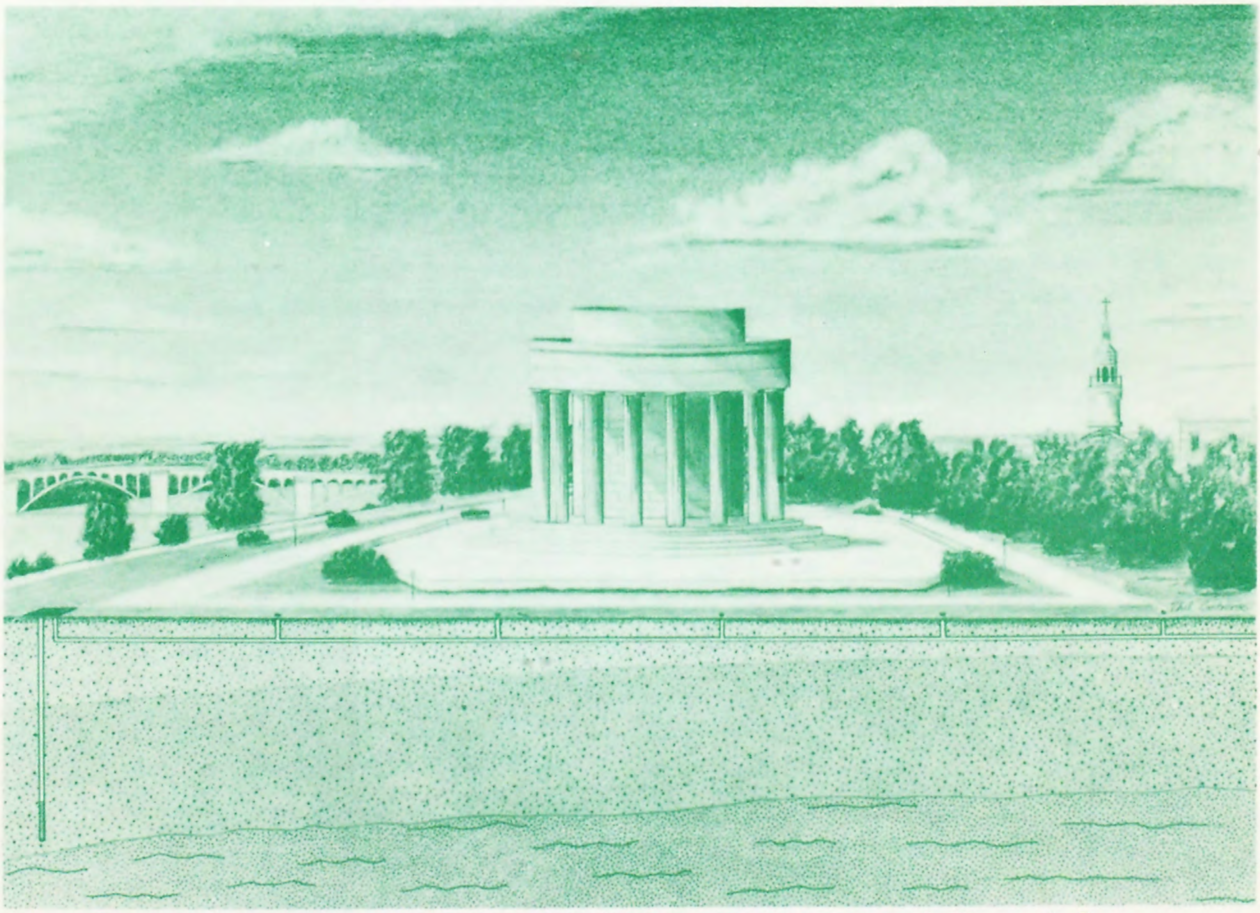
SALINE WATER AT THE BASE OF THE GLACIAL-OUTWASH AQUIFER NEAR VINCENNES, KNOX COUNTY, INDIANA

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS 80-65



Prepared in cooperation with the Indiana Department of Natural Resources
and Department of Water Works, Vincennes, Indiana

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NEAR VINCENNES, KNOX COUNTY, INDIANA

By Robert J. Shedlock

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-65

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Indiana

August 1980

UNITED STATES DEPARTMENT OF THE INTERIOR
CECIL D. ANDRUS, Secretary
GEOLOGICAL SURVEY
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CONTENTS

ILLUSTRATIONS

TABLES

METRIC CONVERSION FACTORS

The inch-pound and other units used in this report can be converted to units used in the metric system as follows:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	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)	0.0929	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)	2.540	centimeter per year (cm/yr)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	3.785	liter per minute (L/min)

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

$$(0.556)\ (°F - 32°) = (°C)$$

SALINE WATER AT THE BASE OF THE GLACIAL-OUTWASH AQUIFER NEAR VINCENNES, KNOX COUNTY, INDIANA

By Robert J. Shedlock

ABSTRACT

A plume of saline water at the base of the glacial outwash aquifer near Vincennes, Indiana, has been drawn into the municipal well field. However, the average chloride concentration of the municipal water, 30 ± 5 milligrams per liter, did not change significantly from 1976 to 1979. The plume, an elongated lens approximately 6,500 feet long by 1,500 feet wide, is 4 feet thick near the well field, and the chloride concentration of the water is 3,500 milligrams per liter. Half a mile to the west the thickness is 18 feet, and the chloride concentration is 5,100 milligrams per liter.

The saline water seems to be entering the outwash aquifer through bedrock fractures near abandoned oil wells west of the well field. The fractures probably intersect unplugged intervals of the abandoned oil wells that convey saline water from bedrock aquifers at unknown depths.

Digital model analysis indicates that doubling the 1978 pumping rate in the well field would cause water-level declines of generally less than 8 feet. Solute-transport model analyses indicate that the chloride concentration of the well-field water would be less than 250 milligrams per liter for a saline-water intrusion rate ten times the model-calibrated rate.

INTRODUCTION

Problem

The Vincennes Water Department obtains all its water from wells in the unconsolidated sands and gravels of the glacial-outwash aquifer underlying the Wabash River valley. The wells are in a single well field about 500 ft (foot) from the Wabash River just outside the west limits of the city. The average pumpage in the well field in 1976 was 3.7 Mgal/d (million gallons per day), and the city's projected demand for water in the year 2000 is 5.2 Mgal/d.

As part of a project to increase the production of the well field, the city installed two new wells in the outwash aquifer about 300 ft west of the well field in July 1976. The chloride concentration of water from one of the new wells was 500 mg/L (milligram per liter), which is considerably higher than the 250-mg/L limit recommended for public water supplies (National Academy of Sciences and the National Academy of Engineering, 1972, p. 61). Several observation wells were installed by the city around the well with the high chloride concentration. Field and laboratory analyses of water in these observation wells indicated a plume of saline water in the outwash aquifer immediately west of the Vincennes well field.

Purpose and Scope

Because of the high chloride concentration of water from one of the new wells, the U.S. Geological Survey, in cooperation with the Indiana Department of Natural Resources and the city of Vincennes, began a 3-yr (year) study in 1976 to (1) define the extent, movement, and, if possible, the source of the saline water; (2) investigate the feasibility of increased pumping from the well field (assuming no increase in chloride concentration); and (3) determine the thickness and hydraulic characteristics of the outwash aquifer in a 56-mi^2 (square mile) study area southwest of Vincennes (fig. 1). The ground-water resources of the entire Wabash River basin were investigated previously by Nyman and Pettijohn (1971), but the outwash aquifer near Vincennes was not studied in sufficient detail to meet the described objectives.

Approach

The areal extent and the saturated thickness of the outwash aquifer were determined by test drilling in the outwash and by installing a network of observation wells in the study area. Another network of observation wells was installed near the well field to define the geometry of the saline-water plume.

However, the occurrence of saline water in the outwash aquifer was investigated in detail only near the well field. The observation wells in the rest of the study area are shallow wells that do not permit detection of saline water at the base of the outwash aquifer.

Pumpage from the Vincennes well field was well documented, but irrigation and other pumpage were estimated. In addition, the following hydraulic parameters were estimated: (1) the magnitude and lateral variations of the

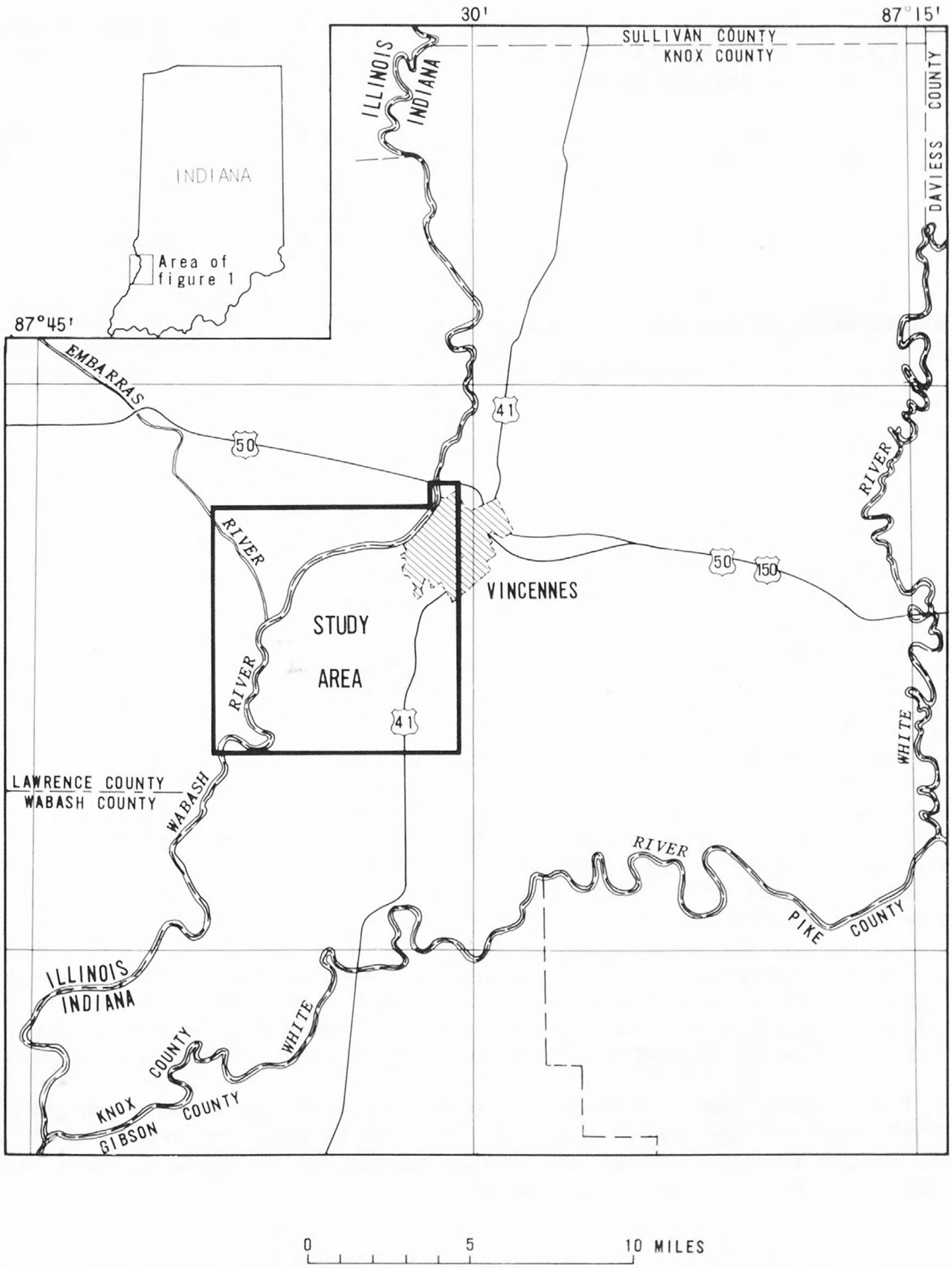


Figure 1. -- Location of the study area near Vincennes, Knox County, Ind.

hydraulic conductivity of the outwash, (2) the effective areal recharge to the outwash from rainfall, and (3) the hydraulic connection between the streams and the outwash aquifer in the study area.

Digital models, constructed to simulate the ground-water flow system in the outwash aquifer, included a model of the entire study area and a smaller, more detailed digital model of a 4-mi^2 area surrounding the well field. Increased pumpage in the Vincennes well field was simulated with both models. In addition, a solute-transport model was constructed to simulate the movement of chloride ions into the well field and to estimate the effect, under increased pumpage, of saline-water intrusion on the chloride concentration of the well-field water.

Location, Drainage, and Climate

Vincennes, a city of about 22,000 people in west-central Knox County in southwestern Indiana, lies on the east bank of the Wabash River along the Indiana-Illinois border. The approximately 56-mi^2 study area, shown in detail in figure 2, generally coincides with the areal extent of the glacial outwash within a 7-mi (mile) by 8-mi section of the Wabash River valley. Most of the study area is farmland within the flood plain of the Wabash River. Altitude in the flood plain ranges from 400 to 425 ft above the National Geodetic Vertical Datum of 1929 (NGVD of 1929). However, a few small bedrock hills rise out of the flood plain in and around the study area. These hills, which are erosional remnants of the adjacent uplands (Fidlar, 1936, p. 176), appear on the surficial geology map (fig. 3) as the small areas within the flood plain where wind-blown silt and sand is mapped. The altitude of the tops of these hills ranges from 450 to 510 ft above NGVD of 1929.

All the drainage in the study area flows into the Wabash River, either within or just a few miles south of the study area. The Embarras River, the only other large stream in the study area, flows into the Wabash River from Illinois. The study area is also drained by several ditches and creeks.

The climate near Vincennes is temperate. Average annual temperature is 54.9°F, and average annual rainfall is 42.2 inches. Monthly average rainfall ranges from 2.4 inches in October to 4.5 inches in May. (See National Oceanic and Atmospheric Administration, 1979.)

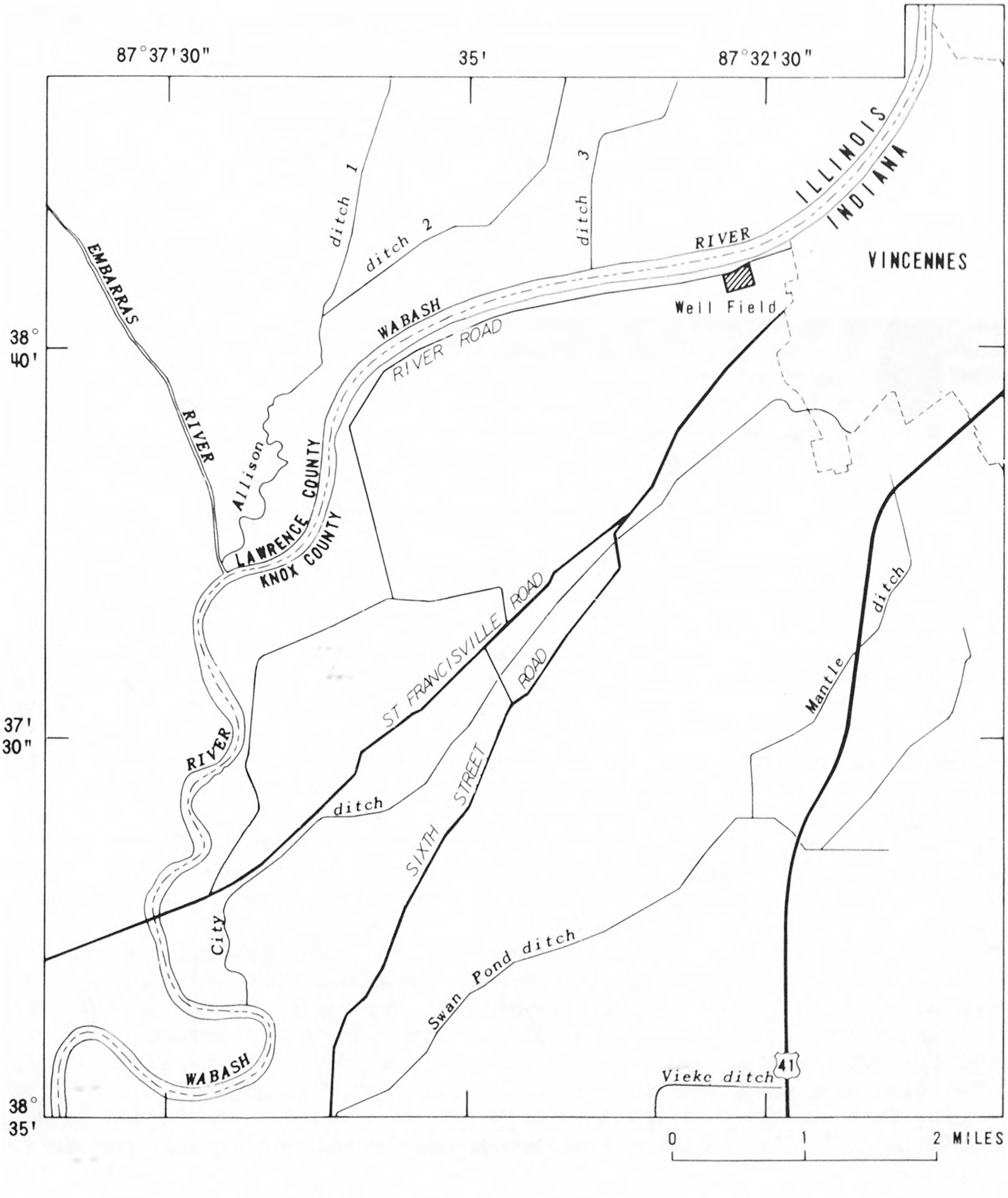


Figure 2.-- Study area near Vincennes, Ind.

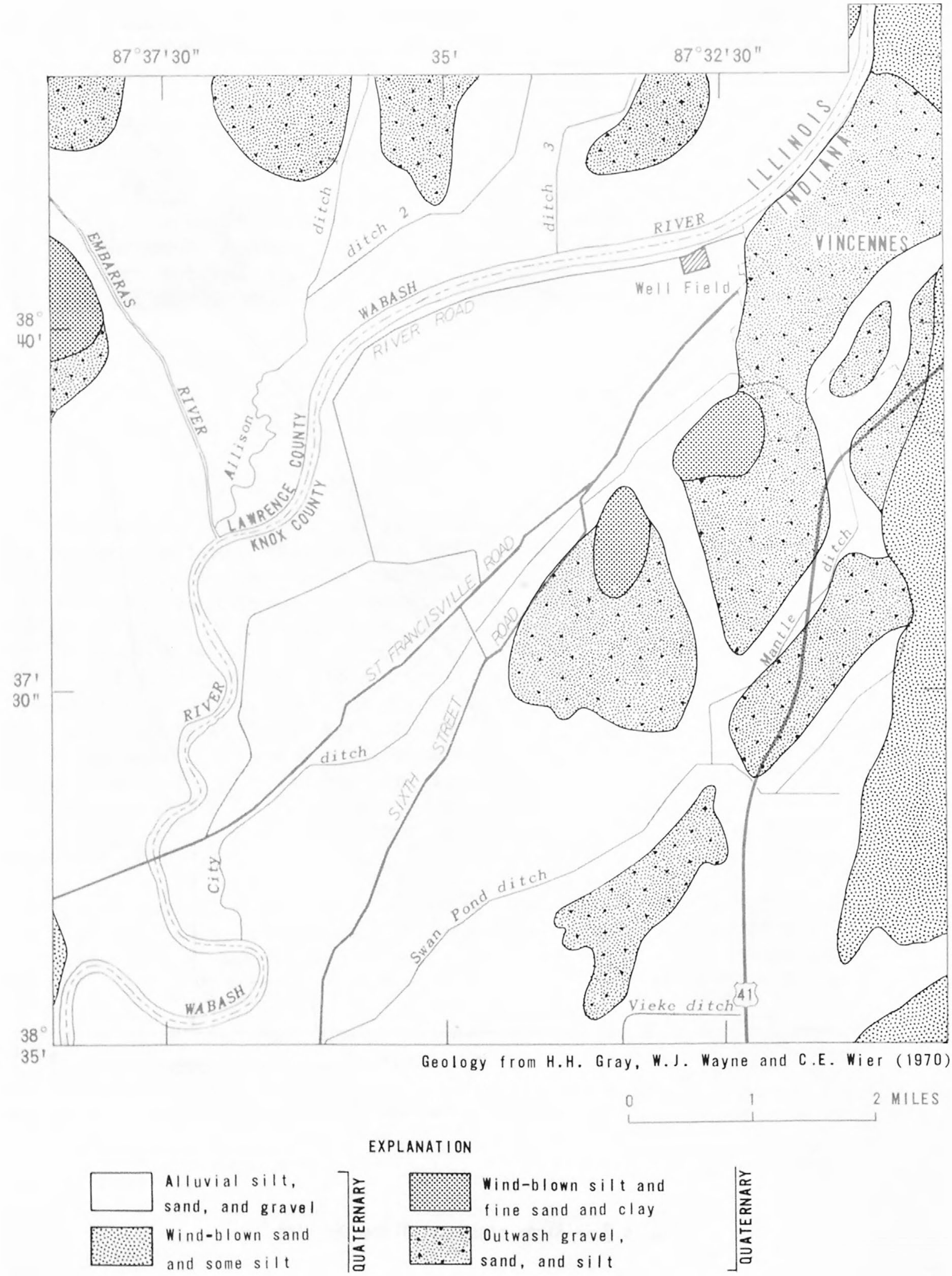


Figure 3. -- Surficial geology near Vincennes, Ind.

