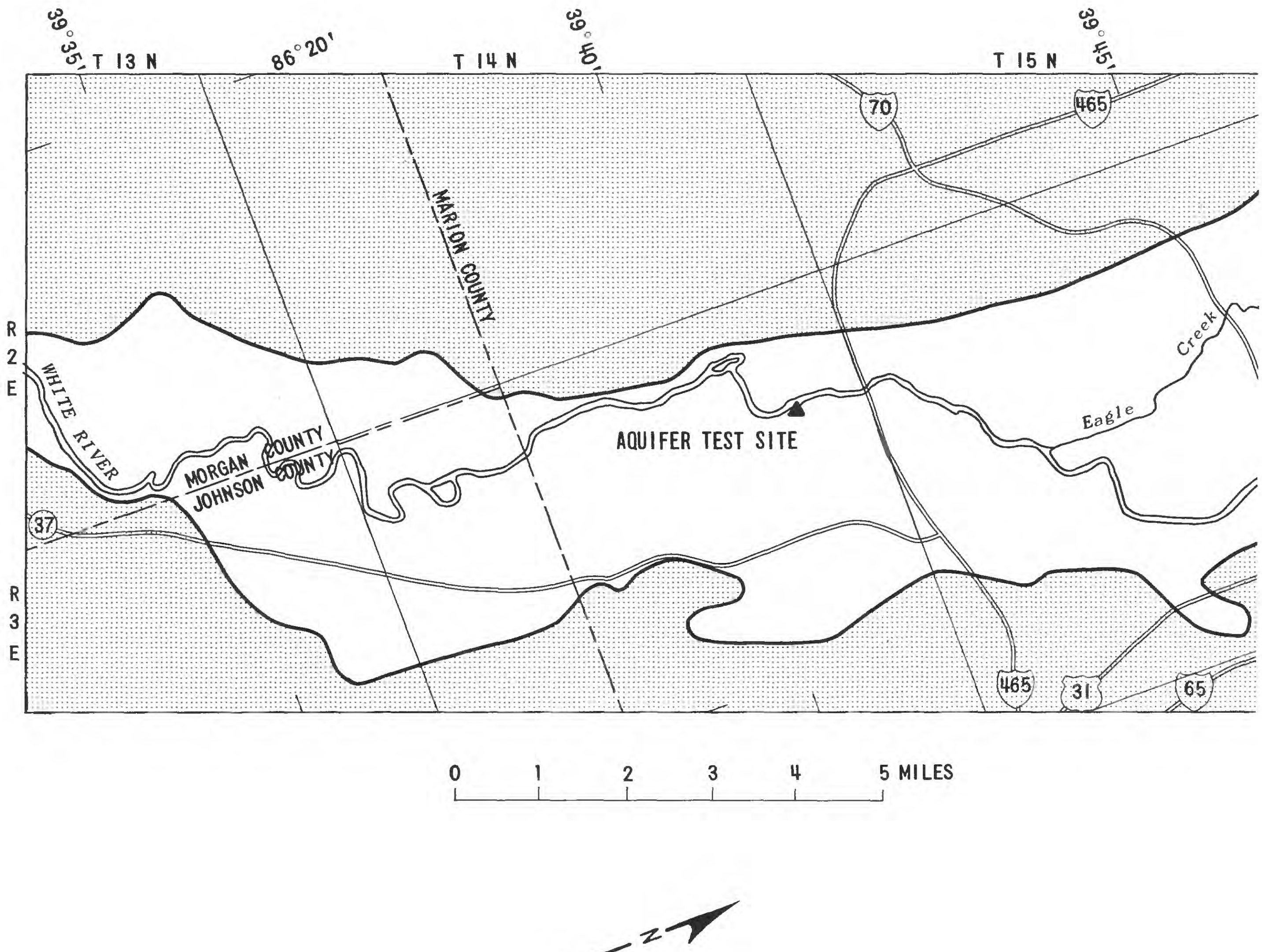
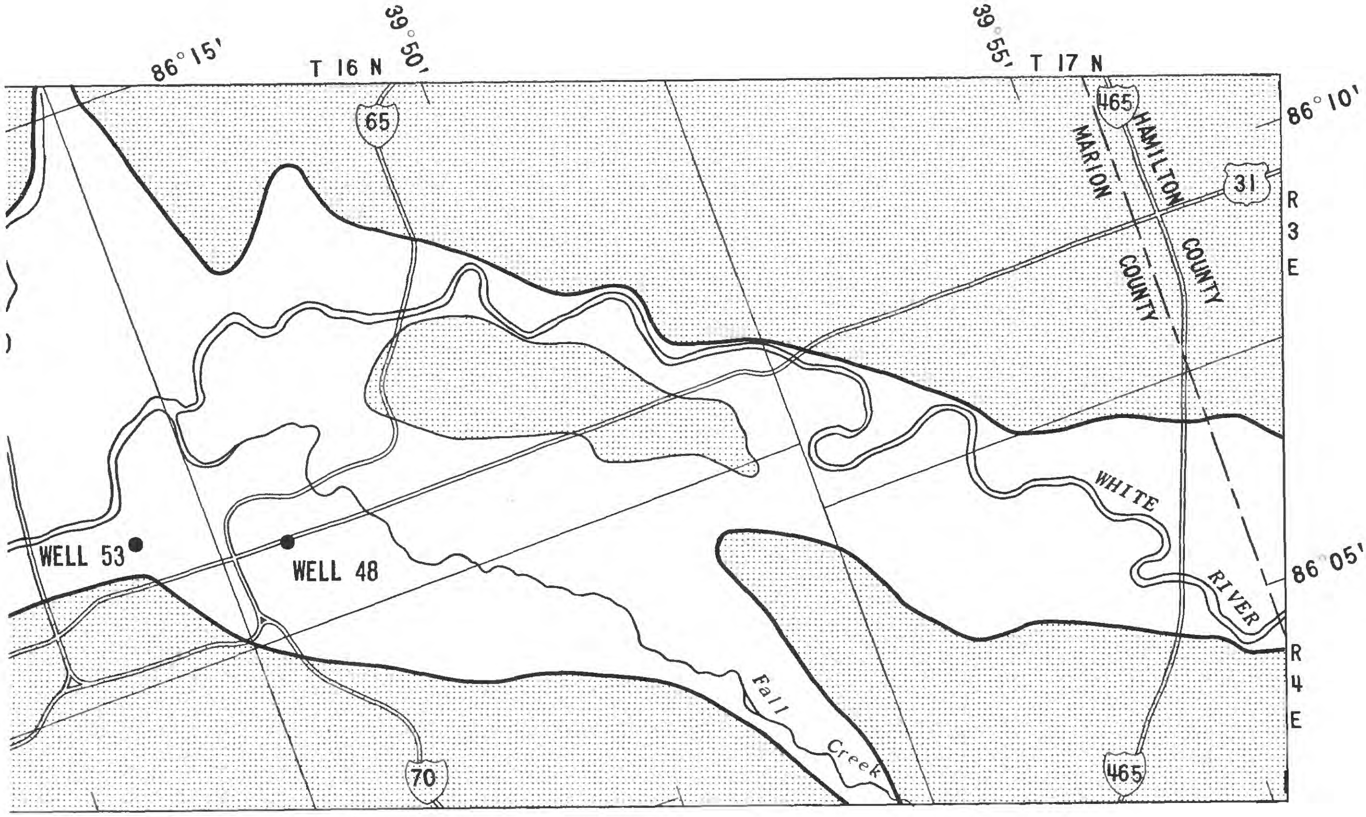



Figure 2.-- Study area.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

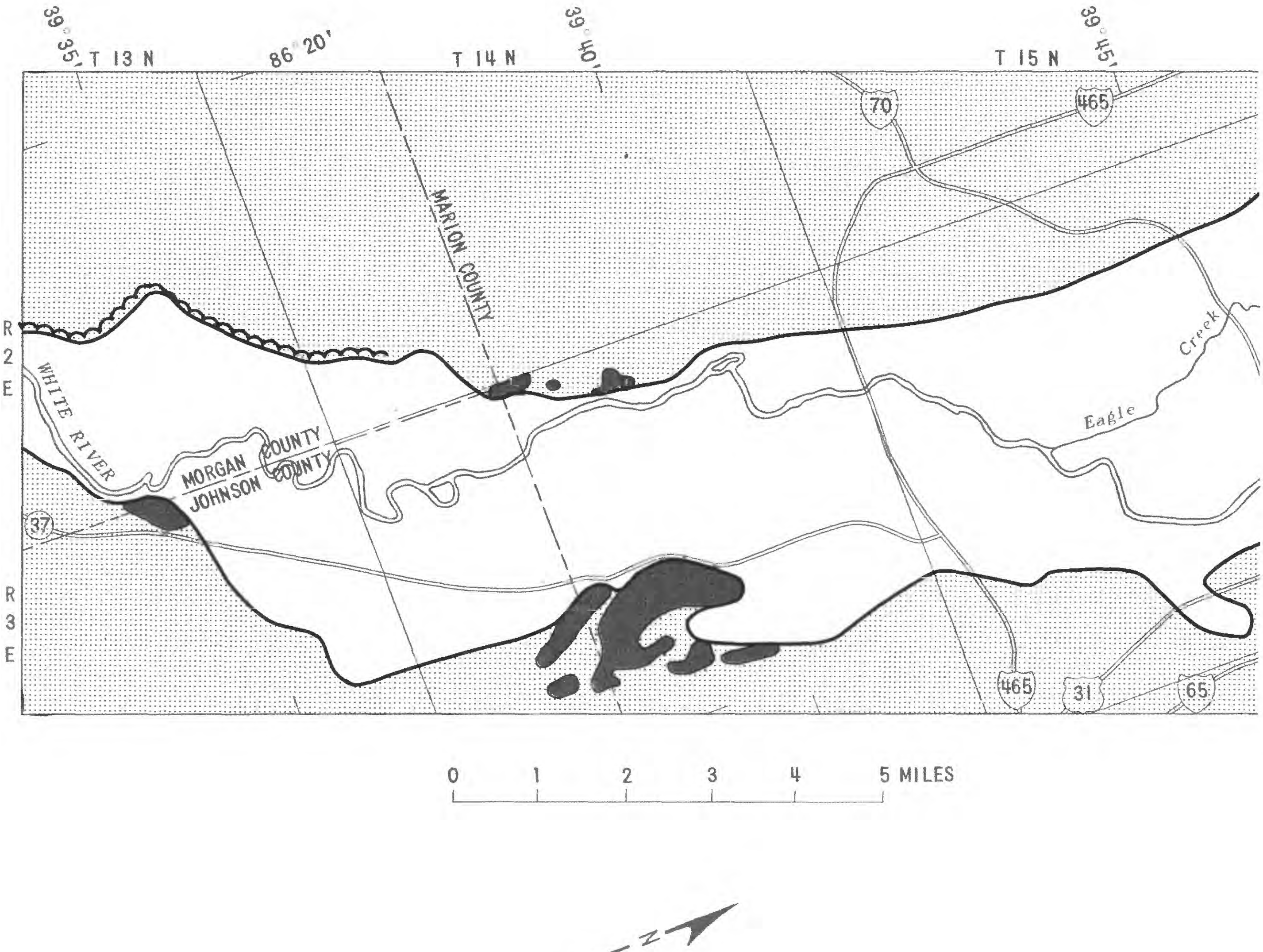
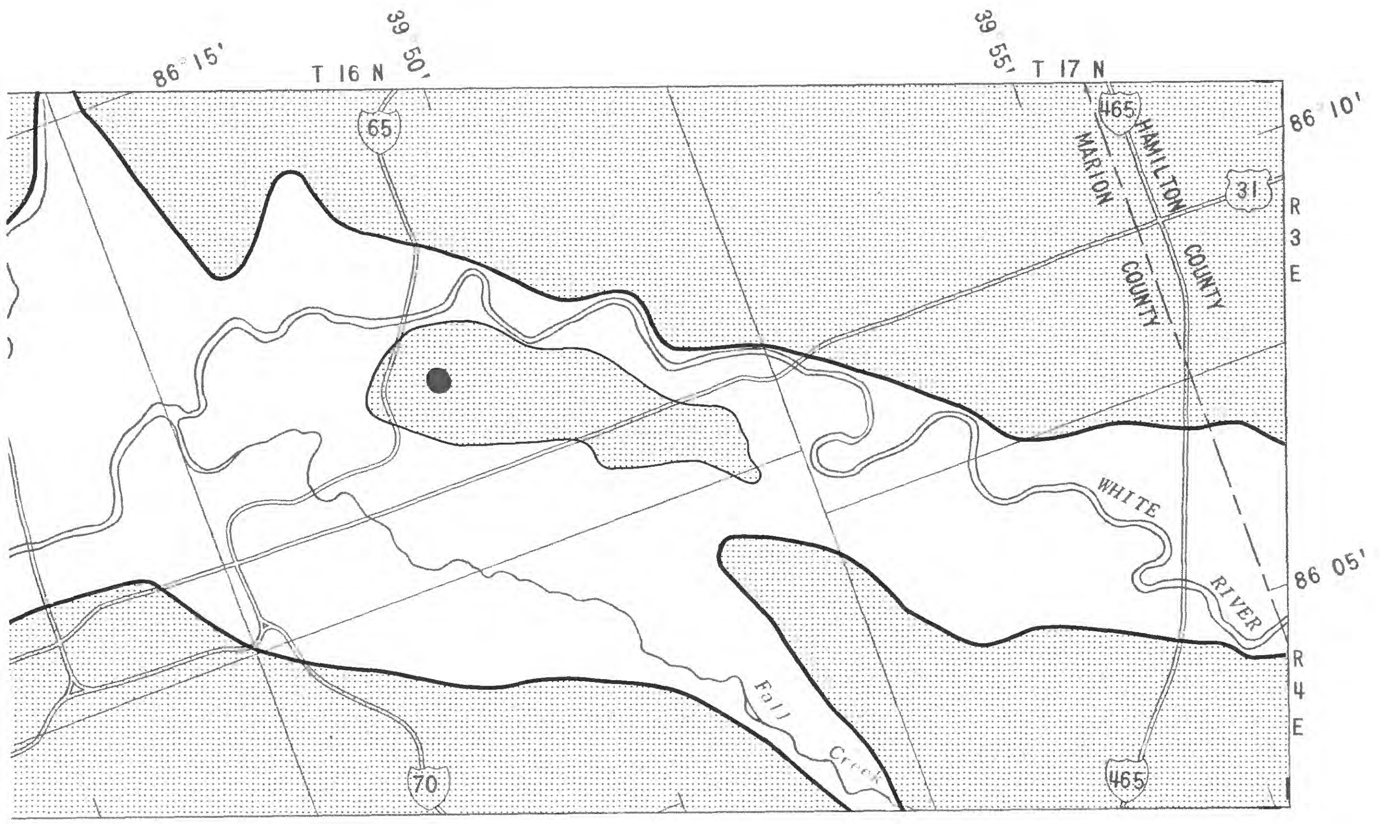



**Figure 3.-- Surficial geology.**




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Kame deposits

Bedrock-valley wall

to clay. The boundary between the outwash and till plain that was delineated by Meyer and others (1975, p. 9) was modified in the current study to exclude the kame from the outwash aquifer because of the clay.

The outwash-till plain boundary west of the White River in Morgan County is different from the boundary in Marion County. The outwash deposits here abut against a steep bedrock-valley wall mantled by the till-plain deposits.

The locations of test holes and wells for which drillers' well logs were available are shown in figure 4. One continuous clay deposit defined by the well logs and delineated in figure 4 is within the outwash beneath the confluence of the White River and Eagle Creek. This 10 to 20 ft thick layer, covering approximately 2 $mi^2$, is a poorly defined or partially eroded extension of the till plain. The clay layer separates an overlying sand and gravel deposit 20 to 40 ft thick from one that is 10 to 20 ft thick.

Average thickness of two other clay layers, one beneath the upstream reach of Eagle Creek and one beneath the upstream reach of Fall Creek is 40 ft. The clay layers are separated from the bedrock by 5 to 10 ft of discontinuous sand and gravel deposits. The tops of both clay layers, therefore, mark the bottom of the outwash deposit. Throughout the rest of the study area, however, the outwash lies directly on the bedrock surface or on discontinuous clay lenses that are in contact with the bedrock surface (fig 5). The outwash may contain other clay layers that have not been interpreted as continuous or extensive in relation to the scale of this study.

The bedrock surface beneath the outwash is Middle Devonian limestone and dolomite (locally known as the Muscatatuck Group), Devonian and lower Mississippian shale (New Albany shale), and Mississippian shale and limestone (Borden Group and Rockford Limestone) as indicated in figure 6. The bedrock surface is, in effect, an aquifer boundary. The Devonian and Mississippian rocks are generally poor sources of water. On the basis of specific capacity data, average hydraulic conductivity of the Devonian limestones and dolomite was calculated to be 100[(gal/d)/$ft^2$] or 13 ft/d compared to a hydraulic conductivity of 2,500[(gal/d)/$ft^2$] or 335 ft/d calculated for the outwash aquifer (Cable and others, 1971, p. C12 and C11). Hydraulic conductivity in the limestone and dolomite, however, may be much greater in isolated areas because of solution channeling along joints and bedding planes.

## Ground-Water Flow System

The outwash aquifer along the White River, Fall Creek, and Eagle Creek is unconfined, and regional ground-water flow is predominantly horizontal. The one continuous clay layer within the outwash described in the preceding section may confine the aquifer locally, but on a regional scale, there are no other significant confining layers within the outwash. In contrast, the aquifers of the till plain are generally confined. At least one confined aquifer is connected to the outwash at virtually every point along the lateral boundaries in Marion County (Meyer and others, 1975, p. 10-12). In Morgan County, however, a bedrock-valley wall forms an effective no-flow boundary west of the White River.

A water-table map of the aquifer was contoured from hydraulic heads measured October 6 to October 10, 1980 (fig. 7). The direction of flow in the aquifer is from the till plain toward the White River, Fall Creek, and to a lesser extent, Eagle Creek, and toward major pumping centers adjacent to the streams.

## Stream-Aquifer Connection

The White River, Fall Creek, and Eagle Creek are the principal streams flowing through the outwash aquifer in Marion County. The connection of the streams to the aquifer is important because the streams are the major discharge drains for the aquifer and are a potential source of recharge to pumping wells. Average discharge and discharges October 8, 1980, for the streams are listed in table 1. The locations of the discharge gages are shown in figure 8. Discharge to the White River is not controlled directly; however, check dams at some locations cause pooling (Meyer and others, 1975, p. 27). Several tributaries to the river, including Fall Creek and Eagle Creek, are regulated by reservoirs. One reservoir is 8.4 mi upstream from the gage on Fall Creek, and another is 4.7 mi upstream from the gage on Eagle Creek.

Table 1.--Discharge at gaging stations

[Data from U.S. Geological Survey, 1982, p. 171, 175, 177, and 183]

| Station number | Station name | Average discharge ($ft^3/s$) | Years averaged | Discharge October 8, 1980 ($ft^3/s$) |
|---|---|---|---|---|
| 03351000 | White River near Nora, Ind. | 1,099 | 1929 to 1980 | 242 |
| 03353000 | White River at Indianapolis, Ind. | 1,398 | 1930 to 1980 | 215 |
| 03352500 | Fall Creek at Millersville, Ind. | 284 | 1929 to 1980 | 62 |
| 03353500 | Eagle Creek at Indianapolis, Ind. | 155 | 1939 to 1980 | 7.7 |

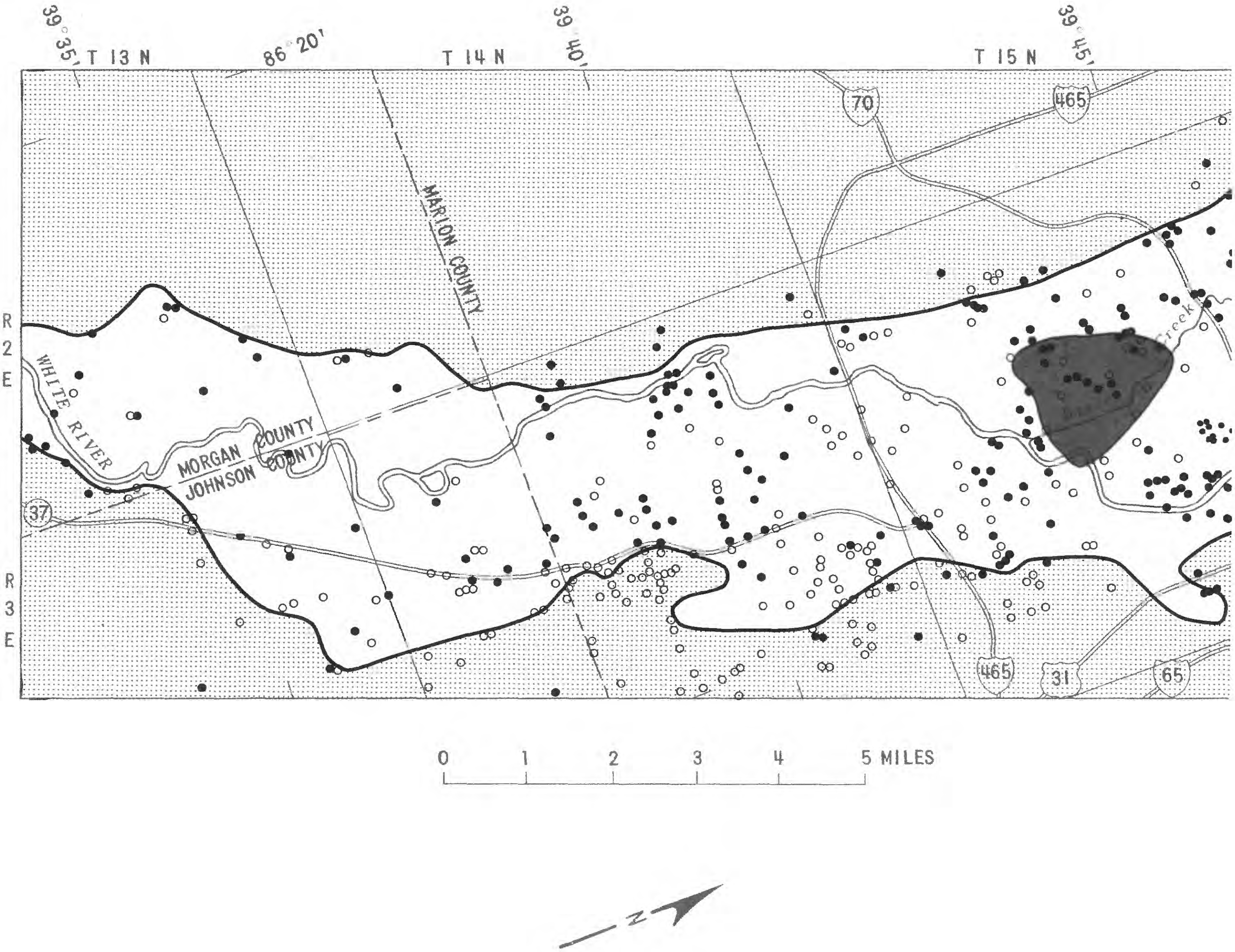
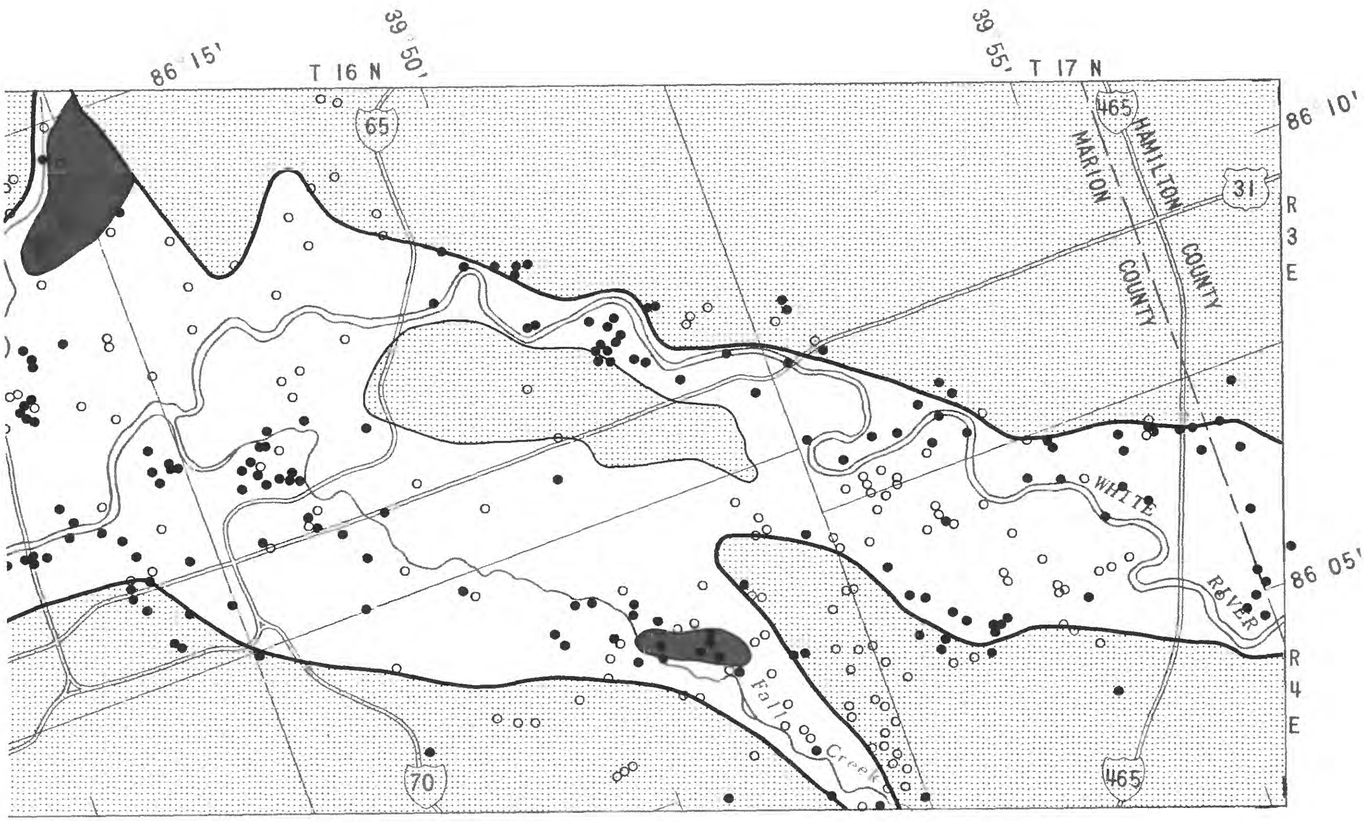



