Hydrogeology and Simulated Ground-Water Flow Through the Unconsolidated Aquifers of Northeastern St. Joseph County, Indiana

By E.R. BAYLESS and L.D. ARIHOOD

Prepared in cooperation with the
INDIANA DEPARTMENT OF NATURAL RESOURCES

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4225

Indianapolis, Indiana
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information, write to:
District Chief
U.S. Geological Survey
Water Resources Division
5957 Lakeside Boulevard
Indianapolis, IN 46278-1996

Copies of this report can be purchased from:
U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, CO 80225

CONTENTS

FIGURES

CONTENTS

FIGURES—Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inches (in.)	0.0254	meter
inches per year (in/yr)	0.0254	meter per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	28.32	liter per second
gallons per minute (gal/min)	0.06309	liter per second
gallons per day (gal/d)	0.0000438	liter per second
million gallons per day (Mgal/d)	0.04380	cubic meter per second

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Hydrogeology and Simulated Ground-Water Flow Through the Unconsolidated Aquifers of Northeastern St. Joseph County, Indiana

By E.R. Bayless *and* L.D. Arihood

ABSTRACT

The U.S. Geological Survey investigated the ground-water resources of northeastern St. Joseph County, Indiana, during 1990-93. The investigation included field measurements of water levels and numerical models of the ground-water-flow system. This report documents the results of that work and includes a description of (1) the hydrogeologic framework, (2) water levels, (3) model sensitivity to variations in hydrogeologic parameters, (4) simulated aquifer response to increased ground-water withdrawals, (5) contributing areas for significant water-withdrawal facilities, and (6) flow paths for hypothetical solute particles originating beneath known contamination sites.

Water levels were measured in a spatially distributed network of 53 monitoring wells. Wells were installed at 36 sites to depths of 18 to 173 feet below land surface. At 15 sites, nested monitoring wells were installed to describe hydraulic gradients between shallow and deep parts of the aquifer system. Water levels were measured during January 1991–November 1992. Water-level measurements indicated that (1) regional ground-water flow is towards the St. Joseph River, (2) depth to water generally is small in the St. Joseph aquifer system compared to that in the Hilltop and Nappanee aquifer systems, and (3) water levels in the deep and shallow parts of the aquifer system are not equal at sites where a confining unit is present.

Simulation of aquifer response to various stresses was examined by use of a numerical model of ground-water flow. A quasi three-dimensional numerical model of the ground-water-flow system was constructed from geologic, hydrologic, and water-use information. The model was calibrated by an adjustment to the hydrogeologic parameter values within known ranges until a suitable correspondence between simulated and measured ground-water levels was achieved. Steady-state ground-water-flow simulations were used to identify sites where increased withdrawals might cause significant aquifer dewatering or induce migration of pollutants from known contamination sites.

Results of the study indicate that an increase in withdrawals by 50 percent at significant water-withdrawal facilities would cause drawdowns generally less than 6 feet in the one-quarter square mile surrounding area. In this simulation, ground-water flows to Juday Creek and the St. Joseph River were reduced by 23 percent and 6 percent, respectively.

The results of particle-tracking analyses indicate that flow paths from recharge areas to significant water-withdrawal facilities operating at 1993 withdrawal rates generally are less than 5 miles long in the upper aquifer but may be more than 12 miles long in the lower aquifer. Travel times between recharge and discharge points are less than 10 years in the upper aquifer but may be as much as 100 years in the lower aquifer.

Particle-tracking analyses indicate that flow paths for solutes originating beneath known contamination sites may pass near to, or be intercepted by, significant water-withdrawal facilities. Most particles are discharged to the St. Joseph River, but some may be discharged to Juday Creek.

INTRODUCTION

During January 1, 1990–December 31, 1994, the U.S. Geological Survey (USGS), in cooperation with the Indiana Department of Natural Resources (IDNR), studied the ground-water resources of northeastern St. Joseph County, Ind. The most productive source of ground water in the study area is the St. Joseph aquifer system, Indiana's only designated sole-source aquifer (Anna Miller, U.S. Environmental Protection Agency, oral commun., 1995). The St. Joseph aquifer system is a thick, glacially deposited sand and gravel sequence that is locally interbedded with poorly permeable, clay-rich sediment (Beaty, 1987). Because the uppermost parts of the aquifer system are highly permeable and the water table occurs at shallow depths, the St. Joseph aquifer system is susceptible to ground-water contamination. Furthermore, as ground-water withdrawals from the St. Joseph aquifer system increase, the possibility of ground-water contamination and resource depletion increases.

For the USGS study, a 227-mi^2 area of northeastern St. Joseph County was identified (fig. 1) where an increased understanding of the regional hydrogeology and aquifer-system response to increased ground-water withdrawals would benefit land-use planners and resource managers. A further consideration of the study was to describe contributing areas for significant water-withdrawal facilities (SWWF's)—facilities capable of pumping at rates greater than 100,000 gal/d (U.S. Geological Survey, 1990)—and discharge points for water originating beneath known sites of contamination.

The goals of this study were accomplished primarily by use of a numerical model of the ground-water-flow system in northeastern St. Joseph County. The numerical model is an efficient way to examine the effects of varying hydrologic stresses, such as drought or increased ground-water withdrawals, on regional ground-water levels. The area considered in the numerical model was the 227-mi^2 study area plus the area 3.5 mi north of the Indiana/Michigan State line and 3 mi east of the St. Joseph County/Elkhart County political boundary. The enlarged study area was necessary to incorporate numerical-model boundary conditions.

Purpose and Scope

This report describes the hydrogeologic framework and simulation of the ground-water flow in the unconsolidated aquifers of northeastern St. Joseph County. The study was accomplished by (1) a compilation and synthesizing of available geologic, hydrologic, and climatic information; (2) a development of numerical models of ground-water flow based on the acquired hydrogeologic information; (3) use of the models to identify contributing areas to SWWF's; and (4) use of the models to identify flow paths for ground water originating beneath known sites of contamination.

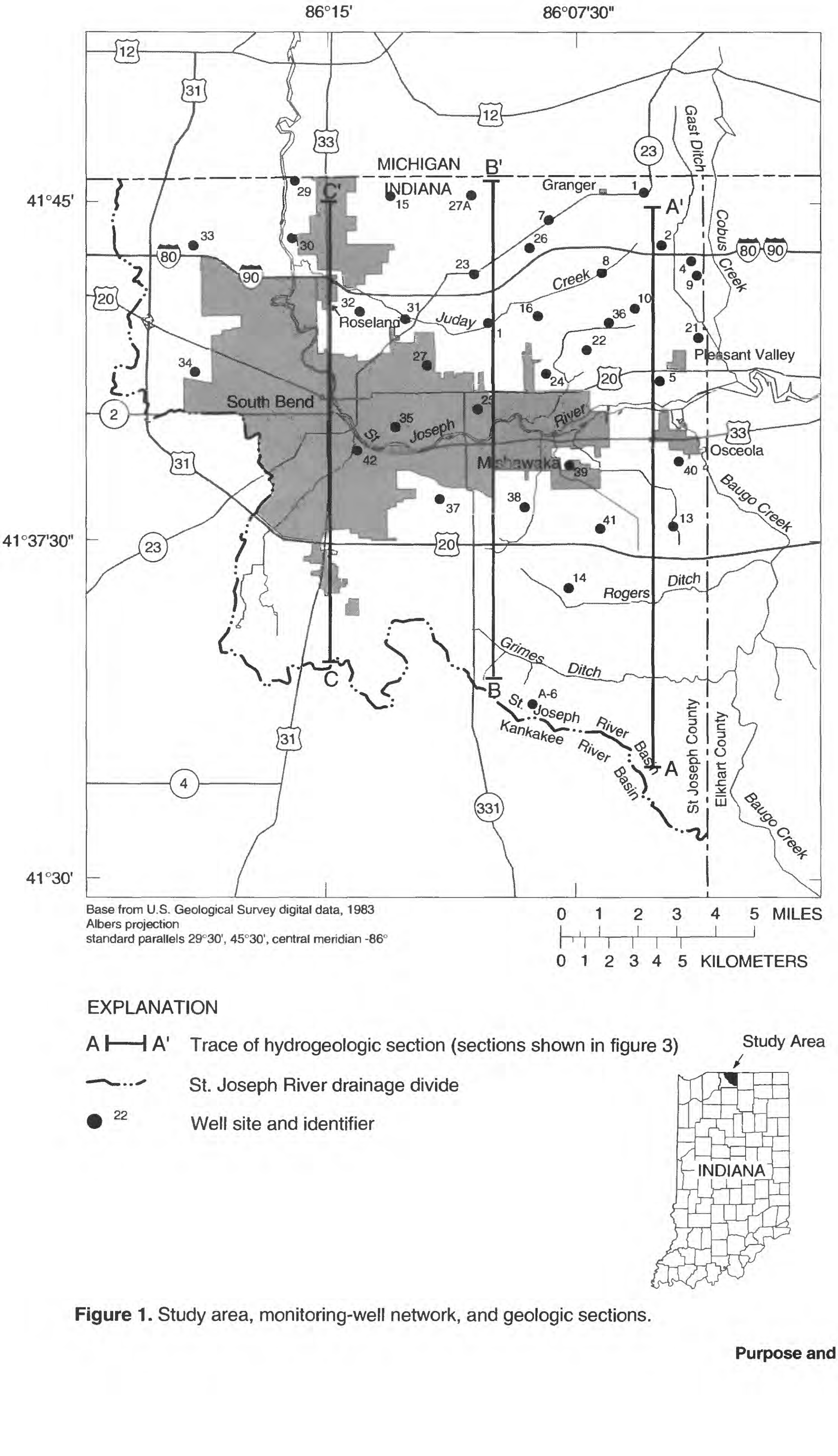


Figure 1. Study area, monitoring-well network, and geologic sections.

The geological data base for the model includes more than 370 well logs. In addition, 53 monitoring wells were installed at 36 sites where geologic information was unavailable. Surface-geophysical measurements were made at six additional sites. Water levels were measured synoptically in the 53-well network at least seven times during water years[1] 1991 and 1992. Water-level measurements were integrated into composite water-level maps previously compiled by Beaty (1987).

Other data required to develop the numerical model, such as recharge rates, hydraulic conductivity of the aquifers, vertical leakance of confining units, streambed conductance, and ground-water-use information, were collected from available sources. These data were used as input information to a computer algorithm that solves the physical equations describing ground-water flow. Solution of the algorithm produced a non-unique numerical model of the regional water table. The difference between simulated and measured water levels was used as an indicator of model accuracy. Individual parameter values were varied within known or acceptable ranges to demonstrate the effect on simulated water levels. The model was calibrated by minimizing the differences between calculated and measured water levels for the 53 monitoring wells in the network. The calibrated model was used to examine (1) aquifer response to increased withdrawals at SWWF's, (2) contributing areas for SWWF's, and (3) flow paths and discharge points for solute particles originating beneath known contamination sites.

Previous Investigations

The hydrogeology of the unconsolidated aquifers of northeastern St. Joseph County is described in several reports published by State and Federal agencies (Beaty, 1987; Crompton and others, 1986; Reussow and Rohne, 1975; Hunn and Rosenshein, 1969; Pettijohn, 1968; Rosenshein and Hunn, 1962; Klaer and Stallman, 1948). These reports summarize available data describing geologic setting, aquifer recharge, climatic variables, hydraulic properties of the geologic units, land use, water use, water levels, and ground-water quality. Bleuer and Melhorn (1989) provide additional geologic information.

Peters and Renn (1988) and Peters (1987) used aquifer-test data to calculate values of hydraulic properties of the aquifers. Bailey and others (1985), Lindgren and others (1985), and Imbrigiotta and Martin (1981) used numerical models to investigate ground-water flow in adjacent areas of the St. Joseph River Basin. The model described in this report refers to these studies for measured and calculated values of hydrologic parameters.

[1]The water year is the 12-month period October 1–September 30; the water year is designated by the calendar year in which it ends.

Acknowledgments

The authors received assistance from many people during this study. Personnel from the Indiana Department of Natural Resources, Division of Water, provided guidance, water use and geologic information, and manuscript reviews. The citizens and officials of South Bend, Mishawaka, and northeastern St. Joseph County allowed access to their properties for well installation and data collection. A special appropriation from the Indiana General Assembly partially funded this study.

DESCRIPTION OF THE STUDY AREA

The study area is the part of St. Joseph County that lies within the St. Joseph River drainage basin (fig. 1). The east boundary of the study area is the political boundary that separates St. Joseph County and Elkhart County, Ind. The north boundary of the study area is the Indiana/Michigan State line. The St. Joseph River drainage basin divide is the south and west boundary.

Within the study area are two metropolitan areas, South Bend and Mishawaka, and several smaller communities. Population of the study area is approximately 210,000 persons (Beaty, 1987). Major industries in the basin include machinery, rubber and plastics, lumber and wood, fabricated metal, and printing and publishing (Beaty, 1987). Agricultural land use (primarily corn, soybeans, and other row crops) accounts for 59.2 percent of the study area (Beaty, 1987).

In 1989, a total of 16 public-supply well fields and 30 noncommunity well fields (such as those at schools and mobile home parks) were in operation. Rural homes and several residential neighborhoods in St. Joseph County that are beyond corporate limits rely on domestic wells.

As many as 79 potential ground-water-contamination sites are in the study area (Michiana Area Council of Governments, 1989). These sites include landfills, dump sites, waste-treatment sites, sludge ponds, waste lagoons, auto-salvage yards and junkyards, recycling stations, and land-reclamation sites. Ground-water contamination has been documented at 13 of these sites (Michiana Area Council of Governments, 1989).

HYDROGEOLOGIC SETTING

Several hydrogeologic factors affect the distribution of ground-water levels and directions of ground-water flow in northeastern St. Joseph County. Most of those factors are included in the numerical model, either explicitly or as lumped parameters that represent a combination of factors. Aquifer recharge is an example of a lumped parameter that describes the integrated effect of precipitation, evaporation, transpiration, and vertical hydraulic conductivity of surficial deposits. The following description of the hydrogeologic setting examines many of these variables and provides a basis for understanding the ground-water hydrology of northeastern St. Joseph County.

General Geology

Physiographic provinces are regions of similar topography and geology. Northeastern St. Joseph County lies entirely within the physiographic provinces known as the Kankakee Outwash and Lacustrine Plain and the Steuben Morainal Lake Area (Malott, 1922). The northern two-thirds of the study area lies within the Kankakee Outwash and Lacustrine Plain, a large outwash plain formed by sediment-laden rivers that drained Pleistocene Epoch glaciers (Malott, 1922). Glacial outwash typically is composed of sand and gravel that grades into finer materials with increasing distance from the source (Thornbury, 1969). The outwash plain in northeastern St. Joseph County is gently undulating flat land that locally descends 15 to 30 ft into the St. Joseph River Valley. Land-surface altitudes on the outwash plain range from about 680 to 800 ft above sea level.

The Steuben Morainal Lake Area, which covers the southern one-third of the study area, is a gently undulating till plain (Malott, 1922). Glacial till is a heterogeneous ice-contact deposit that contains clay, silt, sand, and gravel and has a larger fraction of fine-grained sediment than outwash does (Thornbury, 1969; Krumbein and Sloss, 1951). Local relief is about 170 ft along the boundary between the Kankakee Outwash and Lacustrine Plain and the Steuben Morainal Lake Area. Altitudes are as great as 920 ft above sea level in the Steuben Morainal Lake Area.

Aquifer Properties

The thickness of unconsolidated deposits in the study area ranges from less than 30 ft in the Mishawaka area (Beaty, 1987) to more than 200 ft in areas a great distance from the St. Joseph River Valley. The deposits form three distinct aquifer systems—the St. Joseph aquifer system, the Hilltop aquifer system, and the Nappanee aquifer system—in northeastern St. Joseph County (fig. 2) (Beaty, 1987).

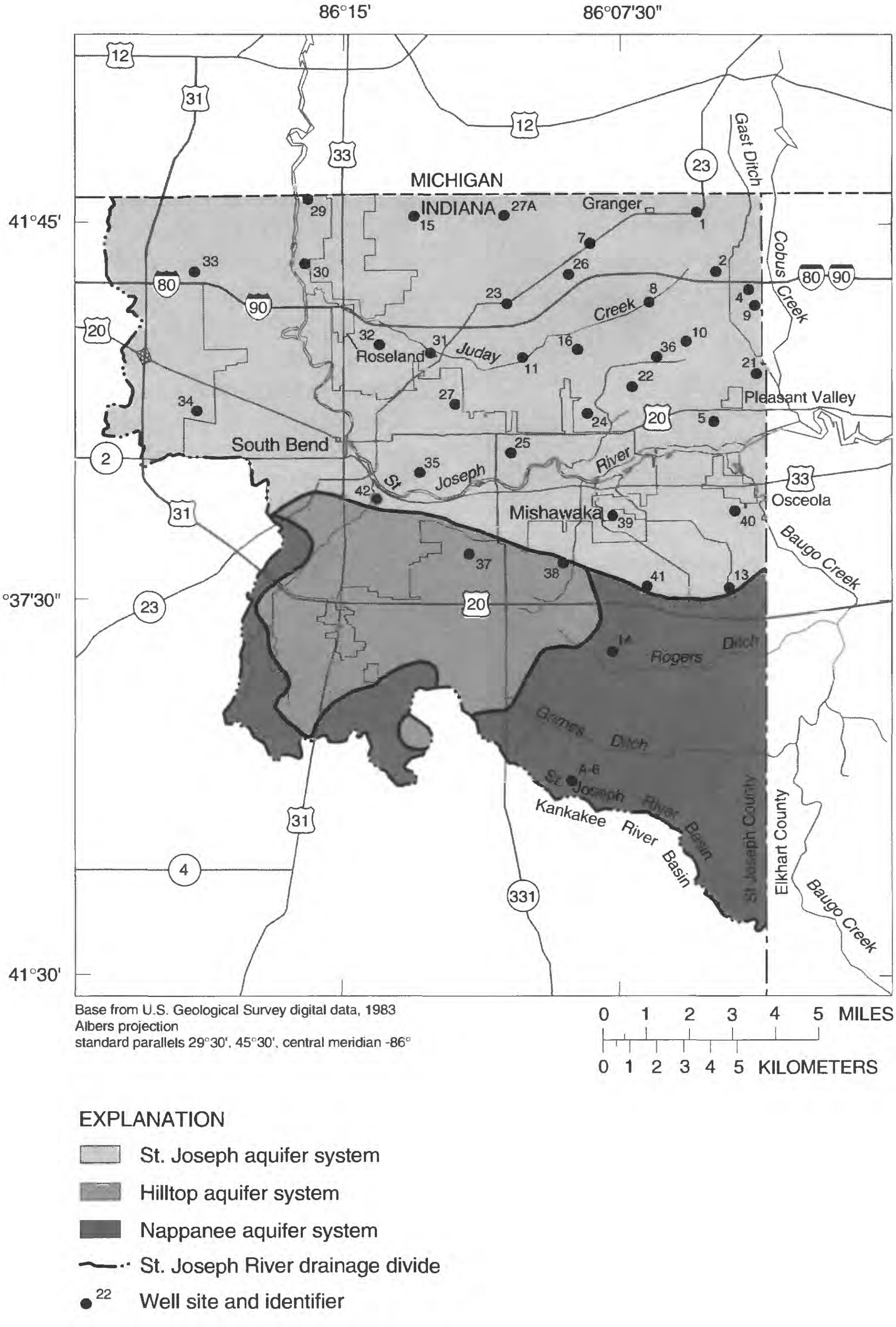


Figure 2. Distribution of aquifer systems in northeastern St. Joseph County, Indiana (modified from Beaty, 1987, pl. 2).

