HYDROLOGIC EFFECTS OF GROUND- AND SURFACE-WATER WITHDRAWALS IN THE HOWE AREA, LAGRANGE COUNTY, INDIANA

By Zelda Chapman Bailey, Theodore K. Greeman, and E. James Crompton

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ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

FACTORS FOR CONVERTING THE INCH-POUND UNITS TO METRIC

(INTERNATIONAL SYSTEM) UNITS

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare
inch per year (in./yr)	2.54	centimeter per year (cm/a)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
gallon per day (gal/d)	3.785	liter per day (L/d)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
million gallons (Mgal)	3,785.	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/yr)	3,785.	cubic meter per year (m^3/a)

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

(0.556) (°F -32°) = °C

HYDROLOGIC EFFECTS OF GROUND- AND SURFACE-WATER WITHDRAWALS IN THE HOWE AREA, LAGRANGE COUNTY, INDIANA

By Zelda Chapman Bailey, Theodore K. Greeman and E. James Crompton

ABSTRACT

Geometry and hydraulic characteristics of a 46.5-square-mile area of the sand and gravel outwash-aquifer system between Fawn and Pigeon Rivers in Lagrange County were defined in a study of the effect of current and potential uses of water on the aquifer, streams, lakes, and wetlands. There are three aquifers: Aquifer 1, a surficial water-table aquifer, ranges from 10 to 60 feet in thickness; its hydraulic conductivity averages 210 ft/d (feet per day), and transmissivity ranges from 5,000 to 16,000 ft^2/d (feet squared per day). Aquifers 1 and 2 are separated by an extensive clay layer that ranges from zero to 50 feet in thickness. Aquifer 2 ranges from 50 to 110 feet in thickness; its hydraulic conductivity averages 360 ft/d, and transmissivity ranges from 5,000 to 35,000 ft^2/d. Aquifer 3 is distinguished from aquifer 2 by a higher clay content. Aquifer 3 ranges from zero to 200 feet in thickness; its hydraulic conductivity averages 25 ft/d, and transmissivity ranges from zero to 5,000 ft^2/d.

A three-layer digital flow model was calibrated to steady-state water levels during autumn 1982. The effects of current and potential development of irrigation on the ground-water and surface-water systems were estimated by transient simulations of five pumping plans. The effect of year-round pumping was estimated by steady-state simulation of a sixth plan.

Plan 1 was a simulation of current irrigational development with pumpage equal to that which supplied water to crops in 1982. Maximum simulated drawdowns were 4 feet in layer 1 and 14 feet in layers 2 and 3. Simulated drawdowns were greater than those observed in 1982.

Plans 2 and 3 were simulations of the current irrigational development with pumping rates that would supply water to crops in a normal and in a dry year. Extent and magnitude of drawdown resulting from each plan are only slightly greater than that for plan 1, and ground-water discharge to streams was reduced only slightly. The effect on the hydrologic system by pumping in plans 2 and 3, therefore, is minimal.

Plans 4 and 5 were simulations of maximum potential irrigational development that would supply water to a corn crop during a normal and a dry year. The maximum simulated drawdowns for plan 4 were 14, 30, and 31 feet in aquifers 1, 2, and 3, respectively. Maximum drawdowns for plan 5 were 15, 32, and 31 feet in aquifers 1, 2, and 3. The decrease in ground-water seepage to streams simulated in plans 4 and 5 is 2 to 3 times that in plans 2 and 3. However, the effect on water levels in the aquifer and streams was mitigated by water induced from aquifer storage.

A result of plan 6, which simulated maximum potential ground-water pumping at steady state, was a decrease in water levels in the aquifers, lakes, and wetlands. Maximum simulated drawdowns in aquifers 1, 2, and 3 were 38, 46, and 45 feet, respectively. Loss of ground-water seepage to streams because of pumping resulted in a decrease in streamflow to nearly the 7-day, 10-year low flow.

INTRODUCTION

St. Joseph River Basin Project

The Indiana Department of Natural Resources was mandated (Indiana Code 13-2-6.1, 1983 Indiana General Assembly) to begin a comprehensive evaluation of availability and current uses of water, as well as future needs. The Department selected the 1,800-square-mile Indiana part of the St. Joseph River basin (fig. 1) as a high-priority area to study. Intensive agricultural irrigation in northeastern Indiana will probably more than double by the year 2000 (Clark, 1980, p. 179).

The purpose of the 4-year St. Joseph River Basin project was to assist the Indiana Department of Natural Resources in development of management tools in two ways: The first way was to apply several methods of hydrologic analysis to areas of potential problems. Two areas (fig. 1), one in Lagrange County, Ind., and St. Joseph and Branch Counties, Mich. (Howe area), and the other in Elkhart and Kosciusko Counties, Ind. (Milford area) were selected for intensive study because they are representative of other areas of potential problems. The second way was to evaluate the current hydrologic-data network in the basin. Improvements for the network have been suggested to the Department of Natural Resources.

A digital ground-water model was developed in the Milford area, and hydrologic-analysis methods other than a digital model were applied to aquifers in both the Milford and Howe areas. This report documents the results of the hydrologic study in which a digital ground-water model for the Howe area was used.

Purpose and Scope of the Howe Area Study

The purpose of studying the Howe area was to (1) describe the hydrologic system, (2) evaluate the effect of current water use on the system, (3) determine the effect of possible future increases in the current rate of use and (4) determine the effect of possible future increases in the distribution and rate of use. This report provides information and techniques to the Indiana Department of Natural Resources for use in managing the water resources of this and similar outwash systems in the St. Joseph River basin.

The 46.5-square-mile area of study is at the northern edge of Lagrange County, Ind. and extends into St. Joseph and Branch Counties, Mich. (fig. 2). Fawn and Pigeon Rivers are the northern and southern boundaries. The eastern and western boundaries were arbitrarily chosen to include an area of irrigation between the rivers. This area was selected because of the opportunity to evaluate the effects of intensive pumping of surface water and ground water on rivers, lakes, wetlands, and the outwash aquifer. The evaluation included mapping the geometry and lithology of the aquifer, defining the ground-water- and surface-water-flow systems and their interaction, and examining the total water budget.

Previous Studies

General hydrologic studies of the St. Joseph River basin or of the part of the basin within Indiana have been made by Pettijohn (1968), Hunn and Rosenshein (1969), and Reussow and Rohne (1975). However, no detailed study has been made in the area around Howe, and only general information can be extrapolated from the basinwide reports. Pettijohn (1968) discussed the different types of aquifers in the Indiana part of the basin. He also summarized the geometry and the transmissivity of the sand and gravel aquifers as well as the rate of recharge to these aquifers in outwash plains, preglacial valleys, kames, eskers, till, and lake sediments. Most useful to the study around Howe were Pettijohn's estimates of recharge to outwash aquifers through various surficial materials, including soil, dune sand, till or lake clay, and kames and eskers. In their discussion of the geologic and hydrologic characteristics of aquifers in St. Joseph County (fig. 1), Hunn and Rosenshein (1969) divided the glacial drift into four units and described the geometry, lithology, and quality of water. In addition, they estimated transmissivity, storage coefficient, and recharge for each unit. A hydrologic atlas by Reussow and Rohne (1975) contains generalized maps on ground water and surface water in the Indiana part of the basin. Water-budget maps containing data on precipitation, runoff, and evapotranspiration were the most useful for the current study.

Acknowledgments

This project was a cooperative effort of the U.S. Geological Survey and the Indiana Department of Natural Resources. Two divisions of the Department provided information and data necessary for the study. The Division of Water updated an inventory of irrigation wells, provided drillers' lithologic logs of high-production wells, and mapped irrigable soils and uses of land. This Division also provided suggestions and advice to the project's staff at each stage of the study. The Division of Fish and Wildlife aerially photographed the area and mapped the wetlands.

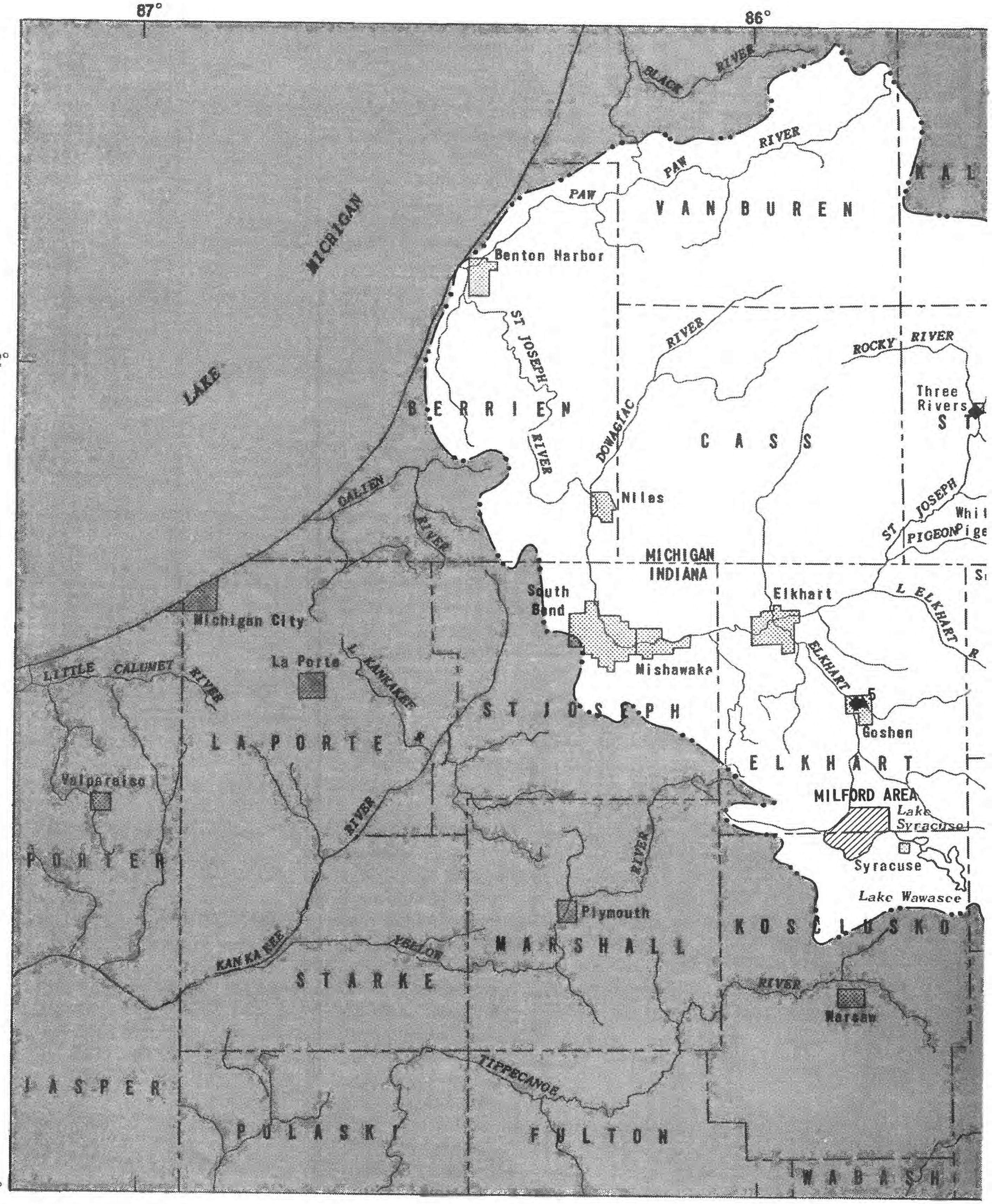
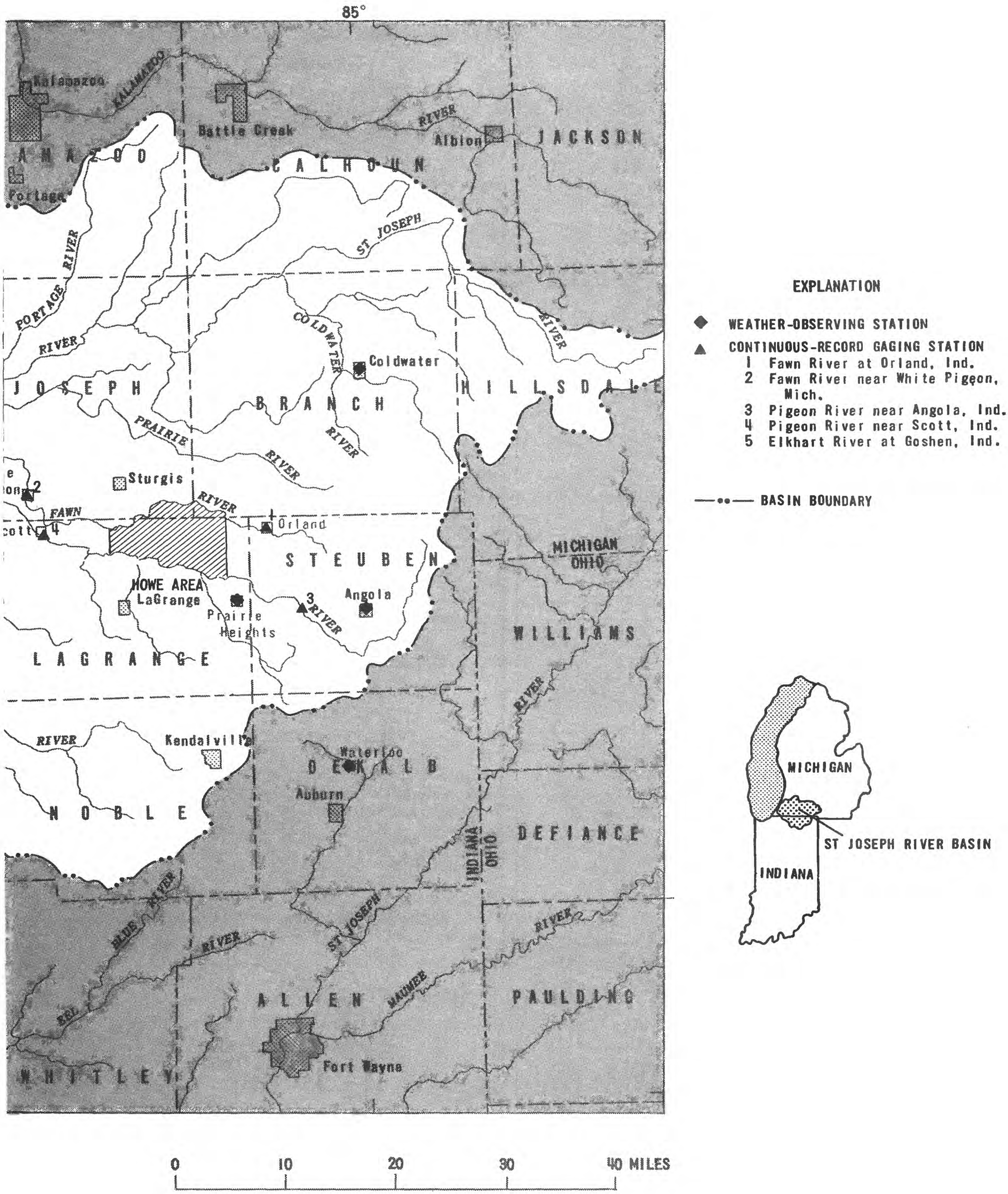


Figure 1.-- St. Joseph River basin.


85°
Kalamazoo
KALAMAZOO
Battle Creek
Albion
JACKSON
CALHOUN
Portage
PORTAGE RIVER
ST JOSEPH
COLDWATER
Coldwater
RIVER
JOSEPH
BRANCH
HILLSDALE
PRAIRIE
RIVER
Sturgis
FAWN
RIVER
Orland
STEUBEN
MICHIGAN
OHIO
HOWE AREA
LaGrange
Prairie Heights
Angola
WILLIAMS
LAGRANGE
Kendallville
Waterloo
DEKALB
Auburn
NOBLE
DEFIANCE
INDIANA
OHIO
BLUE RIVER
EEL
ST JOSEPH
MAUMEE
ALLEN
PAULDING
Fort Wayne
WHITLEY
EXPLANATION
WEATHER-OBSERVING STATION
CONTINUOUS-RECORD GAGING STATION
1 Fawn River at Orland, Ind.
2 Fawn River near White Pigeon, Mich.
3 Pigeon River near Angola, Ind.
4 Pigeon River near Scott, Ind.
5 Elkhart River at Goshen, Ind.
BASIN BOUNDARY
MICHIGAN
ST JOSEPH RIVER BASIN
INDIANA
0
10
20
30
40 MILES

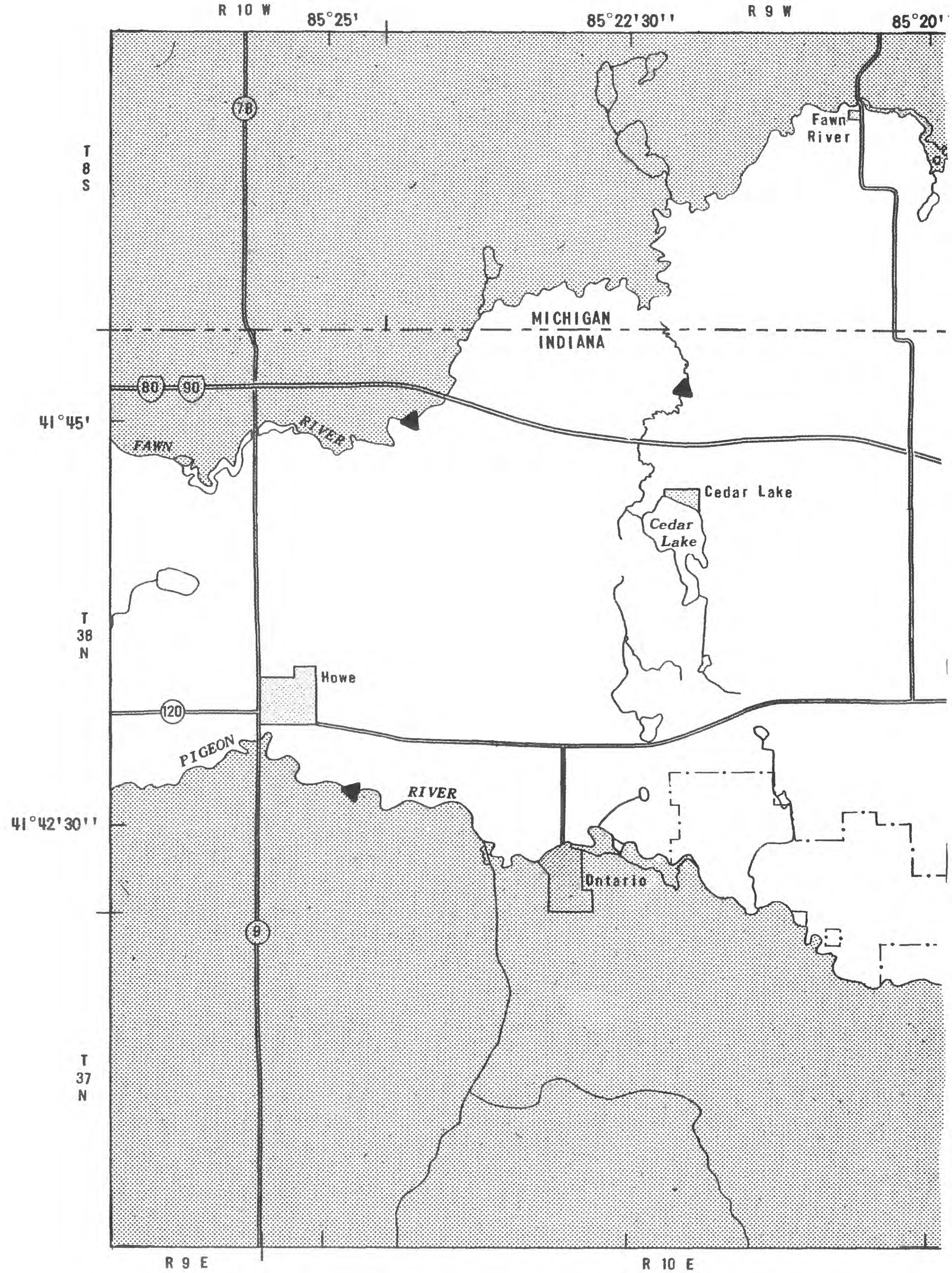
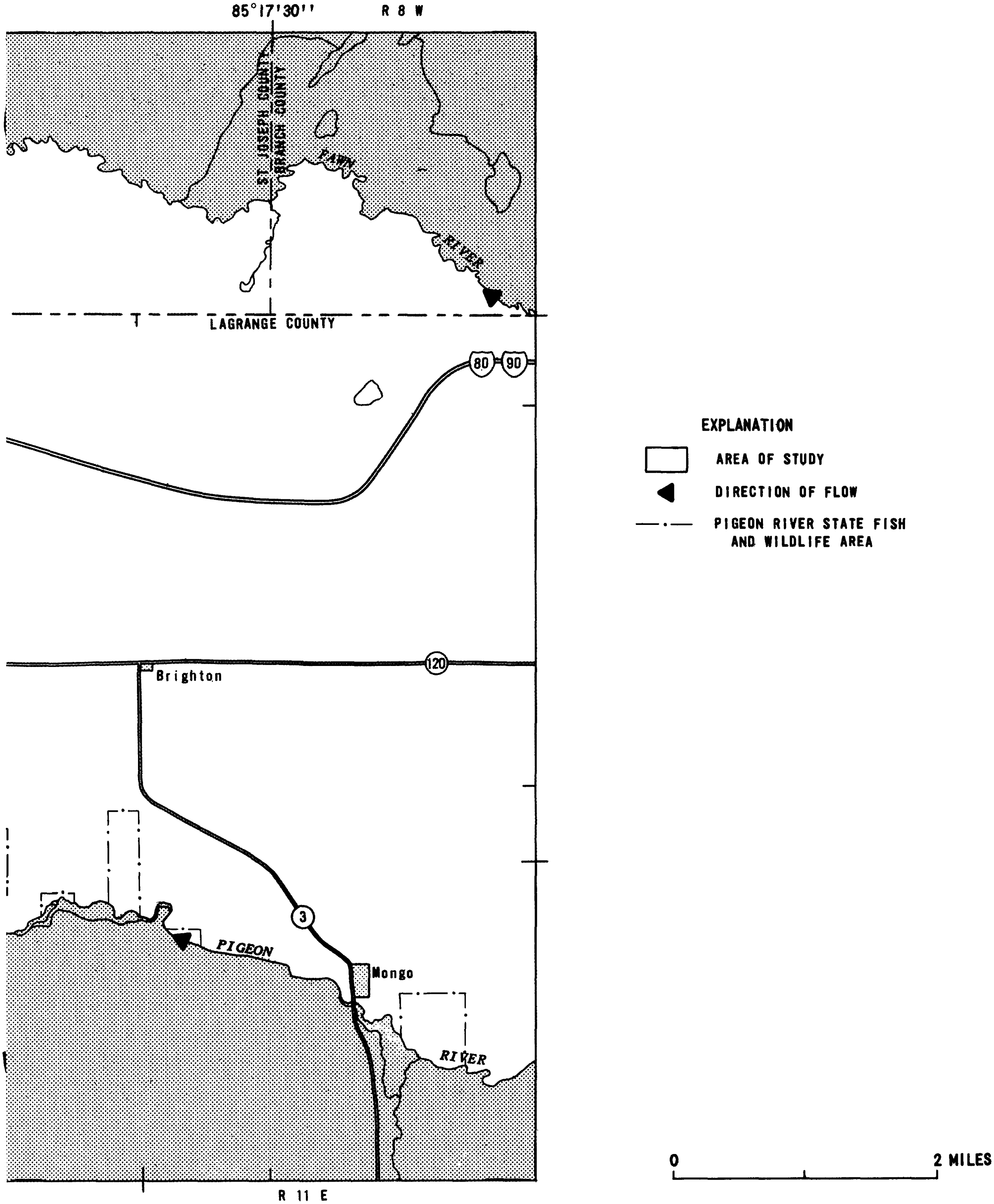


Figure 2.-- Area of study.


85°17'30''
R 8 W
ST. JOSEPH COUNTY
BRANCH COUNTY
PAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
PIGEON
Mongo
RIVER
R 11 E
EXPLANATION
AREA OF STUDY
DIRECTION OF FLOW
PIGEON RIVER STATE FISH AND WILDLIFE AREA
0
2 MILES

Dr. Daniel Wiersma, retired chairperson of the Indiana Water Resources Institute at Purdue University, and Dr. Rolland Wheaton, agricultural engineer at Purdue University, provided technical guidance on agricultural irrigation. Dr. Wheaton wrote a program for estimating water requirements for irrigation.

Dale Redding, agricultural extension agent for Lagrange County, coordinated activities and meetings between the project's staff and the irrigators.

Lithologic logs were provided by Peerless Midwest, Inc.,* Granger, Ind. and Reid and Sons, Inc., Howe, Ind. Information on bench marks, yields of wells, and sewage was provided by the Indiana Toll Road Commission, South Bend, Ind.

Charles Phillips of Phillips and Sons Irrigation Co., Bristol, Ind. and James Fizel of J. and J. Irrigation Co., Lagrange, Ind. provided technical information on irrigational equipment.

Twenty-seven irrigators in Lagrange County permitted their irrigational pumps to be monitored and observation wells to be drilled on their property. Several irrigators collected field data during the 1982 irrigational season. Without this support, much of the data necessary for the study could not have been collected.

APPROACH

Subsurface geometry and lithology were initially mapped using lithologic logs of 200 wells. Final maps incorporated data from an additional 50 test holes drilled in autumn 1981. Forty-eight of the test holes were used as observation wells after installation of 2-in. steel or 4-in. plastic casing. Natural-gamma logs of the 48 observation wells were recorded to distinguish zones of clay and silt within the sand and gravel.

The bedrock surface was mapped using data from lithologic logs of six of the test holes drilled to bedrock and seismic-refraction data provided by the Indiana Geological Survey. A map of the thickness of unconsolidated deposits (Gray, 1983) was used to supplement the sparse data south of Pigeon River.

In addition to the 48 observation wells, two continuous-record observation wells installed before the study and one domestic well were used to monitor water levels (fig. 3). Potentiometric maps were constructed from water-level data collected from these 51 wells in spring and autumn of 1982.

Nine of the observation wells drilled for the study, in addition to the two continuous-record wells, were equipped with continuous water-level recorders. These 11 wells were used to monitor water-level fluctuations during the 1982 water year (October 1981 to October 1982).

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*Use of trade and firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Clusters of two to four wells were installed at various depths to measure vertical head gradients at 13 locations. Of these 13 clusters, 4 are located around Cedar Lake, 2 are along the eastern boundary of the study area, 1 is near the western boundary, and 6 are distributed between Cedar Lake and the eastern boundary.

Surface-water elevations were measured at 33 sites in spring and autumn 1982. Stream discharge was also measured at 24 sites (fig. 3) in autumn 1982 to determine the amount of ground-water seepage to the streams.

Sixty-three high-production pumps draw surface water and ground water (fig. 3). Fifty-six pumps are used for agricultural irrigation during the irrigational season (generally June through August). Forty-three of these pumps draw from ground water, and 13 draw from surface water (table 1). Seven of the 63 pumps draw water for nonagricultural use year round -- 6 from wells and 1 from a stream.

Table 1.--Sources and uses of water

Use of water	Source	Number of pumps
Agricultural irrigation	Surface water:	
	Fawn River	6
	Pigeon River	3
	Cedar Lake (inlet and outlet)	4
	Ground water	43
Nonagricultural	Surface water	1
	Ground water	6
Total		63

The flow rates of 51 pumps were measured during 1982 by a Clampitron portable flow meter. Flow rates for the remaining pumps were estimated by well owners. Time totalizers installed on the irrigation pumps recorded accumulated time of operation during 1982. Estimates of acres irrigated by each system were obtained from irrigators and installers of the pumps. Pumpage for each system in 1982 was calculated from flow rate, total time of operation, and acreage that was irrigated.

Land-use categories for Indiana were delineated from aerial photographs by the Indiana Department of Natural Resources. The area of each category was measured with a computer digitizer by the U.S. Geological Survey.

A three-dimensional, digital ground-water-flow model was constructed to simulate the flow system and to determine the effects of current and simulated pumping on streams, lakes, wetlands, and ground-water levels.

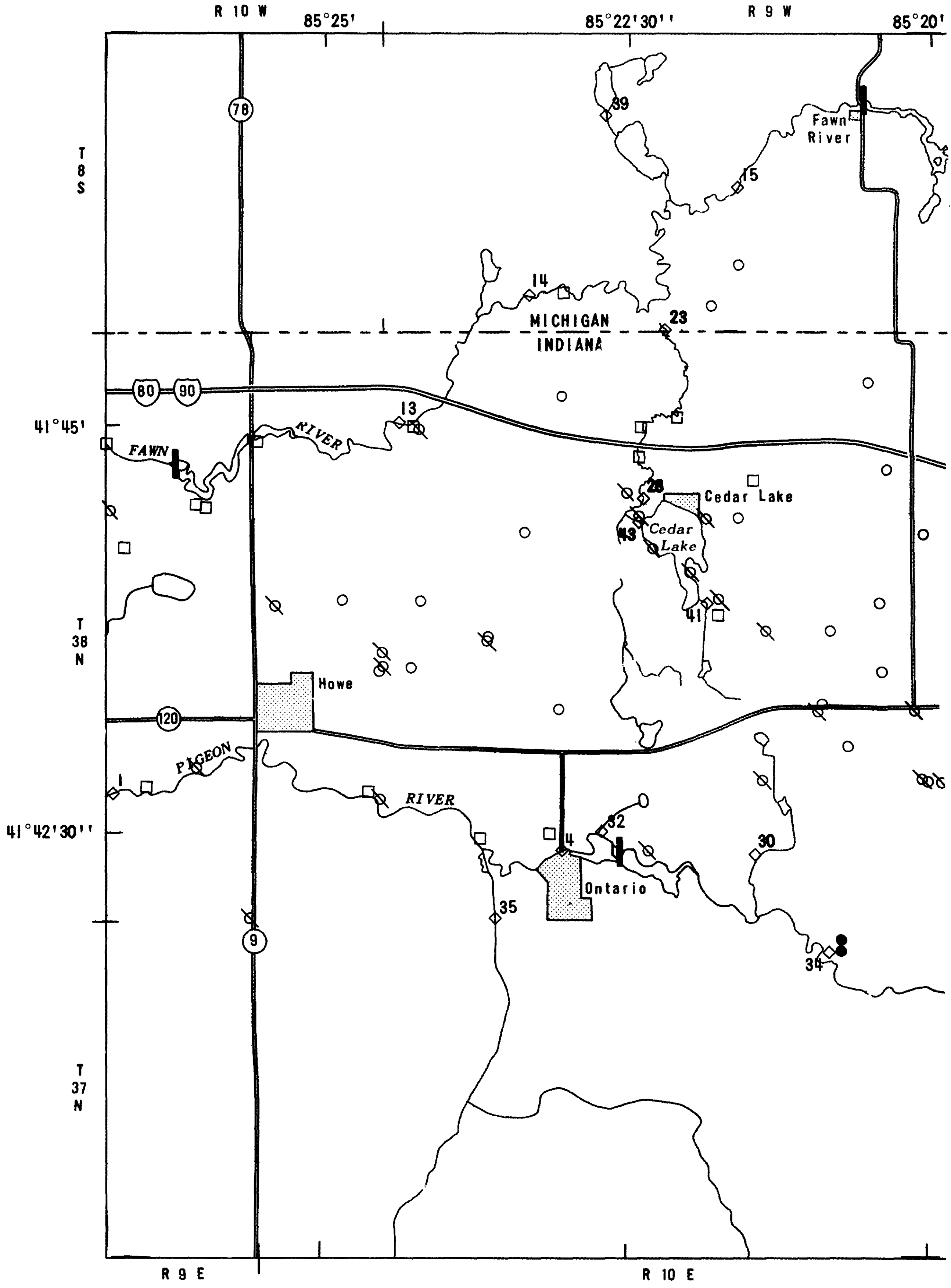
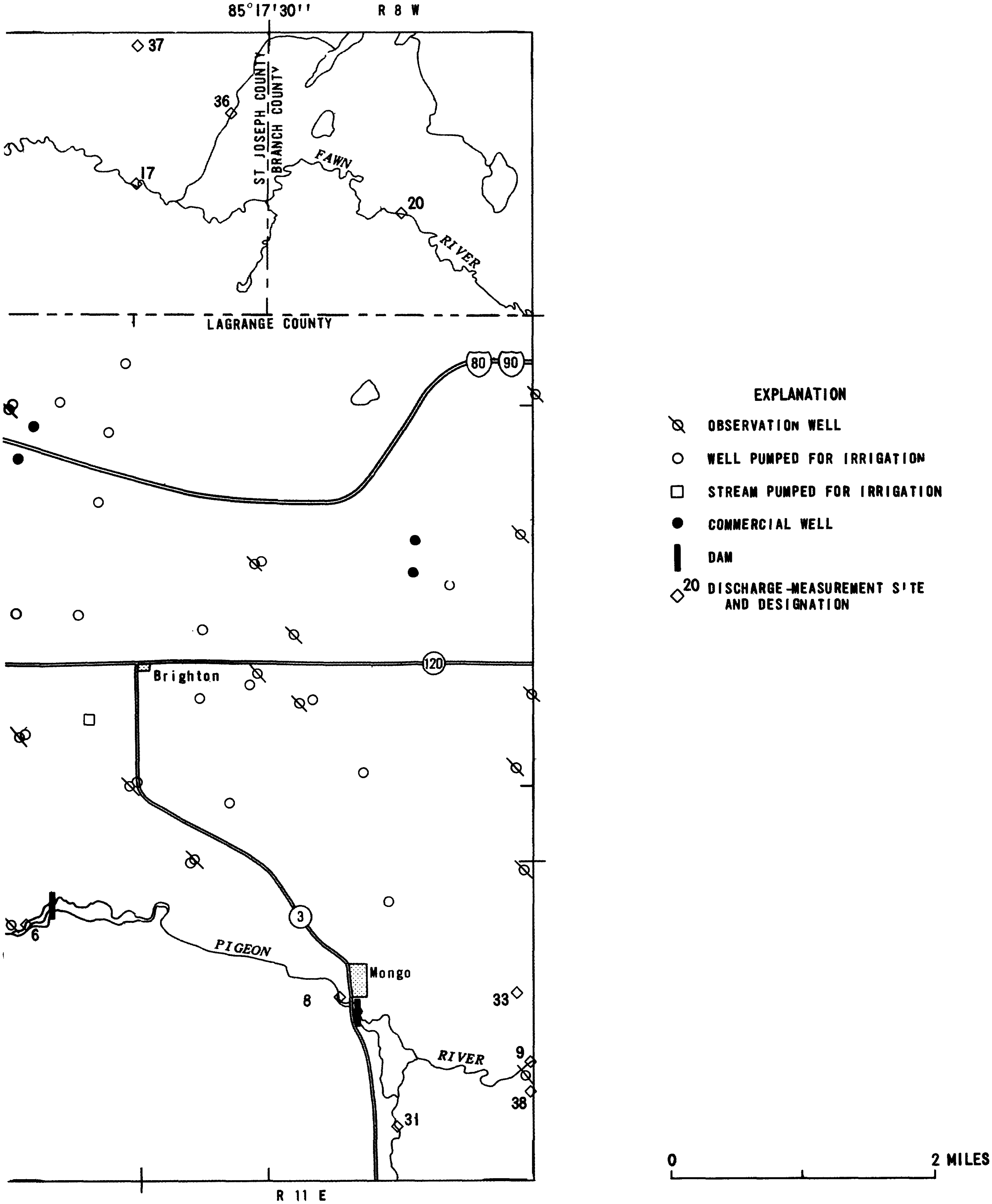


Figure 3.-- Locations of data-collection and pumping sites.



85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
LAGRANGE COUNTY
FAWN
RIVER
37
36
17
20
80
90
120
Brighton
3
PIGEON
RIVER
Mongo
6
8
33
9
38
31
R 11 E
EXPLANATION
OBSERVATION WELL
WELL PUMPED FOR IRRIGATION
STREAM PUMPED FOR IRRIGATION
COMMERCIAL WELL
DAM
20 DISCHARGE-MEASUREMENT SITE AND DESIGNATION
0
2 MILES

Climate

The Howe area has a temperate, continental climate (Trewartha, 1968, p. 321). Howe is surrounded by five weather-observing stations (fig. 1), all within about 20 mi, which have 30 years of temperature and precipitation data (1941-70). Because no long-term records exist for Howe, mean temperature and average precipitation at the five stations were averaged and used to represent climatological data for Howe (table 2). Average annual precipitation is 34.5 in. This is not a weighted average because of the proximity of all the stations. The range of mean monthly temperatures is from 24° F in January to 72° F in July, and the mean annual temperature is 49° F. The average midafternoon relative humidity is 65 percent (Hillis, 1980, p. 3).

Table 2.--Mean temperature and average precipitation near area of study
[Data from National Oceanic and Atmospheric Administration, 1973]

Weather-observing station	Mean annual temperature, 1941-70 (degrees Fahrenheit)	Average annual precipitation 1941-70 (inches)
Angola, Ind.	48.7	35.5
Goshen, Ind.	49.6	34.5
Waterloo, Ind.	49.4	34.7
Coldwater, Mich.	48.3	33.8
Three Rivers, Mich.	49.2	34.2
Average for Howe	49.0	34.5

Geology

Geomorphology and Glacial Deposits

Current topography is a result of drift deposited during the Wisconsinan glacial stage and of subsequent reworking of those deposits by wind and water. Outwash, ground and kame moraines, kames, dunes, wetlands, kettle lakes, and recent alluvium are all present in the area (fig. 4). Elevation ranges from 860 ft above sea level in the west to 1,020 ft in the east. The drift ranges from about 200 to 350 ft in thickness (fig. 5). Sand and gravel deposits up to 100 ft thick, which do not contain distinctive clay layers, were indicated in many lithologic logs. Gravely clay, which is probably buried till, was also indicated in lithologic logs. Most of the clay is in discontinuous lenses. Clay that can be mapped over several square miles is generally less than 20 ft thick but can be as much as 60 ft thick locally. Some of the extensive beds of clay may be lake deposits.

Outwash, most of which consists of sand and gravel but includes some silt, was deposited by meltwater streams that flowed from the glacier. These deposits are regionally extensive (Johnson and Keller, 1972b), and are not limited to the study area. Soils developed on the outwash are Boyer-Oshtemo and Shipshe-Parr associations. They are medium to coarse textured and are well drained (Hillis, 1980, p. 63, 72, 73, and 76). Few drainage channels have developed on these highly permeable soils. Slope of the virtually level to moderately steep surface ranges from zero to 18 percent (Hillis, 1980, p. 31-32).

Ground moraines, found at depth, are composed of till deposited on the surface over which the glacier moved. The till is an unsorted mixture of clay, silt, sand, and gravel.

Kame moraines and kames are recessional deposits composed of stratified gravel, sand, and some silt (Johnson and Keller, 1972b). Soils developed on these deposits, Boyer-Oshtemo associations, are coarse textured and well drained. Slope of the virtually level to moderately steep surface ranges from zero to 25 percent (Hillis, 1980, p. 32-72).

Dunes have formed in areas where silt and sand were available for redistribution by wind. Dunes, generally associated with outwash plains, were formed during glacial recessions. Water percolates rapidly through the thick Plainfield-Chelsea soil associations that developed on the dunes. Dunal slopes range from zero to 12 percent (Hillis, 1980, p. 65, 74).

Muck, peat, and marl have accumulated in and around the kettle lakes and other depressions in the outwash and moraines. Muck and peat are decomposed organic material that contains minor amounts of sand, silt, and clay (Johnson and Keller, 1972b). Marl is a calcareous mud or clay. Soils developed on these materials are the Haughton-Adrian and Edwards-Martisco associations that are virtually level (maximum slope of 2 percent) and are very poorly drained (Hillis, 1980, p. 62, 66, 69, and 70).

Recent alluvium, derived from reworked and redeposited drift, is composed of gravel, sand, silt, and clay in deposits less than 40 ft thick. Sebewa-Plainfield-Guilford-Homer soil associations that have developed from these deposits are moderately coarse textured, poorly drained, and virtually level (maximum slope of 2 percent) according to Hillis (1980, p. 66, 69, 75, and 76).

Bedrock

Bedrock underlying the drift is Coldwater Shale of Mississippian age (Johnson and Keller, 1972b) and dips less than 1° to the north (Deutsch and others, 1960, p. 20-21). The typically gray to greenish-gray, slightly silty

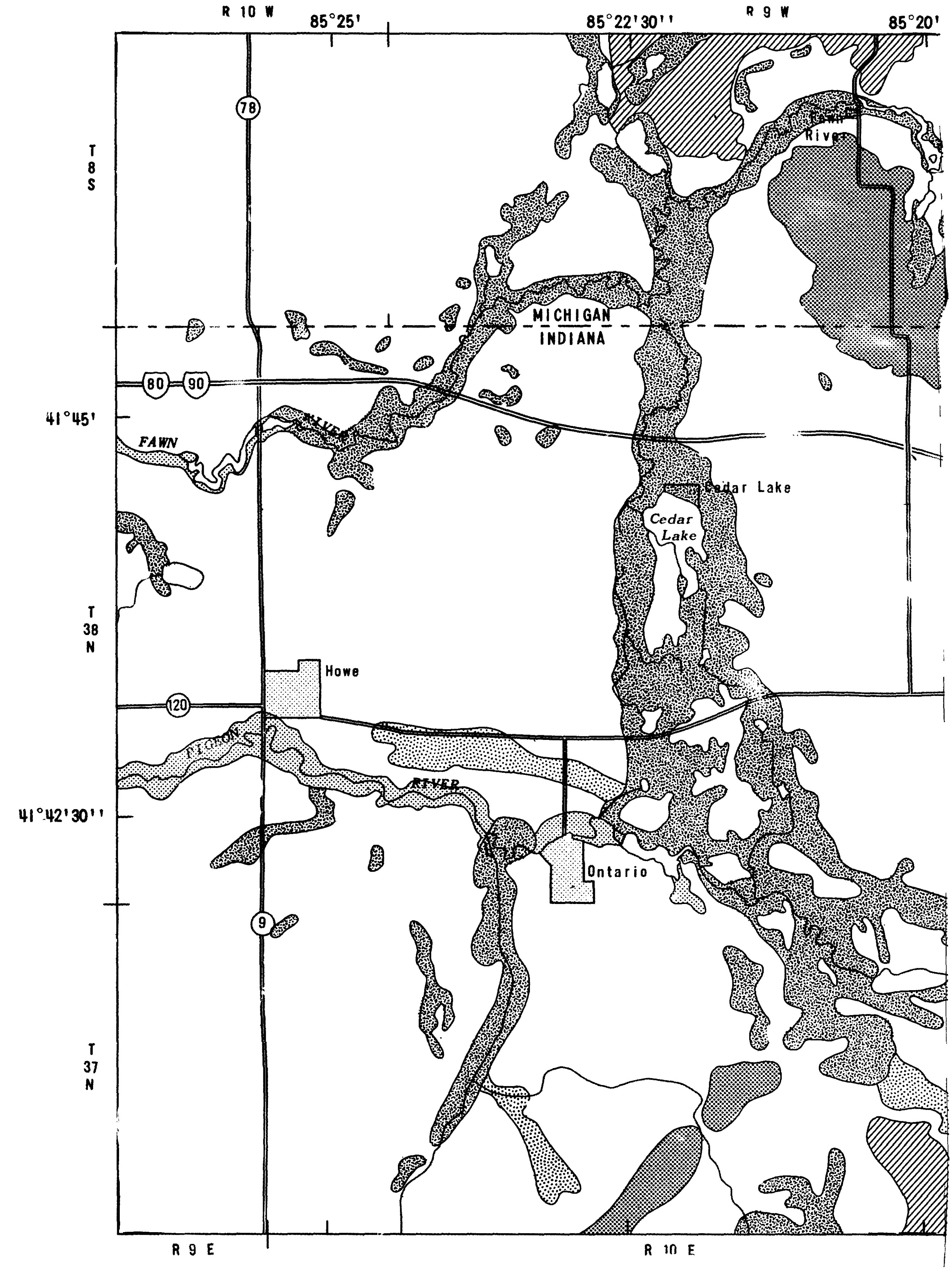
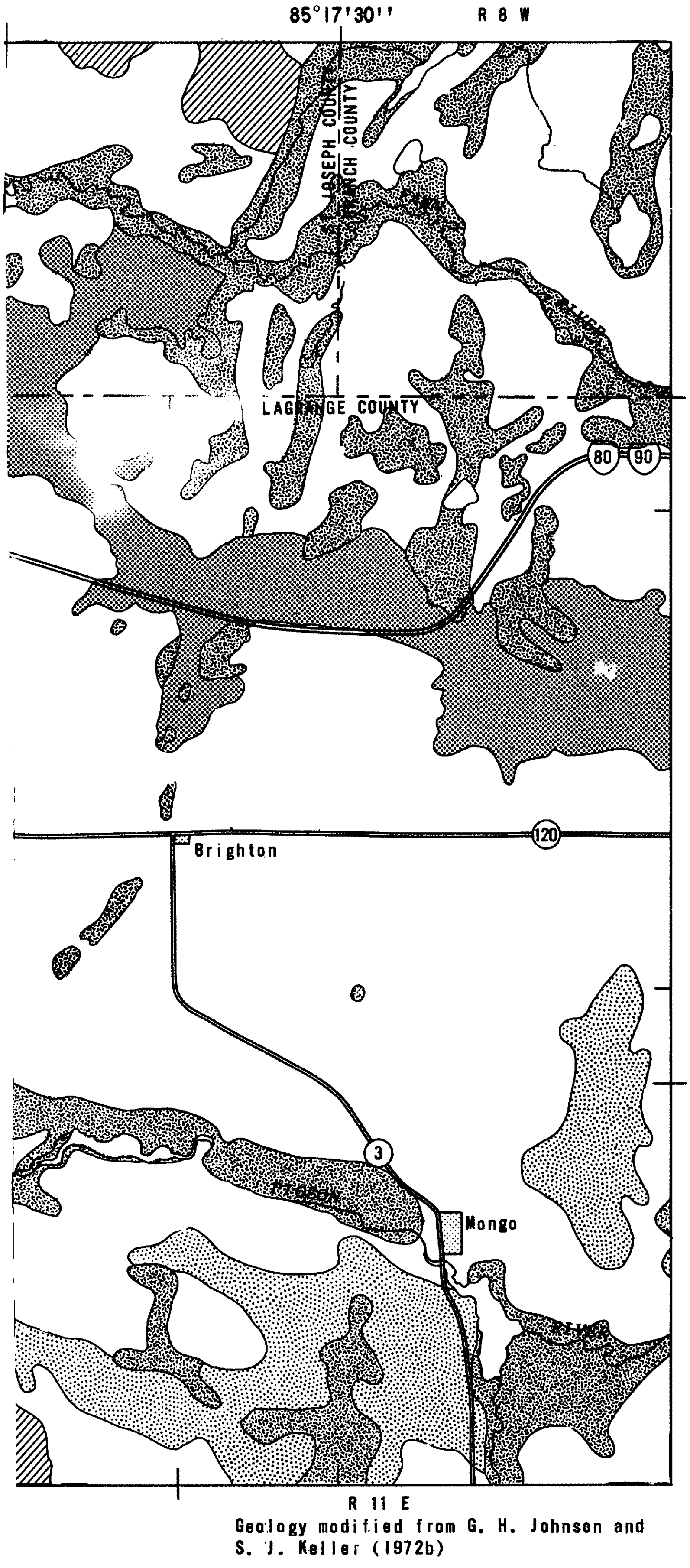


Figure 4.-- Generalized surficial geology and estimates of recharge.