Geologic Setting

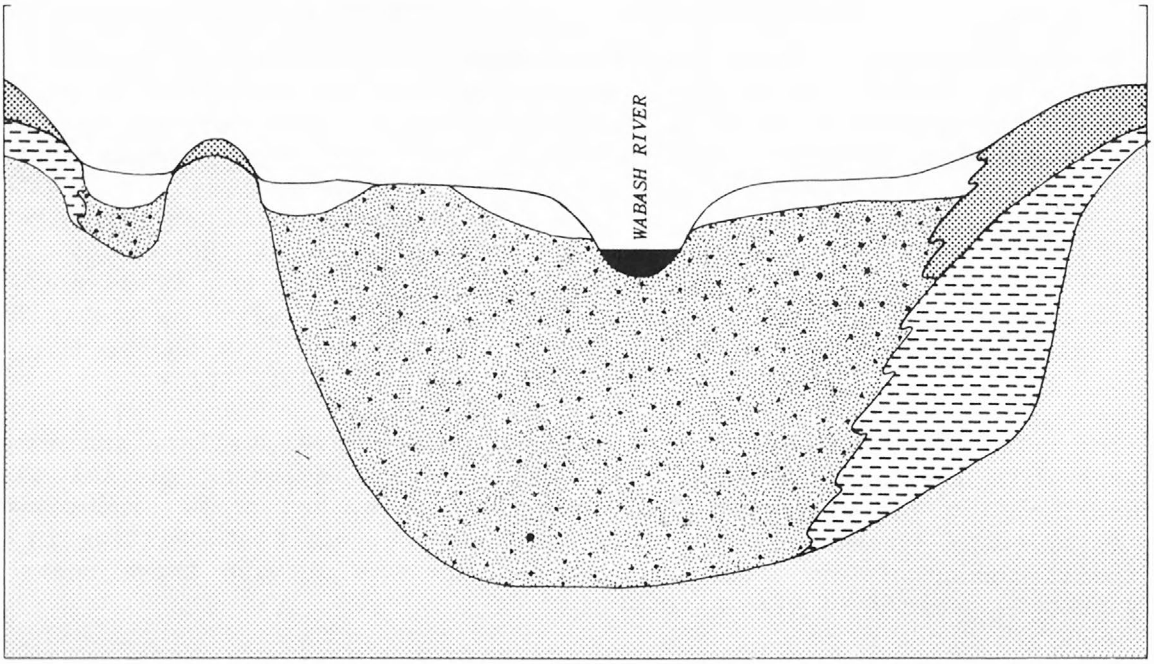
The study area is underlain by the unconsolidated sediments shown on the surficial geology map (fig. 3). These sediments were deposited by glacial processes in the Wabash River valley during the Pleistocene Epoch and were later reworked by wind and water. Figure 4 is a schematic cross section showing the general geometry of the unconsolidated deposits in the Wabash River valley. East and west are not labeled because the figure illustrates stratigraphic relations that are found on both sides of the valley. The glacial outwash consists of coarse sand and fine gravel and is as much as 100 ft thick. The outwash is capped by river alluvium, which is mostly fine sand, silt, and gravel. This alluvium is as much as 30 ft thick, but the topsoil and alluvium together are generally less than 10 ft thick.

The outwash pinches out at the margins of the river valley, and interfingers with the finer sediments of the uplands, including glacial till, lacustrine silt and clay, and windblown sand, silt, and clay. The outwash generally rests directly on the underlying bedrock, but test drilling in the southeast corner of the study area showed that the outwash there rests on clay that is presumably glacial till.

The topography of the bedrock surface and locations of all the test holes, except some near the well field, are shown in figure 5. The bedrock underlying most of the study area is locally known as the Dicksburg Hills Sandstone Member of the Patoka Formation of Pennsylvanian age (Harold Hutchinson, Indiana Geological Survey, oral commun., 1977). This distinctive bluish-gray, medium- to coarse-grained, shaly sandstone is part of a sequence consisting of alternating beds of sandstone and shale of variable thickness and thinner beds of limestone and coal. All but one set of the test-hole cuttings indicates that the bedrock is sandstone. The single exception is a hole near one of the bedrock hills, where cuttings of black shale were recovered. In contrast, drillers' logs indicate that much of the study area is underlain by shale. The discrepancy between the drillers' logs and the Geological Survey test drilling can probably be attributed to an abundance of shale pebbles in the Dicksburg Hills Sandstone Member and to a weathered zone at the top of the sandstone containing clay that adheres to drill tools.

Hydraulic Properties of the Outwash Aquifer

The thickness of the outwash aquifer in the study area was determined by test drilling. Most of the test holes in the outwash aquifer were converted



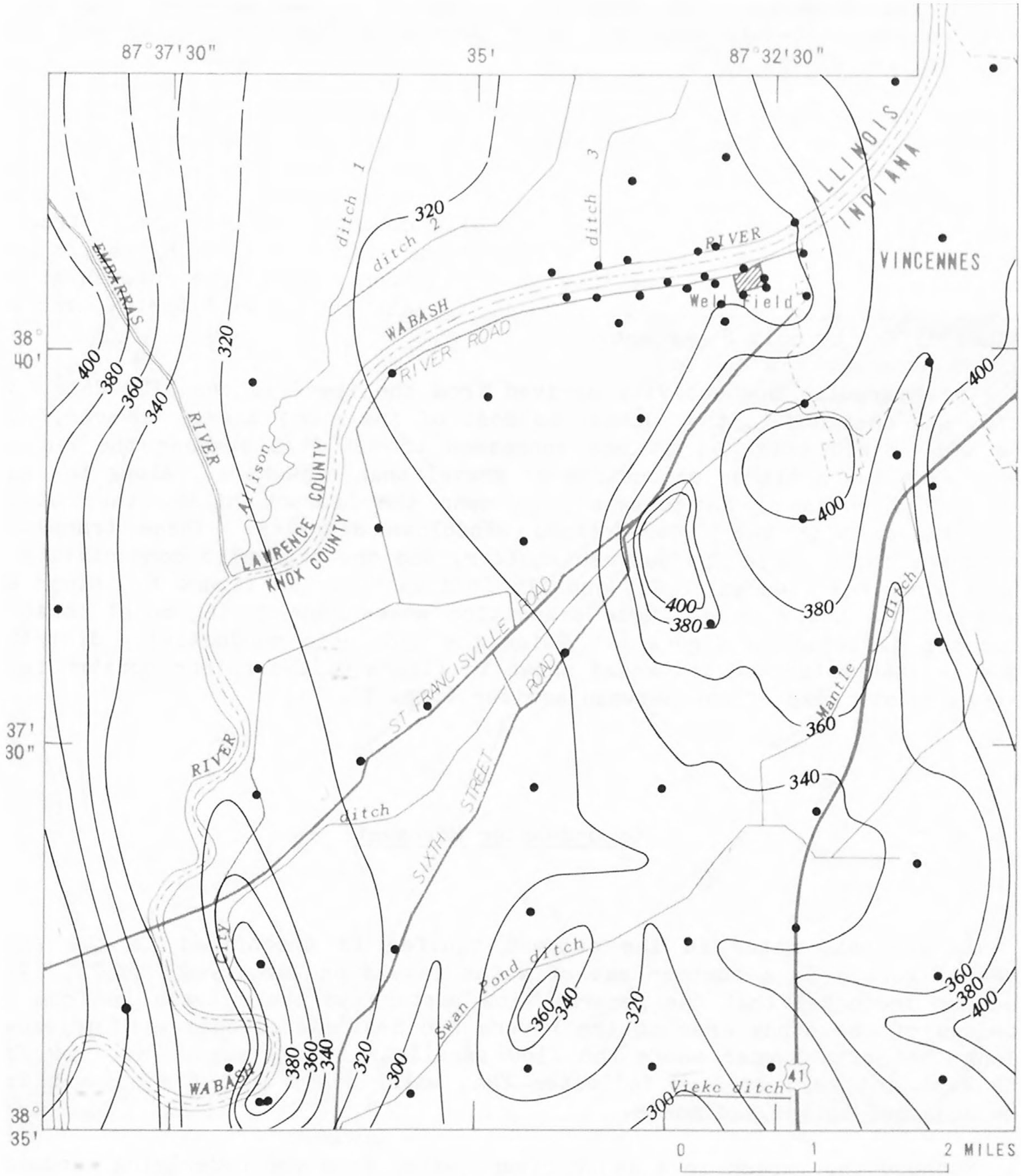
VERTICAL SCALE GREATLY EXAGGERATED

Geology modified from H.H. Gray, W.J. Wayne, and C.E. Wier (1970)

EXPLANATION

Alluvial silt, sand, and gravel	QUATERNARY
Wind-blown silt, fine sand, and clay	QUATERNARY
Outwash gravel, sand, and silt	QUATERNARY
Glacial till, mostly clay	QUATERNARY
Bedrock, sandstone, and some shale	PENNSYLVANIAN

Figure 4. -- General schematic cross section of the Wabash River valley near Vincennes, Ind.



EXPLANATION

—*360*— — Bedrock contour, Interval 20 feet Dashed where approximately located. National Geodetic Vertical Datum of 1929

● Test hole; some holes near well field not shown to avoid clutter

Figure 5.-- Altitude of bedrock surface near Vincennes, Ind.

to observation wells. The saturated thickness of the outwash (fig. 6) is based on the test-hole data and water levels in the observation-well network, January 23-25, 1978.

The average hydraulic conductivity of the outwash was estimated by applying specific-capacity test data obtained from drillers' logs to a method described by Theis (1963) and Meyer and others (1975, p. 18). Logs from wells in the outwash within 60 mi of Vincennes were used for this estimate. The arithmetic mean of the hydraulic conductivities computed from 70 wells was 355 ft/d (foot per day). In addition, a value for hydraulic conductivity of 300 ft/d was obtained in an aquifer test in the outwash at the George Rogers Clark Memorial about 4,000 ft east of the well field. The two values differ by only 8 percent.

The hydraulic conductivity derived from the specific capacity data, 355 ft/d, was assigned to the outwash in most of the study area. However, near the well field (fig. 6) it was increased to 425 ft/d because the outwash there contains a higher percentage of gravel than elsewhere. Along the east and west borders of the outwash and near the bedrock hills, the outwash interfingers with the finer-grained windblown deposits. These transition zones are included in the outwash aquifer, and the hydraulic conductivity in these zones was lowered to 215 and 115 ft/d as shown in figure 6. Minor adjustments in the size of these transition zones made during model calibration are included in figure 6. Using the hydraulic conductivity distribution and the saturated thickness shown in figure 6, the author constructed a transmissivity map of the outwash aquifer (fig. 7).

Ground-Water Movement

In general, water in the outwash aquifer is unconfined in the study area. Figure 8 is a contour map of water levels on January 23 to 25, 1978. The map indicates that the general flow pattern in the outwash is from the borders of the study area to the rivers and drainage ditches within, except along the south border where the flow parallels the border. The flow from the east and west borders indicates that water flows into the outwash from the adjacent upland sediments.

Because the Wabash is a major river, water from the underlying sandstone aquifer probably discharges into the Wabash through the outwash aquifer. In fact, water levels in two sandstone wells near the river, in the area underlain by saline water, indicate upward flow. The wells are completed 20 ft into the sandstone, and, after corrections for density differences, the water levels in the sandstone are 0.05 and 0.10 ft higher than water levels in adjacent wells screened at the base of the outwash.

The upward flow from the sandstone includes a regional component of inflow from outside the study area and a local component representing water that has percolated into the sandstone from the overlying outwash within the

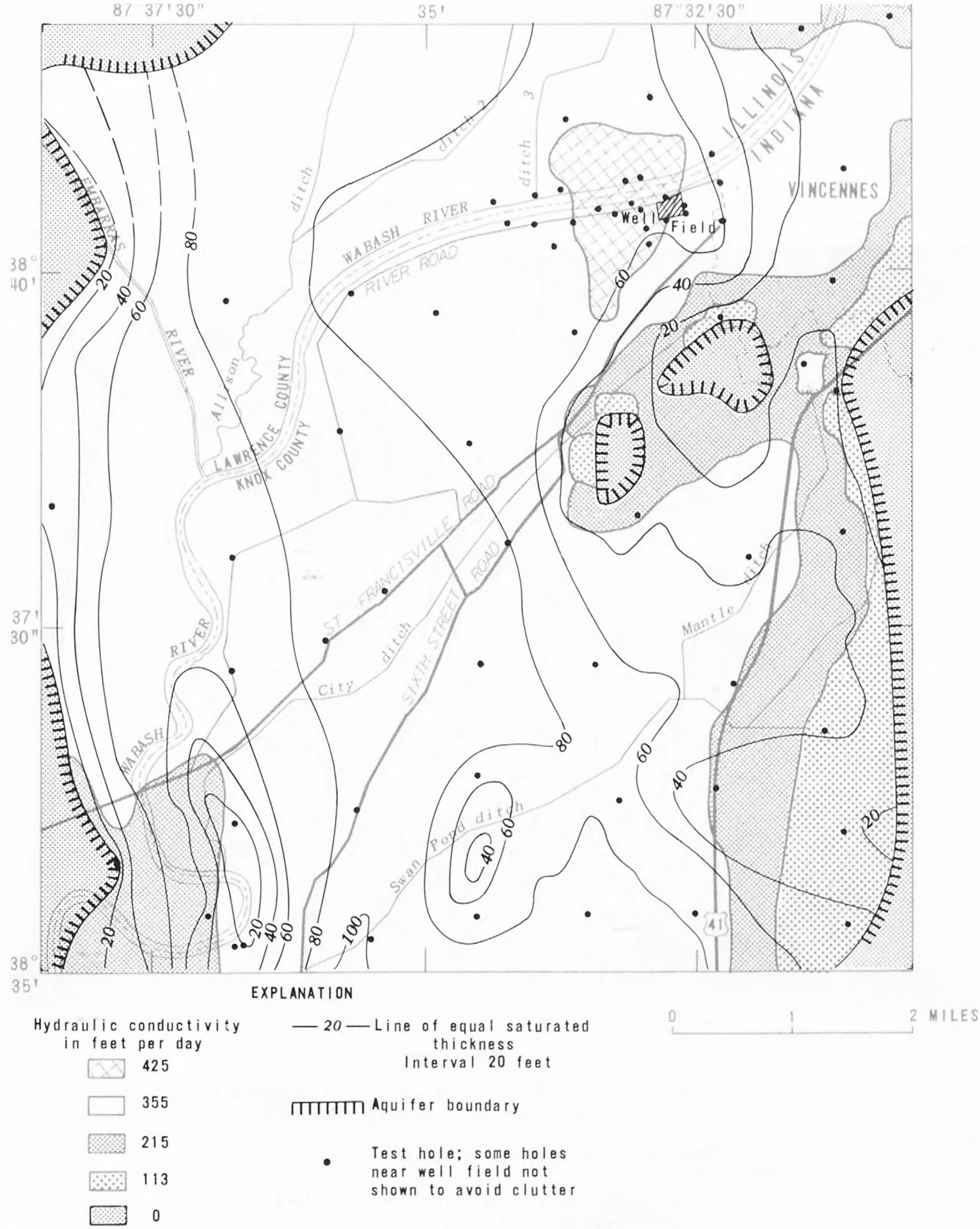
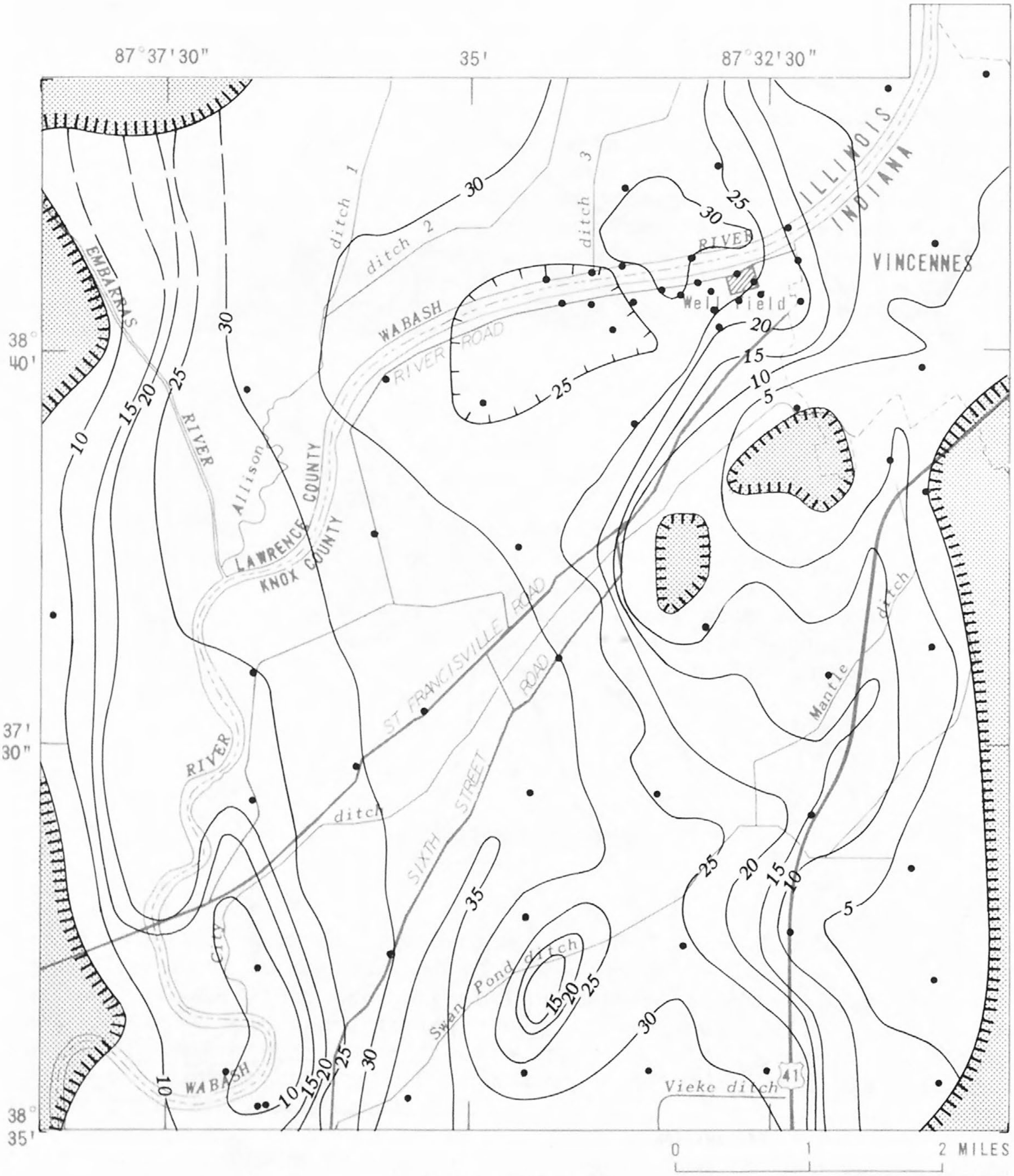


Figure 6.-- Saturated thickness and hydraulic-conductivity distribution of outwash aquifer near Vincennes, Ind., January 23-25, 1978.