Unconsolidated deposits in the northern half of the study area are designated primarily as the St. Joseph aquifer system and are composed of outwash (fig. 2). In many places, outwash deposits of the St. Joseph aquifer system are separated by lesser thicknesses of clay-rich deposits. The clay-rich deposits probably are till or glacial-lacustrine deposits (Beaty, 1987). Where present, the clay-rich deposits may be confining units and may inhibit vertical ground-water flow between aquifers. Geologic evidence in northeastern St. Joseph County, Ind., indicated the existence of three main aquifers, each of which is separated from the other by a confining unit; the entire sequence is underlain by the Ellsworth Shale (fig. 3).

For purposes of this report, the outwash deposits are identified as aquifers 1, 2, and 3; the interlayered clay-rich deposits are identified as confining units 1 and 2. Aquifer 1 occupies relatively small areas in the western and southern parts of the study area. Thickness of aquifer 1 ranges from 0 to about 50 ft (fig. 4). Aquifer 2 is present in all of the study area except the southeastern and southwestern corners. The thickness of aquifer 2 ranges from 0 to more than 150 ft; in most places, however, thickness is 25 to 100 ft (fig. 5). Aquifer 3 is absent in the southeastern part of the study area, primarily designated as the Nappanee aquifer system, but is present elsewhere throughout the study area (fig. 6). The thickness of aquifer 3 ranges from 0 to 225 ft; the greatest thickness is in northeastern St. Joseph County. The horizontal hydraulic conductivity of outwash aquifers in northeastern St. Joseph County ranges from 280 to 600 ft/d (Peters, 1987), and ground-water production rates range from 100 to 1,500 gal/min (Beaty, 1987).

Thickness of the confining units ranges from 0 to about 100 ft; in most places, however, thickness is 10 to 50 ft. Thickness of confining unit 1 ranges from 0 to 125 ft; greatest thickness is in the southeastern and western parts of the study area. The southeastern wedge of confining unit 1 represents till deposits primarily of the Nappanee aquifer system (fig. 7). A large area north of the Indiana/Michigan State line also is overlain by confining unit 1. Thickness of confining unit 2 ranges from 0 to 125 ft in the study area and may be as great as 150 ft north of the State line (fig. 8). Confining unit 2 is absent from the northeastern and northwestern corners of the study area, as well as the southern areas where confining unit 1 is thickest. Water-level data indicate that vertical flow between aquifers may be inhibited where confining units are relatively thick or particularly clay rich. Vertical hydraulic conductivity of the confining units ranges from 0.04 to 0.21 ft/d (Lindgren and others, 1985).

The Hilltop and Nappanee aquifer systems are south and west of the St. Joseph aquifer system (fig. 2). The Hilltop aquifer system is composed of sand and gravel deposits overlain by 5 to 50 ft of clay-rich deposits (Beaty, 1987, p. 50). Pumping rates in the Hilltop aquifer system range from 10 to 250 gal/min (Beaty, 1987, p. 50). The Nappanee aquifer system, in the southeastern part of the study area, consists of thin sand and gravel units (3 to 20 ft thick) contained within thick sequences of till (Beaty, 1987, p. 49). Areal extent of the aquifers is less than 2 mi^2 (Beaty, 1987, p. 49). Pumping rates in the Nappanee aquifer system range from 50 to 600 gal/min (Beaty, 1987, pl. 2). The Nappanee aquifer system rarely is used for nondomestic or nonagricultural purposes.

The Ellsworth Shale of Devonian-Mississippian age underlies the unconsolidated deposits in the study area (Schneider and Keller, 1970). The upper part consists of the grayish-green shale and lenses of dolomite or laminated dolomite (Shaver and others, 1986). The lower part of the Ellsworth Shale consists of alternating grayish-green and brownish-black shale. The Ellsworth Shale dips toward the Michigan Basin (to the north-northeast) at an angle of less than 1°. The Ellsworth Shale is relatively poorly permeable and rarely used as a source of ground water.

Recharge and Discharge

Annual mean precipitation in the entire St. Joseph River Basin is 35 in/yr; the range is 21 to 54 in/yr (Beaty, 1987, p. 19). About 38 in. of precipitation fall on the study area each year.

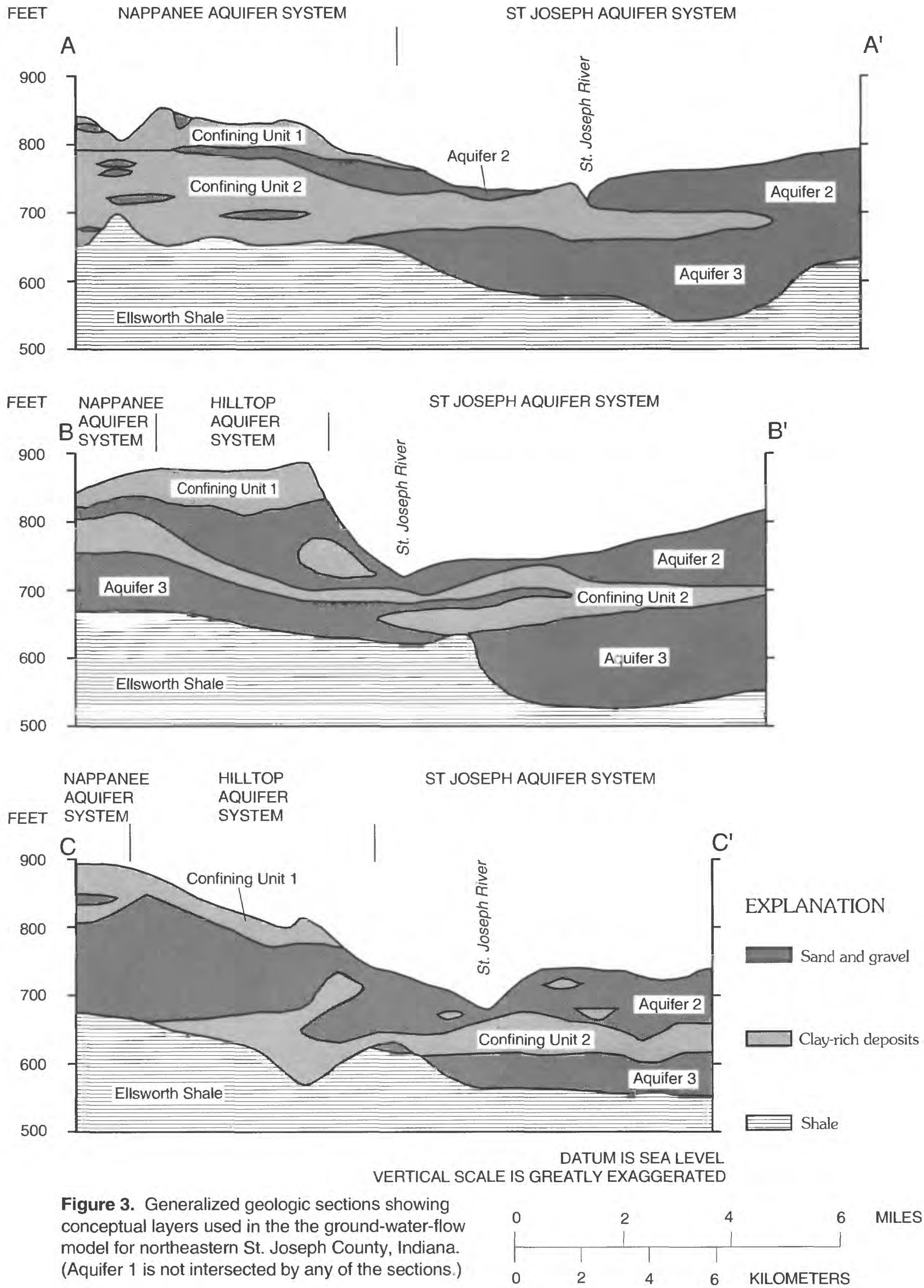


Figure 3. Generalized geologic sections showing conceptual layers used in the the ground-water-flow model for northeastern St. Joseph County, Indiana. (Aquifer 1 is not intersected by any of the sections.)

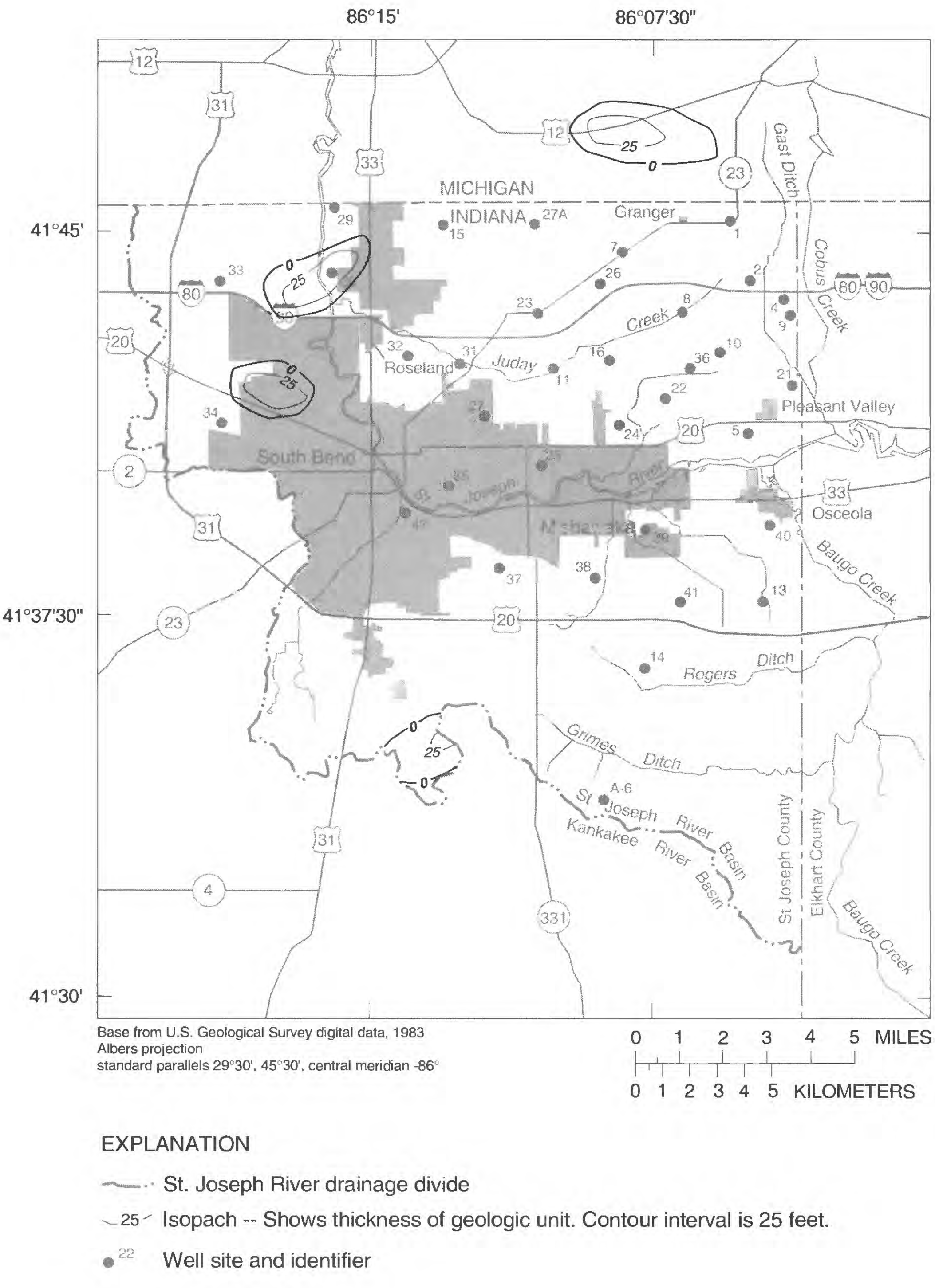
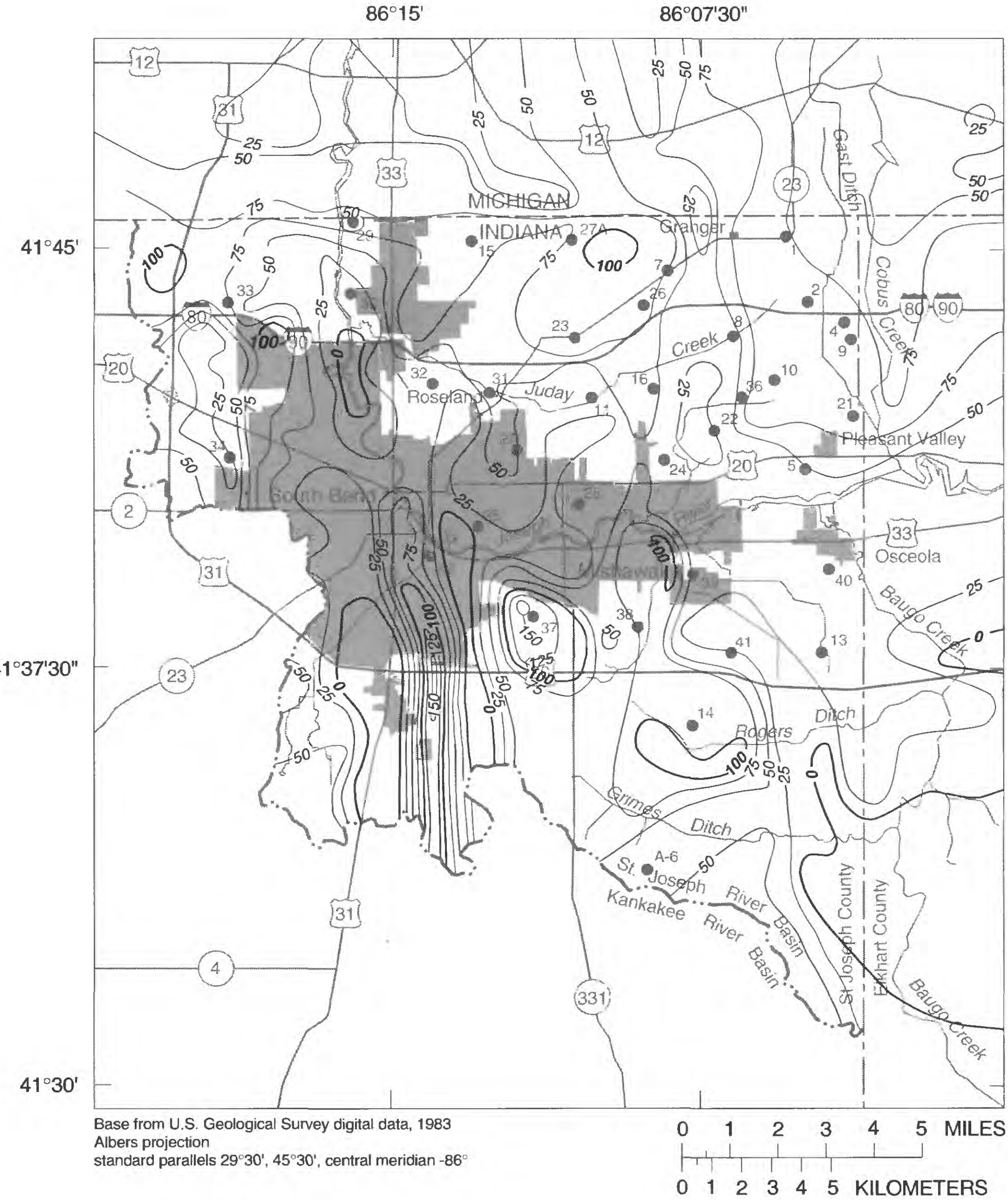


Figure 4. Location and thickness of aquifer 1.



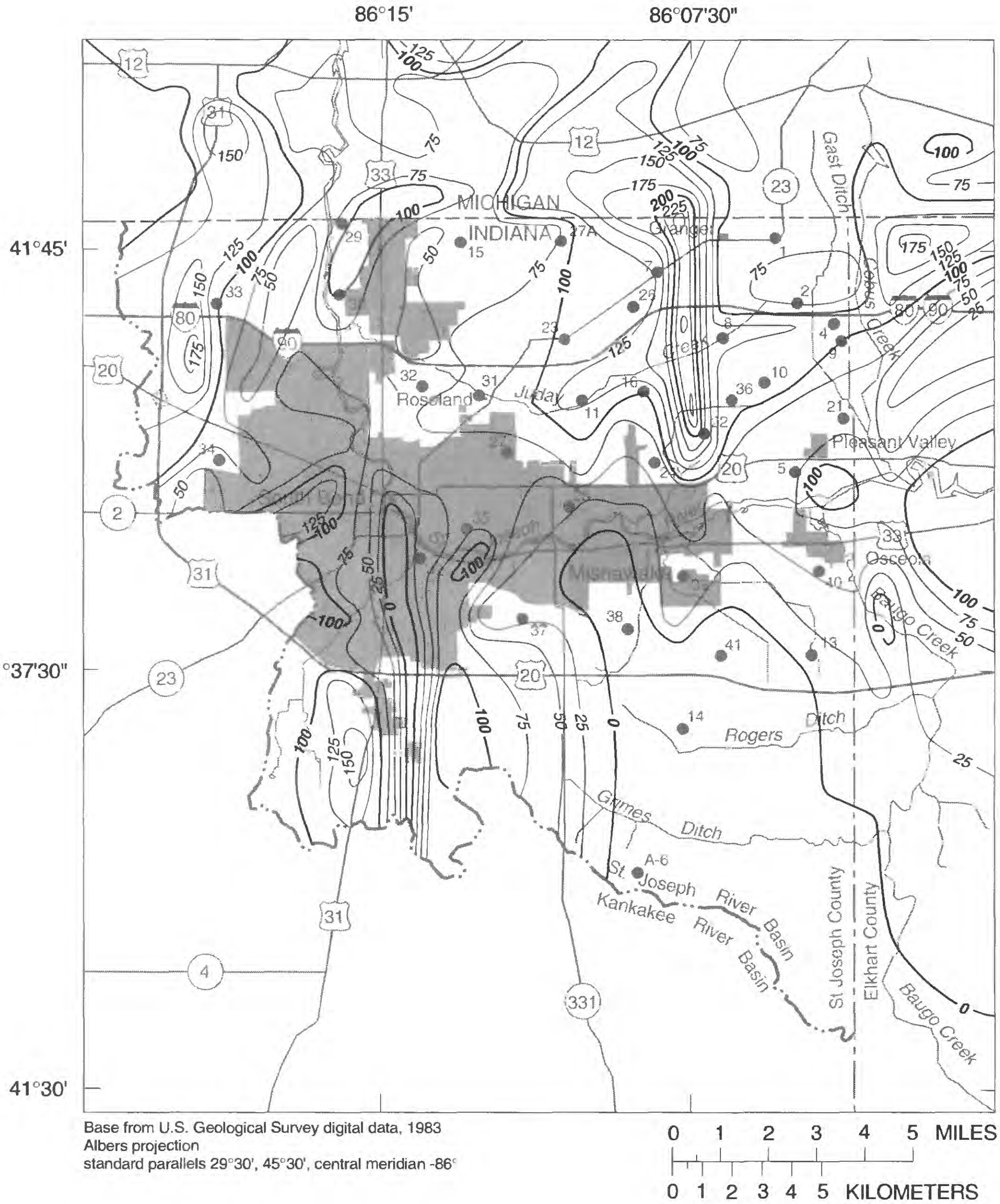
EXPLANATION

St. Joseph River drainage divide

25 Isopach -- Shows thickness of geologic unit. Contour interval is 25 feet.

22 Well site and identifier

Figure 5. Location and thickness of aquifer 2.