Figure 4.-- Locations of test holes and wells for which drillers' well logs were available.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Approximate extent of buried clay layers

● Well that penetrates full saturated thickness of aquifer

○ Well that penetrates at least 50 percent of saturated thickness of aquifer

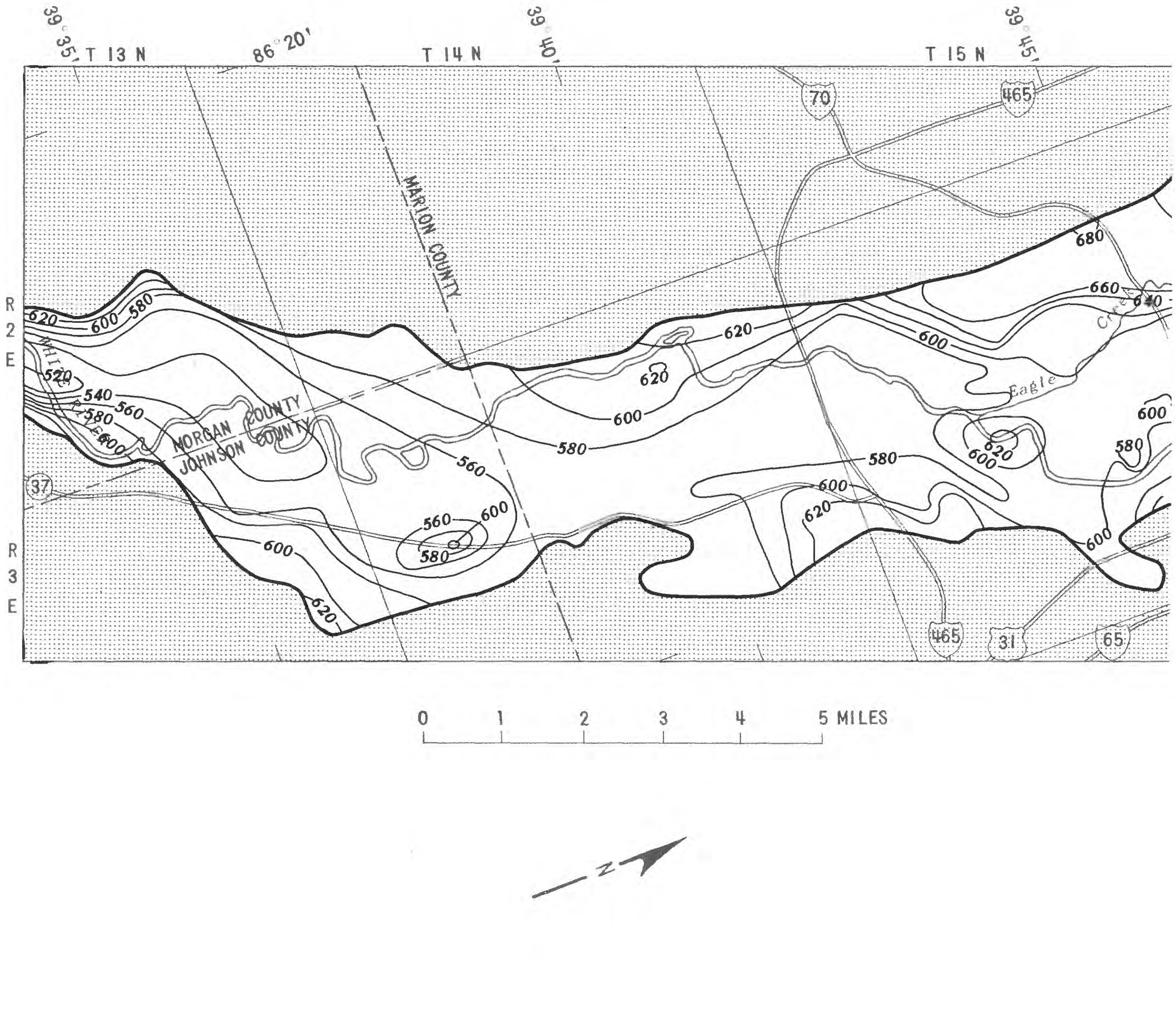
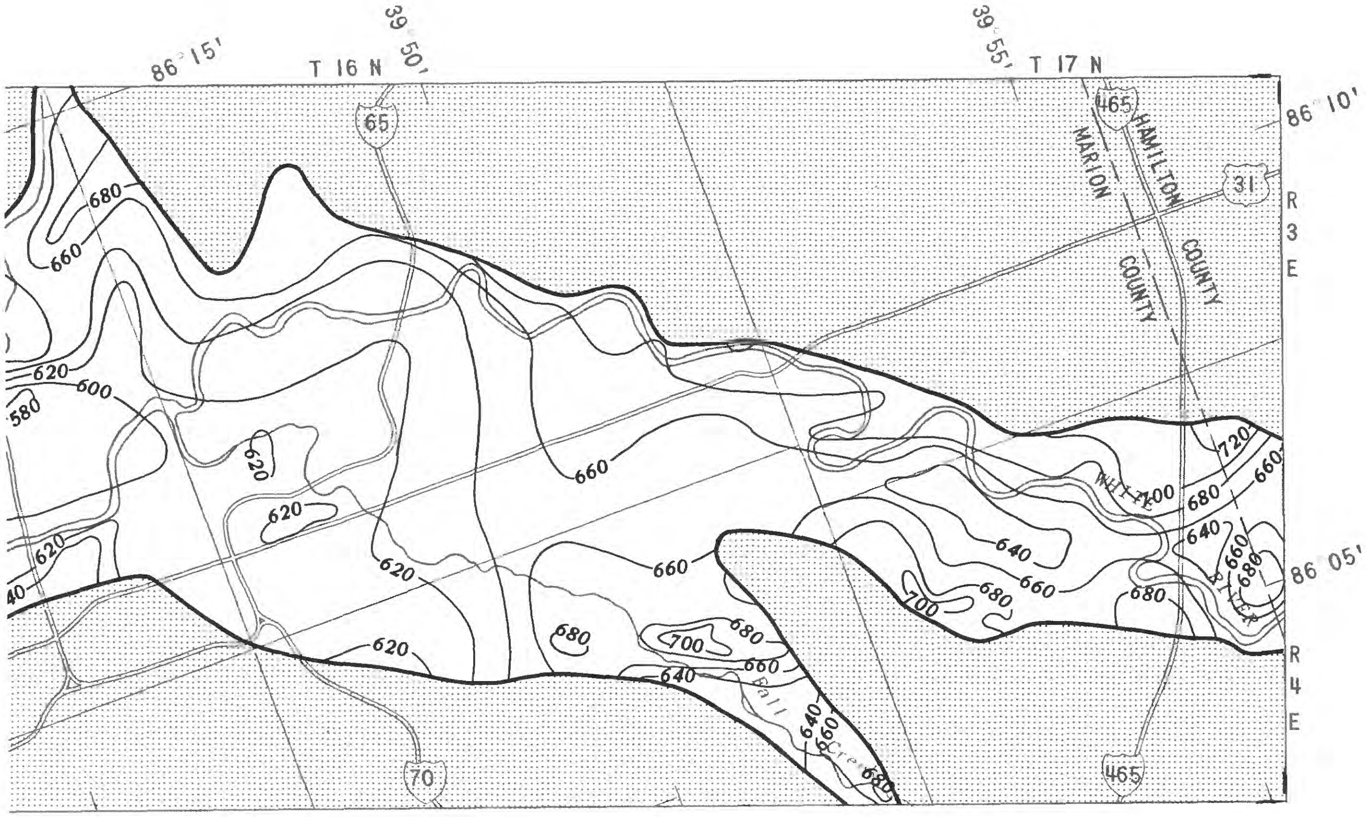



Figure 5.-- Base of the glacial-outwash aquifer.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

620 Line of equal altitude of base. Interval 20 feet

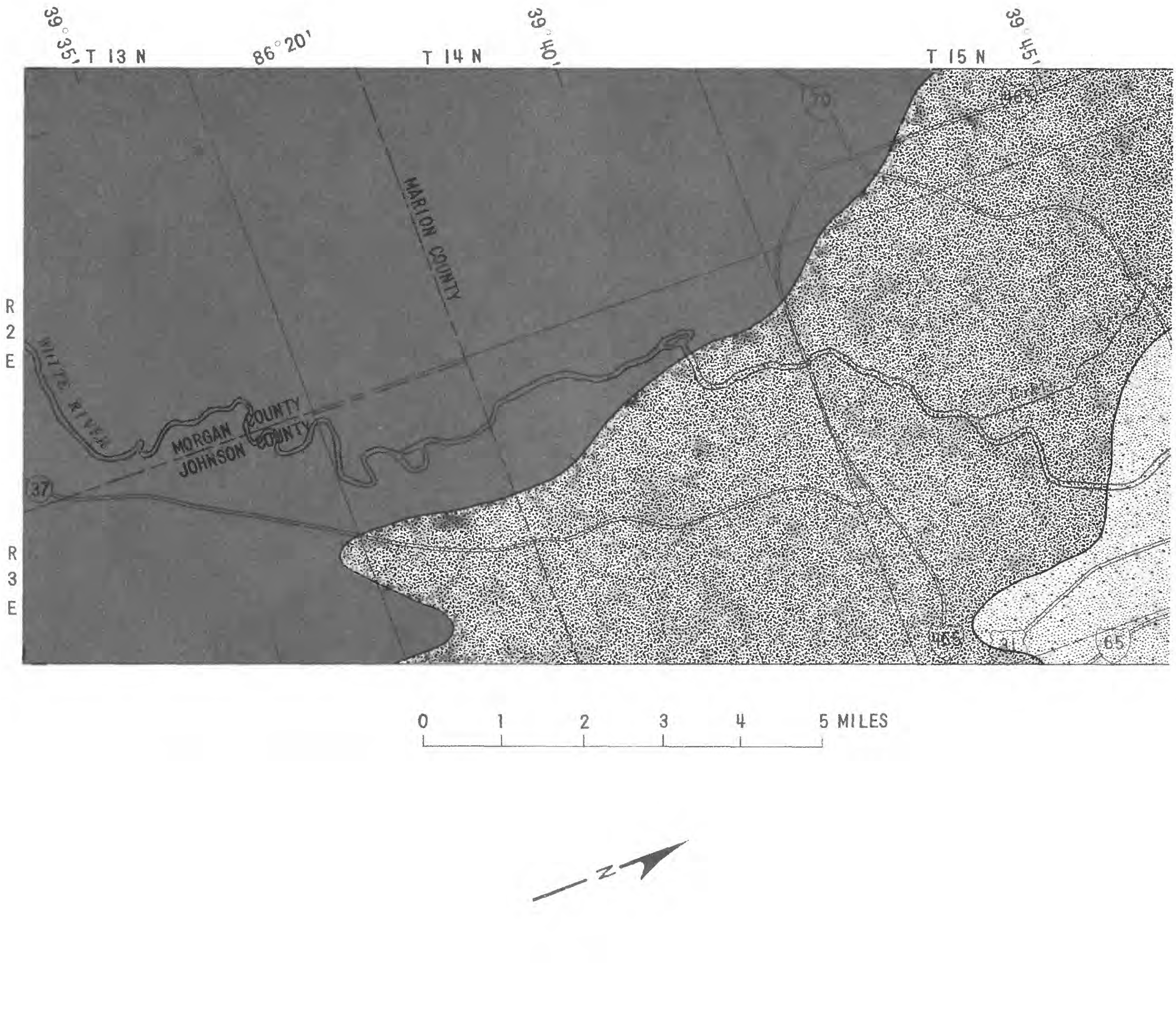
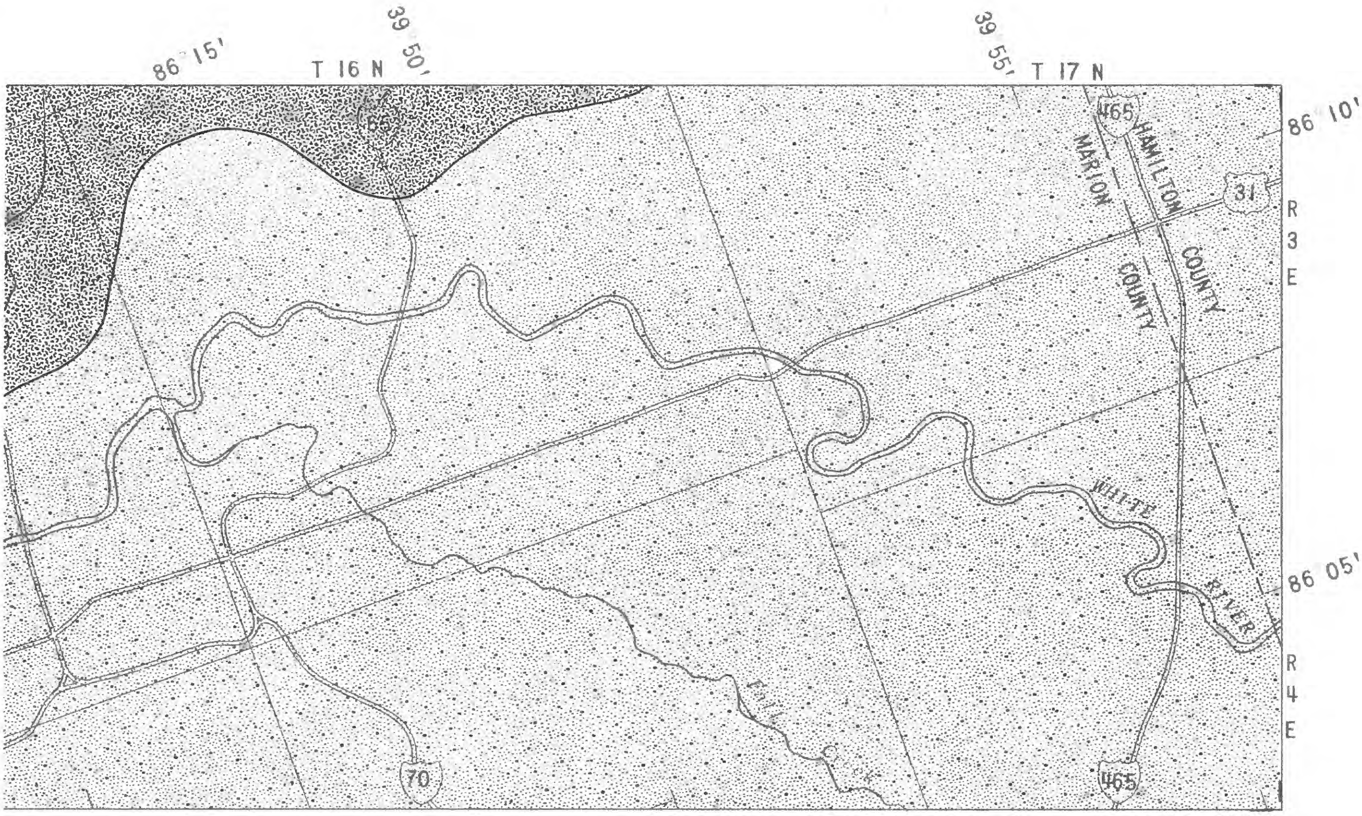



Figure 6.-- Bedrock geology.




Bedrock contacts after H.H. Gray and others (1979)

**EXPLANATION**

| | | |
|---|---|---|
| MISSISSIPPIAN | | Borden Group and Rockford Limestone |
| MISSISSIPPIAN and DEVONIAN | | New Albany Shale |
| DEVONIAN | | Muscatatuck Group (Local usage) Limestone and Dolomite |

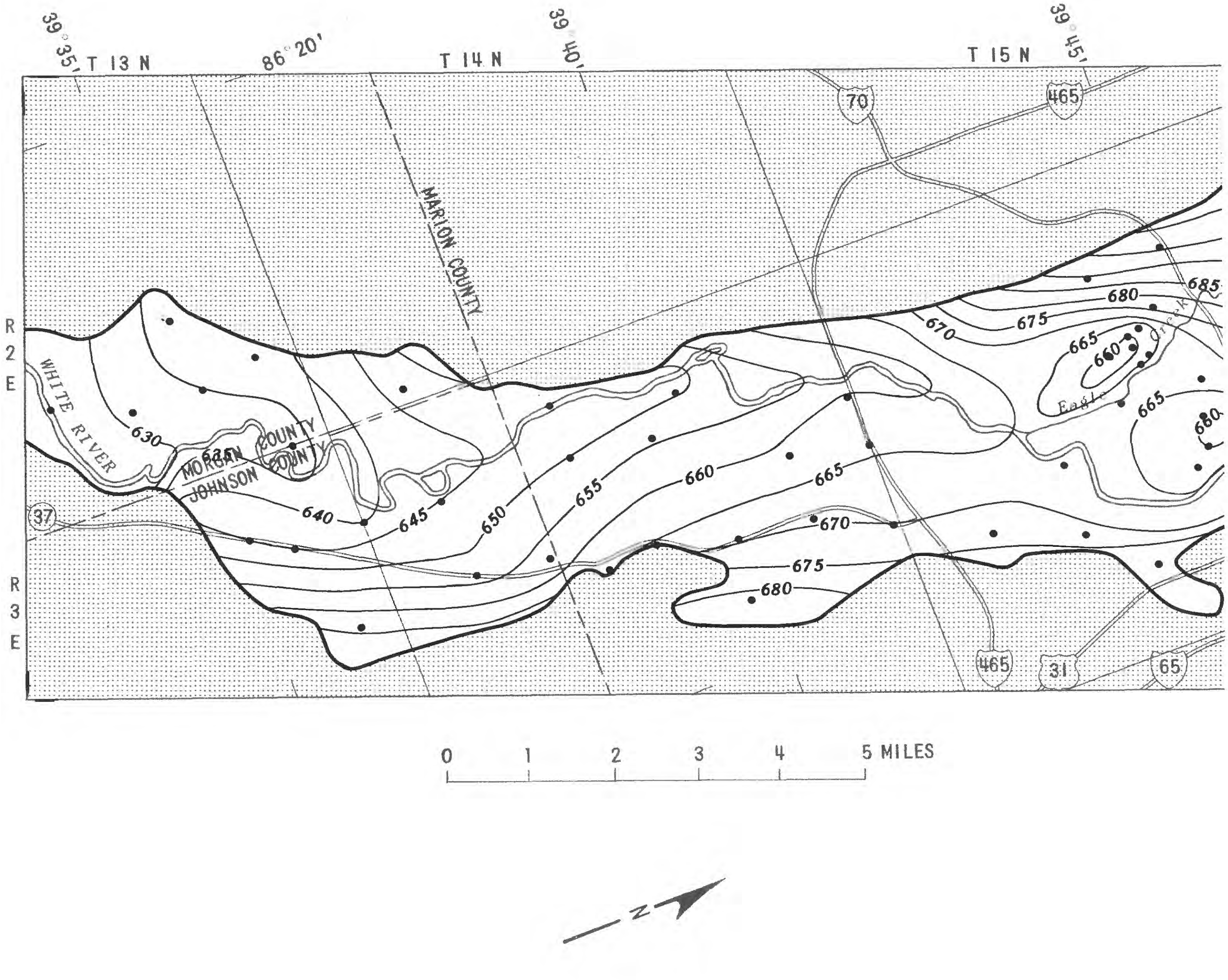
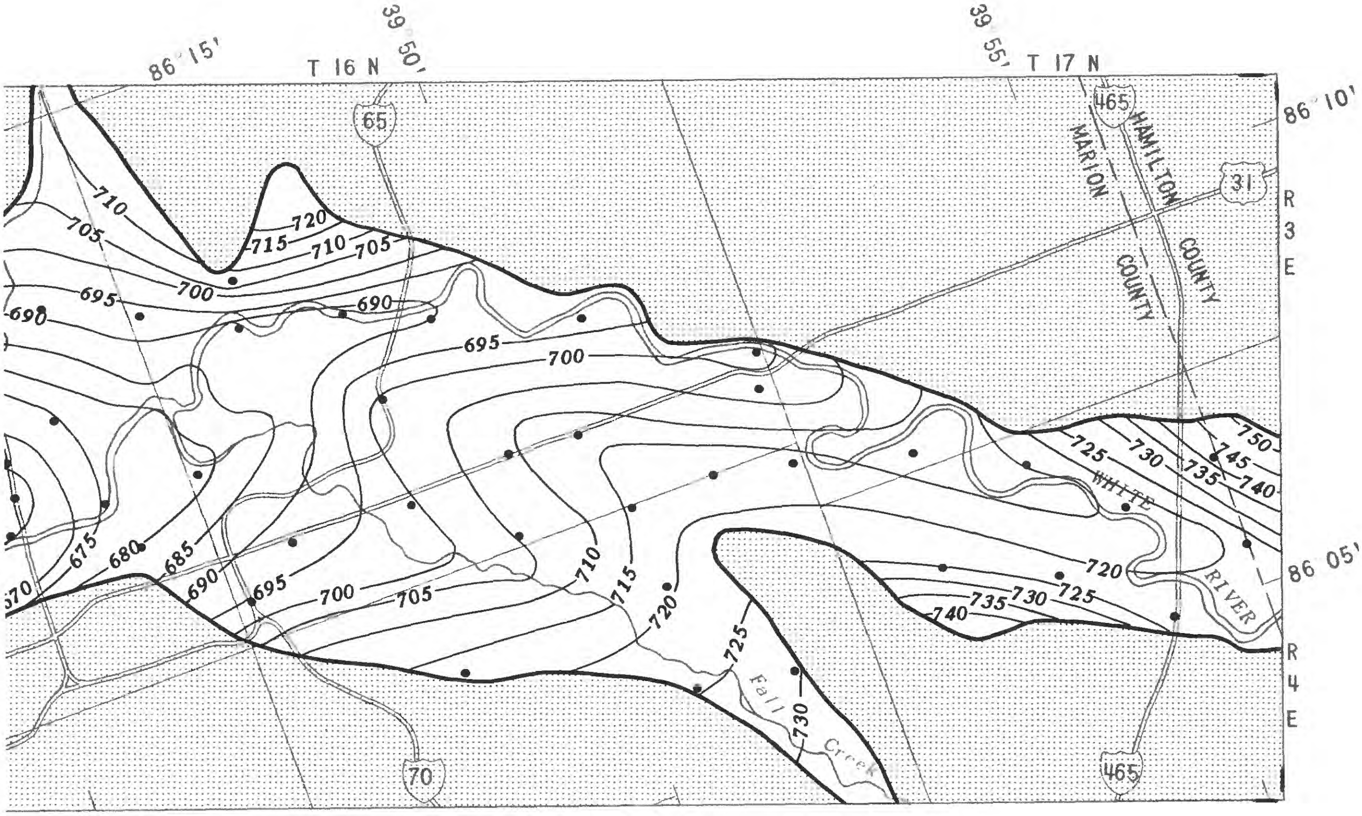