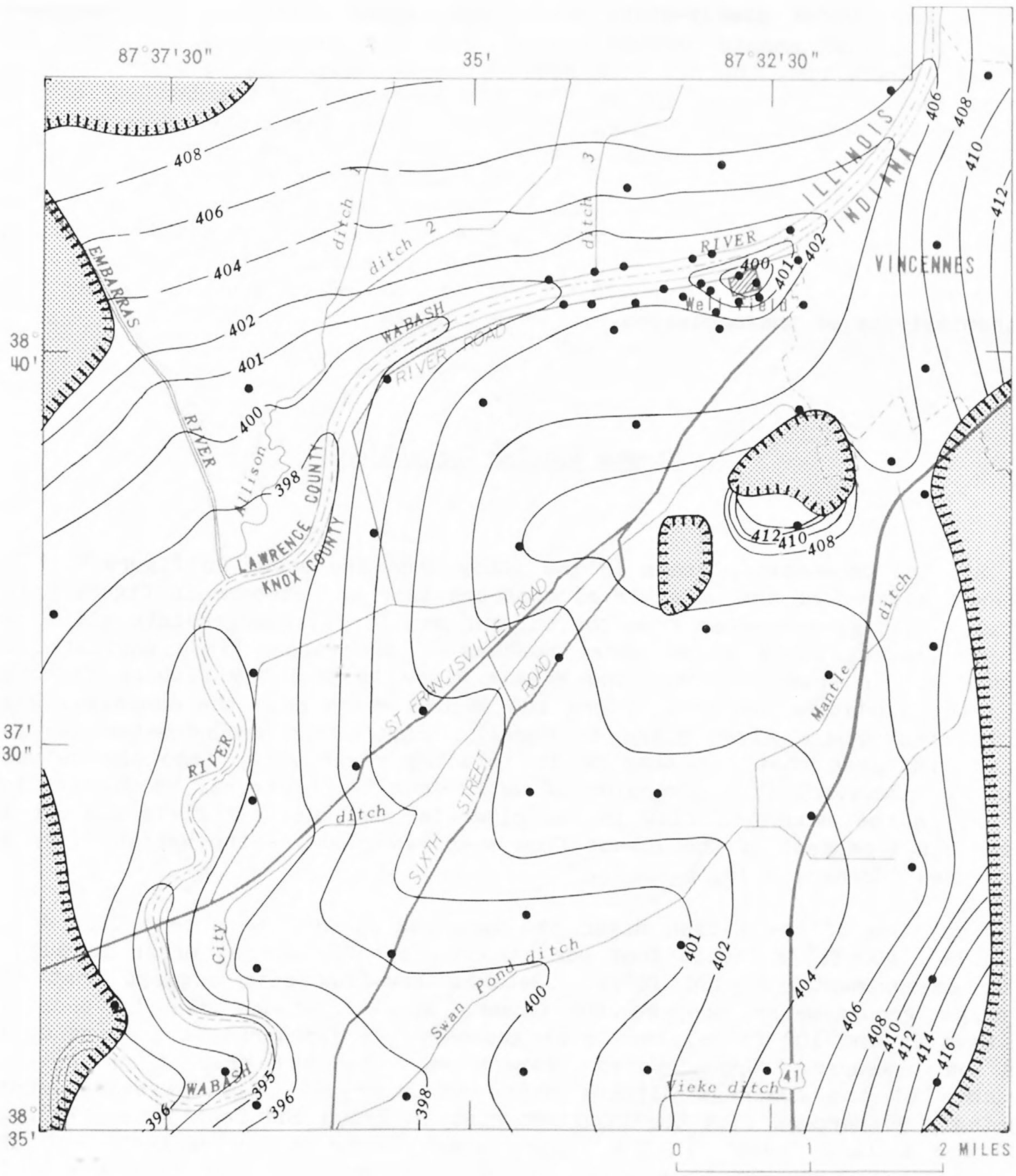
EXPLANATION

—*25*— Line of equal transmissivity, in thousands of feet squared per day. Interval 5000 ft^2/d

Outwash-aquifer boundary

• Test hole; some holes near well field not shown to avoid clutter

Figure 7.-- Transmissivity of outwash aquifer near Vincennes, Ind., January 23-25, 1978.



EXPLANATION

Outwash-aquifer boundary

—396— Water-level contour
Intervals 1 and 2 feet
Dashed where approximate.
National Geodetic Vertical Datum of 1929.

● Observation well

Figure 8. -- Water levels in the outwash aquifer near Vincennes, Ind., January 23-25, 1978.

study area. Under steady-state conditions, local inflow to the sandstone from the outwash should circulate back into the outwash aquifer near the streams. Therefore, the net flow between the sandstone and outwash aquifers should equal the regional inflow from the sandstone at the borders of the study area. However, the regional inflow from the sandstone is probably an insignificant part of the study area water budget because of the large difference in transmissivity between the sandstone and outwash aquifers. On the basis of specific-capacity data for domestic wells in and near the study area, the transmissivity of the sandstone aquifer is estimated to be 130 ft^2/d (square feet per day). The average transmissivity of the outwash aquifer (fig. 7) is about 20,000 ft^2/d, or more than 150 times the transmissivity of the sandstone.

Stream-Aquifer Connection

All the perennial streams in the study area are shown in figure 9. The general pattern of the water-level contours near the streams in figure 8 indicates that ground water from the outwash aquifer discharges into all these streams except along a few short reaches of the Wabash River indicated in figure 9. In these reaches, the Wabash River is probably flowing directly over the sandstone bedrock. Along the shaded reach near the municipal well field, the Wabash River stage is usually higher than ground-water levels, which indicates that the pumpage is inducing river water into the outwash aquifer. However, this diversion of water from the river has no significant effect on the amount of flow in the river because the well-field pumpage is less than 1 percent of the lowest flow ever recorded for the Wabash River at Vincennes (Horner, 1976, p. 213).

The flow of the Wabash River at Vincennes at the 90-percent flow duration is 2,000 ft^3/s (cubic foot per second), and the normal error in such a flow measurement is ± 100 ft^3/s. Because low-flow data suggest that the average ground-water seepage to streams in the study area is probably between 25 and 100 ft^3/s, the total ground-water discharge to streams could not be measured. Ground-water seepage was measured only along several reaches of the drainage ditches shown in figure 9. Seepage measurements during a 90-percent flow duration reported in Nyman and Pettijohn (1968, p. 63) for a large reach of the lower Wabash River valley suggest that the ground-water discharge to streams in the study area at that time was 40-50 ft^3/s. However, an even lower estimate, 30 ft^3/s, is obtained by using methods described in Rorabaugh (1963).

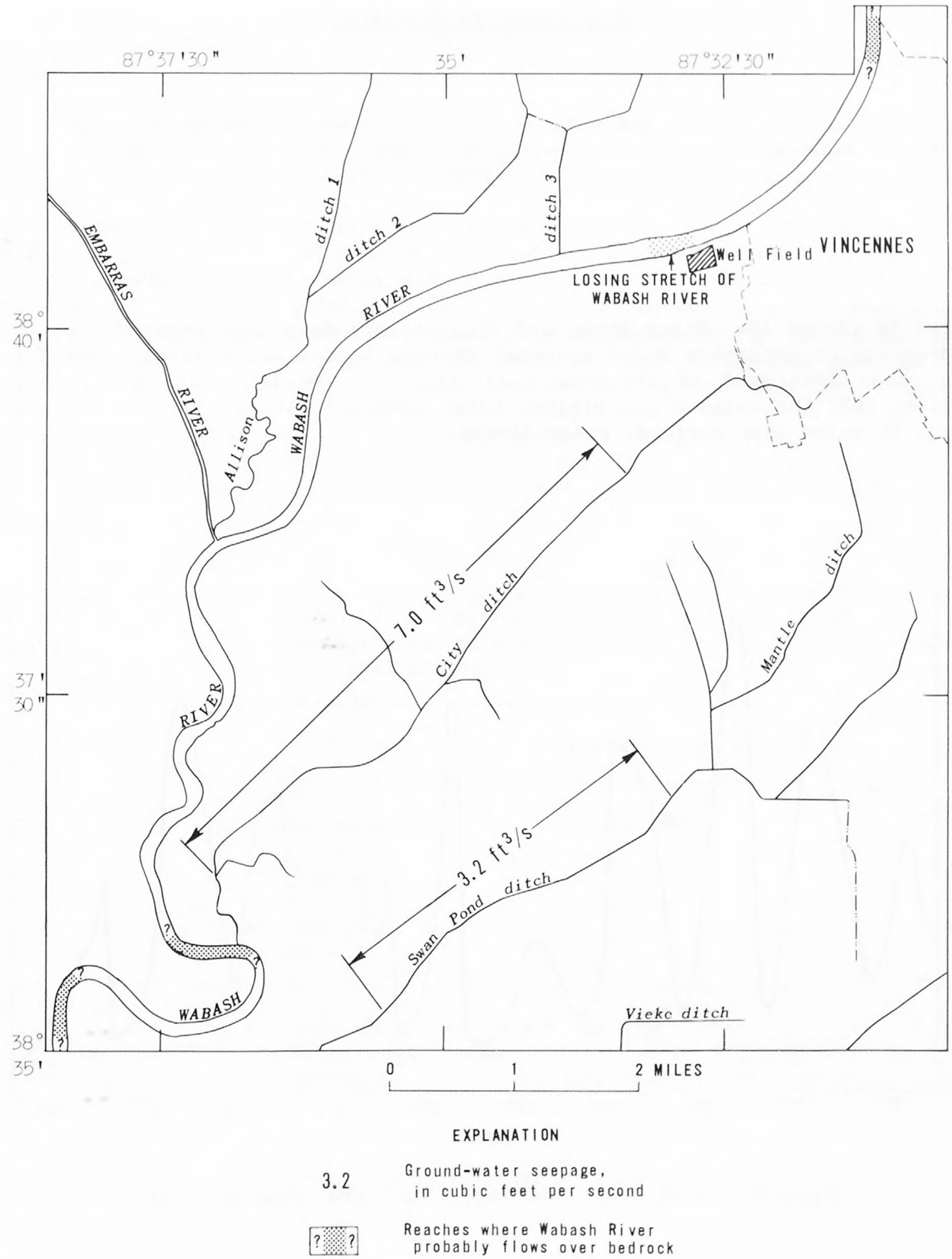


Figure 9.-- Locations of streams and stream-aquifer relations along selected reaches in the study area.

Water-Level Fluctuations

Water levels in the outwash aquifer fluctuate throughout the year because of seasonal changes in recharge and discharge. Fluctuations are also caused by changes in the stage of the Wabash River.

None of the observation wells inside the study area is equipped with a recorder. The closest well equipped with a recorder is 5 mi south of the study area and about 1 mi east of the Wabash River. The hydrograph of this well, Knox 7 (U.S. Geological Survey, 1979, p. 361), from 1967 to 1976 is shown in figure 10. Minor peaks and fluctuations have been removed from the hydrograph to emphasize major seasonal changes in the water level. The figure shows that most of the yearly fluctuations are less than 6 ft. From 1956 to 1978 the maximum and minimum water levels in this well were 3.27 and 11.35 ft below land surface, respectively.

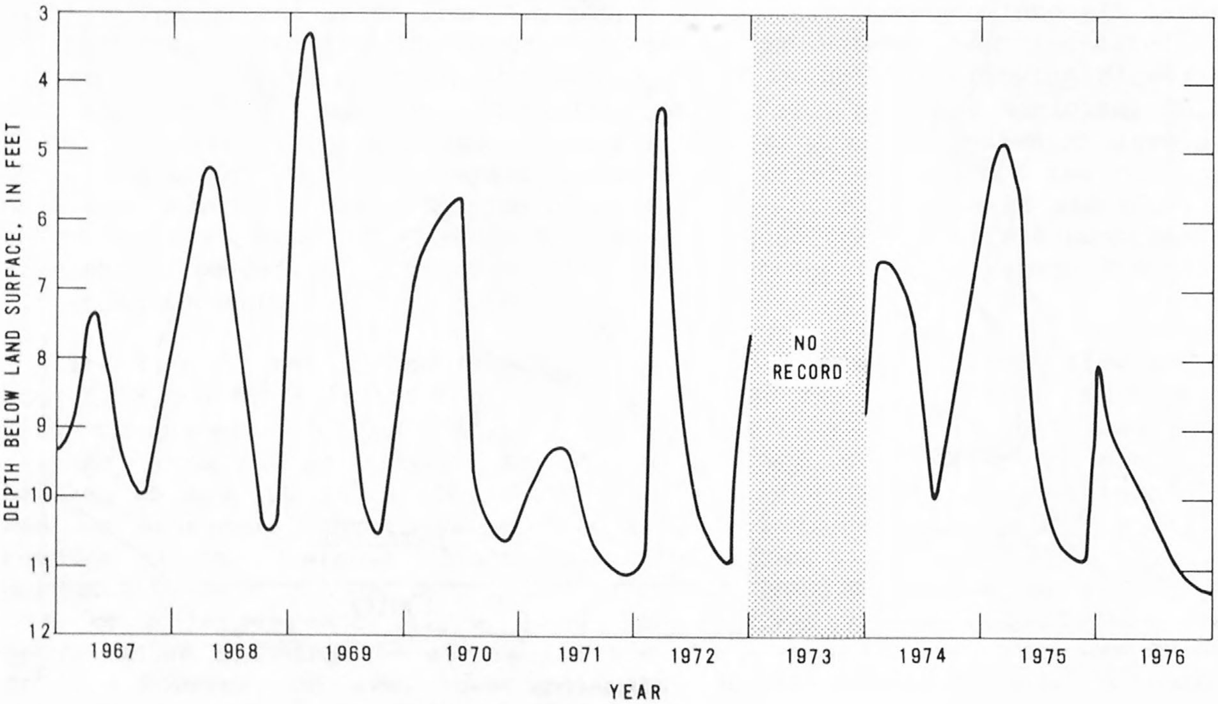


Figure 10. -- Water-level fluctuations in Knox-7 observation well, 1967-76.

Ground-Water Pumpage

The Vincennes well field pumped an average of 3.7 Mgal/d from the outwash aquifer in 1976 and 3.9 Mgal/d in 1977. The well field is the only pumping center in the study area that can be detected on the water-level map in figure 8. Other pumpage from the outwash, either minor (domestic and small industrial pumpage) or seasonal (irrigation), causes very localized or short-term water-level declines. In addition, a few domestic wells are completed in the sandstone bedrock, specifically on or near the bedrock hills.

The estimated total yearly pumpage from the outwash for the period from 1976 through 1977 is summarized in table 1. The irrigation pumpage was estimated by using irrigation rates provided by farmers who kept accurate records. These rates represent normal conditions and were used for all the other irrigation systems in the study area. Although the total irrigation pumpage in the study area normally ranges from 500- to 700-million gallons per growing season, pumpage can approach 1 billion gallons during a dry summer.

Table 1.--Average yearly ground-water pumpage from outwash aquifer from 1976 through 1977

	Millions of gallons[1]
Vincennes well field	1,380
Irrigation	600
Rural, domestic, and industrial	20

[1] All values estimated except for the Vincennes well field.

MODEL ANALYSIS OF OUTWASH AQUIFER

The author used the two-dimensional, finite-difference model of Trescott and others (1976) to simulate ground-water flow in the outwash aquifer. Two flow models were constructed. The first model covers the entire 56-mi^2 study area and is hereafter called the study-area model. This model was used to evaluate the flow system in the outwash aquifer and the interaction between the streams and the aquifer, thus providing a means of evaluating alternate, or additional well fields in the future. The second flow model, hereafter called the well-field model, covers an approximately 4-mi^2 area surrounding the well field. This model was used to simulate ground-water flow near the well field in greater detail than in the study-area model, thus providing better information on water-level declines caused by the projected increase in pumpage. A two-dimensional solute-transport model was also constructed near the well field to simulate and evaluate the movement of chloride into the well field during the present and the projected pumpage. The transport model will be discussed in the section of "Transport-Model Experiments and Discussion."

In both models the outwash aquifer was simulated as a single-layer, water-table aquifer with hydraulically connected streams. Several gravel-pit lakes in the study area were ignored because their areas are generally less than 10 acres. In addition, the contact between the outwash and the underlying sandstone was treated as an impermeable boundary because upward flow from the sandstone is insignificant everywhere except, possibly, beneath the municipal well field.

Study-Area Model

The study-area model, representing approximately 56-mi^2 of the outwash aquifer, is outlined in figure 11. The model has been subdivided into $1{,}000\text{-ft}^2$ (square foot) grid blocks. The outline of the model is irregular, and there are as many as 44 grid blocks in the north-south direction and 38 in the east-west direction.

The east and west boundaries of the study-area model represent the actual areal limits of the outwash as it pinches out at the edges of the Wabash River valley. The south and north boundaries simply represent the limits of the study area, and the outwash aquifer extends beyond these boundaries. Because the water levels shown in figure 8 indicate very little flow across the south boundary, this boundary was simulated as impermeable. All other boundaries were simulated as constant heads that were determined from water-level contours in figure 8.

The outlines of the bedrock hills were simulated as impermeable boundaries, and the areas within the hills were assigned zero transmissivity.

The study-area model was calibrated to water levels observed during January 23-25, 1978. Wabash River levels were measured at several locations at that time, and average pumpage in the well field in January 1978 was 3.6 Mgal/d. The study-area model was not calibrated to the July 25, 1977, water levels used in the well-field model because several important observation wells near the Wabash River had not been installed by July 1977.