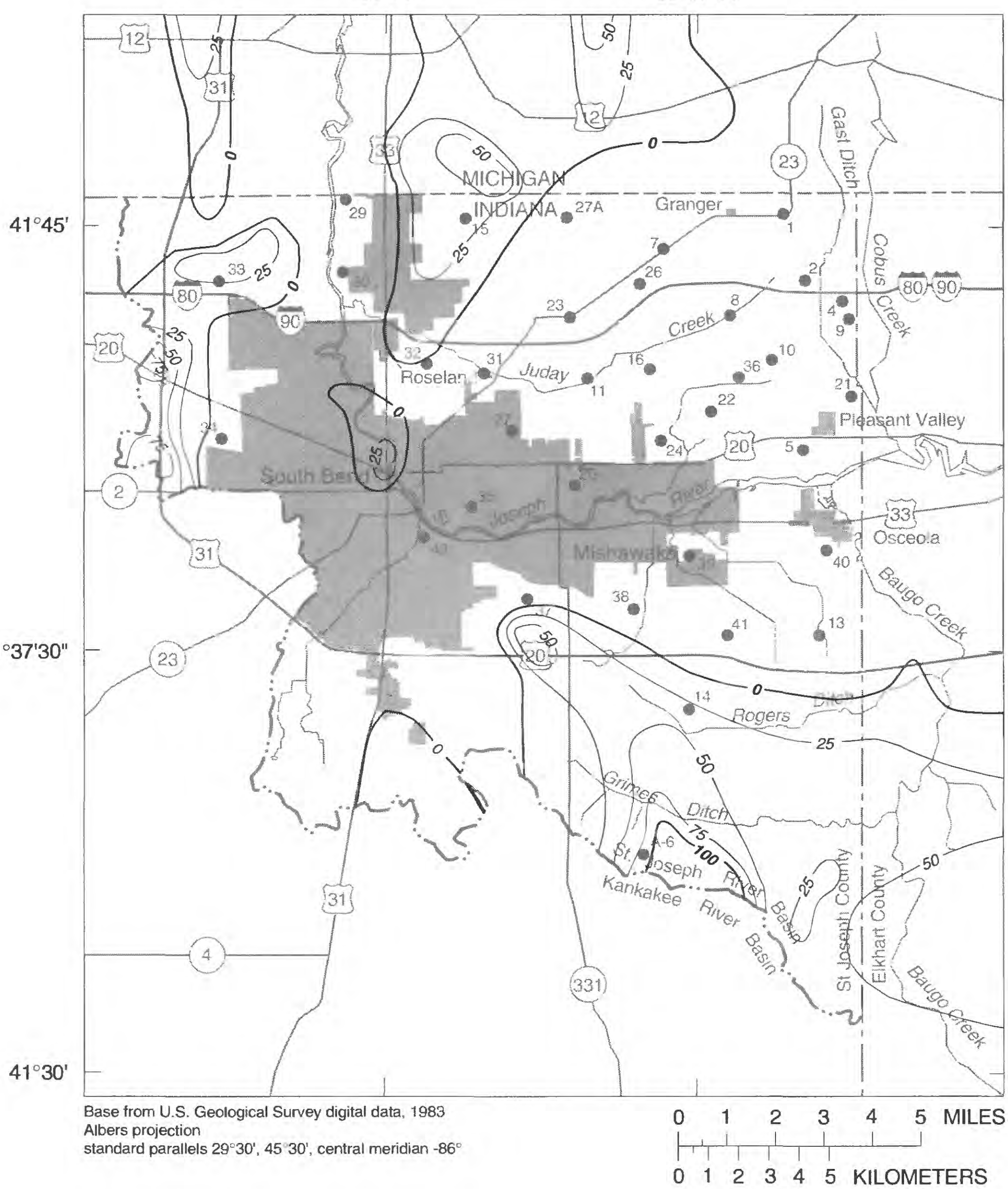
EXPLANATION

St. Joseph River drainage divide

25 Isopach -- Shows thickness of geologic unit. Contour interval is 25 feet.

22 Well site and identifier

Figure 6. Location and thickness of aquifer 3.



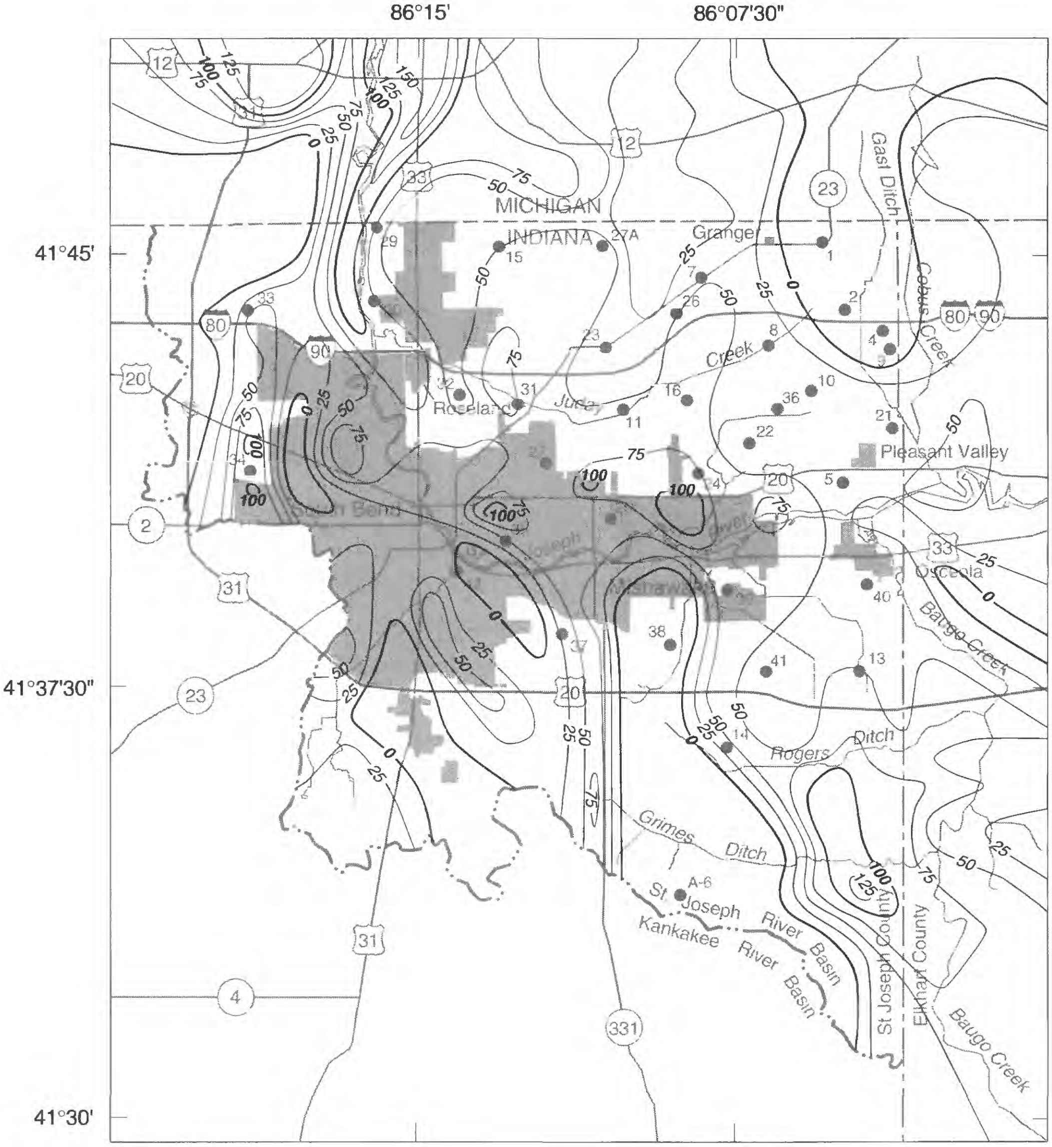
EXPLANATION

St. Joseph River drainage divide

25 Isopach -- Shows thickness of geologic unit. Contour interval is 25 feet.

22 Well site and identifier

Figure 7. Location and thickness of confining unit 1.



Base from U.S. Geological Survey digital data, 1983
Albers projection
standard parallels 29°30', 45°30', central meridian -86°

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

EXPLANATION

St. Joseph River drainage divide

25 Isopach -- Shows thickness of geologic unit. Contour interval is 25 feet.

22 Well site and identifier

Figure 8. Location and thickness of confining unit 2.

Fifty-seven percent of the annual precipitation falls during the growing season (May–October) (Beaty, 1987, p. 19). The annual mean potential evapotranspiration in north-central Indiana is greatest during the growing season and amounts to about 27 in/yr (Newman, 1981).

Previous studies indicate recharge to the St. Joseph aquifer system from precipitation is about 10.6 in/yr (Beaty, 1987). The Hilltop and Nappanee aquifer systems receive less recharge, 6.4 and 3.7 in/yr, respectively (Beaty, 1987), because the poorly permeable till that overlies the aquifers promotes runoff and inhibits infiltration. Precipitation that does not recharge the ground-water system evaporates or transpires into the atmosphere or becomes storm runoff to rivers and ditches. Recharge to the aquifers eventually is withdrawn for public and domestic water uses, commercial and industrial operations, and agricultural irrigation, or it discharges as base flow to the St. Joseph River and its tributaries.

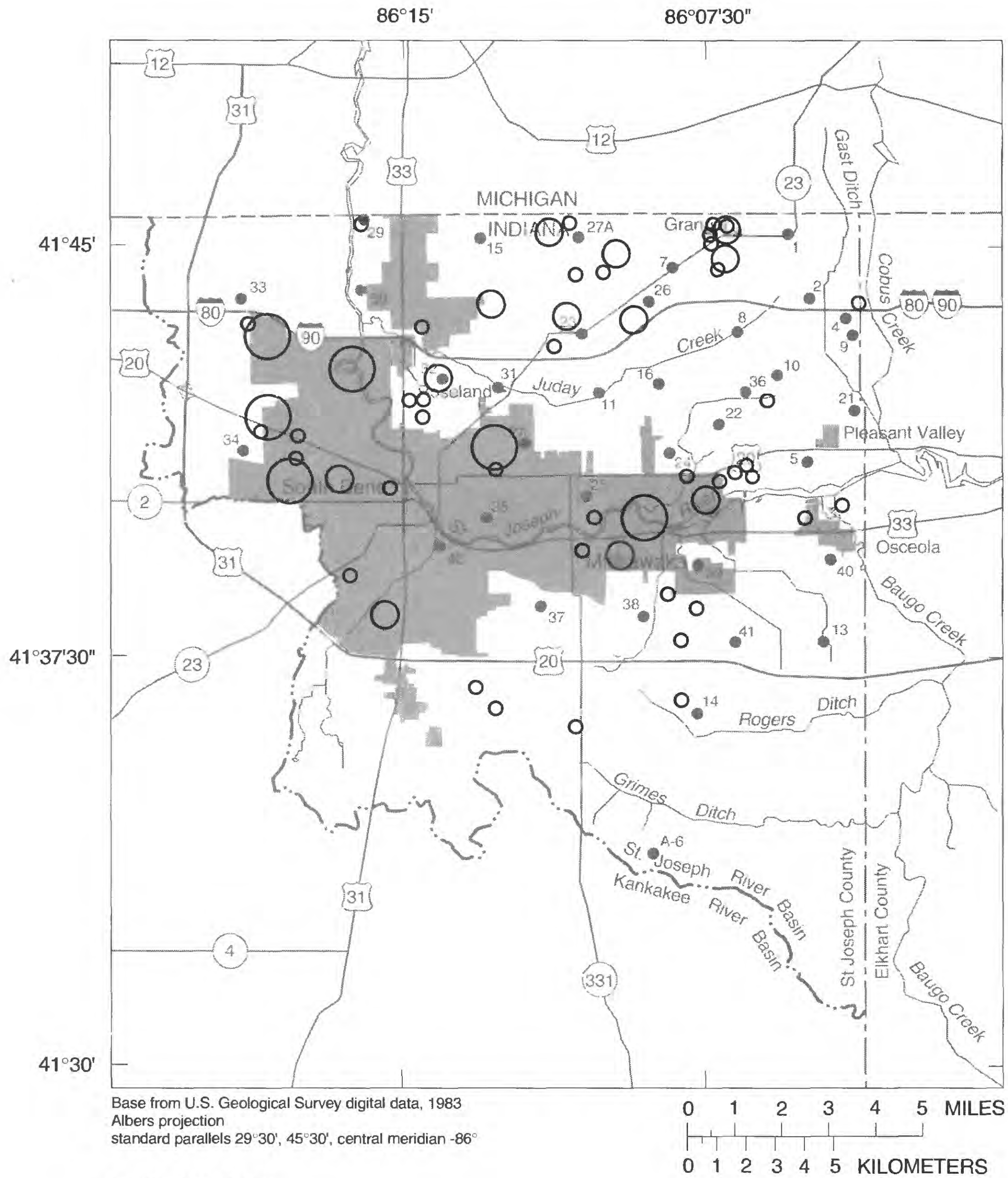
The St. Joseph River is the primary drainage in the study area (fig. 1). The river enters the study area on the eastern county line, meanders westward and slightly southward to the middle of South Bend, and then turns northward and flows into Michigan. The stage and discharge of the St. Joseph River are controlled by dams built for power generation. Major tributaries of the St. Joseph River in the study area are Juday Creek and Baugo Creek (fig. 1). Smaller streams and ditches also are part of the surface-water-drainage systems in St. Joseph County. Few lakes are in the study area, but numerous lakes are immediately north and west of the drainage-basin divide. Lakes and ponds also may be points of local ground-water recharge or discharge.

In addition to ground-water discharges to rivers, streams, lakes, and ditches, large volumes of ground water are extracted by SWWF's. Sixty-two SWWF's were registered with IDNR in 1993 (fig. 9; table 2, at back of report). Ground-water-withdrawal capabilities reported in 1986 for 53 sites (14 percent not reporting) were 122.31 Mgal/d. Actual use at those 53 sites was 34.67 Mgal/d (Beaty, 1987, p. 61). Estimated withdrawals by unregistered users in 1987, primarily domestic-well owners in rural St. Joseph County, accounted for less than 9 percent of the total ground-water production.

Water Levels

During this study, 53 monitoring wells were installed at 36 sites; clusters of 2 or 3 wells were constructed at 15 sites. Thirty-nine of the monitoring wells were north and east of the St. Joseph River. This area currently is experiencing rapid commercial and residential growth and is facing increased demands by SWWF's and domestic well users. The Hilltop and Nappanee aquifer systems are not used as heavily for high-capacity well fields; consequently, these aquifer systems received less attention during this study. Water levels were measured synoptically in the 53-well network at least seven times during water years 1991 and 1992 (table 1, at back of report).

Hydrographs of ground-water levels in the St. Joseph aquifer system indicate similarities and differences between sites where confining units are and are not present. Water-level altitudes in deep wells (completed below the confining unit or at depths greater than 70 ft) and shallow wells (completed above the confining unit or at depths less than 70 ft) at clustered-well sites generally are similar if confining units do not separate upper and lower aquifers. At site 1, for example, the maximum difference in water levels in wells 1-25, 1-85, and 1-173, during water year 1992 was 0.09 ft (fig. 10 and table 1). At sites where a confining unit is present, however, the difference between water-level altitudes in deep and shallow wells is greater. At sites 2, 5, 16, 22, and 31, for example, clay-rich deposits are a definite barrier to vertical ground-water flow, and the altitudes of water levels in deep wells are lower than those in shallow wells



EXPLANATION

St. Joseph River drainage divide

● 22 Well site and identifier

Water withdrawal facilities--Size of symbol is proportional to annual volume of water withdrawn from aquifer 1.

- >0 - 100,000,000 (gallons per year) withdrawn
- >100,000,000 - 1,000,000,000 (gallons per year) withdrawn
- >1,000,000,000 (gallons per year) withdrawn

Figure 9. Locations of significant (ground) water-withdrawal facilities in 1993.

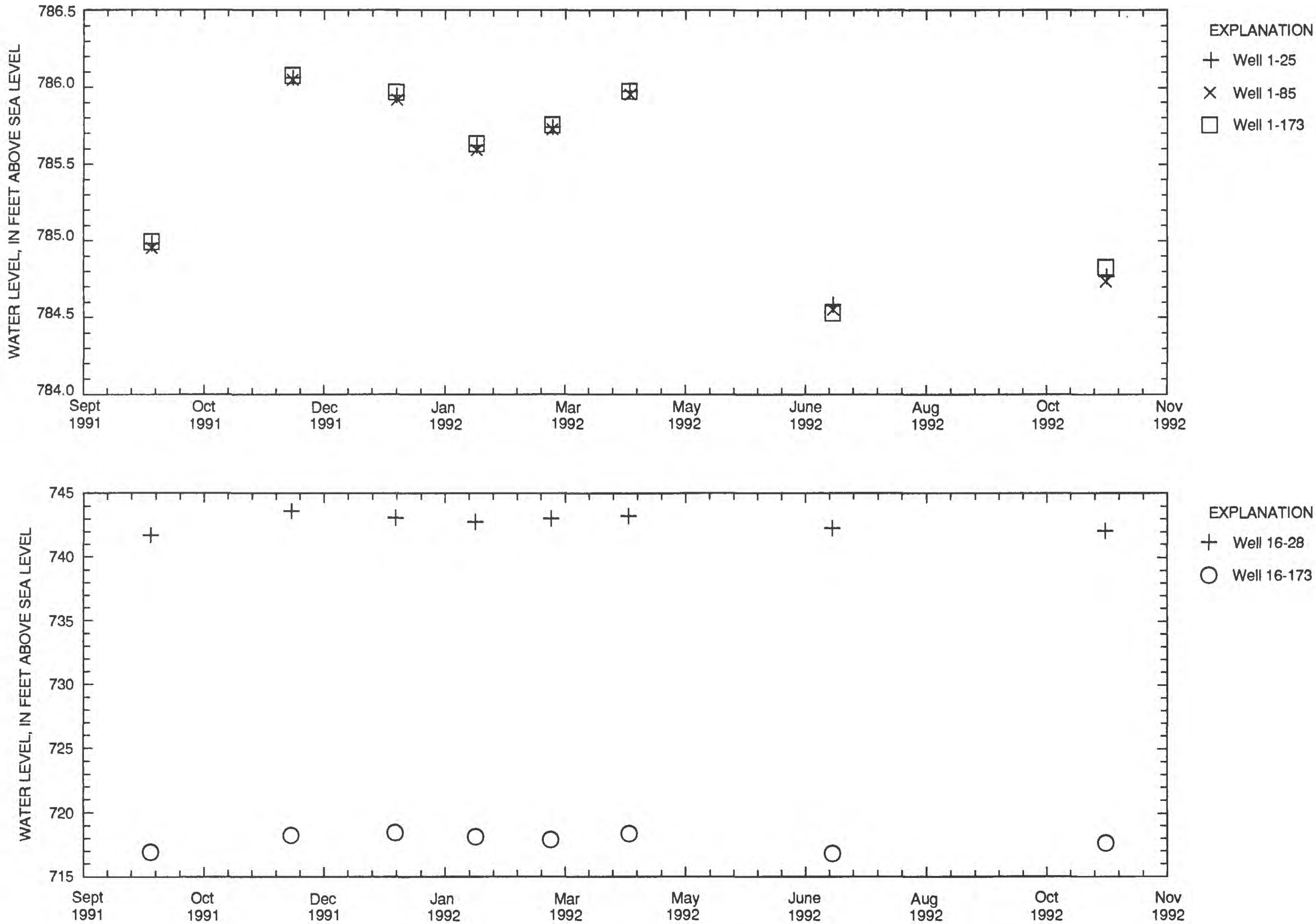


Figure 10. Ground-water levels during water year 1991 at well sites 1 and 16, northeastern St. Joseph County, Indiana.

by an average 1.28 ft, 3.56 ft, 24.67 ft, 24.11 ft, and 13.84 ft, respectively. (A hydrograph for site 16 is shown in figure 10.) A confining unit also separates shallow and deep aquifers at site 8; but at this location, the water levels are higher in the deep well by an average of 0.35 ft. This exception to the usual pattern is probably the effect of Juday Creek, which is less than 20 ft from site 8, drawing down the local water levels in the shallow aquifer.