Geology modified from G. H. Johnson and S. J. Keller (1972b)

EXPLANATION

QUATERNARY (PLEISTOCENE)

RECENT

- ALLUVIUM--Silt, sand, and gravel. Recharge equals 10.5 inches per year
- MARSH, SWAMP, AND LAKE DEPOSITS--Muck, peat, and marl. Recharge equals 4.2 inches per year

WISCONSINAN AND RECENT

- DUNES--Sand and Silt. Recharge equals 25 inches per year

WISCONSINAN

- OUTWASH--Gravel, sand, and silt. Recharge equals 10.5 inches per year
- ICE-CONTACT STRATIFIED DEPOSITS--Kames, kame moraines-gravel, sand, and silt. Recharge equals 6.3 inches per year
- GROUND MORAINE--Till. Recharge equals 4.2 inches per year

0 — 2 MILES

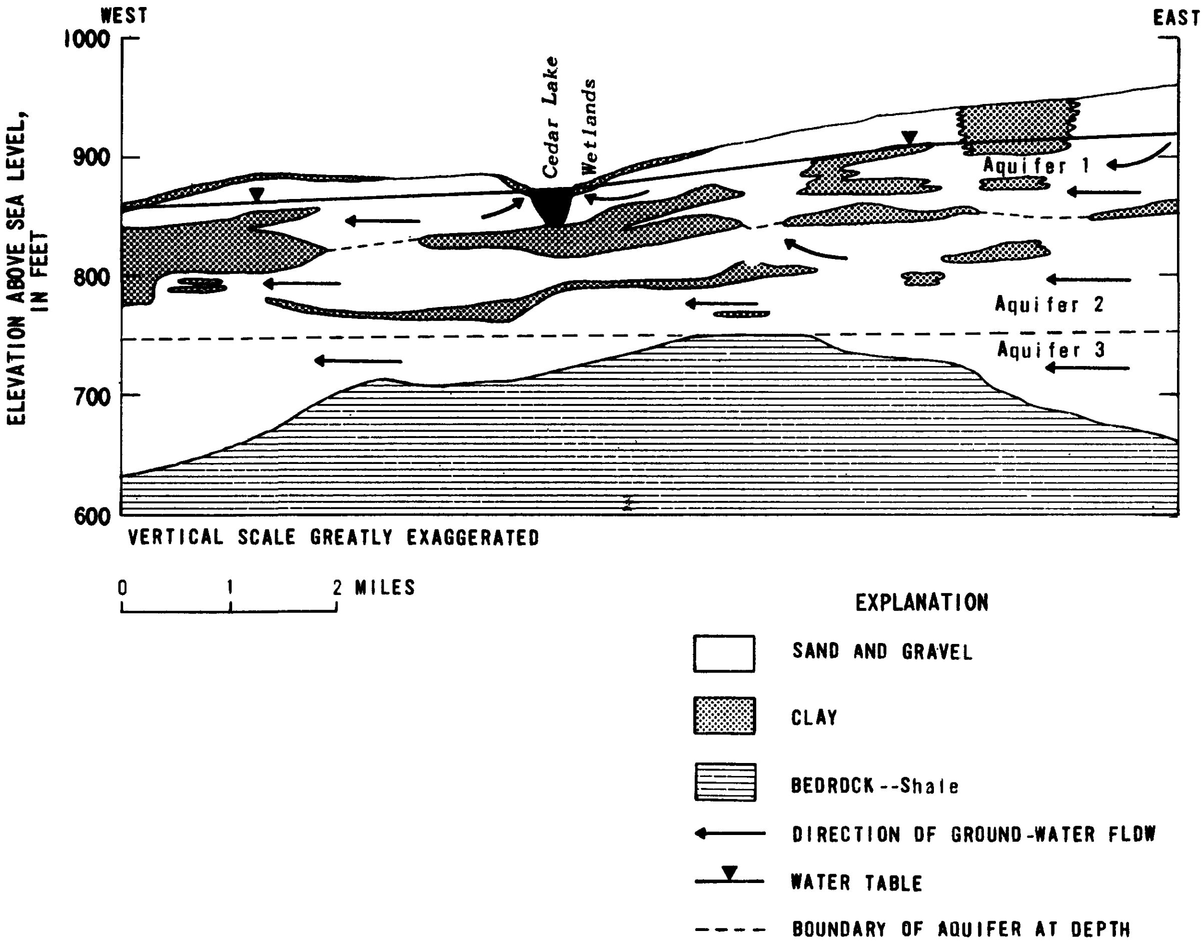


Figure 5.-- Generalized geologic section.

rock contains some brown dolomite and limestone lenses (Shaver and others, 1970, p. 39-40). Steep-sided valleys were eroded into the bedrock, the surface altitude of which ranges from 550 to 765 ft above sea level (fig. 6).

Land Use

Land use is divided into five categories: Towns, agriculture, forest, wetland (including lakes), and forested wetland. Only the 40-mi^2 area between Fawn and Pigeon Rivers in Indiana was categorized (fig. 7). Data were not available for the 6.5-mi^2 area in Michigan (14 percent of the study area).

The principal land use is agriculture, which comprises about 32 mi^2 or 80 percent (table 3) of the area. Urban areas (0.5 mi^2) include Howe (population 500), Mongo, Brighton, and the town of Cedar Lake (fig. 2). Forest and wetlands are mainly associated with marshy areas (fig. 4) near Cedar Lake and Fawn and Pigeon Rivers where tillage is virtually impossible because the soils are poorly drained. Wetlands that are forested comprise 1.2 mi^2, and the remaining wetlands and lakes comprise 1.7 mi^2 (lakes alone are 0.34 mi^2). Forests that are not in wetlands comprise an additional 4.7 mi^2.

Table 3.--Land use in Indiana between Fawn and Pigeon Rivers

Land-use category	Area[1] (mi^2)	Percentage of total
Agriculture	31.9	80
Forest	4.7	12
Wetland and lakes	1.7	4
Forested wetland	1.2	3
Towns	0.5	1
Total	40.0	100

[1]Measured from areas delineated in Figure 7.

Water Use

Ground water and surface water are used in agriculture, commerce, and domestic supply. Water use in 1982 was divided into four categories: Irrigation, commerce, homes, and Curtis Creek Fish Hatchery (table 4). Locations of these withdrawals are shown in figure 8 (domestic-supply withdrawals are not shown).

Water withdrawn for the four major uses in 1982 totaled 1,408 Mgal. Sixty-four percent (903 Mgal) of water withdrawn was used for irrigation, and 88 percent of that was used during the irrigation season (June through August). The Curtis Creek Fish Hatchery was the second largest user of water. Two wells at the hatchery pumped 390 Mgal or 28 percent of the total water used. Commercial users pumped 54 Mgal, which was 4 percent of the total. Water for homes was supplied from private wells. A total of 61 Mgal for domestic use was calculated on the basis of 76.46 gal/d per capita (Indiana Department of Natural Resources, 1982, p. 3) and a population estimated to be 2,200.

Use for livestock and small businesses was not considered to be significant in comparison with other uses and, therefore, was not estimated. Other uses of water include recreation on streams, lakes, and wetlands and electrical-power generation. Two low-head, hydroelectric, generating plants are operated on Fawn River (fig. 3).

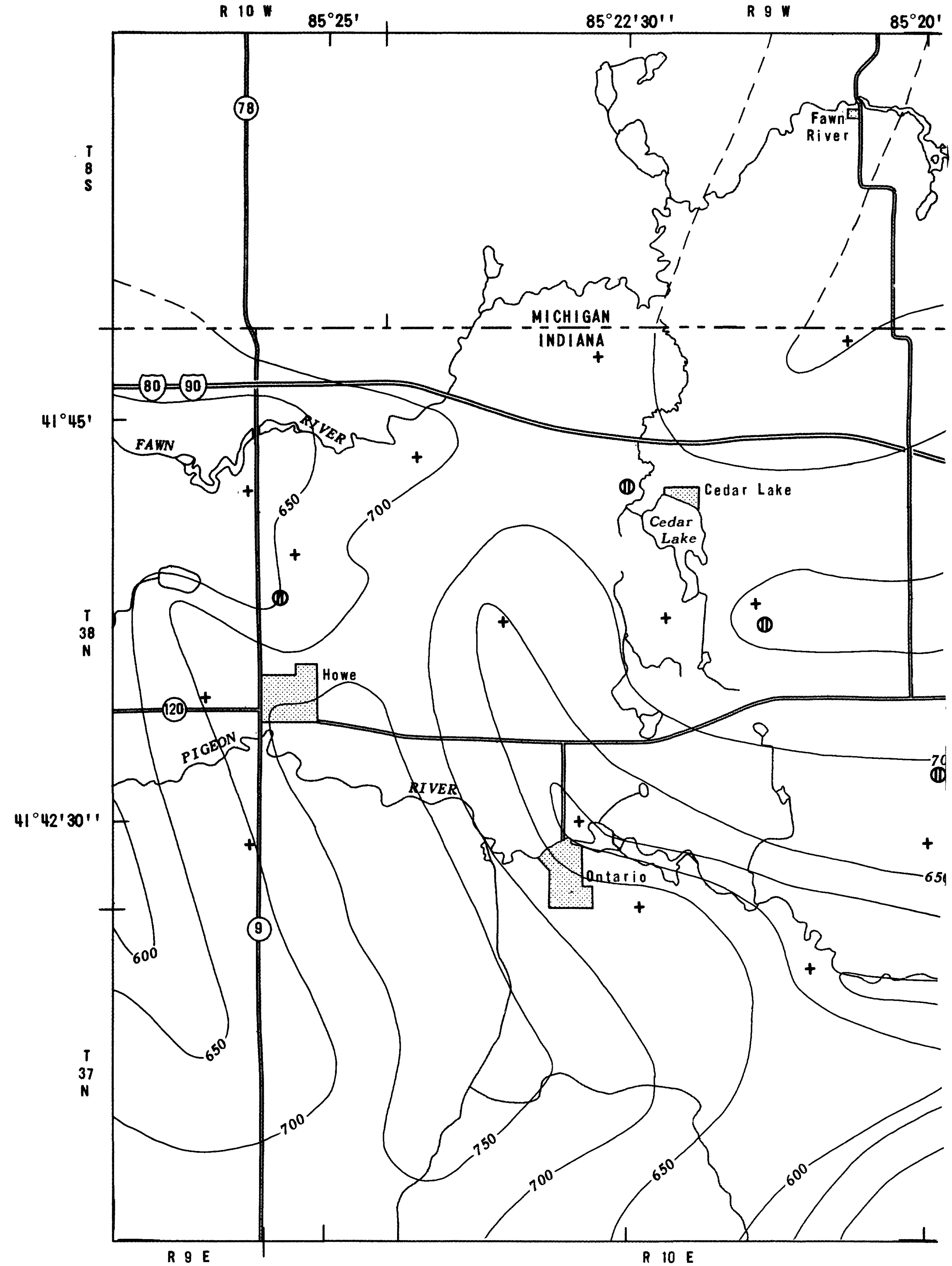
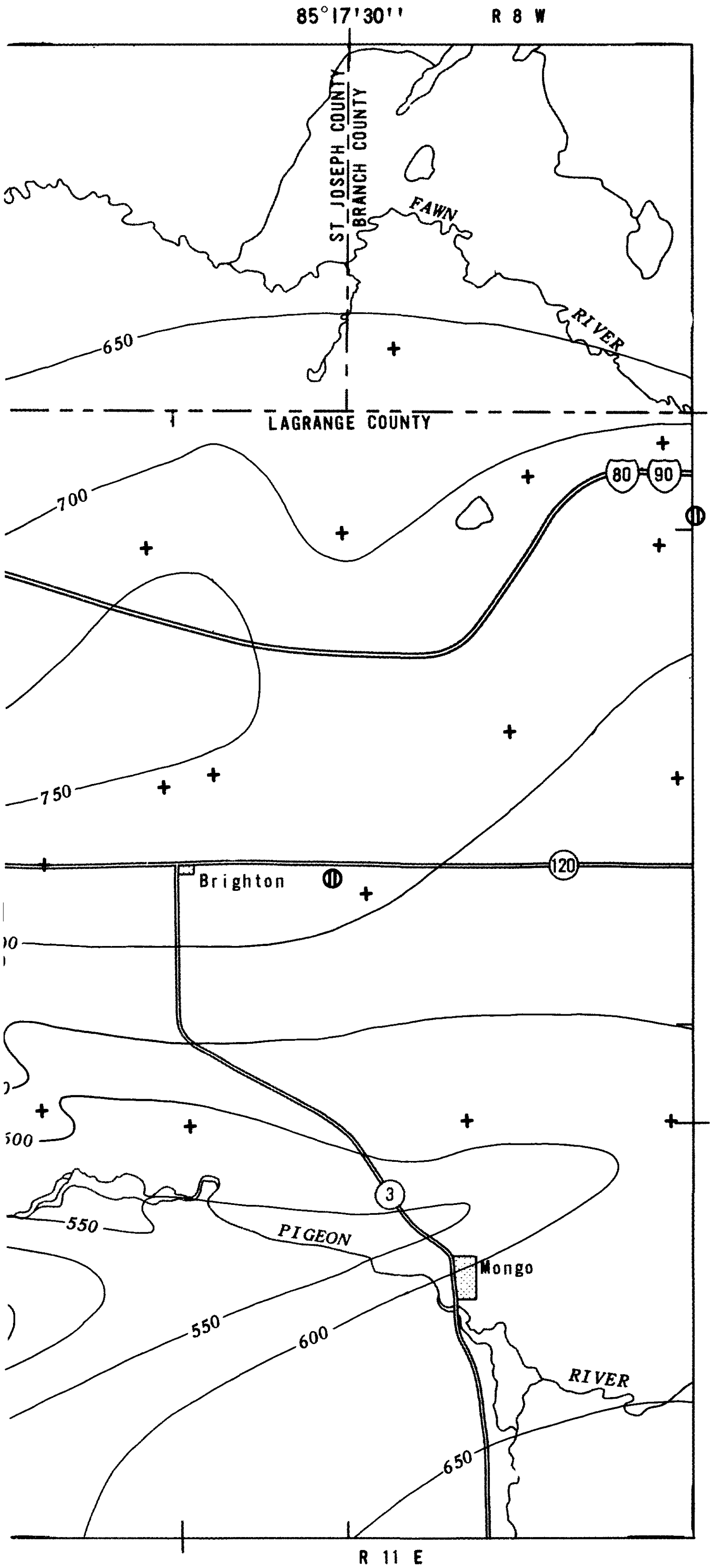


Figure 6.-- Altitude of the bedrock surface.



EXPLANATION

— *700* — **BEDROCK CONTOUR**- Shows altitude of bedrock surface. Dashed where approximately located. Contour interval 50 feet. Datum is sea level

Ⓘ TEST HOLE

+ SEISMIC REFRACTION SITE

0 — 2 MILES

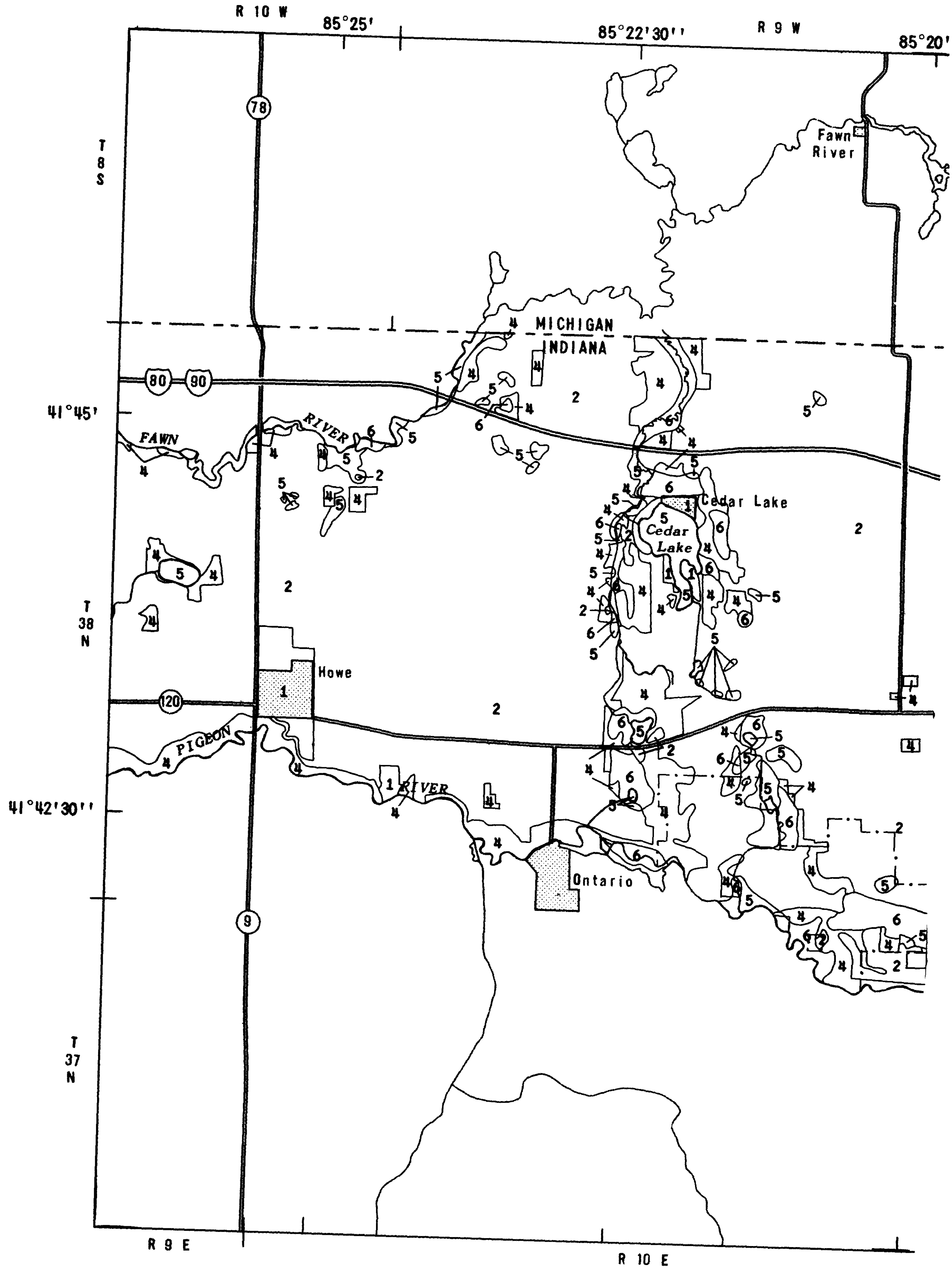
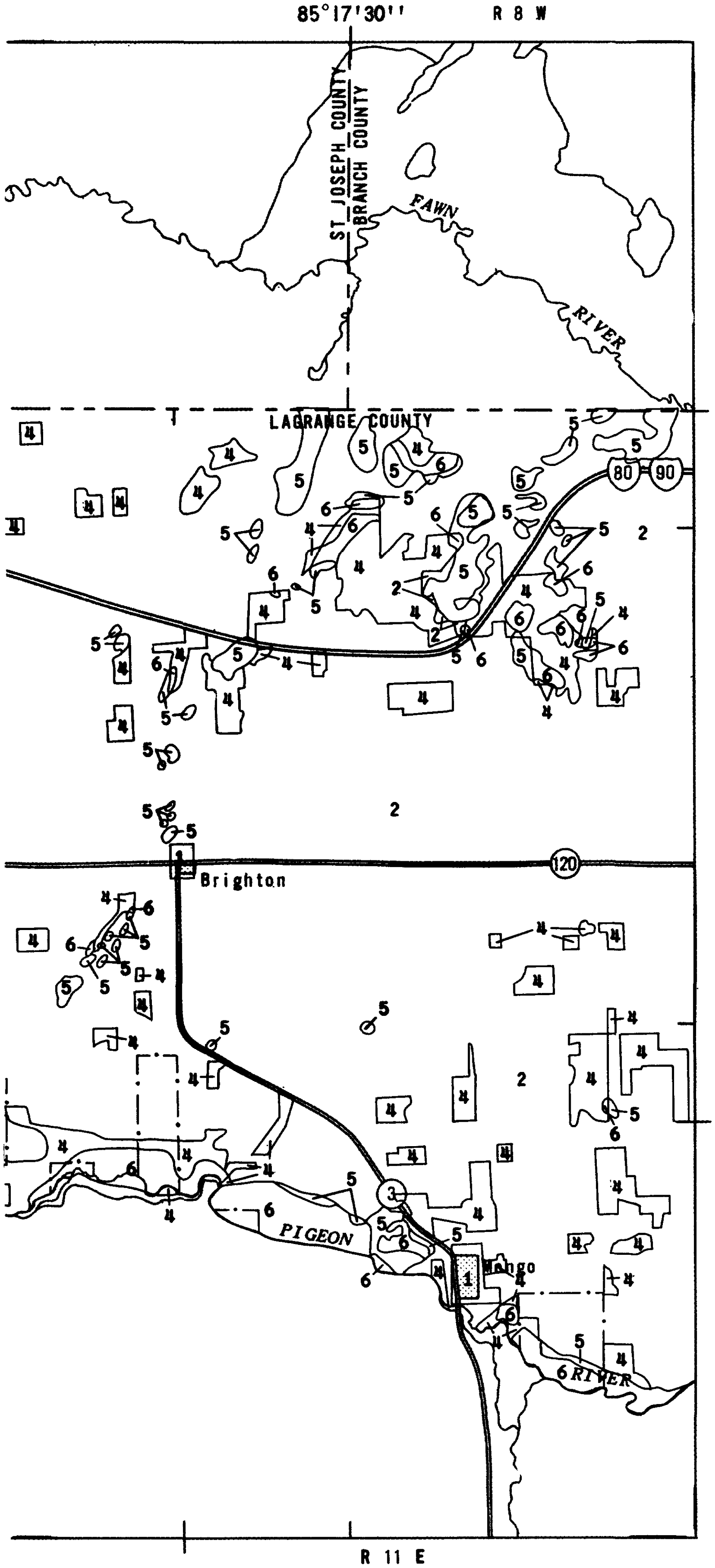


Figure 7.-- Use of land.



EXPLANATION

LAND USE CLASSIFICATIONS

1 Towns
2 Agriculture
4 Forest
5 Wetland and lakes
6 Forested wetland

—·— PIGEON RIVER STATE FISH AND WILDLIFE AREA

0 — 2 MILES

Use of land modified from D. F. Chelf, 1983 and from written commun., C. P. Grady and B. A. Oartel, Indiana Department of Natural Resources, 1982

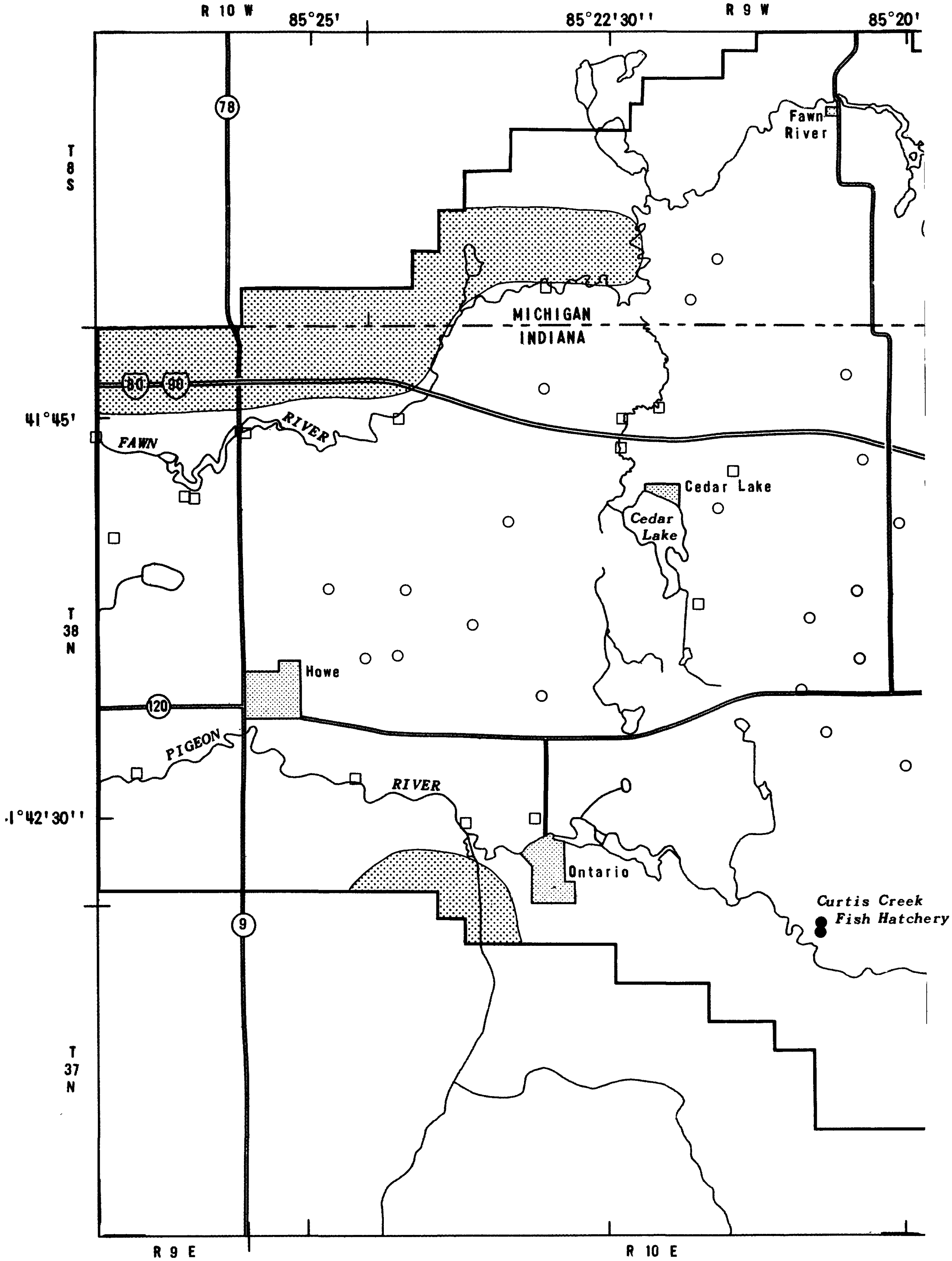


Figure 8.-- Locations of pumping sites and confined areas of aquifer 1.

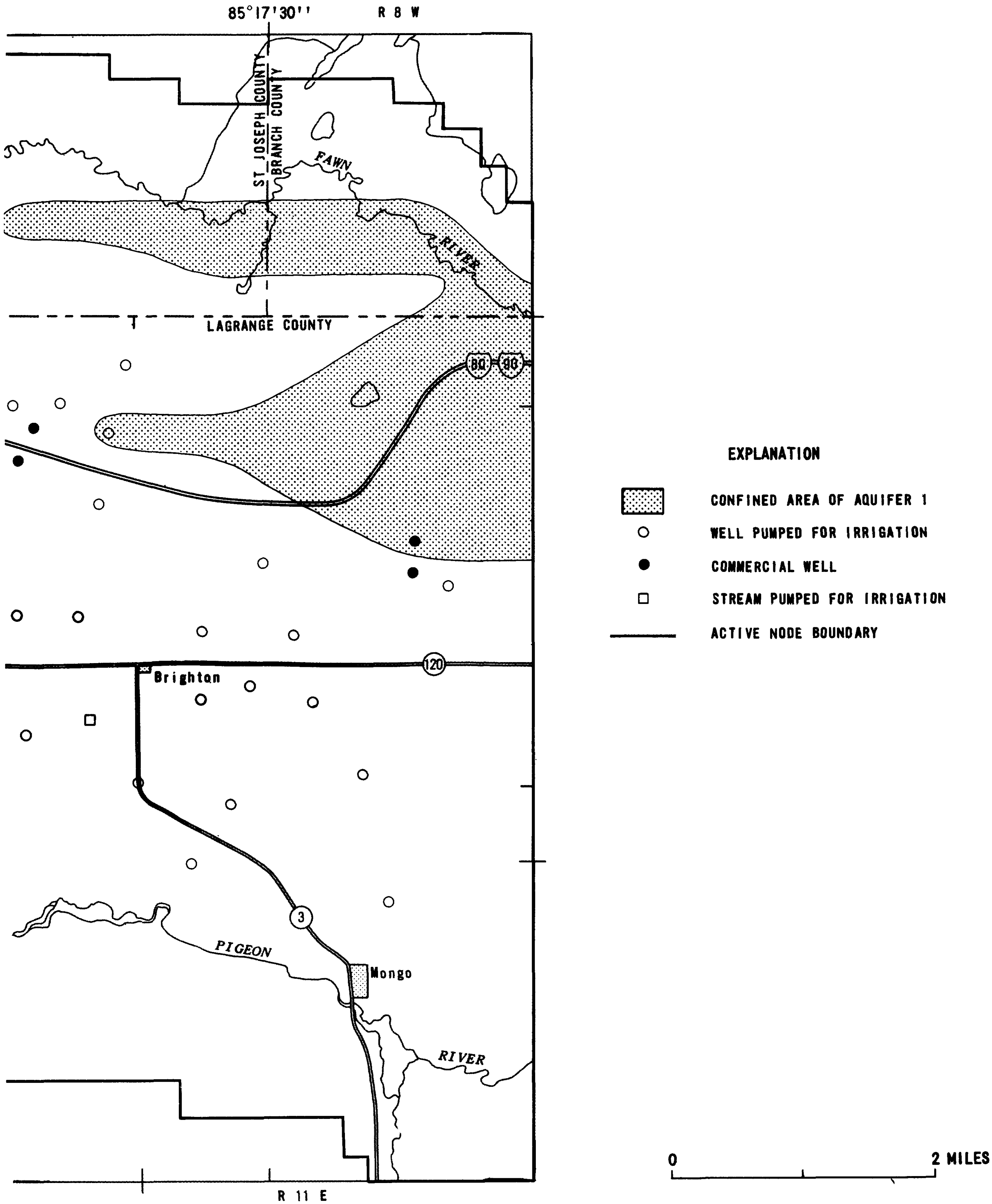

85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
PIGEON
Mongo
RIVER
R 11 E
EXPLANATION
CONFINED AREA OF AQUIFER 1
WELL PUMPED FOR IRRIGATION
COMMERCIAL WELL
STREAM PUMPED FOR IRRIGATION
ACTIVE NODE BOUNDARY
0
2 MILES

Table 4.--Water use in Indiana between Fawn and Pigeon Rivers, 1982

Category	Number of sources	Pumping period	Water used (Mgal)	Percentage of total water used	Water used June-August (Mgal)	Percentage of water used June-August	Source of data
Commerce	4[a]	all year	54	4	14	1	Measured and estimated
Homes	unknown[a]	all year	61	4	15	1	Estimated
Curtis Creek Fish Hatchery	2[a]	all year	390	28	98	10	Estimated
Irrigation:							
Ground water	40	June-Aug	692	49	692	68	Measured and estimated
Surface water	17	June-Aug	211	15	209	20	Measured and estimated
Irrigation total	57		903	64	901	88	
Totals	63		1,408	100	1,028	100	

[a]All sources are ground water.

HYDROLOGY

Surface-Water System

Streams

The Fawn and Pigeon Rivers are major tributaries to the St. Joseph River in the southeastern part of the basin (fig. 1). The drainage area of Fawn River upstream from the west boundary of the area of study is 167 mi^2 and that of Pigeon River is 289 mi^2. The drainage areas within the area of study are 16.9 mi^2 for Pigeon River and 29.6 mi^2 for Fawn River.

Three dams on Pigeon River (fig. 3) are operated for flood control by the Indiana Department of Natural Resources. Two dams on Fawn River (fig. 3) are privately owned low-head dams operated for power generation.

The U.S. Geological Survey has operated continuous-record streamflow stations on the Pigeon River near Angola since 1945 and near Scott since 1968 (fig. 1). Stations were operated on the Fawn River at Orland, Ind., from 1943 to 1947 and near White Pigeon, Mich., from 1957 to 1975 (fig. 1). Discharge recorded at the stations on Fawn River was affected by regulation of flow at dams. Drainage area and mean daily discharge for each station are listed in table 5.

Table 5.--Drainage area and mean daily discharges of stations on Fawn and Pigeon Rivers

Station name[1]	Period of record	Drainage area (mi^2)	Mean daily discharge (ft^3/s)
Fawn River at Orland, Ind.	1943-47	86	48
Fawn River near White Pigeon, Mich.	1957-75	192	159
Pigeon River near Angola, Ind.	1945-82	106	76
Pigeon River near Scott, Ind.	1968-82	361	345

[1]Locations on figure 1.

Lakes and Wetlands

Lakes and wetlands comprise 2.9 mi^2 (7 percent) of the 40.0 mi^2 part of the area of study in Indiana; lakes alone comprise 0.34 mi^2 (less than 1 percent of the study area). Capacity of the lakes is 1,700 acre-feet. The surface area of the largest lake, Cedar Lake, is 0.2 mi^2 (128 acres); the capacity is 1,020 acre-feet; and the elevation is 872 ft. Wetlands, generally around lakes and along streams, consist of 2.5 mi^2 or 1,600 acres.

The lakes and wetlands reduce the variation in streamflow by dampening peaks and supplementing low flow by storage and release of runoff.

Ground-Water System

Hydraulic Characteristics of Deposits and Bedrock

Glacial Deposits

The outwash has been divided into three aquifers (fig. 5) on the basis of differences in lithology and geometry of clay units. These aquifers can be evaluated separately even though they are generally connected regionally. Aquifers 1 and 2 are separated by clay in most areas. Forty-two of the 46 irrigational wells are screened below that clay in aquifer 2. Aquifers 2 and 3 are distinguished by their clay content. Lithologic and gamma logs indicate a much higher clay content in the outwash below an altitude of 750 ft than above.

Aquifer 1 is mainly a water-table aquifer but may be locally confined by surficial clay (fig. 8). Thickness of the clay that separates aquifers 1 and 2 ranges from zero to 50 ft (fig. 9). Horizontal hydraulic conductivity of the clay was assumed to be 0.01 ft/d (Freeze and Cherry, 1979, p. 29). The clay is thickest in the western part of the area and in a narrow strip across the central part. Because large areas between aquifers 1 and 2 are not separated by a well-defined clay, aquifer 2, although generally confined, is probably unconfined in these areas.

Average hydraulic conductivity of each aquifer was calculated from specific-capacity-test data by a method described by Theis and others (1963). Average conductivity of aquifer 1 was 210 ft/d; of aquifer 2, 360 ft/d; and of aquifer 3, 190 ft/d. Hydraulic conductivity at 18 sites was used to calculate the average for aquifer 1. The range was from 160 to 300 ft/d. Hydraulic conductivity for four wells in aquifer 2 ranged from 100 to 850 ft/d. Only two wells were screened in aquifer 3, and their hydraulic conductivities were 110 and 270 ft/d.

The bottom of aquifer 1 is defined by the top of the clay unit (fig. 10). A bottom altitude was projected where the clay is absent (fig. 9). Saturated thickness of aquifer 1 (fig. 11) was calculated by subtracting its bottom altitude from the water-table altitude or from the bottom altitude of a localized clay that overlies small areas of the aquifer. Saturated thickness of aquifer 2 was calculated by subtracting an altitude of 750 ft from the bottom altitude of the overlying clay (fig. 12). Saturated thickness of aquifer 3 (fig. 13) was calculated by subtracting the altitude of the top of the bedrock from 750 ft (fig. 6). Saturated thickness ranges from 10 to 60 ft in aquifer 1, from 50 to 110 ft in aquifer 2, and from zero to 200 ft in aquifer 3.

Transmissivity for each aquifer was calculated as the product of saturated thickness and average hydraulic conductivity (figs. 14-16). In aquifers 1 and 2, the thickness of major clay lenses within each aquifer (figs. 11, 12) was subtracted from the saturated thickness before calculation of transmissivity. Much of aquifer 3, especially in the bedrock valleys (fig. 6), is probably clay, but test drilling below the 750-foot elevation was not sufficient to map the clay in the aquifer. The high clay content of aquifer 3 was accounted for, however, in the digital flow model, discussed later. Transmissivity ranges from 5,000 to 16,000 ft^2/d in aquifer 1. Transmissivity in Cedar Lake (fig. 14) is an artificial value of up to 3.8×10^5 ft^2/d that was assigned for modeling. Transmissivity ranges from 5,000 to 35,000 ft^2/d in aquifer 2 and from zero to 5,000 ft^2/d in aquifer 3.

Storage coefficient and specific yield were calculated for three wells in aquifer 2 from aquifer-test data by analytical techniques (James Peters, U.S. Geological Survey, written commun., 1983). The storage coefficients for two wells in confined areas of the aquifer were 0.0002 and 0.0003. The specific yield of the well in an unconfined area of the aquifer was 0.24.

Bedrock

Few wells penetrate bedrock because the outwash contains an adequate water supply at shallower depths. The shale transmits water poorly and is generally not a good aquifer, although some water may be available from fractures (Reussow and Rohne, 1975). The bedrock, therefore, is virtually impermeable in comparison to the highly permeable outwash.

Hydraulic Connection Between Aquifers and Streams

Flow-duration curves and base-flow measurements were used to study the hydraulic connection between the aquifers and Pigeon and Fawn Rivers.

A flow-duration curve is a cumulative-frequency curve showing the percentage of time that a specified discharge was equaled or exceeded in a given period of record. The chronological sequence of occurence is obscured in the curve (Searcy, 1959, p. 1-2). The overall shape of the curve is related to variability in flow. The flatter the curve the greater the contribution from ground-water and surface-water storage (Searcy, 1959, p.22). A flat slope at the lower end of the curve is an indication of a large quantity of perennial storage in the drainage basin.

Flow-duration curves for Pigeon River near Scott, Ind., and Fawn River near White Pigeon, Mich., are shown in figure 17. These curves are plotted in cubic feet per second per square mile so that they can be compared on a unit basis. flow characteristics of the two rivers are similar even though the periods of record are not concurrent. Flow is probably controlled by surface-water and ground-water storage because the overall slopes are moderately flat. The flat lower end is an indication that flow is sustained by ground-water discharge.