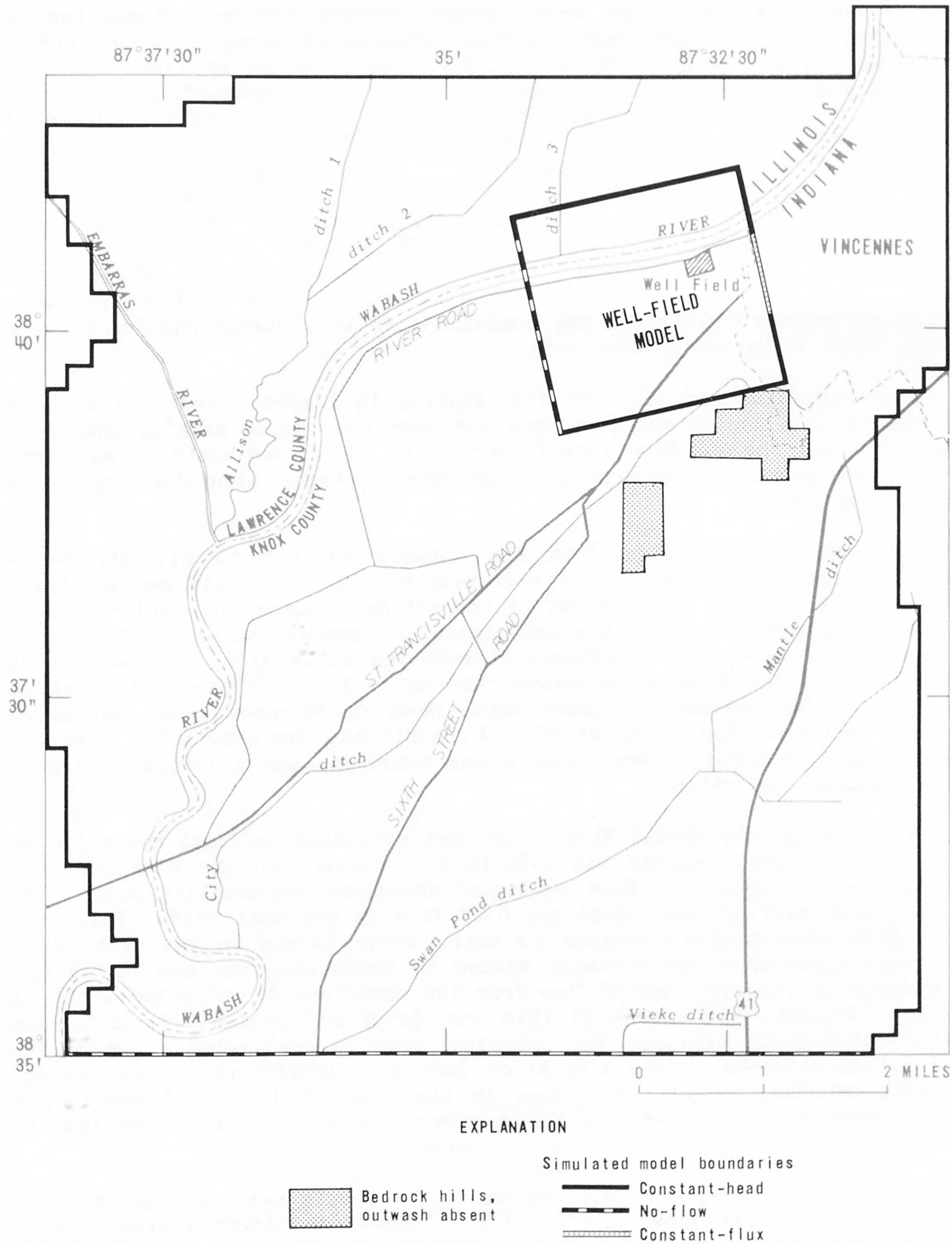


Figure 11.-- Outlines of study-area and well-field digital models.

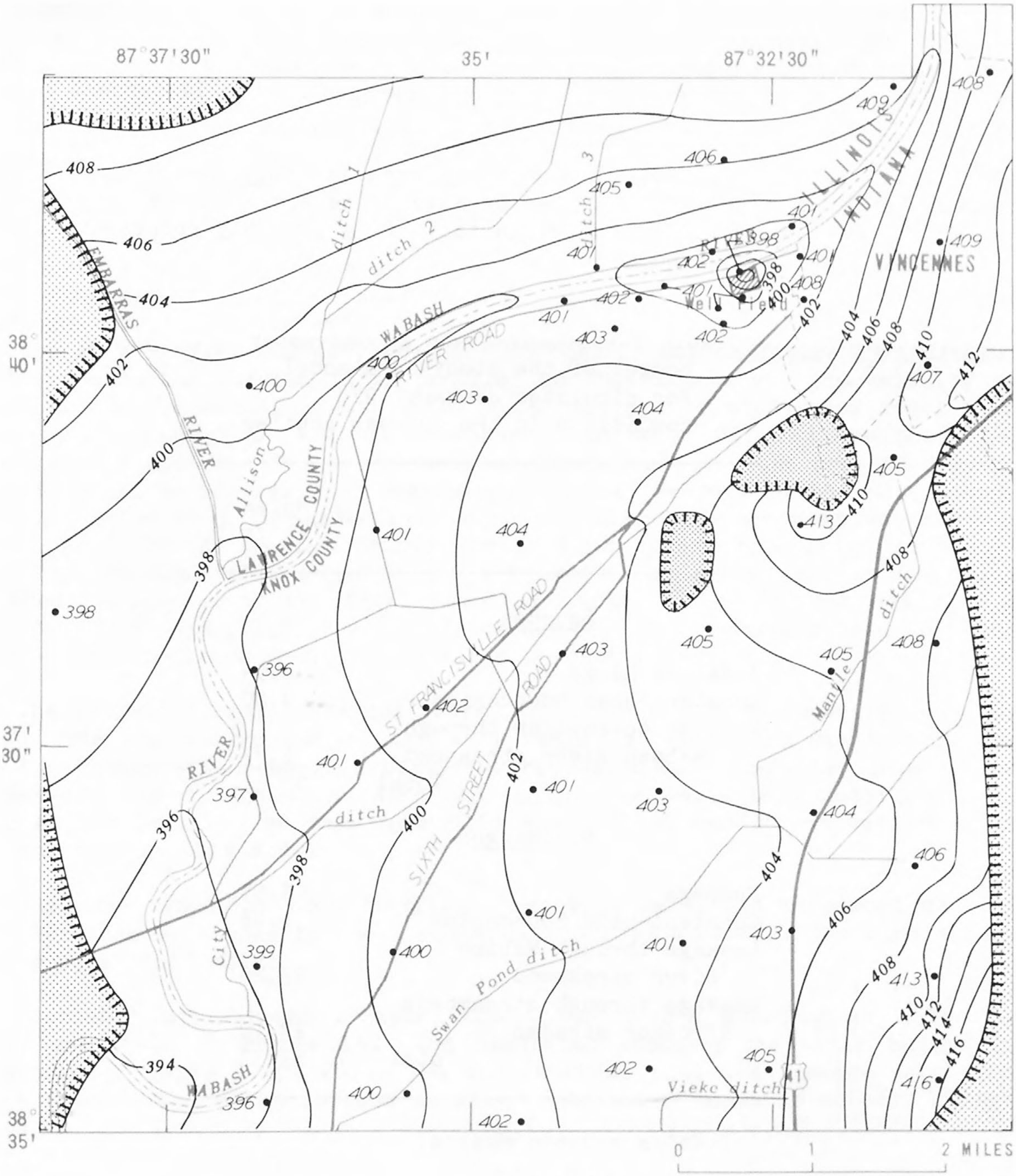
Steady-state conditions were assumed because the well field has been operating for 25 yr with fairly gradual changes in pumpage. Four different recharge rates, namely 11.0, 12.1, 15.0, and 17.0 in./yr (inch per year), were used during model calibration. The only significant effect of increasing the recharge rate from 11.0 in./yr to 17.0 in./yr was to increase the leakage into the Wabash River. The simulated water levels were less than 1 ft higher for a rate of 17.0 in./yr than those for a rate of 11.0 in./yr. The value that yielded the best match between simulated water levels and water levels measured during January 1978, 12.1 in./yr, was used as the recharge rate for all model simulations. This value is close to the 11.9 in./yr used by Gillies (1976) for November conditions in the outwash aquifer along the White River in Hamilton County, Ind., and the 13.5 in./yr used by Meyer and others (1975) for May conditions in the outwash aquifer along the White River in Marion County, Ind.

The hydraulic conductivity distribution in figure 6 includes minor adjustments made during model calibration near the valley margins and bedrock hills, where the outwash interfingers with finer sediments. Few changes were made because there was good agreement between simulated and January 1978 water levels.

Leakage was simulated from the outwash aquifer to all streams and ditches shown in figure 9. The thickness of all streambeds was arbitrarily assigned as 1.0 ft. The hydraulic connection between the aquifer and the streams was adjusted until the best match of observed water levels near the streams was achieved. In several observation wells along the banks of the Wabash River, the difference between the water level in the aquifer and the river level was measured. These water-level differences were used as part of the criteria for calibration. In addition, the hydraulic connection along ditch segments, where seepage was measured, was adjusted to approximate the measured rates.

For most of the Wabash River, the best estimated vertical hydraulic conductivity of the streambed was 0.03 ft/d. However, in the area covered by the well-field model the best estimated streambed conductivity was 0.7 ft/d in the east half of that model and 0.07 ft/d in the west half. This higher streambed conductivity required to match water levels in the east half of the well-field model is probably needed to compensate for the inability of the model to simulate upward flow from the sandstone directly below the well field. However, the effect of this simplification is that the model-simulated water-level declines for increased pumpage are probably greater than the actual declines. This limitation does not significantly bias the model results because, as will be shown in the "Well-Field Model" section, the water-level declines simulated for double the present pumpage are less than 10 ft.

Simulated water-level contours and water levels measured during January 23 to 25, 1978, are shown in figure 12. The water budget simulated by the steady-state condition is given in table 2. The total discharge of ground water to streams, 46.3 ft^3/s, is within the range estimated from the low-flow data referred to in the section, "Stream-Aquifer Connection." Seepage into the Wabash River accounts for 23.2 ft^3/s, and seepage into the drainage



EXPLANATION

—400— Simulated water-level contour Interval 2 feet
National Geodetic Vertical Datum of 1929

Outwash-aquifer boundary

• 400 Water level measured January 23-25, 1978

Figure 12.-- Simulated water levels in the outwash aquifer, study-area model.

ditches accounts for 21.3 ft^3/s. The remaining 1.8 ft^3/s is discharged into the Embarras River. The water budget also shows that the areal recharge term represents 81 percent of the total budget, whereas the inflow rate from the constant-head boundaries of the model represents only 17 percent of the total.

The actual water budget in the study area probably deviates from that shown in table 2 throughout the year because of seasonal changes in recharge and discharge. However, the budget in table 2 is probably representative of the average annual water budget.

Table 2.--Steady-state ground-water budget of the study-area model for simulated January 1978 conditions in the outwash aquifer

	Rates (ft^3/s)[1]
Sources	
Areal recharge	42.94
Constant-head boundaries	9.00
Leakage to aquifer through Wabash River streambed	1.37
Total	53.31
Discharges	
Pumpage	5.55
Constant-head boundaries	1.48
Leakage through Wabash River streambed	23.20
Leakage through streambeds of other streams	23.10
Total	53.33

[1] 1 ft^3/s = 0.646 Mgal/d.

Well-Field Model

The area of the well-field model was designed to include the full areal extent of the saline-water plume (fig. 17, p. 32) and most of the cone of influence from the well-field pumpage (fig. 12). In the model, this area was subdivided into 400 square-grid blocks 500 ft along each side.

The boundaries of the well-field model were arbitrarily chosen within the outwash aquifer. The north and south boundaries, and sections of the east boundary, were simulated as constant-head boundaries as depicted in figures 11 and 13. The water levels used on the constant-head boundaries were determined from water levels measured in July 1977 (fig. 13). The rest of the east boundary was simulated as a constant-flux boundary to limit the flow of water across this part of the boundary during increased-pumpage simulations. Constant-flux conditions were used because water-level declines in some of the increased-pumpage simulations reached this part of the boundary. Even though these water-level declines were less than 2 ft, constant-flux conditions were used so that water-level declines predicted by the model would be maximized. The west boundary of the well-field model was treated as a no-flow boundary because the contour map in figure 13 indicates that water in the outwash flows parallel to that boundary. The validity of these boundary conditions was tested by stressing the study-area model with the average pumpage of 4.2 Mgal/d observed in July 1977 and the projected pumpage of 8 Mgal/d. The water-level declines caused by the projected pumpage along all boundaries were negligible, except the part of the east boundary (simulated as a constant-flux boundary), where the drawdown was about 1 ft or so. The difference between total flux across boundaries simulated with the pumpages of 4.2 Mgal/d and 8 Mgal/d is less than 0.2 ft^3/s, which is about 4 percent of the total incoming boundary flux for pumpage of 4.2 Mgal/d. Therefore, any error introduced by using constant-head or constant-flux boundaries should be within 4 percent.

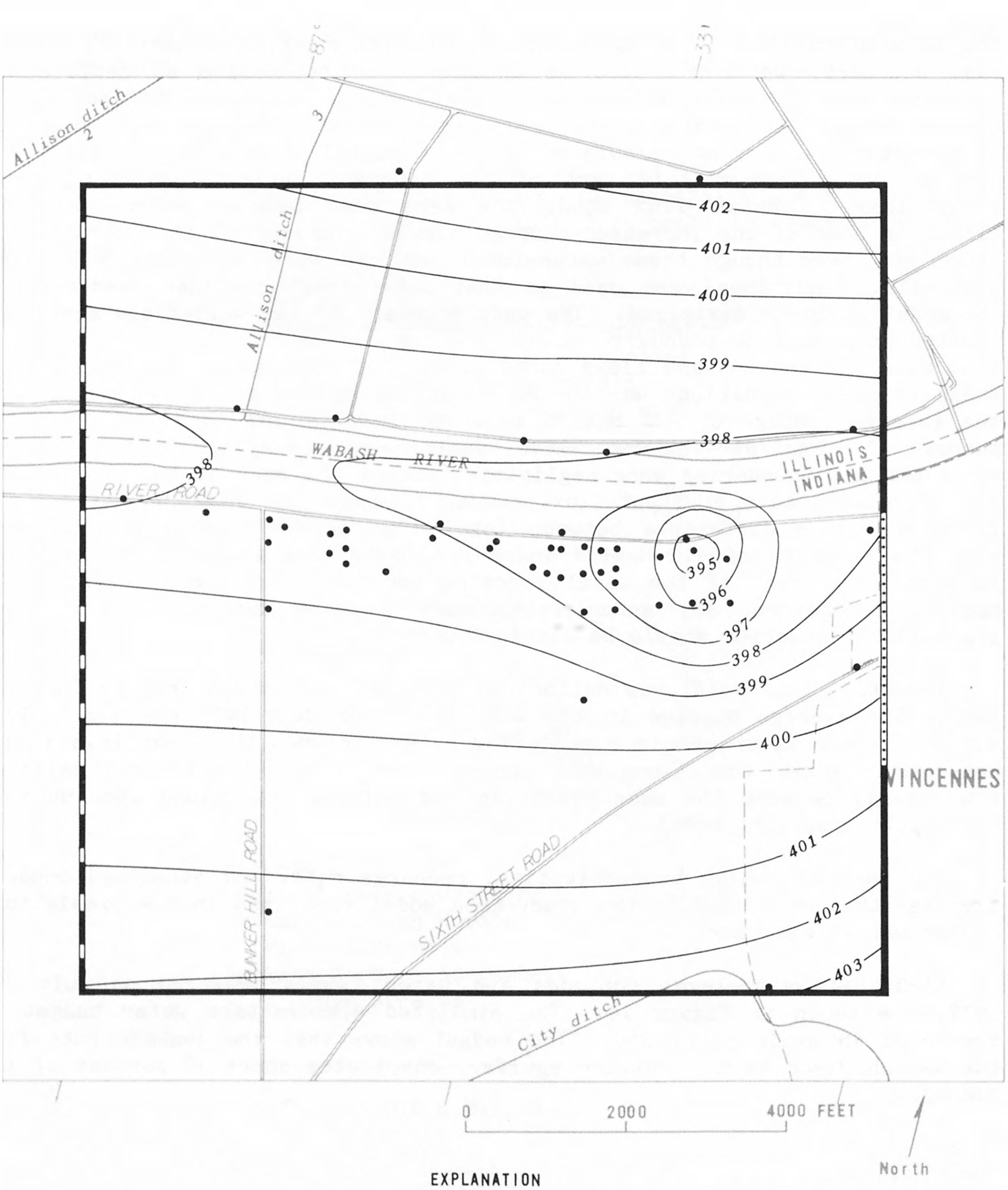
The well-field model was calibrated to water levels measured on July 25, 1977. The average pumpage in the well field for July 1977 was 4.2 Mgal/d, and the Wabash River was in a base-flow recession when the water levels were measured. Summer conditions were chosen for the well-field model calibration mainly because the same hydraulic and initial conditions were used in the solute-transport model.

The same hydraulic conductivities, recharge rate, and streambed conductivities that were used in the study-area model were used in the simulations of the well-field model.

Simulated water-level contours and water levels measured on July 25, 1977, are shown in figure 14. The simulated steady-state water budget is presented in table 3 (p. 26). The budget shows that the leakage rate from the Wabash River to the outwash aquifer contributes about 18 percent of the pumpage.

Simulation of Increased Pumpage in Well Field

The projected pumpage, 8 Mgal/d, was also simulated by the well-field model. Water-level declines predicted by the model analysis for this pumpage at steady state are shown in figure 15 (p. 27). Declines greater than



EXPLANATION

—*399*— Water-level contour
Interval 1 foot
National Geodetic Vertical Datum of 1929

• Test hole

Simulated model boundaries

Constant-head

No-flow

Constant-flux

Figure 13.-- Water levels in glacial-outwash aquifer, well-field model area, July 25, 1977.

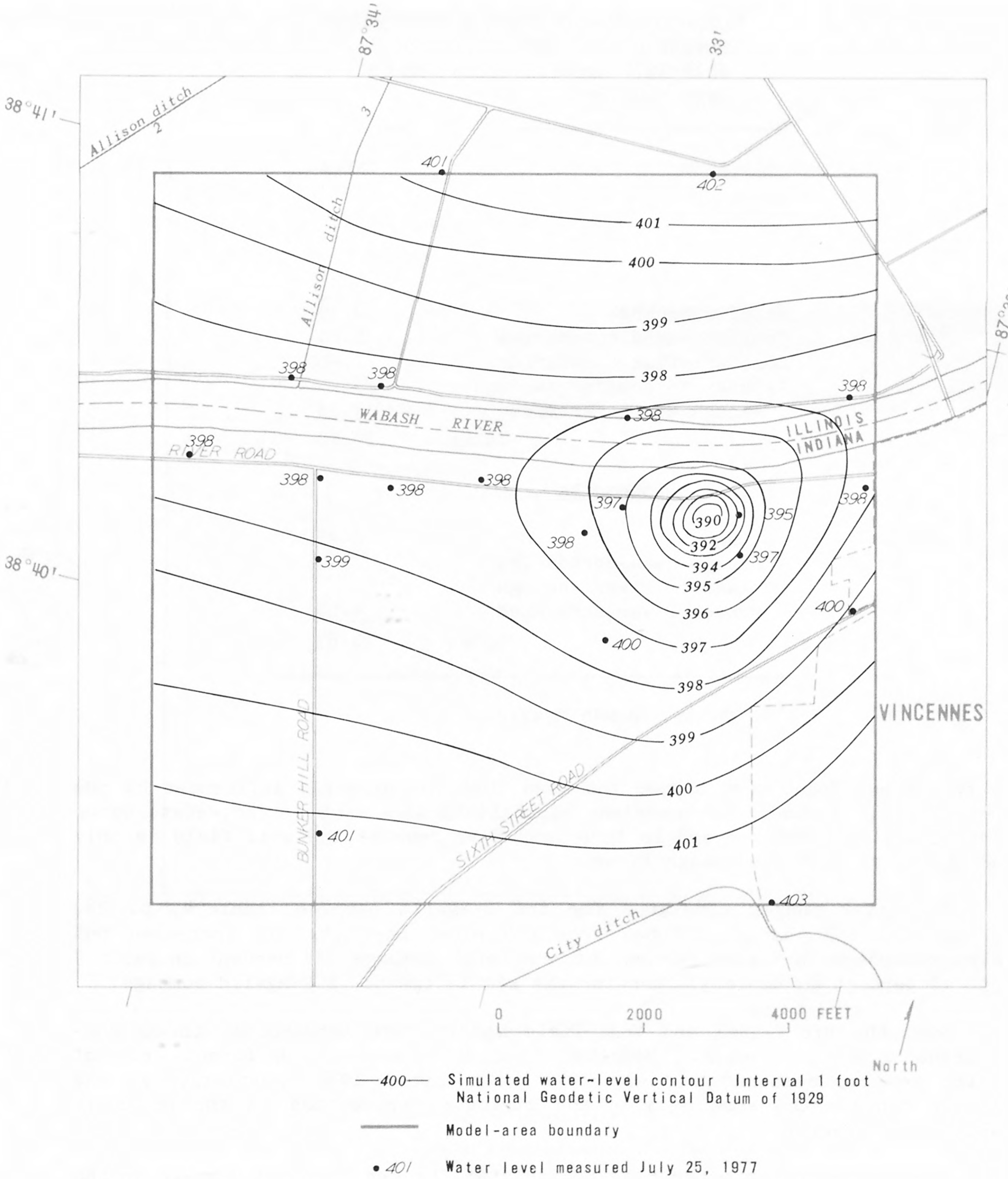


Figure 14.-- Simulated water levels in the outwash aquifer, well-field model.