Temporal variability of water levels in deep and shallow wells was approximately constant during the period of study, regardless of the presence or absence of a confining unit. At site 1, for example, the variability of water levels was 1.48 ft, 1.49 ft, and 1.55 ft in wells completed at 25 ft, 85 ft, and 173 ft, respectively; at site 16, water-level variability was 1.88 ft and 1.71 ft for wells screened at 28 ft and 173 ft, respectively (fig. 10). Proximity of a well site to the St. Joseph River did not seem to affect the temporal variability of water levels. Ground-water levels at all sites are highest in the winter and spring; they decline during summer and begin to recover towards the end of autumn (for example, see fig. 10).

Two wells in the USGS network were in the Nappanee aquifer system (wells 14-135 and A6-152) and one was in the Hilltop aquifer system (37-150) (fig. 1). Hydrographs for wells 14-135 and A6-152 varied by 13.67 ft and 0.55 ft, respectively. The highest levels at site 14-135 occurred during summer and may reflect delayed recharge of the aquifer or irrigation that was not observed during site visits. Water levels at well site 37-150 were measured three times during the study period and varied by 0.93 ft. Compared to the St. Joseph aquifer system, depth to water generally is great in the Hilltop and Nappanee aquifer systems.

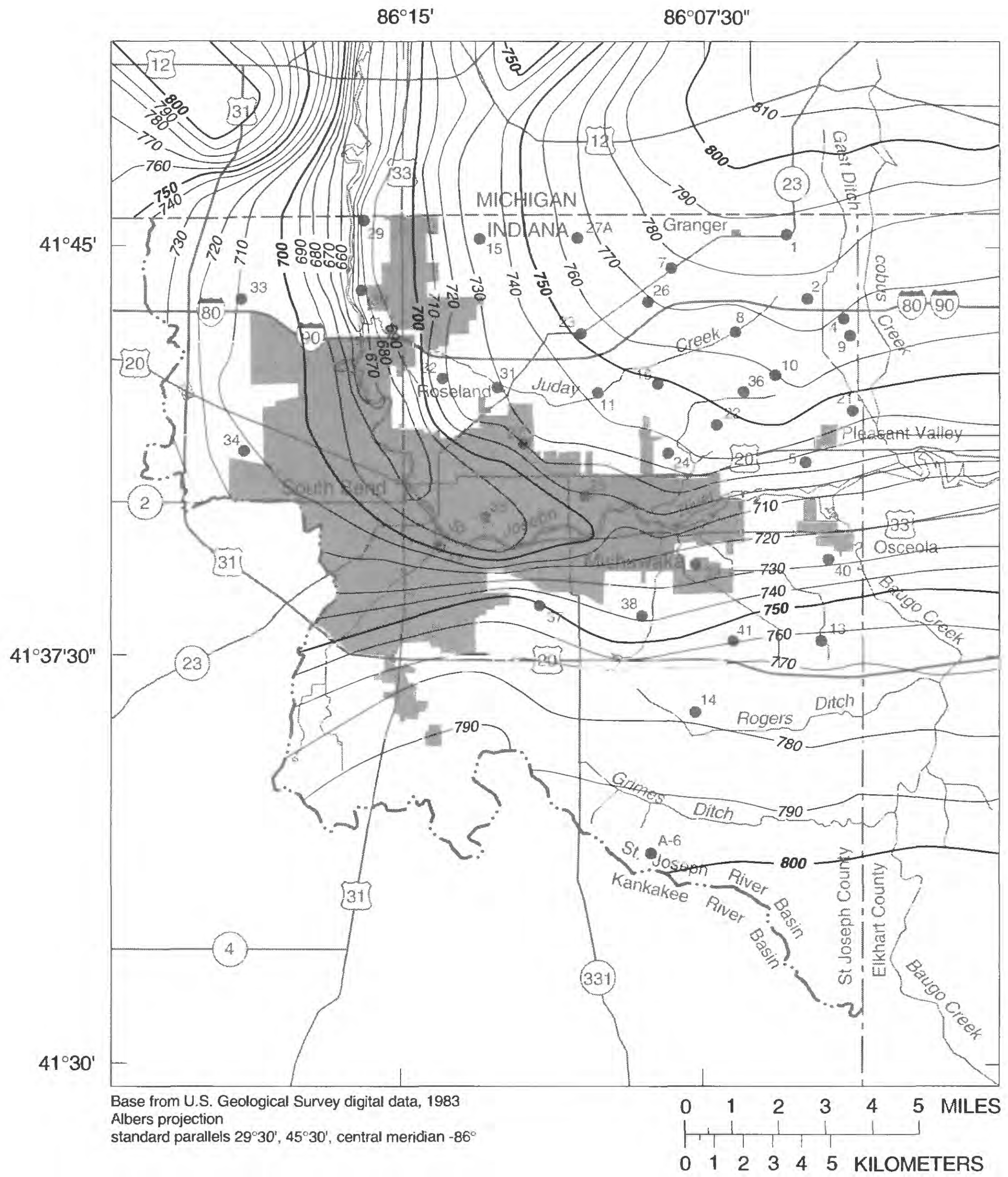
Ground-Water Flow

Ground-water-level maps were assembled for aquifers 2 and 3. No attempt was made to create a ground-water-level map for aquifer 1 because data were available for only one well site. The composite water-level map by Beaty (1987) was the foundation for constructing the ground-water-level maps shown in figures 11 and 12; measured water levels in the deep and shallow wells were used to adjust the composite map to create individual maps for aquifers 2 and 3.

Ground water generally flows from regional recharge areas to regional discharge areas and local discharge sites. Ground-water discharge may occur at natural features such as creeks, rivers, lakes, and ponds, or ground water may discharge at manmade features such as drainage ditches and well fields. Regional ground-water flow in northeastern St. Joseph County is toward the St. Joseph River, the ultimate discharge point in the study area (Beaty, 1987). Local ground-water-flow patterns may be directed toward creeks, lakes, ponds, drainage ditches, and high-capacity well fields. Ground-water flow in deep aquifers typically follows regional flow paths, which may be as long as tens of miles. Ground-water flow in shallow aquifers, by comparison, may be affected by local discharge points; consequently, local flow paths may be as short as a few hundred feet.

SIMULATED GROUND-WATER FLOW THROUGH THE UNCONSOLIDATED AQUIFERS

A numerical model of ground-water flow was constructed to examine (1) simulated aquifer response to increased ground-water withdrawals, (2) contributing areas of SWWF's, and (3) flow paths and discharge points for hypothetical water particles originating beneath known contamination sites. The numerical model was based on a quasi three-dimensional finite-difference computer algorithm by McDonald and Harbaugh (1988). Fundamental assumptions of the model include a steady-state ground-water-flow system and a homogeneous, isotropic porous medium within each model layer. Model-parameter values were constrained by available hydrogeological information. The model was calibrated by minimizing the differences between simulated and field-measured water-table elevations.



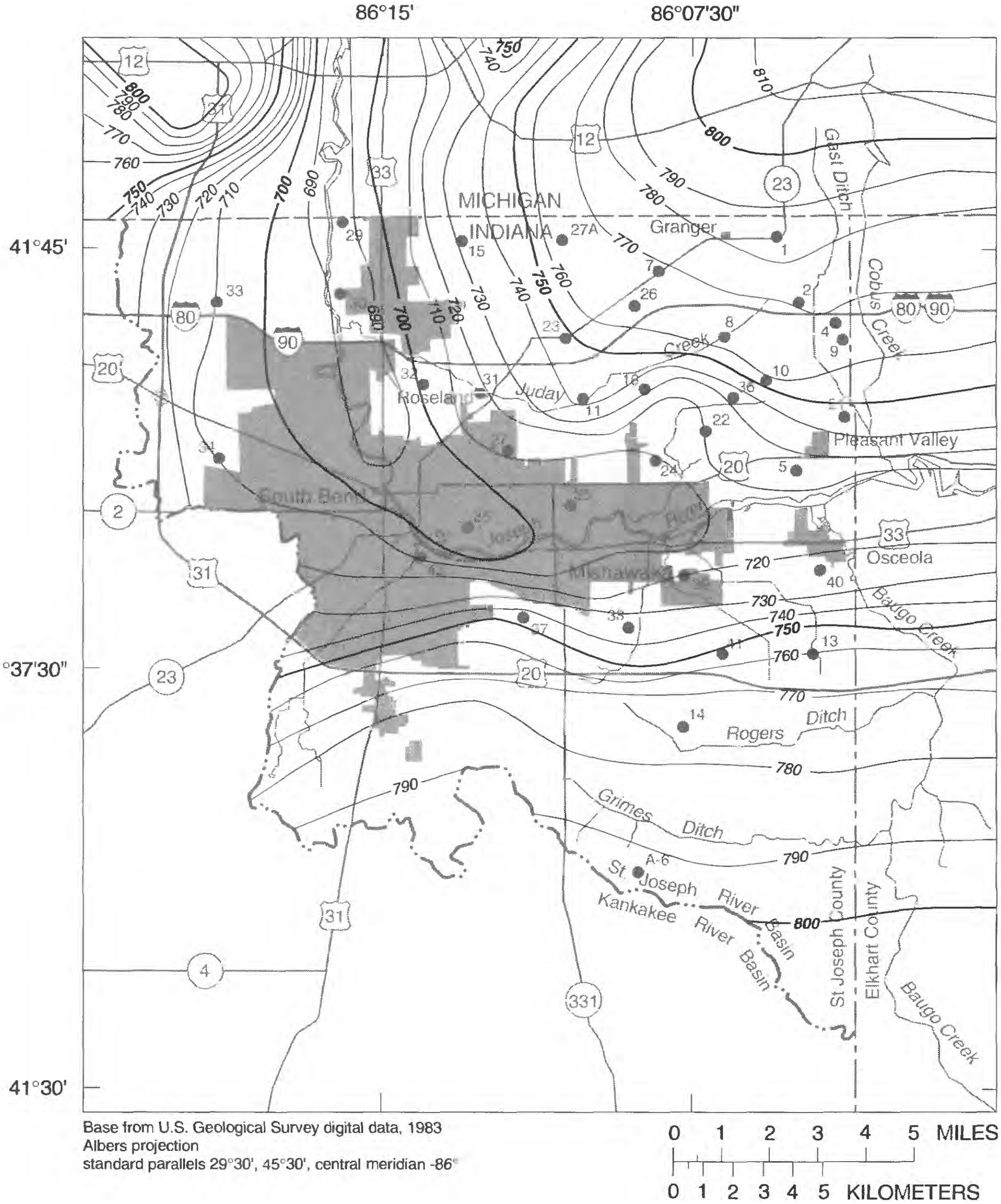
EXPLANATION

St. Joseph River drainage divide

720 Water-level contour--Shows altitude of water level. Contour interval 5 feet. Datum is sea level.

22 Well site and identifier

Figure 11. Altitude and configuration of the ground-water-level surface in aquifer 2.



EXPLANATION

St. Joseph River drainage divide

720 Water-level contour--Shows altitude of water level. Contour interval 5 feet. Datum is sea level.

22 Well site and identifier

Figure 12. Altitude and configuration of the ground-water-level surface in aquifer 3.

Model Conceptualization

The area represented in the numerical model, the "modeled area," is considerably larger than the study area described in the "Introduction" section. The north boundary of the modeled area was 3.5 mi north of the Indiana/Michigan State line, and the east boundary was 3.0 mi east of the St. Joseph County/Elkhart County line (fig. 13). The southwest boundary of the modeled area was the St. Joseph River drainage basin divide.

The study area was divided into a model grid of rectangular cells (fig.13), each with an area of one-quarter mi^2. The center of the cell—the "node"—is the location where the numerical calculations of water level and flow direction were applied.

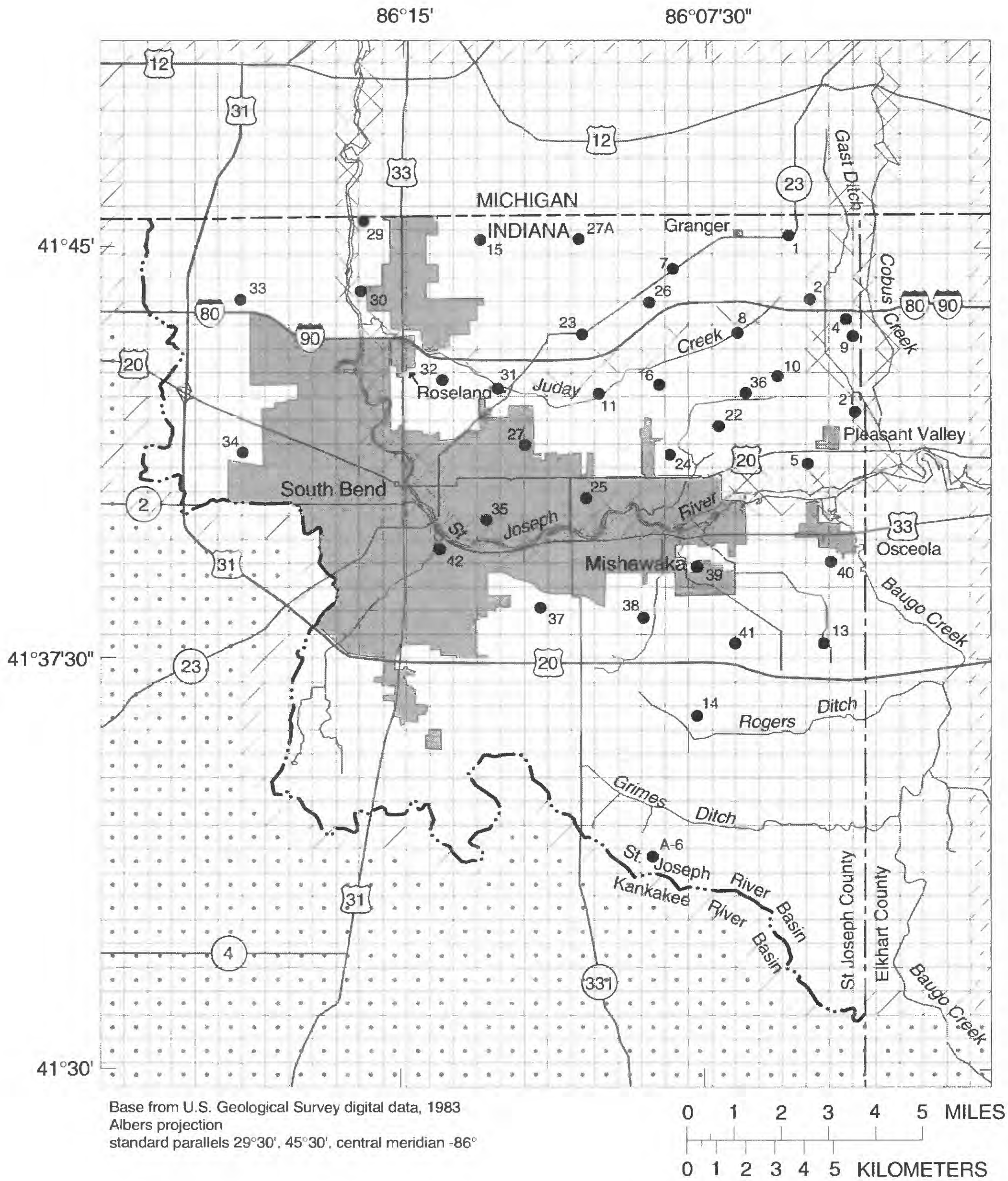
Cell orientation is parallel to the primary directions of ground-water flow. Regional ground-water flow in the study area is towards the St. Joseph River. Because the St. Joseph River reaches are mostly oriented north-south and east-west, the selected cell orientation (which coincidentally parallels the political boundaries) is acceptable. Variable sizing of model cells (commonly used to give detailed information about a small site that lies within a modeled area) was not used in this study because the emphasis was on the regional flow system.

Boundary and Inactive Cells

Accurate identification of boundary conditions can greatly affect simulation results near the boundary, particularly in steady-state simulations such as this one (Anderson and Woessner, 1992). Boundary conditions for the modeled area were established where natural hydraulic boundaries were located; where natural boundaries did not exist, artificial boundaries were established at a sufficient distance from the study area so that they would not affect the simulated water levels. All model boundary cells were identified as "constant-head" cells; water levels were held constant in these cells during all simulations.

The southwestern boundary of the modeled area, the St. Joseph River drainage basin divide, is a hydraulic boundary. Although the surface-water drainage divide may not exactly coincide with the ground-water drainage-basin divide, the surface-water drainage divide generally is accepted as a close approximation for a regional model. Boundary cells along the surface-water drainage divide, marking the southwest boundary of the modeled area, were identified in the numerical model as constant-head cells. The hydraulic heads assigned to the constant-head cells along the southwest boundary of the modeled area were based on maps of the ground-water-level surface (figs. 11 and 12). Assignment of constant heads to these cells was considered acceptable because (1) the boundary was at least 3 mi from the nearest SWWF; (2) the Hilltop and Nappanee aquifer systems, which are adjacent to this boundary, are rarely used by SWWF's; and (3) the main focus of this study is the area north and east of the St. Joseph River. These cells were identified in the numerical model as a constant-head boundary, as opposed to a constant-flux boundary that is sometimes used to simulate drainage divides, because accurate data needed to calculate ground-water fluxes were not available. Cells southwest of the drainage divide were identified as inactive cells and were not considered in the model calculations (fig. 13).

The land beyond the north and northwest boundaries of the modeled area is marked by several lakes, ponds, and poorly drained areas. This boundary extends due north approximately 3.5 mi from the intersection of the St. Joseph River surface-water drainage divide and the Indiana/Michigan State line. The northern boundary of the modeled area is oriented east-west and is positioned 3.5 mi north of the Indiana/Michigan State line. Boundary cells marking the north and northwest limits of the modeled area are identified in the numerical model as constant-head cells. The hydraulic heads assigned to these cells were based on ground-water-level surface maps and



EXPLANATION

- Active model cell
- River cell
- Constant head cell
- Inactive cell
- St. Joseph River drainage divide
- Well site and identifier

Figure 13. Model grid, boundary conditions, and river reaches used in the simulation of ground-water flow.

water levels in the surface-water bodies. These boundary-cell assignments were considered acceptable because the cells are more than 4 mi from the nearest SWWF.