Figure 7.-- Water table.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

675 Line of equal altitude of water table. Interval 5 feet

• Observation well

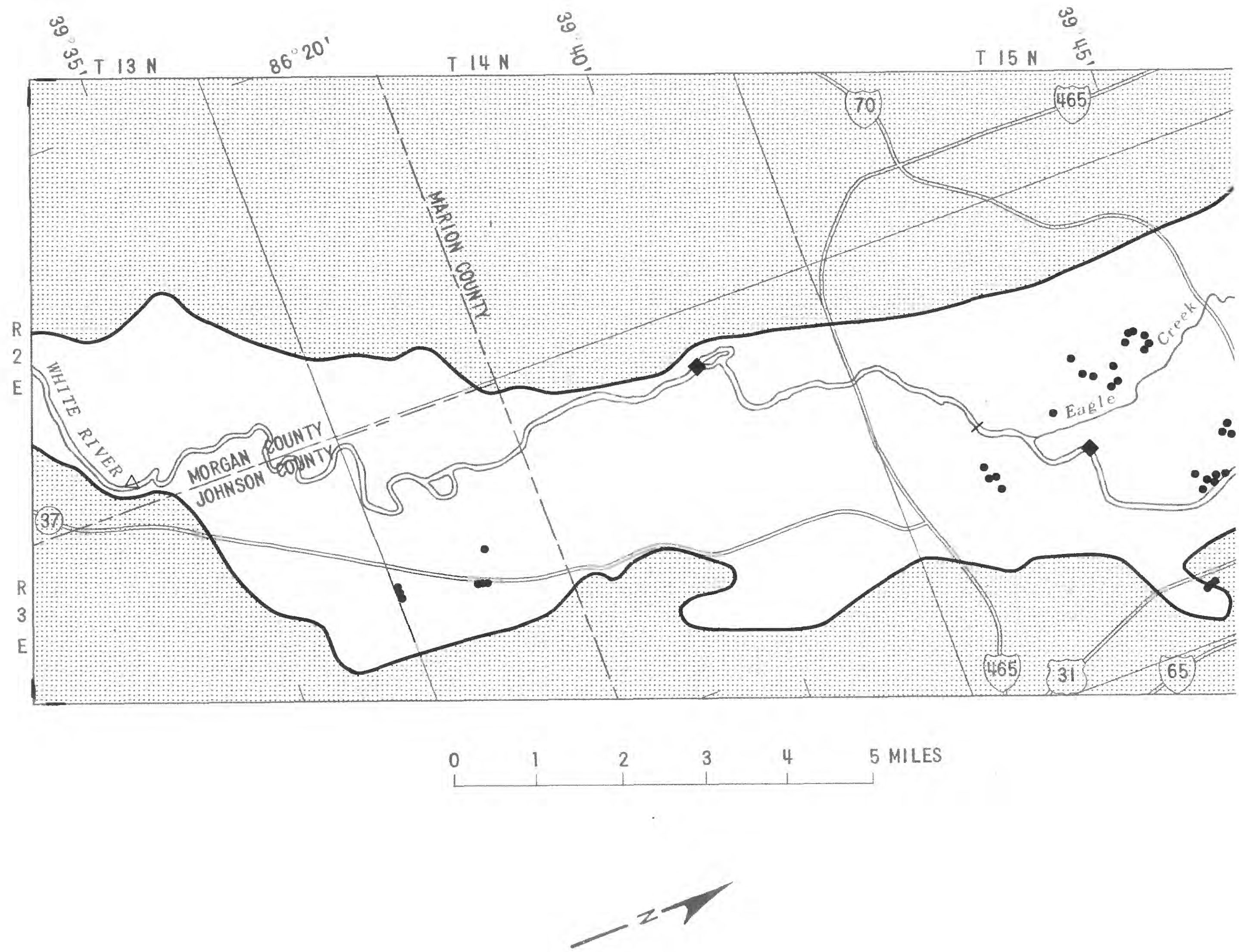
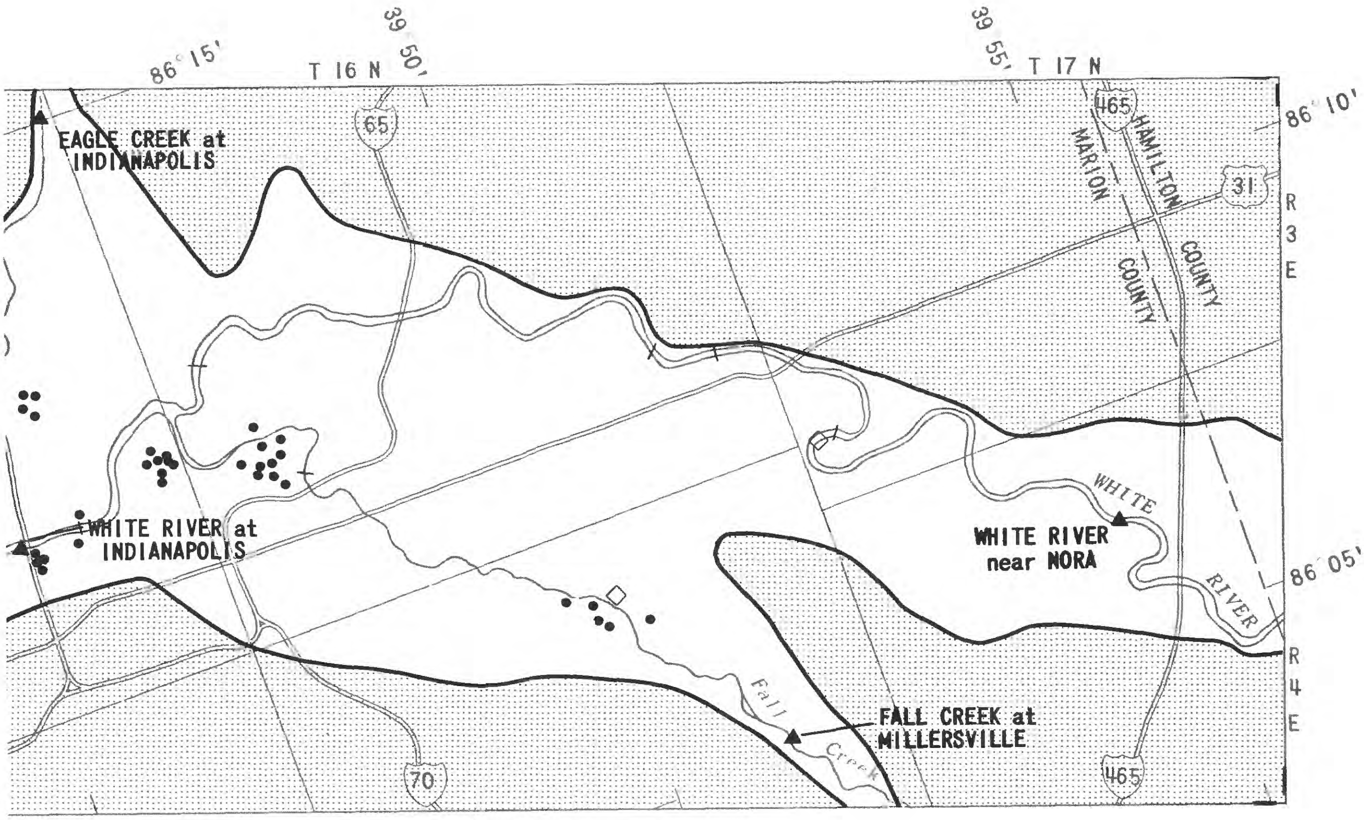



Figure 8.-- Sites of streamflow gain and loss measurements and major ground-water pumpage.




EXPLANATION

Outwash and alluvium

Tipton till plain

▲ Continuous-record gaging station

△ Streamflow-measurement site

◆ Treated-sewage discharge

◇ Surface-water diversions

• Major pumping well

Check dam

Eagle Creek Reservoir is part of the water supply for the Indianapolis area; a larger part of the area's water supply, however, is diverted from the White River and from Fall Creek in northern Marion County. (Reduction in streamflow on the White River from Nora to Indianapolis on October 8, 1980, table 1, was largely due to the diversions.) Treated sewage is discharged directly to the White River and indirectly through a small tributary to the White River in southern Marion County.

Meyer and others (1975, p. 21) used discharges at various locations on the principal streams to calculate ground-water seepage rates. Results were obscured, however, by commercial and industrial activities such as return of cooling water, return of surface-water diversions, channel storage behind check dams, and disposals of sewage. Better results were obtained on the White River in northern Marion and southern Hamilton Counties upstream from the commercial and industrial area. A seepage inflow rate was calculated to be 42 $ft^3/d$ per foot of channel (2.6 $ft^3/s$ per mile of channel) for October 20, 1973 (Meyer and others, 1975, p. 28). Flow duration at that time was 66 percent on the White River near Nora (Horner, 1976, p. 246, and U.S. Geological Survey, 1975, p. 165). Gillies (1976, p. 13) calculated a seepage inflow of 303 gal/d per foot of channel (2.5 $ft^3/s$ per mile of channel) for November 3, 1974 in the same area but over a longer reach of the river. Flow duration at that time was 69 percent on the White River near Nora (See Horner, 1976, p. 246, and U.S. Geological Survey, 1976, p. 158.) Both rates represent seepages in an area of minor ground-water pumpage when compared with pumpage in the commercial and industrial area. Where ground-water pumpage diverts water that would otherwise contribute to streamflow, seepage rates are reduced.

Realizing that uncertainties in the inflow and outflow components prevent accurate measurements of seepage for individual reaches, the author used major inflow and outflow components to analyze total seepage. On September 30, 1980, at a flow duration of 65 percent on the White River near Nora, streamflows into and out of the study area, surface-water diversions, and treated-sewage discharges were recorded. Because of errors inherent in the individual measurements, however, ground-water seepage was calculated to range from 100 to 206 $ft^3/s$, and the seepage rate was calculated to range from 2.0 to 4.1 $ft^3/s$ per mile of channel, an effective error of ± 33 percent.

Additional errors were introduced by the uncertainties in the minor inflows and outflows, some of which might cancel out. Errors caused by storage behind check dams, unmeasured tributary inflows, and urban discharges, however, tend to make the calculated seepage larger than the actual seepage. An extensive investigation beyond the scope of the current study would be required to account for all the uncertainties in the inflow and outflow components of streams in the metropolitan area.

## Effective Recharge

In this report, effective recharge is the part of precipitation that reaches the ground-water flow system. Under steady-state conditions, long-term ground-water discharge to streams in a basin is equal to the long-term total effective recharge applied areally within the basin if surface-water and ground-water divides correspond. Cable and others (1971) used base flow separation methods modified from Busby and Armentrout (1965), multi-year probability methods after Leopold (1959), and 12 long-term stream hydrographs to calculate ground-water discharge and, therefore, total effective recharge within the upper White River basin.

For 50-percent probability of not being exceeded, ground-water discharge was 11.6 in/yr from 1946 to 1966 to the White River reach that drains the study area. Ground-water discharge to Fall Creek was 7.0 in/yr from 1930 to 1943 and ground-water discharge to Eagle Creek was 4.9 in/yr from 1940 to 1966. (See Cable and others, 1971, pl. 2.)

Calibrating an electric-analog model to seasonally high water levels of April and May 1974, Meyer and others (1975, p. 45) used a uniform effective recharge rate of 13.6 in/yr to the outwash aquifer and a variable recharge rate averaging 2.0 in/yr to the till plain in Marion County. Calibrating to seasonally low water levels of November 1974, Gillies (1976, p. 18) used a recharge rate of 11.9 in/yr in a digital model of the outwash aquifer north of Marion County in Hamilton County. Effective recharge to the till plain was calculated to be 3.7 in/yr and was simulated in the digital model as constant flux from the outwash-till-plain boundary.

Effective recharge rates of 12 in/yr to the outwash and 4.0 in/yr to the isolated part of the till plain were used in the current study to calibrate the model to seasonally low water levels for October 1980. The model was insensitive to changes in recharge rates ranging from 10 to 15 in/yr in the outwash and from 3.0 to 5.0 in/yr in the till plain isolated within the outwash while all other variables were held constant. (See "Sensitivity Analysis.")

A major negative component of the effective recharge rate is evapotranspiration. Isolation of this component was beyond the scope of the current study. Meyer and others (1975, p. 38) concluded that most of the water lost to evapotranspiration is from the unsaturated zone and that lowering water levels would not recapture this water.

## Ground-Water Pumpage and Water-Level Fluctuation

A historic account of water-level fluctuation and ground-water pumpage in Marion County through 1973 was reported by Meyer and others (1975, p. 33):

> "...it is apparent that although fluctuations in total ground-water pumpage in Marion County have occurred, the total ground-water pumpage has not changed substantially since the late 1940's. The increase in total demand for water in Marion County has been met instead through increased treatment and distribution of surface water by the Indianapolis Water Company."

The author's survey of commercial, municipal, and industrial users in 1979 also showed little change in ground-water pumpage from the outwash aquifer since 1973 as can be seen in the table that follows:

| Calendar year | Ground-water pumpage ($ft^3/s$) | Calender year | Ground-water pumpage ($ft^3/s$) |
|---|---|---|---|
| 1974 | 41.3 | 1977 | 45.6 |
| 1975 | 39.6 | 1978 | 42.4 |
| 1976 | 42.6 | 1979 | 41.5 |

Measurements of water levels in the observation-well network each spring and autumn from 1974 through 1980 show only minor fluctuations. Water levels in 59 of the 69 observation wells in October 1980 were within ±2 ft of the water levels recorded in autumn 1974. The remaining observation wells were affected by dewatering for construction and aggregate mining or by switching pumps in major well fields.

The minor fluctuations in water levels throughout the aquifer can be attributed to natural climatic cycles. The hydrographs of two observation wells and monthly precipitation shown in figure 9 can be compared with annual precipitation (National Oceanic and Atmospheric Administration, 1980) at Indianapolis in the table that follows:

| Calendar year | Annual precipitation (in.) | Fluctuation (in.) |
|---|---|---|
| 1974 | 41.31 | +1.38 |
| 1975 | 46.72 | +6.79 |
| 1976 | 33.82 | -6.11 |
| 1977 | 38.05 | -1.88 |
| 1978 | 42.94 | +3.08 |
| 1979 | 44.60 | +4.67 |
| 1980 | 34.86 | -5.07 |

The locations of observation wells 48 and 53 are shown in figure 2. In addition to spring highs and autumn lows, the hydrographs indicate a response to persistent wet and dry periods that correspond to wet and dry years. Minimum water levels recorded in 1977 resulted from consecutive dry years in 1976 and 1977. Maximum water levels in 1978 and 1979 correspond to wet years. In 1980, water levels remained high through April but then began a decline in response to a dry year. (The hydrograph of observation well 53 shows a pronounced decline beginning in April 1980 caused, in part, by aquifer tests and construction dewatering approximately 1,500 ft northeast of the well.) During the periods recorded, the water levels fluctuated approximately ±2 ft, but the long-term trend was a virtual steady state that concurs with the ground-water-pumpage data collected through 1979.

## Hydraulic Characteristics

The saturated thickness of the outwash aquifer (fig. 10) was calculated for selected points by subtracting the base of the glacial outwash from the water-table surface. The thickest parts of the aquifer generally conform to valleys developed on the bedrock surface. The thinnest parts of the aquifer result from either bedrock highs or, in a few isolated areas, thick clay deposits on the bedrock surface.

Horizontal hydraulic conductivities at specific points in the aquifer were estimated by assigning transmissivities to the lithologic units reported in the drillers' well logs, summing the transmissivities, and then dividing the total by the saturated thickness. The transmissivities were calculated by multiplying vertical thickness of the lithologic unit by horizontal hydraulic conductivities derived by Meyer and others (1975, p. 18) from specific-capacity data. The assumptions and methods of the nonsteady technique for unconfined aquifers (Theis, 1963) were used by Meyer and others to calculate the horizontal hydraulic conductivities that are listed in the following table:

| Lithology | Horizontal hydraulic conductivity (ft/d) |
|---|---|
| Gravel | 415 |
| Sand and gravel | 240 |
| Sand | 40 |

Silt and clay deposits were assumed to have a negligible horizontal hydraulic conductivity in the calculations. The estimated horizontal hydraulic conductivities were then contoured and grouped into the areas shown in figure 11. From an aquifer test done by Meyer (1978) in southern Marion County (fig. 2), horizontal hydraulic conductivity of the top 49 ft of the aquifer was calculated to be 108 m/d (354 ft/d) and hydraulic conductivity of the streambed

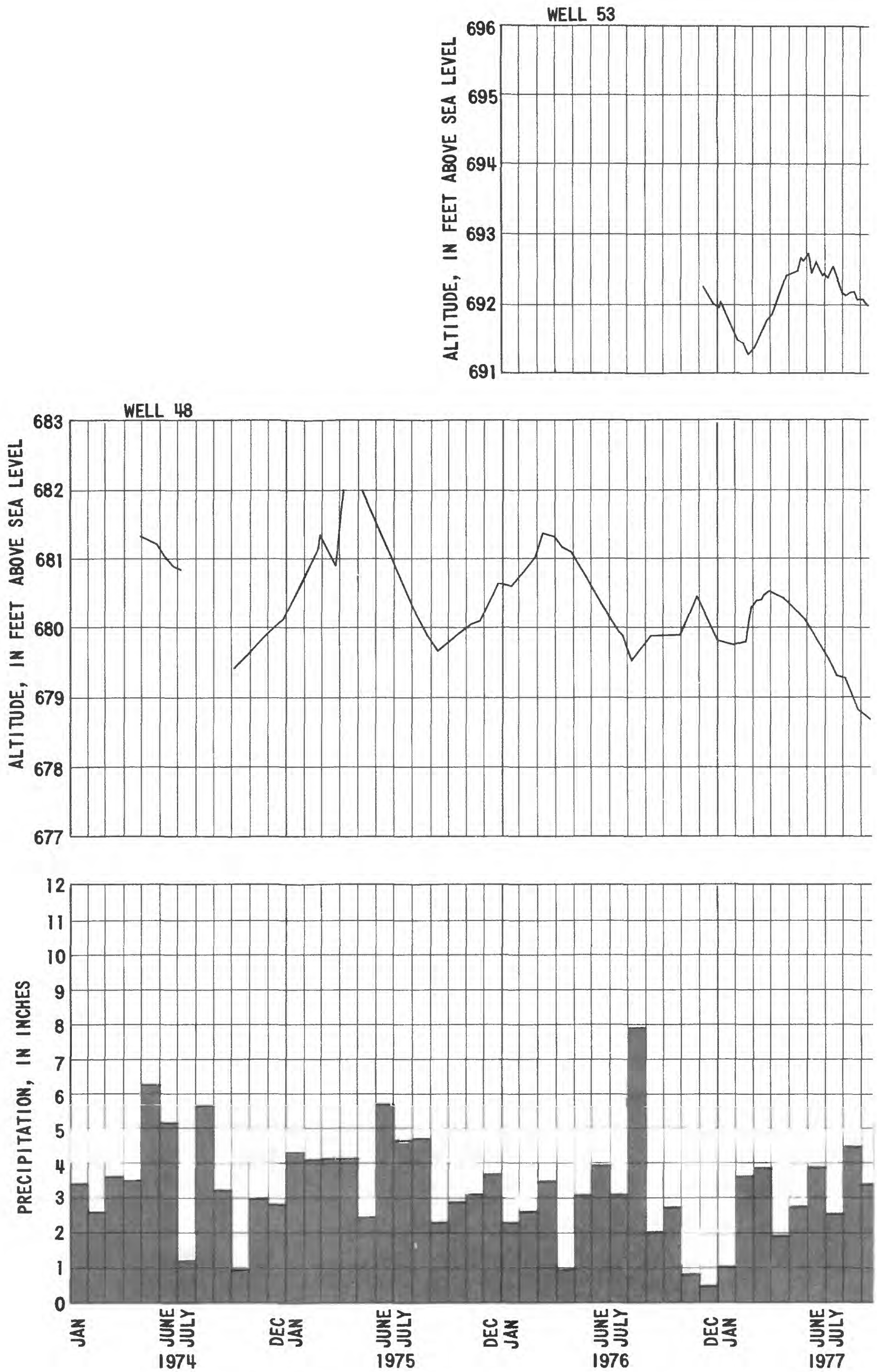
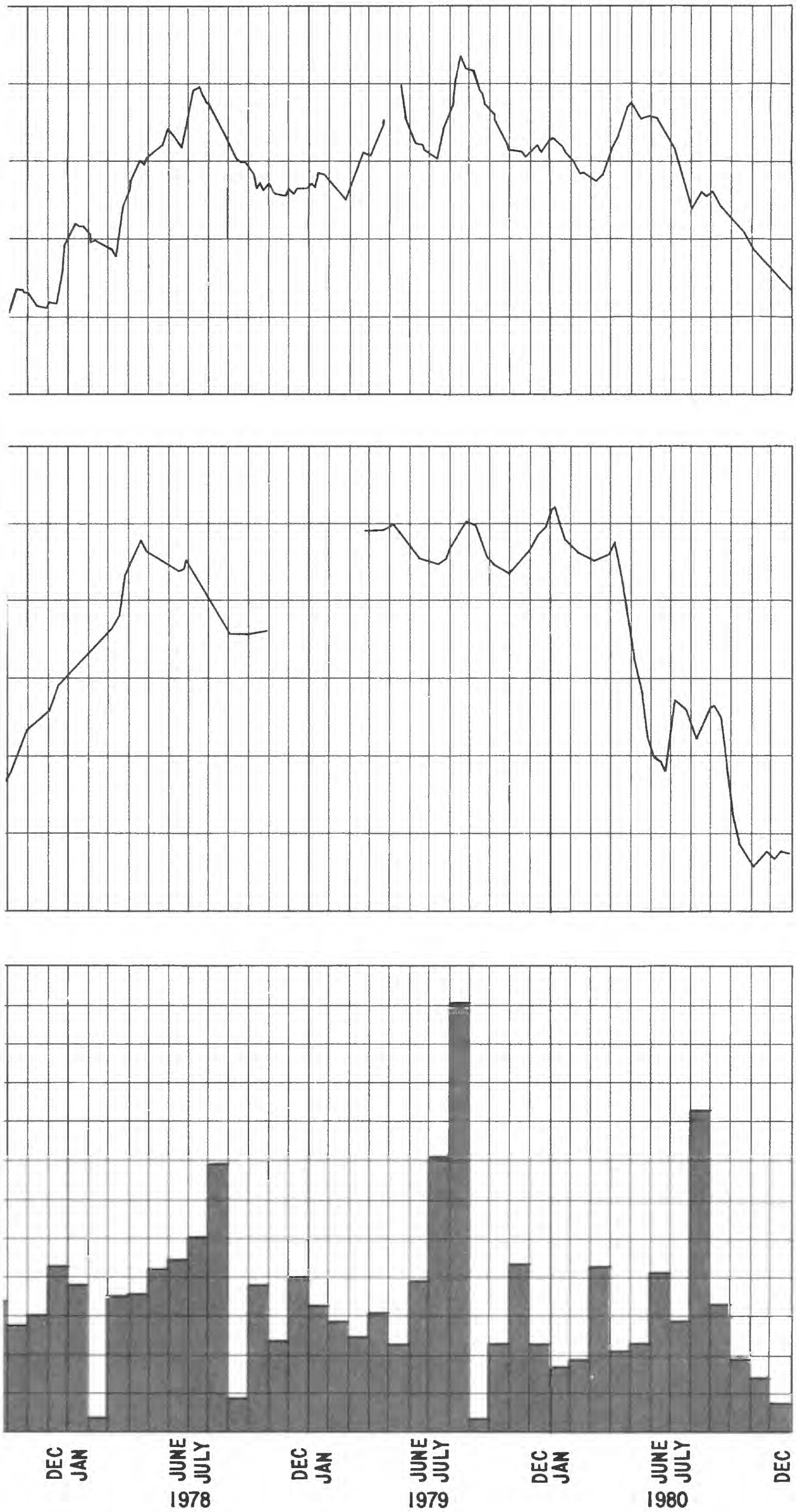



Figure 9.-- Water-level fluctuations in observation wells 48 and 53,




and monthly precipitation at Indianapolis.