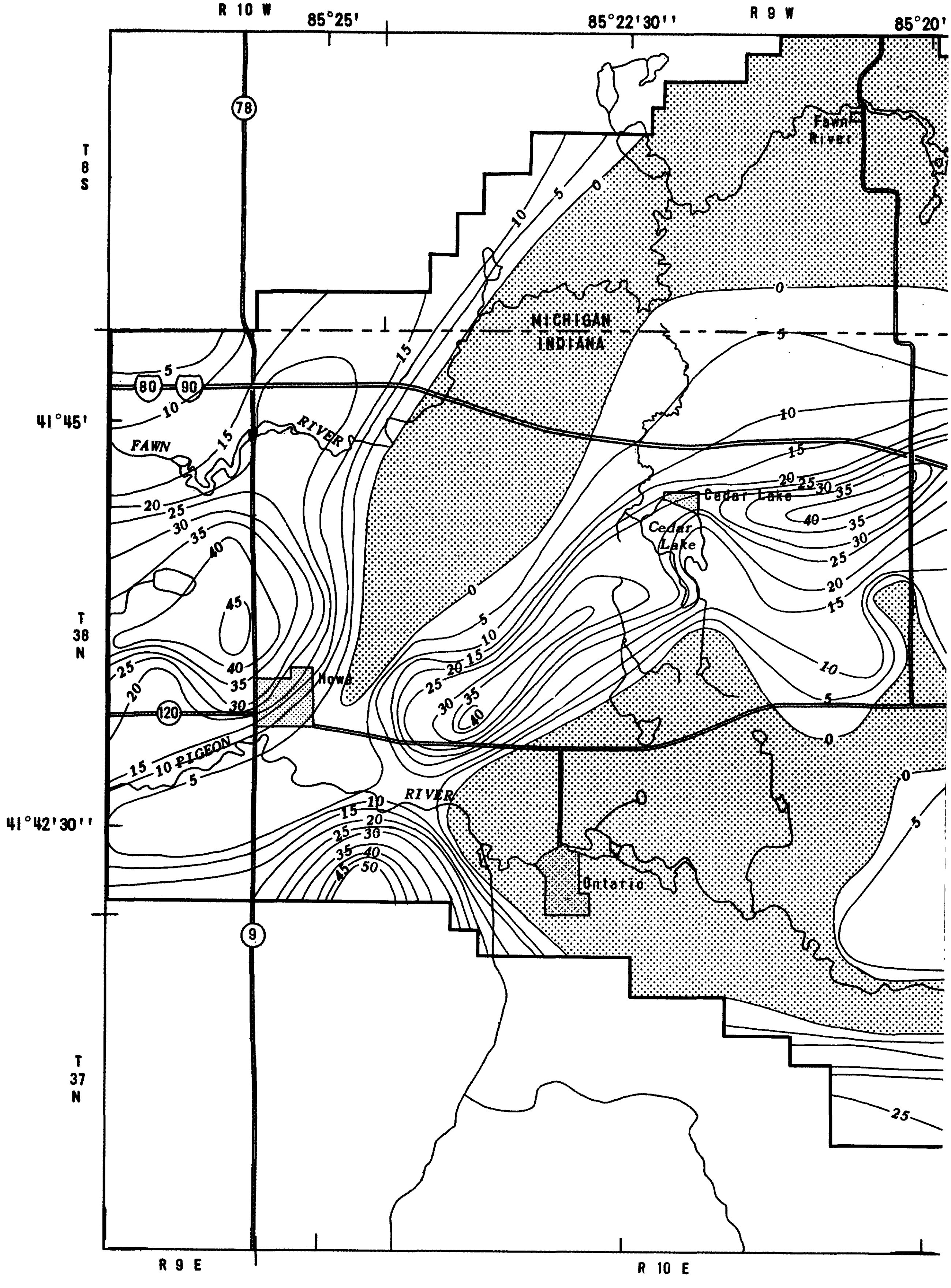
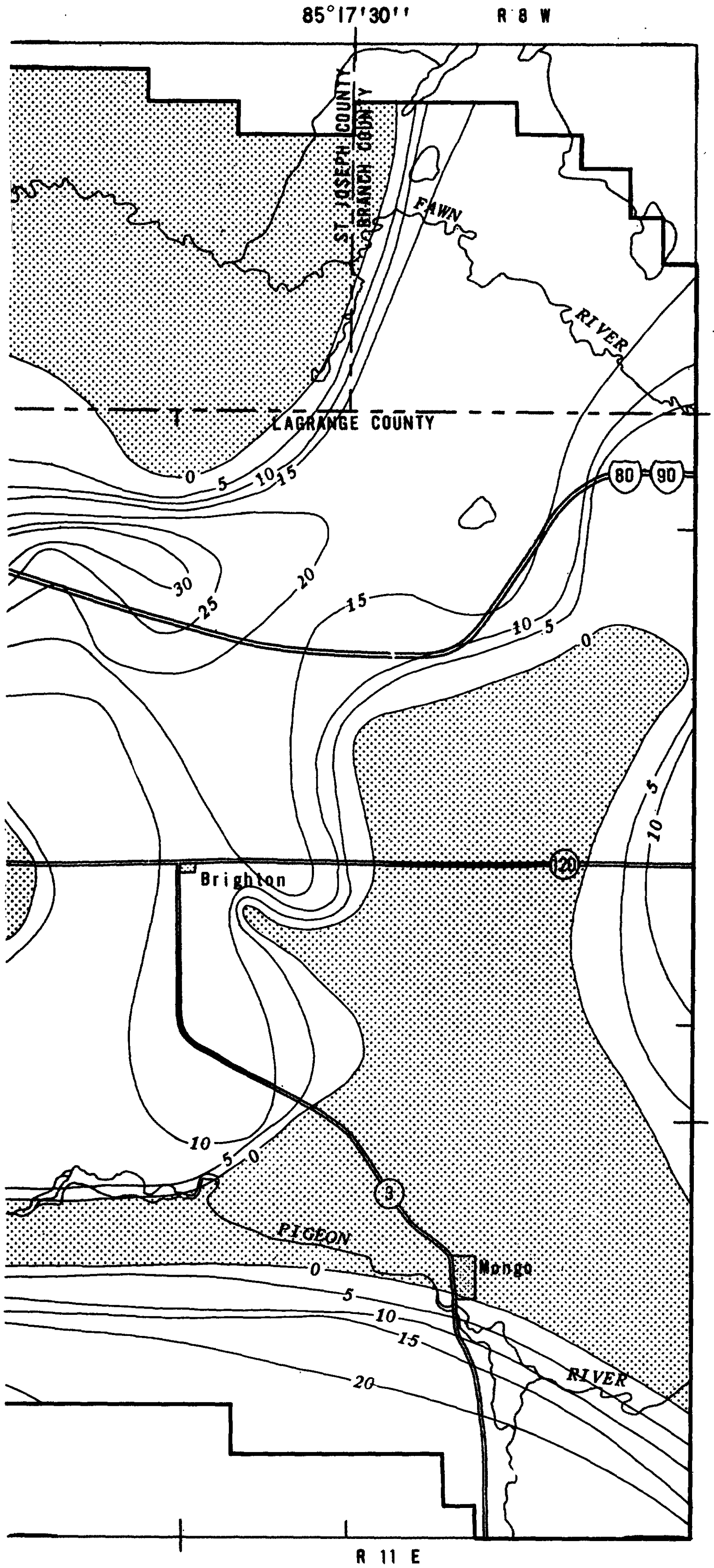


Figure 9.-- Thickness of clay between aquifers 1 and 2.



EXPLANATION

AREA WHERE CLAY IS ABSENT BETWEEN AQUIFERS 1 AND 2

—5— LINE OF EQUAL THICKNESS OF CLAY--Interval 5 feet

ACTIVE-NODE BOUNDARY

0 2 MILES

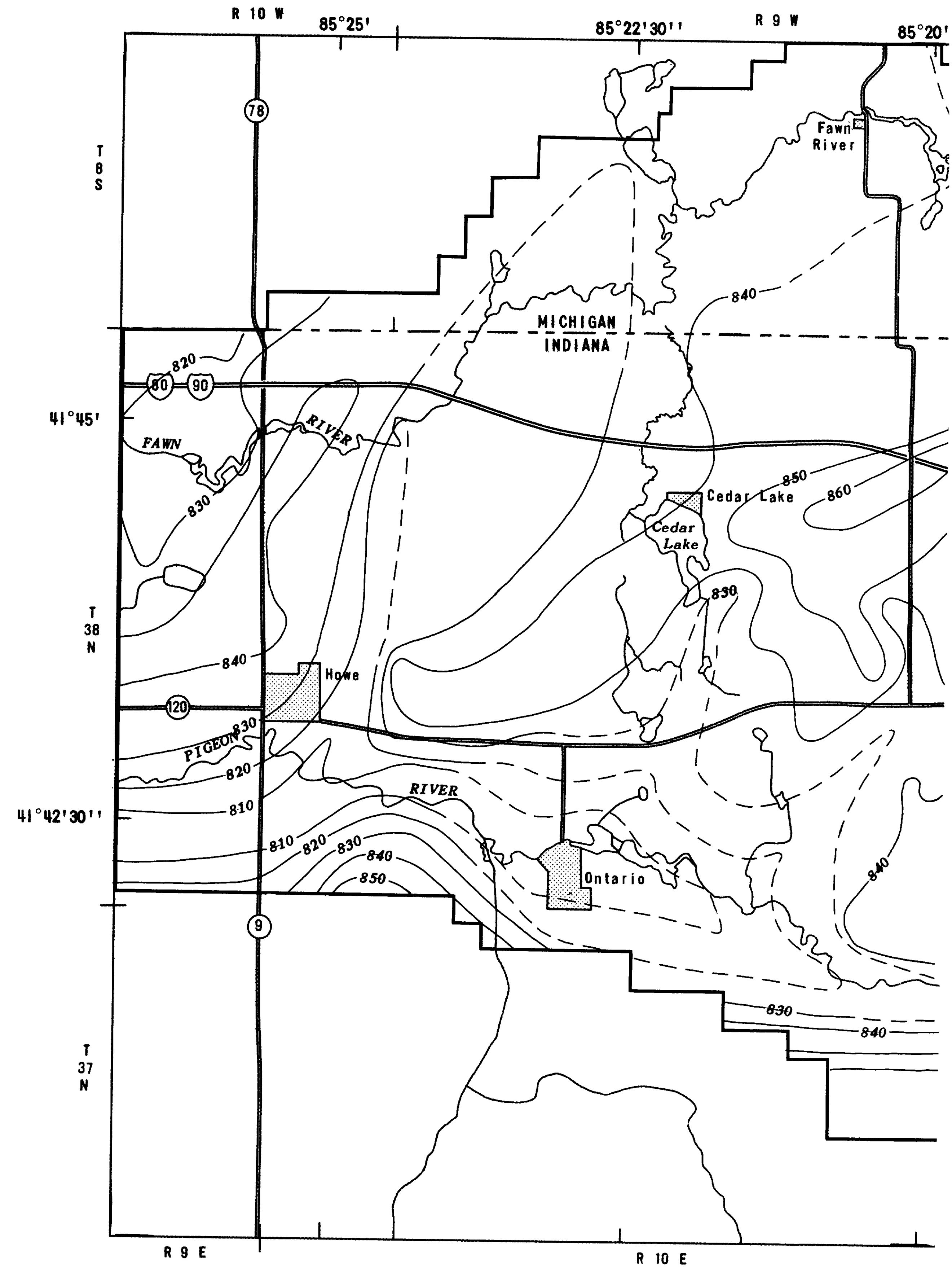
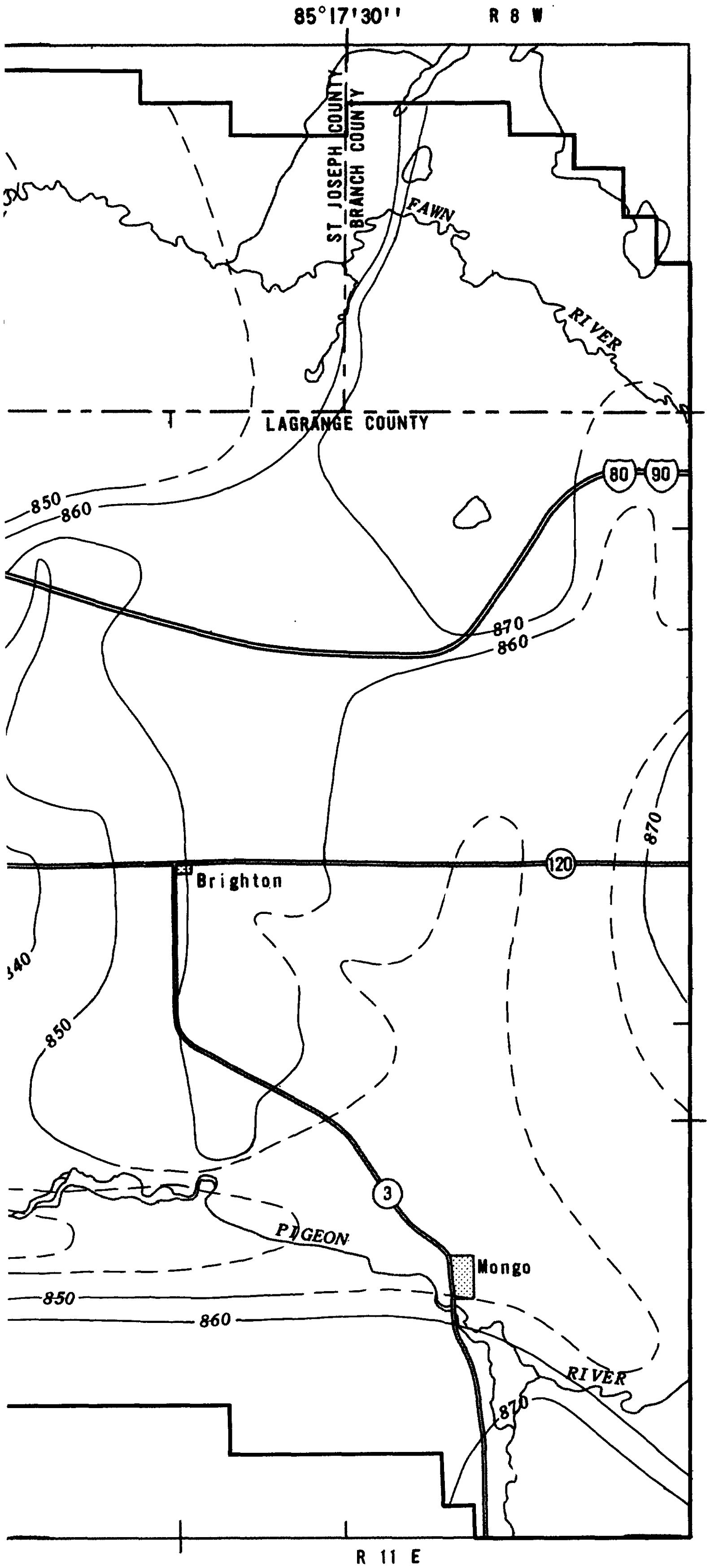


Figure 10.-- Base altitude of aquifer 1.



EXPLANATION

—860— — STRUCTURE CONTOUR--Shows altitude of base of aquifer 1. Dashed where clay unit is missing. Contour interval 10 feet. Datum is sea level

ACTIVE-NODE BOUNDARY

0 — 2 MILES

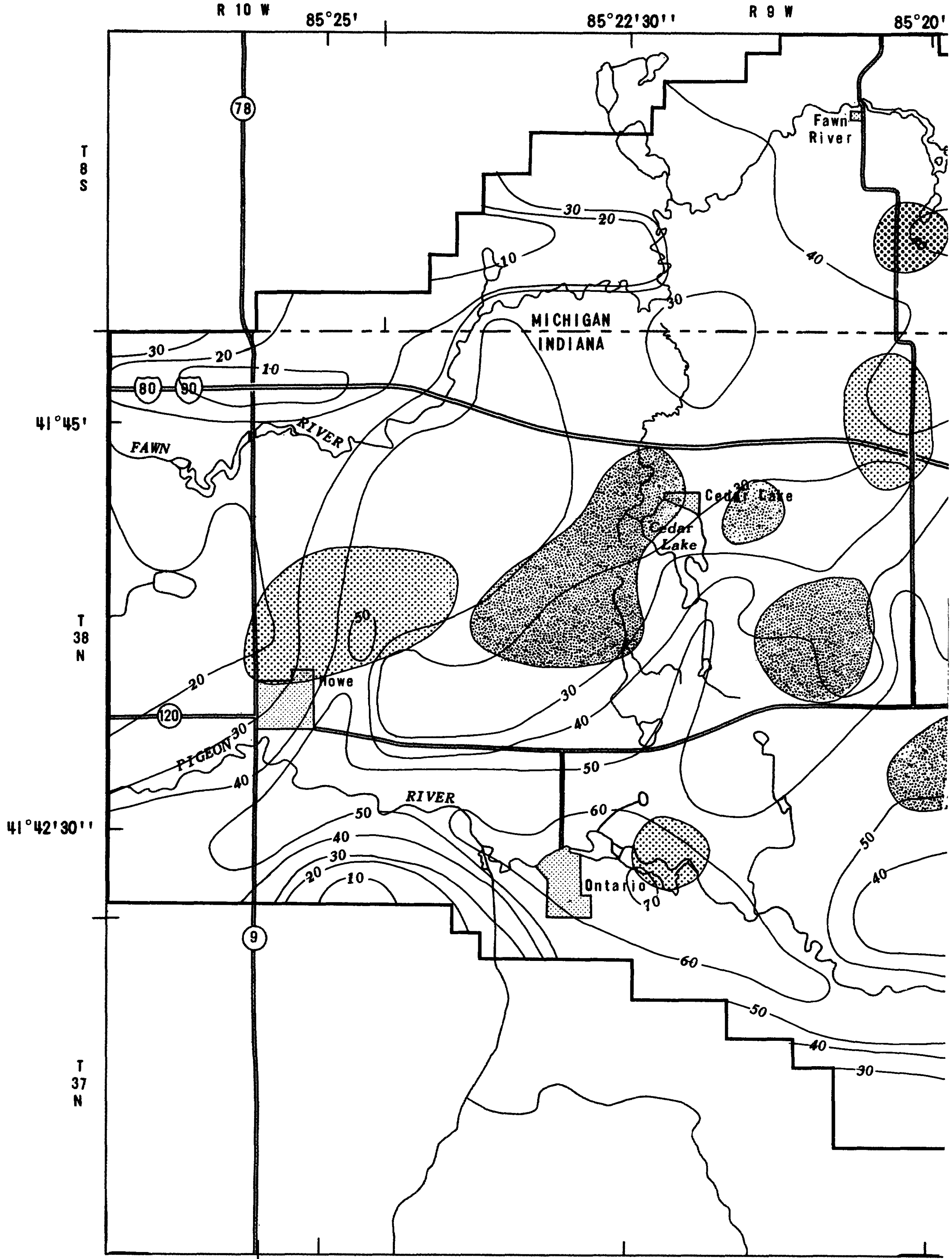
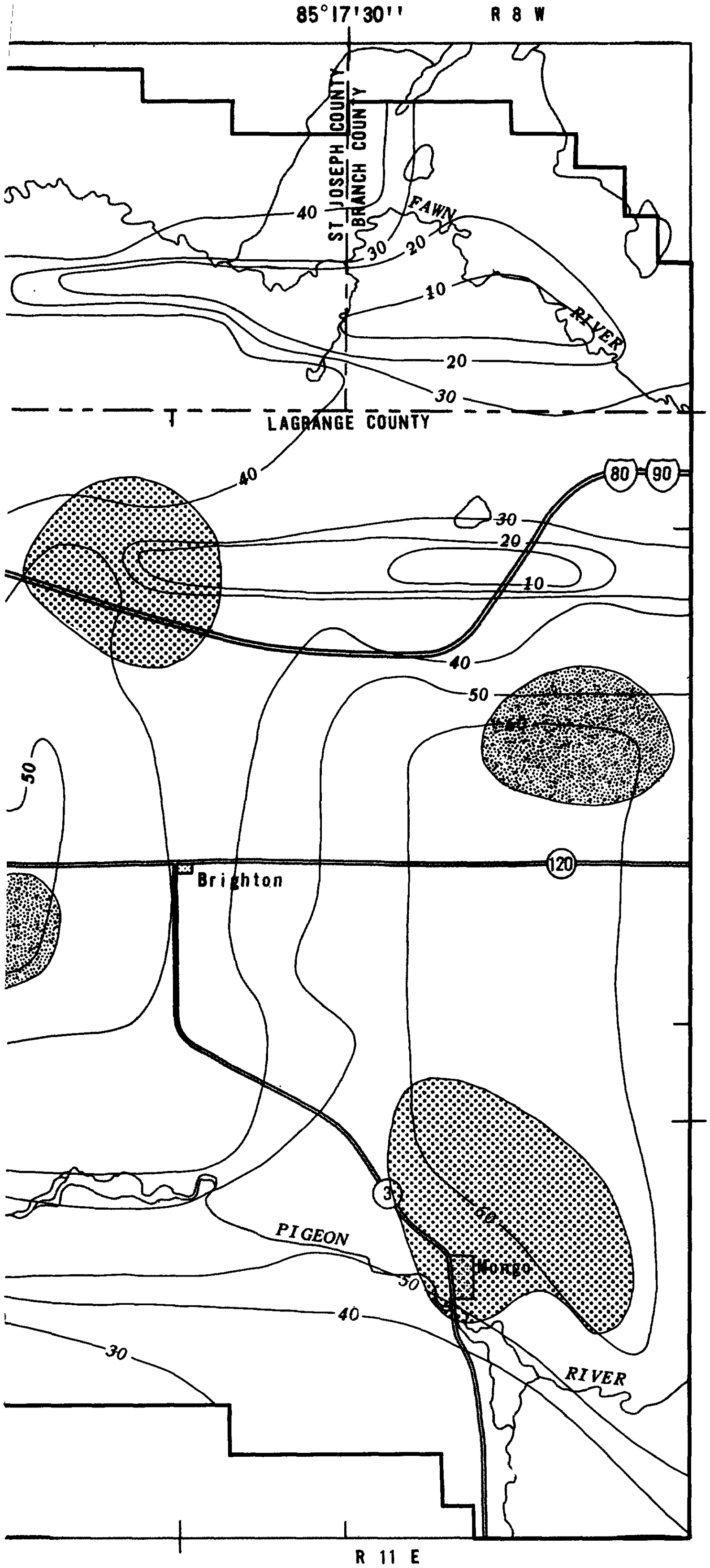


Figure 11.-- Saturated thickness of aquifer 1.



EXPLANATION

CLAY THICKNESS WITHIN AQUIFER 1, IN FEET

10

15

20

—50— LINE OF EQUAL THICKNESS OF SATURATED MATERIAL, AQUIFER 1--Interval 10 feet

ACTIVE-NODE BOUNDARY

0 2 MILES

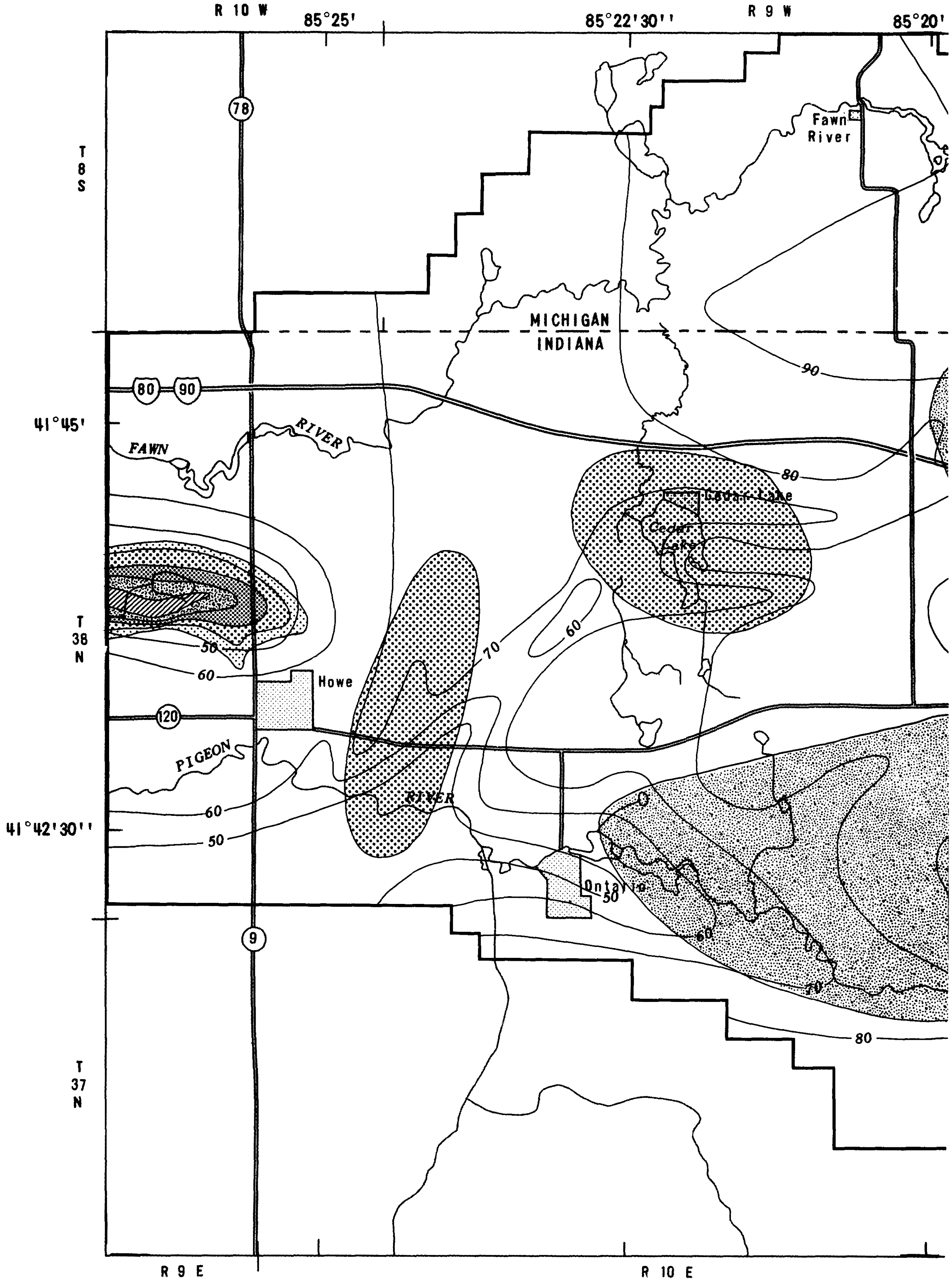
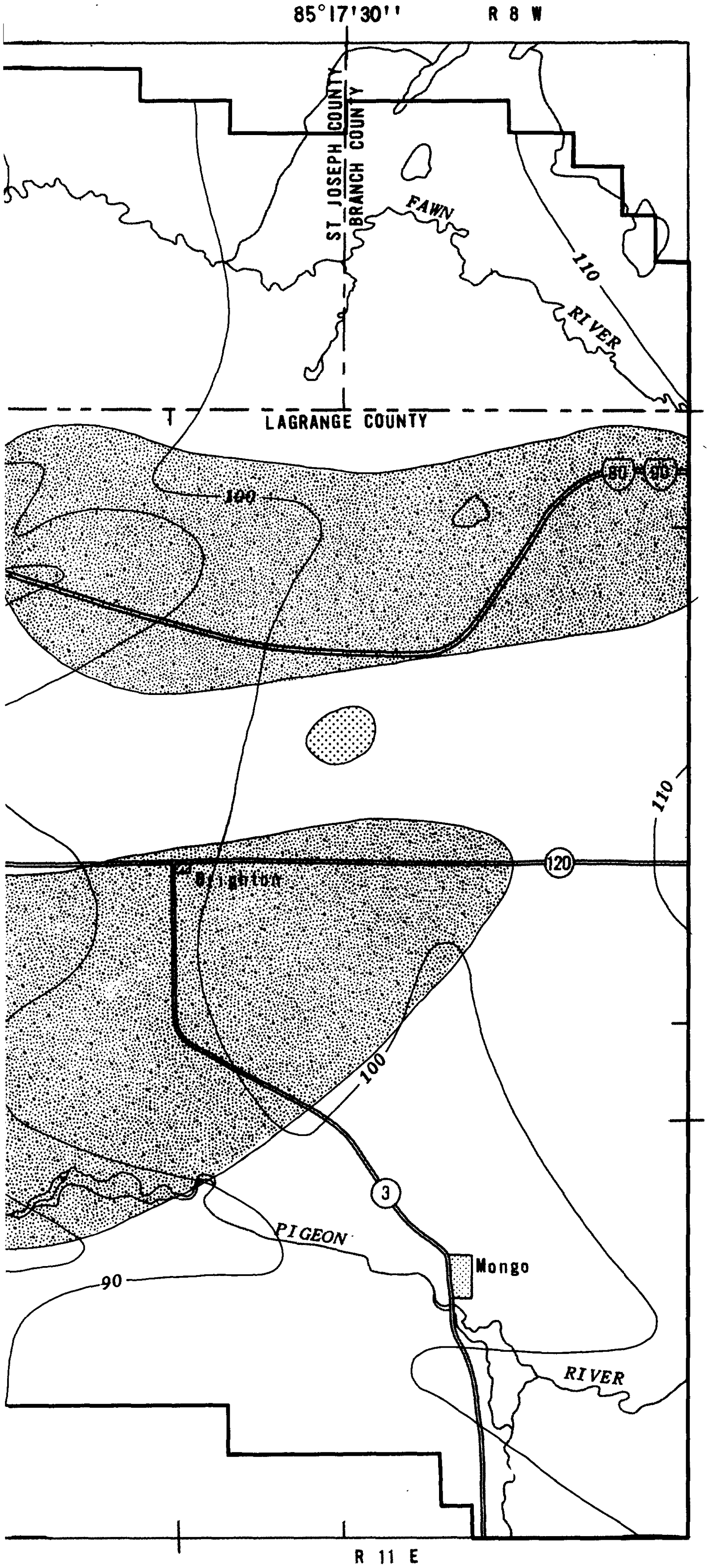


Figure 12.-- Saturated thickness of aquifer 2.



EXPLANATION

CLAY THICKNESS WITHIN AQUIFER 2, IN FEET

10, 15, 20, 30, 40, 50

—100— LINE OF EQUAL THICKNESS OF SATURATED MATERIAL, AQUIFER 2--Interval 10 feet

ACTIVE-NODE BOUNDARY

0 2 MILES

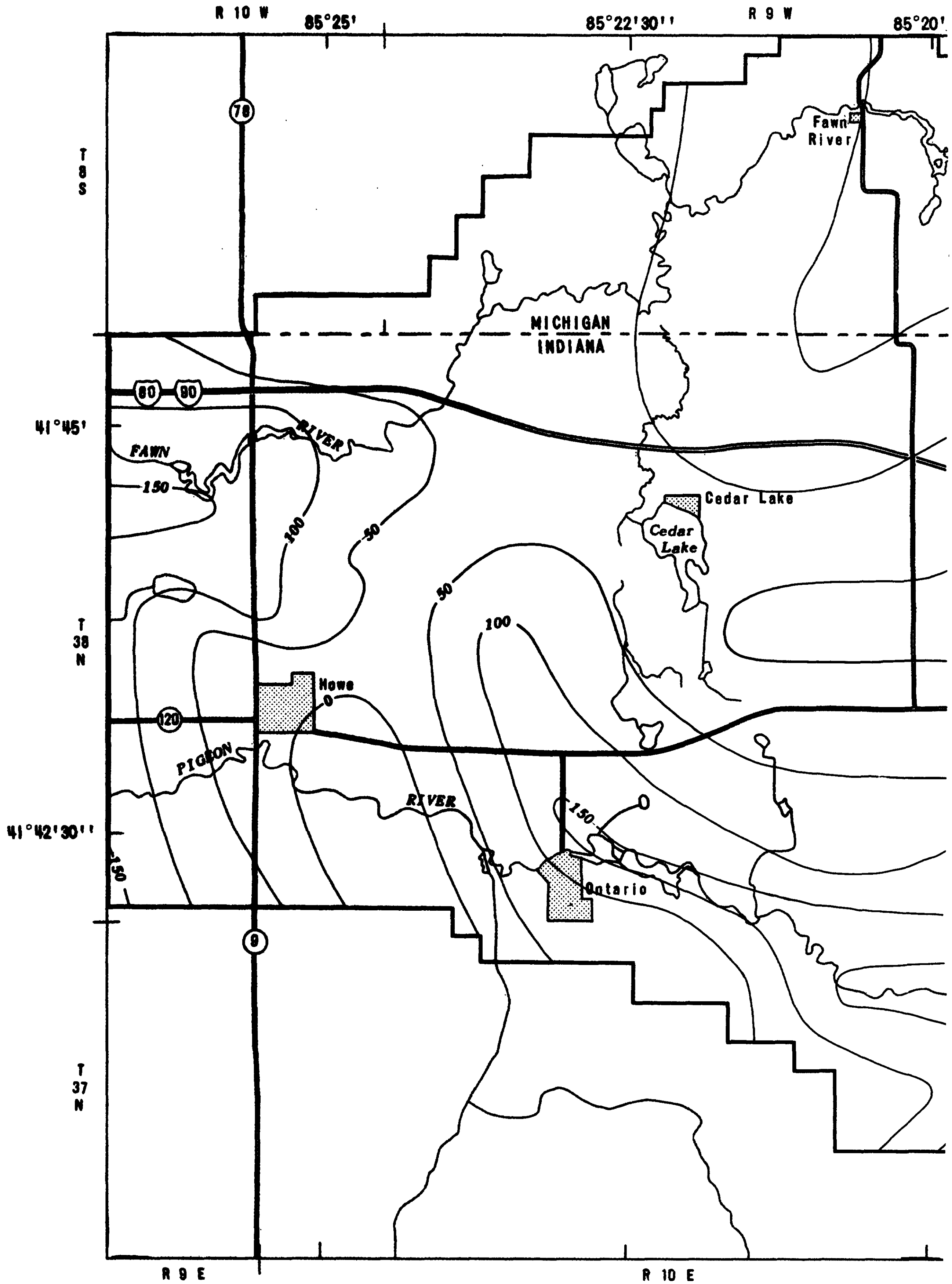
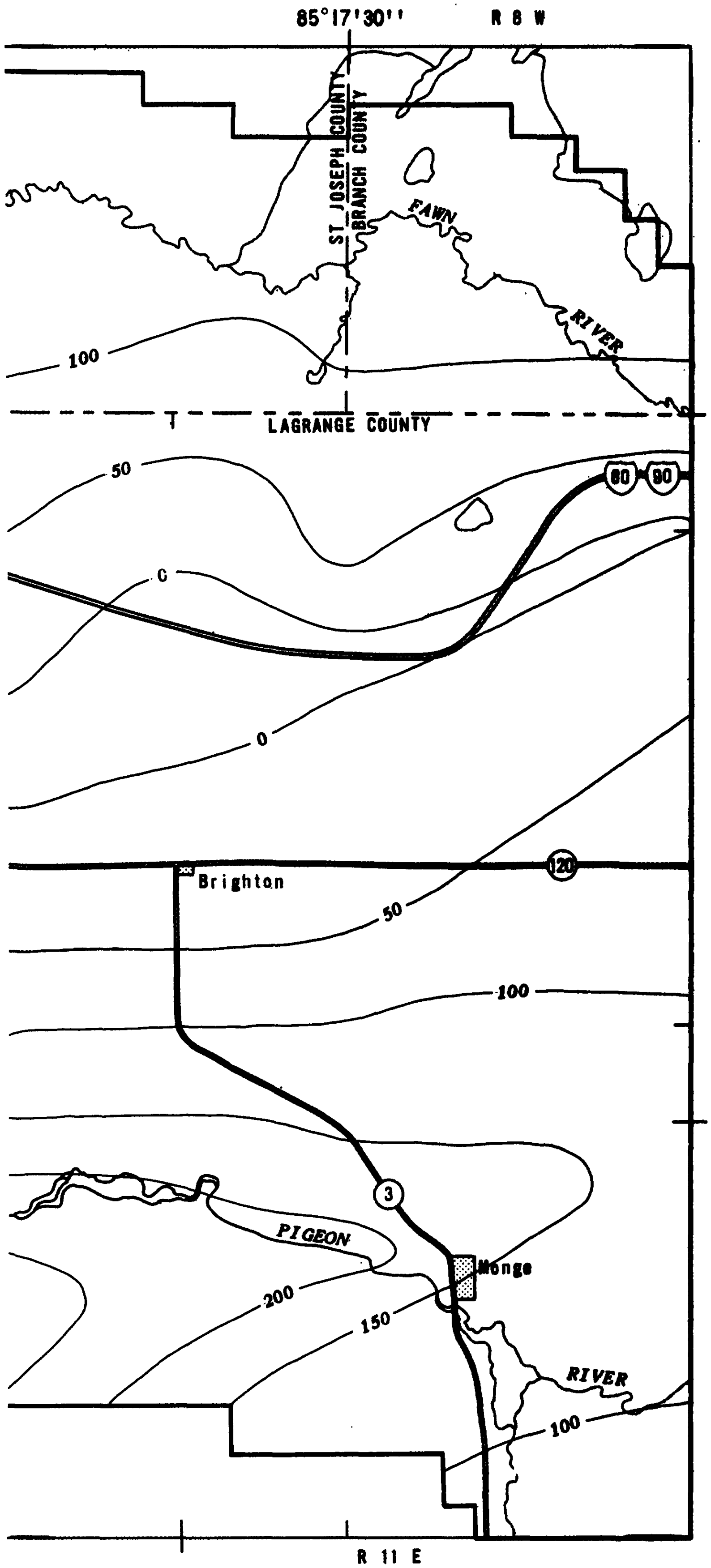


Figure 13.-- Saturated thickness of aquifer 3.



EXPLANATION

—50— LINE OF EQUAL THICKNESS OF SATURATED MATERIAL, AQUIFER 3--Interval 50 feet

▬▬ ACTIVE-NODE BOUNDARY

0 — 2 MILES

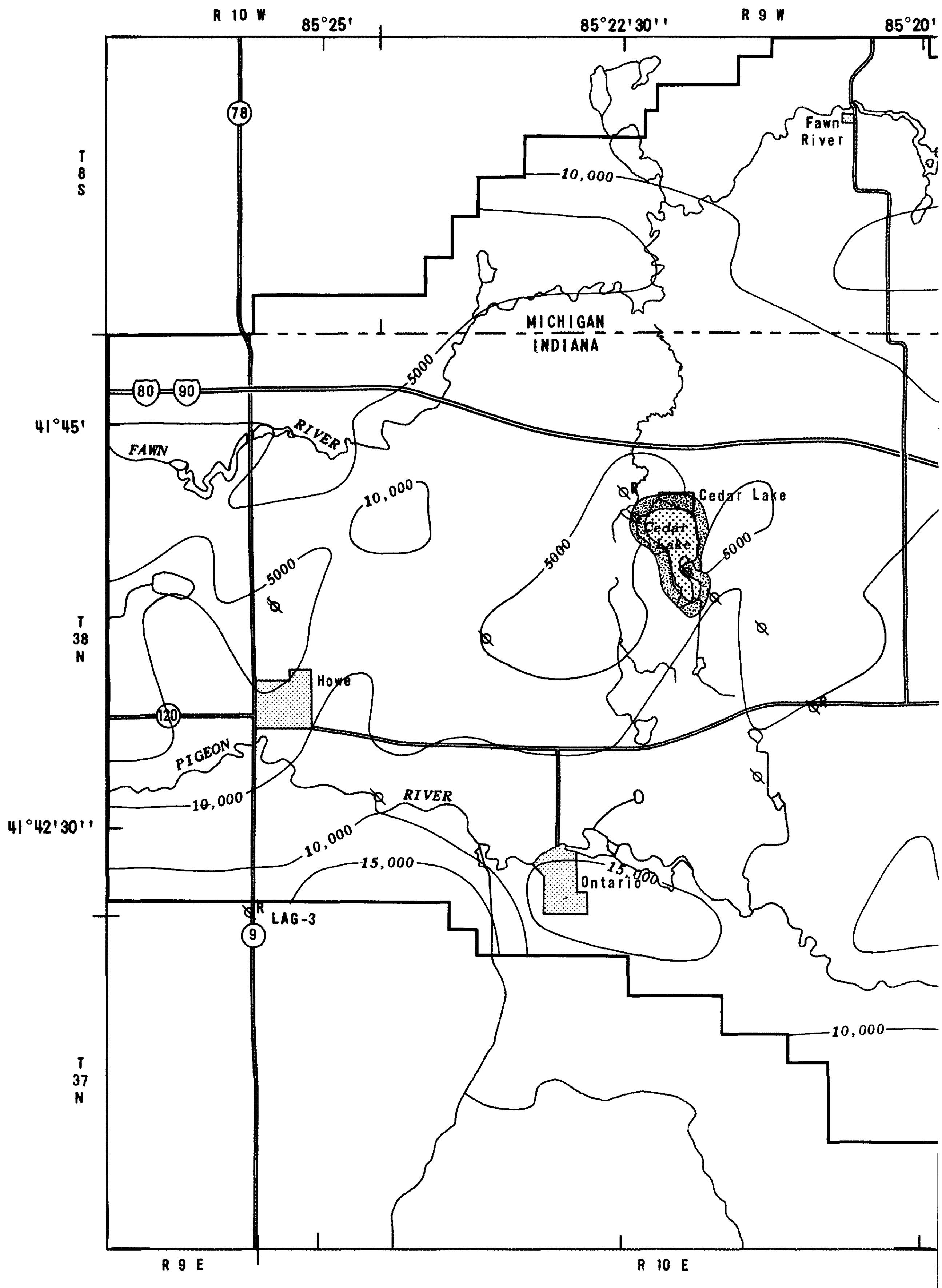
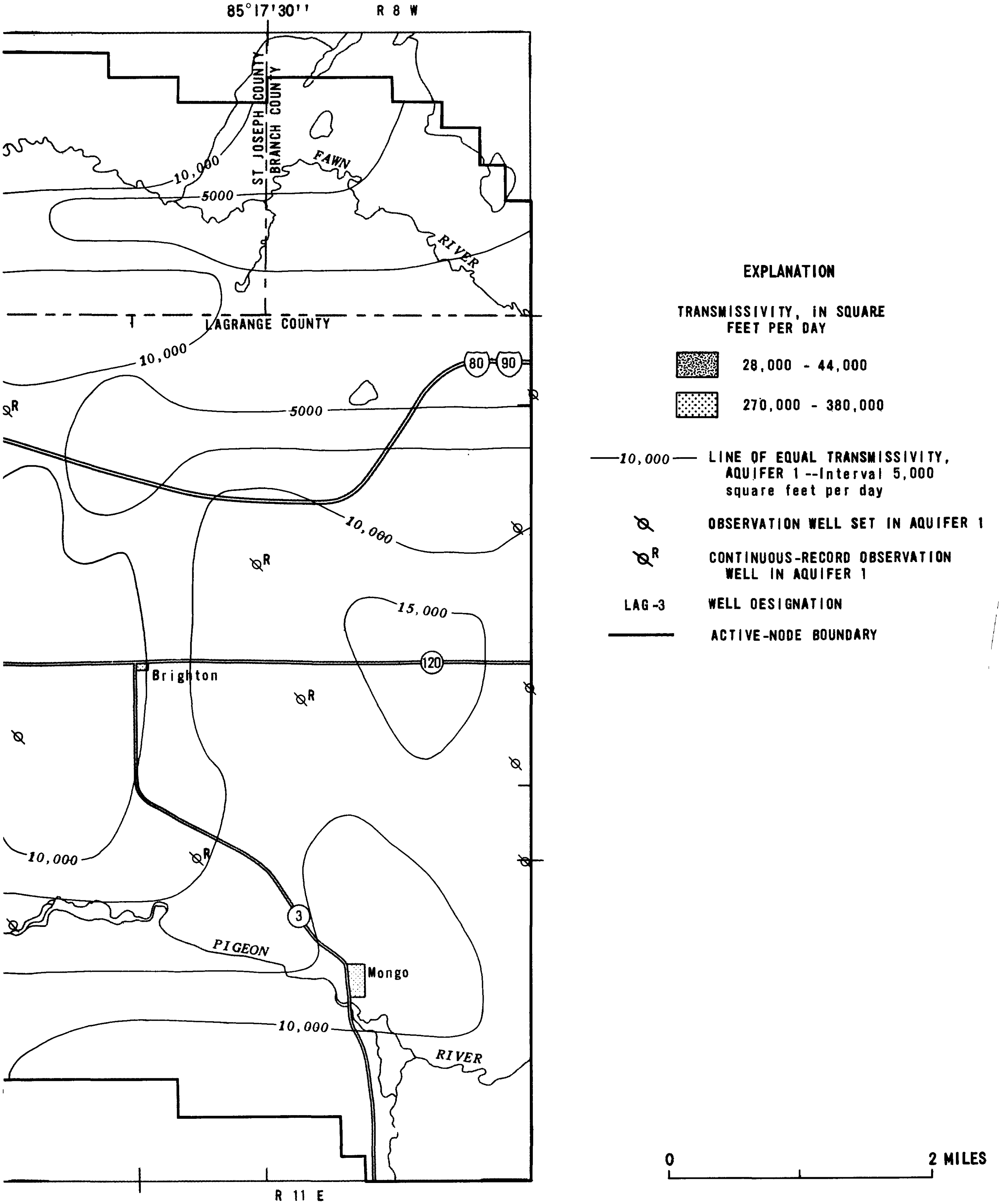


Figure 14.-- Transmissivity of aquifer 1 and locations of observation wells.