The eastern boundary of the modeled area is an artificial boundary established 3.0 mi east of the St. Joseph County/Elkhart County political boundary. The cells that mark the eastern boundary of the modeled area were identified in the numerical model as constant-head cells. Hydraulic heads assigned to boundary cells that mark the eastern limit of the modeled area were based on the ground-water-level surface maps assembled for this study. The boundary cells identifying the eastern limit of the modeled area were considered acceptable because (1) the nearest SWWF is more than 3 mi west of the boundary; (2) similar to the northern boundary, the eastern boundary is in the productive outwash of the St. Joseph aquifer system; and (3) previous studies and the water-level surface map indicated that ground-water flow is primarily from north to south in the area north and east of the St. Joseph River. Therefore, the contributing areas for SWWF's would affect primarily areas due north of their pumping stations. The evidence of a small east-west component of ground-water flow was enough justification to identify these cells as the constant-head type rather than the no-flow type that is sometimes used for cells positioned along a ground-water streamline (Anderson and Woessner, 1992).

The Ellsworth Shale underlies the study area and probably is much less permeable than the glacial-drift deposits. The Ellsworth Shale was identified as a no-flow boundary, which allows no transfer of water across its interface with active model cells.

Active Model Cells

The stratigraphy represented in the active model cells was described from geophysical logs that were recorded during an earlier phase of this study (Bayless and others, 1995) and from more than 370 well-driller's logs on file with IDNR. Geology in the modeled area is portrayed as three aquifers, separated by confining units—the entire sequence underlain by the Ellsworth Shale (fig. 3). Stratigraphy of the St. Joseph aquifer system has been similarly conceptualized in previous model studies of ground-water flow in Elkhart County, Ind. (Imbrigiotta and Martin, 1981; and Lindgren and others, 1985). Isopach maps, constructed for each modeled stratigraphic unit, were used as a basis for assigning cell thicknesses.

Horizontal hydraulic conductivities of the modeled stratigraphic units were selected from ranges published in previous studies. Horizontal hydraulic conductivity of aquifer cells was constant within each layer.

Vertical leakances were used to represent vertical ground-water flow through the confining units. Vertical leakance is the vertical hydraulic conductivity divided by confining-unit thickness. Use of vertical leakance is acceptable if horizontal flow through the confining unit is small; this assumption has been made in similar stratigraphic settings (Imbrigiotta and Martin, 1981; Anderson and Woessner, 1992). Representative hydraulic conductivities were adopted from previous studies (Imbrigiotta and Martin, 1981; Lindgren and others, 1985). Vertical hydraulic conductivity was held constant within each confining unit, and the same value was used for all confining units.

Vertical hydraulic conductivity of streambed sediments in the St. Joseph River and Juday Creek (the two streams included in the model) was initially set to 0.07 ft/d (Imbrigiotta and Martin, 1981, p. 41). Streambed conductance represents the stream-aquifer connection and is calculated as the product of streambed area and the vertical hydraulic conductivity of the streambed sediments divided by the thickness of the bed material. Imbrigiotta and Martin (1981) estimated streambed conductance by matching simulated seepage rates to measured rates in nine reaches of St. Joseph River tributaries; however, they were not able to calculate streambed conductance for the St. Joseph

River because of limitations in the accuracy of flow measurements along the river. The average length and width of a stream reach was determined by averaging the dimensions of reaches in several model cells. Average length of a reach below the dammed pool (fig. 1) was estimated to be 3,500 ft, and average width of a reach below the dammed pool was 200 ft. Reaches in the dammed-pool area were of similar length but stream width was estimated to be 400 ft. As in the model by Imbrigiotta and Martin (1981), a streambed thickness of 1 ft was assumed for all simulations.

Other Model Inputs

Aquifer recharge in the numerical model represents the difference between infiltration and evapotranspiration. Seasonal variations in precipitation and evapotranspiration were not required because computations were made only for the time-averaged steady-state model. Time-averaged recharge (infiltration minus evapotranspiration) has been estimated to be 10.6, 6.4, and 3.7 in/yr for the St. Joseph aquifer system, the Hilltop aquifer system, and the Nappanee aquifer system, respectively (Beaty, 1987).

Initial head arrays for the numerical model were based on water-level maps described in the section, "Ground-Water Flow." Ground-water-level maps of aquifer 2 and aquifer 3 were distinguished at only a few locations where field-measured water levels differed between the two layers (table 1, at back of report).

All simulations were done by use of the data input and equations required for a steady-state system. A steady-state system generally is considered to be a reflection of long-term conditions. The steady-state conditions were simulated to meet the purpose of this study—to describe the long-term effects of additional stresses on the aquifer system.

Model Assumptions

The computer program by McDonald and Harbaugh (1988), used to create the numerical model, uses a finite-difference approximation for solving a set of equations that describe ground-water flow.

The results of a numerical model reflect the accuracy and precision of (1) the input data; (2) the fundamental equations that describe ground-water flow through a porous medium; (3) the finite-difference approximations; and (4) the simplifying assumptions concerning the spatial distribution of hydraulic parameters, such as homogeneity and isotropy. Values for some hydrologic variables used in the model were taken from measurements or estimates published in previous reports on the St. Joseph River Basin. The accuracy of those measurements and estimates and the spatial density of values affect the numerical model's ability to represent the flow system. Unavoidably, certain steps in model development—such as construction of water-level maps and isopach maps—are subject to the modeler's judgement and level of expertise. Inherent in the finite-difference method is the assumption that hydrogeologic parameter values are uniform within individual cells; the accuracy of this assumption is related to the cell dimensions. Generally, the accuracy of a numerical model based on the finite-difference method improves with decreasing cell size because additional data can be included and the hydrogeologic geometry can be more closely simulated. The additional accuracy, however, requires the availability of detailed hydrogeologic information and increased computing capabilities.

Model Calibration

The calibration process consisted of adjusting model-parameter values until the differences between simulated and measured ground-water levels and simulated and measured stream discharges were minimized. The parameter values adjusted were the horizontal hydraulic conductivity of aquifer 2, the horizontal hydraulic conductivity of aquifer 3, the vertical hydraulic conductivity of the confining units, the vertical hydraulic conductivity of the streambed, and the recharge rates to the three different aquifer systems. Thirty water-level measurements in aquifer 2 and 22 measurements in aquifer 3 were used for model calibration; two discharge measurements along Juday Creek also were used.

Initial values of the model parameters were based on the values selected for a ground-water model of adjacent Elkhart County (Imbrigiotta and Martin, 1981). The aquifer system in St. Joseph County is contiguous with the aquifer system in Elkhart County, and the hydraulic characteristics should be similar. Initial values were 400 ft/d for horizontal hydraulic conductivity of the sand and gravel aquifers, 0.07 ft/d for the vertical hydraulic conductivity of the confining unit, 12 in/yr for recharge rate to the outwash, and 0.5 ft/d for the vertical hydraulic conductivity of the streambed.

The first of three significant changes made to the model during calibration was to reduce the number of aquifers being simulated. The initial conceptual model was based on drillers' records and included three sand and gravel aquifers. During calibration, however, the observations were made that (1) aquifer 1 covers only a small percentage of the modeled area, (2) aquifer 1 is not present in the area north and east of the St. Joseph River, (3) no measured water levels for aquifer 1 were available for comparison with simulated values, and (4) aquifer 1 probably has little effect on the regional flow system. Aquifer 1 was inactivated during subsequent runs of the model.

The second significant change to the model concerned the vertical hydraulic conductivity of the confining unit beneath the St. Joseph River. In a previous study by Marie (1975, p. 7), a detailed geologic section indicated erosion of the confining unit and refilling with coarse-grained sediments. Downcutting and refilling with coarse-grained sediments by large rivers, such as the St. Joseph River, has been recorded in other hydrogeologic studies in Indiana (Planert, 1980; Meyer and others, 1975). During calibration, the model results indicated that simulated water levels in the lower aquifer were consistently higher than measured water levels near the river if a vertical hydraulic conductivity of 0.07 ft/d were used. As a result of this observation and the data from Marie (1975), the vertical hydraulic conductivity of the confining unit was increased to 0.7 ft/d beneath the St. Joseph River; this resulted in a decreased gradient across the confining unit and water levels in aquifer 3 that were lower and more similar to measured water levels.

A third change to the model was to increase recharge to the St. Joseph aquifer system above values documented in previous studies. The South Bend area receives about 38 in/yr of precipitation, and aquifer recharge was previously estimated at about 12 in/yr (Beaty, 1987). This study found that an aquifer recharge value of 24 in/yr provided the best model calibration, and that ample evidence was available to support this value. For example, as part of this study, map and site inspections documented few tributaries to Juday Creek or the St. Joseph River in the area of the St. Joseph aquifer system, indicating that surface runoff is an uncommon mechanism for conveying storm-water to the St. Joseph River. The sandy soils and relatively flat topography probably have the effect of causing most precipitation to infiltrate directly into the shallow aquifers. Analysis of storm hydrographs for Juday Creek show that a narrow, runoff peak, probably derived from urban runoff, is proceeded usually by long-duration ground-water-generated rise in streamflow (Fowler and Wilson, 1995). By use of a recharge value of 24 in/yr, simulated ground-water discharge to Juday Creek (16.5 ft^3/s) and measured discharge (18.2 ft^3/s) were in reasonable agreement for a steady-state period in August 1993. In addition, a 24 in/yr recharge produced the least deviation of simulated and measured ground-water levels in the study area.

Recharge rates to the Nappanee aquifer system did not change during model calibration, but the rate to the Hilltop aquifer system was increased from 6.4 to 9.6 in/yr. The surficial deposits of the Hilltop aquifer system are similar to the highly permeable surface of the St. Joseph aquifer system.

The streambed sediments of the St. Joseph River were assigned a vertical hydraulic conductivity of 5 ft/d. The vertical hydraulic conductivity of streambed sediments in tributaries to the St. Joseph River was 50 ft/d. Little silt or clay is in the surficial deposits of the drainage basins, and so the vertical hydraulic conductivity of the streambeds was increased over that used in the model study of Imbrigiotta and Martin (1981). By use of these values for the vertical hydraulic conductivity of streambed sediments, most measured and simulated ground-water levels near streams were in agreement.

The downstream reaches of Juday Creek were conceptualized as having a relatively low vertical hydraulic conductivity. Vertical hydraulic conductivity of streambed sediments for the six farthest downstream cells of Juday Creek was set at 0.05 ft/d to maintain streamflows reported in Fowler and Wilson (1995). The downstream reaches of Juday Creek are convex upward when viewed in profile, a situation that is somewhat uncommon for a stream that is approaching a confluence with a major stream and that is underlain with glacial drift deposits. The channel of Juday Creek, however, is lined with cobble-sized rocks that are hindering the creek from eroding its channel to a convex down profile that is typical of Indiana streams. As a result of this unusual stream profile, the simulations indicated that Juday Creek would lose water to the aquifer in the last six model cells, and there would be no flow in the channel if the vertical hydraulic conductivity were not reduced. Organic particulates, chemical precipitates, clays, and silts may have accumulated in the streambed represented by these six model cells and thereby reduced the vertical hydraulic conductivity.

The water budget associated with the calibrated model is given in table 3. The final values selected for model parameters were the following:

Horizontal hydraulic conductivity of the aquifers (ft/d)	275
Vertical hydraulic conductivity of the confining unit (ft/d)	0.07
Vertical hydraulic conductivity of the confining unit at the St. Joseph River (ft/d)	0.7
Vertical hydraulic conductivity of the streambed of the St. Joseph River (ft/d)	5
Vertical hydraulic conductivity of the streambed of all other streams (ft/d)	50
Vertical hydraulic conductivity of the streambed at the lower end of Juday Creek (ft/d)...........	0.05
Recharge to the St. Joseph aquifer system (in/yr)	24
Recharge to the Nappanee aquifer system (in/yr)	3.7
Recharge to the Hilltop aquifer system (in/yr)	9.6

The accuracy of simulated water levels relative to measured water levels was quantified by calculating the mean absolute error and the bias according to the following equations:

$$\text{Mean absolute error} = \frac{\Sigma|\text{simulated head} - \text{measured head}|}{\text{number of measurements}}$$

$$\text{Bias} = \frac{\Sigma(\text{simulated head} - \text{measured head})}{\text{number of measurements}}$$

The mean absolute error and the bias for the calibrated model were 5.0 ft and 1.8 ft, respectively. The mean absolute error and the bias were divided by the range in measured water levels to estimate the accuracy of the calibrated model. The range in measured water levels was about 100 ft. The percent mean absolute error was 5 percent, and the percent bias was 2 percent.

Table 3. Water budget for the calibrated ground-water-flow model, northeastern St. Joseph County, Indiana
[all values in cubic feet per second]

Inflow		Outflow	
Recharge from precipitation	366	Ground-water withdrawal	57.7
Ground-water recharge from streams	6.8	Ground-water discharge to streams	413
Boundary inflow	128	Boundary outflow	29.8
Total inflow	501	Total outflow	501

Error generally is less than the average (5 ft) for the entire model. The principal anomaly is in the vicinity of three proximally located wells in the northeastern quadrant of the study area; here, simulated water levels in aquifer 3 are 20 to 30 ft higher than the measured water levels (fig. 14). Despite close examination of the physical setting near these wells, the explanation for the anomalously high simulated water levels is unknown. Available pumping records for SWWF's near the three anomalous well sites do not indicate withdrawals sufficient to cause a large cone of depression, and depressed water levels are not evident in aquifer 2. If these three sites are not considered, the mean absolute error is 3.8 ft.

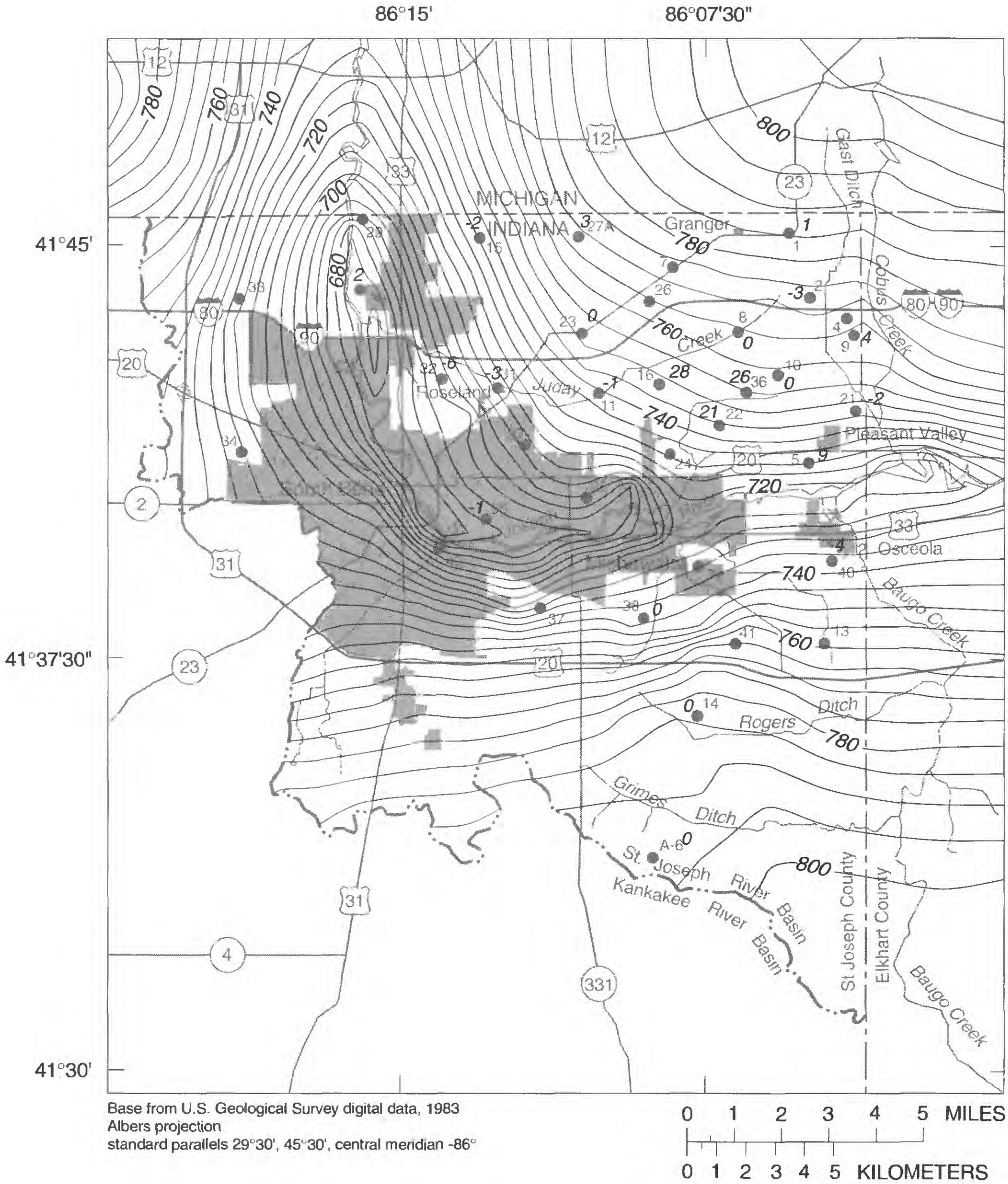
The absolute error of the model (measured water level minus simulated water level) and the simulated steady-state water levels are depicted for aquifer 3 in figure 14. In general, the map of simulated water levels generated from the calibrated model closely approximates the map of measured water levels (fig. 12). Accuracy of the model predictions is better in parts of the study area where monitoring-well information was available for calibration.

One area of apparent disagreement between figures 12 and 14 is near the confluence of Juday Creek and the St. Joseph River. Simulations indicate an area of depressed water levels that isn't present in figure 12. The simulated depression is a result of higher leakance rates for the confining unit near the confluence of Juday Creek and the St. Joseph River (described earlier in this section). In the vicinity of the confluence, the hydraulic head in aquifer 3 is approximately equal to the stage in the St. Joseph River. Absolute mean error for the observation well in this vicinity is 2 ft.

The confining unit thickens beneath the St. Joseph River north of the river's confluence with Juday Creek, and the resulting decrease in leakance causes the simulated heads in aquifer 3 to be as much as 30 ft higher than the river stage. The effect of the elevated water levels in aquifer 3 is a concentricity of water-level contours around the confluence of the St. Joseph River and Juday Creek. Although this water-level contour pattern is uncommon near large rivers, boundary conditions and initial head values were examined and determined to be unrelated to the model solution. Very few measured water levels were available for aquifer 3 in Michigan, and figure 12 is largely based on lakes, ponds, streams, and shallow wells that are more representative of conditions in aquifer 2.

Differences between simulated and measured water levels in aquifer 2 generally are 5 ft or less in the area north and east of the St. Joseph River, the area of greatest interest for model simulations. South and west of the river, differences between measured and simulated water levels in aquifer 2 south range from 5 to 21 ft. Acquiring and including additional hydrogeologic information in the area south and west of the river probably would improve calibration.