Table 3.--Steady-state ground-water budget of the well-field model for July 1977 conditions in the outwash aquifer

	Rates (ft^3/s)[1]
Sources	
Areal reacharge	2.79
Constant-head boundaries	5.28
Constant-flux boundaries	1.45
Leakage to aquifer through Wabash River streambed	1.18
Total	10.70
Discharges	
Pumpage	6.45
Constant-head boundaries	.16
Leakage to river through Wabash River streambed	4.06
Total	10.67

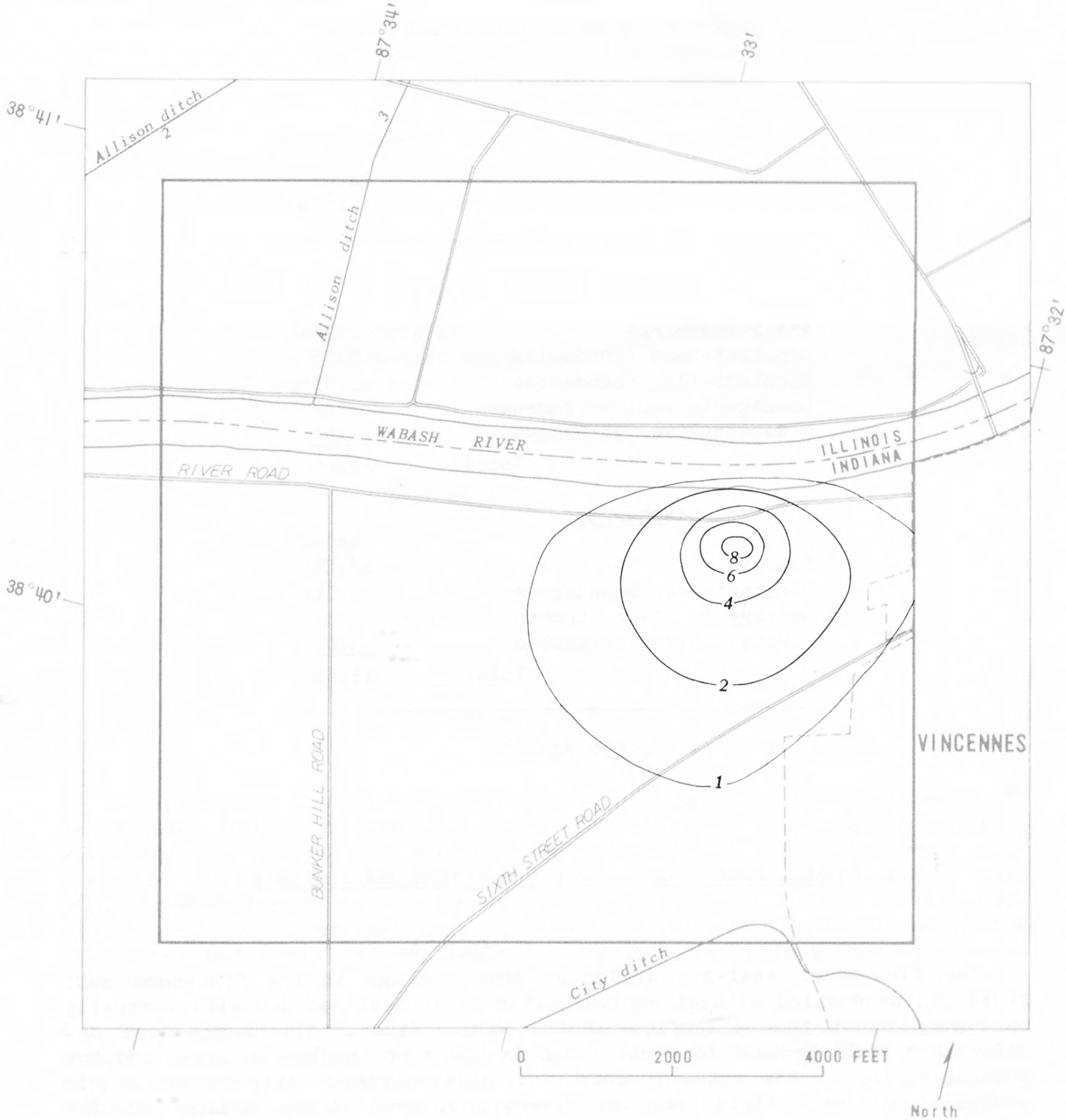
[1] 1 ft^3/s = 0.646 Mgal/d.

1 ft are not found much beyond the area that is currently influenced by the well field. Although no transient simulations were done, steady-state water levels are probably reached in less than 5 yr because the well field is only about 500 ft from the Wabash River.

The water budget simulated for the 8-Mgal/d pumpage (table 4, p. 28) shows that the leakage induced from the river has not only increased but also represents a higher percent of the total pumpage (39 percent in table 4 and 18 percent in table 3) than for the simulation of 4.2-Mgal/d pumpage.

Both the study-area and well-field models were constructed to be consistent with each other. Despite being calibrated to different sets of water levels, measured in July 1977 and January 1978, respectively, the models contain the same aquifer and streambed properties in the areas in which they overlap.

Comparison of the water budget simulated for the 8-Mgal/d pumpage in the study-area model (table 5, p. 29) with the water budget simulated for the 3.6-Mgal/d pumpage (table 2, p. 22) shows that very little additional water has been induced across the boundaries of the study area with more than double the pumpage. Most of the additional water has been derived from leakage induced through the streambed of the Wabash River.



EXPLANATION

Model-area boundary

—6— Line of equal water-level decline
Intervals 1 and 2 feet

Figure 15.-- Water-level declines in the outwash aquifer near the Vincennes, Ind., well field, for simulated 8-Mgal/d pumpage in well-field model.

Table 4.--Steady-state ground-water budget of the well-field model for simulated 8-Mgal/d pumpage in the Vincennes well field

	Rates (ft^3/s)[1]
Sources	
Areal reacharge	2.79
Constant-head boundaries	6.58
Constant-flux boundaries	1.45
Leakage to aquifer through Wabash River streambed	4.84
Total	15.66
Discharges	
Pumpage	12.44
Constant-head boundaries	.12
Leakage to river through Wabash River streambed	3.09
Total	15.65

[1] 1 ft^3/s = 0.646 Mgal/d.

Significance and Limitations of Model Analysis

The flow-model analysis indicates that pumpage in the Vincennes well field can be doubled without serious water-level declines and with virtually no reduction in the streamflow of the Wabash River. The water-level declines are small because the well field is close to the Wabash River and the transmissivity of the outwash aquifer is high. Ground water is easily diverted to the well field from the river, and, even at the present pumping rate, a significant amount of river water is being induced into the outwash aquifer. The same pumpage from wells farther away from the river would cause larger water-level declines.

Table 5.--Steady-state ground-water budget of the study-area model for simulated 8-Mgal/d pumpage in the Vincennes well field

	Rates (ft^3/s)[1]
Sources	
Areal recharge	42.94
Constant-head boundaries	9.17
Leakage to aquifer through Wabash River streambed	6.31
Total	58.42
Discharges	
Pumpage	12.67
Constant-head boundaries	1.45
Leakage to all streams in study area	44.29
Total	58.41

[1] 1ft^3/s = 0.646 Mgal/d.

Nevertheless, the saturated-thickness map (fig. 6, p. 11) and the simulated water budget suggest that large quantities of ground water could be withdrawn from the outwash aquifer in other parts of the study area. However, no other potential well-field sites were investigated during this study because there are no plans to relocate the well field. If an additional well field or new major pumpage is planned in the outwash, the study-area model will be available to simulate any effects caused by new stresses.

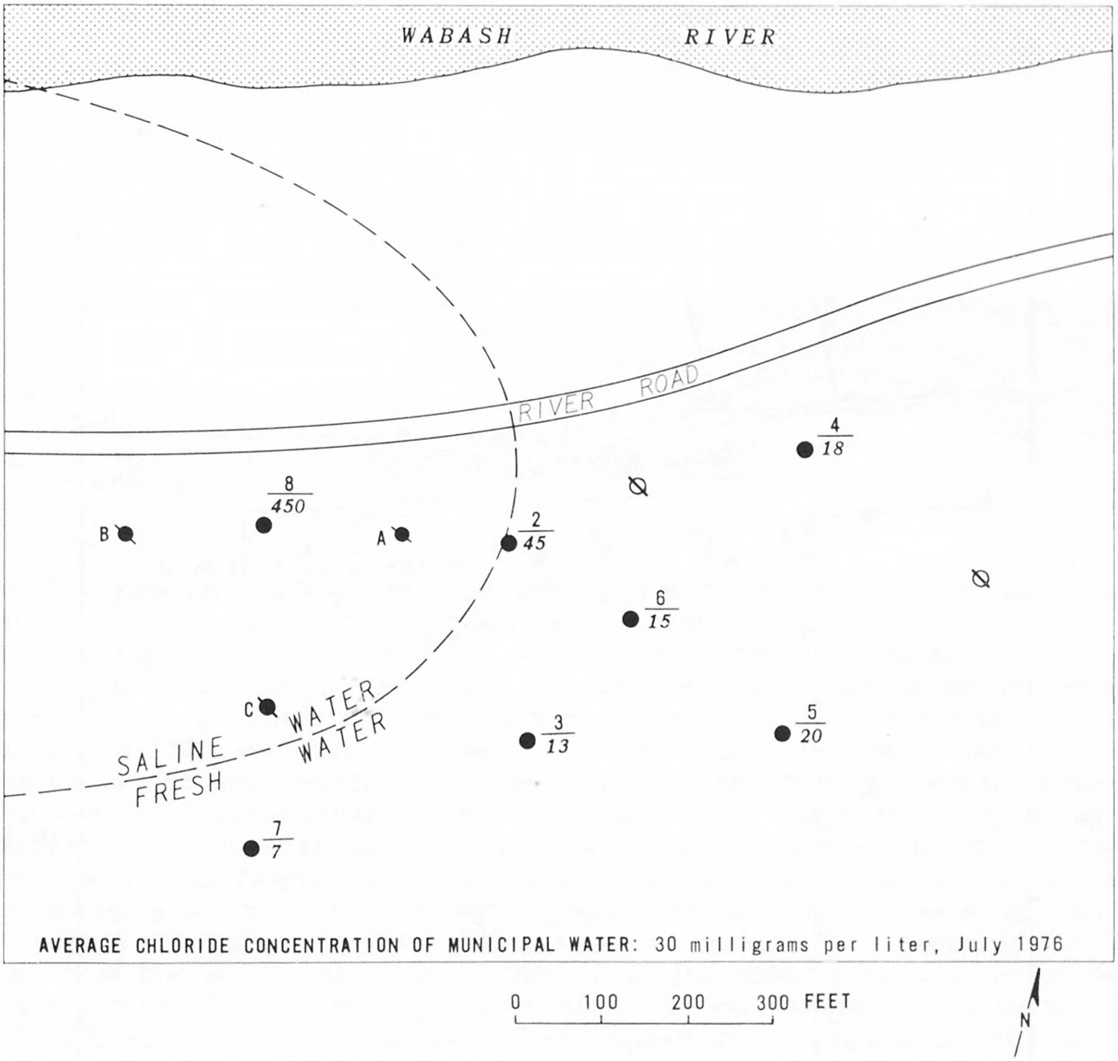
There are limits to what can be accurately simulated in the models constructed in this study. The models cannot represent all details of the real outwash aquifer. For instance, aquifer properties are assumed to be uniform over the entire area of a grid block. In addition, the model can simulate only one pumping well centered in a grid block. Therefore, the singular effects of several wells in a grid block or the effects of a well in the corner of a grid block cannot be simulated in detail. In the well-field model, seven pumping wells were distributed among three grid blocks; in the study-area model, the entire well field was in one grid block. Therefore, problems with well interference in the well field cannot be evaluated with the study-area model and can only be evaluated to a limited degree with the well-field model, if at all. Another limit of the models is that neither one can directly simulate upward flow from the sandstone beneath the well field. Therefore, the models cannot estimate whether this upward flow will become a significant part of the water budget as pumpage in the well field increases. Lastly, the saline-water problem in Vincennes illustrates a very important constraint in using the results of flow-model analysis. Flow-model simulations must not be interpreted without consideration of water quality. An additional quantity of water that is predicted to be available by flow-model analysis may not be usable if the increased pumpage induces an undesirable change in water chemistry.

SALINE WATER NEAR VINCENNES WELL FIELD

In July 1976 the chloride concentration of water from one of two new production wells (well 8 in fig. 16) was nearly 500 mg/L, and a layer of saline water was identified at the bottom of the outwash aquifer west of the well field. The locations of three observation wells, installed by the city within 200 ft of well 8 are shown in figure 16. Both new production wells (well 7 and well 8) were screened in the bottom 30 ft of the outwash, and the three observation wells (A, B, and C, fig. 16) were screened in the bottom 10 ft. The chloride concentration of water collected from the bottom of well 8 and the three observation wells ranged from 2,000 to 3,500 mg/L. However, the chloride concentration of water pumped from well 8 was only 450 mg/L (fig. 16) because the bottom water, which had a higher chloride concentration, was mixed with fresher water coming from the top 20 ft of the screen. Specific conductance profiles of the screened intervals of the three observation wells and the two new production wells indicated that all wells except well 7 contained saline water in the bottom 4 to 8 ft. Furthermore, differences in chloride concentrations among individual wells in the well field (fig. 16) indicated that the leading edge of the saline-water plume had already been drawn into the well field. The chloride concentration of production well 2, which is closest to well 8, was 45 mg/L in July 1976. This concentration was two to three times the chloride concentrations of the other producing wells at that time. There are not enough data to determine how long the saline water has been entering the well field because chloride concentration was not determined daily for individual wells before 1976. However, the chloride concentration of water from well 2 indicates an annual range from 8 to 38 mg/L. Although the concentration does not steadily increase in time, saline water may have been entering the well field since the mid-1960's.

Extent of Saline Water

The areal extent of the saline-water plume was determined by installing observation wells, screened in the bottom 3 ft of the outwash (fig. 17). The wells were sampled nine times between September 1976 and September 1979, and the shape of the plume was virtually unchanged each time. Minor changes



EXPLANATION

● Municipal well, screened in bottom 30 feet

3 Municipal well number
13 Chloride concentration, in milligrams per liter

U.S. Geological Survey observation well, screened in bottom 3 feet

A Municipal observation well and designation, screened in bottom 10 feet

— — Boundary of saline water

Figure 16. -- Chloride concentrations of water from municipal wells, Vincennes, Ind., July 1976.

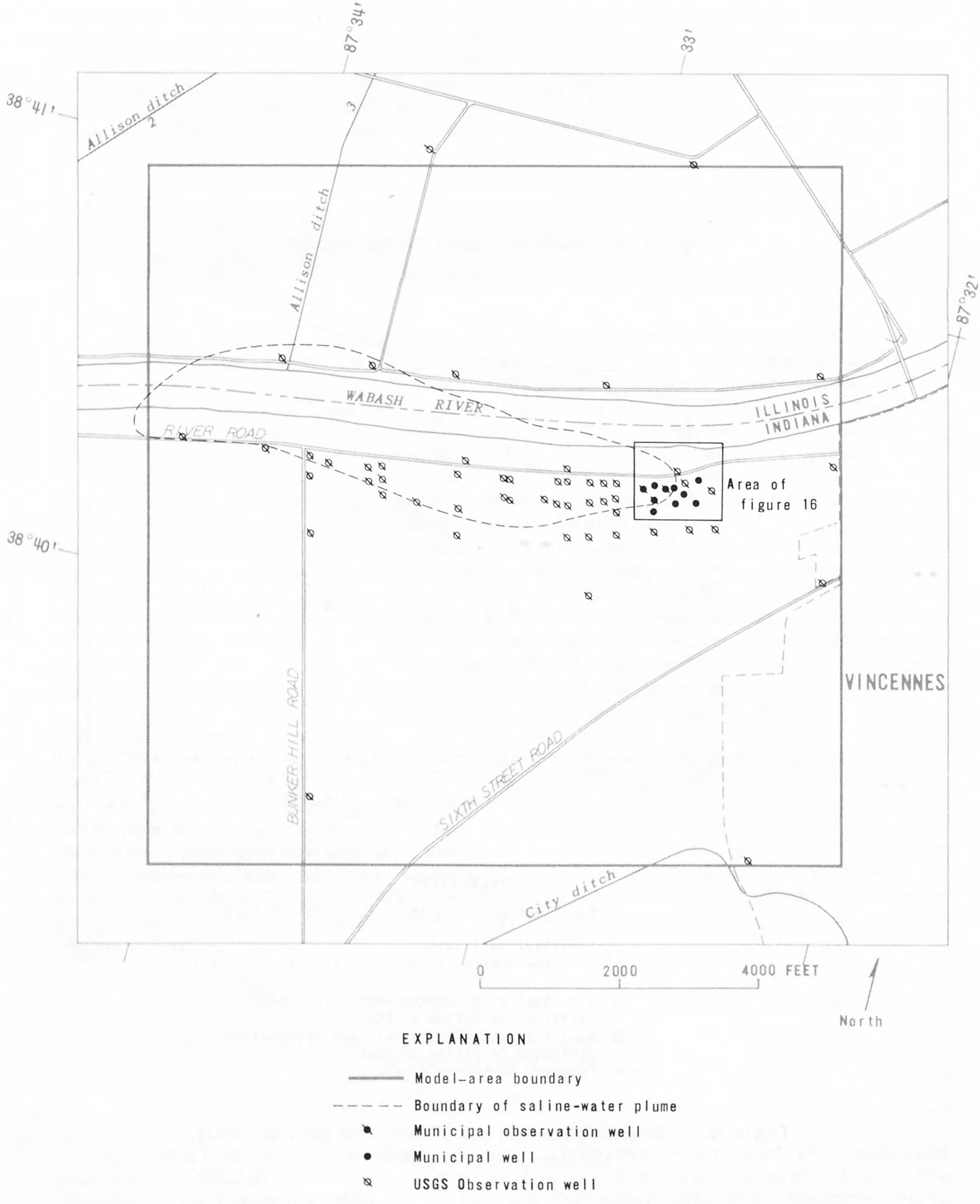


Figure 17.-- Observation and municipal wells in vicinity of saline-water plume.