85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
10,000
5000
LAGRANGE COUNTY
10,000
80
90
5000
10,000
15,000
120
Brighton
10,000
3
PIGEON
Mongo
10,000
RIVER
R 11 E
EXPLANATION
TRANSMISSIVITY, IN SQUARE FEET PER DAY
28,000 - 44,000
270,000 - 380,000
10,000 LINE OF EQUAL TRANSMISSIVITY, AQUIFER 1 --Interval 5,000 square feet per day
OBSERVATION WELL SET IN AQUIFER 1
CONTINUOUS-RECORD OBSERVATION WELL IN AQUIFER 1
LAG-3 WELL DESIGNATION
ACTIVE-NODE BOUNDARY
0
2 MILES

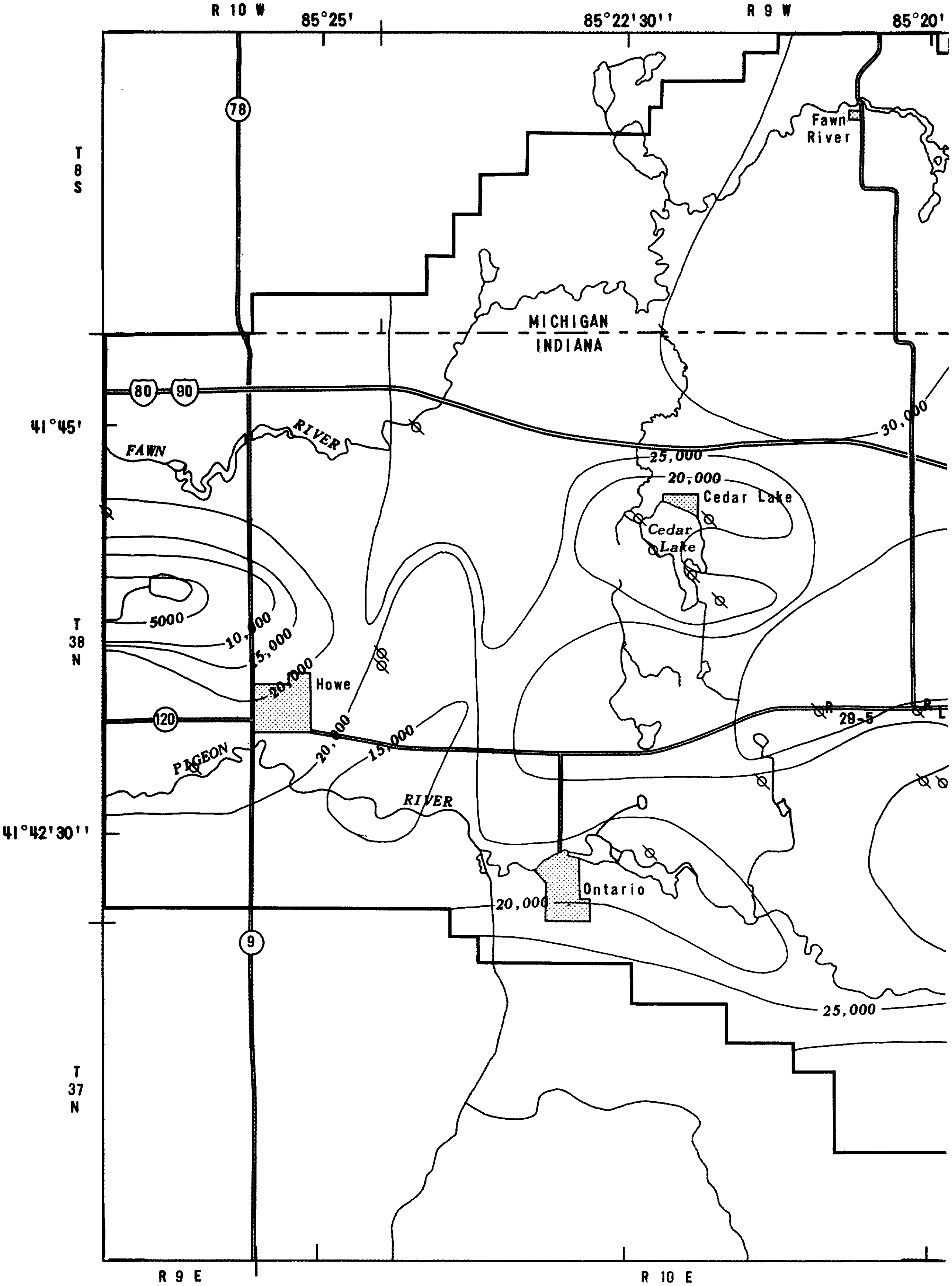
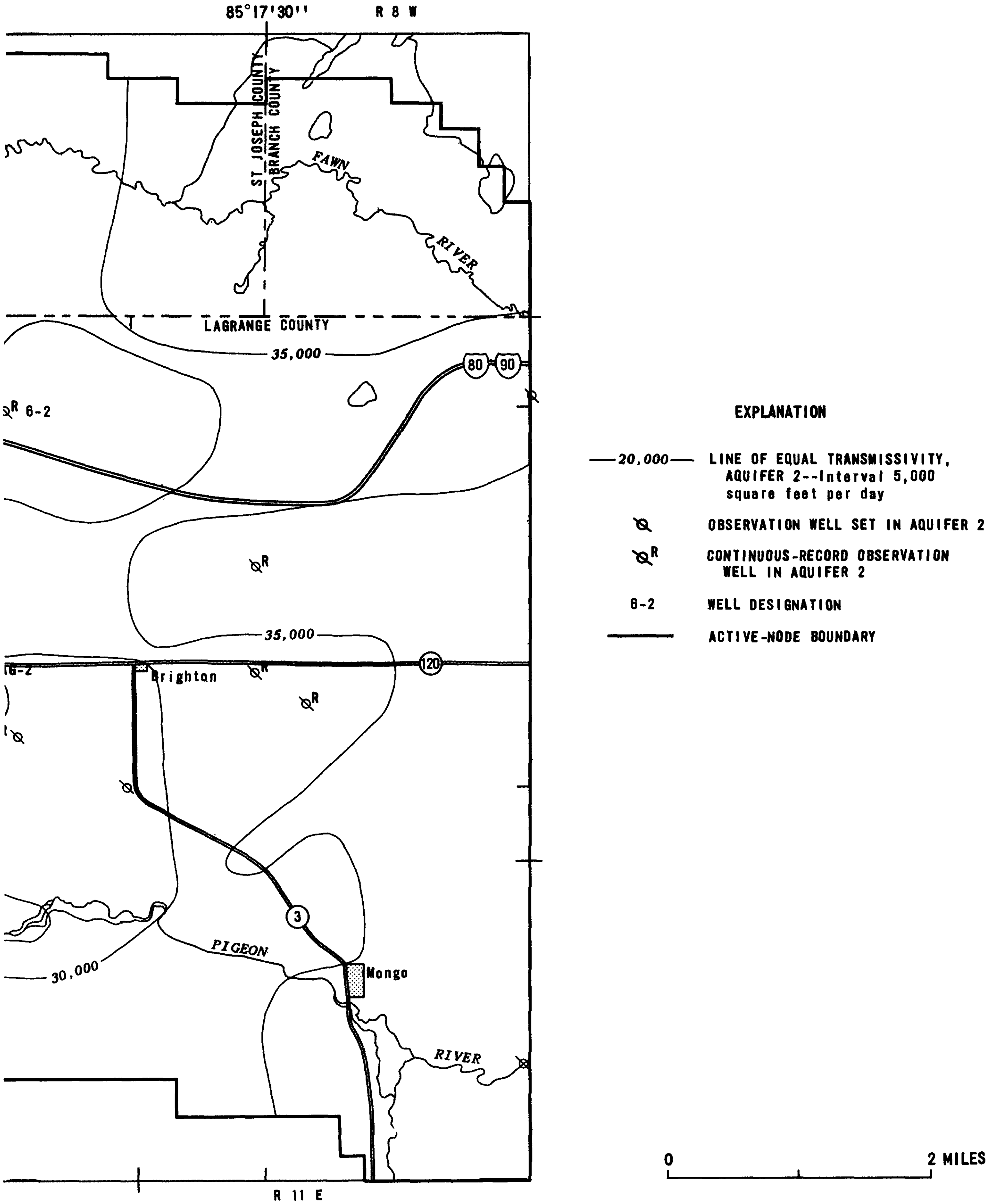


Figure 15.-- Transmissivity of aquifer 2 and locations of observation wells.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
35,000
80
90
6-2
R
35,000
120
Brighton
3
PIGEON
30,000
Mongo
RIVER
R 11 E
EXPLANATION
20,000 LINE OF EQUAL TRANSMISSIVITY, AQUIFER 2--Interval 5,000 square feet per day
OBSERVATION WELL SET IN AQUIFER 2
R CONTINUOUS-RECORD OBSERVATION WELL IN AQUIFER 2
6-2 WELL DESIGNATION
ACTIVE-NODE BOUNDARY
0
2 MILES

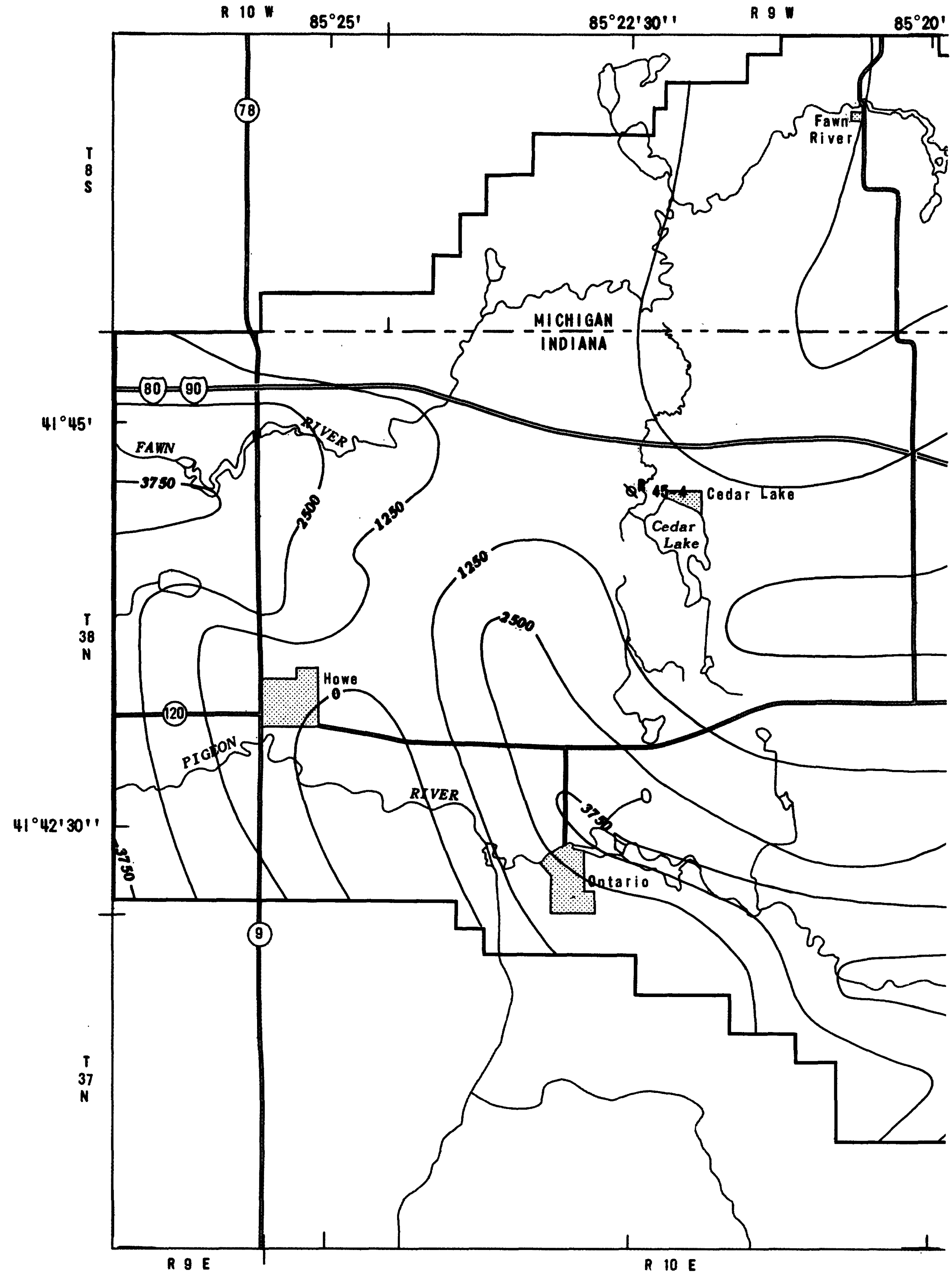
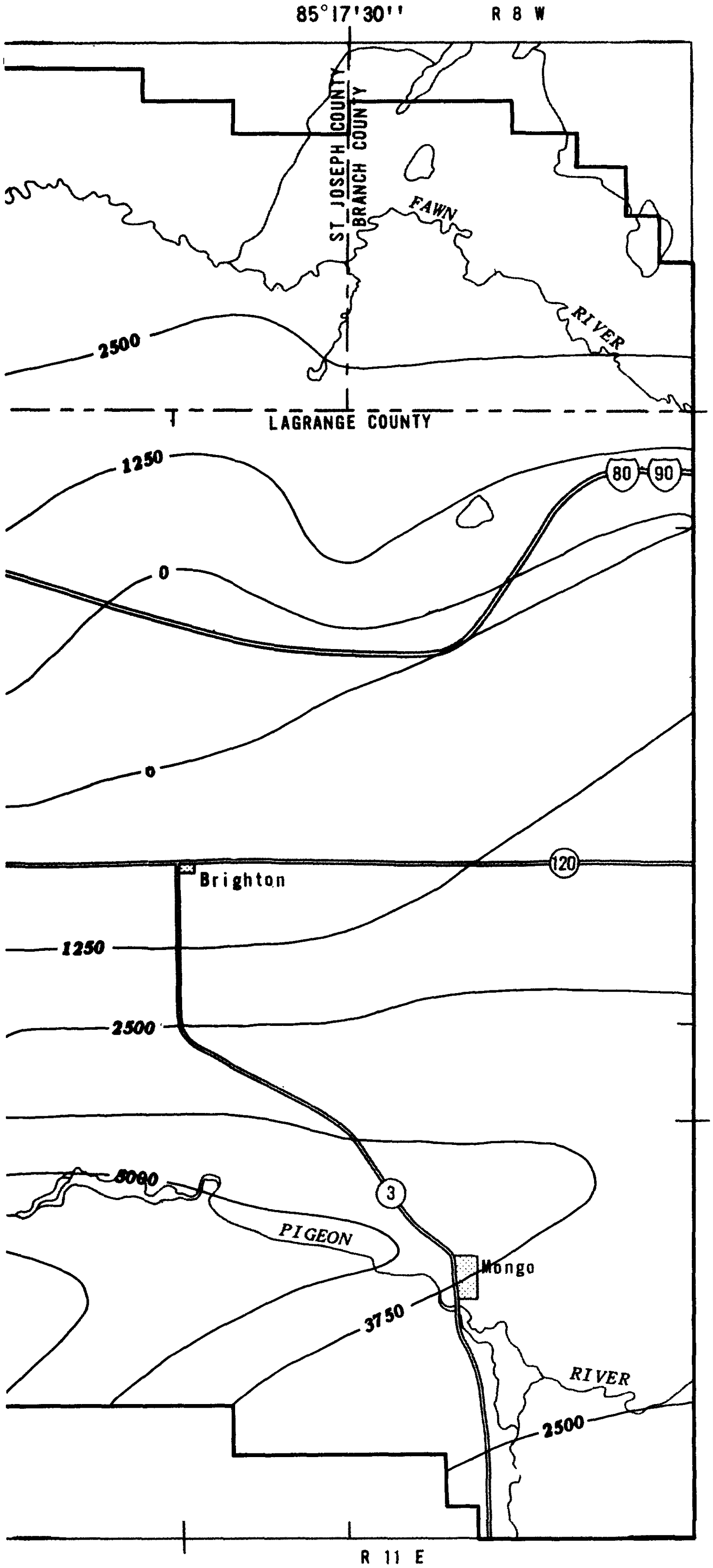


Figure 16.— Transmissivity of aquifer 3 and location of observation well.



EXPLANATION

—5,000— LINE OF EQUAL TRANSMISSIVITY, AQUIFER 3--Interval 1,250 square feet per day

R — CONTINUOUS-RECORD OBSERVATION WELL IN AQUIFER 3

45-4 WELL DESIGNATION

——— ACTIVE-NODE BOUNDARY

0 2 MILES

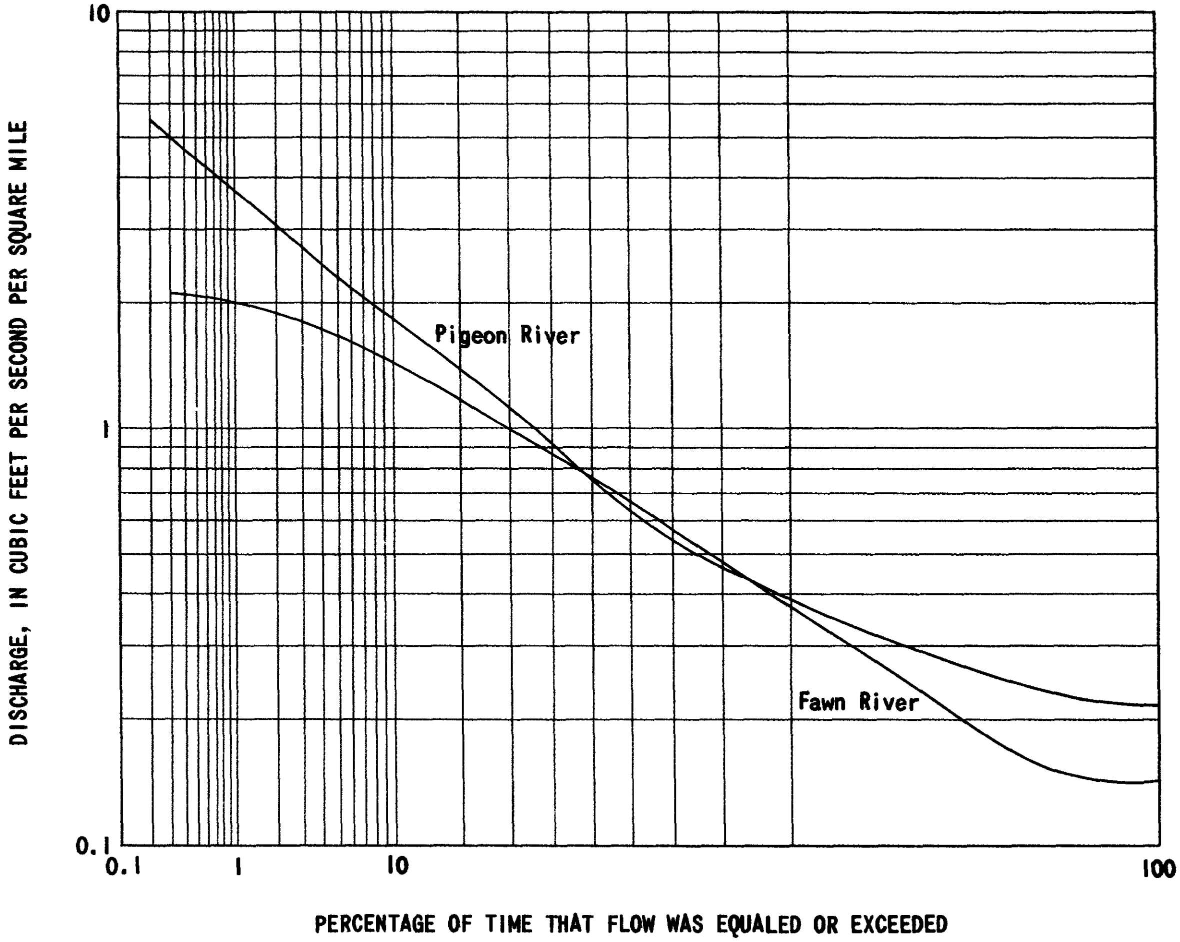


Figure 17.-- Flow duration curves for Pigeon River near Scott, Ind., and Fawn River near White Pigeon, Mich.

On August 31 and September 1-2, 1982, discharge was measured at 12 points in the Pigeon River basin and 12 points in the Fawn River basin to estimate ground-water gain or loss to the streams (fig. 3). Flow duration was 71-percent at Pigeon River near Scott, Ind. The discharge measurements are summarized in table 6. Maximum and minimum gains and losses were calculated to allow for a 5-percent measurement error.

Discharges were measured over a short time so that they could be compared at approximately equal flow durations. These measurements may have been affected by temporary stresses on the surface-water or ground-water systems. However, base-flow measurements of discharge within a basin can provide a more quantitative analysis of ground-water gain or loss to the surface water in a particular area than flow-duration analysis can provide.

Measurements along Fawn River (table 6) were affected by regulation and withdrawal of water from the stream. For example, between sites 17 and 15 discharge decreases from about 57 to 30 ft^3/s and then increases to about 60 ft^3/s at site 14. The decrease between sites 17 and 15 is only an apparent loss resulting from regulation of flow caused by the dam between the two sites. Because flow was regulated, the measurements on Fawn River were unreliable for assessing the hydraulic connection between surface water and ground water in the basin and for calibrating the ground-water-flow model.

Measurements along Pigeon River probably resulted in more reliable estimates of ground-water seepage than those along the Fawn River. The authors assumed that, under natural conditions, seepage along Fawn River would be similar to seepage along Pigeon River. This assumption is probably reliable because of the similarity of the flow-duration curves of the two rivers (fig. 17), especially for the 50- to 80-percent flow durations. Ground-water seepage to Pigeon River was at a uniform rate along the measured reach, and the total rate of contribution of ground water to streamflow in the study area was 40.5 ft^3/s.

From an analysis of flow-duration curves and base-flow measurements, the authors concluded that the ground-water and surface-water systems are well connected. A fairly consistent discharge is sustained by ground-water seepage and by lake and wetland storage with subsequent release to runoff.

Table 6.--Discharges and ground-water gains or losses along Fawn and Pigeon Rivers, August 31 through September 2, 1982
[FR, Fawn River; PR, Pigeon River; tr, tributary]

Measurement site[1]		Discharge Measured (ft^3/s)	Gain or Loss[2] (ft^3/s)	Range of discharge ± 5 percent (ft^3/s)		Range of gain or loss which allows for a 5 percent measurement error[2] (ft^3/s)	
				Maximum	Minimum	Maximum	Minimum
FR-20		31.8		33.4	30.2		
	tr-36	5.8		6.1	5.5		
FR-17		56.9	19.3	59.7	54.1	24.0	14.6
	tr-37	1.2		1.3	1.1		
FR-15		30.4	-27.7	31.9	28.9	-23.3	-32.1
	tr-39	3.9		4.1	3.7		
	tr-41	2.4		2.5	2.3		
	tr-43	1.9		2.0	1.8		
	tr-28	2.6		2.7	2.5		
	tr-23	5.6		5.9	5.3		
FR-14		59.7	19.8	62.7	56.7	24.8	14.8
FR-13		62.3	2.6	65.4	59.2	8.7	-3.5
		Gain	14.0				
PR-9		61.0		64.0	58.0		
	tr-38	1.1		1.2	1.0		
	tr-33	0		0	0		
	tr-31	28.5		29.9	27.1		
PR-8		101.0	10.4	106.0	96.0	19.9	0.9
PR-6		111.0	10.0	116.6	105.4		
	tr-34	2.9		3.0	2.0		
	tr-30	0.04		0.04	0.04		
	tr-32	0		0	0		
PR-4		123.0	9.1	129.2	116.8	21.0	2.8
	tr-35	22.0		23.1	20.9		
PR-1		156.0	11.0	163.8	148.2	26.1	-4.1
		Gain	40.5				

[1]Locations shown in figure 3.
[2]Negative number (loss) indicates flow into ground water (except for site 15).

Recharge

Recharge to the outwash is from precipitation that percolates to the water table. Recharge is less than precipitation because of evapotranspiration and surface runoff.

Average annual precipitation is 34.5 in. and average annual evapotranspiration is estimated to be 25 in. (Reussow and Rohne, 1975). If surface runoff is assumed to be zero, because of the highly permeable soils over most of the area, then maximum annual recharge is 9.5 in.

Pettijohn (1968) reported rates of annual recharge in the St. Joseph River basin through several types of surficial material. Average annual recharge through dune sand is 25 in.; through kames and eskers, 6.3 in.; through till and lake deposits, 4.2 in.; and through soil cover, 10.5 in. The distribution of these rates is shown in figure 4. The recharge over large areas could still average about 9.5 in/yr even though local rates through differing surficial materials may vary.

Evapotranspiration is probably from water intercepted in the soil-moisture zone rather than from the water table, except in the wetlands. Average depth below land surface to the water table during autumn 1982 was 21 ft. Depth to the water table ranges from 2 ft in the wetlands to 60 ft in the eastern part of the area. Water levels in wells in the wetlands are 7 ft or less below land surface, which indicates that evapotranspiration may include water from the water table.

Water-Level Fluctuations

Seasonal ground-water fluctuations are related to recharge and the effects of stresses, such as pumping, on the system. Natural seasonal fluctuations are related to seasonal changes in precipitation, evapotranspiration, and, thus, changes in recharge. Constant fluctuations from year to year are indicative of a ground-water system at steady state, and recharge and discharge are about equal on an annual basis. The period of record for hydrographs in this area is too short to demonstrate whether the system is at steady state, but steady-state is assumed. A representative hydrograph from each aquifer was selected to show the seasonal fluctuations.

Observation well Lagrange 3 (LAG-3) is in aquifer 1 (fig. 14). The hydrograph (fig. 18) was incomplete during 1981, but the water-level fluctuation during the 1982 water year (October 1981 to October 1982) was as much as 5.4 ft. Effects of irrigational pumping are not observable on the graph, but fluctuations are closely related to changes in stage of the Pigeon River.

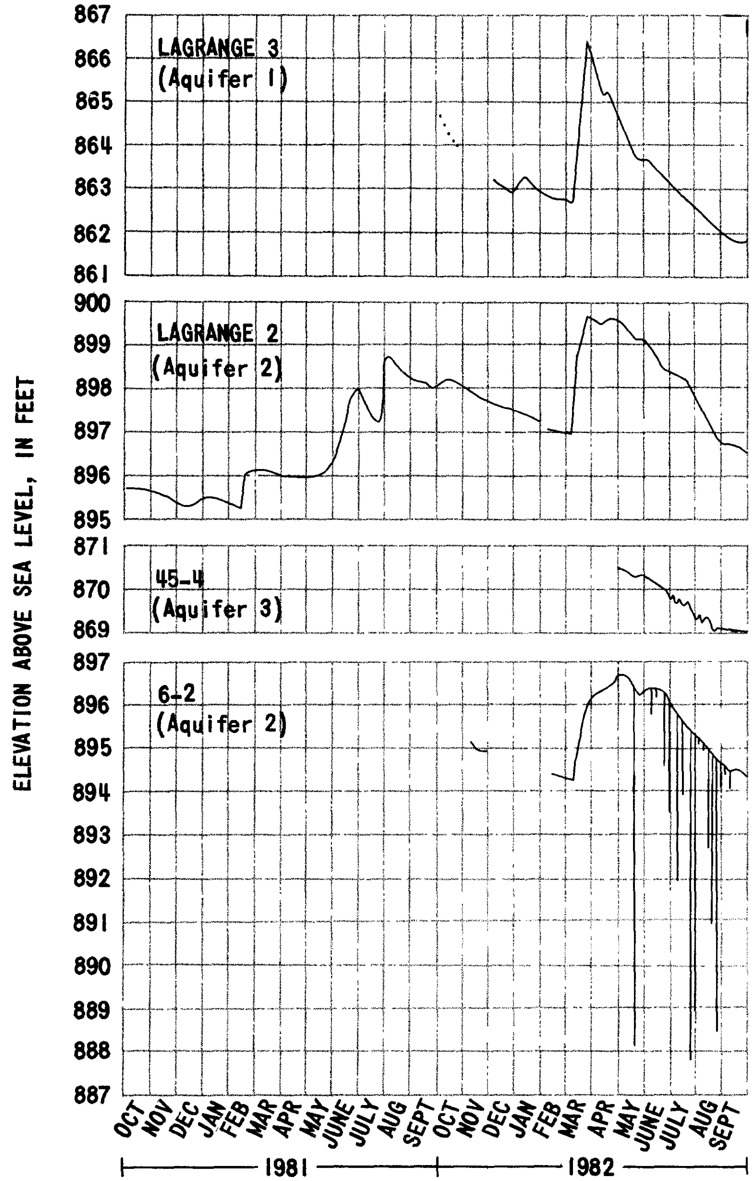


Figure 18.-- Water levels in observation wells LaGrange 3, LaGrange 2, 45-4, and 6-2.

Water levels in aquifer 2 have been continuously recorded at observation well Lagrange-2 (LAG-2) since May 1980 (fig. 15). In 1981, the maximum water-level fluctuation was 3.5 ft (fig. 18). The maximum water-level fluctuation for the period of record was 4.4 ft. Short-term, water-level fluctuations of less than 0.1 ft, possibly due to irrigational pumping, were recorded but are not detectable at the scale of this hydrograph (fig. 18). Although observation well Lagrange-2 is surrounded by irrigation wells, any effect of pumping is minimal compared to the natural water-level change during seasonal irrigation.

The only continuous water-level data available for aquifer 3 were from well 45-4 north of Cedar Lake (fig. 16). Although the data span a short period of time (fig. 18), the water-level fluctuation in the deep aquifer is smaller than in the shallower aquifers for the period of record.

Water levels around Howe are typically high in the spring and gradually lower through the summer and autumn as precipitation declines (fig. 19) and evapotranspiration increases. However, this pattern is not observable in the hydrograph for Lagrange-2 during the 1981 water year because of generally low precipitation from October through March and much higher than average precipitation from April through September (figs. 18 and 19). The normal pattern is observable in hydrographs for the 1982 water year because monthly precipitation was closer to the long-term averages during that period; therefore, data from the 1982 water year more nearly represent average conditions than data from 1981. However, ground-water levels were probably higher than normal at the beginning of the water year because of higher than normal recharge during 1981 and the unusually high volume of snowmelt that accompanied the higher-than-average rain in spring 1982.

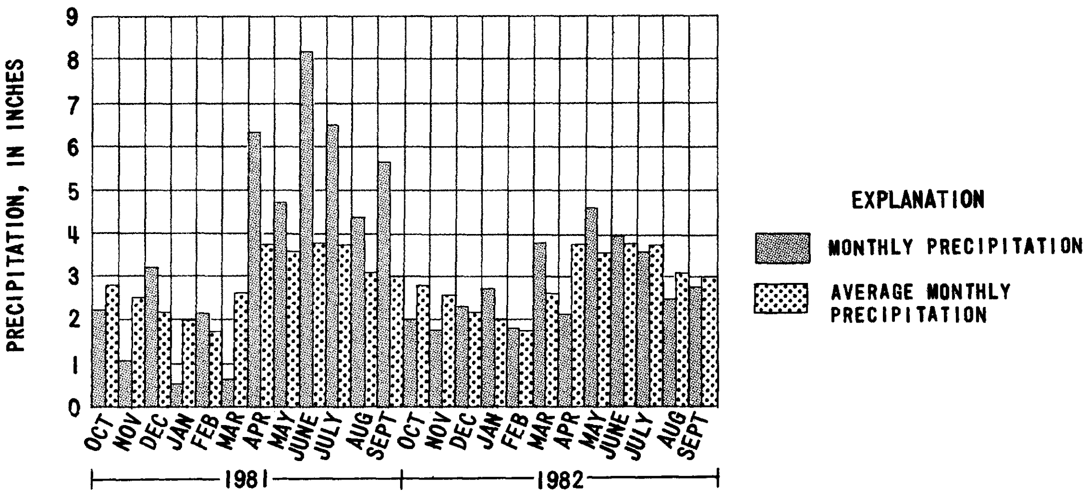


Figure 19.-- Precipitation near Howe, Ind.

The effects of pumping aquifer 2 for irrigation, from late May to September 1982, are shown in the hydrograph of well 6-2 (fig. 18). This well (figs. 3 and 15) is 154 ft from a pumping well. However, the natural seasonal decline in water level can also be seen if a smooth line is drawn (as in fig. 18) through most of the data points that represent water levels during periods of no pumping. This pattern of decline is similar to the declines in Lagrange- 2 and -3, which are virtually unaffected by pumping. Other hydrographs of wells near irrigational pumping are similar to the pattern in the hydrograph of well 6-2. Although effects of irrigation on water levels can be locally severe near the wells during pumping, water levels recover rapidly to near normal for that time of year. Thus, water-level declines in summer are probably caused by ground-water seepage to streams, low stream stage, and evapotranspiration rather than by irrigational pumping.

Figure 20 is a hydrograph of the effects of pumping on water levels during discrete periods of pumping. Well 29-5 (figs. 3 and 15) is 297 ft from an irrigational well. The two wells are in aquifer 2. The water level was drawn down to nearly its minimum level in less than 10 minutes after pumping began.

The drawdown curve was nearly horizontal for the remainder of the pumping time. After pumping was stopped, recovery was just as rapid as the initial drawdown. Although water-level declines near irrigational wells can be locally significant, the water levels recover quickly after pumping is stopped and return to near background levels.

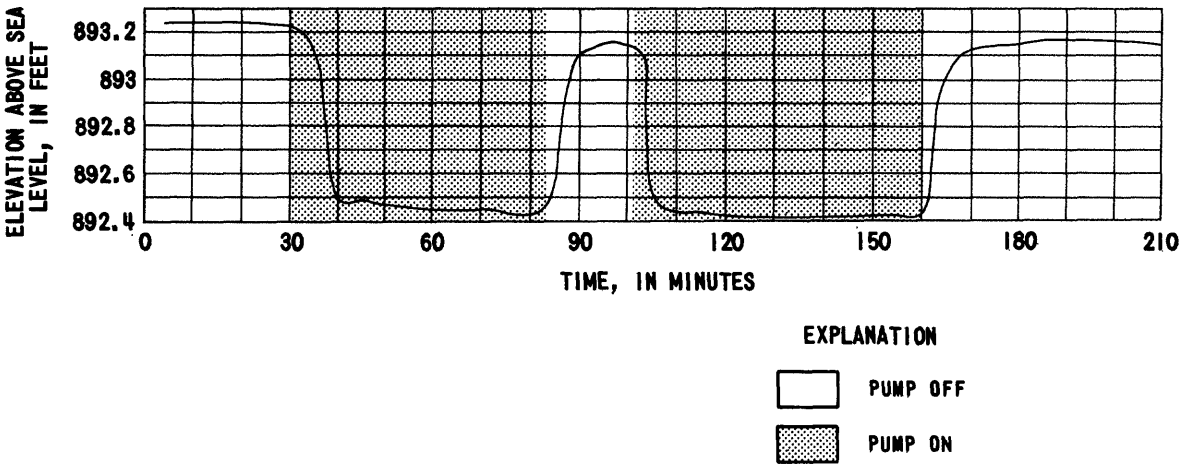


Figure 20.-- Water levels in observation well 20-5.

Ground-Water Flow

The upper part of the outwash, aquifer 1, is a water-table aquifer (fig. 5), except for the areas shown in figure 8 where surficial deposits are clay. The outwash below aquifer 1 is generally confined by extensive, thick clay deposits. The outwash aquifer system is recharged by precipitation and ground-water inflow across the boundary of the area of study. Discharge is by seepage into Fawn and Pigeon Rivers, by pumping, by ground-water underflow, and by evapotranspiration in the wetlands.

Regional flow is from east to west. The local pattern of flow is dominated by flow toward Fawn and Pigeon Rivers. The ground-water divide corresponds closely to the surface water divide which is along State Highway 120 across the middle of the area.

Flow lines were constructed for aquifer 1 (fig. 21) from a potentiometric surface at 5-foot contour intervals. The flow lines are equidistantly spaced at the eastern boundary, and the flow into the area is widely dispersed toward Fawn and Pigeon Rivers. Only a small percentage of that flow crosses the western boundary as ground-water underflow.

Water levels in wells around Cedar Lake indicate that ground water flows into and out of the lake. A complex system of local flow (not shown in fig. 21) has developed around the lake. In the upper part of the outwash, ground-water flow is locally diverted into the lake on three sides and out on the surface-water-outlet side (fig. 21); that is, water levels in wells around the lake are higher than the elevation of the lake, except at the northwestern (outlet) side where they are lower.

Flow in the outwash is generally horizontal. However, water levels in nested wells along the east boundary are indicative of downward flow. Flow is upward under the wetlands (figs. 5 and 7) and rivers.

HYDROLOGIC EFFECTS OF WATER WITHDRAWALS

Quantitative techniques were developed to determine the effects of surface-water withdrawals on the elevation of Cedar Lake and on the streamflow of Pigeon River. A digital ground-water-flow model was constructed to simulate the flow system. The model was used to estimate the components of the water budget and to evaluate the effects of current and hypothetical pumping on the hydrologic system.

Surface-Water Withdrawals

Cedar Lake

A method was devised to estimate the rate of pumping from Cedar Lake that could be sustained by allowing the level of the lake to decline to the legal minimum elevation, 871.9 ft. First, a flow-duration curve was constructed for Cedar Lake by a station-correlation technique (Riggs, 1972). By this technique, discharges at a partial-record station are plotted against the mean daily discharge of a continuous-record station for the same day. After the correlation is developed, the flow-duration curve for the partial-record site can be estimated from the duration curve of the long-term continuous-record site.

Lake levels and discharges at the outlet (fig. 3, site 43) of Cedar Lake were measured daily. The discharge for the outlet was plotted against stage of the lake (fig. 22) and was also plotted against mean daily discharge of the Elkhart River at Goshen (fig. 23, location shown in fig. 1). Construction of the flow-duration curve for the outlet of Cedar Lake (fig. 24) was based on the flow-duration curve for the Elkhart River at Goshen and a corresponding discharge at the outlet (from fig. 23). For example, if the discharge of the Elkhart River is 380 ft^3/s at 50-percent flow duration, then the corresponding discharge for the outlet of Cedar Lake (fig. 23) is 2.7 ft^3/s. Discharge can be estimated from the flow-duration curve for the outlet.

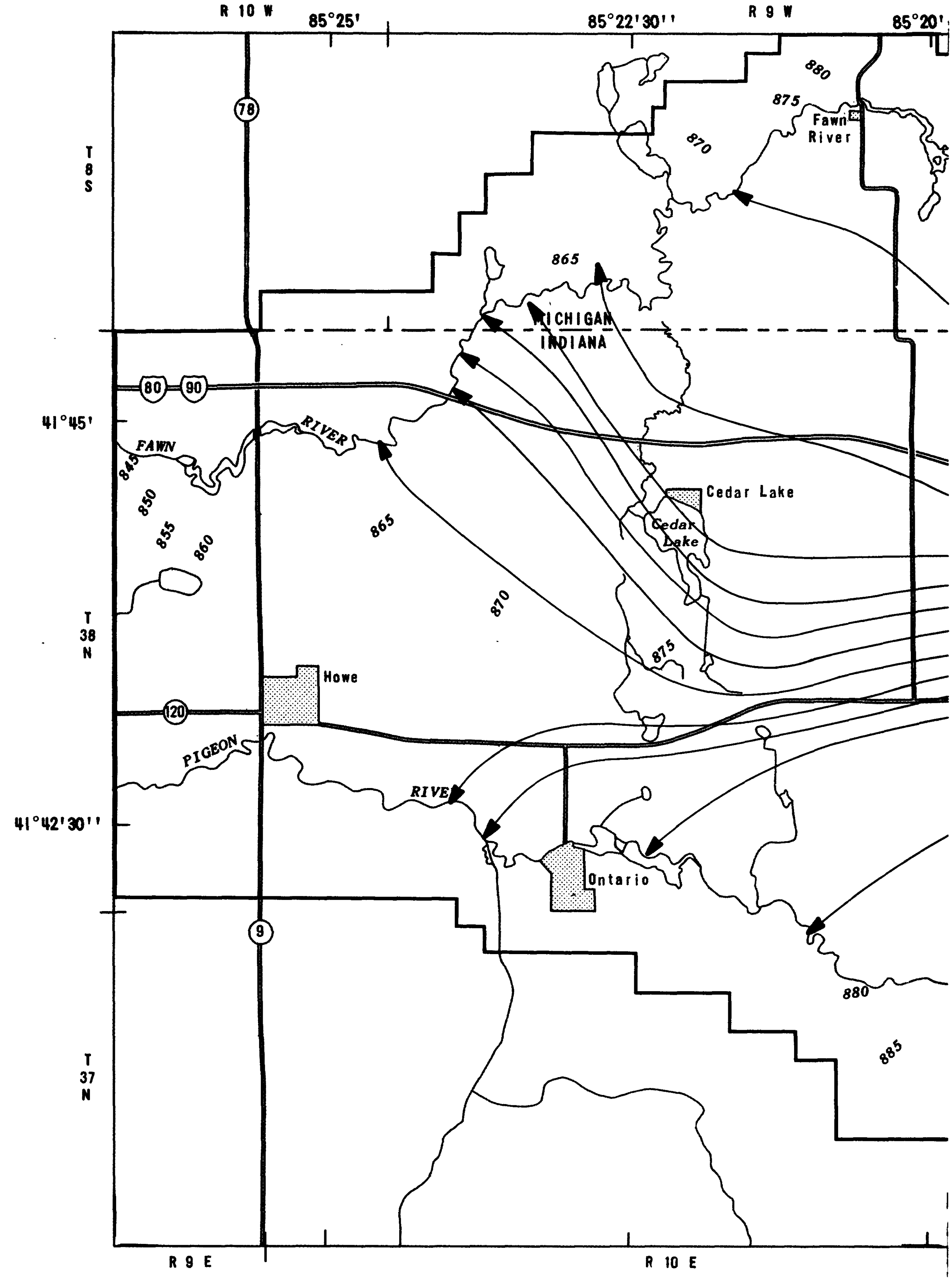
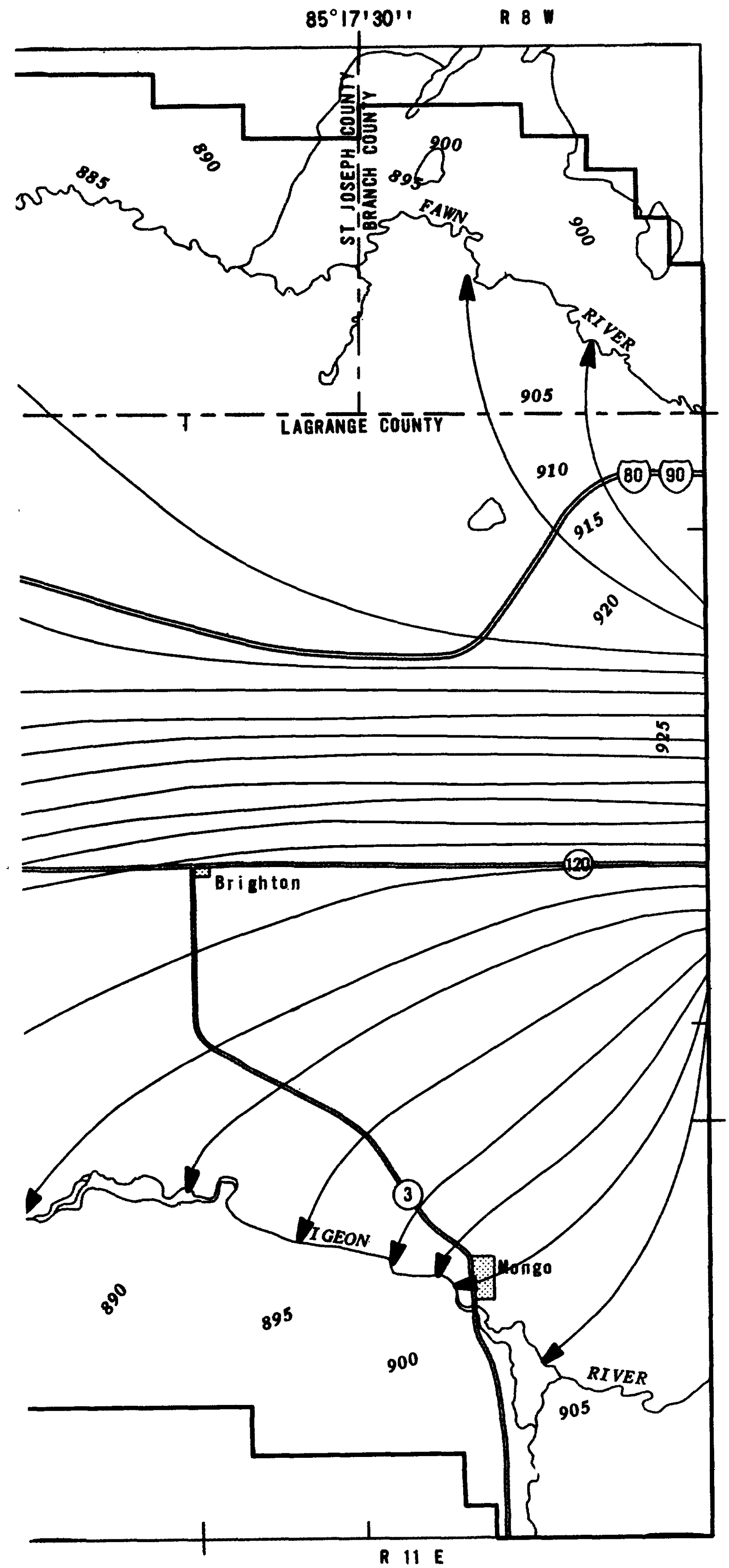


Figure 21.-- Generalized ground-water flow in aquifer 1.