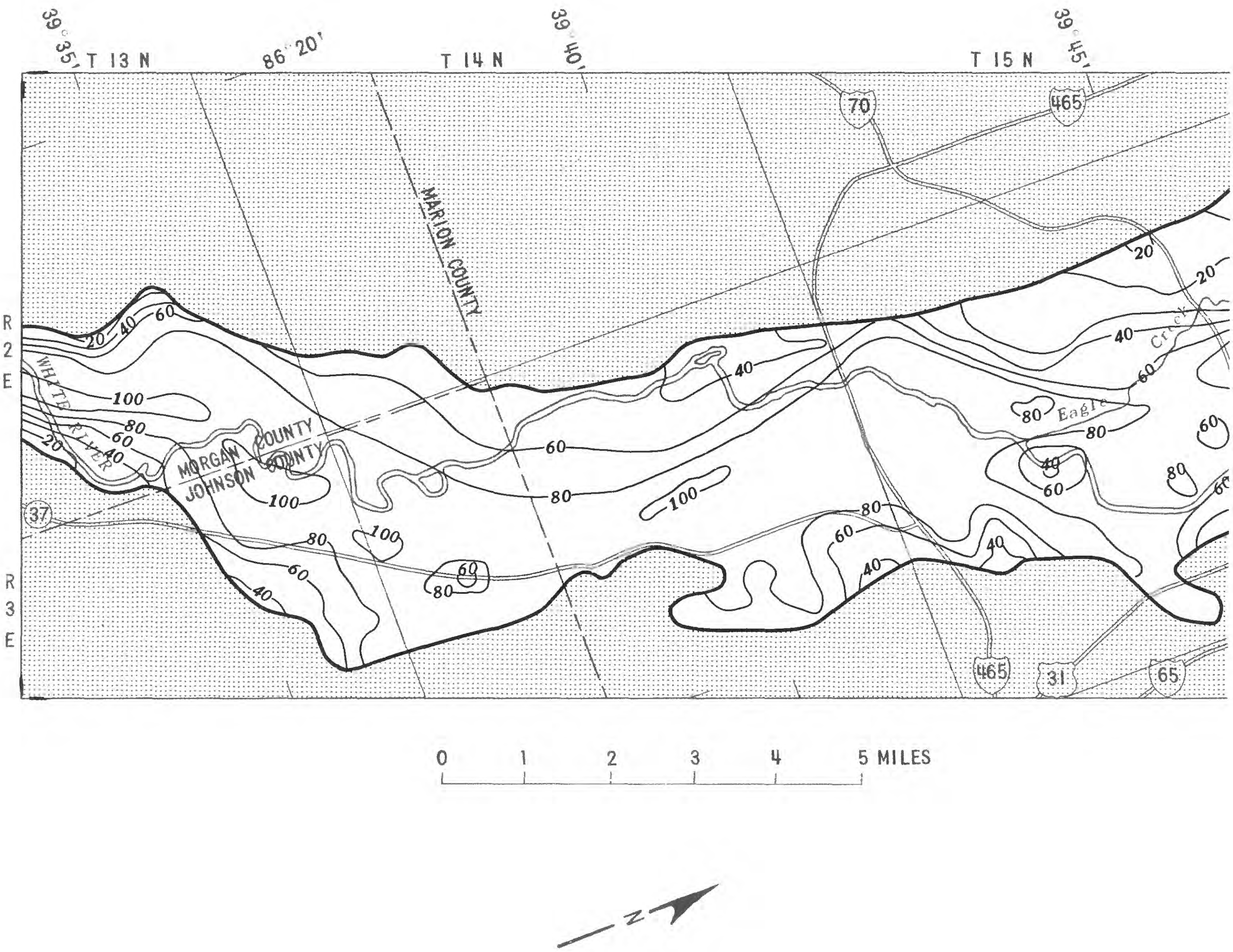
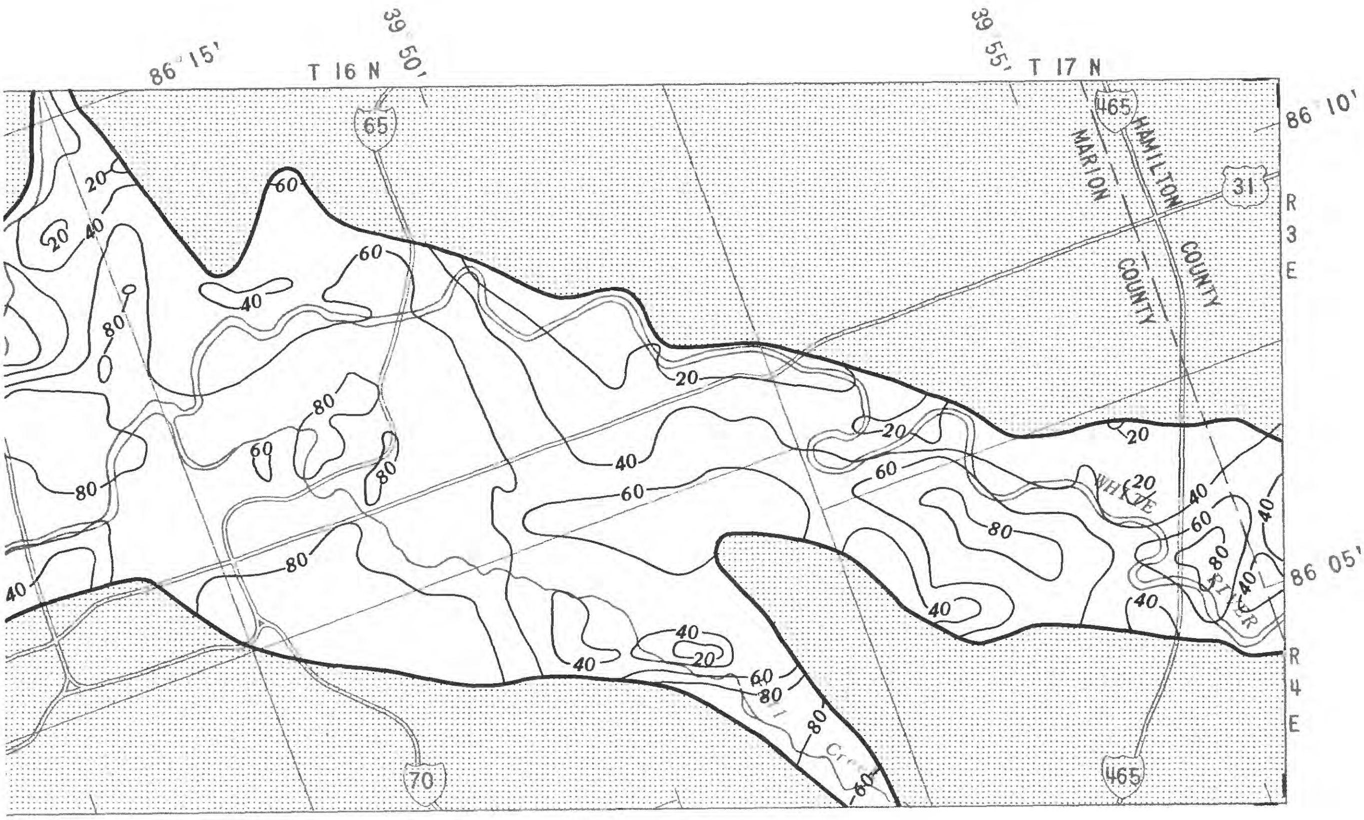



Figure 10.-- Saturated thickness of the outwash aquifer.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

60 Line of equal thickness. Interval 20 feet

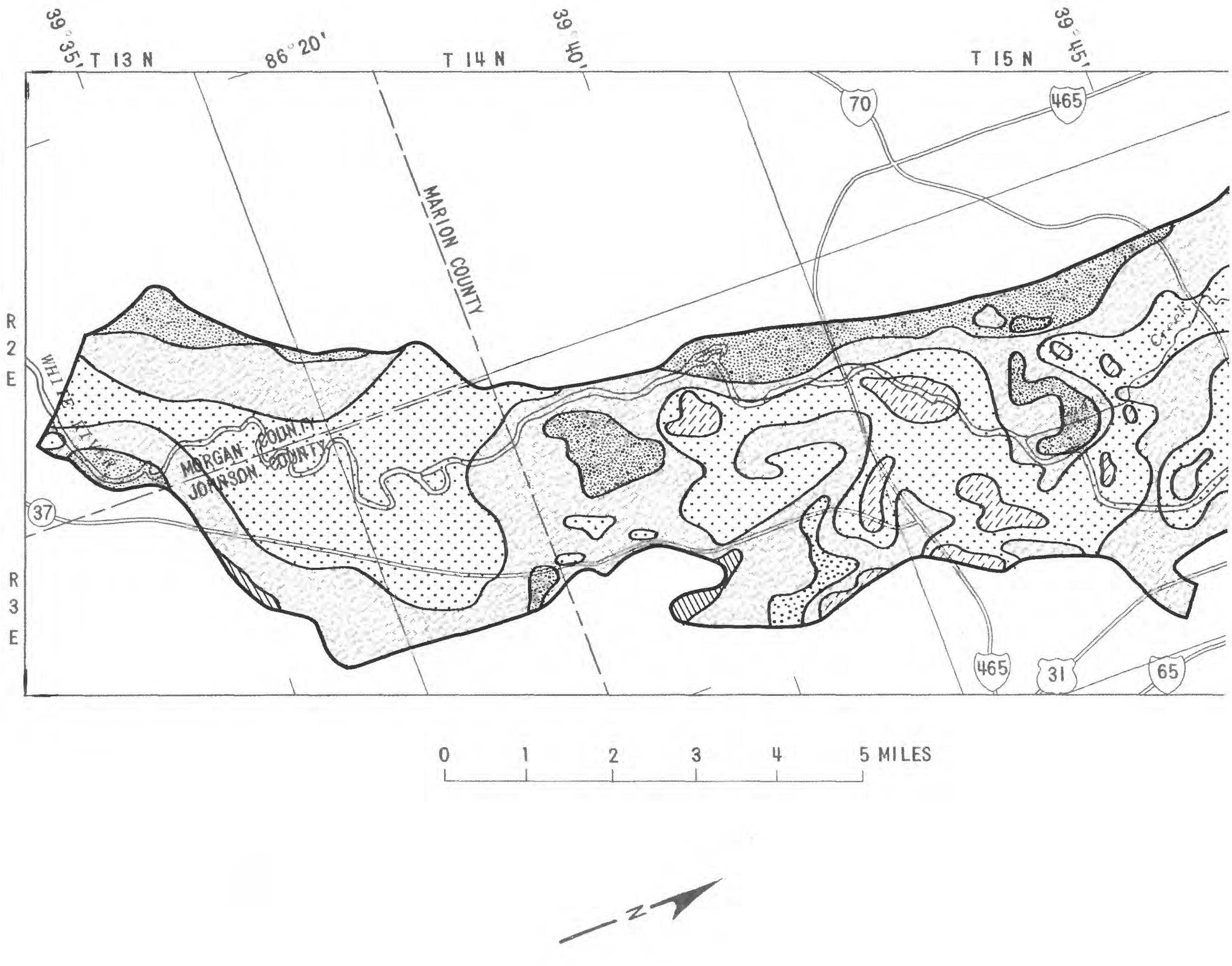
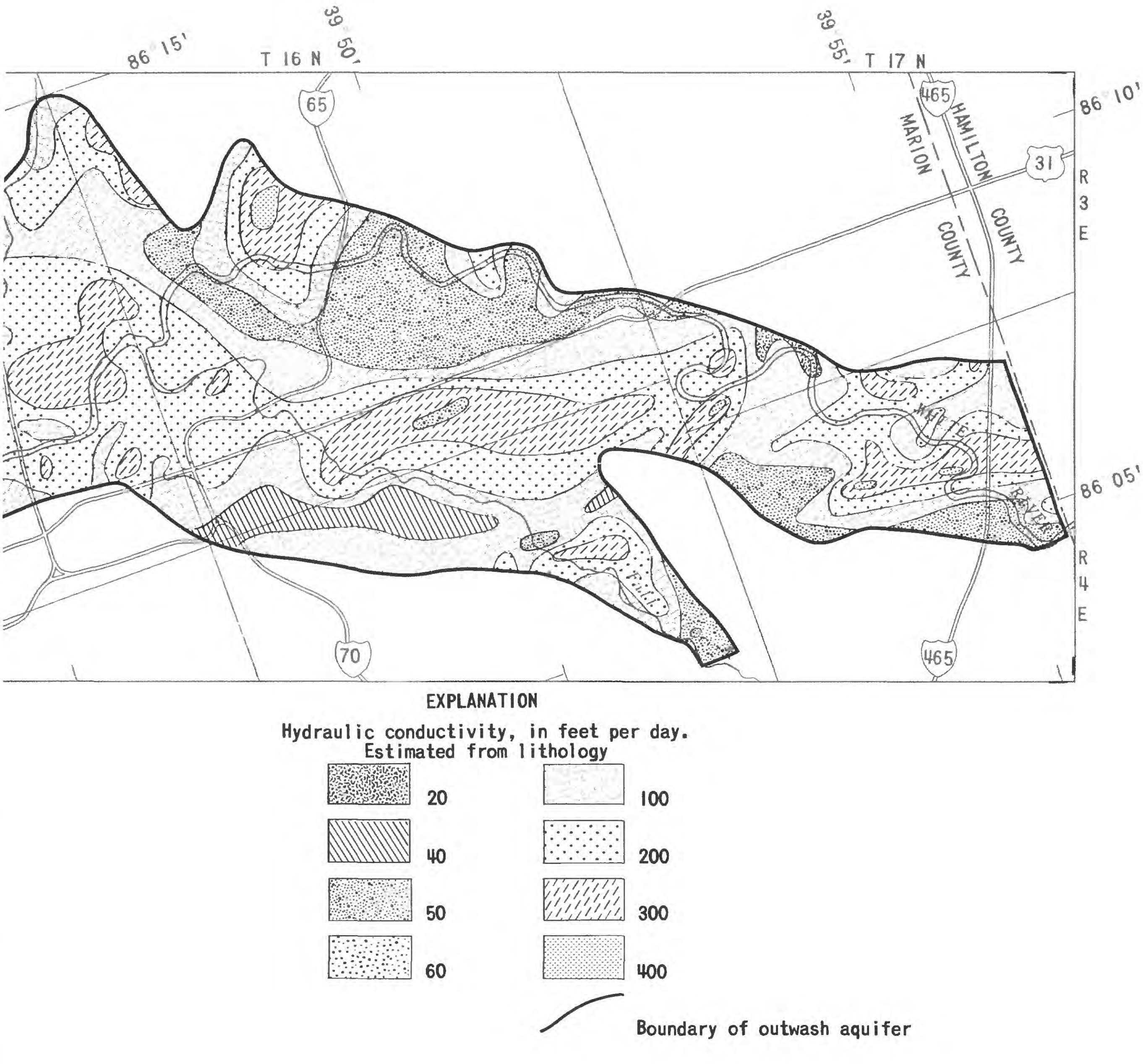



Figure 11.-- Estimates of hydraulic conductivities of the outwash aquifer.



86°15'
T 16 N
39°50'
65
39°55'
T 17 N
465
MARION COUNTY
HAMILTON COUNTY
31
86°10'
R 3 E
WHITE RIVER
86°05'
R 4 E
Fall
70
465
EXPLANATION
Hydraulic conductivity, in feet per day.
Estimated from lithology
20
40
50
60
100
200
300
400
Boundary of outwash aquifer

was calculated to be 2.2 m/d (7.2 ft/d). The distance-drawdown techniques of Stallman (1963) and the assumptions of Bennett and others (1967) were used by Meyer to calculate the horizontal hydraulic conductivity. For comparison, the horizontal hydraulic conductivity at the aquifer test site was estimated by the method described in the preceding paragraph to be 390 ft/d for the top 49 ft of the aquifer.

## DIGITAL MODEL OF THE OUTWASH AQUIFER

The finite-difference model for aquifer simulation in two dimensions (Trescott and others, 1976) was used to analyze ground-water flow in the unconfined outwash aquifer. Steady-state conditions that were assumed in the model analysis are approximated by the following equation:

$$\frac{\partial}{\partial x}\left(K_x b \cdot \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y b \cdot \frac{\partial h}{\partial y}\right) = \pm W_{(x,y)}$$

where

- x and y are the coordinates of the finite-difference grid,
- $K_x$ and $K_y$ the principal components of hydraulic conductivity,
- b the saturated thickness of the aquifer,
- h the hydraulic head of the aquifer,

and

- W the recharge to or discharge from the aquifer.

The aquifer was assumed to be isotropic and to have horizontal flow. Recharge to or discharge from the aquifer was assumed to be instantaneous through the entire saturated thickness. These assumptions are valid except where the aquifer contains extensive clay layers. (See "Geologic Setting".) The equation-solving scheme chosen for model analysis was the strongly implicit procedure, which is one of the three equation-solving schemes available as options in the model.

Vertical leakage to and from the White River, Fall Creek, and Eagle Creek was simulated in the model (fig. 12). Leakage at steady-state was simulated by Darcy's equation with a limit imposed on the maximum leakage downward through the streambed (Trescott and others, 1976, p. 11). Hydraulic heads of the individual stream nodes were assumed to be constant, and the streambed was assigned a unit thickness.

Pumping locations and withdrawls for 1974 through 1979 were used as input to the model. After minor adjustments to locate the pumping with respect to the finite-difference grid, the locations and withdrawals were held constant through calibration, sensitivity analysis, and pumping simulations.

The boundaries of the unconfined outwash aquifer were modeled as constant heads during calibration, except for the west lateral boundary in Morgan County, which was modeled as a no-flow boundary. The bottom of the aquifer was initially assumed to be a no-flow boundary.

After calibration, ground-water fluxes from the boundaries other than the no-flow boundaries were calculated with constant heads. Then both constant-head and constant-flux boundaries were used in the sensitivity analysis and in the pumping simulations.

## Calibration

The digital model was calibrated to water levels of October 6 to 10, 1980, when flow duration on the White River near Nora was 67 percent. After initial adjustments of the size and the shape of the hydraulic-conductivity groups within the data constraints, the stream-aquifer connections were adjusted. The hydraulic conductivity of the streambed was simulated as 7 ft/d, as determined in an aquifer test adjacent to the White River in southern Marion County (Meyer, 1978). The hydraulic conductivity of the streambed was then adjusted near major pumping centers until water levels in and near the pumping centers were approximated. Finally, the conductivities that permitted the approximation near the pumping centers were extended to the rest of the stream. Final conductivities for an assumed streambed thickness of 1 foot are given in the table that follows:

| Stream | Hydraulic conductivity of Streambed (ft/d) |
|---|---|
| White River | 1.0 |
| Fall Creek | .025 to .05 |
| Eagle Creek | .10 to .20 |

Three areas that did not conform to the original concepts of the model required further adjustments. In two areas, water flows through high and then low transmissivity before discharging into the White River (fig. 13). Saturated thickness decreases by approximately 50 percent down the flow path in the two areas. It was necessary to double the hydraulic conductivity in one of the two areas and to triple it in the other to approximate the water levels. The adjustment suggests that the bedrock is hydraulically connected to the outwash aquifer in the two areas and that the saturated thickness in both areas was larger than was originally assumed. The third area that did not conform to the original concepts of the model was in and near the area of the heaviest pumpage and the area of the continuous clay layer beneath the mouth of Eagle Creek. The hydraulic conductivities were increased 100 to 200 percent in the area to approximate the cone of depression formed by the pumpage. This adjustment indicates that the hydraulic conductivities in the area of the buried clay layer are inaccurate; however, they do allow an approximation of ground-water flow. This area of the model was not within the cone of influence in any of the pumping simulations and, therefore, had no effect on the results. The final model-simulated hydraulic conductivities and the extent of the clay layer are in figure 14.

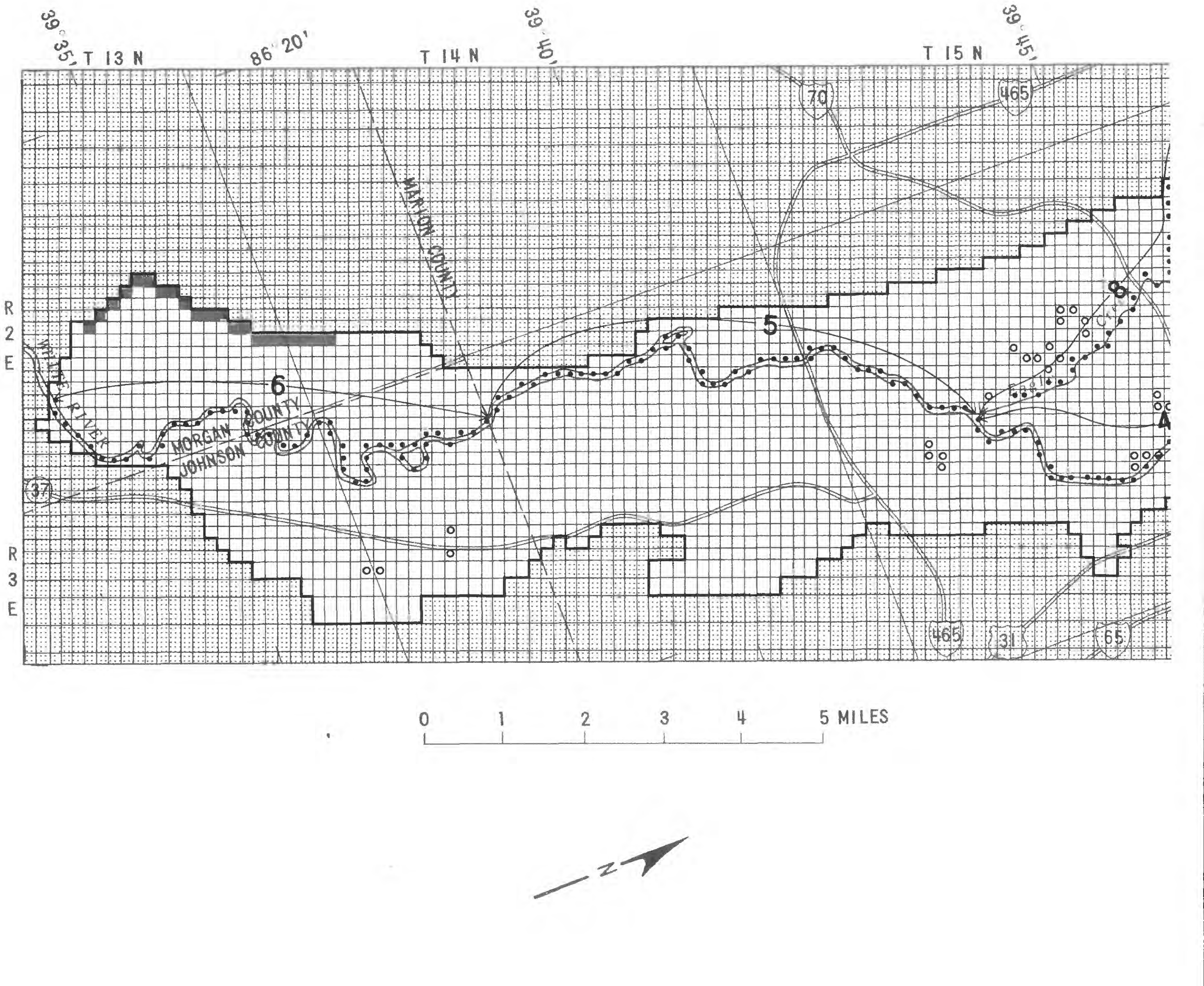
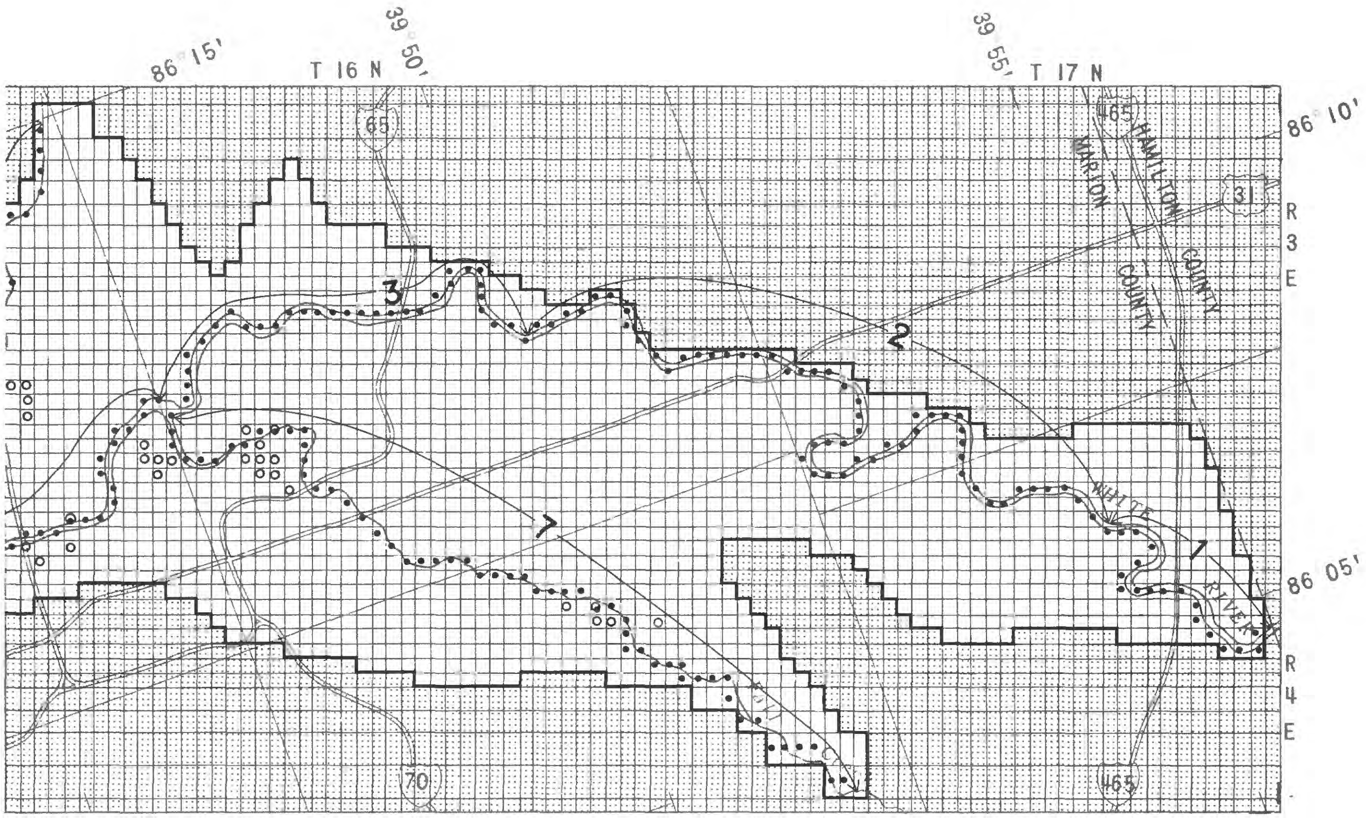



Figure 12.-- Finite-difference grid and modeled stream reaches.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Constant-head or constant-flux boundary

No-flow boundary

Stream node

Pumping node (1980)