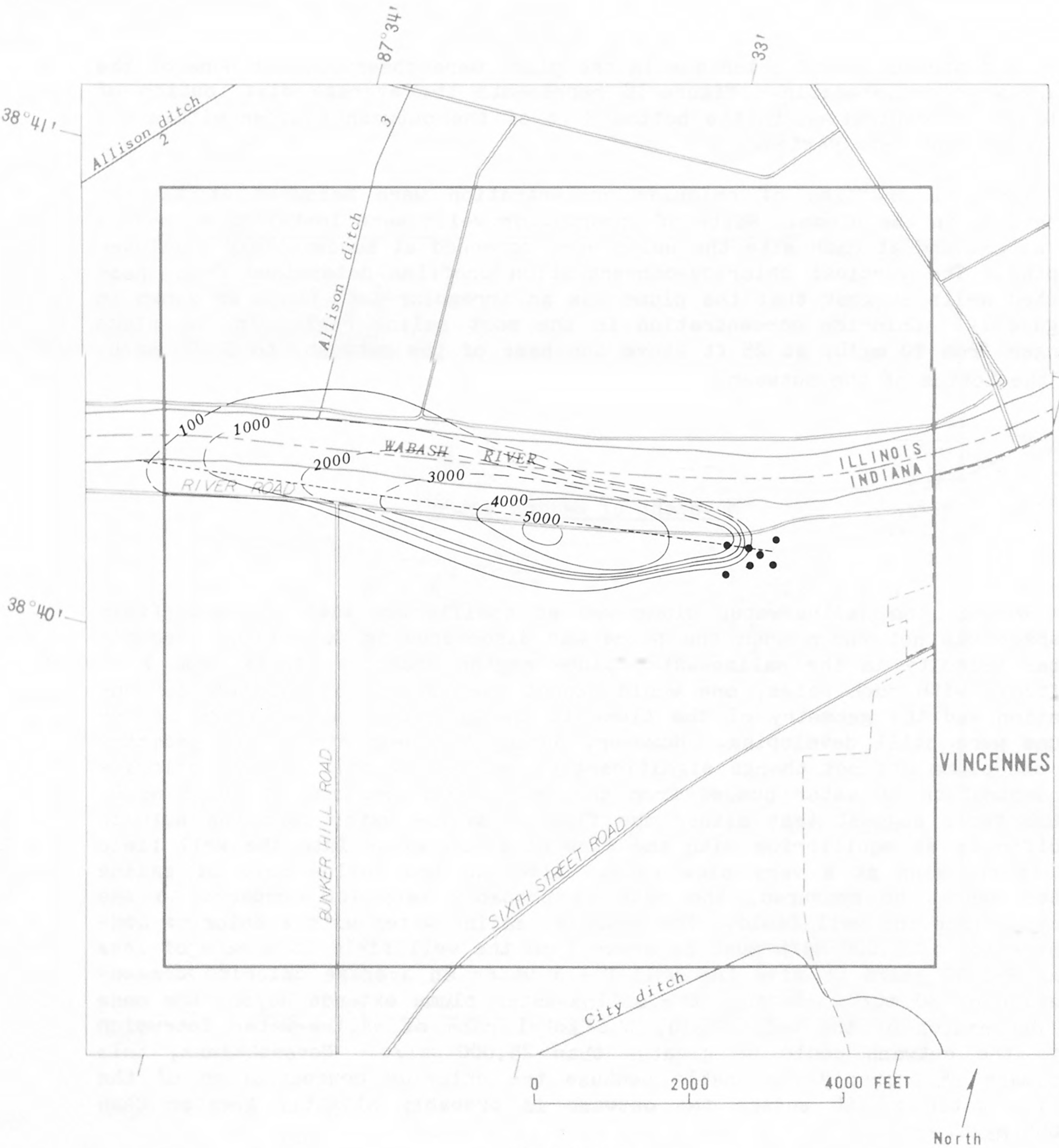
in the distribution of chlorides in the plume were observed, but none of the changes were systematic. Figure 18 represents the average distribution of chloride concentration in the bottom 3 ft of the outwash aquifer within the plume for the 3-yr period.

Vertical profiles of chloride concentration were measured at several locations in the plume. Nests of observation wells were installed at several sites, and at each site the wells were screened at successively shallower depths. The vertical chloride-concentration profiles determined from these nested wells suggest that the plume has an irregular-lens shape as shown in figure 19. Chloride concentration in the most saline region in the plume ranges from 70 mg/L, at 25 ft above the base of the outwash, to 5,100 mg/L, at the bottom of the outwash.

Movement of Saline Water

Whether the saline-water plume was at equilibrium with the well-field pumpage was not known when the plume was discovered in July 1976. Ground-water velocity in the saline-water plume region probably ranges from 1 to 3 ft/d. With such rates, one would expect the pattern of chloride concentration and the geometry of the plume to change within a few years if the plume were still developing. However, during the 3-yr study, the geometry of the plume did not change significantly, and the monthly average chloride concentration of water pumped from the well field remained at 30 $\pm$5 mg/L. These facts suggest that either the flow of saline water into the outwash aquifer is at equilibrium with the flow of fresh water into the well field or is changing at a very slow rate. Although the inflow rate of saline water cannot be measured, the rate is probably very low compared to the pumpage from the well field. For example, saline water with a chloride concentration of 5,000 mg/L must be drawn into the well field at a rate of less than 25,000 gal/d to give the well-field water an average chloride concentration of 30 mg/L. Because the saline-water plume extends beyond the cone of depression of the well field, the total rate of saline-water intrusion into the outwash could be greater than 25,000 gal/d. Nevertheless, this estimate is probably reasonable because the chloride concentration of the saline water as it enters the outwash is probably slightly greater than 5,000 mg/L.

In spite of its slow intrusion rate, the saline water caused the Vincennes Water Department to delay using their two new wells for more than 2 yr after installation. During the study, the actual use of different combinations of the older pumping wells in the well field did not significantly affect the average monthly chloride concentration of the municipal water and the general outline of the plume. However, the leading edge of the plume in the well field shifted slightly when different combinations of the pumping wells were used. This shifting was most pronounced when production well 2 (fig. 16) was taken in or out of service because it had been the well closest to the plume and was intercepting most of the saline water.



EXPLANATION

Model-area boundary

—3000— — Line of equal chloride concentration. Interval 100 and 1000 milligrams per liter. Dashed where approximate

• Municipal well

------------ Approximate line of general cross section in figure 19

Figure 18. -- Average chloride concentrations in the saline-water plume at the base of the outwash aquifer, September 1976-September 1979.

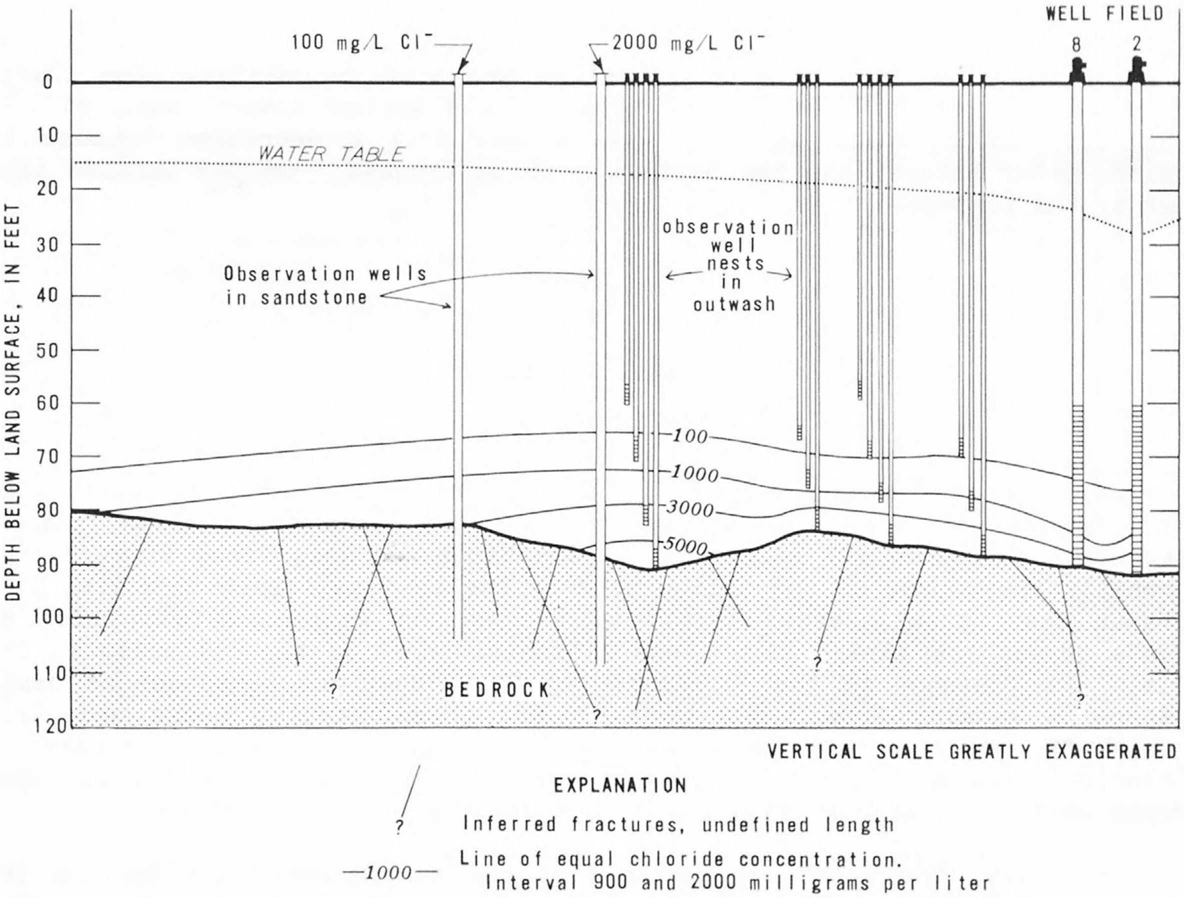


Figure 19.-- Generalized cross section near the Vincennes well field along the long axis of the saline-water plume.

The shifting of the leading edge of the saline water encouraged the Vincennes Water Department to start using the new wells. On December 22, 1978, well 8 (fig. 16), the new well within the plume, was connected to the system at a pumping rate of 500 gal/min. Well 8 initially produced water with a chloride concentration of 450 mg/L and raised the concentration of the municipal water to 150 mg/L. By June 1979, well 8 was being pumped at 1,000 gal/min. The chloride concentration of water from well 8 had decreased to 75 mg/L, and that of water from the municipal well field had decreased to 40 mg/L.

The chloride concentration in well 2 was also decreasing. The leading edge of the saline-water plume apparently migrated toward well 8. The chloride concentration in both well 8 and well 2 decreased because the saline water between the two wells was being flushed from the outwash aquifer by the pumpage.

Source of Saline Water

Layering of the saline water at the bottom of the glacial-outwash aquifer suggests that the saline water has moved up into the aquifer from the bedrock. Abandoned oil wells west of the Vincennes well field (fig. 20) are probably the source of the saline water. The abandoned wells are within the Beaman East Consolidated oilfield (Carpenter and Keller, 1976), which extends across the Wabash River into Illinois. Most of the oil wells in this field are finished in the Mississippian Ste. Genevieve Limestone at depths generally ranging from 1,800 to 1,900 ft. Mississippian rocks underlying the study area contain saline water (Walker, 1959). Walker reported a chloride concentration of 49,426 mg/L for a sample from one of the two abandoned wells in Illinois (fig. 20) in the Ste. Genevieve Limestone.

Initially, the author suspected that the saline water was leaking into the outwash aquifer from the surface casings of some of the abandoned wells. Plugging records from the Indiana Oil and Gas Division showed that the casing had been removed from the bedrock sections of the wells but that the surface casing remained and was cut off a few feet below the ground. The records also showed that bedrock sections of the boreholes had been plugged with approximately 50 ft of cement above the producing zone, 50 ft of cement at the top of the bedrock, and 25-50 ft of cement at the top of the surface casing. The sections of the borehole between the cement plugs were filled with drilling mud.

The author used a magnetometer to locate most of the abandoned oil wells within the saline-plume area. Six of the eight wells within the plume in Indiana were located by this tool (fig. 20). Because the abandoned oil wells were plugged, no water samples were obtained directly from them. Instead, a small-diameter observation well, screened in the bottom 3 ft of the outwash aquifer was installed a few feet downgradient from each of the six

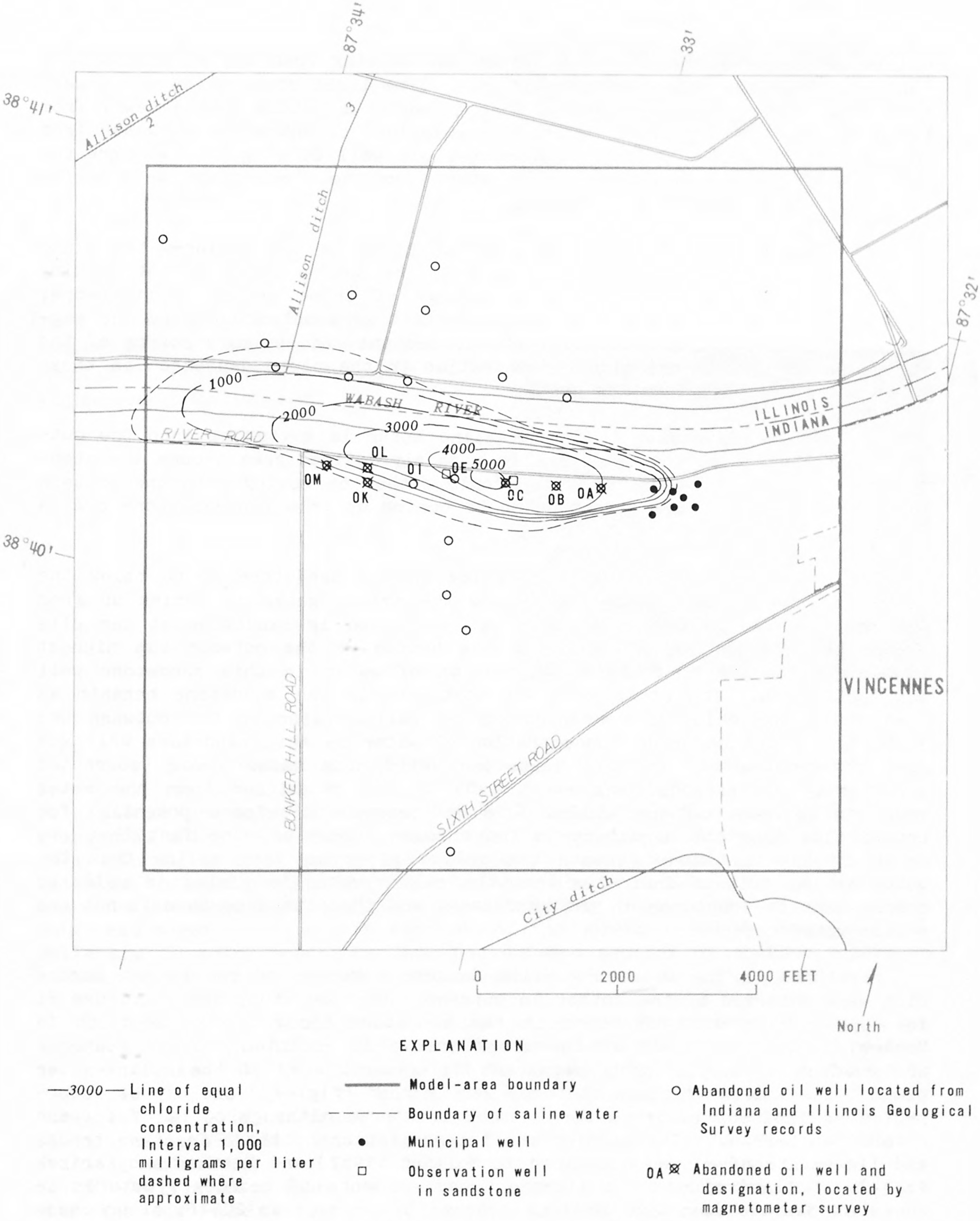


Figure 20.-- Abandoned oil wells and outline of the saline-water plume near the Vincennes well field.

oil wells to determine if saline water was leaking from any of the surface casings. Chloride concentrations of water from these observation wells were no higher than chloride concentrations in wells a little farther away from the abandoned oil wells. In fact, the chloride concentration of water from an observation well 100 ft from abandoned oil well OC (fig. 20) was greater than the chloride concentration of water from the observation well a few feet from the abandoned well.

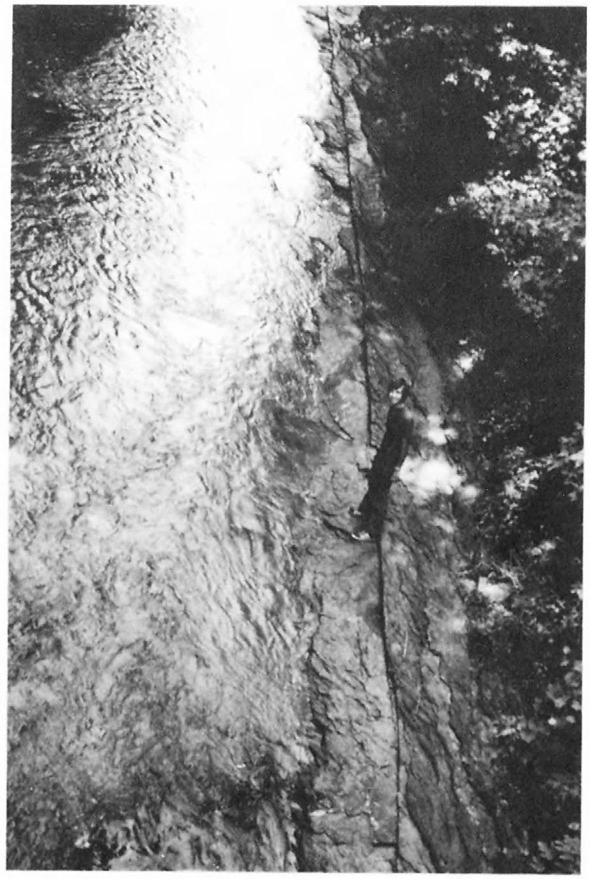
The absence of high chloride concentrations in the saline-water plume near the abandoned oil wells suggests that the saline water is not leaking into the outwash from the surface casings of those wells. Furthermore, neither of the two oil wells in the plume that were not located by the magnetometer survey (OE and OI, fig. 20) is probably the primary source of the saline water because chloride concentration in the plume decreases as these wells are approached from the east.

The evidence suggests that the saline water is moving up into the outwash from the underlying sandstone in a poorly-defined area around the abandoned oil wells. The saline water could either be moving into the outwash through fractures in the sandstone or be coming up from the sandstone over a broad area.

Two observation wells were installed in the sandstone 20 ft below the bottom of the outwash to determine how the saline water is coming up from the sandstone (fig. 19). One well was installed in sandstone at the site where the chloride concentration at the bottom of the outwash was highest (5,100 mg/L). The chloride concentration of water in this sandstone well was 2,000 mg/L. The other well was installed in the sandstone beneath an area where the chloride concentration of saline water in the outwash was 3,500 mg/L. The chloride concentration of water in this sandstone well was less than 100 mg/L. In both sandstone wells, the water level (corrected for density differences) was about 0.05 to 0.1 ft higher than the water level in adjacent outwash wells. This difference indicated a potential for upward flow from the sandstone to the outwash. However, the fact that the water in the sandstone beneath the saline plume is less saline than the water in the outwash indicates that the saline water is rising in selected zones, such as fractures in the sandstone, and that the sandstone is not the saline-water reservoir.

Fractures in the Dicksburg Hills Sandstone Member of the Patoka Formation were observed by the author in outcrops near the study area. Figure 21 is a photograph of a fracture in the sandstone along the Plass ditch in Decker, Ind., 4 mi south of the study area. In addition, linear features are evident on aerial photographs of the general area of the saline-water plume. The traces of these features were mapped (fig. 22) and can be interpreted as indirect evidence for bedrock fractures although 80 ft of outwash covers the bedrock. The mapping and interpretation of these fracture traces and lineaments have been described in Mollard (1957) and Lattman and Parizek (1964). Mollard cited such lineaments as evidence of bedrock fractures in areas of Saskatchewan and Manitoba covered by as much as 200 ft of unconsolidated sediments and noted that many oilfields in the North American midcontinent are in fractured zones.

Figure 21.-- Fracture in the Dicksburg Hills Sandstone Member of the Patoka Formation (local usage). Looking south in Plass ditch, 4 miles south of the study area.