The simulated water-level surface for aquifer 2 is not depicted in the report. It was discovered during this study that parts of aquifer 2 are not water-bearing deposits—a contoured water-level surface for aquifer 2 would be discontinuous and difficult to interpret. In the parts of aquifer 2 that are water bearing, contours of the water-level surface would be similar to those pictured in figure 11. The water-level surfaces shown in figures 11 and 12 were constructed from a composite surface for the



EXPLANATION

St. Joseph River drainage divide

760 Water-level contour--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 5 feet. Datum is sea level.

-2 Difference between the simulated and measured water levels

● 22 Well site and identifier

Figure 14. Simulated steady-state ground-water-level surface and absolute error for calibrated model at well sites in aquifer 3.

study area that did not differentiate between shallow and deep aquifer deposits—as a result, the contour lines in figure 11 indicate that the ground-water surface is continuous, whereas the simulations indicate that this may not be true.

Model Sensitivity

The purpose of the sensitivity analysis was to determine the effect of each model parameter on simulated water levels. Parameters that substantially affect simulated water levels must be accurate for model results to be reliable.

Model sensitivity was examined by incrementally varying each of the parameters from one-half to twice the calibrated value and observing the mean absolute error and bias that resulted. The parameters examined were the same as those varied during calibration: horizontal hydraulic conductivity of the aquifers, vertical hydraulic conductivity of the confining unit, recharge rates to the aquifers, and vertical hydraulic conductivity of the streambeds. The model sensitivity of each parameter is illustrated in figure 15 (because several values are used for vertical hydraulic conductivity of the streambeds, the caption for the x-axis of the associated graph of sensitivity refers to the multiplier of the calibrated values rather than the value itself, as done in the other graphs).

On the basis of mean absolute error and bias, the analyses indicate the following order of parameter sensitivities, from least sensitive to most sensitive: vertical hydraulic conductivity of the streambeds, vertical hydraulic conductivity of the confining units, horizontal hydraulic conductivity of aquifer 2, horizontal hydraulic conductivity of aquifer 3, and recharge to aquifer 2. This information indicates that accurate estimates of the recharge rates and the horizontal hydraulic conductivities of the aquifers are the most important data for modeling the ground-water-flow system in northeastern St. Joseph County.

If a parameter value greatly differs from values used for similar geologic formations or hydrogeologic settings, then additional data need to be acquired to support use of the selected value. In this study, model calibration indicates that recharge rates are about twice the previously reported rates (Meyer and others, 1975, p. 48; Imbrigiotta and Martin, 1981, p. 44; Bergeron, 1981, p. 34) are required to minimize errors in the model of the St. Joseph aquifer system. Additional study would be beneficial to confirm this discrepancy.

In addition to recharge, the model is sensitive to the horizontal hydraulic conductivity of the aquifers. The model probably is more sensitive to horizontal hydraulic conductivity of aquifer 3 than to that of aquifer 2 because ground-water withdrawals from aquifer 3 are greater.

Simulation Results

The ground-water model was used to simulate (1) aquifer response to increased ground-water withdrawals, (2) source areas for SWWF's, and (3) flow paths and discharge points for particles originating beneath known contamination sites.

Simulated Ground-Water Availability

Ground-water availability was examined by simultaneously increasing ground-water-withdrawal rates by 50 percent at all SWWF's. The 50-percent increase over 1993 production rates—a reasonable estimate of future demands on the resource—was useful for examining how the aquifer might respond.

The simulations of increased ground-water withdrawals indicated that maximum drawdowns would be about 6 ft in aquifer 2 and 10 ft in aquifer 3 (fig. 16). The maximum drawdowns were computed only for the cells where the heaviest withdrawals were made; however, in both aquifers, the area sustaining depressed water levels of 2 ft or more was several square miles. Although the

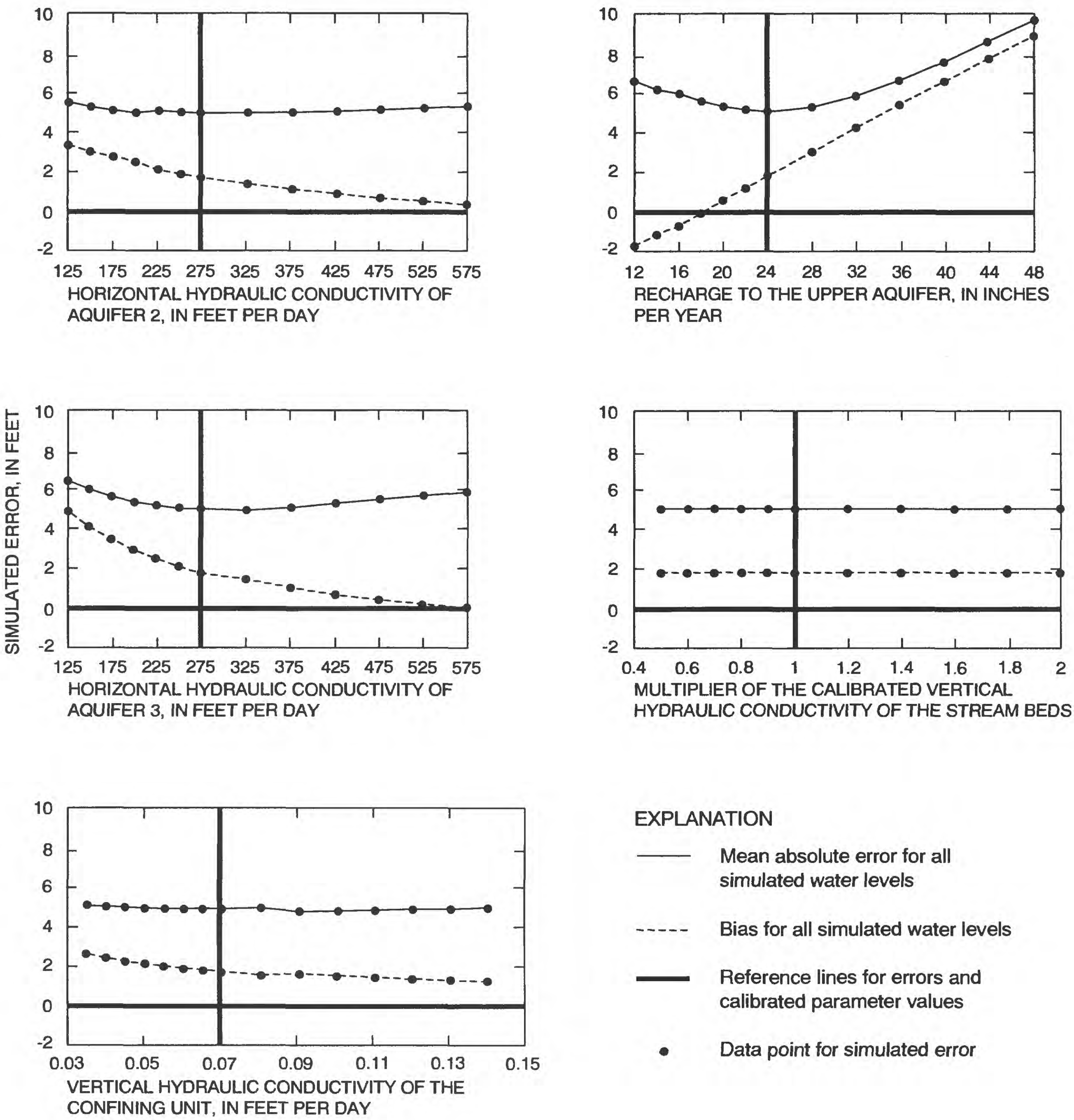


Figure 15. Relation between simulated errors and variation in parameter values for the ground-water-flow model, northeastern St. Joseph County, Indiana.

maximum drawdowns are averages for the entire simulated cell (one-quarter mi^2), drawdowns at a single well within that cell might be significantly greater.

In aquifer 2 and aquifer 3, the area where ground-water levels would be depressed by a 50-percent increase in withdrawals includes 2 to 3 mi of the lower reaches of Juday Creek (fig. 16). If a 50-percent increase in withdrawals were realized, ground water that would usually discharge to streams would be unavailable, and a decrease in streamflow would be expected. This model indicated that a 50-percent increase in ground-water withdrawals would cause a 19-ft^3/s loss of streamflow in the St. Joseph River and a 3.8-ft^3/s loss of streamflow in Juday Creek; these losses represent a 6-percent and a 23-percent reduction of ground-water flow to the channels of the St. Joseph River and Juday Creek, respectively.

Simulated Particle Transport

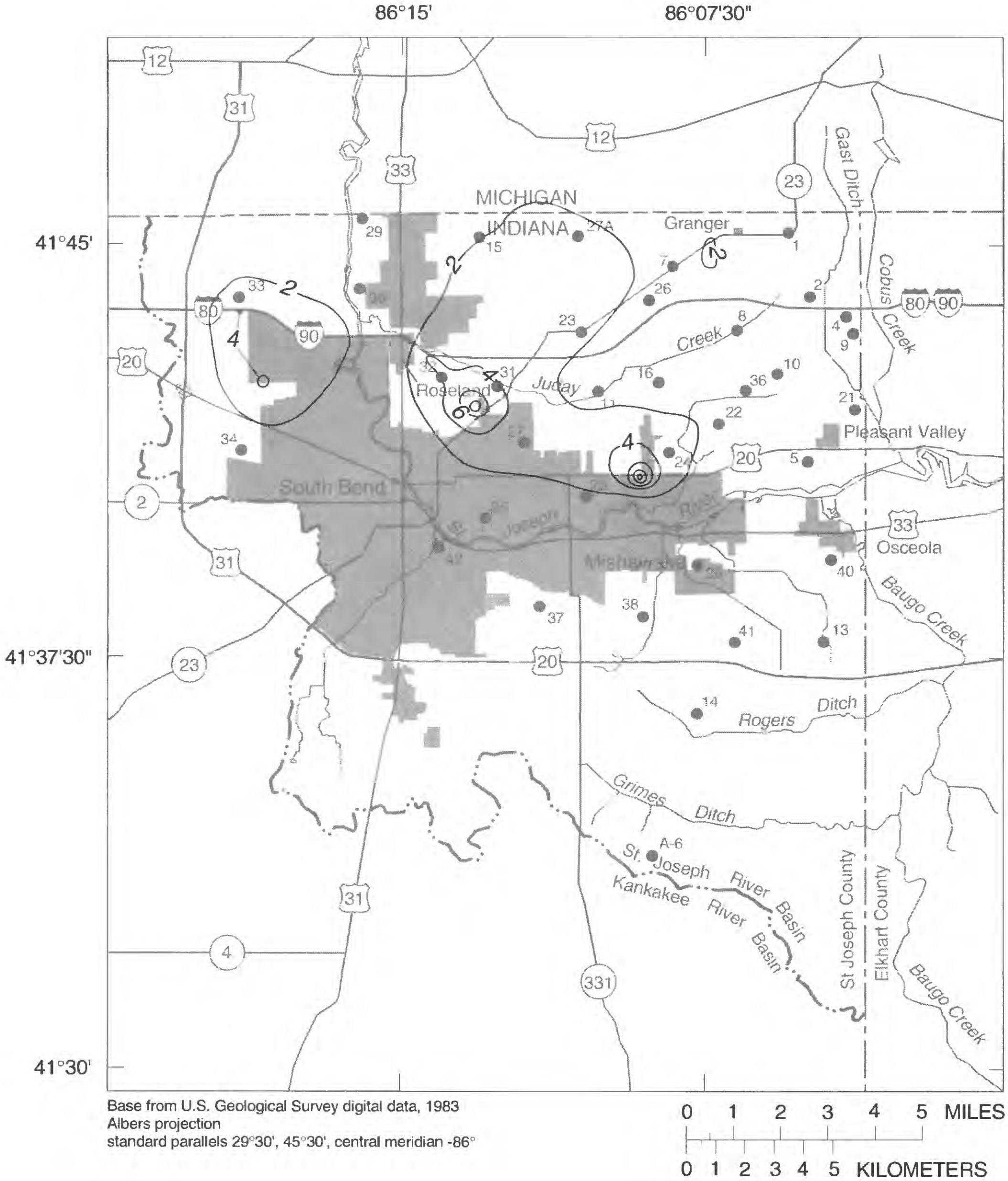
The particle-tracking program MODPATH (Pollock, 1989) was used to determine the source, flow path, and travel time of water to the largest SWWF's in the study area. The particles whose flow paths are examined are inert and hypothetical—they could be water molecules or any nonreactive constituent in the ground water. Particle tracking is a useful way to examine the potential pathways that ground water might follow enroute to discharge at lakes, ponds, rivers, or SWWF's.

The land-surface area that contains the starting locations for all flow paths to a single withdrawal site is the contributing area for that well. The particle paths shown in figure 17 are not the only ones possible; instead, the flow paths shown in figure 17 describe only the general ground-water-flow paths that particles might follow if introduced into the system. The number of particles tracked in this analysis was limited to improve the clarity of the figure, but use of additional particles would not substantially affect the contributing areas.

The flow-path lengths and the travel times for particles are related to ground-water-withdrawal rates and the hydraulic properties of the aquifers pumped. In general, the calculated flow paths are perpendicular to contours of the ground-water-level surface. Simulations indicate that flow paths to wells in aquifer 3 can be more than 12 mi long and travel times generally are 50 to 100 years. The long flow paths and travel times are associated with SWWF's withdrawing ground water from aquifer 3. Times required for particles to reach wells withdrawing water from aquifer 3 are substantially increased because recharge must flow through a confining unit, which has lower permeability and retards the flow of water.

Flow paths in aquifer 2 generally are less than 5 mi, and travel times are usually less than 10 years. Exceptions to this general observation are the long paths that originate in the southern part of the study area and end at a well field that is located near the St. Joseph River (fig. 17). This well field withdraws a relatively large amount of ground water—about 2,500 gal/min—and, as a result, the flow paths originate several miles away. The distances between 5-year time increments for this SWWF are noticeably longer than those associated with other well sites and probably indicate increased flow velocities caused by water-level gradients that are greater than those located north and west of the river.

Figure 18 shows the starting locations for particles that, in figure 17, were shown to eventually be carried along the flow path to the SWWF's. Although not clear from figure 17, figure 18 shows that simulated flow paths originate close to and distant from the SWWF's. Starting locations for particles that eventually flow to the SWWF's north and east of the St. Joseph River—the primary focus of this study—can be used to identify the entire contributing area for each SWWF. South and west of the St. Joseph River, the contributing areas for four of five well sites extend beyond the model boundary, indicating that the conceptual boundary selected for the model may not be appropriate south and west of the river or that a more sophisticated model for particle transport is needed to



EXPLANATION

St. Joseph River drainage divide

—2— Line of equal water level decline--Interval 2 feet

● 22 Well site and identifier

Figure 16. Water-level decline in aquifer 3 caused by a 50-percent increase in ground-water withdrawals at all sites.

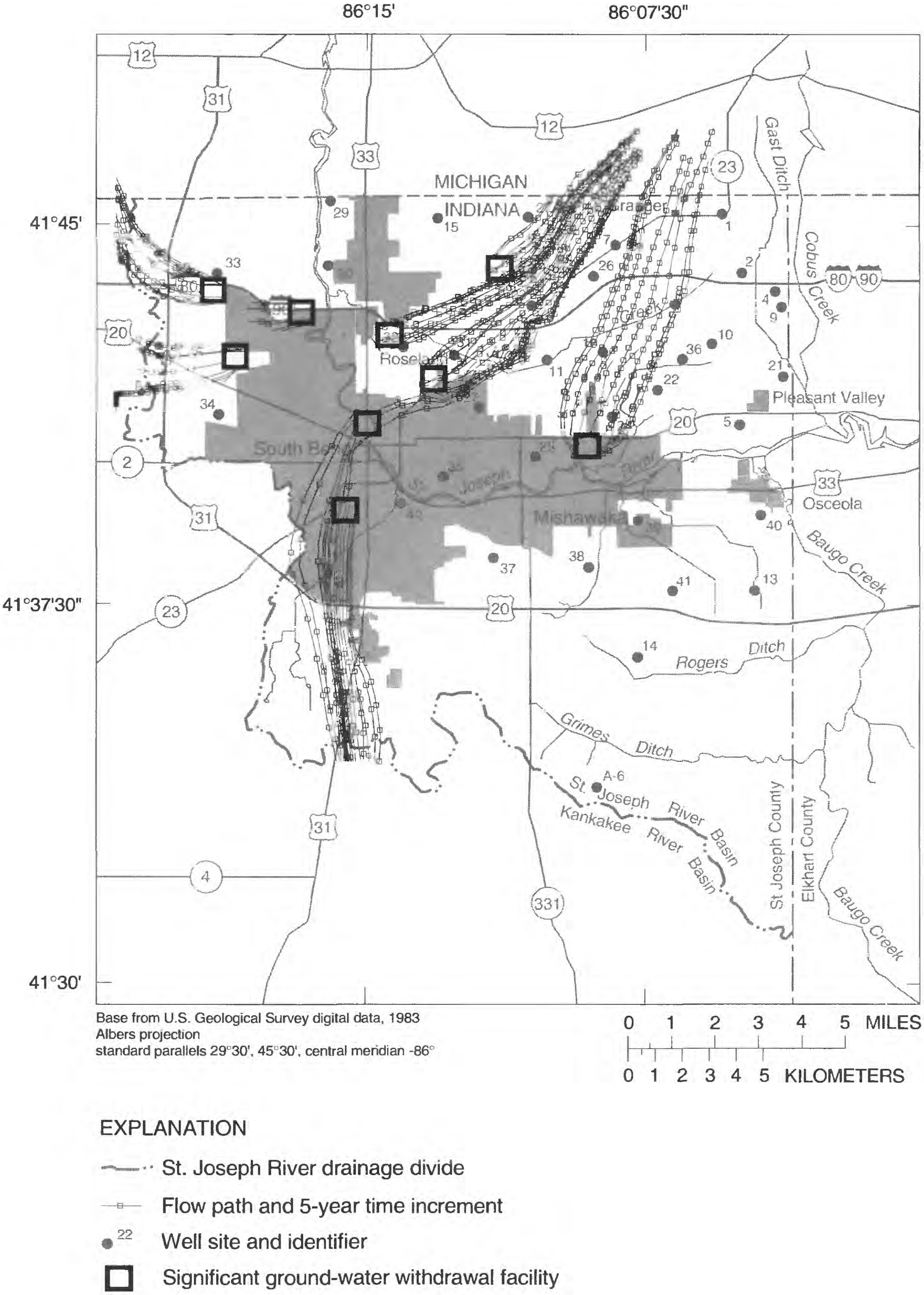
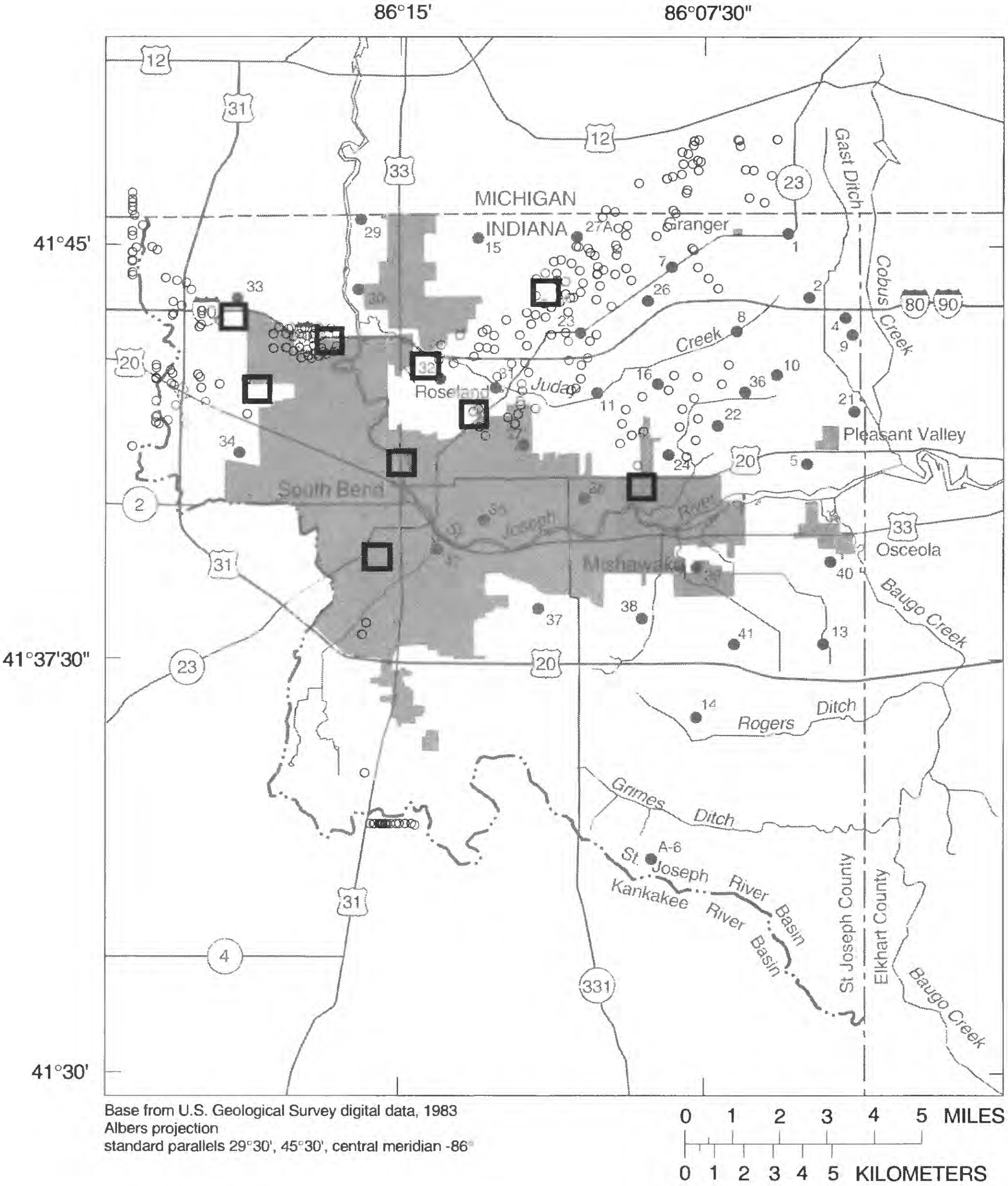