5

Modeled stream reach

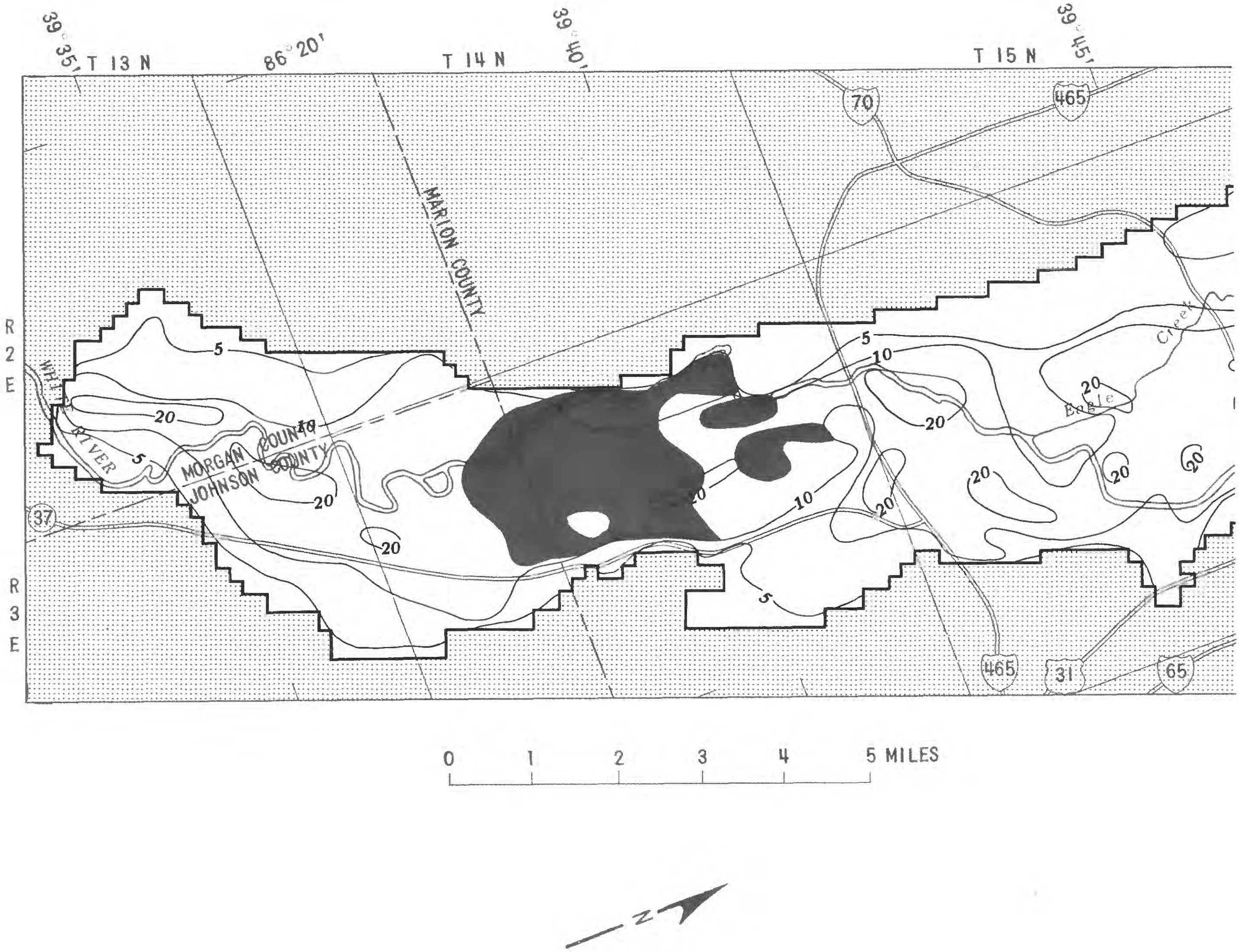
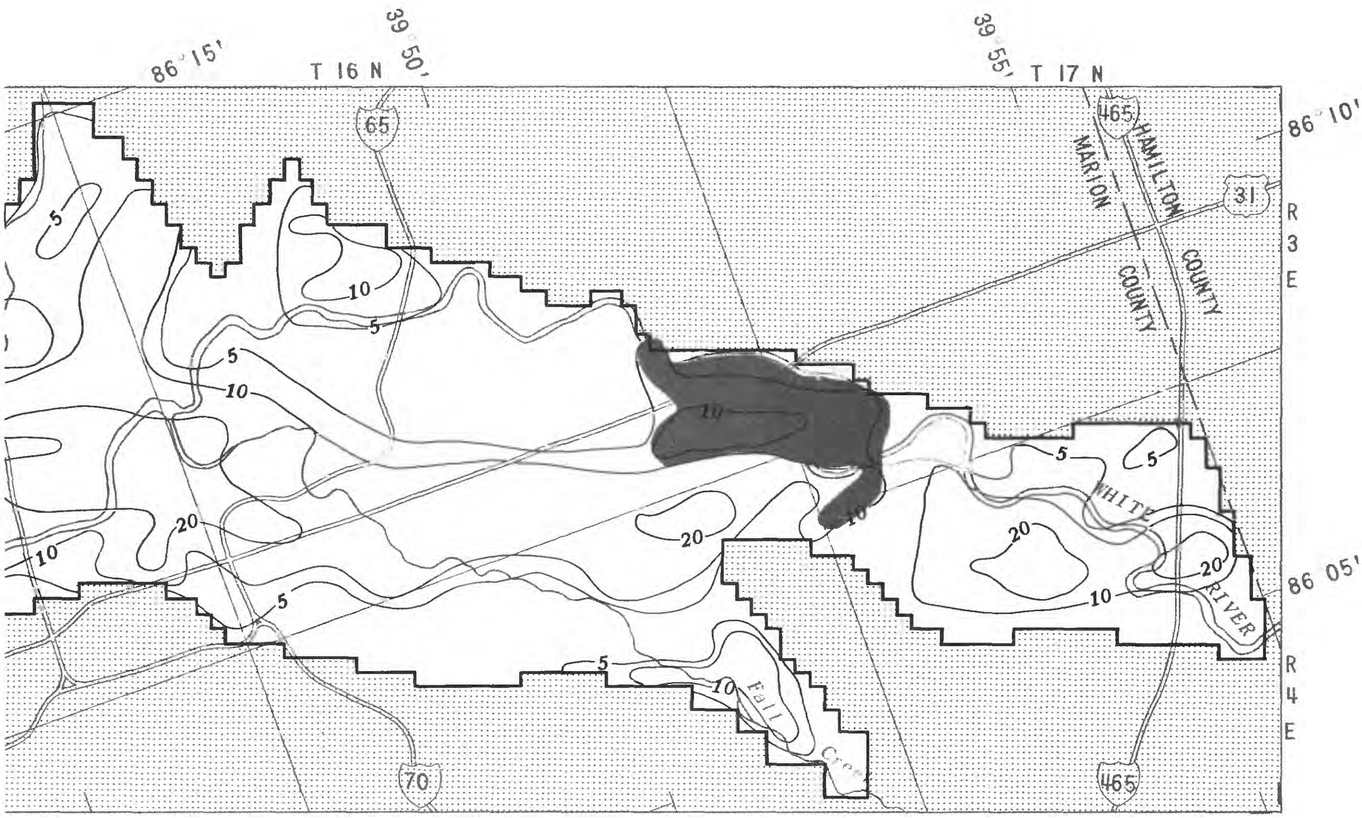



Figure 13.-- Model-simulated transmissivities.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Areas adjusted to compensate for flow through base of aquifer

Line of equal transmissivity, in thousands of square feet per day. Intervals 5000 and 10,000

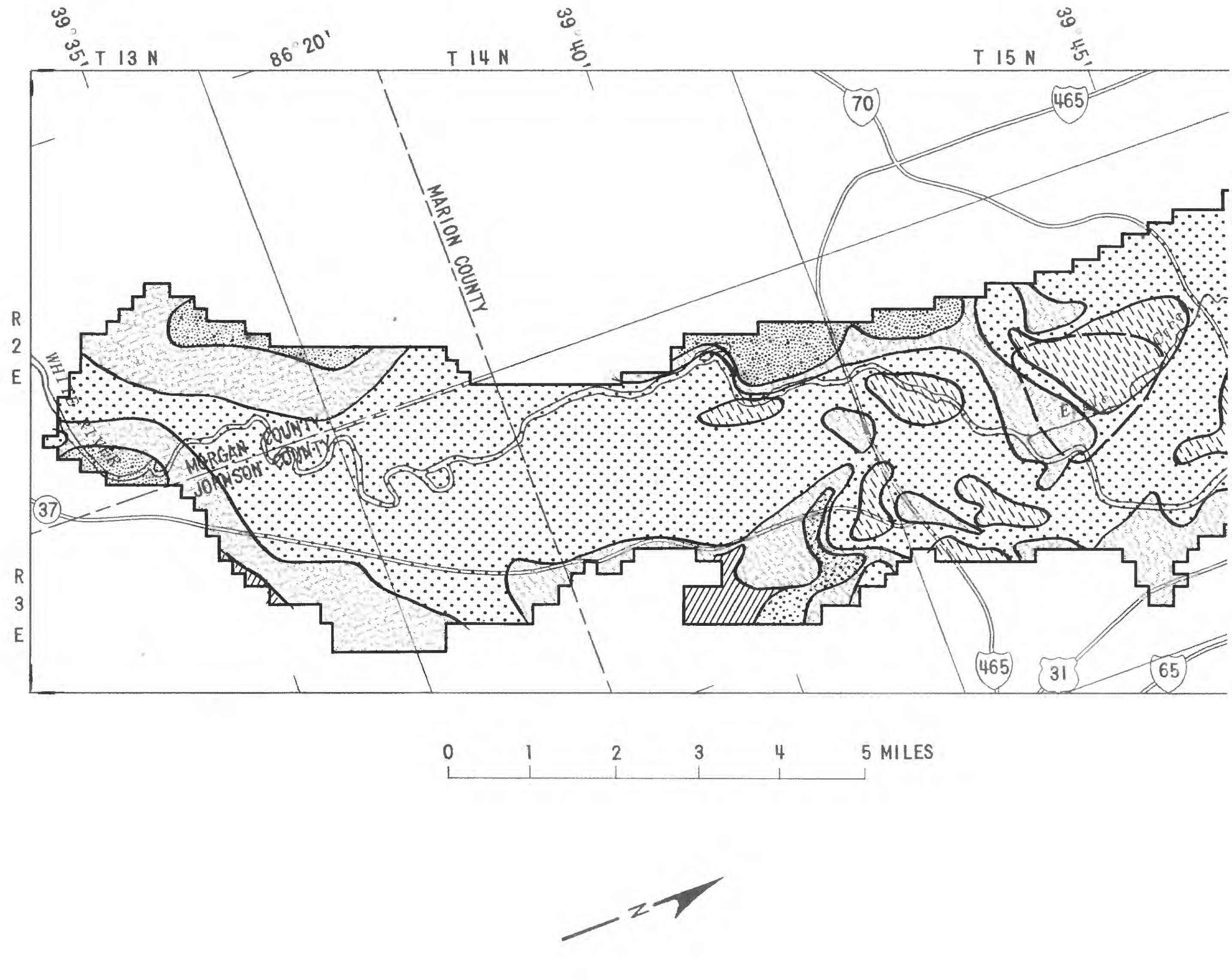
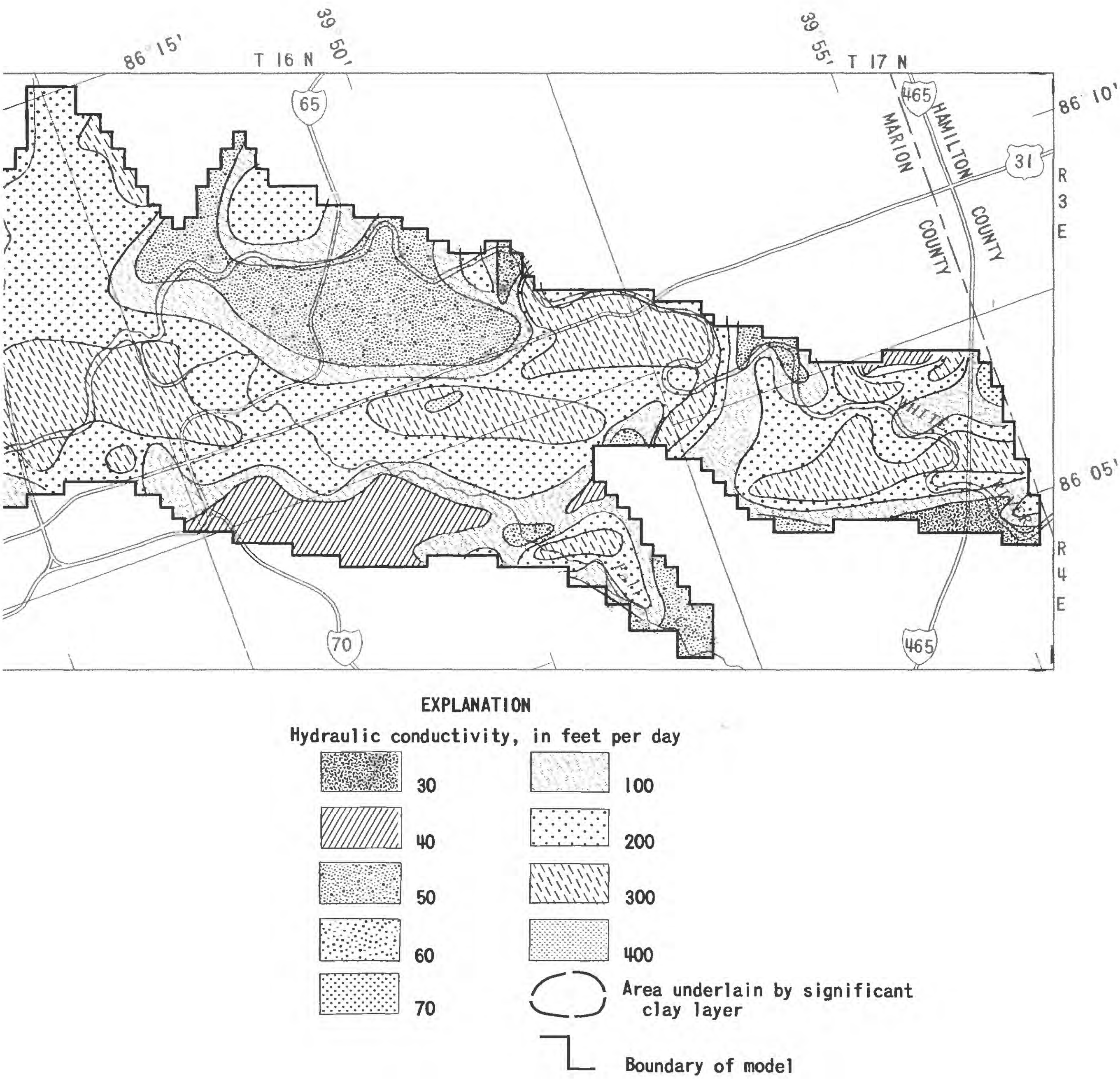



Figure 14.-- Model-simulated hydraulic conductivities.


86°15'
T 16 N
39°50'
39°55'
T 17 N
65
465
MARION COUNTY
HAMILTON COUNTY
31
86°10'
R 3 E
86°05'
R 4 E
70
465
EXPLANATION
Hydraulic conductivity, in feet per day
30
40
50
60
70
100
200
300
400
Area underlain by significant clay layer
Boundary of model

Model-simulated water levels are shown in figure 15. A positive sign indicates that model-simulated water levels are higher than measured levels by the amount shown. Conversely, a negative sign indicates that model-simulated water levels are lower than measured levels. Summing the absolute differences between the model-simulated water levels and the measured water levels and dividing by the total number of wells within the modeled area, 82, gives an average absolute difference of 1.4 ft.

## Ground-water Budget

The water budget of the digital model calibrated to water levels in the aquifer in October 1980 are summarized in table 2. Nearly half of the recharge to the aquifer (48 percent) was direct effective recharge from precipitation. Flux from the model boundaries, primarily representing flow from the confined aquifers of the till plain, accounted for 41 percent of the recharge. Seepage from major streams induced by ground-water pumpage accounted for the remaining 11 percent of recharge. Ground-water pumpage from the aquifer was 29 percent of discharges, and ground-water seepage to the principal streams was 68 percent. Flux out of the model area was 3 percent of discharges.

Table 2.--Model-simulated ground-water budget

| Recharge | | | Discharge | | |
|---|---|---|---|---|---|
| Inflow | Rate ($ft^3/s$) | Percent of total | Outflow | Rate ($ft^3/s$) | Percent of total |
| Direct recharge | 69 | 48 | Existing pumpage | 42 | 29 |
| Boundary flux | 60 | 41 | Boundary flux | 5 | 3 |
| Leakage from streams | 16 | 11 | Seepage to streams | 98 | 68 |
| Total | 145 | 100 | Total | 145 | 100 |

Model-simulated seepage to and from the reaches shown in figure 12 are listed in table 3. The sum of ground-water seepages in the model (82 $ft^3/s$) was less than the lowest seepage estimated from analysis of streamflow gains and losses (100 $ft^3/s$). As indicated in the section "Stream-Aquifer Connection," however, the estimate of seepages tended to be high because of unmeasured inflows and storage behind check dams.

Model-simulated seepage rates to the principal streams varied significantly. Average seepage to the White River was 2.0 $ft^3/s$ per mile of channel (at the low end of the range of seepage rates derived from analysis of gains and losses). The seepage rate to Fall Creek, however, was just 0.4 $ft^3/s$ per mile of channel because of losses induced by pumping and because the hydraulic conductivity of the streambed of Fall Creek was simulated to be 5 percent or less than that of White River. Meyer and others (1975, p. 46) also suggested that the hydraulic conductivity of the streambed of Fall Creek was less than that of the White River.

The average seepage rate of water from Eagle Creek to the aquifer was 0.3 $ft^3/s$ per mile of channel because major pumping centers along the lower reach of the creek have reversed the direction of ground-water flow and the creek is recharging the aquifer near the pumping center. Increasing the hydraulic conductivity of the streambed by a factor of four had little effect on the calibrated model (table 3).

Table 3.--Model-simulated seepages

| Stream | Reach | Model-calibrated simulated seepage rates ($ft^3/s$) | Hydraulic conductivity of streambed (four times calibrated values) ($ft^3/s$) |
|---|---|---|---|
| White River | 1 | 5.2 | 5.1 |
| Do. | 2 | 18 | 18 |
| Do. | 3 | 9.7 | 11 |
| Do. | 4 | 4.8 | 6.2 |
| Do. | 5 | 19 | 19 |
| Do. | 6 | 23 | 23 |
| Fall Creek | 7 | 4.1 | 2.5 |
| Eagle Creek | 8 | [1]-2.0 | -2.7 |
| Total | | 82 | 82 |

[1]Negative sign indicates seepage from the stream to the aquifer.

## Sensitivity

After calibration, the sensitivity of the model to uniform changes in hydraulic conductivity, recharge, and stream-aquifer connection was tested, and sensitive limits of these variables were defined. The sensitivity was calculated by a standard statistical test, the RMSE (root mean square error) of the difference between measured and simulated water levels. The following equation was used:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (h_1 - h_0)^2}$$

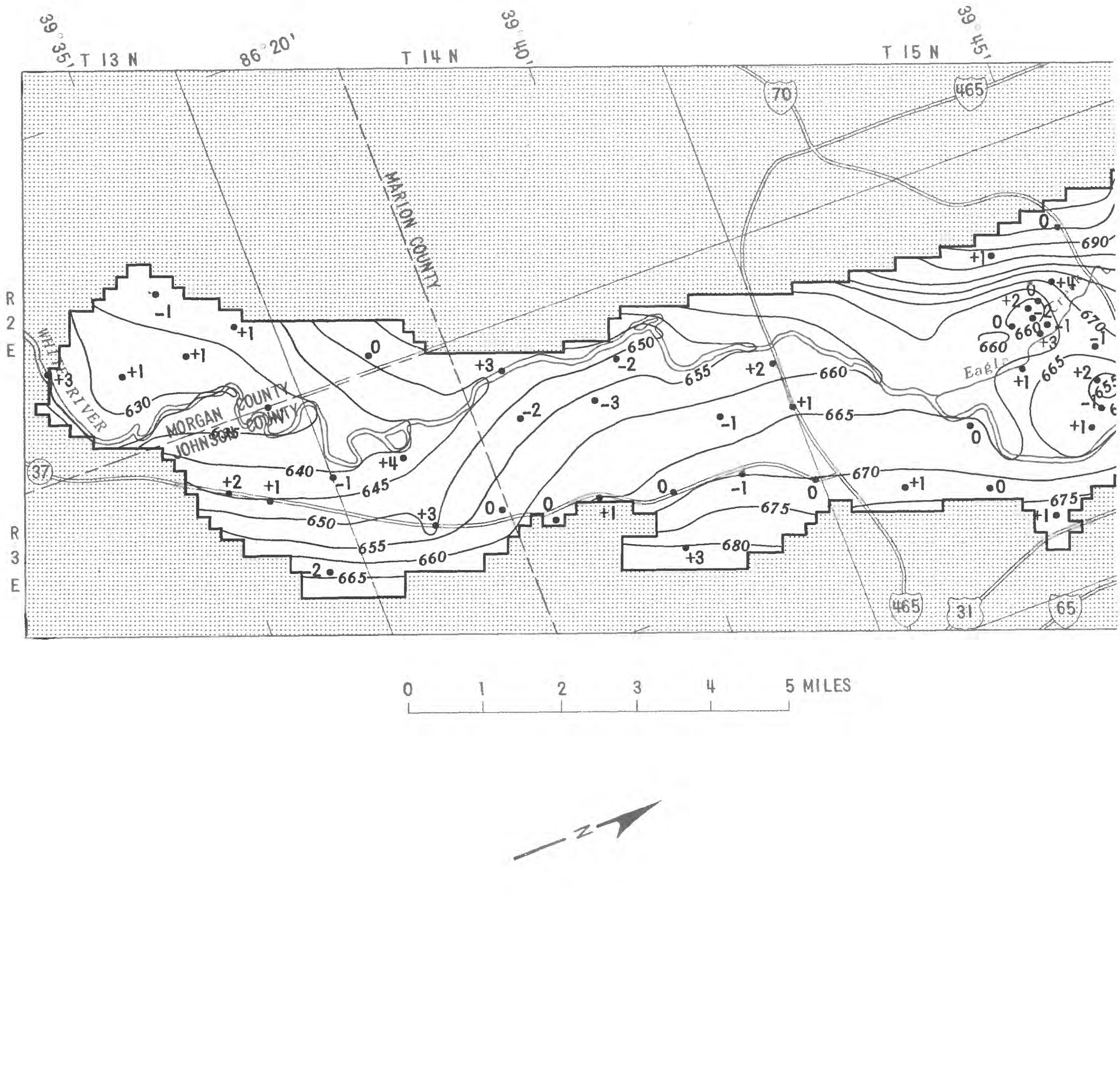
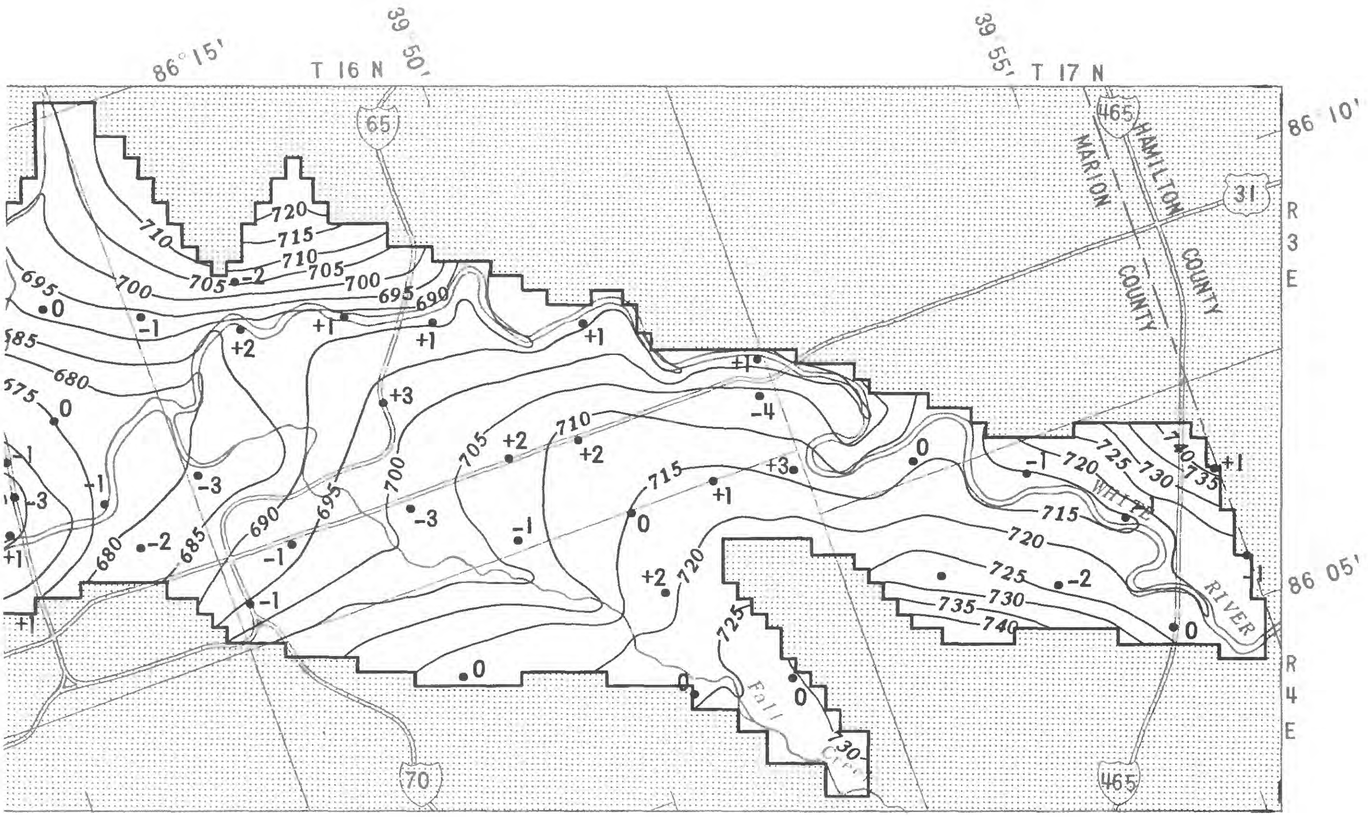



Figure 15.-- Model-simulated water levels.



**EXPLANATION**

Outwash and alluvium

Tipton till plain

670 Line of equal water level (simulated). Interval 5 feet

+2
-2 Deviation from measured water level

• Observation well

where

$N$ is the number of measurments (82),

$h_0$ the simulated water level,

and

$h_1$ the measured water level.