The fracture traces in figure 22 probably do not represent deep regional fractures connected to a saline-water reservoir. Otherwise, the saline water would probably be seeping into the outwash aquifer from most of the fractures, which would result in a much larger plume. Although the density of fracture traces is nearly the same within the plume as beyond, the saline water is apparently only seeping into the outwash aquifer through fractures near the abandoned oil wells. The most likely explanation is that saline water has moved into the open sections of the boreholes of the abandoned oil wells and is being conducted into the outwash aquifer by shallow fractures in the sandstone that intersect the boreholes.

The reservoir rocks of the saline water are not known. Although the abandoned wells are finished in the Ste. Genevieve Limestone, this formation is not necessarily the saline-water reservoir. In fact, the saline-water reservoir is more likely to be younger Mississippian or possibly even Lower Pennsylvanian rocks because these rocks are penetrated by the sections of the oil-well boreholes that were only filled with drilling mud. Low density drilling muds were used in oil wells recently drilled in Knox County, Ind. (J. Riddell, oral commun., 1977), and light muds were probably also used when the abandoned wells were plugged. Because such muds probably do not permanently seal the boreholes from inflows of formation water, saline water could be flowing into the boreholes from any saline water-bearing zone that is penetrated by the abandoned oil wells.

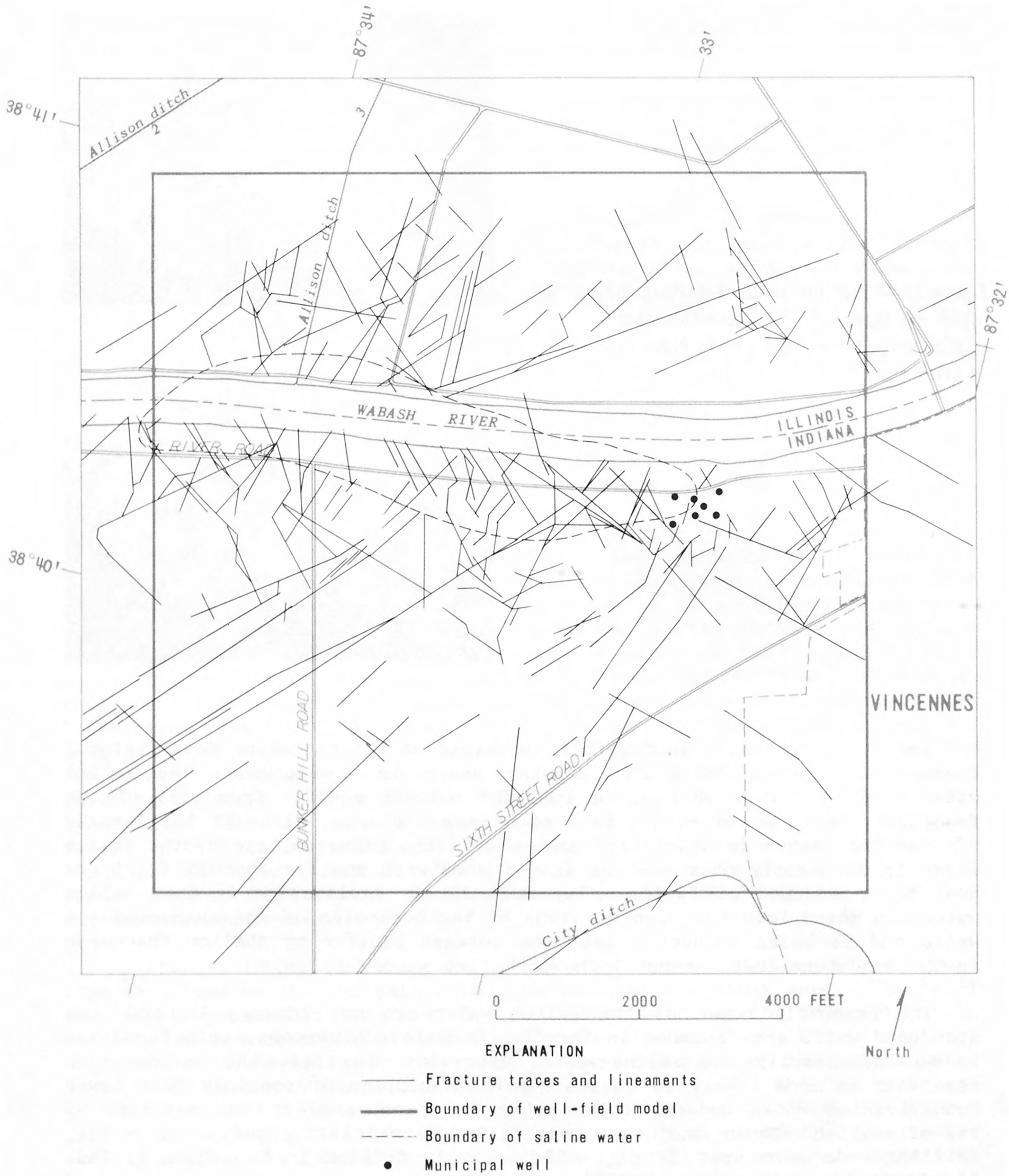


Figure 22. -- Fracture traces and lineaments mapped from aerial photographs of area near Vincennes well field. Aerial photographs provided by Indiana Department of Natural Resources.

Possible Causes of the Saline-Water Intrusion

The saline water at the bottom of the outwash has come up from the bedrock, but its position in the outwash does not seem to represent the regional saline water-freshwater interface. The depth to this interface and the hydraulic head difference allowing the saline water to flow upward from its source into the outwash aquifer are unknown. Part of this head difference is probably due to water-level declines in the outwash aquifer caused by pumpage in the Vincennes well field. However, according to unpublished maps prepared by the Indiana and Illinois Geological Surveys, there are several oil fields within a 15-mi radius of Vincennes where saline water is being injected under pressure to increase oil production. The injection pressure may be increasing the head difference between the saline-water reservoir and the outwash aquifer. The injected saline water may also be leaking into shallow bedrock formations.

Much of the head difference between the saline water in the bedrock and water in the outwash may be natural. Carswell and Bennett (1963, pl. 3) found that the regional saline water-freshwater interface cones upward under river valleys in northwestern Pennsylvania. The Wabash River valley is a major discharge area for ground water, and much of the head difference under the Wabash River that is allowing upward flow of saline water may be natural. Keros Cartwright of the Illinois Geological Survey (oral commun., 1977) reported areas in Illinois along the Lower Wabash valley south of Vincennes where saline water seems to be discharging naturally into shallow freshwater aquifers.

Saline Water Beyond the Well-Field Region

The investigation of possible occurrences of saline water in the outwash aquifer in parts of the study area outside the well-field model region was beyond the budget and scope of this study. The observation wells in most of the study area are screened only 5 to 15 ft below the water table and are too shallow to allow detection of saline water in the lower sections of the outwash aquifer. Nevertheless, the specific conductance of the water in most of the shallow wells was measured. Most of the conductances were less than 800 µmho/cm at 25° C (micromho per centimeter at 25 degrees Celsius), which indicates a chloride concentration of less than 50 mg/L. Water samples with a higher conductance were analyzed for chloride. Only two samples had chloride concentrations exceeding 100 mg/L, and both were within a few thousand feet of active and (or) abandoned oil wells. The sample having the greater chloride concentration, 500 mg/L, was from an observation well in Illinois, in the west-central part of the study area. The other sample, whose chloride concentration was 160 mg/L, was from a well near the large meander in the Wabash River, in the southwest corner of the study area in Indiana.

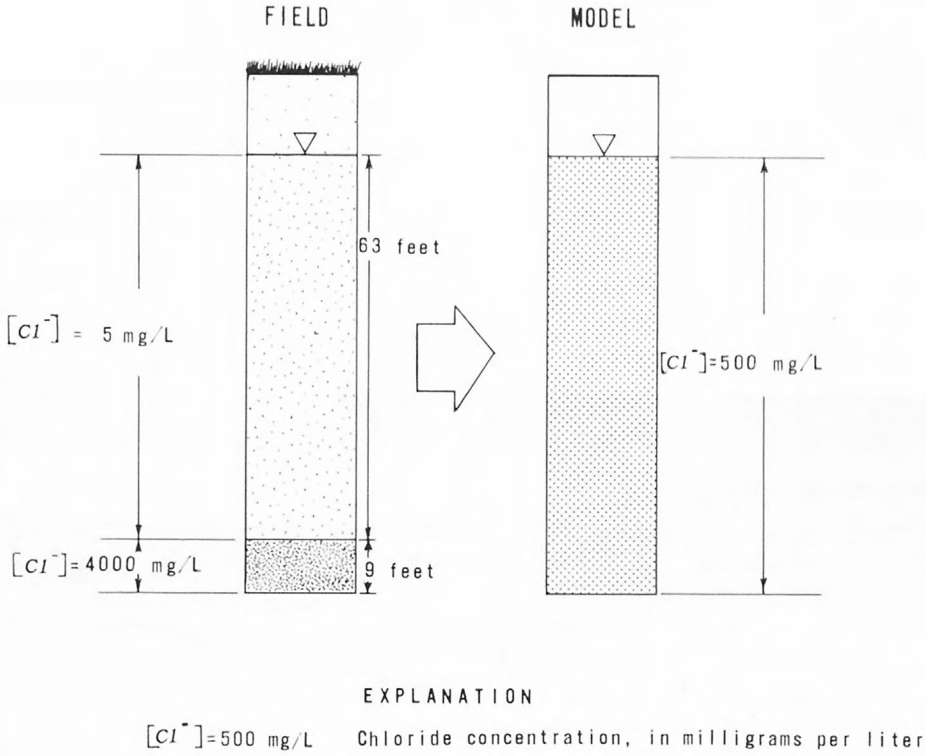
The two chloride concentrations exceeding 100 mg/L indicate a potential for saline-water problems in other parts of the study area, especially near the many active and abandoned oil wells there. Even if the saline-water plume near the Vincennes well field is the only significant body of saline water in the study area, there is no guarantee that a saline-water plume will not develop near a new well field. Major pumpage in the outwash aquifer anywhere in the study area, and particularly near abandoned or active oil wells, may eventually induce upward flow of saline water.

SIMULATION OF INCREASED INTRUSION OF SALINE WATER

The effects of increased intrusion of saline water into the outwash aquifer on the chloride concentration of the well-field water were investigated by use of a solute-transport model developed by Konikow and Bredehoeft (1978). The model simulates both flow and solute transport in one or two dimensions and uses the method of characteristics to solve the transport equation. In the method of characteristics, several traceable particles or points, representing dissolved constituents, are uniformly distributed in each grid block. The initial concentration assigned to each particle is the average solute concentration of the water in the grid block containing the particles. The model computes time increments in which every particle is moved a distance proportional to the length of the time increment and the velocity of the ground water at the location of the particle. Normally, from 4 to 9 particles per grid block provides satisfactory results for most two-dimensional transport problems. The model computes changes in solute concentration with time caused by convective transport, hydrodynamic dispersion, and fluid mixing. In addition, the model assumes that the solute does not react or adsorb and that the density of the fluid is uniform.

The solute-transport model was used to simulate the movement of chloride into the well field. Because there was no way to predict the effect of increases in pumping on the intrusion rate of saline water in the well field, hypothetical conditions were simulated in the model. The hypothetical conditions were various increases in the chloride concentration of the saline-water plume and a doubling of the present pumpage. Simulation of these conditions provided an estimate of the effects of such increases on the chloride concentration of the water from the well field.

The Konikow and Bredehoeft model was used primarily to simulate the general movement of chloride into the well field. However, the model is two-dimensional and thus assumes that the solute is evenly distributed throughout the entire saturated thickness of the aquifer. Because the saline water is only found at the bottom of the outwash aquifer, the average chloride concentration for the full saturated thickness of the aquifer (as depicted in figure 23) had to be computed. This simplification does not seriously affect the ability of the model to simulate the average rate of movement of chloride into the well field.



$$\frac{9 \text{ feet}}{72 \text{ feet}} \times 4000 \text{ milligrams per liter} \approx 500 \text{ mg/L}$$

Figure 23.-- Averaging process used to obtain chloride concentration in two-dimensional, solute-transport model.

Transport-Model Calibration

Initially, the author constructed a steady-state, solute-transport model by using the same grid system, boundary conditions, and hydraulic parameters that were used in the well-field flow model. The respective chloride concentrations within most of the grid blocks in the plume region were held constant at each grid block as shown in figure 24. The average chloride concentration of the well-field water in July 1977, 30 mg/L, was successfully simulated by the model with only minor adjustments to the estimated values of the concentration assigned to each grid block.

The final transport model used in all simulations covers a smaller area and has a finer grid system than the initial model. The model (fig. 25) was subdivided into an 11 by 22 grid of square blocks, 400 ft^2 along each side. The west boundary of the model was simulated as a no-flow boundary, and the other boundaries were simulated as constant heads.

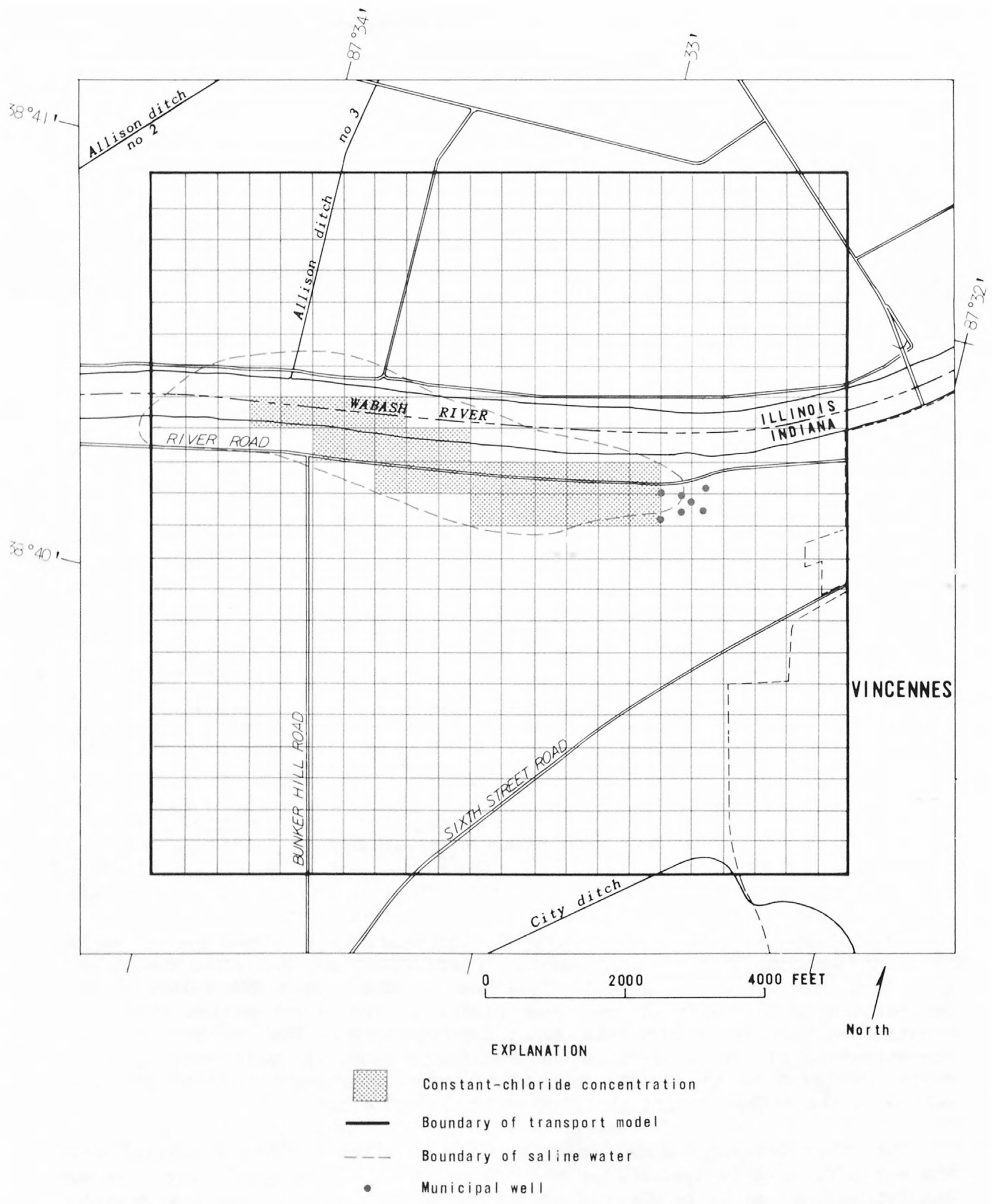
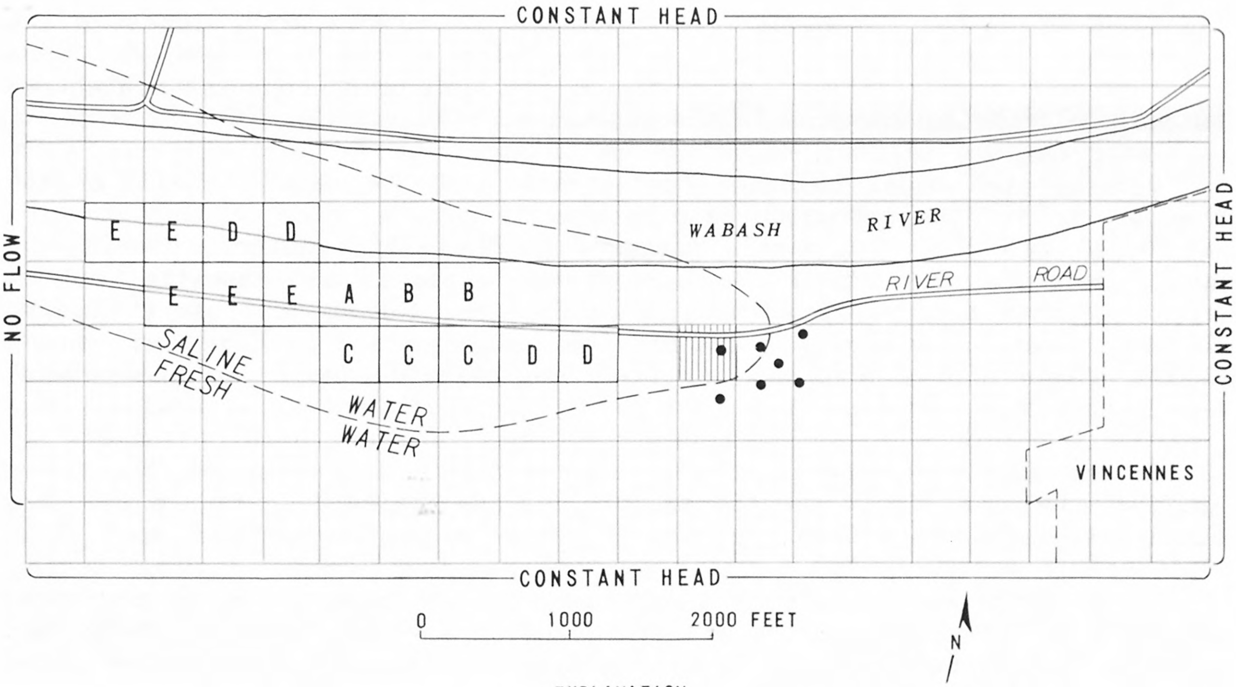


Figure 24.-- Distribution of constant concentration of chloride in transport model.



EXPLANATION

- — — Boundary of saline water
- ● Municipal well
- E — Saline-water source grid block
- Grid block representing pumping well at west edge of well field

Saline-water intrusion rates used in source nodes x 10^{-3} feet per second

A = 5.6
B = 4.8
C = 3.2
D = 1.6
E = 0.8

Figure 25.-- Saline-water source grid blocks and intrusion rates of saline water used in solute-transport model.

For consistency, the same hydraulic parameters and initial conditions that were used in the well-field flow model were used in the transport model. The only exception was the rate of leakage through the Wabash River streambed, which in the transport model is about 50 percent less than that in the well-field model. The leakage rate was intentionally decreased to impede the migration of chloride from the aquifer to the river. This tended to maximize the amount of chloride reaching the well field without significantly changing water levels or ground-water velocities in the model.