Figure 17. Simulated flow paths from selected points of recharge to significant water-withdrawal facilities.



EXPLANATION

St. Joseph River drainage divide

Well site and identifier

Starting location of flow path that enters a simulated production well

Significant ground-water withdrawal facility

Figure 18. Starting locations for flow paths that end at significant water-withdrawal facilities.

simulate this setting. The level of pre-model data acquisition and analysis for the southwestern part of the study area was not as intensive as the area north and east of the St. Joseph River. Further refinement of the model and its parameter values would be needed to resolve discrepancies in the simulation in the areas south and west of the St. Joseph River.

In addition to its use for determining the source of water to wells, MODPATH was used to determine the flow paths and ultimate discharge points for particles originating beneath documented sites of contamination. This analysis does not indicate anything about the quality of water along the flow path, which can be affected by many physical, chemical, and biological processes that occur in the subsurface. Simulated flow paths that originate beneath contamination sites, however, might be used to locate sites where water-quality analyses could be done to test for mobile constituents. The contamination sites used in this analysis were identified as "known contamination sites" by the Michiana Area Council of Governments (1989). Model cells containing the contamination sites were identified and several particles were distributed across the ground-water-level surface in that cell. Starting locations, flow paths, and ultimate discharge points for particles originating beneath the contamination sites are shown in figure 19.

The flow paths depicted in figure 19 are based on the assumption that a particle that enters a cell containing a simulated well or stream will not be withdrawn or discharged unless all ground water flowing into the cell is captured by the well or stream; otherwise, the particle continues along a flow path towards its ultimate discharge point. This conceptual model tends to route most particles to the St. Joseph River, the primary point of discharge in the study area; some ground water discharges to Juday Creek. This conceptual model indicates that ground water from known contamination sites does not discharge to any SWWF, but flow paths from several contamination sites appear to pass near these well fields. Particles in this set of simulations require from 1 to 100 years to travel from their starting points to their ultimate discharge points, but most travel times are less than 10 years.

By use of a different assumption, particles were allowed to discharge to the first stream or well along their flow paths, regardless of whether some or all of the ground water is captured by the well or stream. Some results were different than those from the previously described model. Numerical simulations based on this conceptual model indicate that eight SWWF's would intercept some particles that originated beneath known contamination sites. Some combination of these two conceptual models may represent the actual situation.

Model Limitations

Reliability of the results given in this report can be judged on the basis of the data and design limitations associated with the model. Limitations associated with the use of the model for northeastern St. Joseph County are described here.

Model reliability is enhanced if calibration data are available for a period when the aquifers are heavily stressed. Errors in model-parameter values generally are amplified when the flow system is modeled for transient conditions. Conditions during the 1991-92 well-measurement period could not be used to examine a period of aquifer stress because withdrawal rates at that time did not significantly stress the system. During model calibration, however, USGS investigators used water levels for several wells near SWWF's where some indication of aquifer stress might be observed.

Within the study area, the most appropriate application of results is to the area north and east of the St. Joseph River because (1) data for model parameterization and calibration were most abundant in the area north and east of the St. Joseph River, (2) the river was a permanent hydrologic boundary that was suitable as one boundary condition, and (3) the model was insensitive to the artificially established hydrologic conditions along the north and east sides of the modeled area.

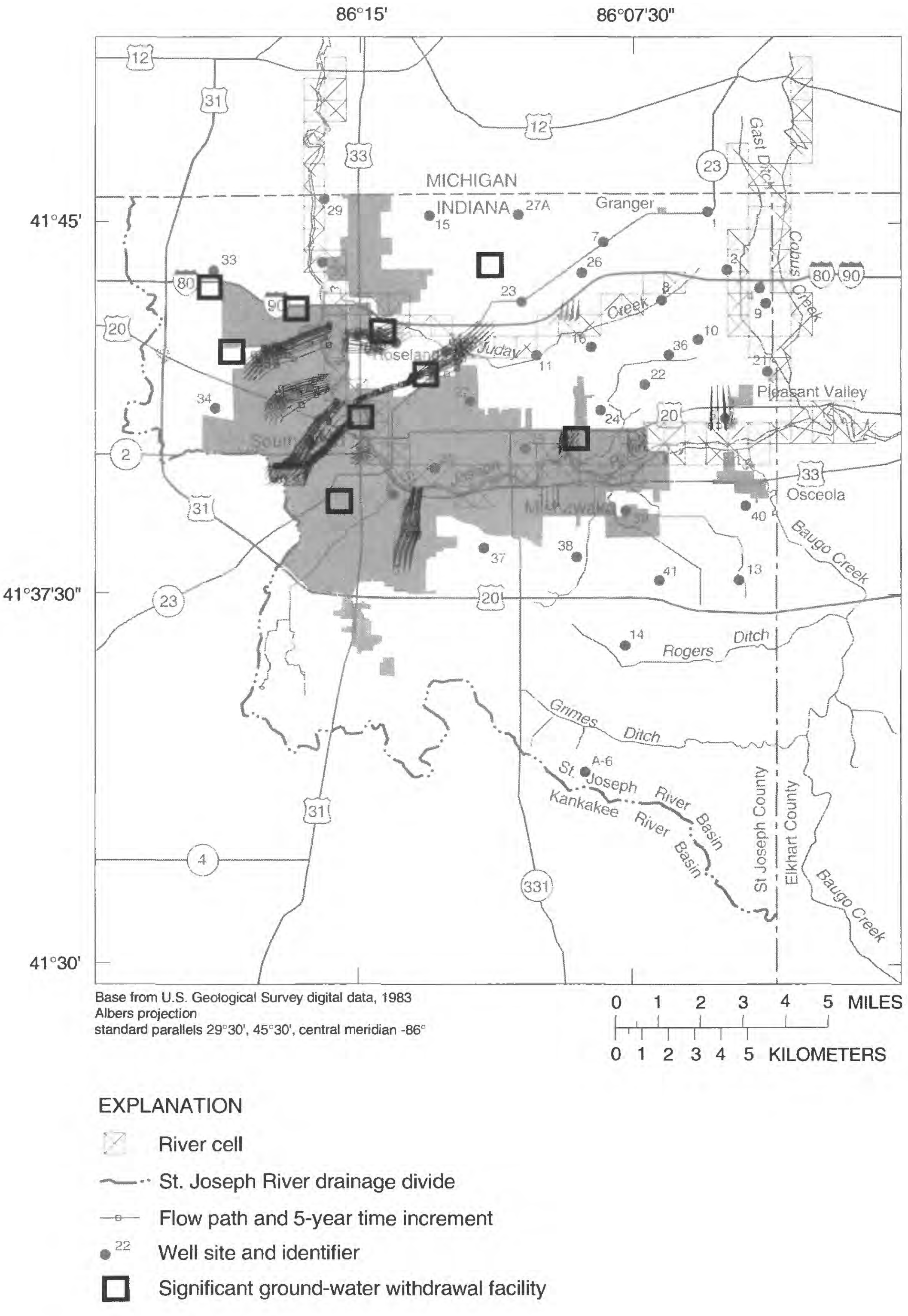


Figure 19. Flow paths from sites of contamination to points of discharge.

In general, the most appropriate application of model results is also limited to areas greater than the dimensions of one model cell (0.25 mi^2); the ground-water levels reported for each cell are calculated at the node and do not indicate the range of ground-water levels that might exist within that cell.

Assignment of boundary conditions along the north and east sides of the study area as both constant head and constant flux nodes produced no effect on either the simulated drawdown at SWWF's or the model's water-budget calculations. Simulated ground-water levels near artificial boundary conditions, however, may be less reliable than simulated ground-water levels that are distant from boundary cells.

Available data indicate that confining unit 2 is present in most parts of the modeled area. Additional lithologic data may reveal locations where the unit is absent and change the conceptual ground-water exchange between aquifers 2 and 3 in these simulations. Simulated drawdowns and flow directions might be altered at such locations.

Porosity was the only additional hydrogeologic parameter that was required for particle-tracking simulations. Porosities used for the aquifers (0.35) and confining units (0.45) in the particle-tracking analyses were reported averages for outwash and interbedded clays (Morris and Johnson, 1967, p. D29). Porosities for geologic units in the modeled area were not measured in this study or in previous investigations. Use of different porosities would not affect the size or shape of the delineated contributing area but could change the location of simulated 5-year time increments.

SUMMARY AND CONCLUSIONS

The water supply for northeastern St. Joseph County is withdrawn primarily from permeable glacial deposits that are vulnerable to contamination from human activity at land surface. To determine the source and availability of future drinking-water supplies, the USGS and the IDNR cooperatively examined the ground-water resources of a 227-mi^2 area in northeastern St. Joseph County, Ind.

The ground-water resources of northeastern St. Joseph County were investigated by collection and analysis of field data, compilation of available water-well records, and simulation of ground-water flow by use of a numerical model. Field data consisted of water-level measurements from monitoring wells, streamflow measurements at Juday Creek, and surface-geophysical measurements. About 370 well drillers' records, collected by IDNR, were combined with logs for 53 wells drilled during this study to construct isopach maps of aquifers and confining units. The isopach maps and other hydrogeologic information were used to construct and calibrate a numerical model that simulated ground-water flow. The simulations were used to determine the effect of increased withdrawals on ground-water levels, local streamflow, and ground-water-flow paths. Particle-tracking analyses were used to delineate the contributing areas for SWWF's and the discharge points for known contamination sites.

The ground-water-flow system in northeastern St. Joseph County contains three aquifer systems: the St. Joseph, the Hilltop, and the Nappanee. The St. Joseph aquifer system consists of outwash deposits that can exceed thicknesses of 200 ft. The outwash aquifers may be separated vertically by a confining unit of till or lacustrine deposits. South of the St. Joseph aquifer system are the topographically higher Hilltop and Nappanee aquifer systems. The Hilltop aquifer system consists of sand and gravel deposits overlain by 5 to 50 ft of clay-rich till. The Nappanee aquifer system consists of thin sand and gravel deposits (3 to 30 ft) contained within thicker sequences of till.

The ground-water model developed in this study represents two extensive aquifers as individual layers; the confining unit is represented by a vertical leakage term. Fifty-three measured water levels and two streamflow measurements along Juday Creek were used to help calibrate the model.

The closest agreement between simulated and measured water levels and fluxes was found with the following set of model-parameter values:

Horizontal hydraulic conductivity of the aquifers (ft/d)	275
Vertical hydraulic conductivity of the confining unit (ft/d)	0.07
Vertical hydraulic conductivity of the confining unit near the St. Joseph River (ft/d)	0.7
Vertical hydraulic conductivity of the streambed of the St. Joseph River (ft/d)	5
Vertical hydraulic conductivity of the streambed of all other streams (ft/d)...............	50
Vertical hydraulic conductivity of the stream be at the lower end of Juday Creek (ft/d)...........	0.05
Recharge rates to aquifers (in/yr)	3.7–24

This set of parameter values resulted in a mean absolute error of 5.0 ft between simulated and measured water levels. The sensitivity analyses indicated that an accurate estimate of recharge rate and horizontal hydraulic conductivity of aquifer 3 is the most critical information needed for an accurate representation of the flow system in the numerical model.

The calibrated recharge rate for the St. Joseph aquifer system is higher than that used for most ground-water systems in Indiana; additional recharge data would be required to improve confidence in the calibrated rate. If the measured recharge rate were actually lower than the calibrated rate, then ground-water availability may be less than the model simulations indicate.

The calibrated model was used to determine the effect of a 50-percent increase in pumpage at all SWWF's. Maximum simulated drawdowns, when averaged across an entire 0.25 mi^2 cell, were 6 ft in aquifer 2 and10 ft in aquifer 3. The 50-percent increase in withdrawals caused a loss of 19 ft^3/s in streamflow of the St. Joseph River and loss of 3.8 ft^3/s in streamflow of Juday Creek.

Flow paths to SWWF's at current withdrawal rates were investigated. Flow paths to wells in aquifer 3 can be as long as 12 mi, and travel times can be 50 to 100 years. Long flow paths and greater travel times were simulated at SWWF's, where aquifer 2 and aquifer 3 are separated by a confining unit and withdrawals were being made from the lower aquifer. The longer travel times and the natural filtering properties of the clay- and silt-rich confining unit may partially protect water in the lower aquifer from human-related contamination. Flow paths in aquifer 2 are typically less than 5 mi long, and travel times are usually less than 10 years. Ground water withdrawn from aquifer 2 is probably more susceptible to contamination from human activities than is water in the lower aquifer.

The flow paths of ground water that originate beneath known contamination sites and the ultimate discharge points of that ground water also were investigated. Ground water originating beneath contamination sites generally discharges to the St. Joseph River; under some conditions, however, this water may be partially captured by 8 of the 10 largest SWWF's. The flow-path analysis does not in any way describe the quality of water along the flow paths, but results may be used to locate monitoring wells intended to study the transport of constituents away from known contamination sites.

REFERENCES CITED

Anderson M.P., and Woessner, W.W., 1992, Applied groundwater modeling: San Diego, Calif., Academic Press, 381 p.

Bailey, Z.C.; Greeman, T.K.; and Crompton, J.E., 1985, Hydrologic effects of ground- and surface-water withdrawals in the Howe area, LaGrange County, Indiana: U.S. Geological Survey Water Resources Investigations Report 85-43, 130 p.

Bayless, E.R.; Westjohn, D.B.; and Watson, L.R., 1995, Use of surface and borehole geophysics to delineate the glacial-drift stratigraphy of northeastern St. Joseph County, Indiana: U.S. Geological Survey Water-Resources Investigations Report 95-4041, 63 p.

Beaty, Judith, 1987, Water resource availability in the St. Joseph River Basin, Indiana: Indiana Department of Natural Resources, Division of Water, Water Resource Assessment 87-1, 139 p.

Bergeron, M.P., 1981, Effect of irrigation pumping on the ground-water system in Newton and Jasper Counties, Indiana: U.S. Geological Survey Water-Resources Investigations Report 81-38, 73 p.

Bleuer, Ned, and Melhorn, W.N., 1989, Glacial terrain models, north-central Indiana—The application of downhole logging to analysis of glacial vertical sequences: South Bend, Ind., Notre Dame University, Geological Society of America, North-Central Section, Field Trip 2 (guidebook), 52 p.

Crompton, E.J.; Peters, J.G.; Miller, R.L.; Stewart, J.A.; Banaszak, K.J.; and Shedlock, R.J., 1986, Review of the hydrologic data-collection network in the St. Joseph River Basin, Indiana: U.S. Geological Survey Water-Resources Investigations Report 86-4157, 51 p.

Fowler, K.K., and Wilson, J.T., 1995, Characteristics, transport, and yield of sediment in Juday Creek, St. Joseph County, Indiana, 1993-94: U.S. Geological Survey Water-Resources Investigations Report 95-4135, 48 p.

Hunn, J.D., and Rosenshein, J.S., 1969, Geohydrology and ground-water potential of St. Joseph County, Indiana: Indiana Department of Natural Resources, Division of Water, Bulletin 33, 20 p.

Klaer, F.H., and Stallman, R.W., 1948, Ground-water resources of St. Joseph County, Indiana, Part 1. South Bend area: Indiana Department of Conservation Bulletin 3, 177 p.

Krumbein, W.C., and Sloss, L.L., 1951, Stratigraphy and sedimentation (2d ed.): San Francisco, Calif., W.H. Freeman and Company, 660 p.

Imbrigiotta, T.E., and Martin, Angel, Jr., 1981, Hydrologic and chemical evaluation of the ground-water resources of northwest Elkhart County, Indiana: U.S. Geological Survey Water-Resources Investigations Report 81-53, 149 p.

Lindgren, H.A.; Peters, J.G.; Cohen, D.A.; and Crompton, E.J., 1985, Hydrologic effects of ground- and surface-water withdrawals in the Milford area, Elkhart and Kosciusko Counties, Indiana: U.S. Geological Survey Water-Resources Investigations Report 85-4166, 76 p.

Malott, C.A., 1922, The physiography of Indiana, *in* Handbook of Indiana geology: Indiana Department of Conservation Publication 21, p. 59–256.

Marie, J.R., 1975, Hydraulic characteristics and water-supply potential of the aquifers in the vicinity of the wastewater treatment plant, South Bend, Indiana: U.S. Geological Survey Water-Resources Investigations 49-74, 26 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meyer, William; Reussow, J. P.; and Gillies, D. C., 1975, Availability of ground water in Marion County, Indiana: Open-File Report 75-312, 87 p.