A subroutine programmed by D. B. Sapik of the Geological Survey (written commun., 1981) was added to the finite-difference model to calculate the RMSE.

The horizontal hydraulic conductivity of the aquifer was changed through a range of values while all other variables were held constant. RMSE's were calculated for each change, first for a constant-head boundary and then for a constant-flux boundary. The ratio of the changed horizontal hydraulic conductivity to the calibrated horizontal hydraulic conductivity was then plotted against the RMSE's (fig. 16). The same procedure was followed in testing the sensitivity of the model to uniform changes in effective recharge and hydraulic conductivity of streambed, which are also plotted in figure 16.

The graphs indicate that the model was generally more sensitive to changes in horizontal hydraulic conductivity than to changes in effective recharge or hydraulic conductivity of the streambed and that the model was insensitive to increases in hydraulic conductivity of the streambed. The model was also more sensitive to constant-flux boundaries than to constant-head boundaries because simulations with constant-head boundaries adjust flow from the boundaries to accomodate changes in variables. Simulations with constant-flux boundaries, however, limit flow from the boundaries to that at calibration.

The sensitivity of the model to changes in selected variables is given in table 4. The limiting values of the variables were defined by the constant-flux boundary curves and by an RMSE of 2.0 ft. Individually, any of the variables in table 4 could be uniformly changed within the ranges listed and the model would generally remain insensitive.

Table 4.--Limits of sensitivity for selected model variables

| Variable | Values at calibration | Sensitivity limits[1] |
|---|---|---|
| Hydraulic conductivity | 30 to 400 ft/d | 25 to 450 ft/d |
| Recharge rate to outwash | 12 in/yr | 10 to 15 in/yr |
| Recharge rate to till plain | 4.0 in/yr | 3.2 to 5.0 in/yr |
| Streambed conductivity[2] | .025 to 1.0 ft/d | .013 to 4.0 ft/d |

[1]Limits were defined for changes in one variable at a time while all other variables were held constant.

[2]For a streambed thickness assumed to be 1 ft.

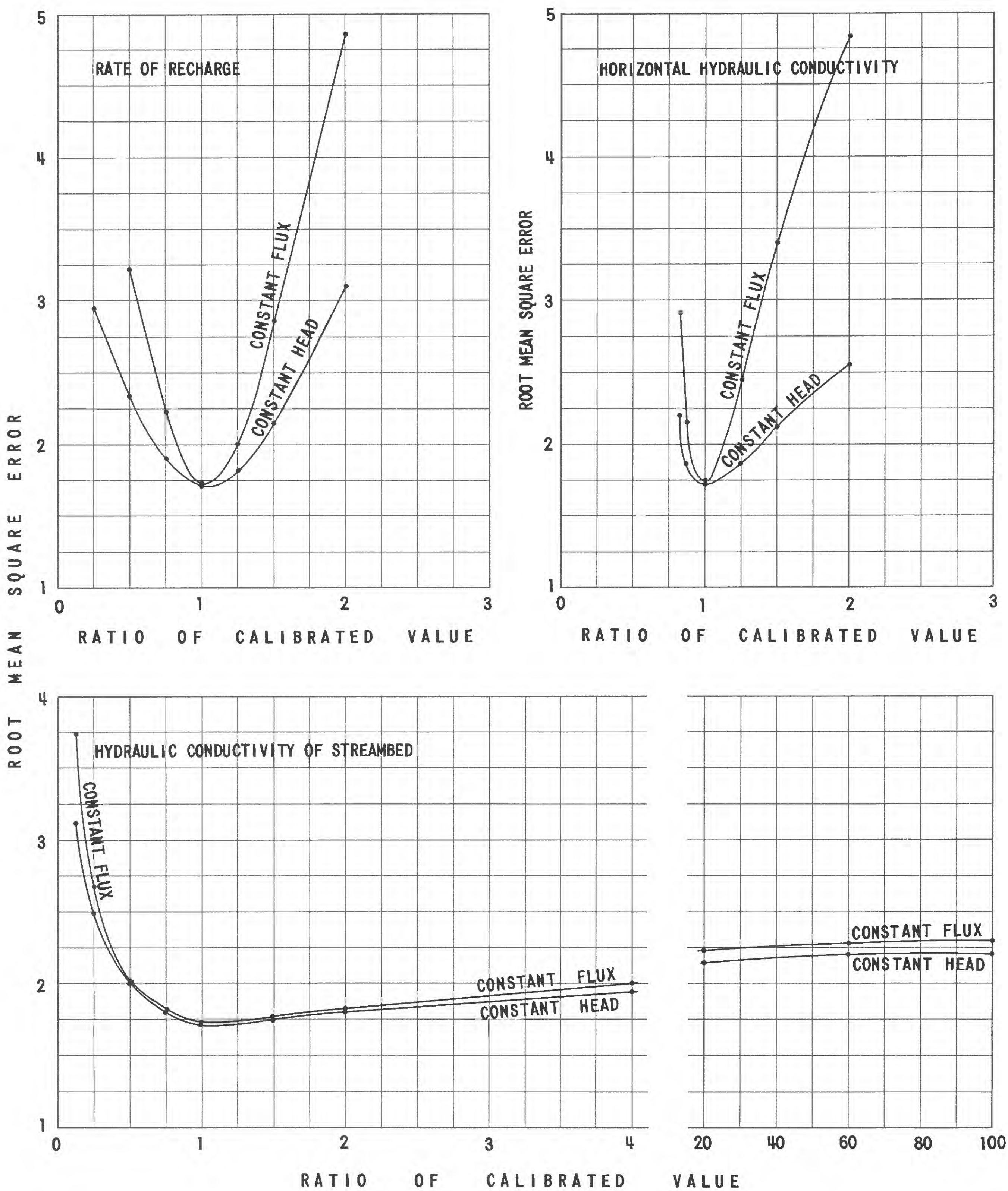



Figure 16.-- Sensitivity of the model to changes in selected variables.

Formal sensitivity analysis was not expanded beyond the testing of single-variable changes. Because the sensitivity of the model to a given variable is dependent on the values assigned to all other variables, the ranges in sensitivity could vary appreciably if changes were made to two or more variables at the same time.

Some modeled areas were more sensitive to changes in the variables listed in table 4 than others. Data collection in and an awareness of such areas could improve future applications of the model. To illustrate that some modeled areas are more sensitive than others, the author assigned values to variables beyond the limits in table 4. Constant-head boundaries were used because constant-flux boundaries were so sensitive that they masked the more sensitive areas.

A decrease in horizontal hydraulic conductivity of 19 percent from the model-calibrated values caused model-simulated water-level declines exceeding 3 ft near large pumping centers (fig. 17). The declines were proportional to the pumping rate. Conversely, an increase in horizontal hydraulic conductivities of 19 percent would cause model-simulated water levels to rise, but to a lessor degree than the declines because the model is slightly more sensitive to increases in horizontal hydraulic conductivity than to decreases.

A 75-percent decrease in hydraulic conductivity of the streambed caused model-simulated water-level declines exceeding 3 ft in an area along Eagle Creek adjacent to one of the heaviest pumping centers in the model, but water levels rose more than 3 ft around an unstressed area of Fall Creek (fig. 18). A 9,900-percent increase in hydraulic conductivity of the streambed caused opposite but roughly equal effects on water levels in the same two areas and also caused a rise in water levels around a third area near a major pumping center at the mouth of Fall Creek (fig. 19). This area was insensitive to decreases in hydraulic conductivity of the streambed but was sensitive to large increases because the values at calibration were already at the upper limit of sensitivity.

The effects of decreases in recharge rates were straightforward. Decreases caused water levels to decline adjacent to the no-flow boundary and in the isolated part of the till plain where recharge was low at calibration. Increases in recharge rates caused equal but opposite effects in the same two areas.

# PUMPING SIMULATIONS

## Analog and Digital Models

In the analog-model analysis by Meyer and others (1975, p. 55), hypothetical pumping locations were chosen to conform to areas of maximum saturated thickness, maximum transmissivity, and proximity to major streams. Pumping locations in the digital model analysis were chosen as closely as possible to those of the analog-model analysis to conform to the same criteria and to provide for a comparison of the two models. Drawdown limits of one-half and two-thirds saturated thickness used in the analog-model analysis were also chosen for the digital-model analysis so that the results of the experiments could be directly compared.

Comparison of the effects on water levels and streamflows between the two models is not straightforward because of several basic differences in the models. In any comparison of results, the following differences in the two analyses should be considered:

1. The electric-analog model simulated the unconfined outwash aquifer, confined till-plain aquifers, and carbonate aquifers in the approximately 400 $mi^2$ of Marion County (fig. 1). The digital-model analysis simulated the outwash aquifer in approximately 90 $mi^2$ in Marion County and northern parts of Johnson and Morgan Counties. Boundaries and treatment of the boundaries are, therefore, significantly different.

2. In the analog-model analysis, which involved a much larger and more complex system than the digital-model analysis, the till plain isolated between the White River and Fall Creek was assumed to have a minimal effect on recharge to the outwash system. In the digital-model analysis concentrating on the outwash aquifer, recharge to the same isolated till plain was assumed to be much less than to the outwash.

3. The analog-model analysis was calibrated to conditions of April and May 1974 (Meyer and others, 1975, p. 45) and variables in the model represent seasonally high water levels. The digital-model analysis was calibrated to conditions of October 1980, and variables in this model represent seasonally low water levels.

4. The pumping experiments in the analog-model analysis simulated only the proposed increase in pumpage (Meyer and others, 1975, p. 56). In the digital-model experiments, the established pumpage plus the increased pumpage was simulated.

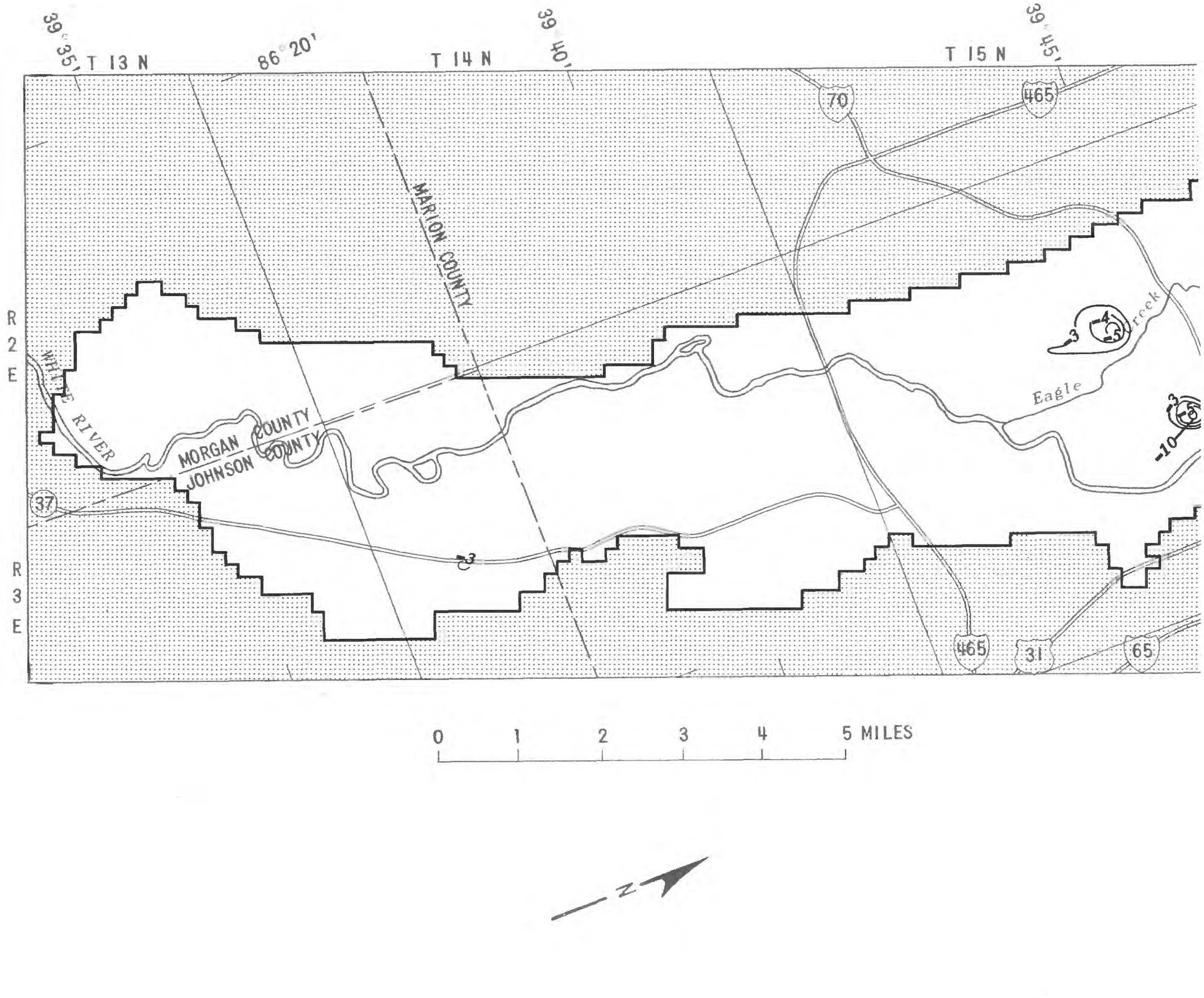
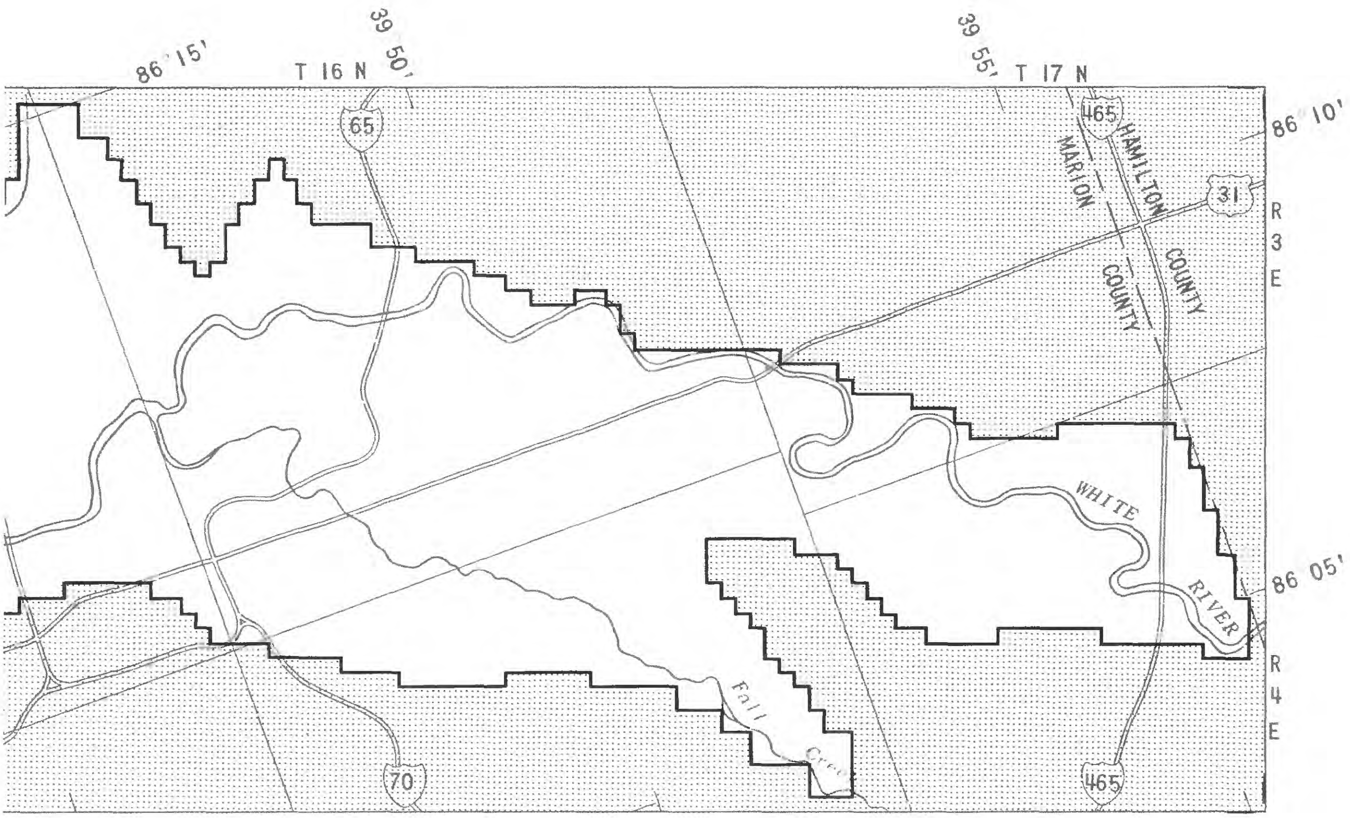



Figure 17.-- Modeled areas that are sensitive to changes in horizontal hydraulic conductivity.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Line of equal decline in water level. Intervals 1 and 5 feet

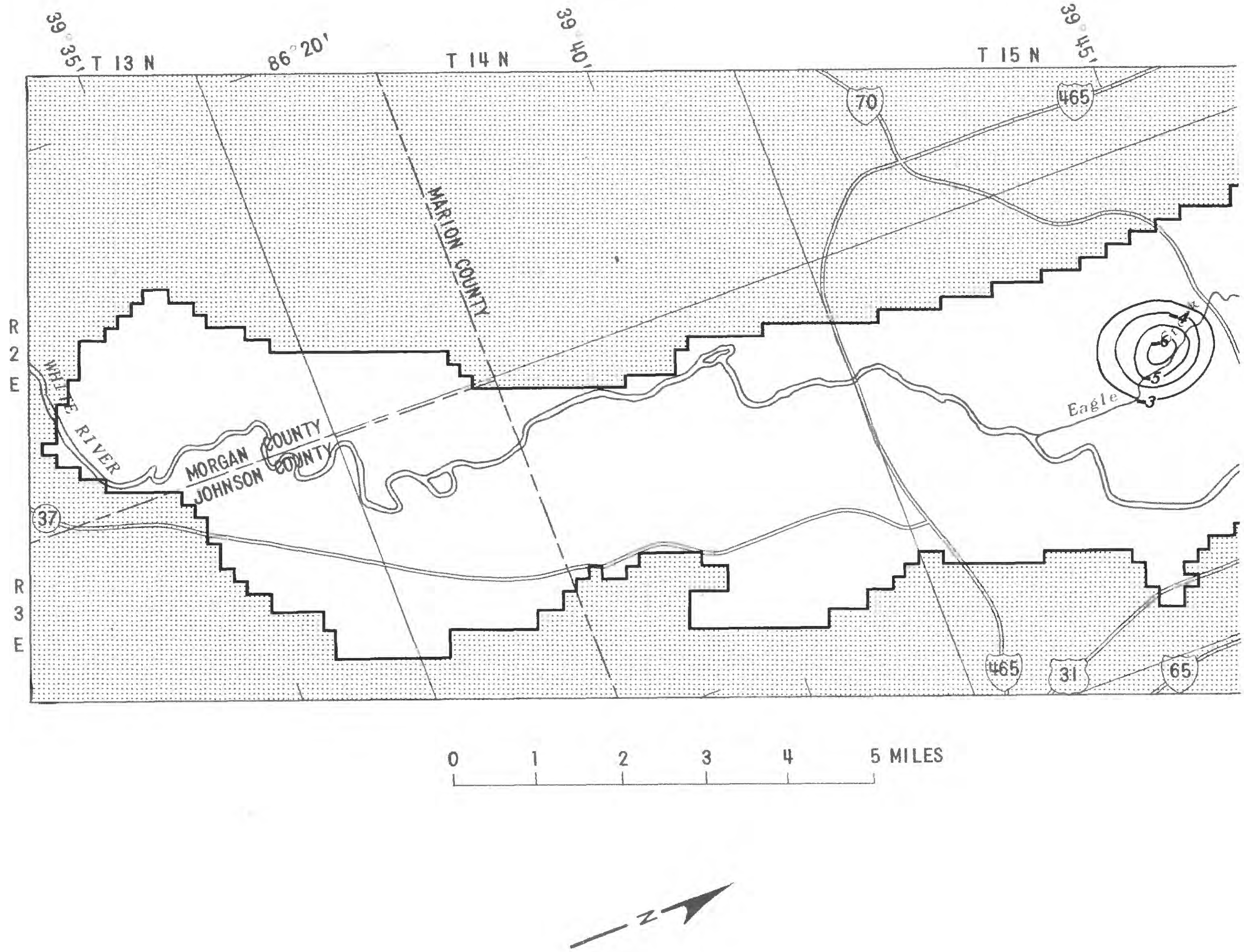
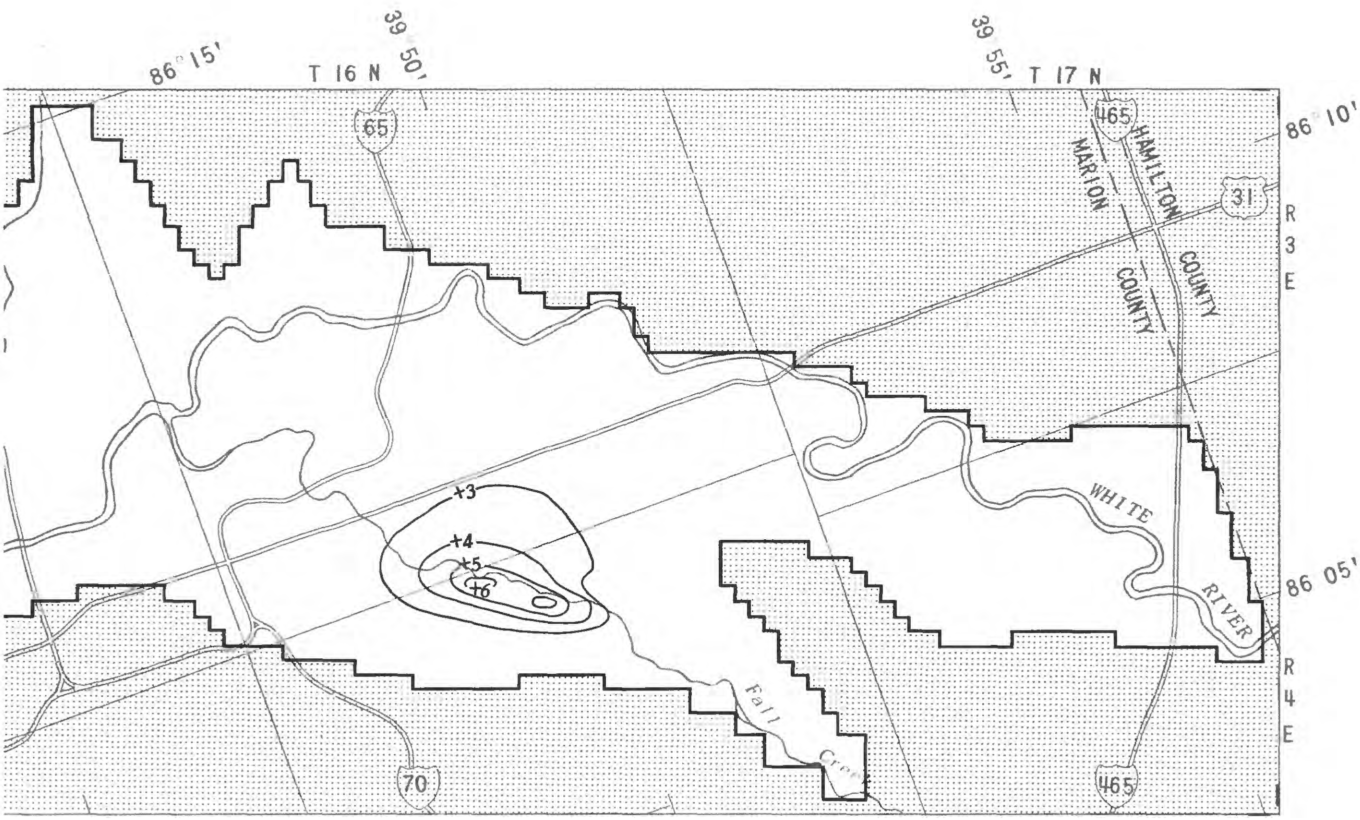



Figure 18.-- Modeled areas that are sensitive to decreases in hydraulic conductivity of the streambed.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