EXPLANATION

920 — LINE OF EQUAL WATER LEVEL, LAYER 1--Interval 5 feet

OBSERVATION WELL

DIRECTION OF FLOW

ACTIVE-NODE BOUNDARY

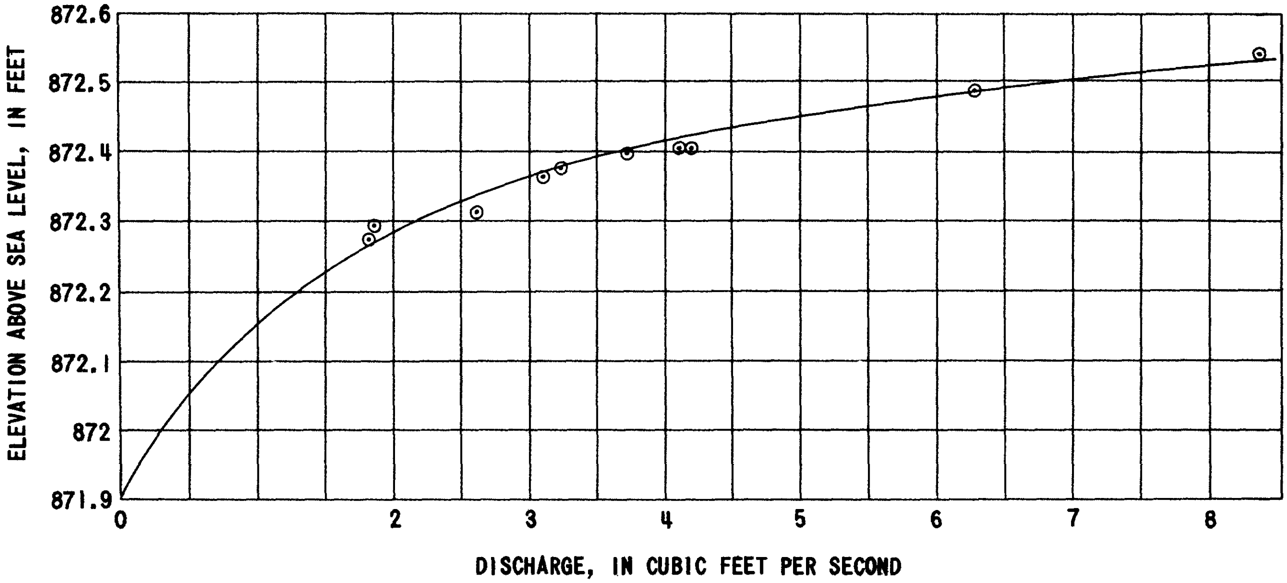


Figure 22.-- Stage and discharge at the outlet of Cedar Lake.

Discharge from Cedar Lake may be estimated from the flow-duration curve, but local conditions may cause errors in the estimate. Two factors that affect the lake, especially during the growing season, are evaporation and withdrawal of water for irrigation. Use of the duration curve, therefore, requires adjustments for evaporation and pumping losses. Daily pan-evaporation data for the weather-observing station at Prairie Heights (fig. 1) are available for estimating evaporative losses at Cedar Lake. Discharge measurements at the inlet and the outlet of Cedar Lake (table 7) indicate that inflow exceeds outflow. Two possible causes for this difference are evaporation and seepage from the lake to the ground-water system.

The stage-discharge curve (fig. 22) and flow-duration curve (fig. 24) can be used to estimate how much water could be pumped from Cedar Lake to lower the elevation to the legal minimum of 871.9 ft. For example, at 80-percent flow duration, the discharge at the outlet of Cedar Lake would be about 1.8 ft^3/s (fig. 24), and the elevation would be 872.26 ft (fig. 22). The lake would have to be lowered 0.36 ft to reach the legal minimum, and, during the lowering of the lake, outflow would be lowered from 1.8 ft^3/s to zero (fig. 22). This lowering to zero would not be linear, thus, by integrating the curve (fig. 22) between 1.8 ft^3/s (872.26 ft) and zero (871.9 ft), the average outflow during that time would be 0.8 ft^3/s. Inflow and outflow were measured simultaneously only three times (table 7), and only two of these were done when flow was at 80-percent flow duration (about 1.8 ft^3/s). Average inflow based on these two measurements is 2.7 ft^3/s. If evaporation and ground-water seepage are neglected, then the amount of water available for pumping from the lake is equal to the sum of inflow, outflow, and lake storage capacity.

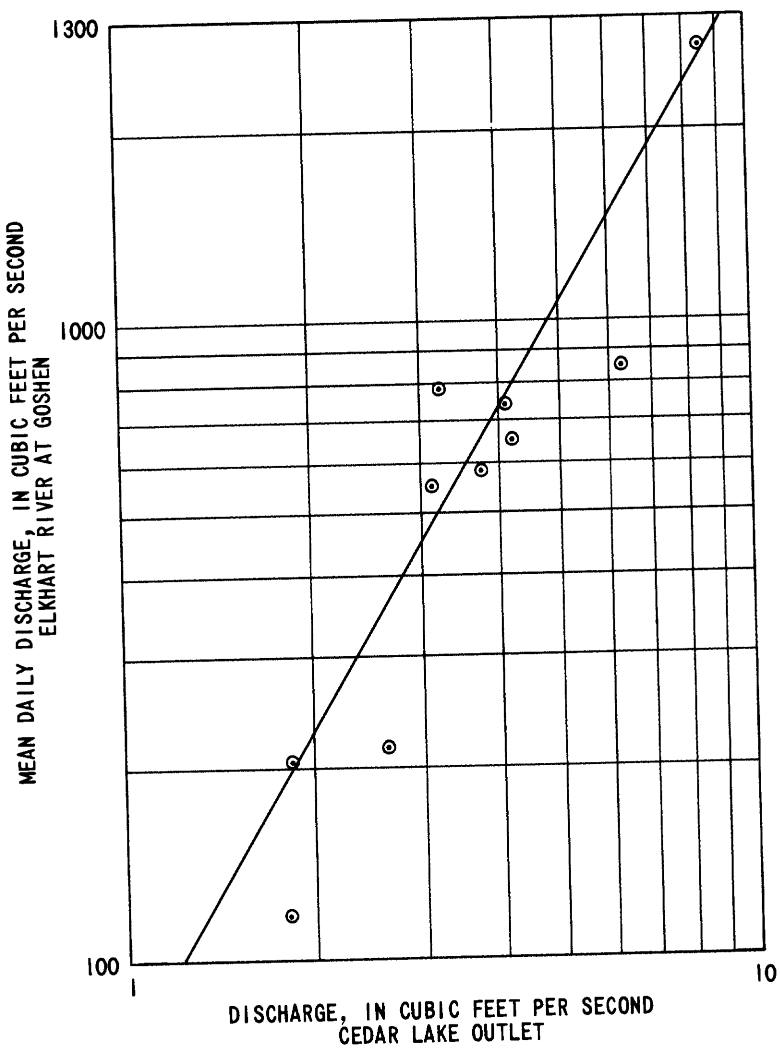


Figure 23.-- Discharge at the outlet of Cedar Lake and the Elkhart River at Goshen, Ind.

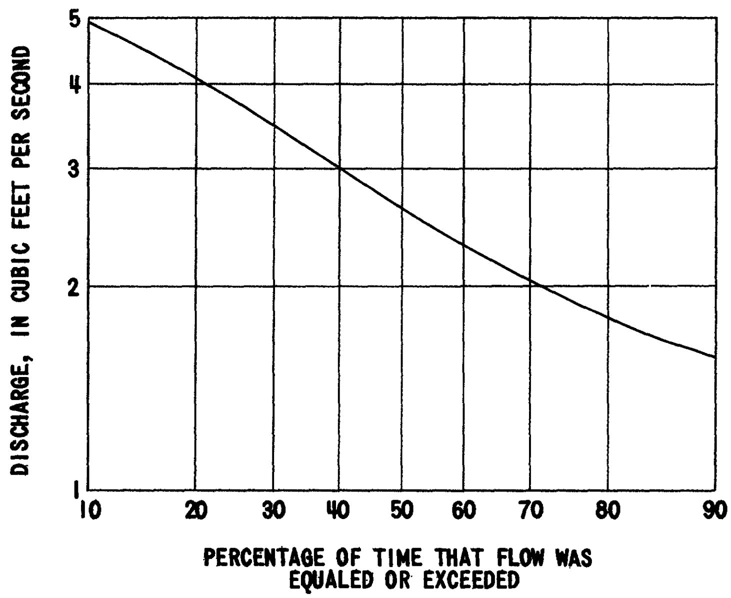


Figure 24.-- Flow duration for the outlet of Cedar Lake.

Table 7.--Discharges at the inlet and outlet of Cedar Lake
[A dash indicates no measurement]

Date	Discharge at inlet (site 41)[1] (ft^3/s)	Discharge at outlet (site 43)[1] (ft^3/s)	Lake elevation (ft)
12-04-81	--	4.20	872.41
12-08-81	--	3.74	872.40
3-09-82	--	4.13	872.41
3-26-82	--	8.37	872.54
5-28-82	--	6.28	872.49
6-17-82	--	3.13	872.37
7-09-82	--	3.25	872.38
9-02-82	2.43	1.86	872.30
10-19-82	3.27	2.63	872.32
9-09-83	2.94	1.84	872.28

[1] Locations of measurement sites are shown in figure 3.

As an example, based on the conditions given above, a pumping rate was calculated that could be sustained over a 50-day period. Inflow, at a rate of 2.7 ft^3/s, amounts to 266 acre-feet; outflow, at an average of 0.8 ft^3/s, amounts to 79 acre-feet; and lake storage capacity, for a 0.36-foot elevation change over the 0.2 mi^2 lake area, amounts to 46 acre-feet. Thus, 233 acre-feet are available for pumping from the lake, and a pumping rate of 2.35 ft^3/s (1,055 gal/min) probably could be sustained over the 50-day period.

During the 1982 irrigational season, the volume of water withdrawn from the Cedar Lake inlet was equivalent to a volume resulting from continuous pumping at a rate of 1.5 ft^3/s (674 gal/min) for 27 days.

Streamflow

A rating curve for Pigeon River (fig. 25) at site 6 west of Mongo (fig. 3) was developed to determine if river stage would change enough during a pumping simulation to warrant changing the elevation of the river in the model.

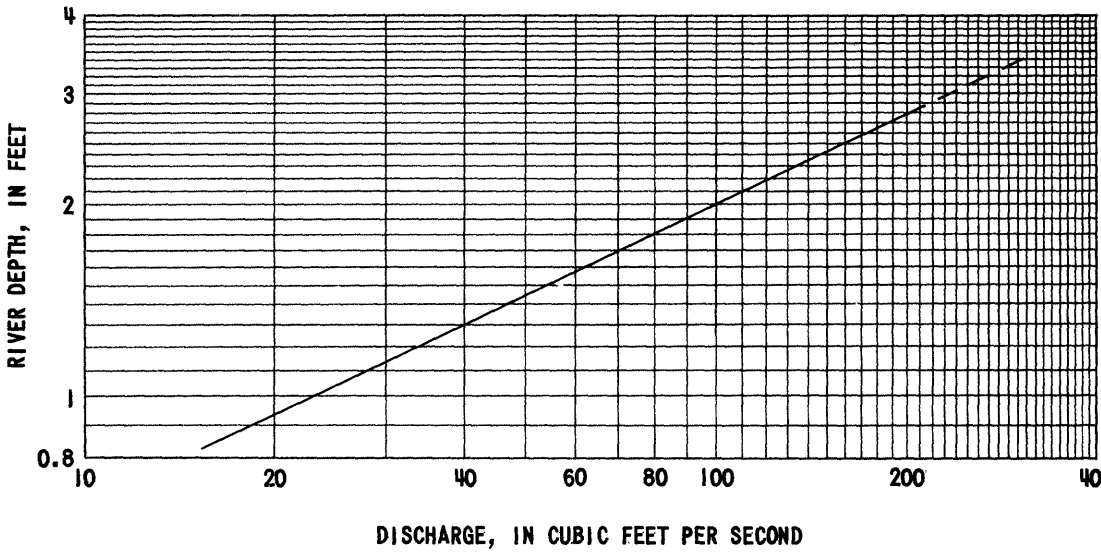


Figure 25.-- Depth and discharge of the Pigeon River at site 6 west of Mongo, Ind.

A flow-duration curve for site 6 (fig. 3) on Pigeon River was estimated by transfer of flow-duration data from Pigeon River near Scott on a drainage-area basis. The Manning equation was used to calculate the depth of Pigeon River for discharges estimated from the flow-duration curve (table 8). The equation is

$$Q = \frac{1.486}{n} AR^{2/3}S^{1/2}$$

where Q is discharge, in cubic feet per second;
n the roughness factor;
A the cross sectional area, in square feet;
R the hydraulic radius, in feet; and
S the channel slope, in feet per foot.

Table 8.--Discharge and depth of stream for Pigeon River at site 6[a]

Percentage of flow duration	Discharge (ft^3/s)	Depth of stream (ft)
50	150	2.4
60	126	2.2
70	108	2.1
80	92	1.9
90	78	1.8
7 day, 10 year	39	1.3

[a]Location on figure 3.

Estimates of each variable for Pigeon River were made from available data. Cross-sectional area was assumed to be uniform, and the channel shape was determined to be trapezoidal from a cross section of the channel at each measuring site (fig. 3). The bank-slope ratio of the trapezoid is 1 to 6.3, and the base is 26 ft. Channel slope, calculated from topographic maps, averaged 0.000784 ft/ft. The Manning equation was used to calculate a channel roughness of 0.048 from estimates of channel roughness at each measurement site and the channel slope. Thus, for the discharges in table 8, depth (hydraulic radius) was calculated and the rating curve (fig. 25) was constructed.

If all irrigable land in proximity to Pigeon River were irrigated, the resulting pumpage would total 15 ft^3/s. (This subject is discussed in the section, "Simulation of Pumpage.") The increment of flow between the 90-, 80-, 70-, and 60-percent flow durations ranges from 14 to 18 ft^3/s (table 8). Pumpage from streams (15 ft^3/s) is within this range. Only a 0.1 to 0.2 ft difference in stream depth is calculated for this range from the Manning equation. The decrease in depth, if discharge was reduced from that at the 60- to the 90-percent flow duration (a difference of 48 ft^3/s), would be only 0.4 ft.

Ground-Water Withdrawals

Model Assumptions

The finite-difference model developed by McDonald and Harbaugh (1983) was used to simulate the three-dimensional flow system in the outwash. The following simplifications and assumptions were made to simulate the complex hydrologic system;

1. The bedrock under the outwash is an impermeable boundary.

2. Flow in the sand and gravel of each aquifer is horizontal (fig. 26).

3. Flow (leakage) between the aquifers, whether divided by clay or not, is vertical (fig. 26).

4. Storage in the clay between aquifers has a negligible effect on the ability of the model to simulate the flow system.

5. At the scale of the model, any extensive clay deposits in the aquifers are not treated as confining layers and do not significantly affect the flow system.

6. On a regional scale, each aquifer is homogeneous and isotropic, that is, hydraulic conductivity is the same both vertically and horizontally.

7. Ground water flows through Cedar Lake.

8. Wetlands are hydraulically connected to the ground-water system.

9. The ground-water system is near steady state.

Local deviations from these assumptions can cause localized differences between model-calculated and observed ground-water conditions, but the overall model analysis will not be adversely affected by these local deviations.

Conceptual Model

The outwash aquifer system was divided into three layers to simulate ground-water flow. Layers 1, 2, and 3 in the model (fig. 26) correspond to aquifers 1, 2, and 3. Most of layer 1 is unconfined but may be confined locally as described in the section "Glacial Deposits." Layer 2 was simulated as confined, but where there is no confining clay layer in the real system, the connection between layers 1 and 2 was assigned a large vertical hydraulic conductivity to facilitate vertical flow. Layer 3 was also simulated as a confined layer.

The only clay unit through which vertical leakage was simulated was the one that separates layers 1 and 2. For clay lenses thicker than 5 feet within an aquifer layer, saturated thickness and transmissivity of the layer were reduced proportionately. However, the smaller clay lenses were not treated as confining beds, so any confinement caused by them was not simulated.

The possible effect of pumping on Cedar Lake and surrounding wetlands was a strong influence on the design of the model. Ground-water altitudes on three sides of the lake are higher than the elevation of the lake, so that ground water probably flows into Cedar Lake (fig. 21) along those sides. However, water probably seeps from the lake into the ground-water system along the northwestern side (fourth side), where the ground-water elevation is lower than the elevation of the lake. Thus, the authors perceived the lake as being a highly transmissive part of layer 1 (fig. 14). Simulation of ground-water flow through the lake, as well as fluctuation of the lake's level, were based on this concept. The wetlands and channels within the wetlands were simulated as drains that can gain water from the aquifer but cannot lose water. Thus, if the water table would drop below the bottom of the drain, the drain (wetland) would be dry, but no water would have leaked into the aquifer.

Elevations of the water surface of Pigeon and Fawn Rivers were assumed to be constant, and ground-water gain or loss through the streambed was simulated.

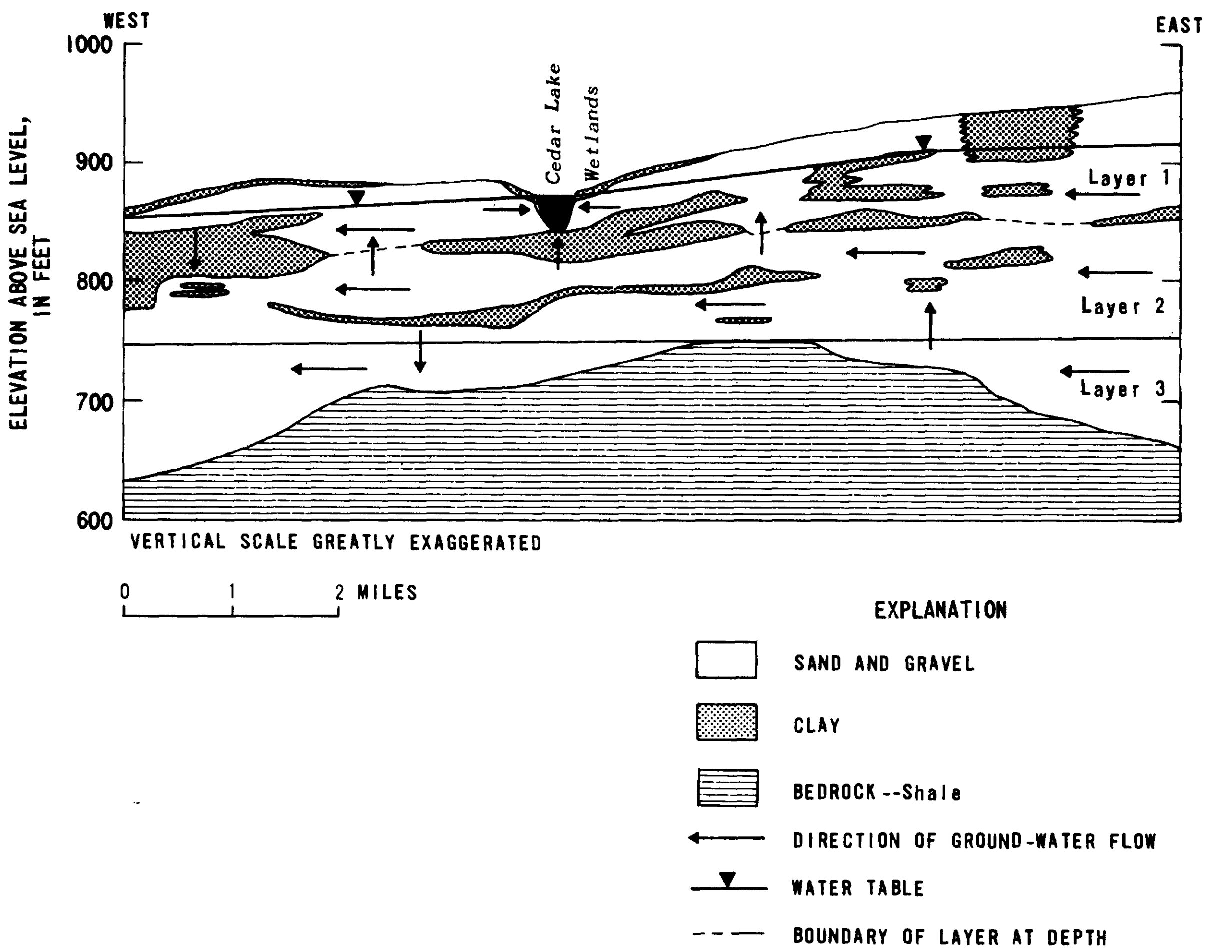


Figure 26.-- Generalized geologic section showing design of the digital model.

Model Construction

The 85-square-mile grid of the model is an 8.6-by 9.9-mile rectangle consisting of variable size blocks (fig. 27). Because of inactive blocks outside the area of study, the area of simulated ground-water flow is only 65 mi^2. The smallest blocks, in the Cedar Lake area, are 500 by 500 ft; the largest, near the eastern boundary, are 1,500 by 1,500 ft. Sizes were determined by the resolution necessary or the spacing required to center irrigational wells in the blocks.

Input for layer 1 included estimates of initial water levels, its bottom altitude, average horizontal hydraulic conductivity, altitude of the top of the aquifer where it may be confined, and recharge. Initial water levels were from the potentiometraic map that was constructed from water levels measured August 31 through September 2, 1982 (fig. 21). The bottom altitude of layer 1 is shown in figure 10. An average hydraulic conductivity of 210 ft/d, calculated from specific-capacity data, was used. The top of layer 1 corresponds to the water table or, in the confined areas (fig. 8), to the bottom of clay overlying aquifer 1. Thus, confined and unconfined aquifers were simulated in various areas of the same layer. A shift from confined to unconfined aquifers can be simulated if the aquifer beneath the confining bed is dewatered. Recharge rates applied to layer 1 are shown in figure 4. Evapotranspiration was not simulated because its effect was included in the recharge rate.

Fawn and Pigeon Rivers were simulated as streams hydraulically connected to layer 1 through leaky streambeds (river nodes on fig. 27). Their courses were followed as closely as possible within the constraints of the grid. Some lakes were also simulated by river nodes.

Conductance was used to simulate leakage from river nodes. Stream- and lake-bed conductances (C) were calculated by the following equation:

$$C = KA/b$$

where K is vertical hydraulic conductivity of the streambed, in feet per day;
A is the area of the river within the node, in square feet; and
b is the streambed thickness, in feet.

Thickness of streambeds was assumed to be 1 ft to simplify calculations; a vertical hydraulic conductivity of 1 ft/d was used initially for all streams. Stage for each river node was calculated from water-surface elevations measured at certain points on August 31 through September 2, 1982, and a uniform gradient between those measured points was assumed. A 2-foot depth of water in the rivers was assumed.

Cedar Lake was simulated as part of layer 1 having a transmissivity of about 3×10^5 ft^2/d. This method of simulating a lake in glacial deposits was used by Winter (1976, p. 5 and 6).

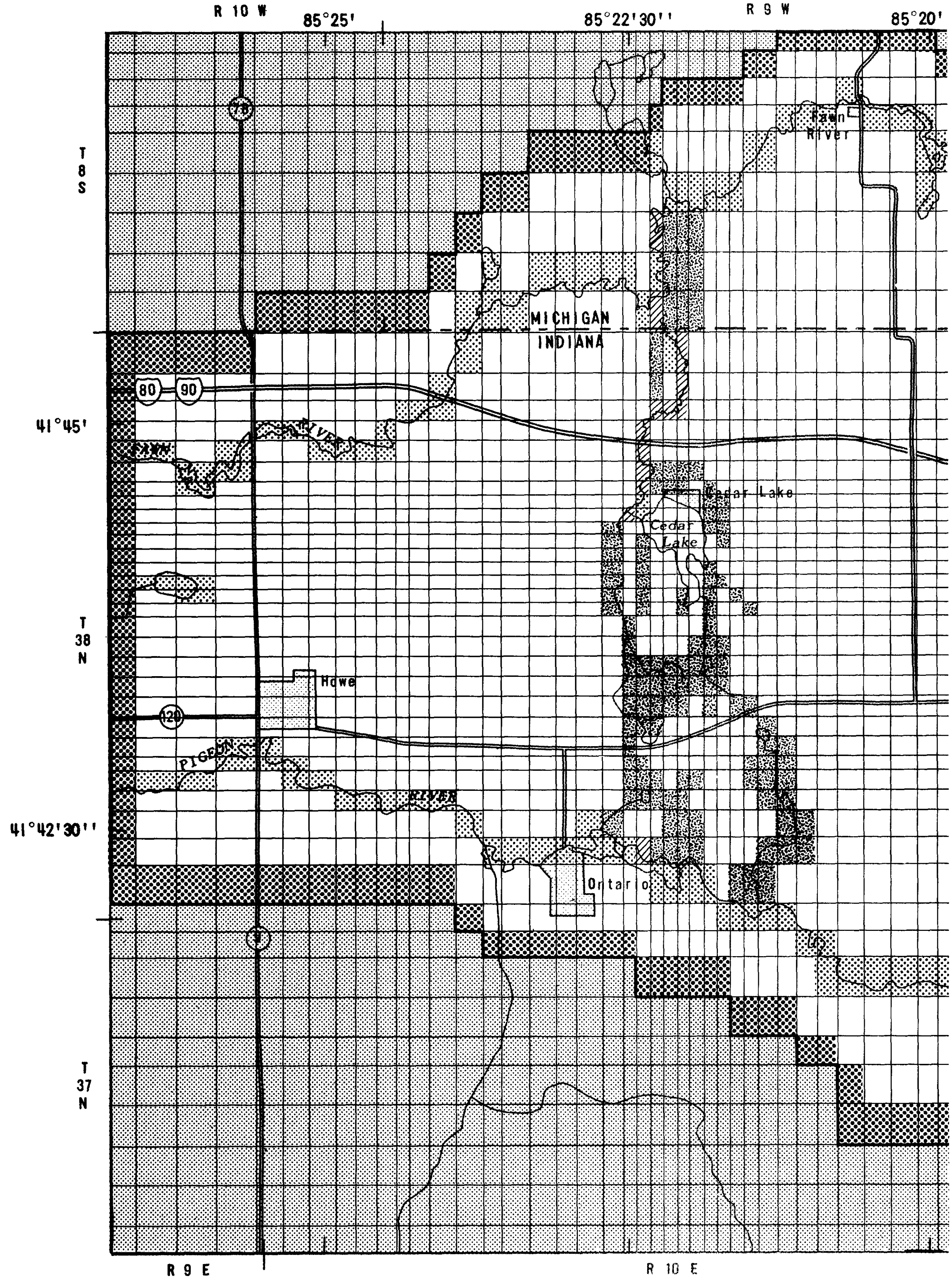
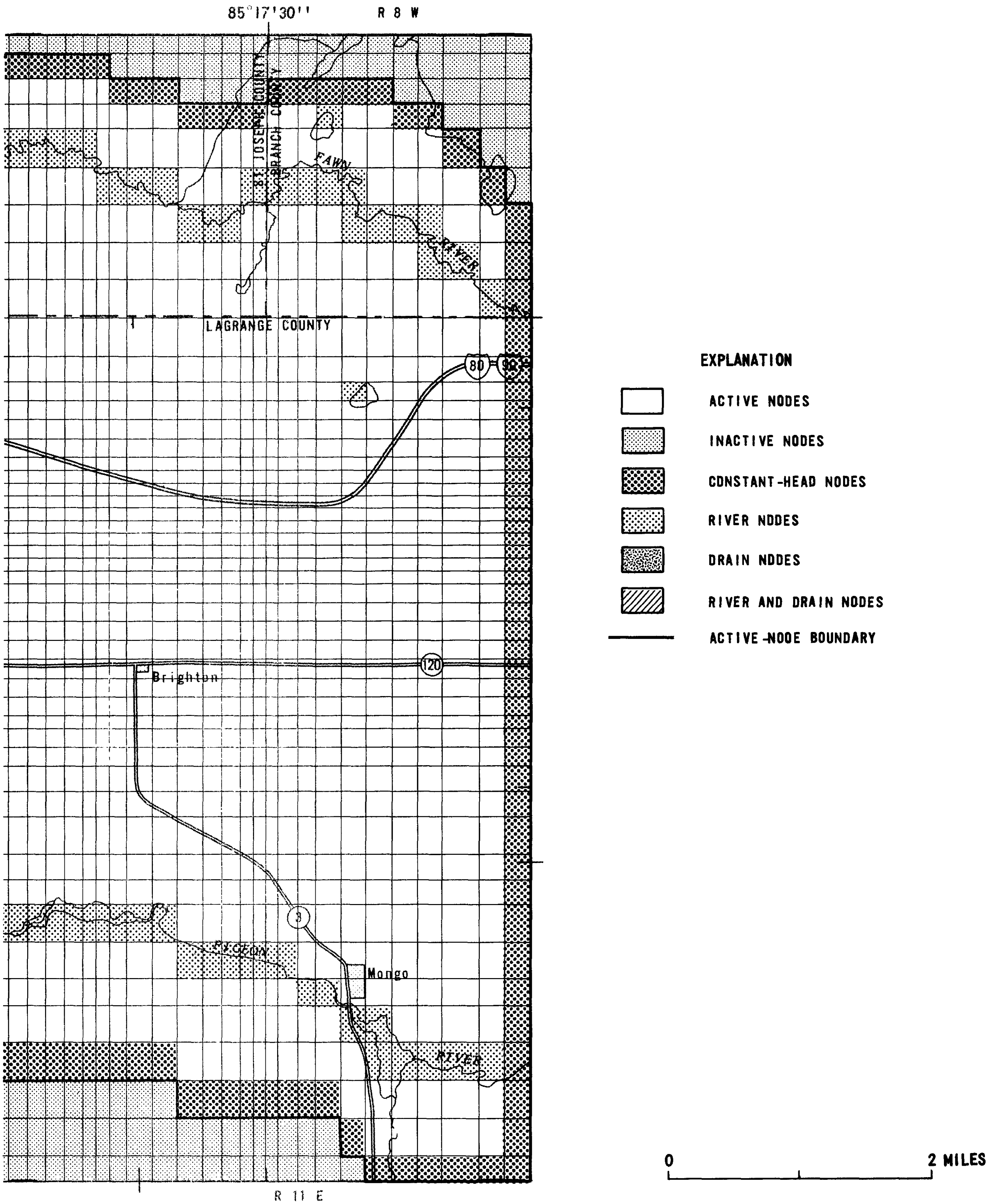


Figure 27.— Finite-difference grid for the digital flow model.


85°17'30''
R 8 W
ST. JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
PIGEON
Mongo
RIVER
R 11 E
EXPLANATION
ACTIVE NODES
INACTIVE NODES
CONSTANT-HEAD NODES
RIVER NODES
DRAIN NODES
RIVER AND DRAIN NODES
ACTIVE-NODE BOUNDARY
0
2 MILES

The wetlands and major channels within them were simulated as drains in layer 1 (fig. 27). Bottoms of drains were assumed to be 1 ft below the water table. Conductance (C) of the bottom was calculated by

$$C = Q/\Delta h$$

where Q is discharge, in cubic feet per second; and
Δh is the change in water level in the drain, in feet.

Conductance between the wetlands and underlying aquifer was unknown, but discharge from the wetlands was assumed to equal ground-water gain in the streams, about 0.5 $ft^3/s/mi^2$. The maximum possible change in water level in a drain was 1 ft because bottoms were set at 1 ft below the water table. Thus, conductance equaled discharge, and those measurements within a particular node varied only with the area of drain in that node. Drainage ditches in the wetlands (channels in the drain nodes, fig. 27) were simulated as being deeper than 1 ft, but conductance was low because of their small area in a node.

Vertical coefficients of leakage between layers 1 and 2 are the quotients of the vertical hydraulic conductivity of the clay (0.001 ft/d) divided by the thickness. Vertical hydraulic conductivity was assumed to be one-tenth of the horizontal hydraulic conductivity, 0.01 ft/d (Freeze and Cherry, 1979, p. 32). Where clay is absent, coefficients of leakage were calculated by

$$\text{Coefficient of leakage} = \frac{2K_{L1}\,K_{L2}}{K_{L1}b_{L2} + K_{L2}b_{L1}} \qquad (1)$$

where K is vertical hydraulic conductivity, in feet per day;
b is thickness, in feet;
L1 is layer 1; and
L2 is layer 2.

Vertical hydraulic conductivities of the aquifers, 21 ft/d for layer 1 and 36 ft/d for layer 2, were assumed to be one-tenth of the average horizontal hydraulic conductivity.

Input for layer 2 included estimates of initial water-levels and transmissivity. Water levels were based on measurements made during August 31 through September 2, 1982. Transmissivity is shown in figure 15.

Vertical-leakage coefficients between layers 2 and 3 were calculated using equation (1) because the aquifers are not separated by a layer of clay. The vertical hydraulic conductivity of layer 3 used to calculate leakage coefficients was 10 ft/d.

Input for layer 3 included estimates of initial water-levels and transmissivity. Only one observation well was screened in layer 3, so the water-level distribution was assumed to be the same as for layer 2. Transmissivity is shown in figure 16. The average hydraulic conductivity for layer 3 from specific-capacity data (190 ft/d) was not used to calculate transmissivity. The lowest conductivity (110 ft/d) was used, because the calculation of average conductivity was based on only two wells. Those wells are probably screened in local areas of higher conductivity than that of most of the aquifer and do not represent the general characteristics of the aquifer indicated by test borings.

Model Boundaries

The upper boundary of the model is the water table, except where a surficial confining clay is present (fig. 8). The lower boundary is bedrock and was assumed to be impermeable. This boundary underlies layer 3; but where layer 3 is absent (fig. 13), the bedrock underlies layer 2. Initially, Fawn and Pigeon Rivers were to form the northern and southern boundaries of the model. However, because neither stream fully penetrates the aquifer, the boundaries were extended beyond the rivers to a distance of approximately 10 times the thickness of the aquifer (as much as 3,000 ft).

The model is surrounded by constant-head nodes (fig. 27) in all layers because ground water flows across all lateral boundaries. The constant-head nodes were used to calculate the rate of ground-water flow across those boundaries. Constant-heads were based on water-level data from observation wells on the boundaries of the area that was modeled. These boundaries are arbitrary and do not necessarily simulate any physical feature or natural hydrologic boundary.

Model calibration

The ground-water-flow model was calibrated to autumn 1982 water levels, which were assumed to be at steady state, and to ground-water seepage to streams that was measured August 31 through September 2, 1982.

The hydraulic conductivity of each layer was adjusted during calibration, but the conductivities of layers 1 and 2 were left at their initial values because simulated water levels changed very little in response to the adjustments. Hydraulic conductivity in layer 3 was lowered to 25 ft/d to improve the matching of water levels and leakages between layers 2 and 3. The lower conductivity also resulted in more realistic transmissivity. Adjustments of vertical leakage between layers 2 and 3 resulted in the most significant changes in model-calculated water levels in those layers and in the water budget. Many values of vertical hydraulic conductivity for the clay between layers 1 and 2 were tested but the initial value, 0.001 ft/d, was retained. However, the vertical hydraulic conductivity under Cedar Lake was adjusted to 1×10^{-7} ft/d to produce a better match of water levels around the lake. This value was the lowest conductivity that could be assigned without causing mathematical instability in the model. This approach to modeling the lake has precedent in the lake-modeling work of Winter (1975, p. 5). In the modeled area, rate of leakage from layer 2 through the layer of clay into layer 1 was 43 ft^3/s and from layer 1 through the layer of clay into layer 2 was 11 ft^3/s.

Thickness and lateral extent of clay between layers 1 and 2 (fig. 9) are interpretations based on evaluation of all available data, but, because the clay within the outwash is complex and difficult to map and correlate, other interpretations are possible. Several simulations were done to test whether a continuous layer of clay between layers 1 and 2 would result in a better simulation of the system. Vertical hydraulic conductivity was simulated in the range from 1 to 1 x 10^{-4} ft/d. Matches of water levels in two of five simulations improved, but because matches to stream seepage were unacceptable, the original clay distribution was retained. The vertical leakage value between layers 2 and 3 for the calibrated model was one order of magnitude lower than the initial value. The rate of leakage from layer 3 into layer 2 was 4.2 ft^3/s and from layer 2 into layer 3 was 2.5 ft^3/s. The net rate of vertical leakage into layer 1 was 32 ft^3/s, into layer 2 was 12 ft^3/s, and out of layer 3 was 2 ft^3/s.

Recharge and conductance of the streambeds in the model were adjusted during calibration but initial values were retained. Ground-water seepage to Pigeon River, estimated to be 38 ft^3/s by the model, is a close match of the measured seepage. Seepage to Fawn River was estimated to be 36 ft^3/s by the model.

Initial water levels and constant heads for layer 3 were assumed to be the same as for layer 2 on the basis of water levels that indicated little difference in head between aquifers 2 and 3. Water levels are probably similar because conductance between these aquifers is high. Model-calculated water levels for layers 2 and 3 also were close.

Some measured water levels were difficult to duplicate during calibration, probably because some of the model assumptions oversimplify the complex hydrologic system. For example, Peters, (U.S. Geological Survey, written commun., 1983) found that clay lenses of moderate areal extent within the aquifers locally confine the aquifer. Matching simulated water levels to measured water levels from these areas was not always possible because of the simplified geometry of the model. Also, because of the clay lenses, the aquifer hydraulic conductivity was anisotropic in some areas; and therefore, local flow cells in those areas could not be simulated at the scale of the model.

Model-calculated and measured water levels for each layer are shown in figures 28 through 30. A summary of the steady-state water budget is presented in table 9. The pumping shown in that table is from year-round pumping of five commercial wells.

Table 9.--Steady-state ground-water budget of the outwash, modeled for autumn 1982

Sources and discharges	Flow (ft^3/s)	Percentage of total
Sources:		
Boundary flux	58	56
Areal recharge	39	37
Leakage from streambeds	7	7
Total	104	100
Discharges:		
Boundary flux	16	15
Ground-water seepage to streams	85	82
Ground-water seepage to drains	1	1
Pumpage	2	2
Total	104	100

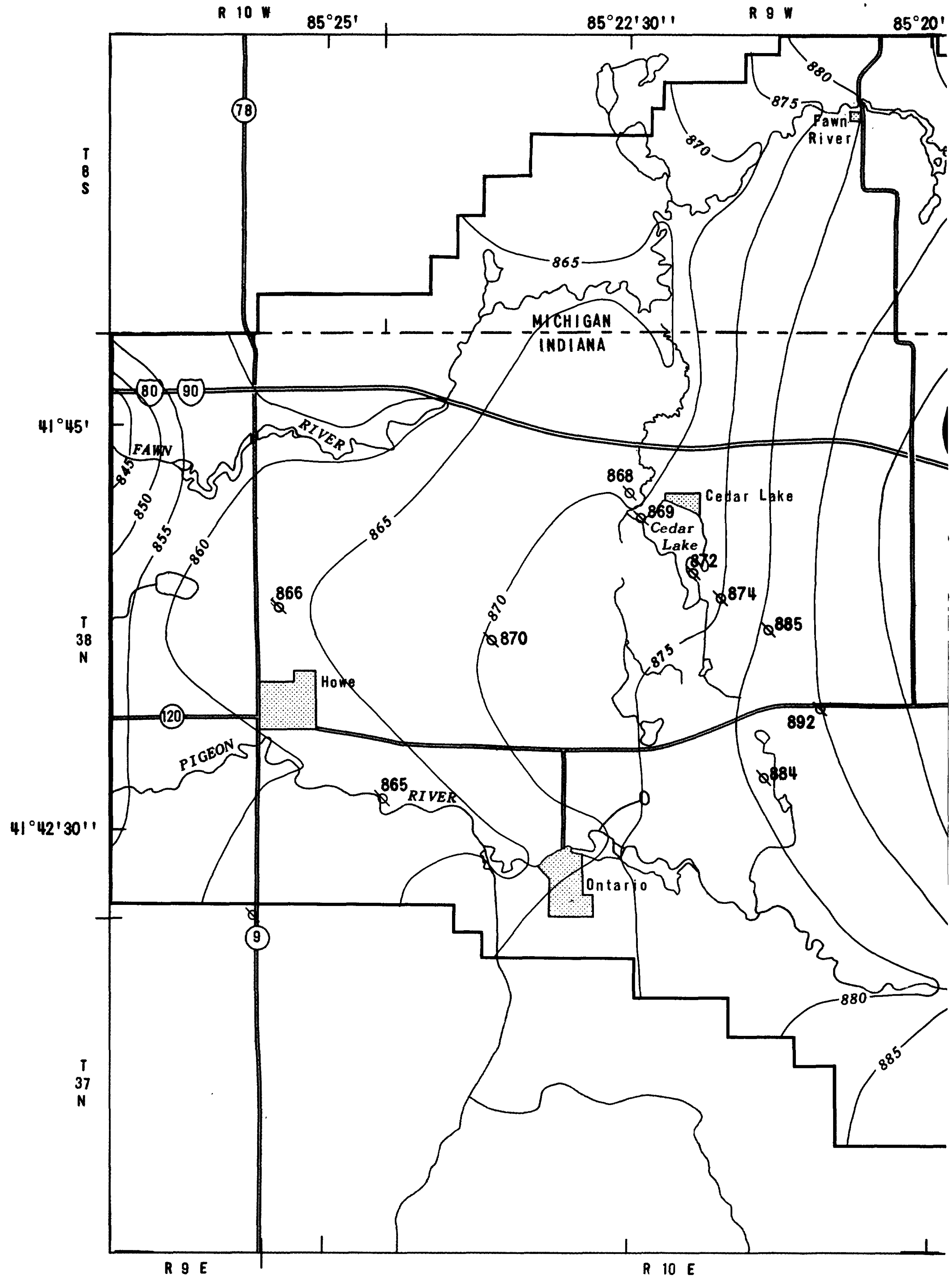
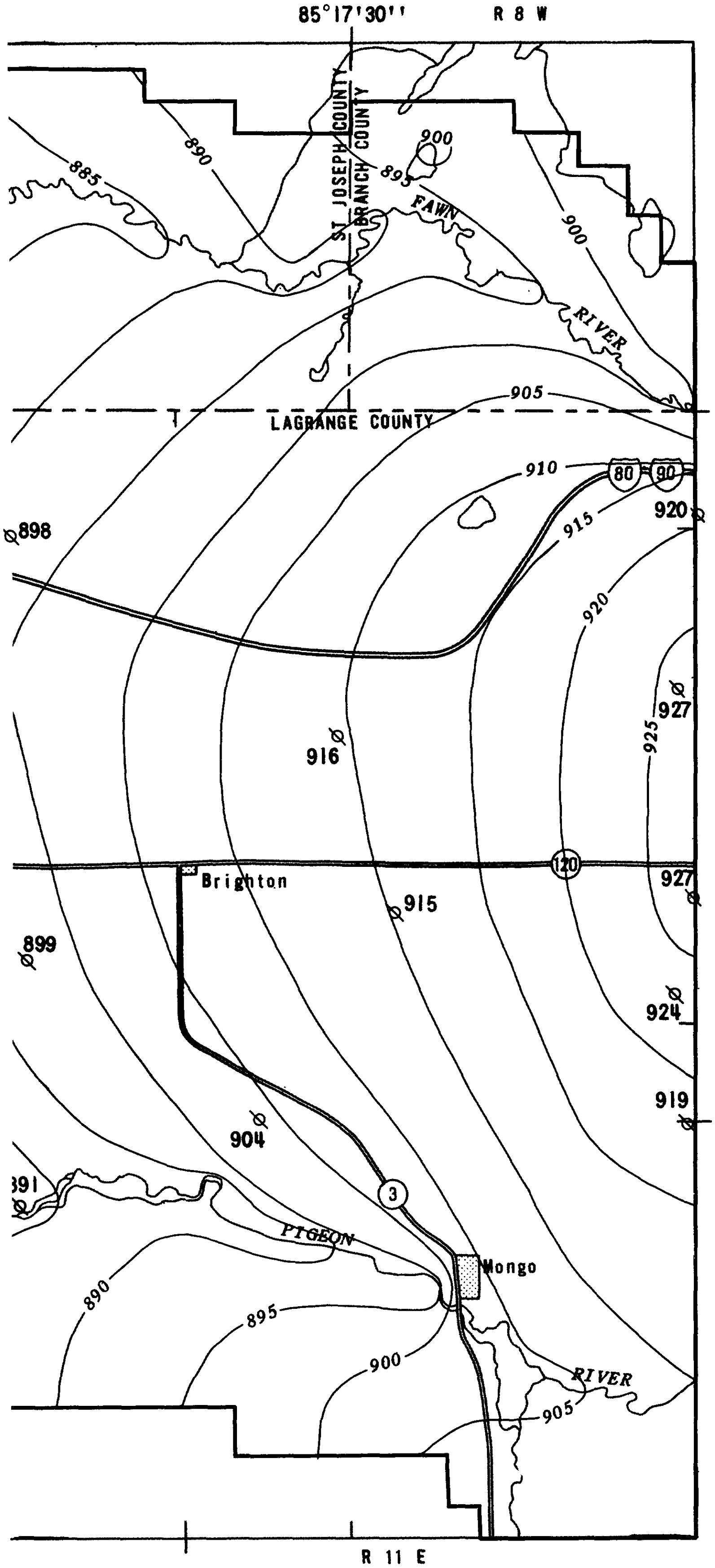


Figure 28.-- Relation of calibrated, steady-state water levels in layer 1 and water levels measured August 31 through September 2, 1982.