Michiana Area Council of Governments, 1989, St. Joseph County potential groundwater contamination sites: 1 sheet, scale 1:90,000.

Morris, D. A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60: U.S. Geological Survey Water-Supply Paper 1839-D, 42 p.

REFERENCES CITED—Continued

Newman, J.E., 1981, Weekly water-use estimates by crops and natural vegetation in Indiana: West Lafayette, Ind., Purdue University, Agricultural Experiment Station Bulletin 344, 26 p.

Peters, J.G., 1987, Description and comparison of selected models for hydrologic analysis of ground-water flow, St. Joseph River Basin, Indiana: U.S. Geological Survey Water-Resources Investigations Report 86-4199, 125 p.

Peters, J.G., and Renn, D.E., 1988, Effects of agricultural irrigation on water resources in the St. Joseph River Basin, Indiana, and implications for aquifer yield: U.S. Geological Survey Water-Resources Investigations Report 87-4273, 35 p.

Pettijohn, R.A., 1968, Reconnaissance of the ground-water resources of the St. Joseph River Basin in Indiana, Appendix to the State water plan of the Division of Water: U.S. Geological Survey, 32 p.

Planert, Michael, 1980, Ground-water availability near Fort Wayne, Allen County, Indiana: U.S. Geological Survey Water-Resources Investigations 80-34, 54 p.

Pollock D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Reussow, J.P., and Rohne, P.B., Jr., 1975, Water resources of the St. Joseph River Basin in Indiana: U.S. Geological Survey Hydrologic Investigations Atlas HA-537, 3 sheets, scales 1:500,000 and 1:250,000.

Rosenshein, J.S., and Hunn, J.D., 1962, Ground-water resources of northwest Indiana, preliminary report—St. Joseph County: Indiana Department of Conservation Bulletin 15, 318 p.

Schneider, A.F., and Keller, S.J., 1970, Geologic map of the 1° x 2° Chicago quadrangle, Indiana, Illinois, and Michigan, showing bedrock and unconsolidated deposits: Indiana Department of Natural Resources, Geological Survey Regional Geologic Map 4, 1 sheet, scale 1:250,000.

Shaver, R.H.; Ault, C.H.; Burger, A.M.; Carr, D.D.; Droste, J.B.; Eggert, D.L;, Gray, H.H.; Harper, Denver; Hasenmueller, N.R.; Hasenmueller, W.A.; Horowitz, A.S.; Hutchison, H.C.; Keith, B.D.; Keller, S.J.; Patton, J.B.; Rexroad, C.B.; and Wier, C.E. 1986, Compendium of paleozoic rock-unit stratigraphy in Indiana—A revision: Indiana Department of Natural Resources, Geological Survey Bulletin 59, 203 p.

Thornbury, W.D., 1969, Principles of geomorphology (2d ed.): New York, John Wiley and Sons, 549 p.

U.S. Geological Survey, 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

SUPPLEMENTAL DATA

Table 1. Ground-water levels measured in northeastern St. Joseph County, Indiana, water years 1991–92

[All water levels and land-surface elevations in feet above sea level; *, dry well; --, no measurement]

Date measured	Well number (land-surface elevation)							
	1-25 (800.12)	1-85 (800.14)	1-173 (799.83)	2-25 (779.21)	2-139 (778.19)	4-25 (775.36)	5-33 (753.12)	5-70 (751.61)
01/25/91	786.62	--	--	773.32	--	768.04	--	--
06/07/91	787.08	--	--	773.30	--	767.75	--	--
07/25/91	785.96	--	--	772.16	--	765.94	725.08	725.30
07/31/91	785.77	--	--	772.02	--	765.77	724.91	725.13
08/01/91	--	--	--	--	--	--	--	--
10/05/91	784.98	784.95	784.99	773.73	772.47	--	--	--
10/06/91	--	--	--	--	--	--	724.24	724.48
10/07/91	--	--	--	--	--	--	--	--
12/02/91	786.06	786.04	786.07	773.74	772.47	767.77	725.28	725.53
12/03/91	--	--	--	--	--	--	--	--
01/14/92	785.94	785.91	785.96	773.19	771.93	767.13	725.32	725.57
01/16/92	--	--	--	--	--	--	--	--
02/16/92	785.62	785.59	785.63	773.32	772.06	766.91	725.04	725.29
03/19/92	785.74	785.72	785.75	773.19	771.92	766.96	724.94	725.18
04/20/92	785.97	785.94	785.97	773.21	771.97	769.14	725.06	725.32
07/14/92	784.58	784.55	784.52	772.17	770.75	765.76	724.34	724.56
11/04/92	784.76	784.73	784.82	773.75	772.48	767.19	724.44	724.67
11/05/92	--	--	--	--	--	--	--	--
	5-133 (749.66)	7-33 (793.99)	8-22 (765.75)	8-148 (765.74)	9-25 (770.46)	9-99 (770.47)	10-18 (765.02)	10-103 (765.16)
01/25/91	723.46	--	--	--	766.76	--	--	--
06/07/91	722.31	--	--	--	766.62	--	--	--
07/25/91	721.53	777.11	759.89	--	764.62	--	--	--
07/31/91	721.40	776.98	--	--	764.48	--	--	--
08/01/91	--	--	--	--	--	--	760.85	--
10/05/91	--	775.87	761.98	762.25	766.30	766.34	764.37	764.46
10/06/91	721.10	--	--	--	--	--	--	--
10/07/91	--	--	--	--	--	--	--	--
12/02/91	721.88	776.41	760.72	761.25	766.67	766.73	762.88	762.94
12/03/91	--	--	--	--	--	--	--	--
01/14/92	721.94	776.53	760.54	760.97	765.99	766.05	762.39	762.44
01/16/92	--	--	--	--	--	--	--	--
02/16/92	721.74	776.16	760.87	761.17	766.01	766.07	763.12	763.18
03/19/92	721.65	776.10	760.58	760.98	765.95	766.02	762.52	762.57
04/20/92	721.81	776.19	760.64	761.01	766.02	766.08	762.91	762.97
07/14/92	721.15	775.27	760.41	760.58	764.65	764.85	762.00	762.05
11/04/92	721.22	774.97	760.99	761.35	766.50	766.55	763.60	763.66
11/05/92	--	--	--	--	--	--	--	--

Table 1. Ground-water levels measured in northeastern St. Joseph County, Indiana, water years 1991–92—Continued

Date measured	Well number (land-surface elevation)							
	11-37 (754.72)	11-95 (754.51)	13-23 (766.37)	14-135 (844.20)	15-35 (751.56)	15-130 (751.18)	16-28 (753.83)	16-173 (753.92)
01/25/91	742.56	742.64	--	--	--	--	--	--
06/07/91	742.64	742.40	--	--	--	--	--	--
07/25/91	741.45	741.02	751.55	--	--	--	742.22	--
07/31/91	--	--	--	--	--	--	--	--
08/01/91	741.33	740.91	--	--	734.63	--	--	--
10/05/91	--	--	--	--	--	--	741.63	717.02
10/06/91	741.20	741.18	750.05	--	--	--	--	--
10/07/91	--	--	--	774.86	734.49	734.51	--	--
12/02/91	741.76	742.23	751.28	775.38	735.20	735.23	743.51	718.39
12/03/91	--	--	--	--	--	--	--	--
01/14/92	--	741.59	751.51	775.46	735.19	735.06	742.98	718.58
01/16/92	--	--	--	--	--	--	--	--
02/16/92	740.95	741.41	751.42	775.05	734.86	734.88	742.65	718.27
03/19/92	740.98	741.44	751.86	775.14	734.91	734.94	742.90	718.05
04/20/92	741.33	741.33	752.23	775.59	735.02	735.05	743.07	718.47
07/14/92	740.57	740.55	750.48	788.53	733.80	733.93	742.11	716.87
11/04/92	740.77	740.77	750.09	787.57	734.48	734.51	741.83	717.66
11/05/92	--	--	--	--	--	--	--	--
	21-23 (758.04)	21-133 (757.79)	22-30 (756.68)	22-148 (756.15)	23-55 (790.51)	23-133 (790.31)	24-22 (746.93)	25-38 (741.82)
01/25/91	--	--	750.10	--	--	--	737.98	--
06/07/91	--	--	748.74	--	--	--	737.60	--
07/25/91	747.25	--	--	--	754.30	--	734.94	709.69
07/31/91	747.10	--	--	--	754.13	--	--	--
08/01/91	--	--	747.09	--	--	--	--	--
10/05/91	--	--	--	--	753.90	753.96	--	--
10/06/91	747.57	747.32	747.15	723.47	--	--	735.18	709.01
10/07/91	--	--	--	--	--	--	--	--
12/02/91	748.59	748.36	749.35	724.63	753.39	753.52	737.64	709.03
12/03/91	--	--	--	--	--	--	--	--
01/14/92	748.15	747.93	--	--	752.90	753.02	736.54	708.77
01/16/92	--	--	748.58	724.65	--	--	--	--
02/16/92	747.97	747.72	748.33	724.44	752.67	752.98	736.32	708.58
03/19/92	748.01	747.77	748.70	724.25	753.04	753.17	736.91	708.49
04/20/92	748.01	747.77	748.70	724.25	753.04	753.17	736.91	708.49
07/14/92	747.16	746.90	747.29	723.30	752.02	752.07	735.08	708.46
11/04/92	747.91	747.71	747.69	723.87	751.32	751.62	735.61	708.22
11/05/92	--	--	--	--	--	--	--	--

Table 1. Ground-water levels measured in northeastern St. Joseph County, Indiana, water years 1991–92—Continued

Date measured	Well number (land-surface elevation)							
	26-30 (785.75)	27-28 (743.37)	27A-60 (829.32)	27A-148 (829.47)	29-68 (697.19)	30-29 (695.88)	30-148 (696.22)	31-23 (733.17)
01/25/91	--	--	*	--	--	--	--	--
06/07/91	--	--	*	--	--	--	--	--
07/25/91	766.64	733.00	*	--	--	--	--	--
07/31/91	--	--	*	--	--	--	--	--
08/01/91	--	--	*	--	--	--	--	726.60
10/05/91	765.42	--	*	--	--	--	--	726.45
10/06/91	--	732.40	*	--	--	--	--	--
10/07/91	--	--	*	767.72	687.94	--	674.26	--
12/02/91	766.18	733.71	*	767.99	--	--	--	726.99
12/03/91	--	--	*	--	688.34	675.25	674.95	--
01/14/92	765.95	733.05	*	767.88	688.02	674.86	674.92	726.75
01/16/92	--	--	*	--	--	--	--	--
02/16/92	765.60	732.64	*	767.64	688.10	674.64	674.64	726.62
03/19/92	765.52	732.87	*	767.50	688.16	674.85	674.84	726.68
04/20/92	765.60	733.20	*	767.32	688.30	674.80	675.42	726.88
07/14/92	764.70	732.55	*	765.81	687.43	673.63	673.78	726.07
11/04/92	764.44	732.00	*	766.43	--	--	--	726.45
11/05/92	--	--	*	--	688.43	674.47	674.53	--
	31-138 (732.89)	32-148 (730.55)	33-65 (783.10)	34-33 (733.24)	35-52 (716.67)	36-168 (760.15)	37-150 (902.62)	38-50 (763.98)
01/25/91	--	--	--	--	--	--	--	--
06/07/91	--	--	--	--	--	--	--	--
07/25/91	--	--	730.78	707.26	690.39	--	--	734.97
07/31/91	--	--	--	--	690.32	--	--	--
08/01/91	--	--	730.85	707.15	--	--	--	--
10/05/91	715.45	705.20	--	--	--	723.61	--	--
10/06/91	--	--	--	--	--	--	--	--
10/07/91	--	--	730.59	706.46	689.01	--	--	733.85
12/02/91	716.38	706.06	--	--	689.66	724.94	--	734.14
12/03/91	--	--	730.56	706.80	--	--	--	--
01/14/92	716.74	706.53	730.12	706.57	689.84	725.10	--	734.18
01/16/92	--	--	--	--	--	--	--	--
02/16/92	716.44	705.95	730.08	706.30	689.59	724.78	--	734.00
03/19/92	716.33	705.86	730.03	706.29	689.79	724.58	750.85	734.15
04/20/92	716.58	706.37	729.07	706.43	690.04	725.01	749.92	734.38
07/14/92	714.99	704.60	--	705.81	688.93	723.49	750.53	733.67
11/04/92	715.85	705.74	--	--	689.27	724.34	--	733.28
11/05/92	--	--	728.37	705.69	--	--	--	--

Table 1. Ground-water levels measured in northeastern St. Joseph County, Indiana, water years 1991–92—Continued

Date measured	Well number (land-surface elevation)				
	39-25 (735.10)	40-78 (736.31)	41-23 (764.98)	42-33 (713.33)	A6-149 (851.78)
01/25/91	728.43	--	--	--	--
06/07/91	728.73	--	--	--	--
07/25/91	727.45	--	754.99	690.54	--
07/31/91	--	--	--	--	--
08/01/91	--	--	--	--	--
10/05/91	--	--	--	--	--
10/06/91	--	721.89	755.01	--	--
10/07/91	728.08	--	--	690.41	--
12/02/91	729.43	723.06	755.32	690.57	792.17
12/03/91	--	--	--	--	--
01/14/92	728.61	722.56	755.06	690.45	792.61
01/16/92	--	--	--	--	--
02/16/92	728.58	722.45	755.30	690.45	792.48
03/19/92	728.69	722.55	755.39	690.45	792.51
04/20/92	728.61	722.75	755.49	690.51	792.46
07/14/92	727.54	721.71	754.85	690.75	792.06
11/04/92	728.76	721.98	754.93	691.12	791.84
11/05/92	--	--	--	--	--

Table 2. Ground-water-withdrawal site numbers, geographic locations, model cell locations, 1993 ground-water withdrawals, and withdrawal capacities, northeastern St. Joseph County, Indiana

[UTMN, Universal Transverse Mercator northing; UTME, Universal Transverse Mercator easting; gal/yr, gallons per year; gal/min, gallons per minute]

Site number	Geographic location		Model			1993 withdrawal (1,000 gal/yr)	Withdrawal capacity (gal/min)
	UTMN	UTME	Row	Column	Layer		
1	4612740	570550	19	23	3	76,737	146
2	4612925	570525	19	23	3	1,871,615	1,050
3	4611450	569975	18	22	3	217,359	750
4	4611525	570050	18	22	3	80,008	1,000
5	4613500	572950	17	25	3	167,760	750
6	4613450	572950	17	25	3	168,770	750
7	4614500	565750	17	17	3	2,039	638
8	4615125	565950	17	17	3	8,250	955
9	4612750	569050	18	21	3	9,674	85
10	4611825	568550	19	20	3	60,000	1,000
11	4614525	558650	16	8	2	115,630	80
12	4613925	573425	17	26	3	18,575	2,000
13	4614005	573425	17	26	3	22,872	2,000
14	4616175	557525	15	7	3	1,118,501	1,388
15	4615350	565525	16	16	3	1,775,650	2,777
16	4617975	560550	13	10	2	1,361,886	2,604
17	4610975	560850	21	11	3	5,986	1,042
18	4609475	561875	22	12	3	740,323	1,388
19	4620250	565350	10	16	3	200,837	400
20	4619050	557475	12	6	3	1,032,965	2,000
21	4615525	558850	15	8	2	44,240	600
22	4615600	558850	15	8	2	36,340	600
23	4614175	572375	24	16	2	2,133	150
24	4612920	576390	18	30	3	2,189	235
25	4622700	573105	8	25	2	1,740	100
26	4606525	572175	25	25	3	3,552	200
27	4614690	574395	18	28	3	4,500	300
28	4614315	574505	17	27	3	21,610	165
29	4614480	574000	16	27	3	2,635	200
30	4622750	562950	8	13	2	24,816	239
31	4622250	563250	8	13	2	2,239	75
32	4619350	562825	11	13	3	520	100
33	4615700	557500	15	6	3	880	150
34	4619400	556700	12	6	3	3,000	150
35	4622900	560850	8	11	2	670	55
36	4621300	569425	9	21	2	15,000	1,000
37	4621750	570425	9	22	2	15,000	1,000
38	4616800	575000	14	28	3	1,232	500
39	4622550	567150	8	18	3	40,320	800
40	4622525	567425	8	18	3	72,225	300
41	4622950	568200	8	19	3	50,400	1,000
42	4609700	572500	25	25	3	13,500	500
43	4610025	571575	24	24	3	8,610	500
44	4613100	577675	20	32	3	3,739	100
45	4617080	563700	14	14	3	145,272	1,000
46	4617150	563810	14	14	3	228,686	1,000
47	4616520	563820	14	14	3	313	650
48	4616370	563100	15	13	3	12,275	600
49	4616925	563220	14	14	3	75,905	500
50	4616975	563100	14	13	3	29,601	1,300
51	4614000	560000	19	9	3	152,340	349

Table 2. Ground-water-withdrawal site numbers, geographic locations, model cell locations, 1993 ground-water withdrawals, and withdrawal capacities, northeastern St. Joseph County, Indiana—Continued

Site number	Geographic location UTMN	Geographic location UTME	Model Row	Model Column	Model Layer	1993 withdrawal (1,000 gal/yr)	Withdrawal capacity (gal/min)
52	4608930	571920	26	24	3	2,401	100
53	4621125	568350	9	20	3	77,580	1,400
54	4621750	569875	9	21	2	114,930	1,500
55	4621520	572975	9	25	2	27	224
56	4621520	573025	9	25	2	360	1,503
57	4621450	573075	9	25	2	625	80
58	4601520	563900	27	15	2	59	50
59	4605525	568400	26	20	3	1,912	100
60	4618550	567825	12	19	2	1,795	499
61	4618550	567400	12	19	2	1,127	150
62	4619000	567510	12	19	2	168	55
63	4619100	570300	11	22	2	92,236	275
64	4619250	570375	11	22	2	145,457	300
65	4619625	568100	11	19	2	301,749	1,250
66	4619875	568030	11	19	2	371,858	1,000
67	4621575	573325	9	26	2	89,941	190
68	4621575	573400	9	26	2	88,532	108
69	4621525	573450	9	26	2	156,586	360
70	4622050	573650	10	26	2	53,492	120
71	4622100	573650	10	26	2	58,716	100
72	4622050	573550	10	26	2	65,985	100
73	4622275	573660	10	26	2	45,358	100
74	4622350	573650	10	26	2	40,709	75
75	4622350	573650	10	26	2	26,328	75
76	4622250	573590	10	26	2	35,640	75
77	4622250	573500	10	26	2	35,640	75
78	4622400	573450	10	26	2	37,852	75
79	4618700	567910	12	19	2	154	195
80	4618999	567900	12	19	2	16	105
81	4618910	567720	12	19	2	23,564	525
82	4618750	567625	12	19	2	153	105
83	4620075	577900	10	31	2	387	154
84	4607300	564800	23	27	2	10,676	101
85	4613750	561975	20	12	2	79,056	150
86	4606125	565625	26	17	3	38	46
87	4606050	565550	26	17	3	1	254
88	4622675	573600	9	27	2	2,694	42
89	4622750	573650	8	27	2	991	27
90	4622800	573675	8	27	2	991	27
91	4622300	573290	9	26	3	967	65
92	4622375	573290	8	26	3	67	75

☆ U.S. GOVERNMENT PRINTING OFFICE: 1996—747-764