+4 Line of equal rise in water level. Interval 1 foot

-4 Line of equal decline in water level. Interval 1 foot

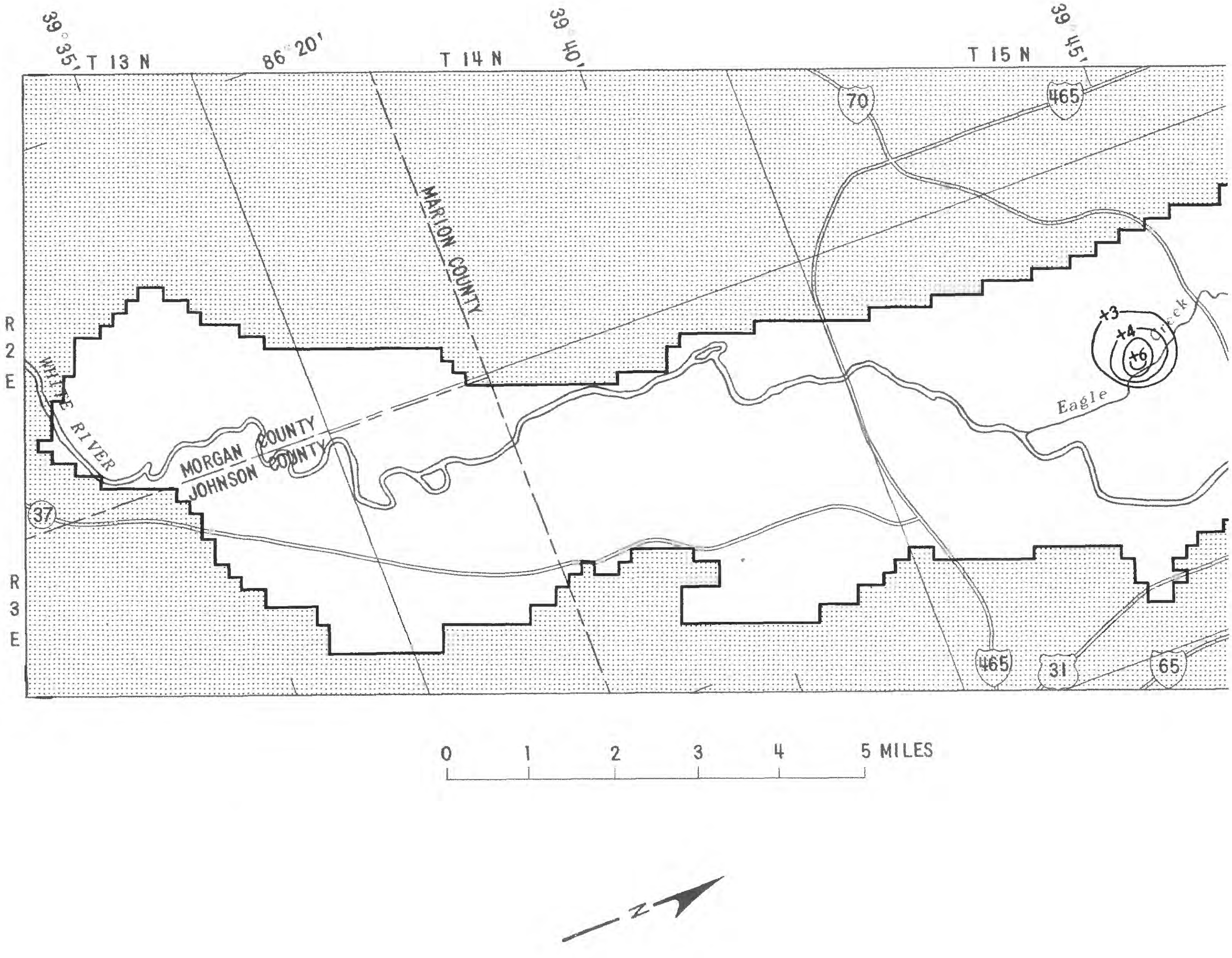
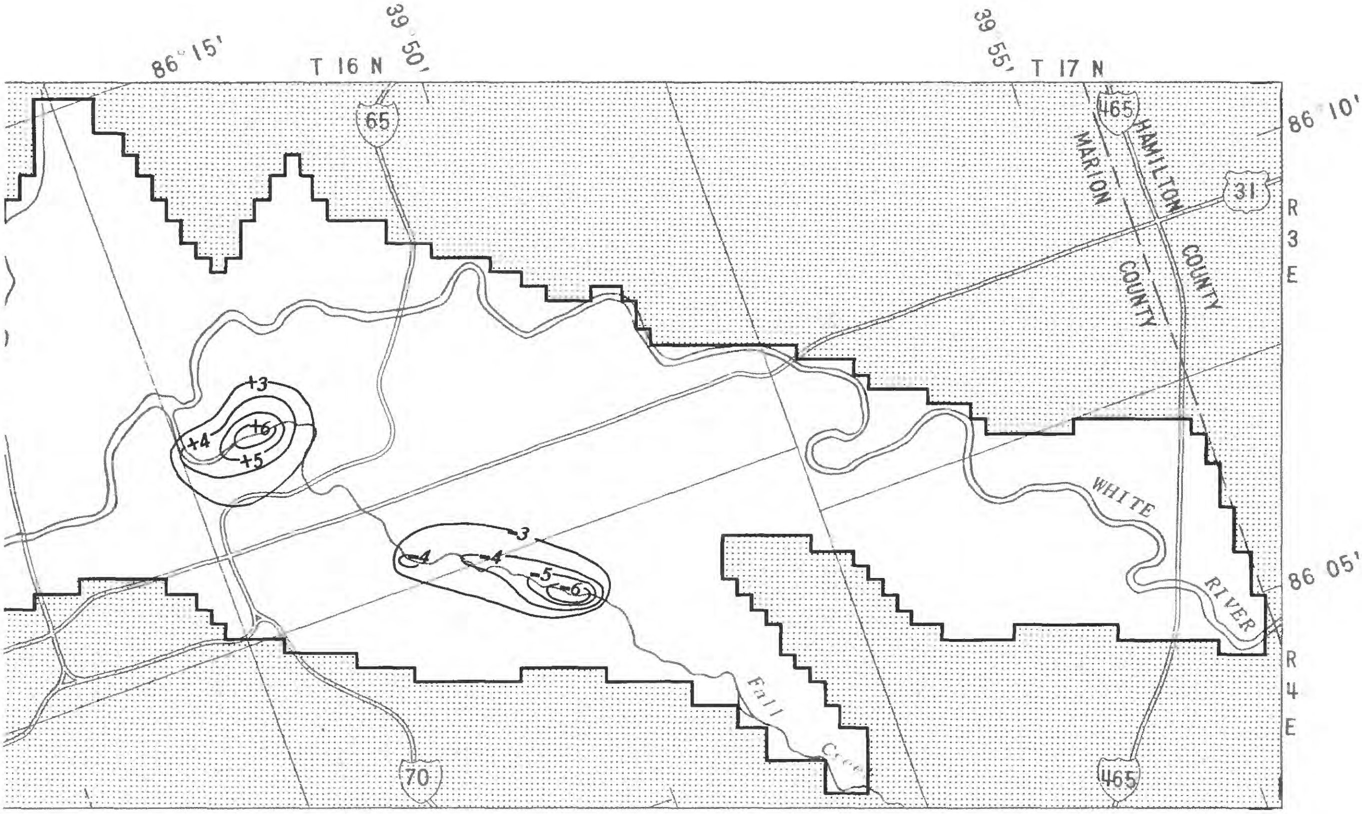



Figure 19.-- Modeled areas that are sensitive to large increases in hydraulic conductivity of the streambed.




**EXPLANATION**

Outwash and alluvium

Tipton till plain

Line of equal rise in water level. Interval 1 foot

Line of equal decline in water level. Interval 1 foot

## Drawdown Limit of 50-percent Saturated Thickness

The calibrated model, which simulates water levels and pumpage rates of October 1980, was used to simulate the effects of additional, hypothetical pumpages from the aquifer. The location and number of pumping wells were chosen as closely as possible to those of the previous analog-model analysis (Meyer and others, 1975, p. 62) and remained constant throughout the pumping simulations.

A drawdown limit of 50-percent saturated thickness was selected to give a conservative estimate of the amount of water that could be pumped from the aquifer. The drawdown limit was applied to 78 pumping wells that were assumed to be 1 ft in diameter and screened through the entire saturated thickness (fully penetrating). Pumping rates were adjusted by trial and error in each well until drawdowns were within ±2 ft (3 percent) of 50-percent saturated thickness. A subroutine in the digital model was used to calculate the drawdown in the well as opposed to the drawdown in the pumping node (Trescott and others, 1976, p.8). The pumpage simulated for individual wells ranged from 0.27 to 5.73 $ft^3/s$ and averaged 1.25 $ft^3/s$. Simulated pumpages required to meet the drawdown limit in the digital model and in the analog model (Meyer and others, 1975, p. 59) are presented in the table that follows:

| Pumping area | Analog model | | Digital model | |
|---|---|---|---|---|
| | $ft^3/s$ | Mgal/d | $ft^3/s$ | Mgal/d |
| 1 | 32 | 21 | 35 | 23 |
| 2 | 16 | 11 | 21 | 14 |
| 3 | 39 | 26 | 41 | 27 |
| Total | 89 | 58 | 97 | 64 |

Pumping locations are indicated in figure 20.

Constant-flux boundaries were used in the digital-model experiments. The pumpage results are conservative because constant fluxes limit flow from the boundaries to that at calibration; actual pumpage would induce additional flow across the boundaries. The results are not conservative, however, compared to the analog-model results in which all Marion County was modeled. Therefore, the constant-flux boundaries provide a reasonable representation of the actual boundary condition. The constant-head boundary was included in the analysis so that an upper limit to the induced boundary flow could be defined; however, the amount of water induced by this boundary condition is greater than that which would be induced by actual pumping. Actual pumping would lower water levels at the boundaries, whereas the simulation maintains a constant head at the boundaries.

Water-level declines caused by a simulated pumpage of 97 $ft^3/s$ would be between the levels contoured for constant-flux (fig. 20) and constant-head (fig. 21) boundaries. The 97 $ft^3/s$ withdrawn from the aquifer was derived from intercepted discharge (ground water that would have discharged to the stream), induced leakage from the stream or boundary flux (ground water flowing across model boundaries). The contribution of each source would be within the limits imposed by the type of boundary simulated as indicated in the table that follows:

| Source | Boundary | |
|---|---|---|
| | Constant flux ($ft^3/s$) | Constant head ($ft^3/s$) |
| Intercepted discharge | 62 | 52 |
| Induced leakage from the stream | 35 | 15 |
| Boundary flux | 0.0 | 30 |
| Total | 97 | 97 |

The net reductions in streamflow (ground water that would have discharged to the stream plus induced leakage from the stream) resulting from a simulated pumpage of 97 $ft^3/s$ was also defined within the limits of the type of boundary simulated (table 5). Actual reductions in streamflow and induced leakages from the streams would be within the limits defined by the boundary conditions.

Table 5.--Effects of a simulated pumage of 97 cubic feet per second on streamflow

| Stream | Reach[1] | Model-calibrated seepage to streams ($ft^3/s$) | Net reduction in streamflow caused by pumping ($ft^3/s$) | | Induced leakage from the streams caused by pumping ($ft^3/s$) | |
|---|---|---|---|---|---|---|
| | | Constant flux and constant head | Constant flux[2] | Constant head[3] | Constant flux[2] | Constant head[3] |
| White River | 1 | 5.2 | 3.6 | 2.6 | 0 | 0 |
| Do. | 2 | 18 | 23 | 15 | 5.0 | 0 |
| Do. | 3 | 9.7 | 10 | 8.8 | .3 | 0 |
| Do. | 4 | 4.8 | 21 | 15 | 16 | 10 |
| Do. | 5 | 19 | 25 | 16 | 6.0 | 0 |
| Do. | 6 | 23 | 2 | 0 | 0 | 0 |
| Fall Creek | 7 | 4.1 | 12 | 9.3 | 7.9 | 5.2 |
| Eagle Creek | 8 | [4]-2.0 | 0 | 0 | 0 | 0 |
| Total | | 82 | 97 | 67 | 35 | 15 |

[1]Reaches indicated in figure 12.
[2]Boundary flow limited to flux at calibration.
[3]Boundary flow unlimited.
[4]Negative sign indicates flow induced from stream.

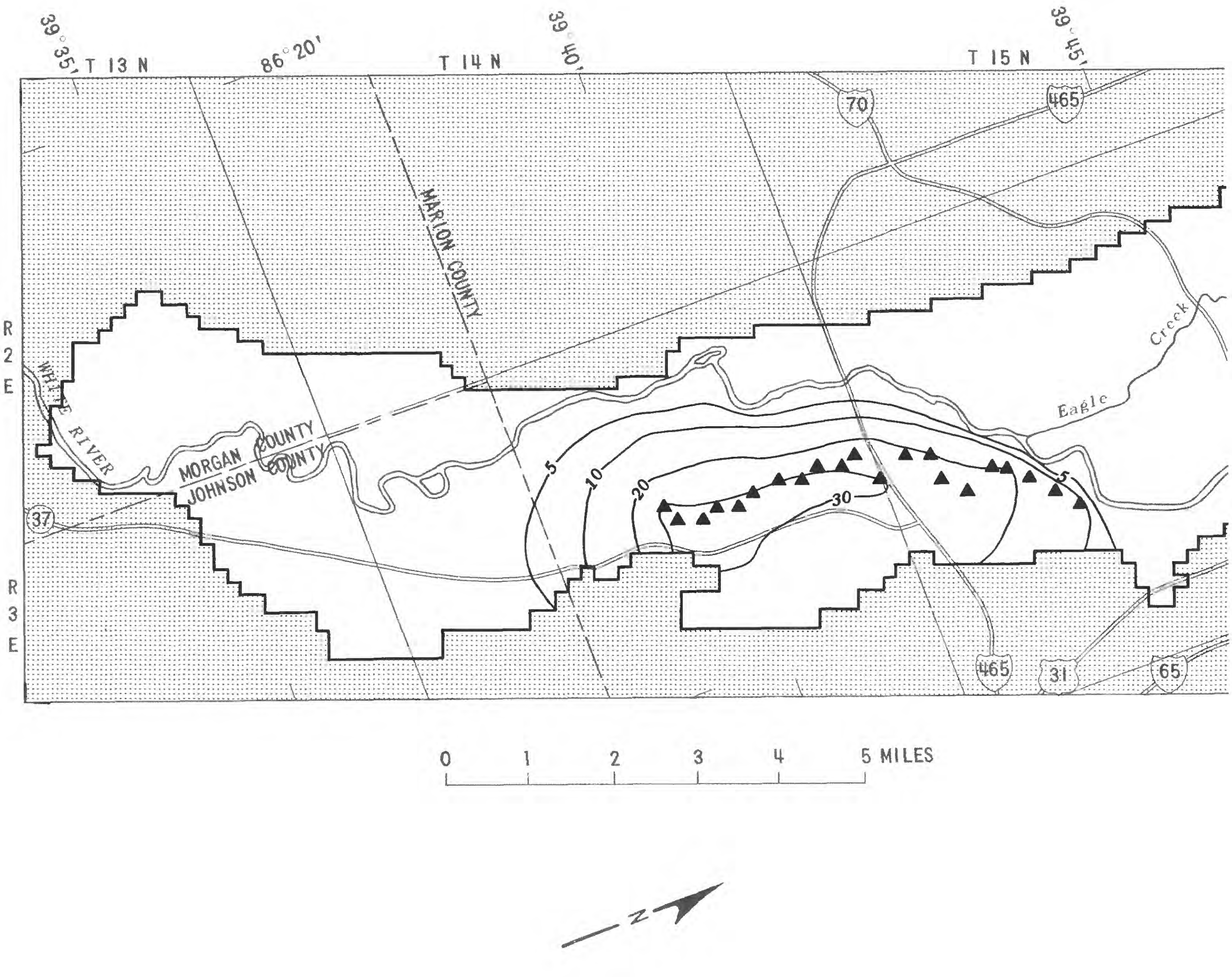
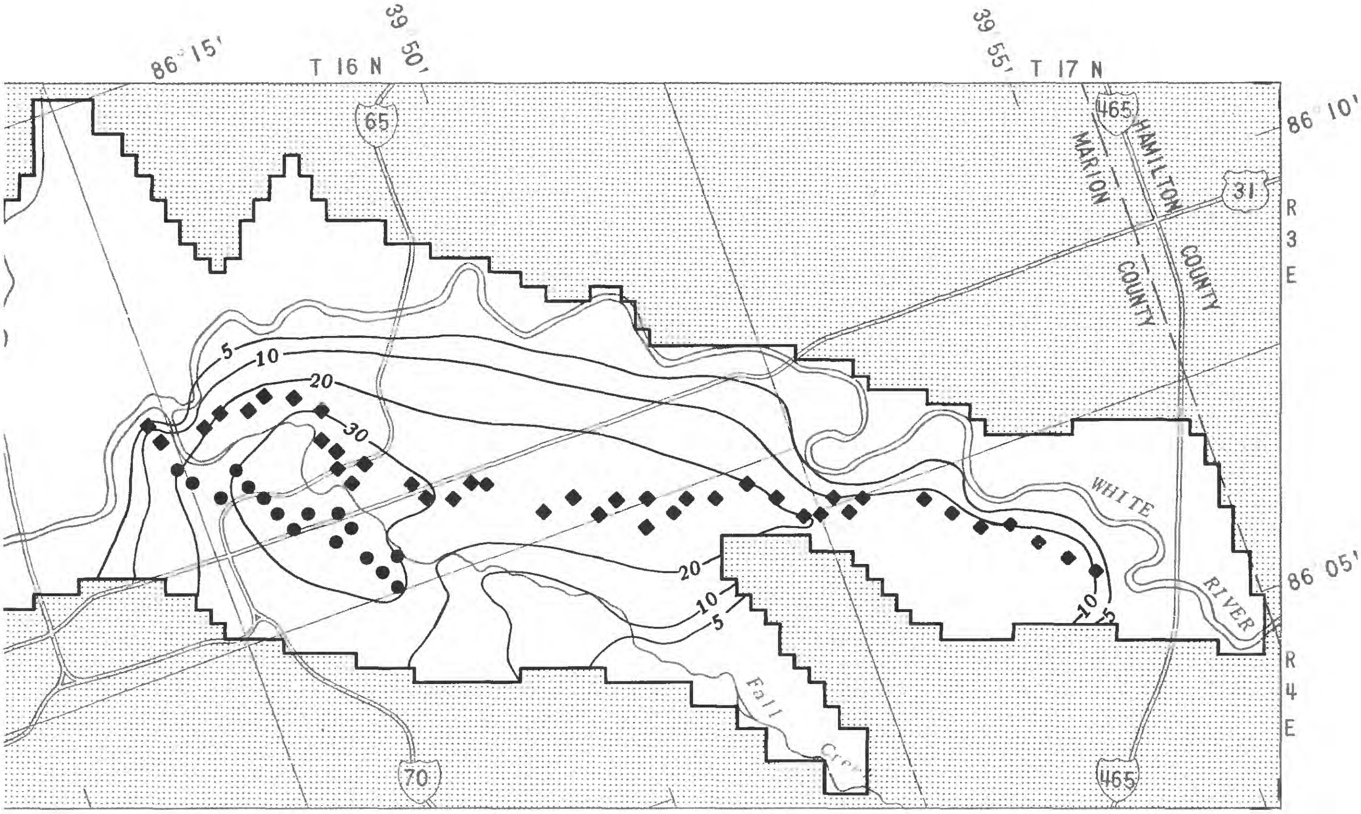



Figure 20.-- Water-level declines caused by simulated pumpage of 97 cubic feet per second (constant-flux boundaries).


86°15'
T 16 N
39°50'
39°55'
T 17 N
86°10'
86°05'
R
3
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4
E
65
465
31
70
MARION COUNTY
HAMILTON COUNTY
WHITE RIVER
Fall Creek
5
10
20
30


EXPLANATION
Outwash and alluvium
Tipton till plain
20
Line of equal drawdown.
Intervals 5 and 10 feet
Pumping area 1
Pumping area 2
Pumping area 3

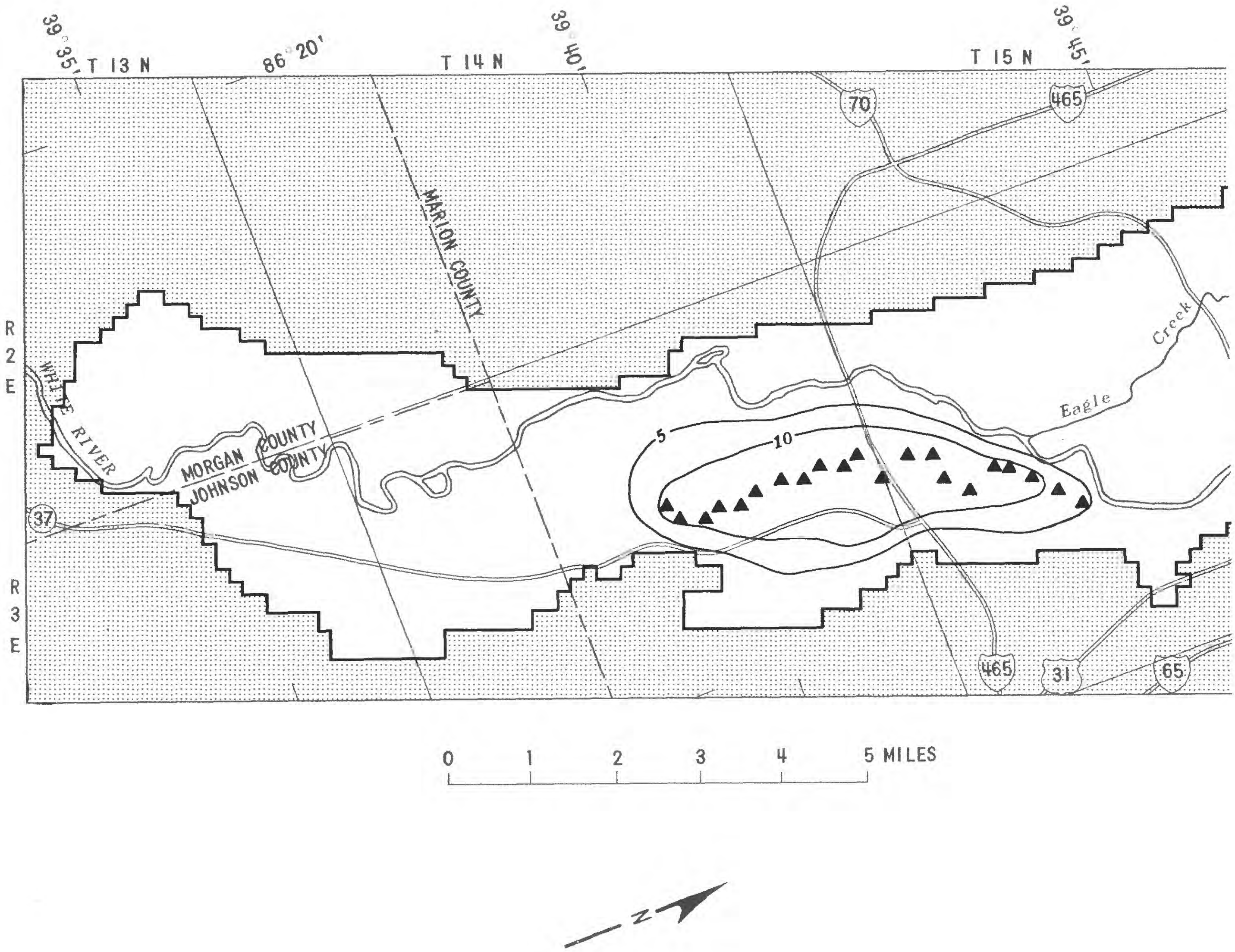
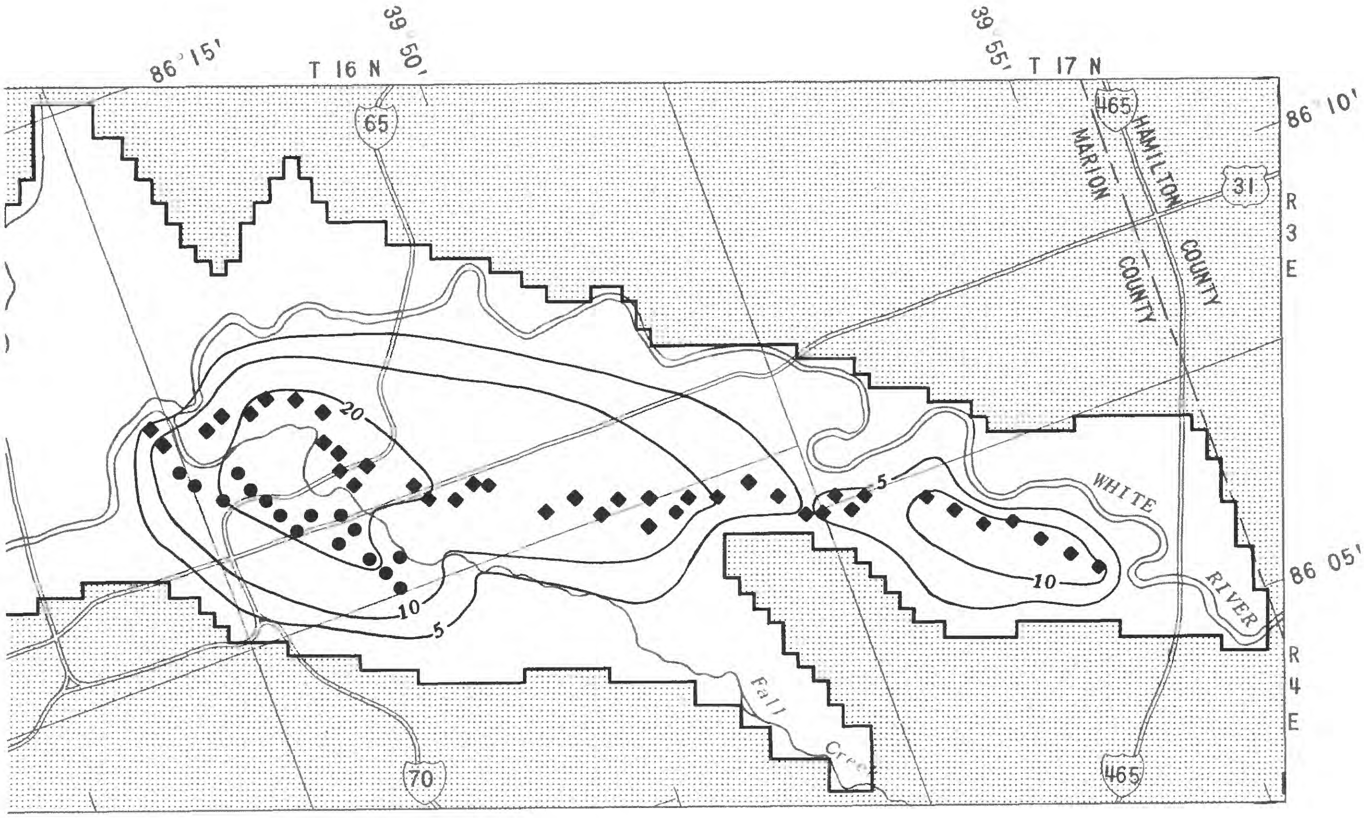



Figure 21.-- Water-level declines caused by simulated pumpage of 97 cubic feet per second (constant-head boundaries).