The inflow of saline water from the bedrock to the outwash aquifer was simulated by means of various fluxes applied at several grid blocks in the central region of the plume (fig. 25). Using fluxes is probably a more realistic way to simulate the chloride source than using constant concentration of chloride as was done in the initial model.

Because the actual chloride concentration of the water intruding into the outwash and the intrusion rate were not known, a chloride concentration of 10,000 mg/L was arbitrarily assigned to the saline water. Use of the actual rate and the actual chloride concentration is not essential to the model analysis because, as demonstrated earlier, the actual rate of upward seepage of saline water is small and has little effect on the flow system. What is important is that the net influx of chloride ions into the outwash be realistically simulated.

The saline-water source grid blocks and the influx rates that were applied at each block in the transport model are depicted in figure 25. The cumulative influx rate from all these grid blocks is 3,270 ft^3/d.

Other parameters and their values used in the transport model are shown in table 6. The porosity value obtained from the aquifer test, 0.28, was lowered to 0.20 in the model to ensure that the average ground-water velocity would not be underestimated.

Table 6.--Parameters used in calibrated solute-transport model

Porosity = 0.20

Longitudinal dispersivity = 100 ft

$$\frac{\text{Transverse dispersivity}}{\text{Longitudinal dispersivity}} = 0.1$$

The transport model was calibrated to the observed chloride concentrations by varying the influx rates and locations of the saline-water source grid blocks. The final influx rates and locations of the saline-water source blocks used in the transport model are shown in figure 25; the observed distribution of chloride concentration in the saline-water plume and the best simulated distribution are shown in figure 26. Flow in the model was assumed to be steady, and all simulations were run for a 6-yr period to allow the system to reach equilibrium. In addition, initial chloride concentrations outside the source blocks were assumed to be zero. The contours of the simulated chloride concentrations are in general agreement with the observed chloride contours. However, the simulated contours are slightly displaced from the observed contours. This displacement is probably due to slight differences between the flow field in the model and the flow field in the outwash. In addition, the simulated chloride concentration of the water from the municipal wells, 32 mg/L, agrees well with the average measured concentration, 30 mg/L.

Before increased saline-water intrusion rates were simulated in the model, the response of the calibrated model to changes in the dispersivity parameters was tested. In one experiment, the longitudinal dispersivity was increased from 100 to 300 ft, and the ratio of transverse to longitudinal dispersivity was increased from 0.1 to 0.5. These increases resulted in a model-derived plume that was larger than the observed plume. Nevertheless, the simulated value for the chloride concentration of the well-field water for this experiment, 29 mg/L, is nearly the same as the actual value, 30 mg/L. In another experiment, the longitudinal dispersivity was decreased to 25 ft, and the ratio of transverse to longitudinal dispersivity was decreased to 0.01. These decreases resulted in a model-generated plume whose area was smaller but whose chloride concentrations were higher than those of the observed plume. The simulated chloride concentration of the well-field water, 47 mg/L, is about 50 percent higher than the actual value.

The experiments show that the solute-transport model responds to changes in dispersivity but do not necessarily prove that the dispersivity values in the model are representative of the actual values. Different dispersivity values would probably have been assigned to calibrate the model if different chloride concentrations and saline-water influxes had been used in the source area. Nevertheless, the experiments show that significant changes in the dispersivity do not radically alter the simulated chloride concentration of the well-field water.

Transport-Model Experiments and Discussion

As pumpage in the Vincennes well field increases and water-level declines reach the source area of the saline-water plume, the rate at which saline water enters the outwash aquifer is likely to increase. Eventually, the chloride concentration of the well-field water should increase in response to the increased saline-water intrusion rate. However, the rate of

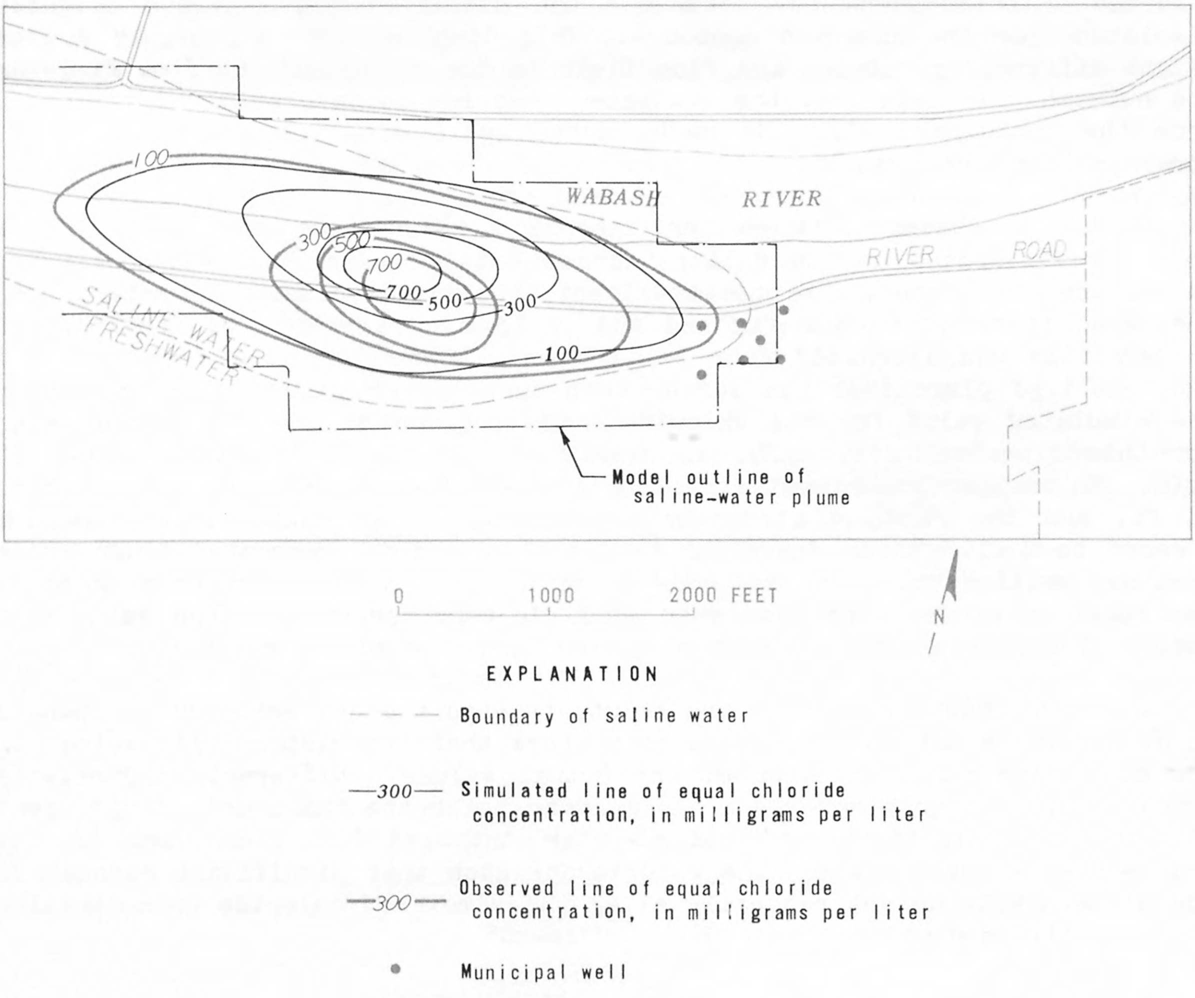


Figure 26.-- Simulated and observed chloride concentrations.

increase cannot be predicted. Because of this uncertainty, the only alternative for using the solute-transport model to evaluate the effects of increases in the saline-water intrusion rate was to simulate these conditions by arbitrarily increasing the intrusion rates.

Several experiments were run in which the calibrated saline-water intrusion rate was increased by factors of 2, 4, and 10 times under a steady-state pumping stress of 8 Mgal/d in the well field. The experiments simulated a 6-yr period, which was sufficient time for chloride to move from the source area to the well field. The maximum number of tracer particles per grid block and the shortest particle movement interval permitted by the model were used to increase the model's resolution. The average yearly chloride concentration in the well field stabilized after 2 to 3 yr, although chloride concentrations throughout the model oscillated because of the discontinuous movement of discrete tracer particles into and out of model grid blocks. The results of these model experiments are summarized in table 7 (p. 50).

The experiments with the calibrated model suggest that only a major increase in the saline-water intrusion rate would adversely affect the quality of the well-field water. For instance, a simulated tenfold increase in the intrusion rate indicates that the chloride concentration of the well-field water will increase to 153 mg/L, which is well below the 250 mg/L State and Federal recommended limits for drinking water (National Academy of Sciences and the National Academy of Engineering, 1972, p. 61).

The experiments also generally indicate the time required for the chloride concentration in the well field to respond to an increase in the saline-water intrusion rate in the source area. The relation of chloride concentration to time in two experiments is shown in figure 27. The data are for a model grid block that represents a pumping well at the west edge of the well field (fig. 25). The upper curve in figure 27 represents a saline-water intrusion rate that was two times the calibrated rate, whereas the lower curve represents an intrusion rate that was ten times the calibrated rate. In both experiments, the well-field pumpage was 8 Mgal/d. The scatter in the data is caused by the discontinuous movement of discrete tracer particles referred to previously.

Caution must be used in interpreting the curves in figure 27. For example, the model assumes that there is no saline-water plume in the aquifer and that the chloride concentration of the well field water is zero at the start of each simulation. Each model experiment is actually simulating the growth of a new plume at a higher rate of saline-water intrusion than the current rate. Therefore, the curves in figure 27 would not represent the real increase in the chloride concentration at the west edge of the well field after an increase in the saline-water intrusion rate. Nevertheless, the curves generally indicate the minimum time required for a front of increased chloride concentration in the source area to migrate to the well field.

Table 7.--Results of transport-model experiments

Increase in calibrated saline-water intrusion rate	Simulated steady-state chloride concentration of well-field water
2 times	51 mg/L
4 times	76 mg/L
10 times	153 mg/L

For both experiments, the curves show that the chloride concentration at the west edge of the well field begins to level off after about 2 yr. In addition, comparison of the two curves shows that the chloride concentration at this observation point increases at a faster rate for the tenfold increase in the calibrated saline-water intrusion rate than for a twofold increase. Thus, the rate at which the chloride concentration of the well-field water responds to increases in the saline-water intrusion rate depends on the magnitude of the increase.

However, the real response of the well-field water chloride concentration to an increase in the saline-water intrusion rate would probably be slower than that shown by the curves in figure 27 because the intrusion rate is more likely to increase gradually rather than instantaneously, as assumed in the model. In addition, because there is no plume at the beginning of each model simulation, the concentration gradients are higher in the model than they would be in the field, and the effects of dispersion are probably overestimated in the model.

In summary, the model experiments, although not predictions, indicate that the full effect of an increase in the saline-water intrusion rate in the source area would not reach the well field until after 2 yr or more. Furthermore, the experiments suggest that the rate at which saline water enters the outwash aquifer can increase tenfold before adversely affecting the quality of the well-field water.

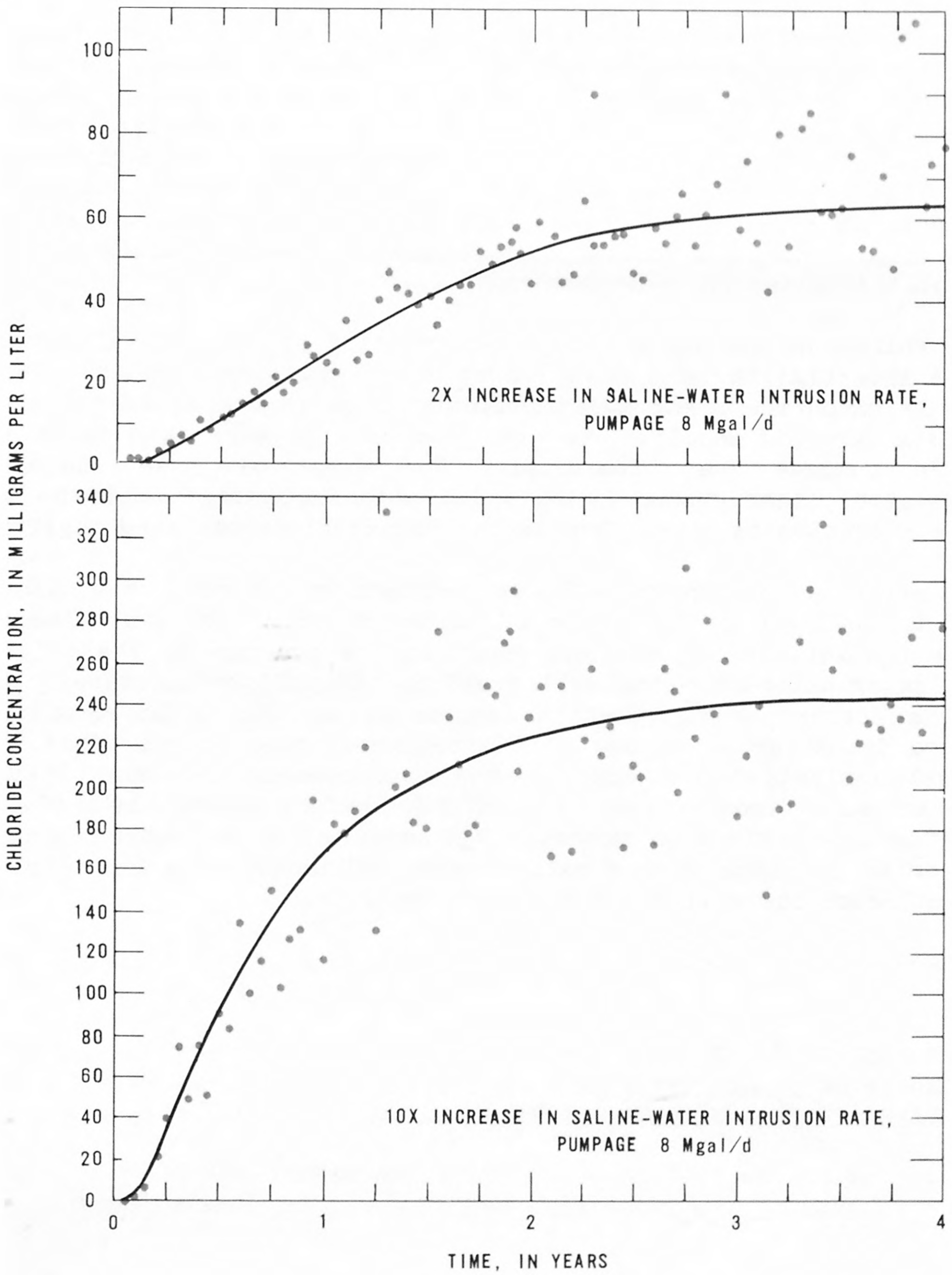


Figure 27.-- Variation in simulated chloride concentration with time for pumping well at west edge of the Vincennes well field.

SUMMARY AND CONCLUSIONS

A layer of saline water lies at the base of the glacial-outwash aquifer from which the city of Vincennes, Ind., derives its entire water supply. The saline-water plume has been drawn into the well field, but the rate of intrusion seems to be stable because the shape of the plume has not changed and the chloride concentration of water from the well field has not increased significantly since 1976. The saline water is probably entering the outwash through fractures in the underlying sandstone bedrock within an area of abandoned oil wells. The fractures probably intersect the abandoned oil wells, which penetrate saline water-bearing rocks. However, the exact source of the saline water is unknown.

The thickness and hydraulic characteristics of the glacial-outwash aquifer were investigated in a 56-mi^2 area southwest of Vincennes. The outwash aquifer is unconfined, and two-dimensional flow in the aquifer was simulated by two digital-flow models. Pumpage of 8 Mgal/d, more than twice the average 1978 pumpage, was simulated. The model analysis indicates that water-level declines caused by this increase in pumpage would be small and that the reduction in streamflow in the Wabash River would be negligible.

The relation between water-level declines in the outwash aquifer and increases in the rate of intrusion of saline water is unknown. Therefore, no definite predictions can be made about future changes in the chloride concentration of water from the well field as the pumpage increases. Nevertheless, the effects of hypothetical increases in the saline-water intrusion rate were investigated by use of a two-dimensional, solute-transport model. The model analysis indicates that the saline-water intrusion rate can increase several times, possibly tenfold, before adversely affecting the quality of the well-field water. The model also indicates that the full effect of an increase in the saline-water intrusion rate in the source area would not reach the well field in less than 2 yr.

Carpenter, G. L., and Keller, S. J., 1976, Oil development and production in Indiana during 1975: Indiana Department of Natural Resources, Geological Survey Division, Mineral Economics Series 22, 25 p.

Carswell, L. D., and Bennett, G. D., 1963, Geology and hydrology of the Neshannock quadrangle, Mercer and Lawrence Counties, Pennsylvania: Pennsylvania Geological Survey, Bulletin W15, 90 p.

Fidlar, M. M., 1936, Features of the valley floor of the Wabash River near Vincennes, Indiana: Indiana Academy of Science Proceedings, 1935, v. 45, p. 175-182.

Gillies, D. C., 1976, Availability of ground water near Carmel, Hamilton County, Indiana: U.S. Geological Survey Water-Resources Investigations 76-46, 27 p.

Gray, H. H., Wayne, W. J., and Wier, C. E. 1970, Geologic map of the 1°x2° Vincennes quadrangle and parts of adjoining quadrangles, Indiana and Illinois, showing bedrock and unconsolidated deposits: Indiana Department of Natural Resources, Geological Survey Division, scale 1:250,000.

Horner, R. G., 1976, Statistical summaries of Indiana streamflow data: U.S. Geological Survey Water-Resources Investigations 35-75, 526 p.

Konikow, L. F., and Bredehoeft, J. D., 1978, Computer model of two-dimensional solute transport and dispersion in ground water: U.S. Geological Survey Techniques of Water-Resources Investigations, book 7, chap. C2, 90 p.

Lattman, L. H., and Parizek, R. R., 1964, Relationship between fracture traces and the occurrence of ground water in carbonate rocks: Journal of Hydrology, v. 2, p. 73-91.

Meyer, William, Reussow, J. P., and Gillies, D. C., 1975, Availability of ground water in Marion County, Indiana, with a section on Water quality by W. J. Shampine: U.S. Geological Survey Open-File Report 75-313, 87 p.

Mollard, J. R., 1957, Areal mosaics reveal fracture patterns on surface materials in southern Saskatchewan and Manitoba: Oil in Canada, August 5, p. 26-50.

National Academy of Sciences and the National Academy of Engineering, 1972 [1974], Water quality criteria, 1972: Washington, D.C., U.S. Government Printing Office, 594 p.

National Oceanic and Atmospheric Administration, 1979, Climatological data, Indiana: NOAA Environmental Data Service, Annual Summary 1978, v. 83, no. 13, 13 p.

Nyman, D. J., and Pettijohn, R. A., 1971, Wabash River basin comprehensive study--Appendix G, Ground Water: U.S. Geological Survey open-file report, 100 p.

Rorabaugh, M. I., 1963, Estimating changes in bank storage and ground-water contribution to streamflow: International Association of Science and Hydrology Publication 63, p. 432-441.

Theis, C. V., 1963, Estimating the transmissibility of a water table aquifer from the specific capacity of a well, in Bentall, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 332-336.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments, in Automated data processing and computations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 7, chapter C1, 116 p.

U.S. Geological Survey, 1979, Water-resources data for Indiana, water year 1978: U.S. Geological Survey Water-data Report IN-78-1, 383 p.

Walker, F. H., 1959, Natural brines of Indiana and adjoining parts of Illinois and Kentucky: Indiana Department of Conservation, Geological Survey, Report of Progress no. 13, 58 p.

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