EXPLANATION

—920— LINE OF EQUAL WATER LEVEL, LAYER 1--Interval 5 feet

915 OBSERVATION WELL AND MEASURED WATER LEVEL--In feet above sea level

ACTIVE-NODE BOUNDARY

0 2 MILES

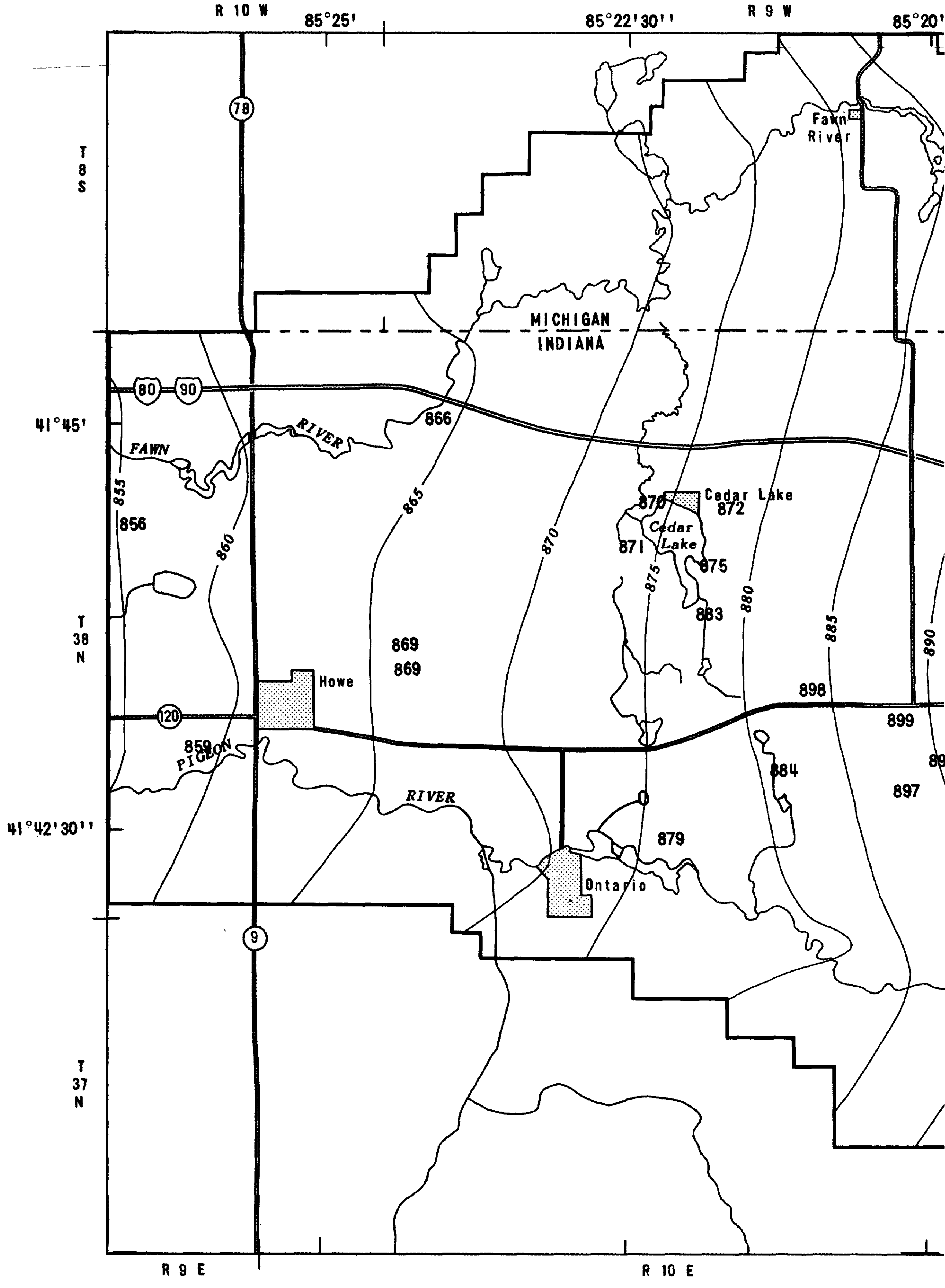
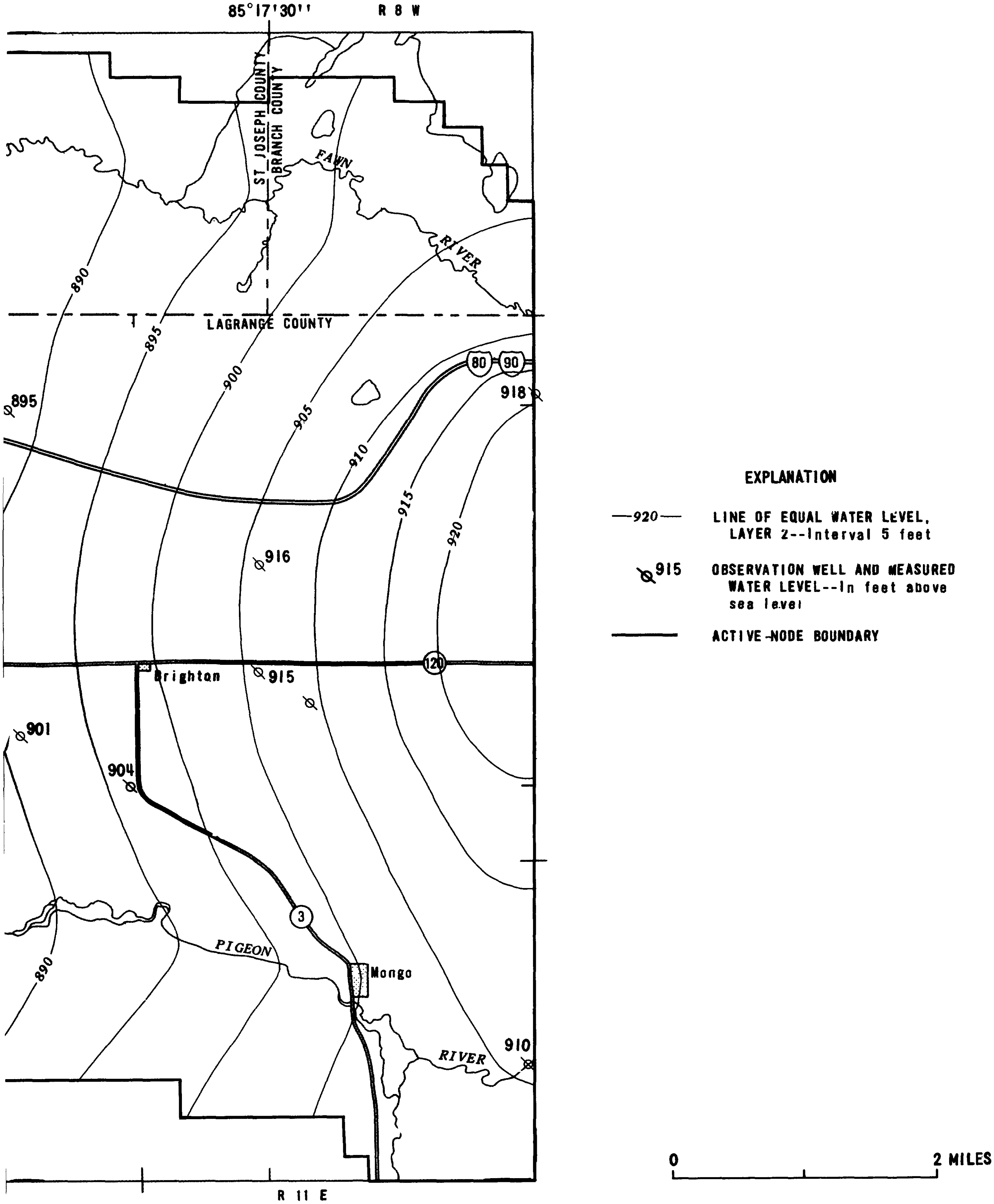


Figure 29.-- Relation of calibrated, steady-state water levels in layer 2 and water levels measured August 31 through September 2, 1982.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
890
895
900
905
910
915
920
80
90
918
895
916
120
Brighton
915
901
904
3
PIGEON
Mongo
RIVER
910
890
R 11 E
EXPLANATION
920 LINE OF EQUAL WATER LEVEL, LAYER 2--Interval 5 feet
915 OBSERVATION WELL AND MEASURED WATER LEVEL--In feet above sea level
ACTIVE-NODE BOUNDARY
0
2 MILES

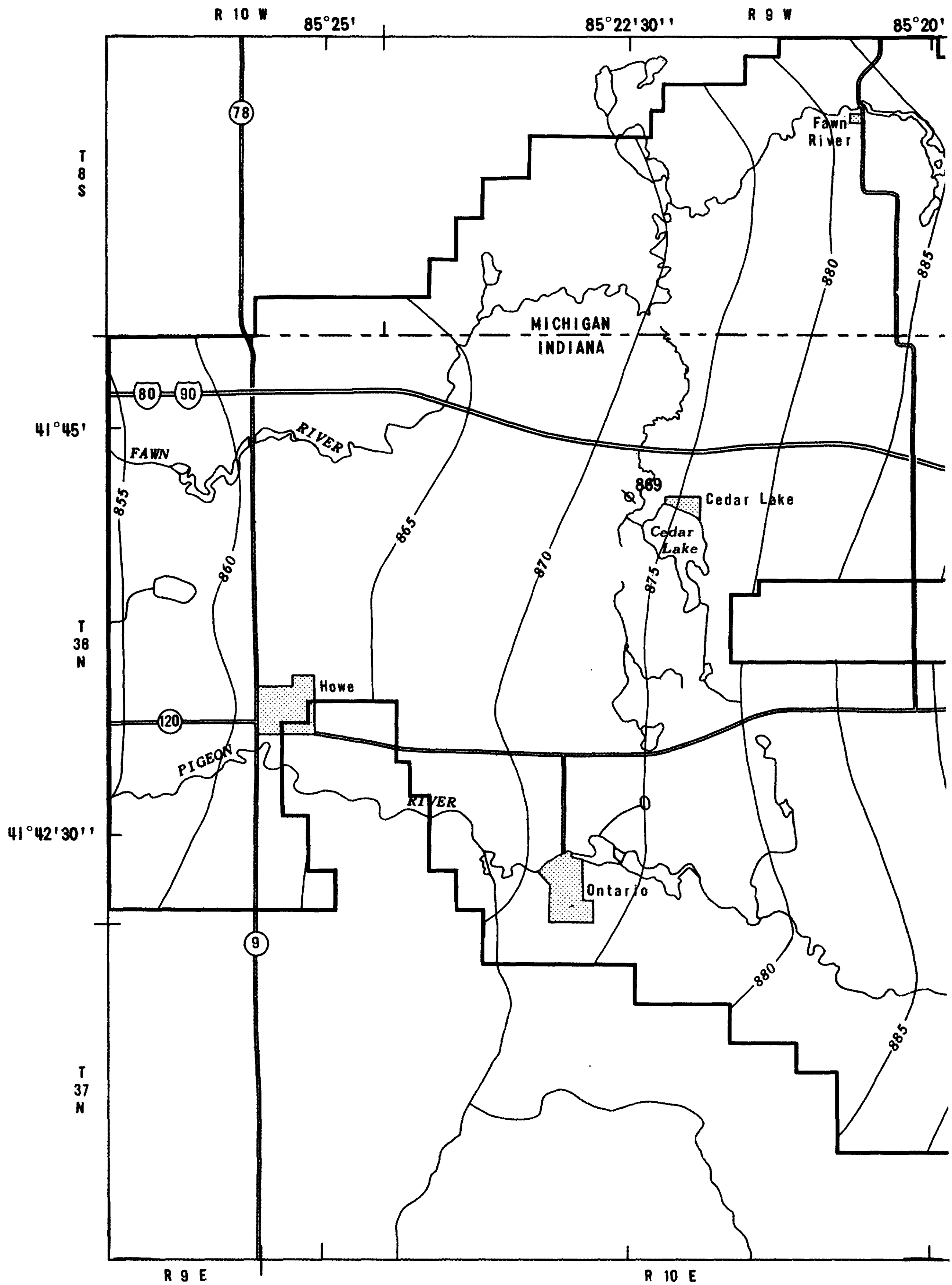
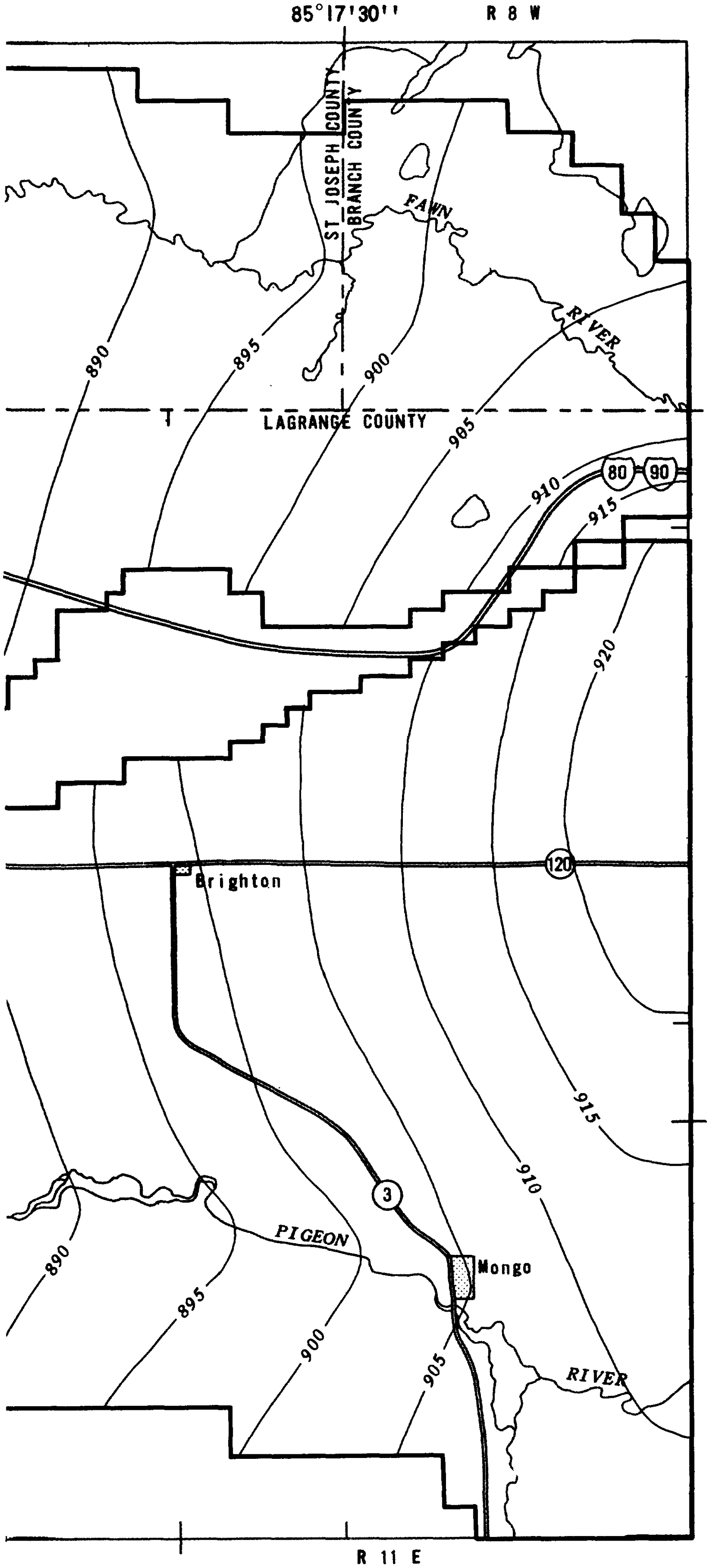


Figure 30.-- Relation of calibrated, steady-state water level in layer 3 and a water level measured September 1, 1982.



EXPLANATION

—920— LINE OF EQUAL WATER LEVEL, LAYER 3--Interval 5 feet

869 OBSERVATION WELL AND MEASURED WATER LEVEL--In feet above sea level

ACTIVE-NODE BOUNDARY

Sensitivity Analyses

The response of the model to adjustments in recharge, hydraulic conductivity of the aquifers, coefficients of leakage between layers, and hydraulic conductivity of streambeds was evaluated by sensitivity analyses. The ranges of adjustments for the four variables were from 0.1 to 5 times the calibrated recharge; from 0.3 to 5 times the hydraulic conductivities of the aquifers; from 0.1 to 10 times the vertical leakage between layers; and from 0.05 to 50 times the hydraulic conductivity of the streambeds. The hydraulic conductivity of each aquifer was adjusted by the same multiple for each sensitivity test (rather than being adjusted individually while the other two were held constant). Likewise, both leakage layers were adjusted by the same multiple for each test.

Differences between measured and simulated water levels were used as indicators of the sensitivity of the model to adjustments of a variable. The root mean square error (RMSE), a statistical procedure, was calculated for measured and simulated water levels by

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

where N is number of observations (46);

h_i^m is the measured water level, in feet; and

h_i^c is the calculated water level, in feet.

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

RMSE for all variables at the values used in the calibrated steady-state model is 6.17 ft. Net seepage to the streams was also a consideration in calibration, so the net seepage for each sensitivity test was compared with that of the calibrated model, 78 ft^3/s. Sensitivity analyses were done only with the constant-flux boundaries of the calibrated model because the additional water induced through constant-head boundaries masks the sensitivity of a variable (Bailey and Imbrigiotta, 1982, p. 45-46); that is, the model seems to be insensitive to any adjustments of a variable where constant-head boundaries are used. The model was arbitrarily defined as sensitive to changes in variable values when the RMSE exceeded 7.17 ft, which is 1 foot more than the RMSE of the calibrated model.

Initial values for recharge (fig. 4) were retained for the calibrated model. For the sensitivity analyses, recharge was adjusted from 0.1 to 5 times the calibrated value (fig. 31), or from 1 to 52 in./yr over most of the outwash. Acceptable water-level matches were obtained in a range of recharge from about 0.75 to 3.5 times the calibrated values, but net seepage to the streams was close to that in the calibrated model only in a very narrow range. The calibrated values are not the best possible matches to measured water levels, but are the best match to measured seepage to the streams. Therefore, the model is sensitive to adjustments in recharge.

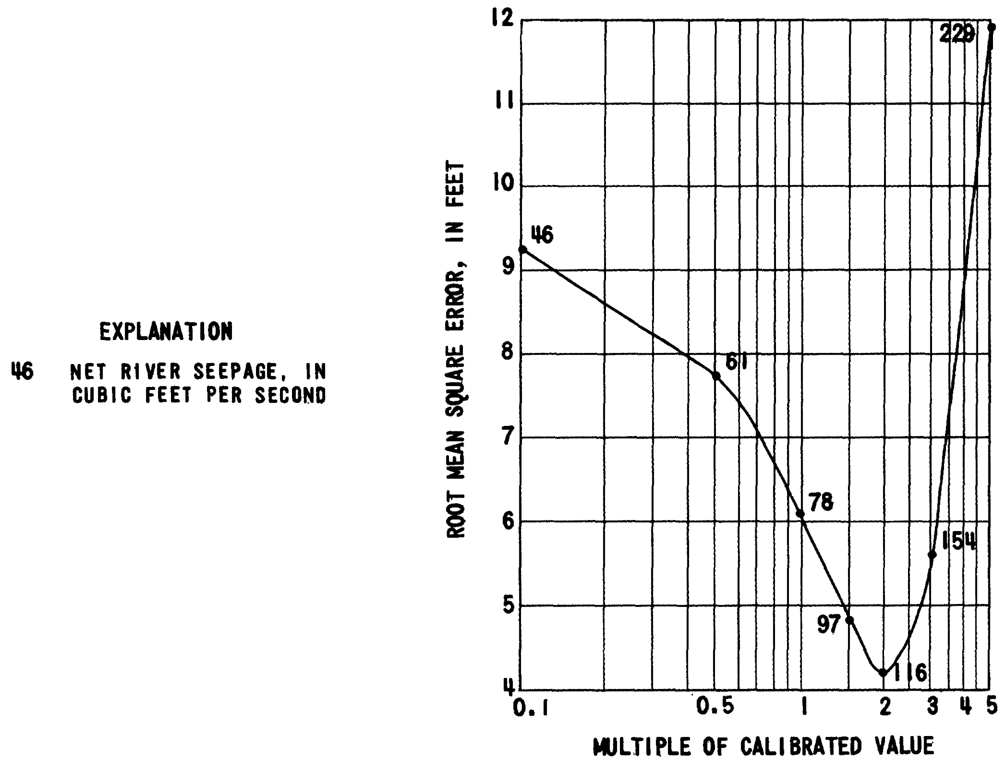


Figure 31.— Sensitivity of the digital flow model to adjustments in recharge.

Hydraulic conductivities in the calibrated model were 210 ft/d for layer 1, 360 ft/d for layer 2, and 25 ft/d for layer 3. For the sensitivity analyses, conductivities were adjusted from 0.3 to 5 times (fig. 32), or from 63 to 1050 ft/d for layer 1, from 108 to 1800 ft/d for layer 2, and from 7 to 125 ft/d for layer 3. Slightly better water-level matches could have been obtained by using 0.75 times the calibrated values but seepage to streams was also lowered. Acceptable water-level matches could be produced by values from about 0.6 to 1.1 times the calibrated conductivities. Water levels were sensitive to adjustments in conductivities in all layers at once, but were not as sensitive during calibration when hydraulic conductivity was adjusted in only one layer at a time.

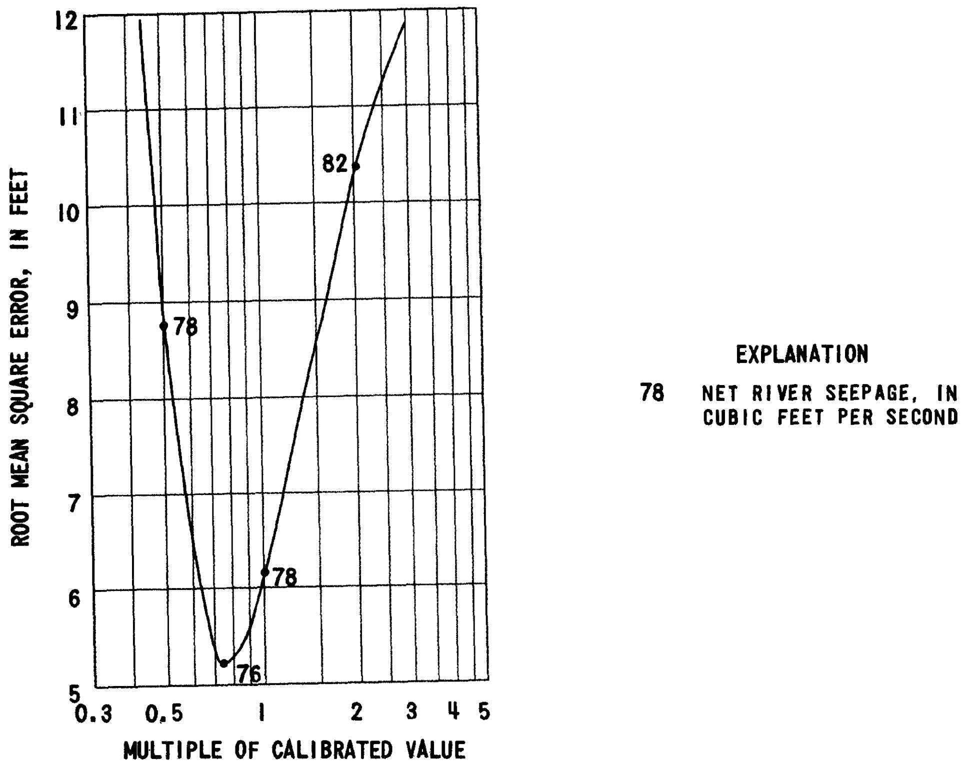


Figure 32.-- Sensitivity of the digital flow model to adjustments in hydraulic conductivity of aquifers.

Many combinations of values for vertical leakage between the layers were tested during calibration, but usually the adjustments were made by orders of magnitude. For the sensitivity analyses, vertical leakage was adjusted from 0.1 to 10 times the calibrated values (fig. 33). There is little difference between the RMSE (and net seepage to streams) for the calibrated model and for 0.1 times the calibrated values. Closer water-level matches could be obtained between 0.1 and 1 times, and 0.2 times gives the lowest RMSE. Those multiples less than 1, however, give a much worse match in layer 3, and, although some water levels in layers 1 and 2 are better matched, several individual data points have a much worse match than in the calibrated model. Seepage to streams is not very sensitive to these adjustments of vertical leakage between layers. This insensitivity may be due to adjustments of the same magnitude in both leakage layers, because seepage to streams was more sensitive to adjustments in leakage during calibration.

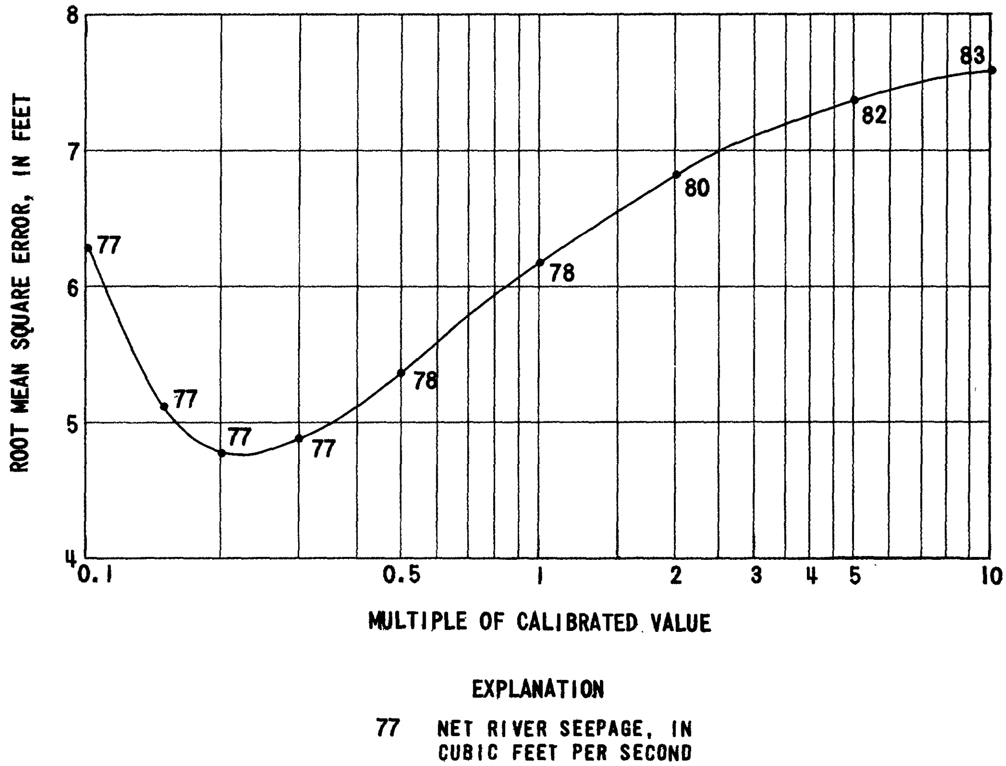


Figure 33.-- Sensitivity of the digital flow model to adjustments in

Hydraulic conductivity of the streambeds was 1 ft/d for the calibrated model and was adjusted from 0.05 to 50 times in the sensitivity tests (fig. 34). Water levels and seepage to streams are not particularly sensitive to this wide range of adjustments in the unstressed model. The effects of the hydraulic conductivity are more evident when a system is heavily pumped. A better water-level match could be obtained, but seepage to the streams would be lower than that measured. Also, because of other evidence of a good connection between ground-water and surface-water systems, 1 ft/d was a more appropriate value than 0.1 ft/d.

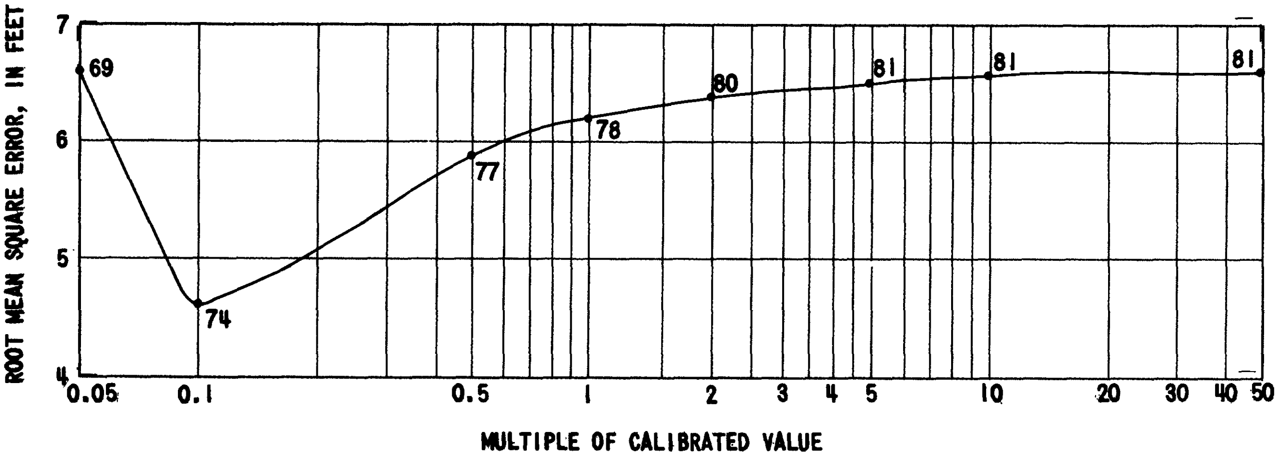


Figure 34.-- Sensitivity of the digital flow model to adjustments in hydraulic conductivity of streambeds.

Simulation of Pumpage

Design of Pumping Plans

Pumping plans were designed to test the flow system's response during one season to five different irrigational pumping schemes:

Plan 1. Simulation of current wells and surface-water sites pumping the same volume of water needed for irrigation in 1982.

Plan 2. Simulation of pumping from current wells and surface-water sites needed for irrigation in a normal year.

Plan 3. Simulation of pumping from current wells and surface- water sites needed for irrigation in a dry year.

Plan 4. Simulation of pumping from wells and surface-water sites in all irrigable lands needed for irrigation in a normal year.

Plan 5. Simulation of pumping from wells and surface-water sites in all-irrigable lands needed for irrigation in a dry year.

The calibrated steady-state model was modified before the five transient pumping plans were done. Each constant-head boundary node was replaced by the model-calculated flux. A specific yield of 0.2 was assigned to layer 1, and a storage coefficient of 0.0002 was assigned to layers 2 and 3. These values were estimated by methods from Lohman (1972, p. 53-54) and are similar to those calculated for aquifer tests in the study area (James Peters, U.S. Geological Survey, written commun. 1983). Initial water levels used were those resulting from the steady-state calibration.

A sixth pumping plan was designed to assess the effects of long-term, high pumping rates, not necessarily for irrigation, on ground-water levels and streamflow:

Plan 6. A steady-state simulation of the ground-water pumping used in plans 4 and 5.

Five commercial wells that pump an average of 1.96 ft^3/s year-round were included in all the pumping plans because they were part of the calibration (fig. 35). Current irrigational wells were not included in plans 4, 5, and 6 so that a more consistent distribution of simulated wells could be made.

Normal and dry hydrologic conditions used in pumping simulations were defined on the probability of precipitation. Precipitation during normal and dry periods was defined as the amount of precipitation that is equaled or exceeded 50 and 80 percent of the time (Deborah Chelf, Indiana Department of Natural Resources, Division of Water, oral commun., 1983).

In plan 1, current irrigational wells (fig. 35) were pumped for 15 days at rates based on data collected during 1982 to obtain the 4.0 in. of water needed for the growing season that year.

In plan 2, current irrigational wells (fig. 35) were pumped at a rate of 5 gal/min/acre for 27.3 days to obtain the 7.2 in. of water needed for a growing season of normal precipitation (Chelf, 1983, p. 5).

In plan 3, current irrigational wells (fig. 35) were also pumped at a rate of 5 gal/min/acre, but pumping continued for 36.8 days to obtain the 9.7 in. of water required during a dry growing season (Chelf, 1983, p. 5).

The following criteria were used to design plans 4 and 5: (1) An irrigational water requirement for corn of 7.2 in. during a normal growing season and 9.7 in. during a dry growing season, (2) minimum plot of 40 acres and maximum plot of 160 acres for one irrigational pump, (3) maximum pumping rate of 1,000 gal/min (2.2 ft^3/s) for each well, (4) land designated as irrigable (fig. 36), and (5) stream withdrawals simulated for irrigable land within one-half mile of a stream. In plan 4, simulating a normal year, wells were pumped for 27.3 days. In plan 5, simulating a dry year, wells were pumped for 36.8 days.

The distribution of wells and the pumping rates used in plans 4 and 5 were also used in plan 6, but the wells were pumped year-round until steady state was achieved.

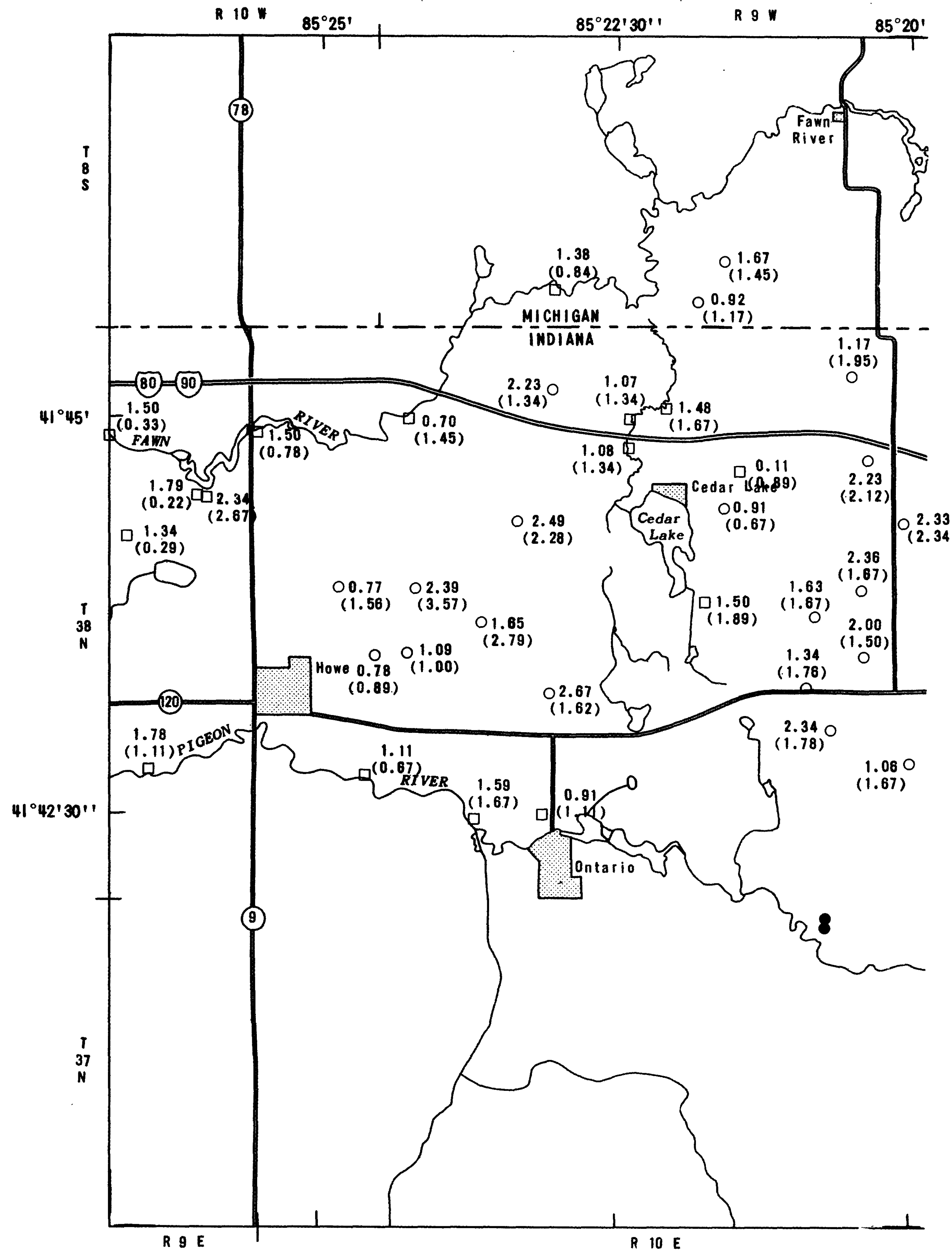
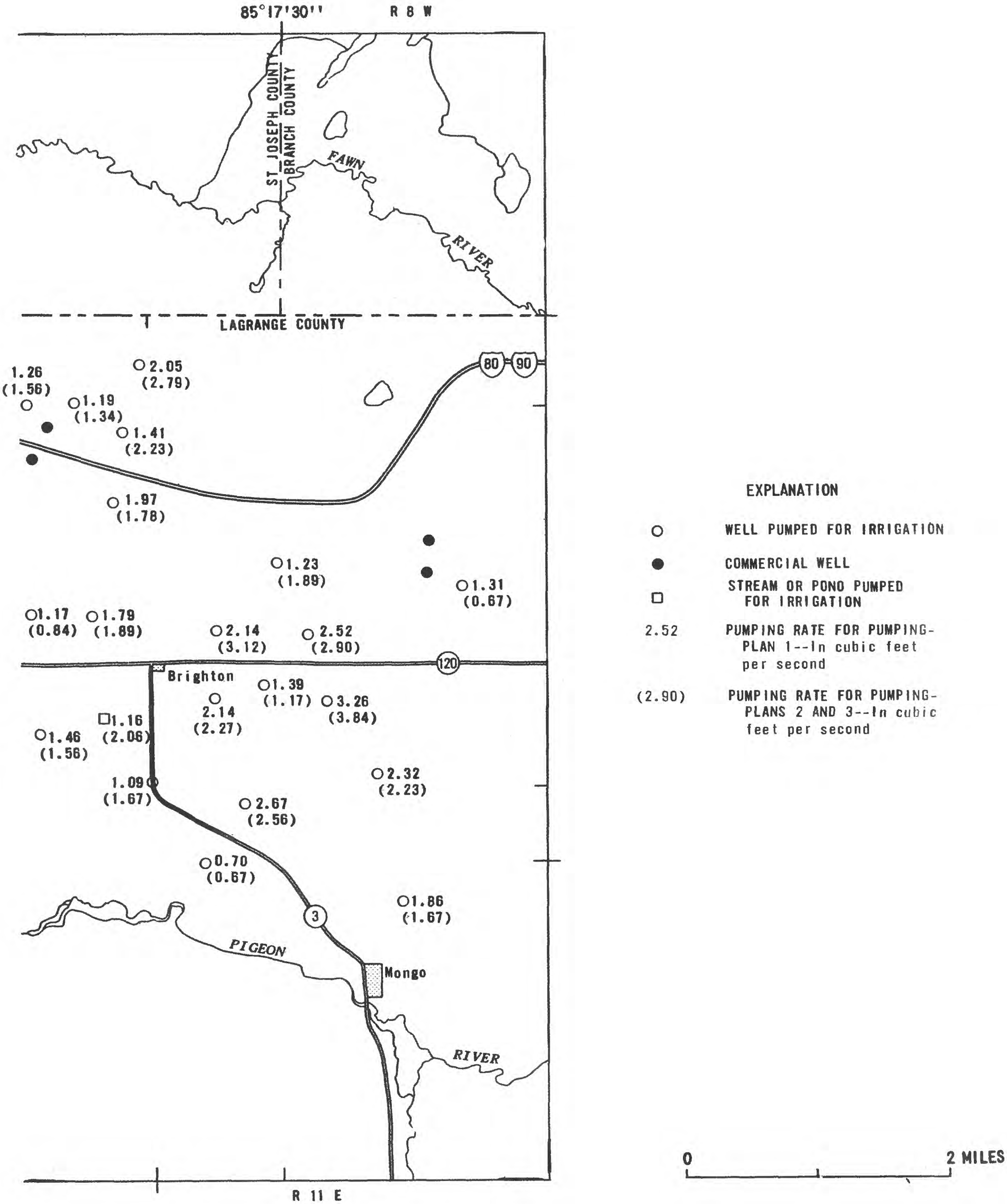


Figure 35.-- Locations and pumping rates of irrigational pumps.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
1.26
(1.56)
2.05
(2.79)
1.19
(1.34)
1.41
(2.23)
1.97
(1.78)
1.23
(1.89)
1.31
(0.67)
1.17
(0.84)
1.79
(1.89)
2.14
(3.12)
2.52
(2.90)
120
Brighton
1.39
(1.17)
3.26
(3.84)
2.14
(2.27)
1.16
(2.06)
1.46
(1.56)
2.32
(2.23)
1.09
(1.67)
2.67
(2.56)
0.70
(0.67)
1.86
(1.67)
3
PIGEON
Mongo
RIVER
R 11 E
EXPLANATION
WELL PUMPED FOR IRRIGATION
COMMERCIAL WELL
STREAM OR PONO PUMPED FOR IRRIGATION
2.52 PUMPING RATE FOR PUMPING-PLAN 1--In cubic feet per second
(2.90) PUMPING RATE FOR PUMPING-PLANS 2 AND 3--In cubic feet per second
0
2 MILES

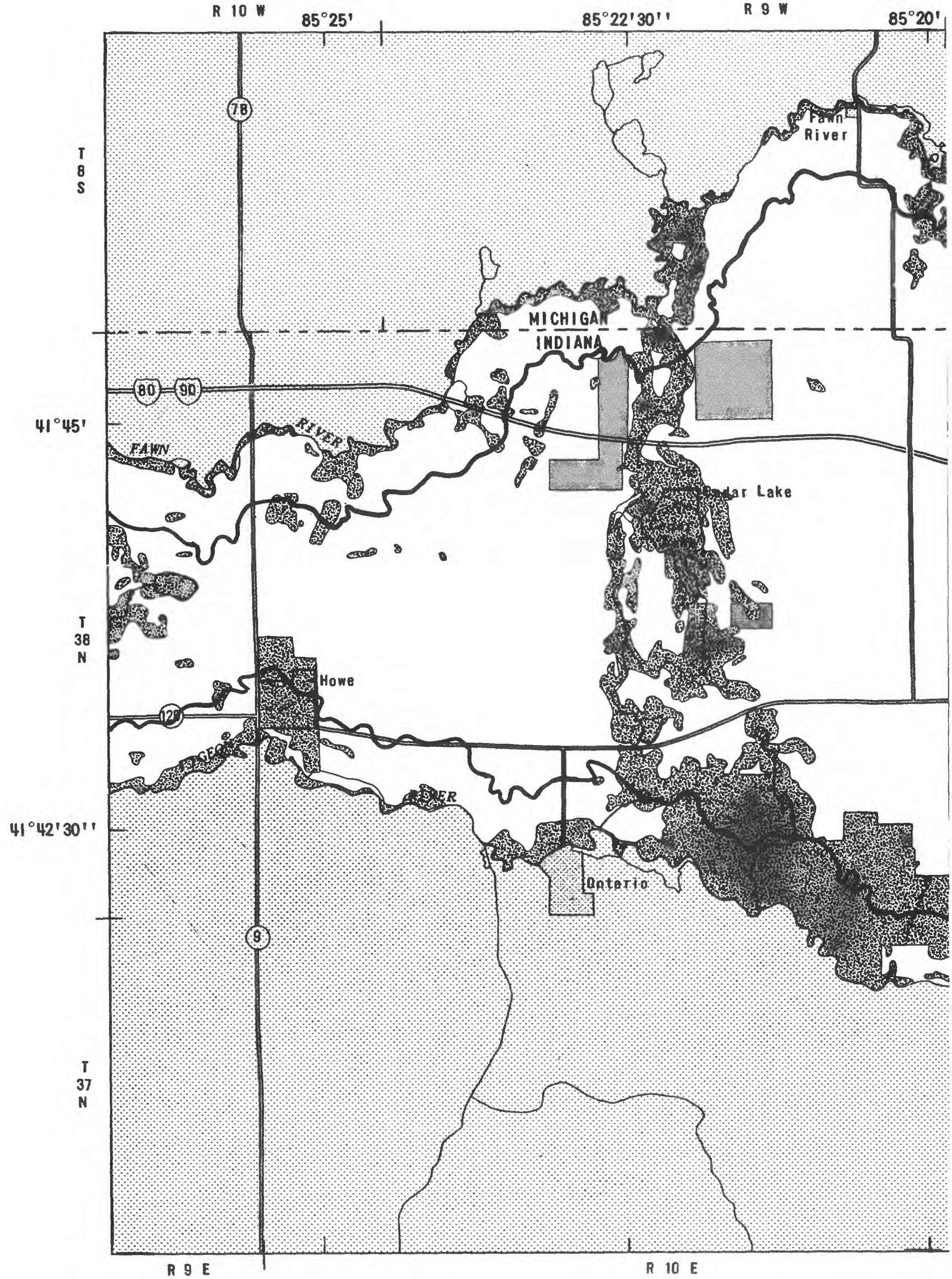
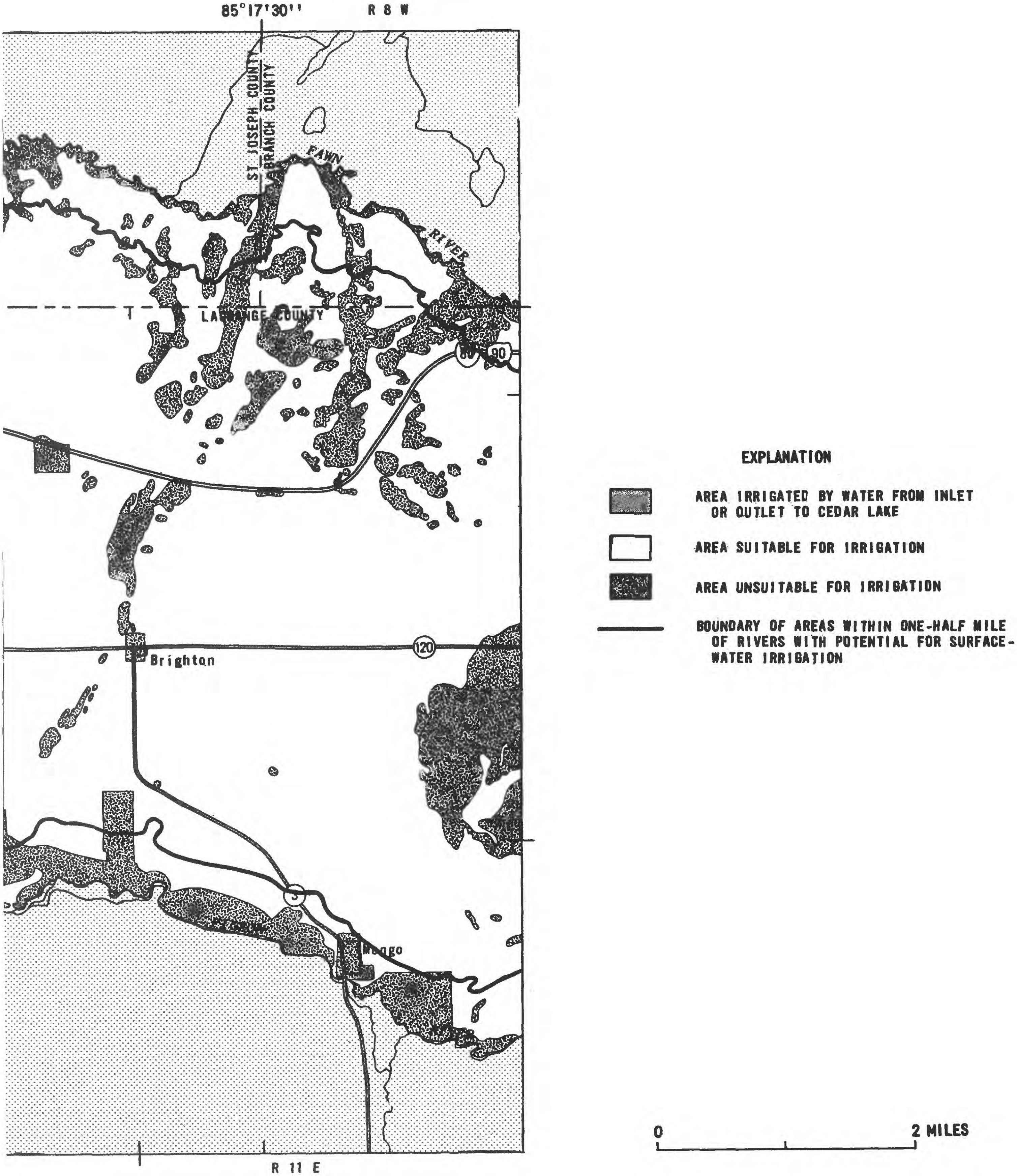


Figure 36.-- Irrigable land.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
Mongo
R 11 E
EXPLANATION
AREA IRRIGATED BY WATER FROM INLET OR OUTLET TO CEDAR LAKE
AREA SUITABLE FOR IRRIGATION
AREA UNSUITABLE FOR IRRIGATION
BOUNDARY OF AREAS WITHIN ONE-HALF MILE OF RIVERS WITH POTENTIAL FOR SURFACE-WATER IRRIGATION
0
2 MILES

The locations and pumping rates of the simulated wells and surface-water pumps for plans 4, 5, and 6 are shown in figure 37. The wells pump from layer 2 and the rates are based on an application rate of 5 gal/min/acre. There are 150 wells and 44 surface pumps (17 on Pigeon River and 27 on Fawn River). Pumping from surface water was not an input variable in the model, but loss from the streams and the effect on streamflow was calculated. The pumping plans are summarized in table 10.