**EXPLANATION**

Outwash and alluvium

Tipton till plain

20 Line of equal drawdown. Intervals 5 and 10 feet

▲ Pumping area 1

● Pumping area 2

◆ Pumping area 3

Reductions in streamflows were smaller than the streamflows recorded October 8, 1980 (table 1), a time of seasonal low flow when flow duration was 67 percent at Nora. The reductions, however, were within the range of the 7-day, 10-year low flows recorded on the White River near Nora and on Fall Creek at Millersville as shown in the table that follows:

| Stream | Net reduction in streamflow ($ft^3/s$) | | 7-day, 10-year low flow[1] ($ft^3/s$) |
|---|---|---|---|
| | Constant flux | Constant head | |
| White River | 85 | 58 | 83 near Nora |
| Fall Creek | 12 | 9.3 | 39 at Millersville |
| Total | 97 | 67 | 122 |

[1]Seven-day, 10-year low flows are from Stewart (1983, p. 115 and p. 121).

## Drawdown Limit of 67-percent Saturated Thickness

Meyer and others (1975, p. 58) chose a drawdown limit of two-thirds (67-percent) saturated thickness for pumping simulations in the analog-model analysis because this drawdown should provide close to the maximum practical discharge from individual wells. The 67-percent limit was applied to 78 fully penetrating wells assumed to be 1 foot in diameter in the digital model analysis so that the models could be compared. Pumpage rates were adjusted by trial and error until drawdowns were within 3 ft (±5 percent) of 67-percent saturated thickness. A subroutine in the digital model was used to calculate the drawdowns in the well as opposed to the drawdown in the pumping node (Trescott and others, 1976, p. 8). The simulated pumpage ranged from 0.26 to 6.7 $ft^3/s$ and averaged 1.47 $ft^3/s$. Simulated pumpages required to meet the drawdown limit and the results of a similar simulation with the analog model (Meyer and others, 1975, table 5, p. 59) are in the table that follows:

| Pumping area | Analog model | | Digital model | |
|---|---|---|---|---|
| | $ft^3/s$ | Mgal/d | $ft^3/s$ | Mgal/d |
| 1 | 39 | 25 | 42 | 27 |
| 2 | 22 | 14 | 24 | 16 |
| 3 | 50 | 32 | 49 | 21 |
| Total | 111 | 71 | 115 | 64 |

Constant-flux boundaries, which limit flow from the boundaries to that at calibration, were used in the simulation; therefore, the pumpage results are conservative. The results, however, are close to those simulated in the analog model in which all Marion County was modeled.

Water-level declines caused by a simulated pumpage of 115 $ft^3/s$ would be between the levels contoured for constant-flux (fig. 22) and constant-head (fig. 23) boundaries. The 115 $ft^3/s$ was derived from intercepted discharge, induced leakage from the streams, or boundary flux. The contribution of each source would be within the limits imposed by the type of boundary simulated as shown in the table that follows:

| Sources of water | Boundary: Constant flux ($ft^3/s$) | Boundary: Constant head ($ft^3/s$) |
|---|---|---|
| Intercepted discharge | 64 | 59 |
| Induced leakage from the streams | 51 | 19 |
| Boundary flux | 0 | 37 |
| Total | 115 | 115 |

The net reduction in streamflow (ground water that naturally discharged to the streams plus induced leakage from the stream) caused by a simulated pumpage of 115-$ft^3/s$ was defined within the limits imposed by the type of boundary simulated (table 6). Actual reductions in streamflows and induced leakages from the streams would be within the limits defined by the boundaries simulated.

The reductions in streamflows were smaller than those recorded October 8, 1980 (table 1). The simulated reductions, however, were in the range of or greater than the 7-day, 10-year low flow on the White River near Nora as indicated in the table that follows:

| Stream | Boundary: Constant flux ($ft^3/s$) | Boundary: Constant head ($ft^3/s$) | 7-day, 10-year low flow[1] ($ft^3/s$) |
|---|---|---|---|
| White River | 102 | 68 | 83 near Nora |
| Fall Creek | 13 | 10 | 39 at Millersville |
| Totals | 115 | 78 | 122 |

[1]Seven day, 10-year low flows are from Stewart (1983, p. 115 and p. 121).

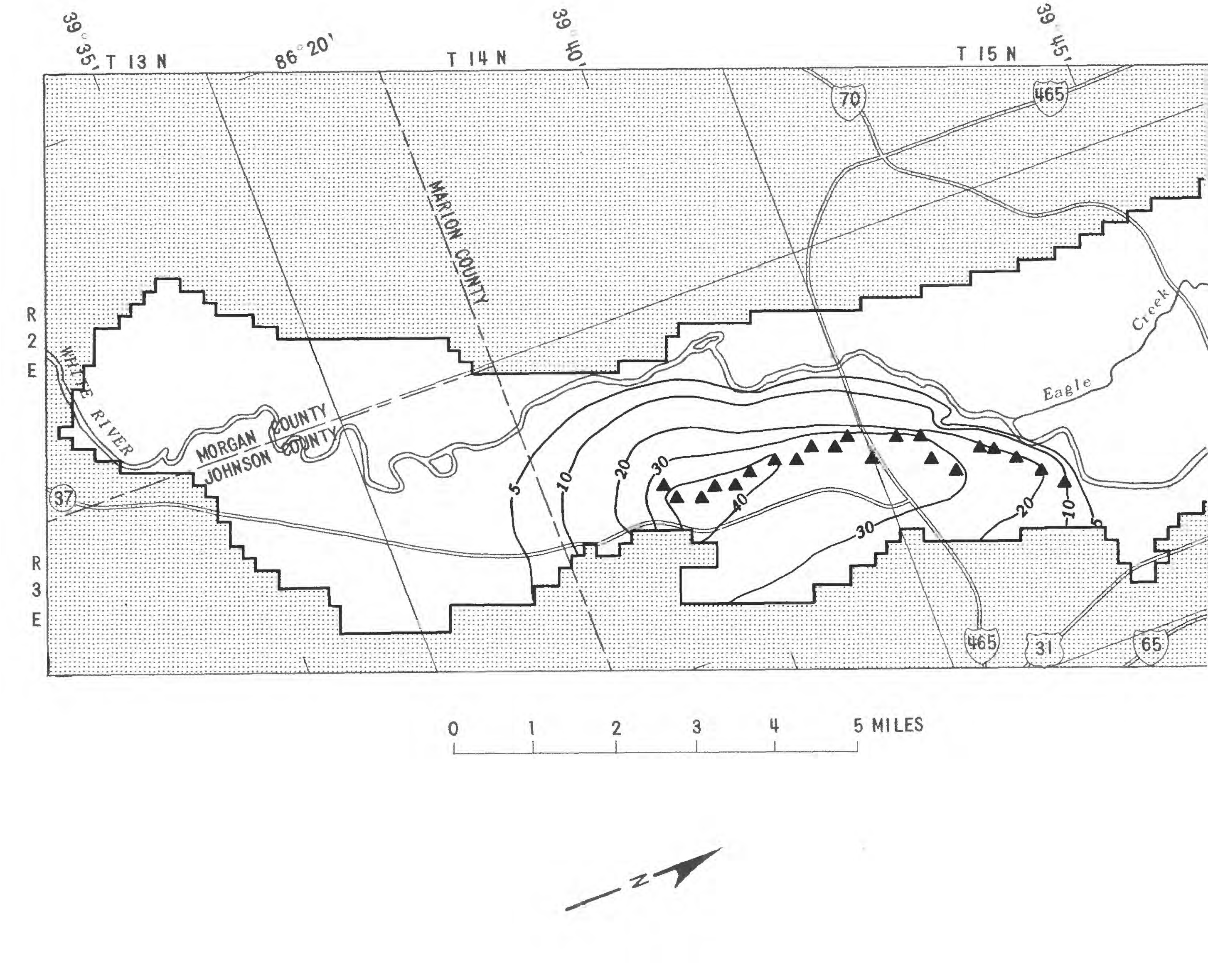
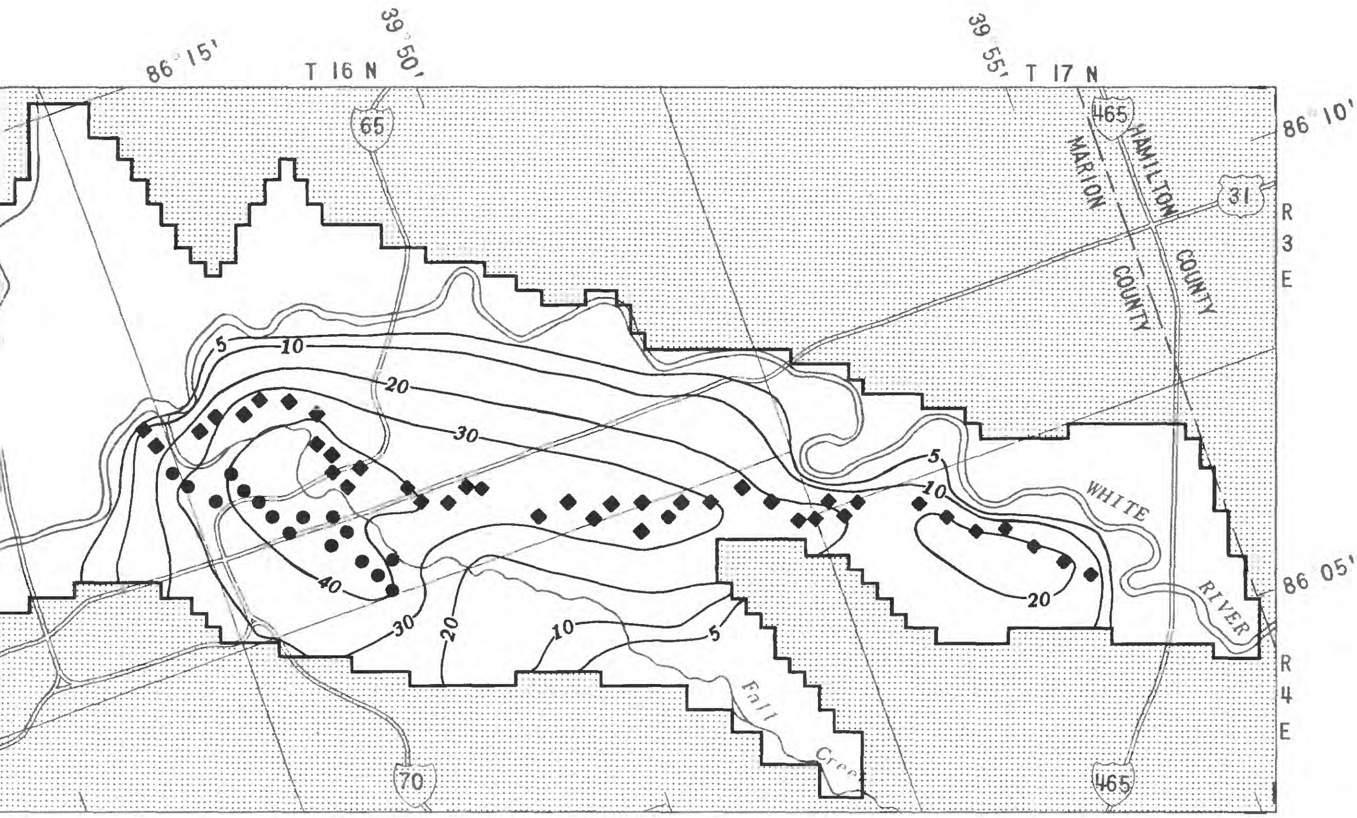



Figure 22.-- Water-level declines caused by simulated pumpage of 115 cubic feet per second (constant-flux boundaries).




**EXPLANATION**

Outwash and alluvium

Tipton till plain

20 Line of equal drawdown. Intervals 5 and 10 feet

▲ Pumping area 1

● Pumping area 2

◆ Pumping area 3

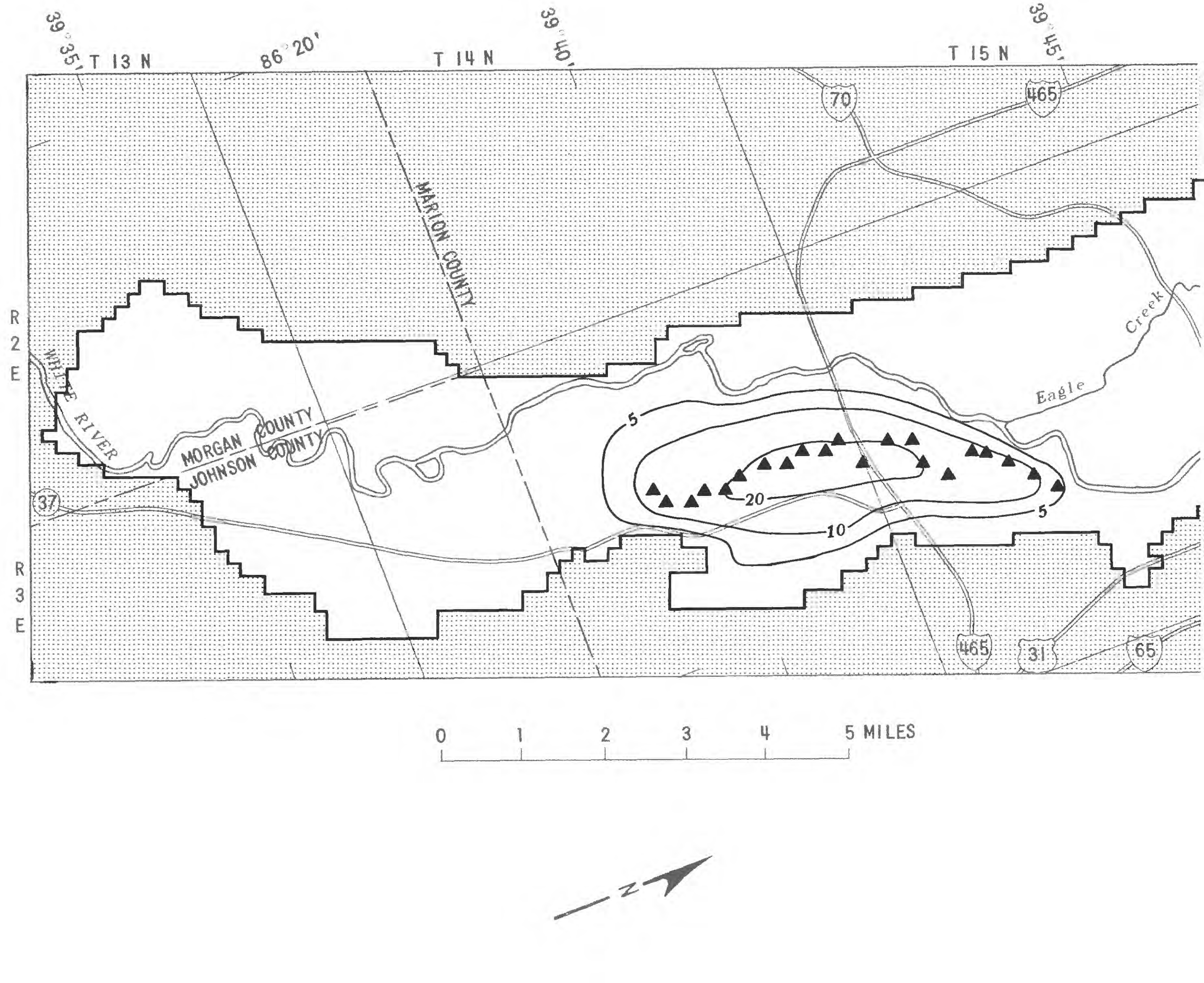
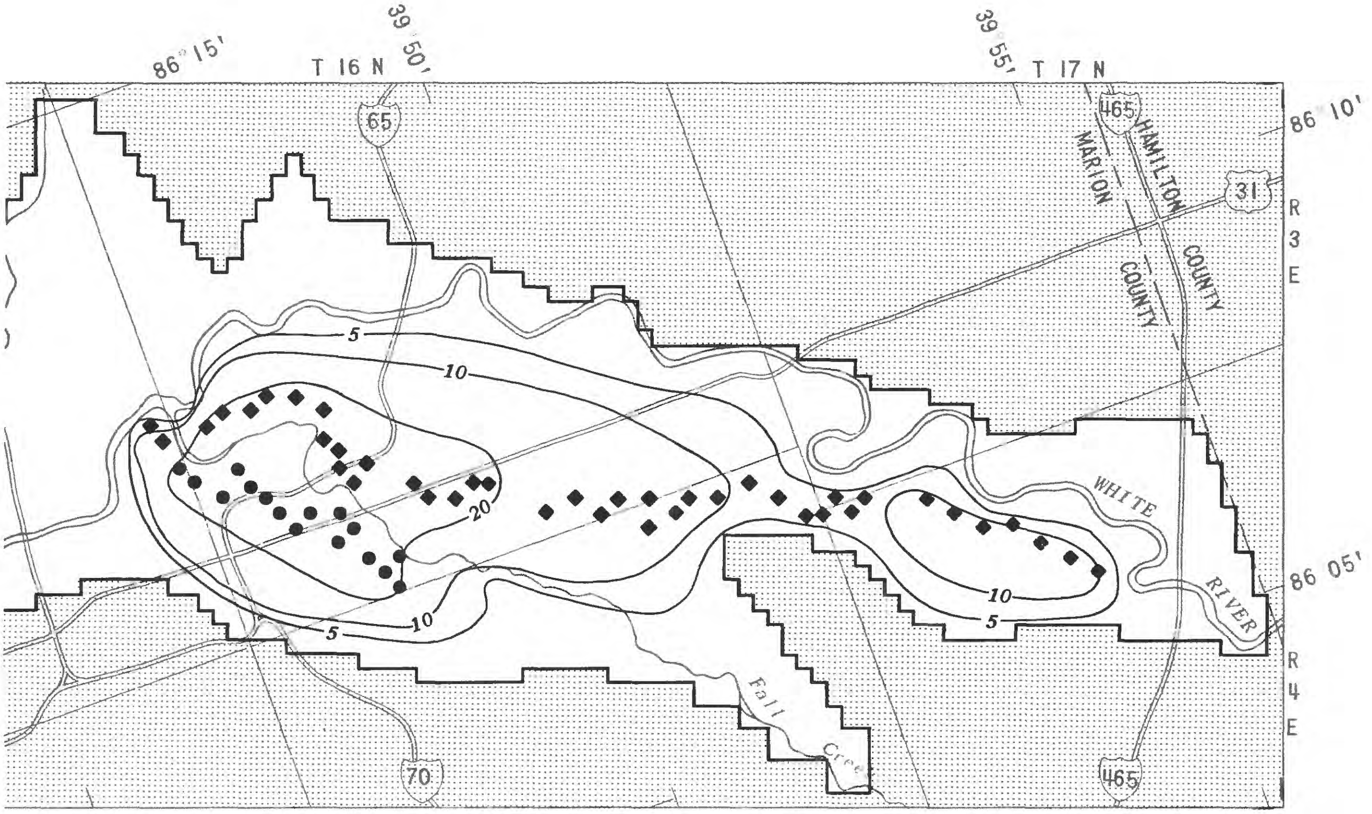



**Figure 23.-- Water-level declines caused by simulated pumpage of 115 cubic feet per second (constant-head boundaries).**




**EXPLANATION**

Outwash and alluvium

Tipton till plain

20 Line of equal drawdown. Intervals 5 and 10 feet

▲ Pumping area 1

● Pumping area 2

◆ Pumping area 3

Table 6.--Effects of a simulated pumpage of 115 cubic feet per second on streamflow

| Stream | Reach[1] | Model-calibrated ground-water seepage to streams ($ft^3/s$) | Net reduction in streamflow caused by pumpage ($ft^3/s$) | | Induced leakage from the streams caused by pumpage ($ft^3/s$) | |
|---|---|---|---|---|---|---|
| | | | Constant flux[2] | Constant head[3] | Constant flux[2] | Constant head[3] |
| White River | 1 | 5.2 | 4.2 | 3.1 | 0.0 | 0.0 |
| Do. | 2 | 18 | 27 | 18 | 9.0 | .0 |
| Do. | 3 | 9.7 | 12 | 10 | 2.3 | 0.3 |
| Do. | 4 | 4.8 | 24 | 17 | 19 | 12 |
| Do. | 5 | 19 | 32 | 20 | 12 | 1.0 |
| Do. | 6 | 23 | 2 | .0 | .0 | .0 |
| Fall Creek | 7 | 4.1 | 13 | 10 | 8.9 | 5.9 |
| Eagle Creek | 8 | [4]-2.0 | .0 | .0 | .0 | .0 |
| Total | | 82 | 115 | 78 | 51 | 19 |

[1] Reaches are indicated in figure 11.
[2] Represents boundary flow limited to fluxes at calibration.
[3] Represents unlimited boundary flow.
[4] Negative sign indicates flow induced from stream.

## SUMMARY AND CONCLUSIONS

The outwash aquifer is a continuous, unconfined sand and gravel deposit containing isolated boulder, silt, and clay deposits along the White River, Fall Creek, and Eagle Creek. At the edges of the valleys of the White River and the upstream reaches of Fall Creek and Eagle Creek, the outwash intergrades with deposits of the Tipton till plain. The direction of flow in the aquifer is from the till plain toward the White River, Fall Creek, and Eagle Creek, and toward major pumping centers. The aquifer was at virtual steady state from 1974 through 1980, when only minor fluctuations in pumpages and water levels were recorded.

A two-dimensional, finite-difference model of the outwash aquifer was calibrated to water levels of October 6 to 10, 1980. The simulated water budget indicated that effective recharge from precipitation provided 48 percent of water to the aquifer and that boundary flux from the confined aquifers of the Tipton Till Plain provided 41 percent. Leakage through the streambeds of White River, Fall Creek, and Eagle Creek induced by pumping provided the remaining 11 percent. Pumpage from the outwash aquifer was 29 percent of the total discharges, and natural seepage to White River, Fall Creek, and Eagle Creek was 68 percent of discharges. Subsurface flow out of the modeled area accounted for the remaining 3 percent.

The digital model was slightly more sensitive to changes in hydraulic conductivity than to changes in effective recharge rates or hydraulic conductivity of the streambed. The model, however, was insensitive to increases in hydraulic conductivity of the streambed.

The calibrated model was used to simulate the effects of additional, hypothetical pumpages from the aquifer. Hypothetical pumpages simulated by the digital model were based on electric-analog model simulations that Meyer and others (1975, p. 58) used to estimate the availablity of water in the aquifer. The analog-model simulations were repeated to provide a comparison of the two models. A drawdown limit of 50-percent saturated thickness applied to 78 fully penetrating pumping wells assumed to be 1 foot in diameter produced 97 $ft^3/s$ from the aquifer. This result is conservative because constant-flux boundaries were used in the simulation. Constant-flux boundaries limit flow from the boundaries to that at calibration, whereas actual pumpage would induce additional flow from boundaries. The result is not conservative, however, compared with the analog-model result, 57.5 Mgal/d (89 $ft^3/s$), in which all Marion County was modeled (Meyer and others, 1975, p. 84). Therefore, the constant-flux boundaries provide a reasonable representation of the actual boundary conditions.

Reductions in streamflows caused by a simulated pumpage of 97 $ft^3/s$ and constant-flux boundaries were 85 $ft^3/s$ in the White River and 12 $ft^3/s$ in Fall Creek. These reductions were smaller than the streamflows measured during the calibration period, October 6 to 10, 1980. The reductions in streamflows, however, are large compared with the 7-day, 10-year low flows of 83 $ft^3/s$ on White River near Nora and 39 $ft^3/s$ on Fall Creek at Millersville (J. Stewart, 1983, p. 115 and p. 121). Therefore, 97 $ft^3/s$ is considered to be the limit of water available from the outwash aquifer in Marion County.

A drawdown limit of 67-percent saturated thickness applied to 78 fully penetrating wells assumed to be 1 ft in diameter produced 115 $ft^3/s$ from the aquifer. Reductions in streamflows caused by a simulated pumpage of 115 $ft^3/s$ were 102 $ft^3/s$ in the White River and 13 $ft^3/s$ in Fall Creek. These reductions are smaller than the streamflow recorded during the calibration period. The reduction in streamflows on the White River, however, exceeds the 7-day, 10-year low flow, 83 $ft^3/s$, near Nora. Therefore, pumpage of 115 $ft^3/s$ is considered to be beyond the limit of ground-water available from the outwash aquifer in Marion County.

The pumping simulations in this report were designed soley on the basis of hydrologic considerations. The simulations, therefore, provide an estimate of the availability of ground water in Marion County for managing and planning and are not intended as a practical guide for well-field design. The actual availability of ground water in Marion County, however, will depend on the number, distribution, and efficiency of future pumping wells and the relation of those pumping wells to local hydrologic conditions. Proximity to the major streams, local stream-aquifer connection, distance to aquifer boundaries, and local boundary conditions will determine the availability of ground water at any point in the aquifer as well as aquifer characteristics.

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