Table 10.--Summary of simulated pumping

[A dash indicates that information does not apply in the category]

Pumping plan	Number of pumps			Pumpage (ft^3/s)			Number of days of pumping		
	Ground water	Surface water	Total	Ground water[1]	Surface water	Total	Normal year	Dry year	1982
1	40	17	57	69.0	22.3	91.3	--	--	15
2	40	17	57	73.4	20.3	93.7	27.3	--	--
3	40	17	57	73.4	20.3	93.7	--	36.8	--
4	150	44	194	202.8	37.6	240.4	27.3	--	--
5	150	44	194	202.8	37.6	240.4	--	36.8	--
6	150	0	150	202.8	0	202.8	steady	state	--

[1] An additional 1.96 ft^3/s pumped from five commercial wells is included in each simulation.

Effects of Simulated Pumping

The effects of simulated pumping on the hydrologic system were assessed by mapping the extent and the magnitude of ground-water level declines simulated by the model and by calculating reductions in streamflow. Both constant-flux and constant-head boundaries were used for each pumping plan to establish maximum and minimum water-level declines and worst- and best-case water budgets.

Simulated water-level declines for all the pumping plans are summarized in table 11. Drawdown in layers 1 and 2, with constant-flux boundaries are shown for pumping plans 1 through 5 (figs. 38-44, 46, 48, and 50). Drawdowns in layers 1 and 2, which have constant-head boundaries, are shown for plans 4 through 6 (figs. 45, 47, 49, and 51-53) where the drawdowns were significantly different from those simulated for constant-flux boundaries. In all simulations, drawdown in layer 3 was nearly identical with that in layer 2, so no maps for layer 3 are shown.

Effects of simulated pumping on flow in Pigeon River were assessed by three methods: (1) Comparison of simulated flow with flow measured in autumn 1982; (2) comparison of simulated flow with flow based on a flow-duration curve developed from mean daily discharges during the entire year; and (3) comparison of simulated flow with flow based on a flow-duration curve developed from mean daily discharge during June, July, and August.

Table 11.--Maximum and minimum water-level declines for pumping simulations

Pumping plan	Boundary CF = constant flux CH = constant head	Layer	Maximum drawdown (ft)	Minimum drawdown (ft)
1	CF	1	4	0
	CF	2	14	<1
	CF	3	14	<1
	CH	1	4	0
	CH	2	14	0
	CH	3	14	0
2	CF	1	6	0
	CF	2	15	<1
	CF	3	15	<1
	CH	1	6	0
	CH	2	14	0
	CH	3	14	0
3	CF	1	7	0
	CF	2	15	<1
	CF	3	15	<1
	CH	1	6	0
	CH	2	15	0
	CH	3	14	0
4	CF	1	14	0
	CF	2	30	1
	CF	3	31	1
	CH	1	5	0
	CH	2	29	0
	CH	3	29	0
5	CF	1	15	0
	CF	2	32	1
	CF	3	31	1
	CH	1	6	0
	CH	2	30	0
	CH	3	29	0
6	CH	1	38	0
	CH	2	46	0
	CH	3	45	0

The single set of streamflow measurements from autumn 1982 was used as criteria for the steady-state calibration and for comparison to streamflow simulated in plan 1 but was not representative for the normal and dry periods simulated in the other pumping plans. To estimate flows for these periods, the authors developed flow-duration curves with streamflow data collected from 1968 through 1981 at Pigeon River near Scott. These curves were then compared with the modeled seepage to Pigeon River. Flows during normal and dry irrigational

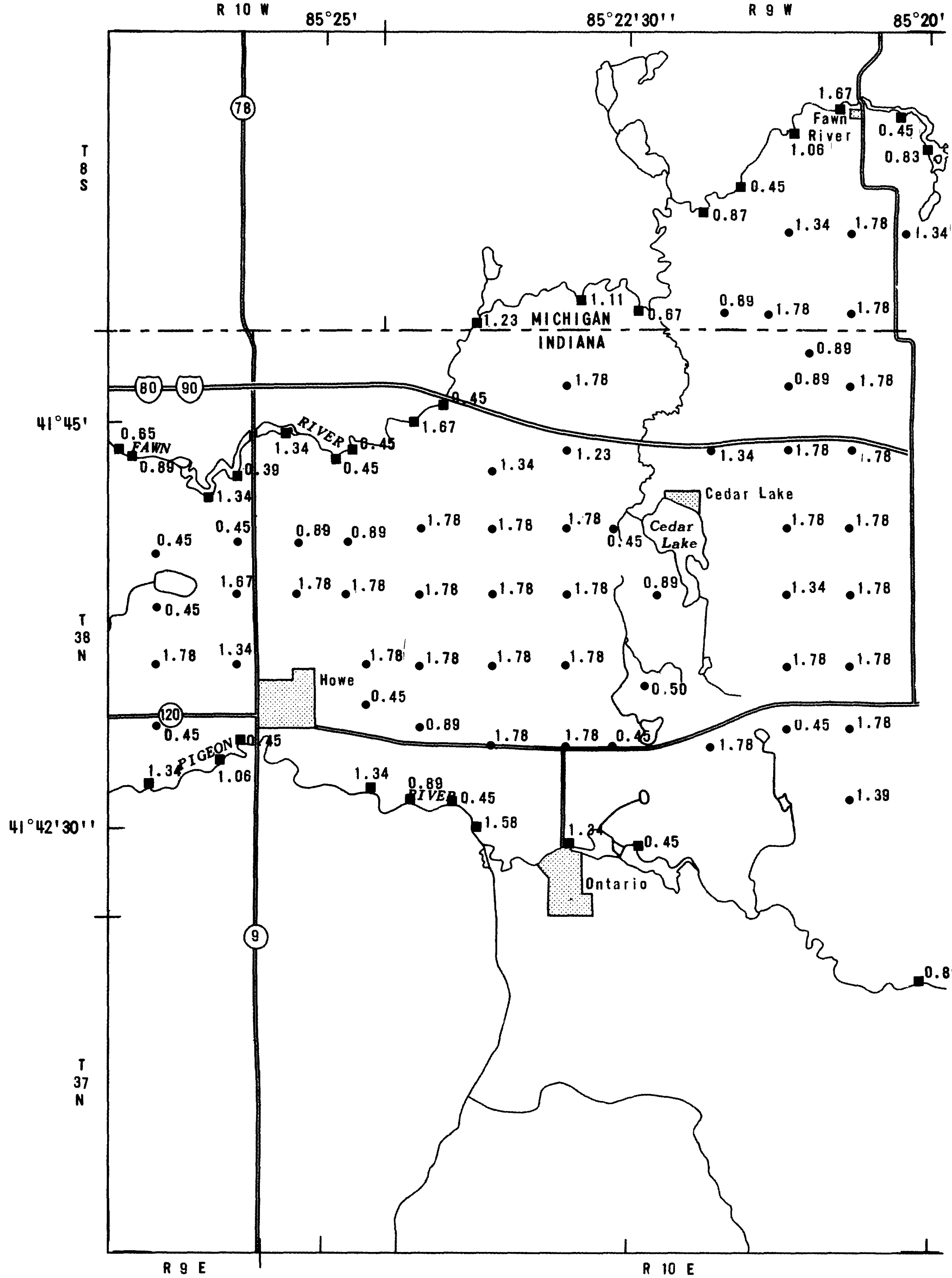
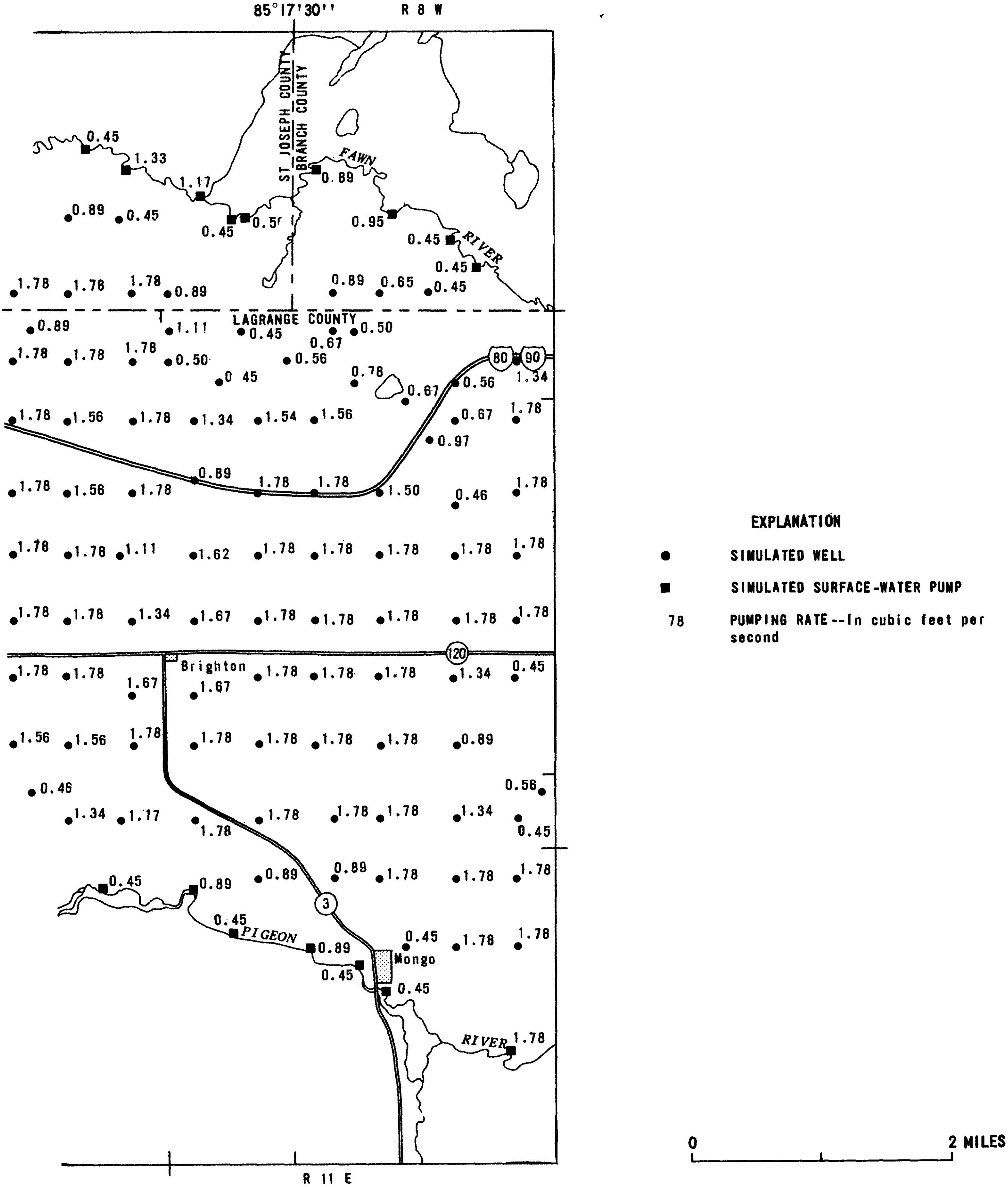


Figure 37. Locations and pumping rates of simulated wells and surface-water pumps.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
LAGRANGE COUNTY
FAWN
RIVER
80
90
120
Brighton
3
PIGEON
RIVER
Mongo
R 11 E
EXPLANATION
SIMULATED WELL
SIMULATED SURFACE-WATER PUMP
78 PUMPING RATE--In cubic feet per second
0
2 MILES

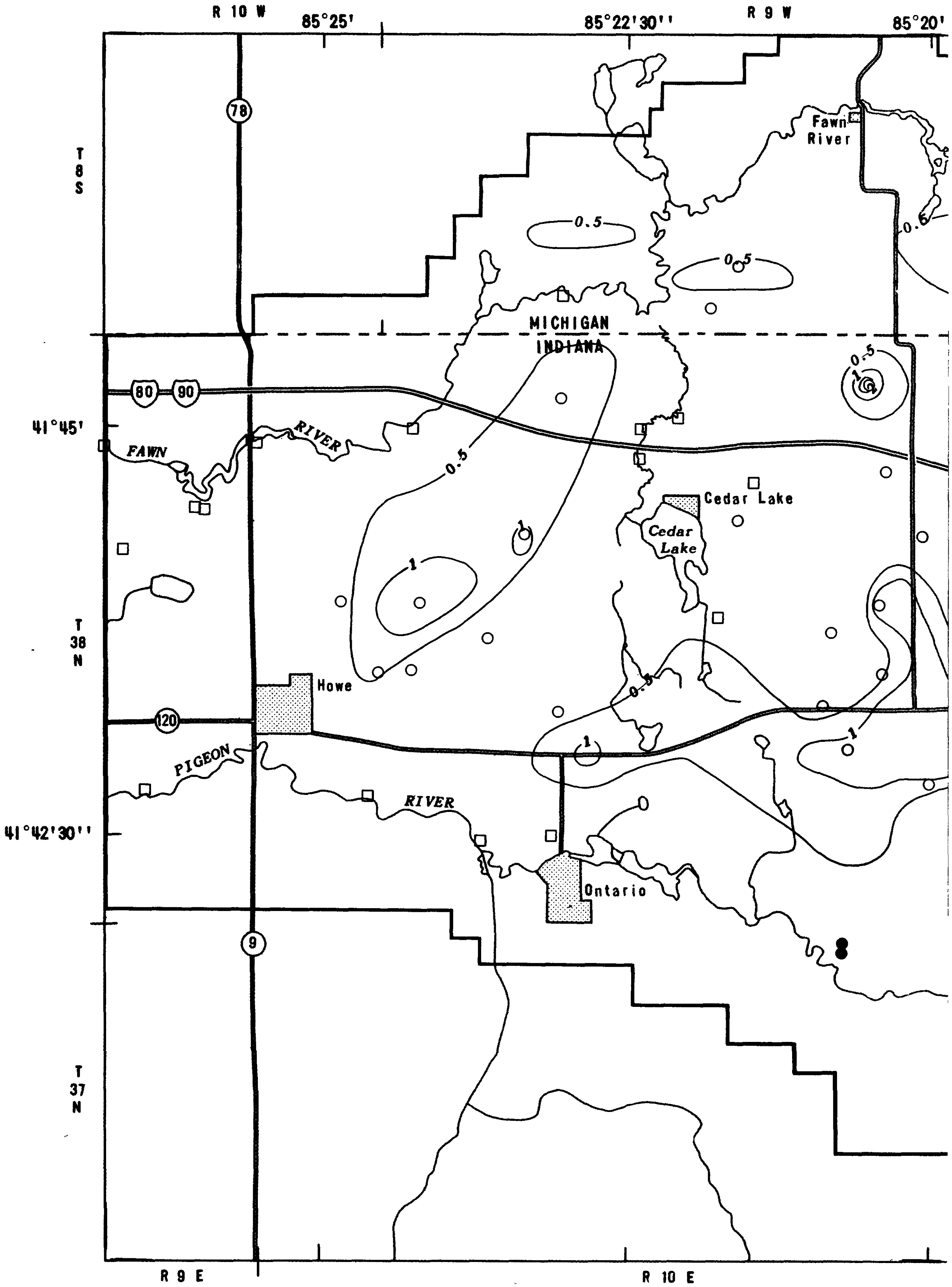
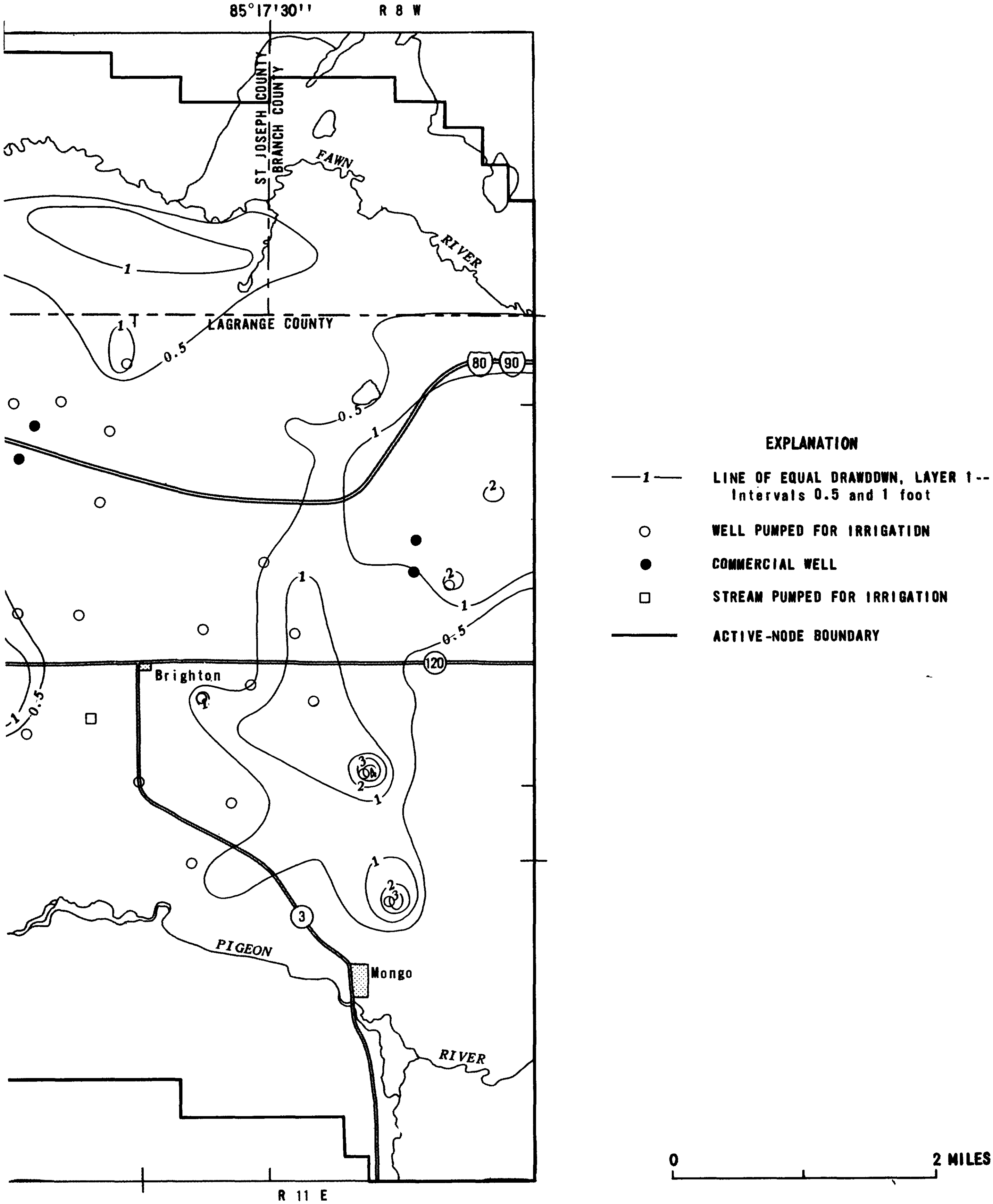


Figure 38.-- Drawdown in layer 1 for pumping-plan 1 with constant-flux boundaries.



85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
Brighton
PIGEON
RIVER
Mongo
R 11 E
EXPLANATION
LINE OF EQUAL DRAWDOWN, LAYER 1-- Intervals 0.5 and 1 foot
WELL PUMPED FOR IRRIGATION
COMMERCIAL WELL
STREAM PUMPED FOR IRRIGATION
ACTIVE-NODE BOUNDARY
0
2 MILES

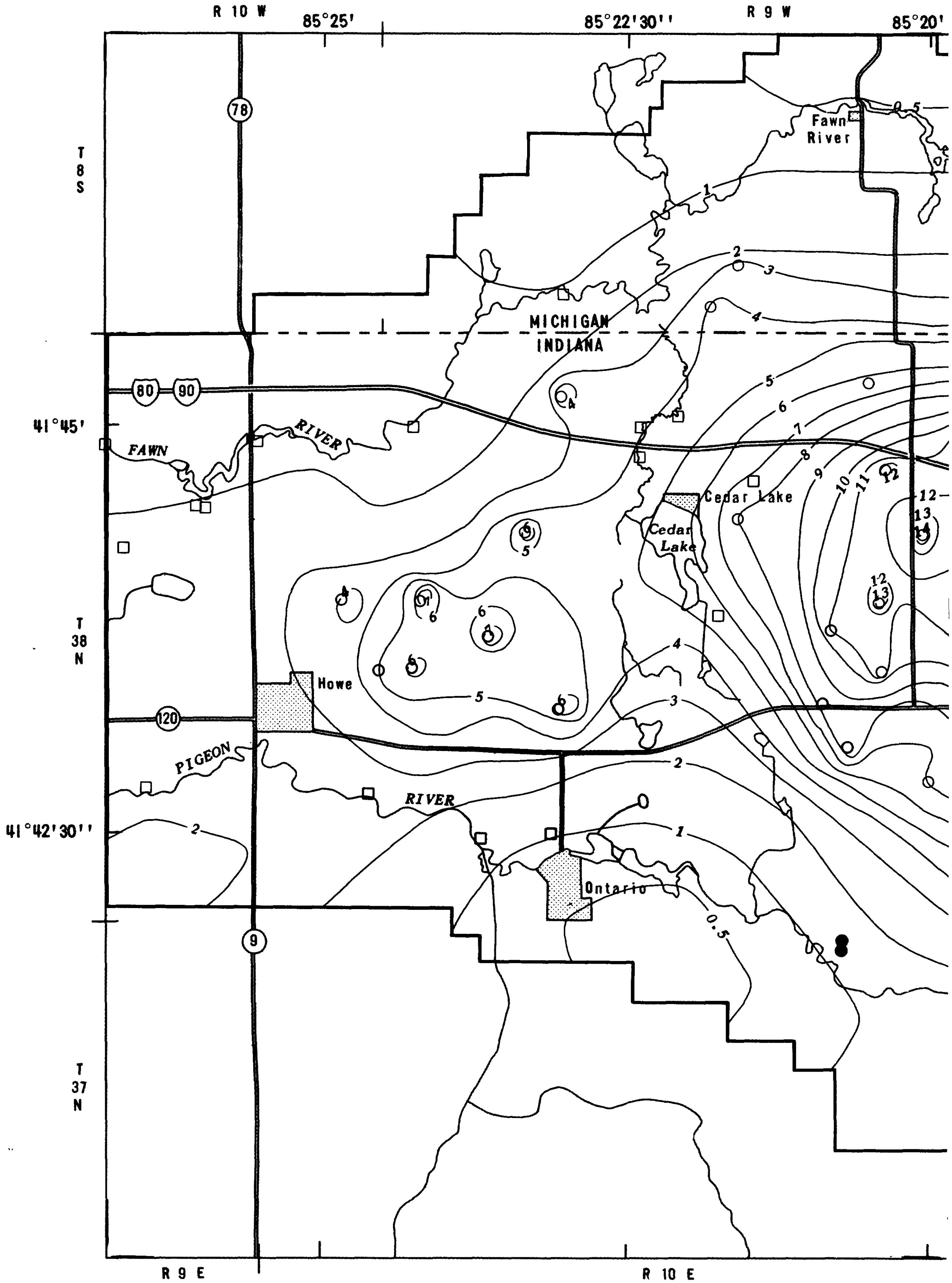
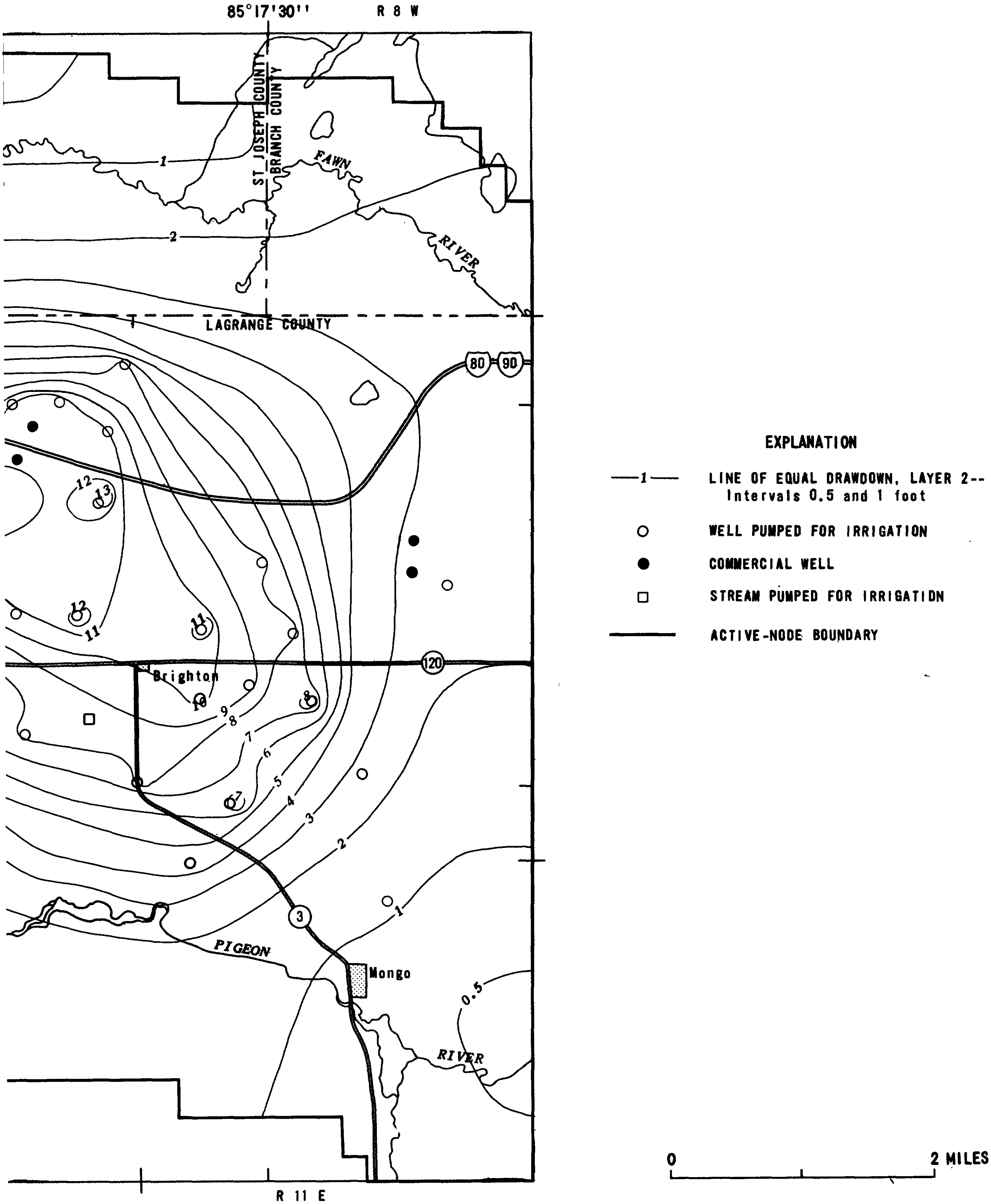


Figure 39.-- Drawdown in layer 2 for pumping-plan 1 with constant-flux boundaries.



85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
PIGEON
Mongo
RIVER
R 11 E
EXPLANATION
LINE OF EQUAL DRAWDOWN, LAYER 2-- Intervals 0.5 and 1 foot
WELL PUMPED FOR IRRIGATION
COMMERCIAL WELL
STREAM PUMPED FOR IRRIGATION
ACTIVE-NODE BOUNDARY
0
2 MILES

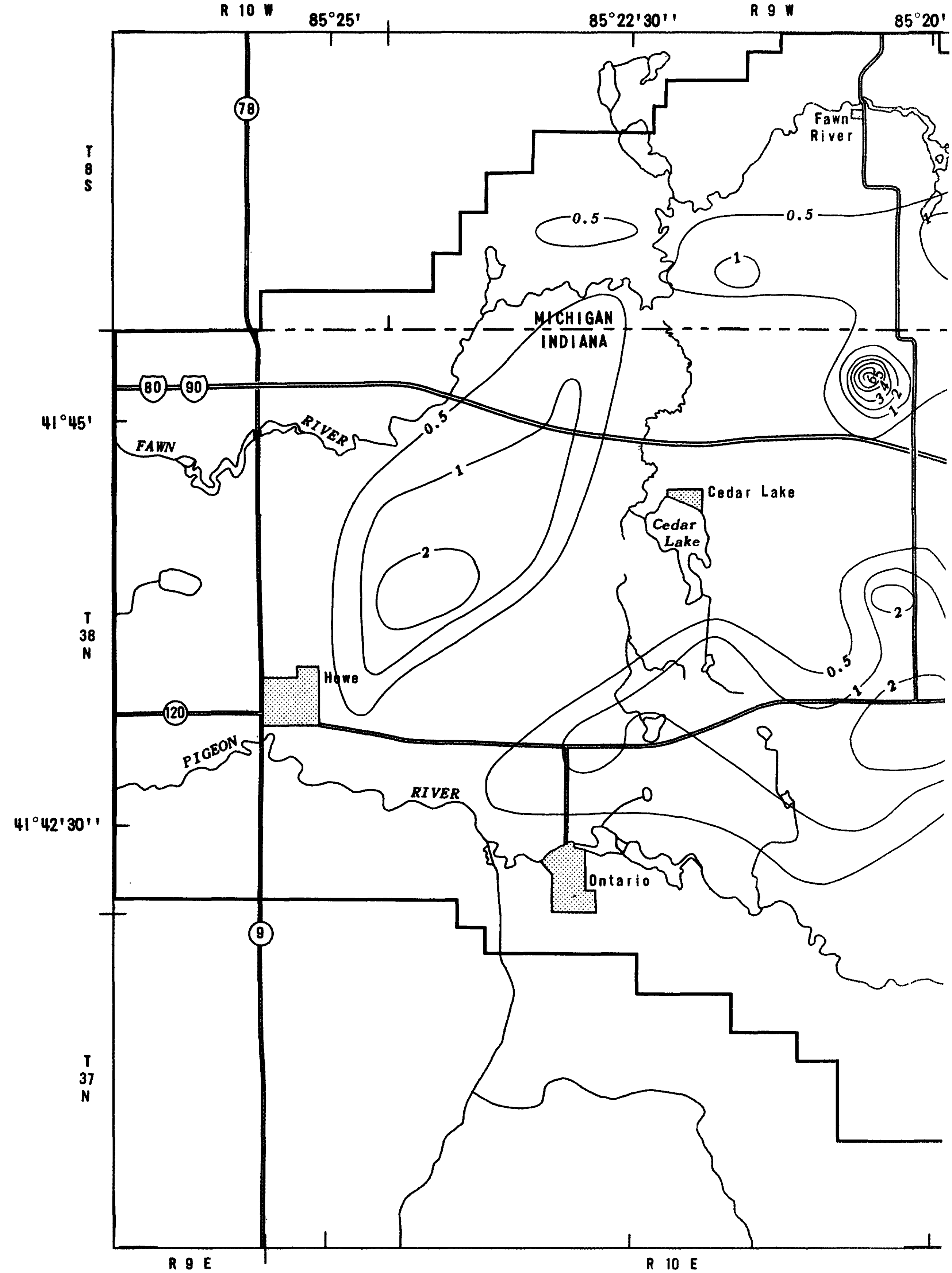
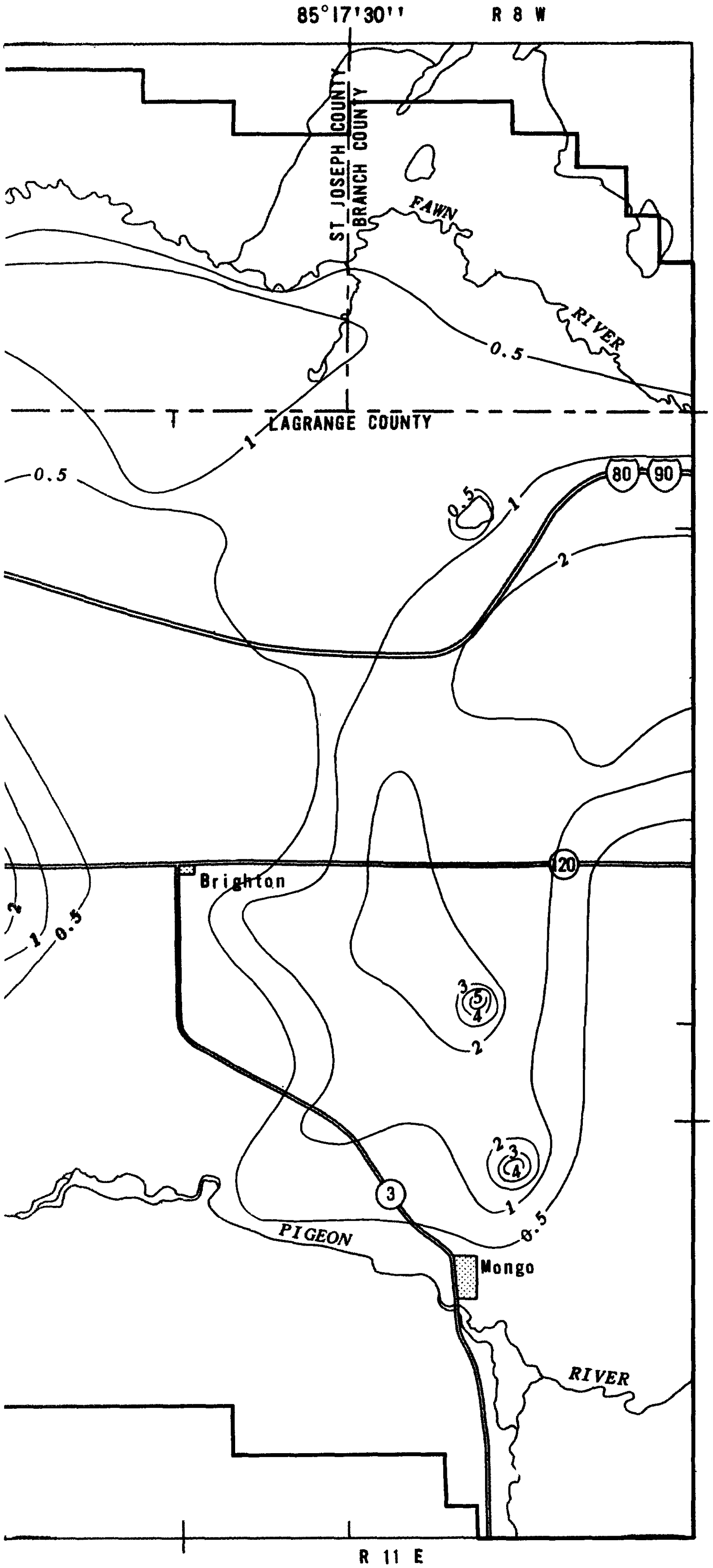


Figure 40.-- Drawdown in layer 1 for pumping-plan 2 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1-- Intervals 0.5 and 1 foot

ACTIVE-NODE BOUNDARY

0 2 MILES

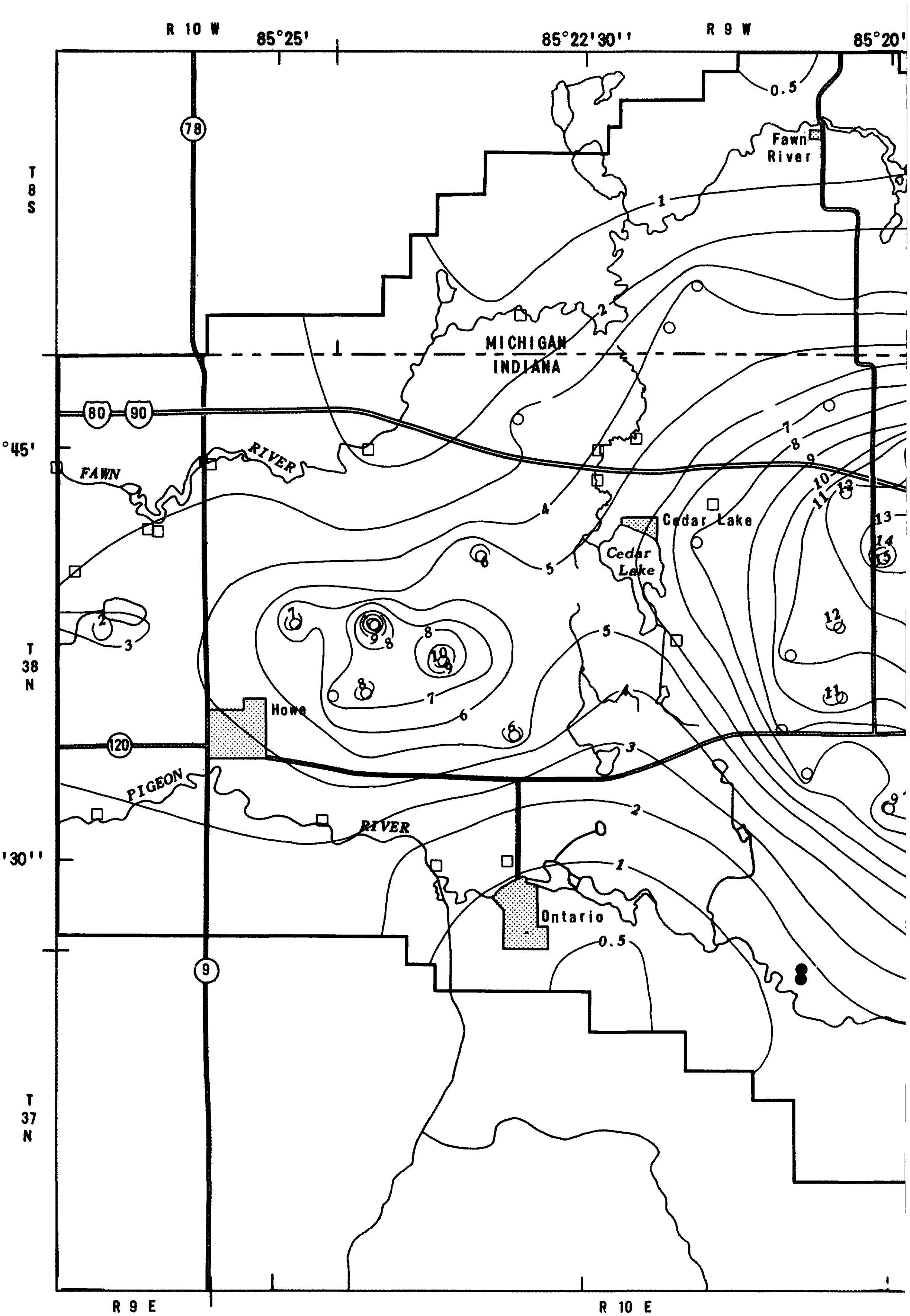
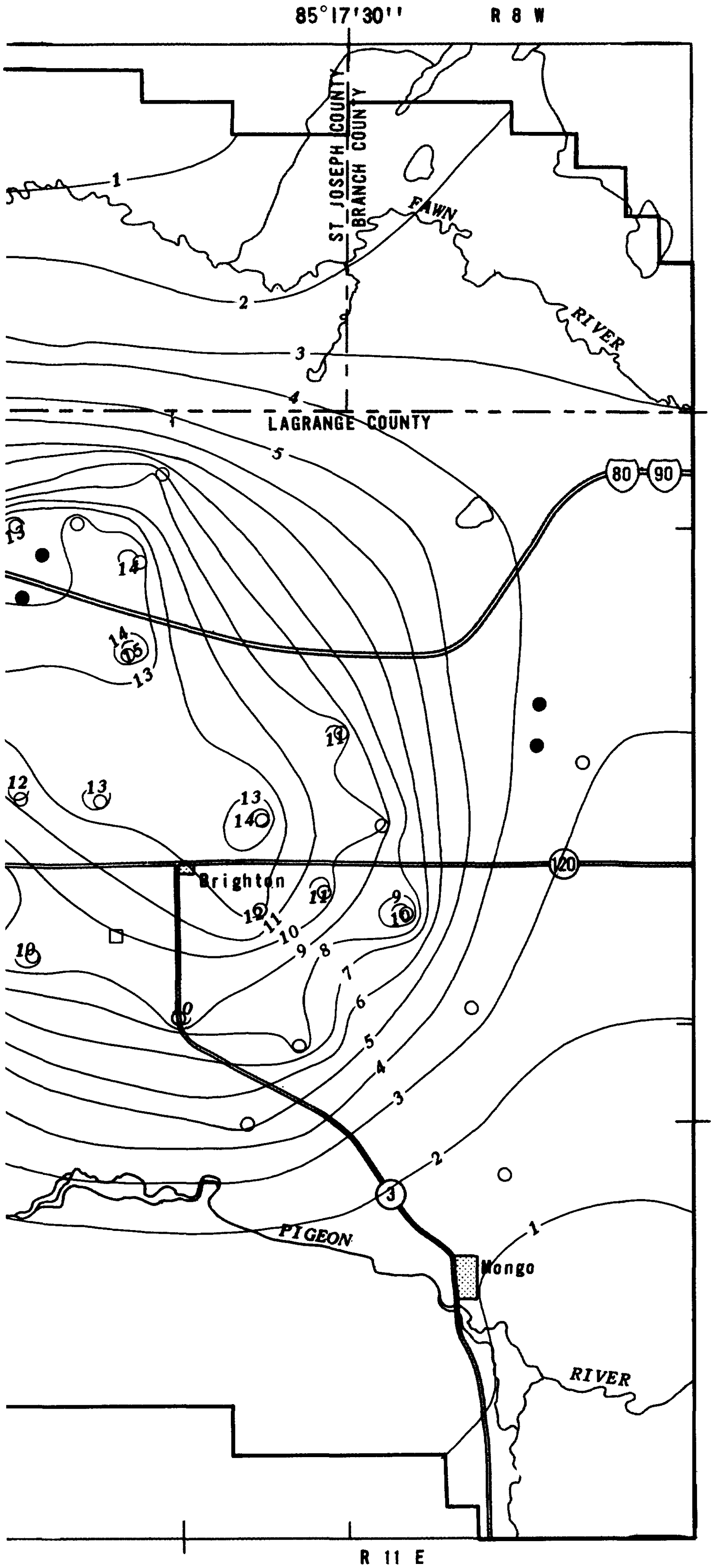


Figure 41.-- Drawdown in layer 2 for pumping-plan 2 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 2-- Intervals 0.5 and 1 foot

○ WELL PUMPED FOR IRRIGATION

● COMMERCIAL WELL

□ STREAM PUMPED FOR IRRIGATION

—— ACTIVE-NODE BOUNDARY

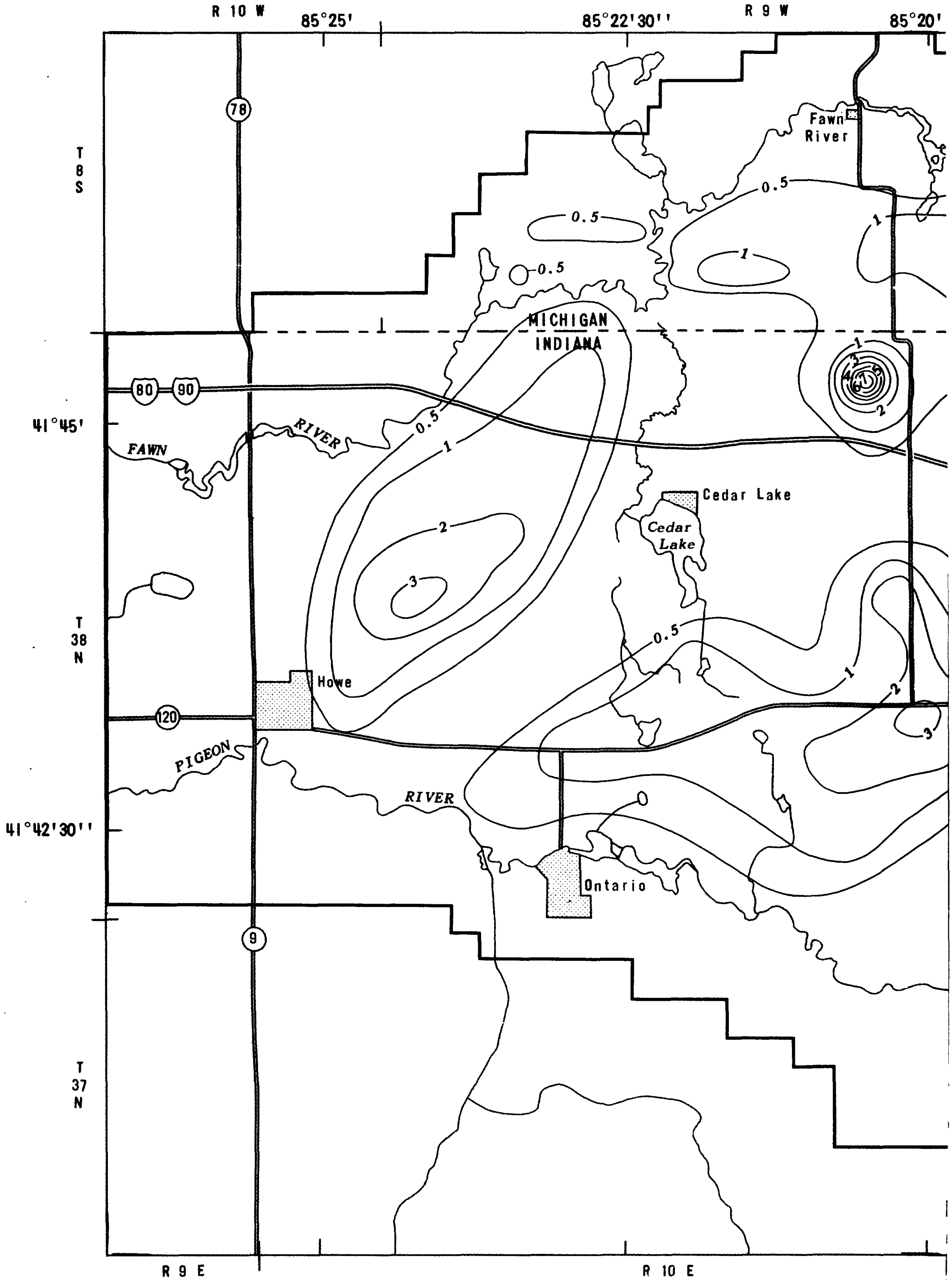
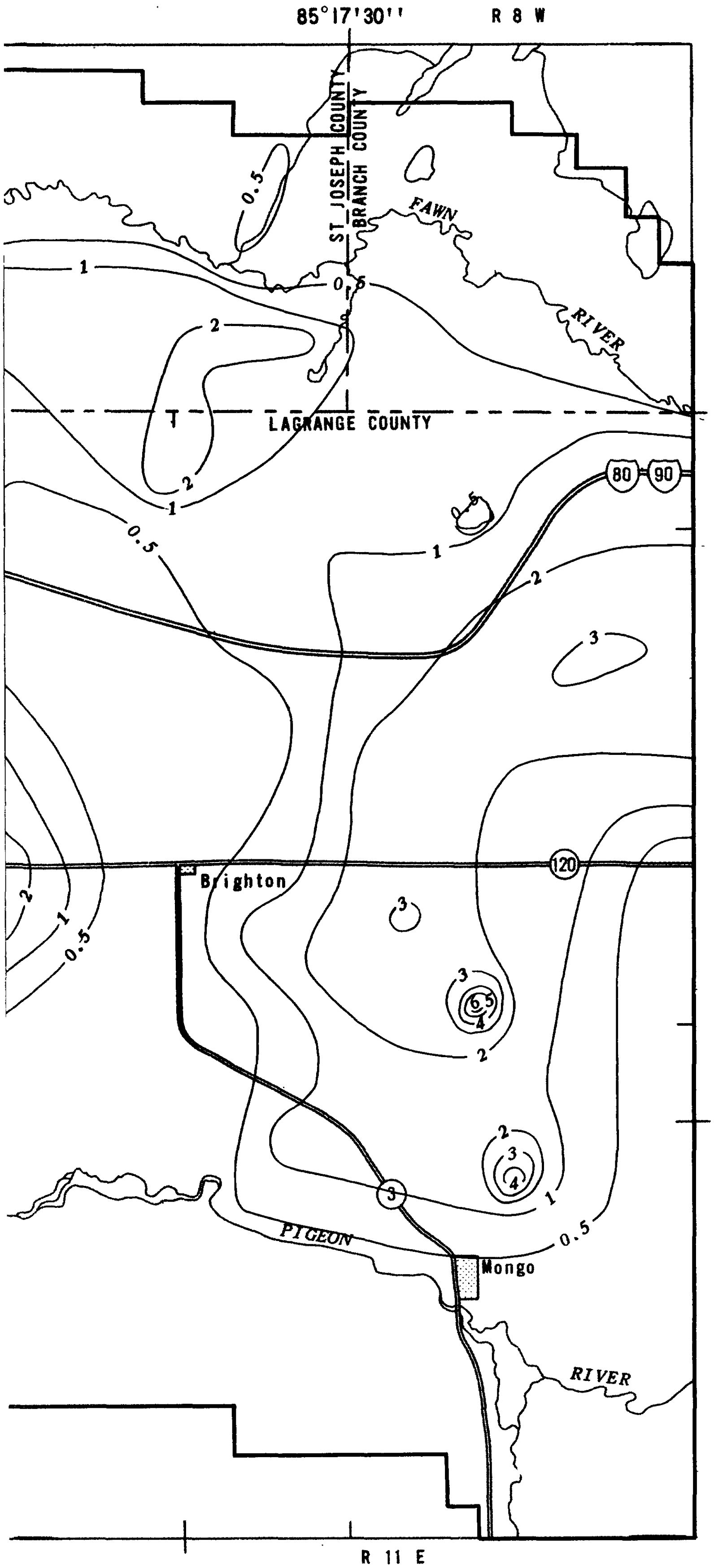


Figure 42.-- Drawdown in layer 1 for pumping-plan 3 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1-- Intervals 0.5 and 1 foot

ACTIVE-NODE BOUNDARY

0 2 MILES

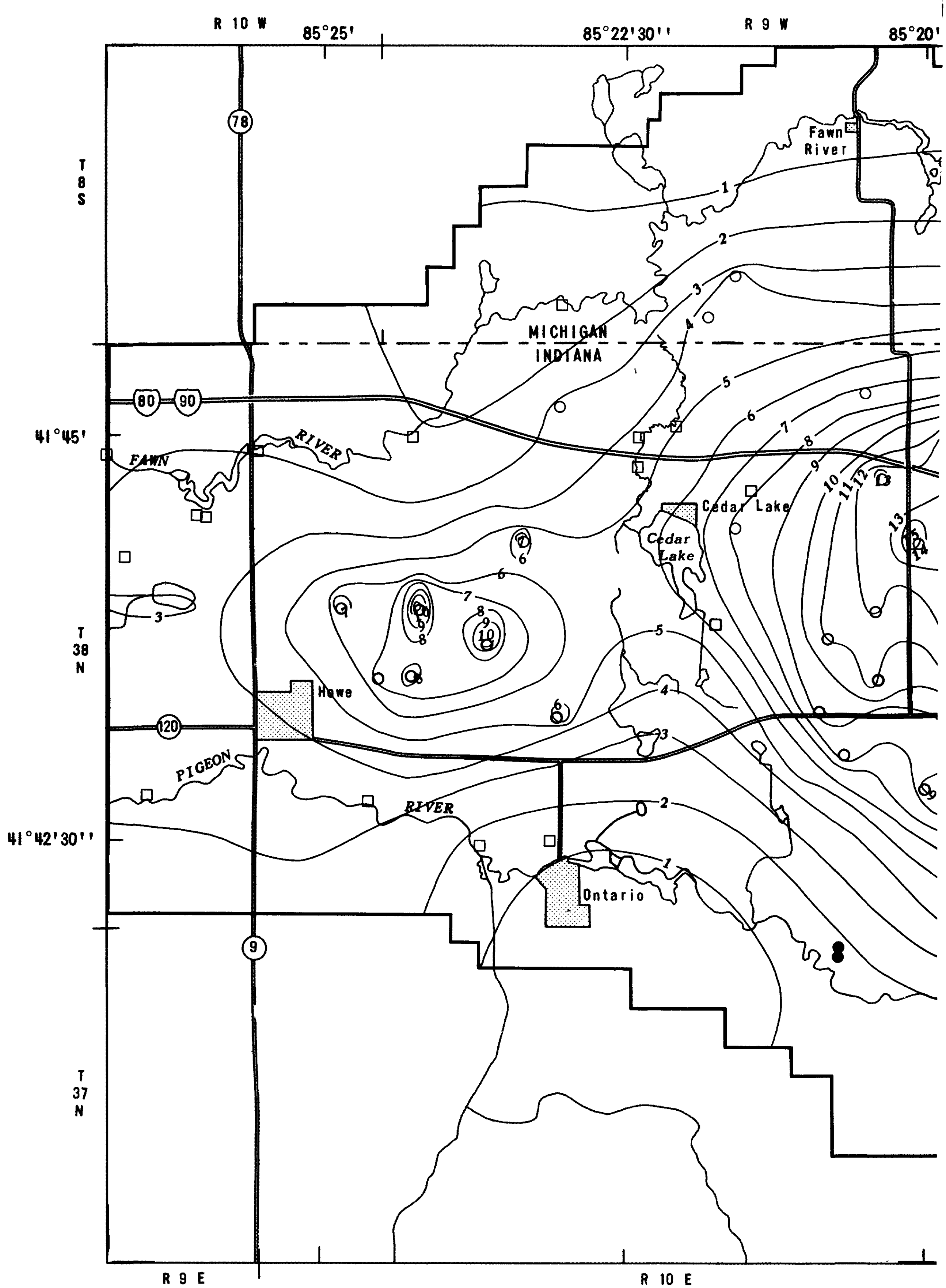
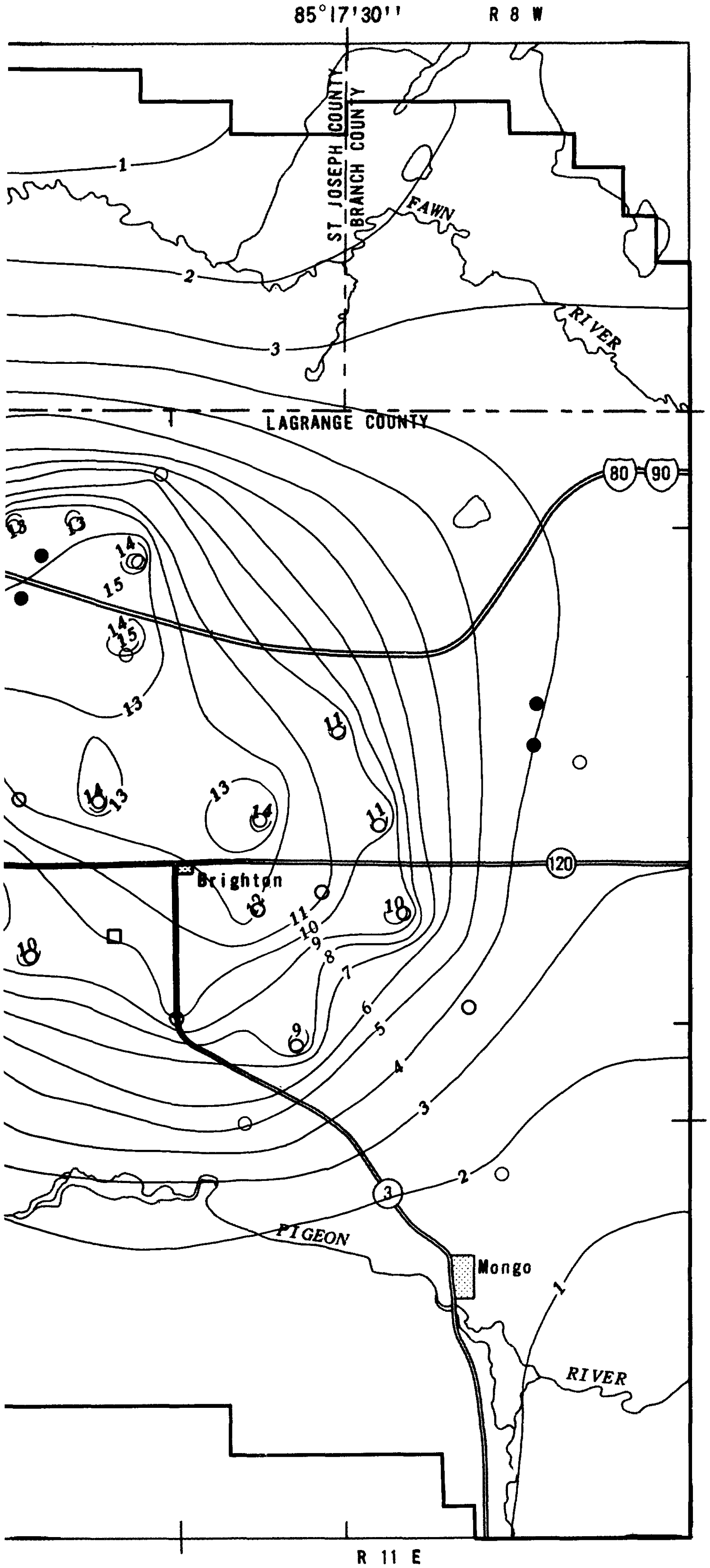


Figure 43.-- Drawdown in layer 2 for pumping-plan 3 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 2-- Interval 1 foot

○ WELL PUMPED FOR IRRIGATION

● COMMERCIAL WELL

□ STREAM PUMPED FOR IRRIGATION

▬ ACTIVE-NODE BOUNDARY

0 2 MILES

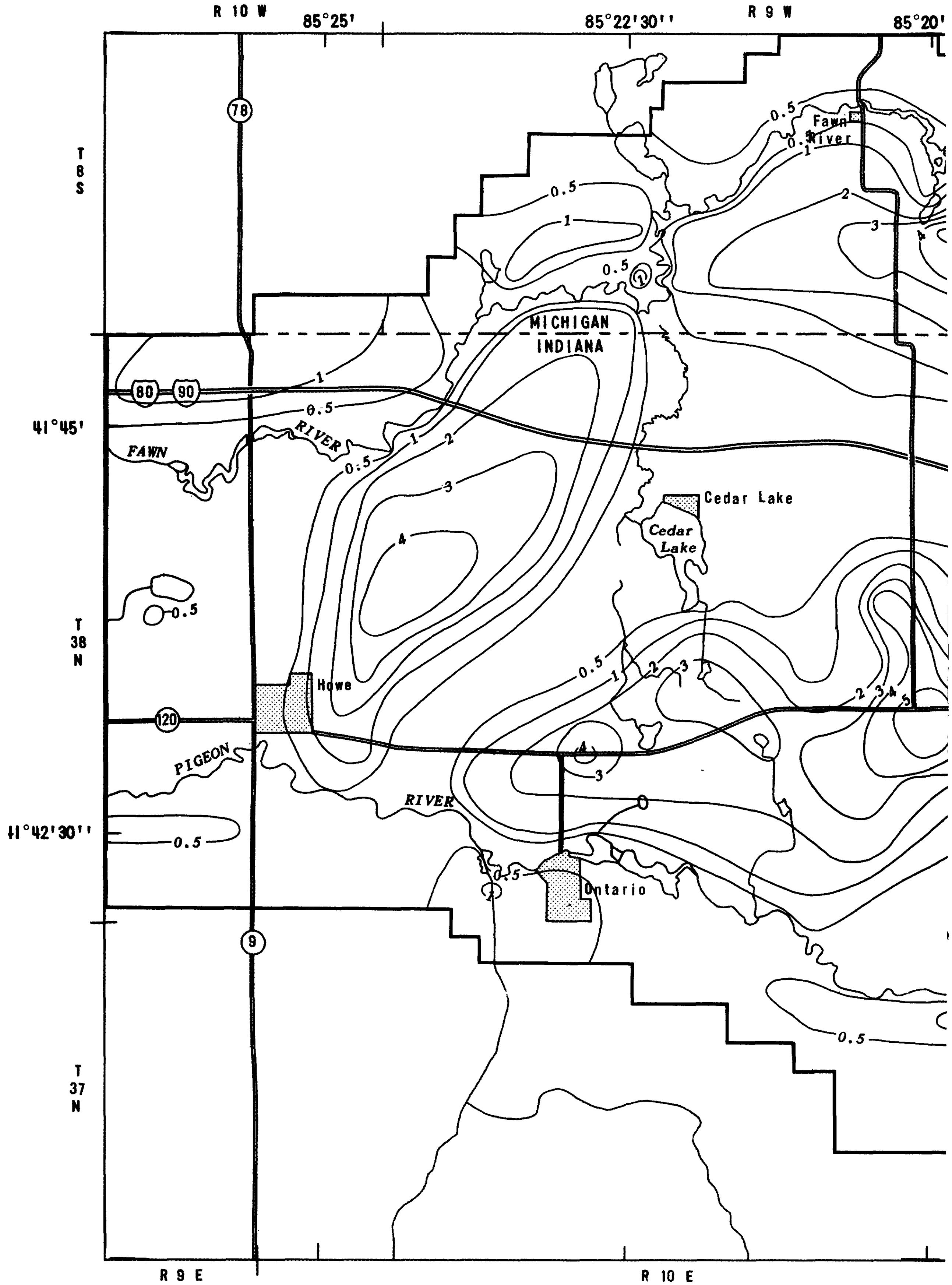
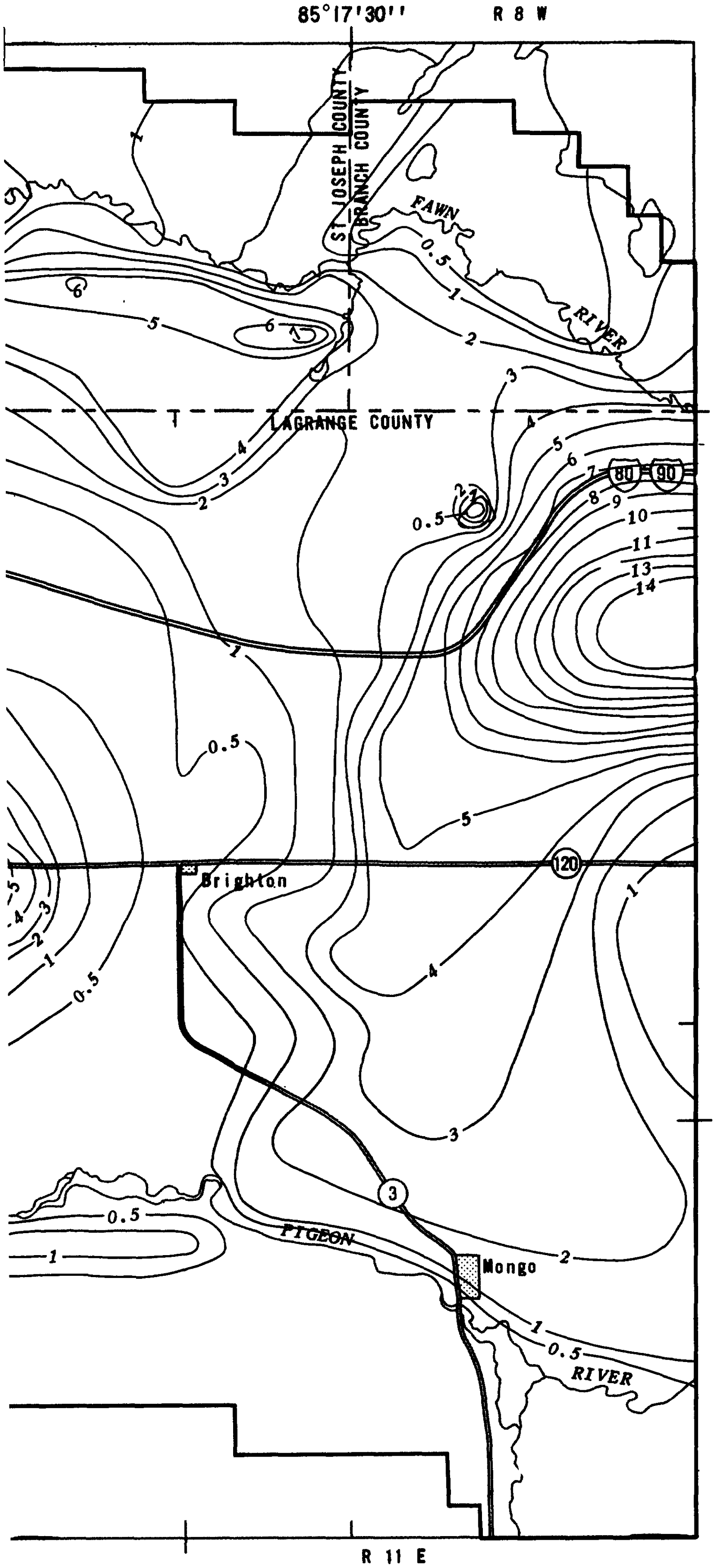


Figure 44.-- Drawdown in layer 1 for pumping-plan 4 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1-- Intervals 0.5 and 1 foot

▬▬ ACTIVE-NODE BOUNDARY

0 — 2 MILES

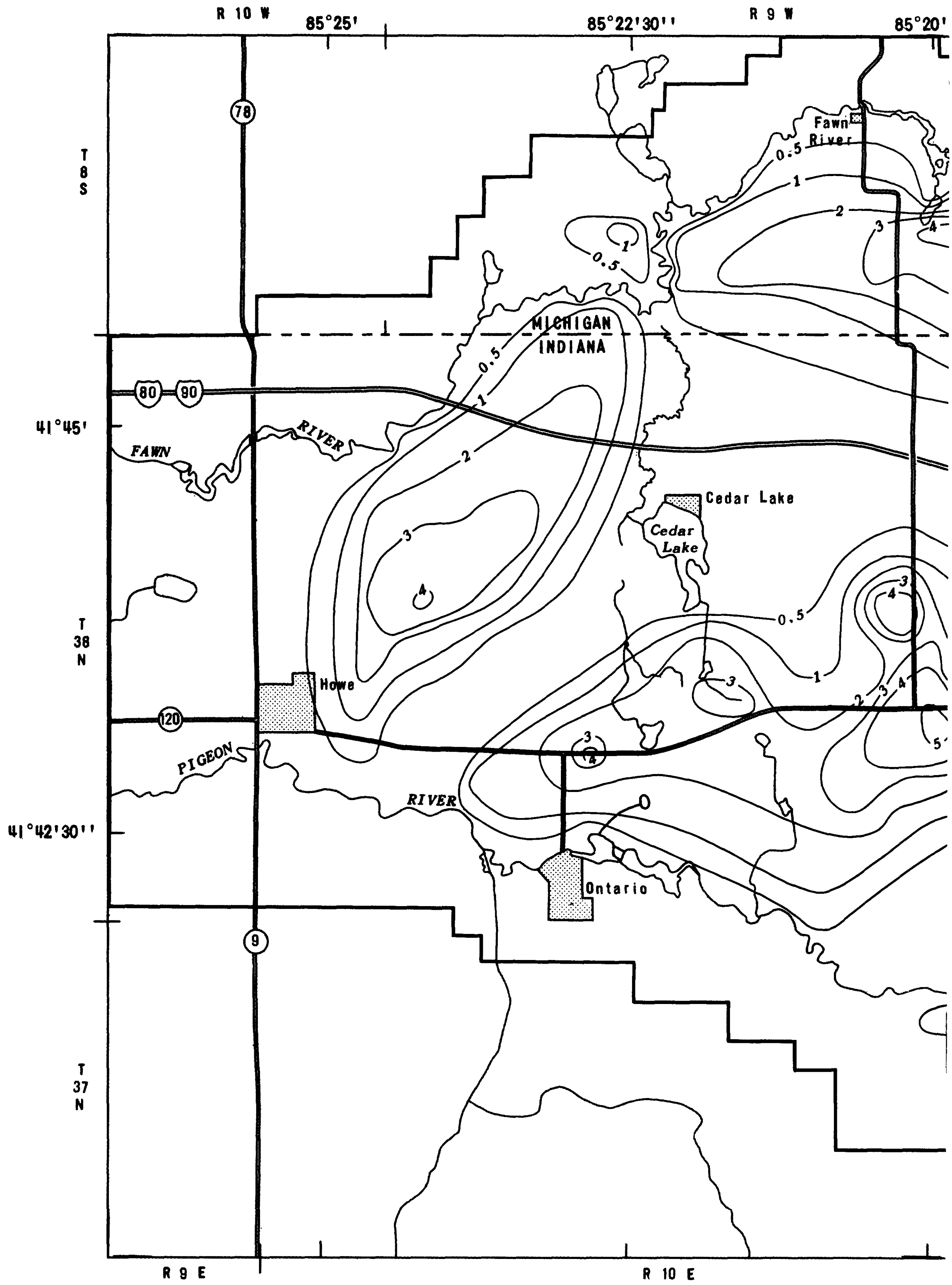
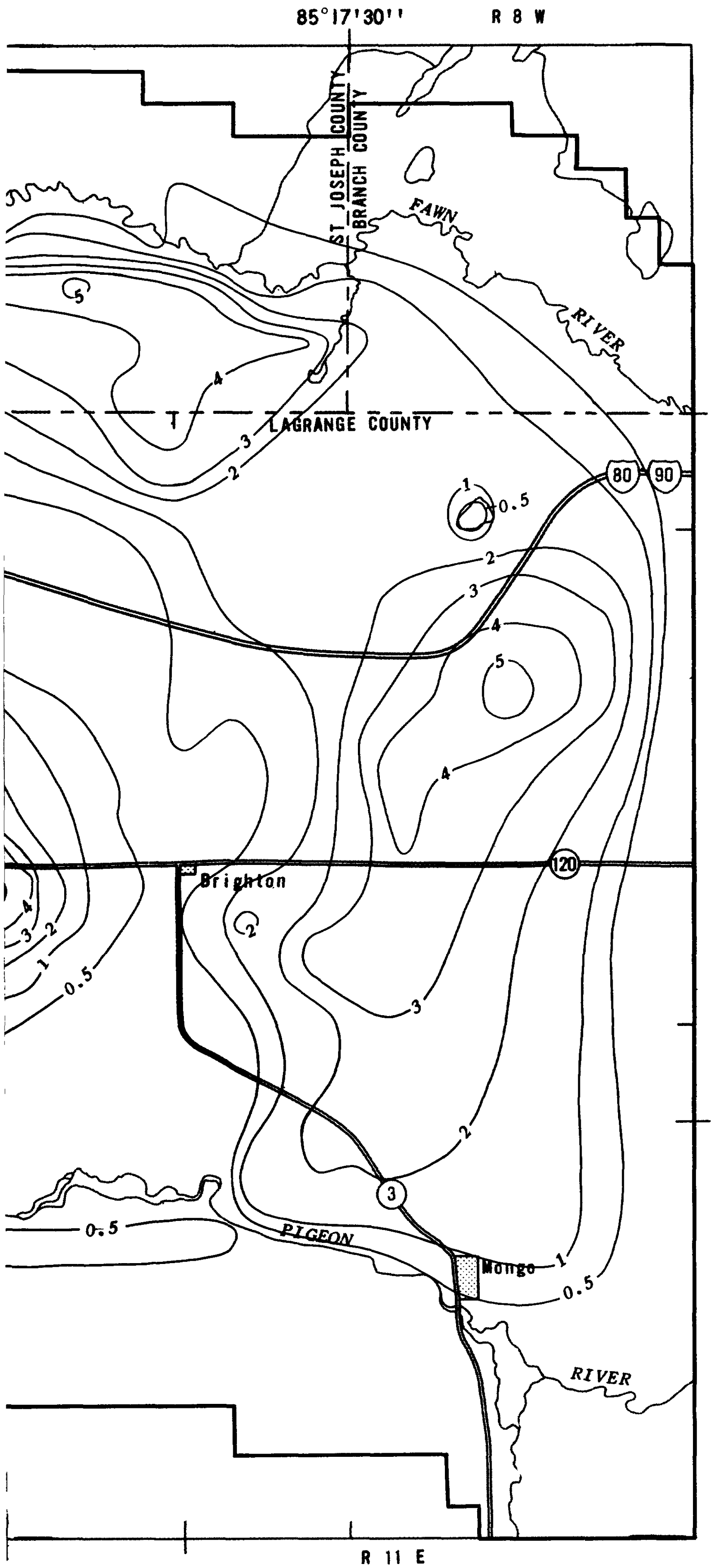


Figure 45.-- Drawdown in layer 1 for pumping-plan 4 with constant-head boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1--
Intervals 0.5 and 1 foot

▬▬ ACTIVE-NODE BOUNDARY

0 — 2 MILES

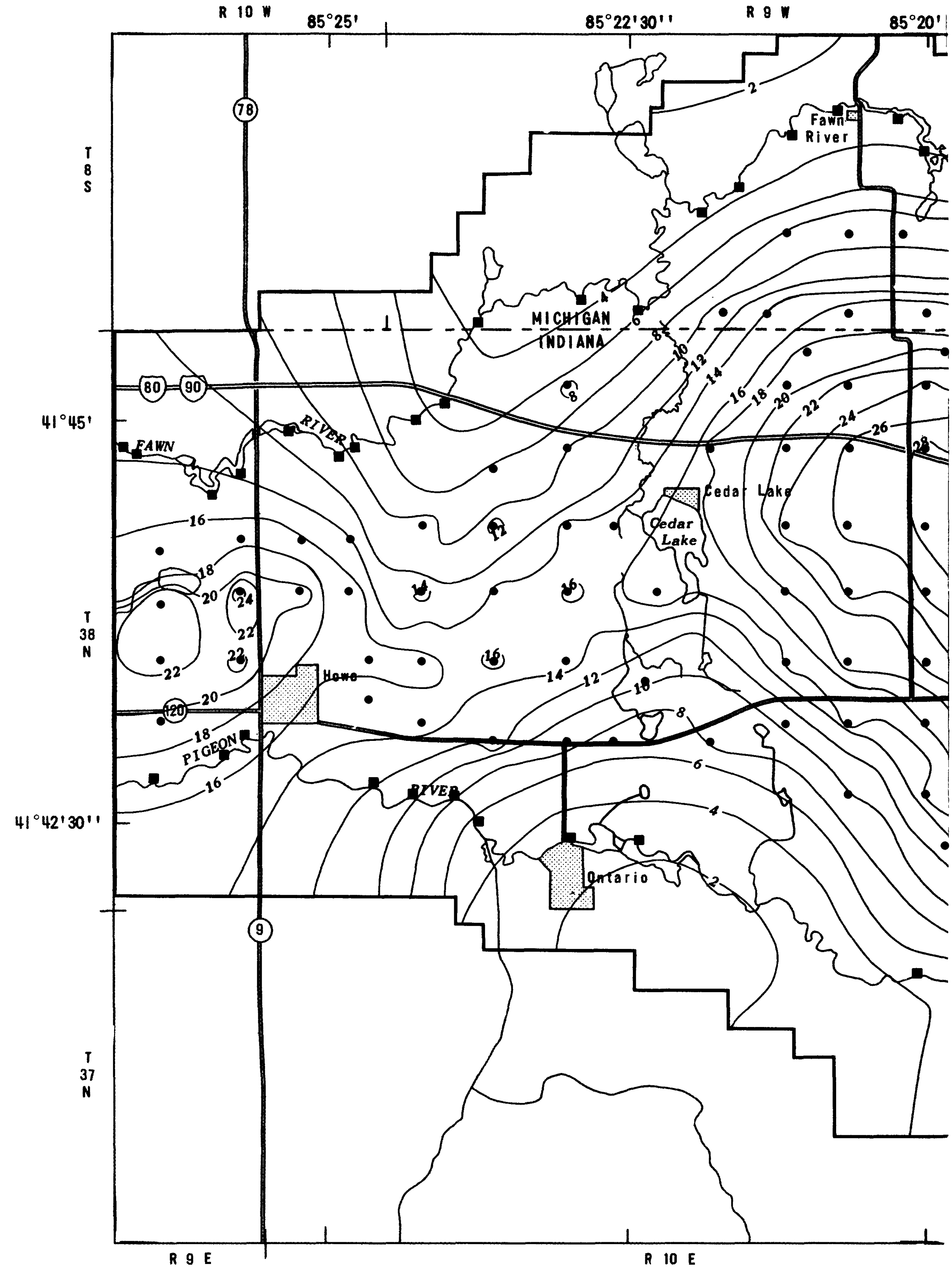
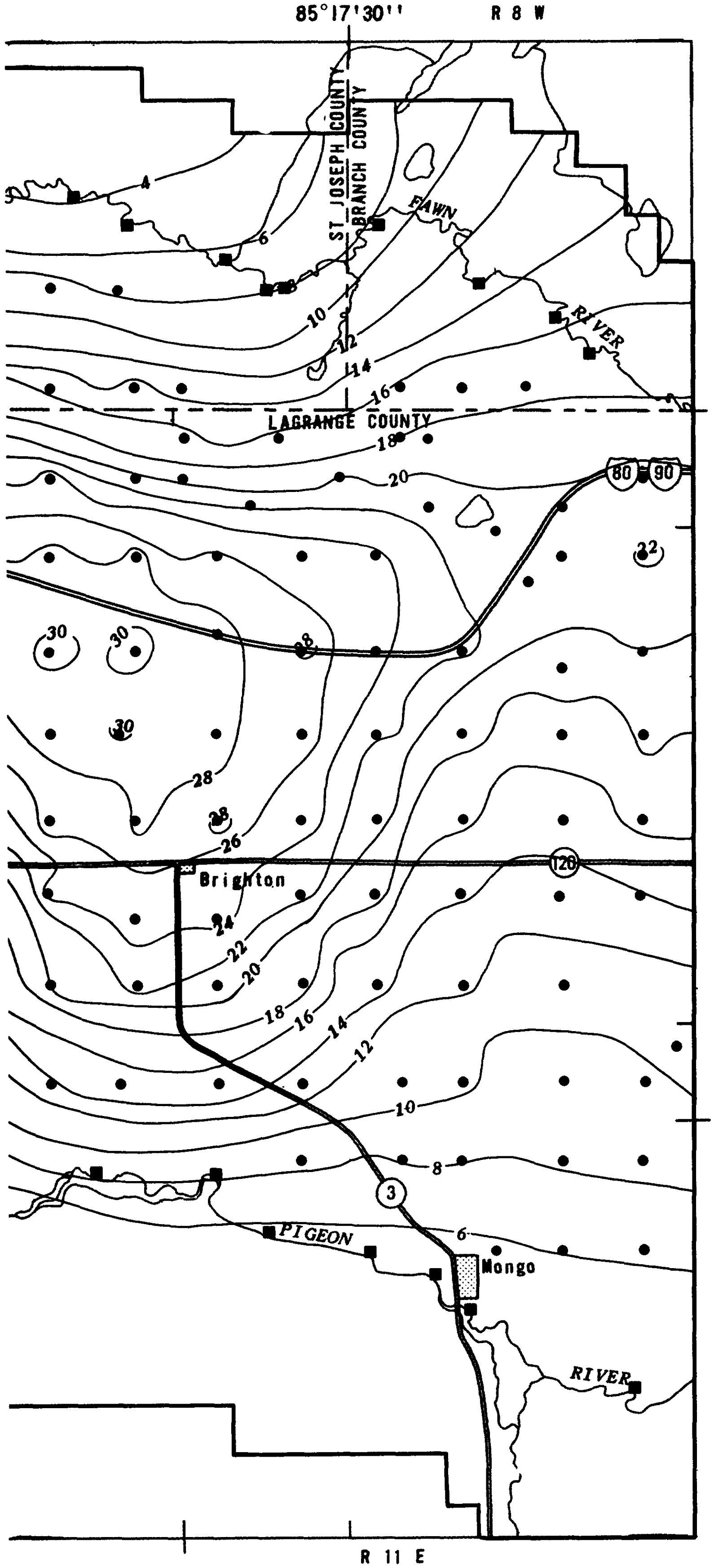


Figure 46.-- Drawdown in layer 2 for pumping-plan 4 with constant-flux boundaries.



EXPLANATION

—2— LINE OF EQUAL DRAWDOWN, LAYER 2-- Interval 2 feet

● SIMULATED WELL

■ SIMULATED SURFACE-WATER PUMP

▬ ACTIVE-NODE BOUNDARY

0 2 MILES

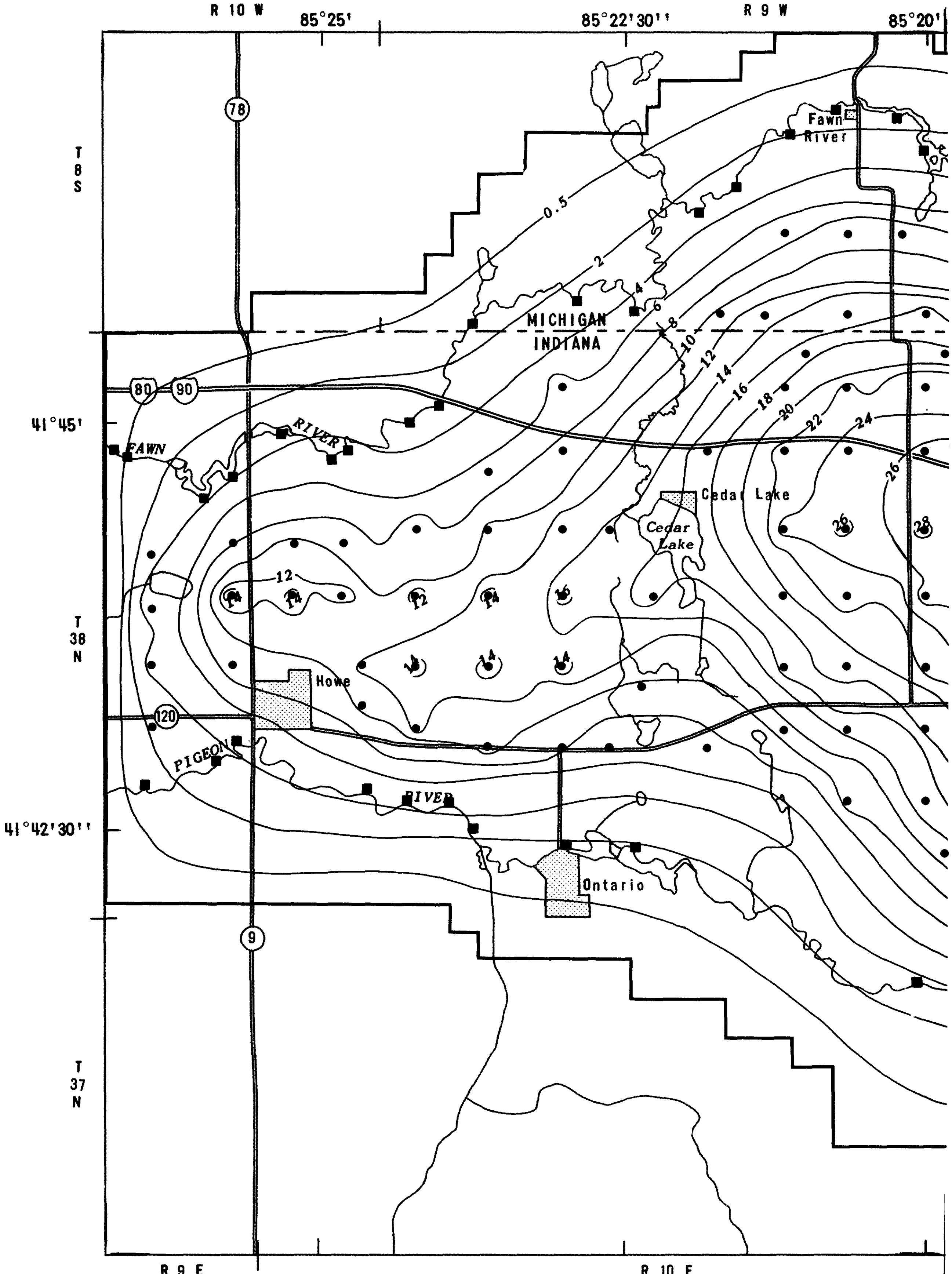
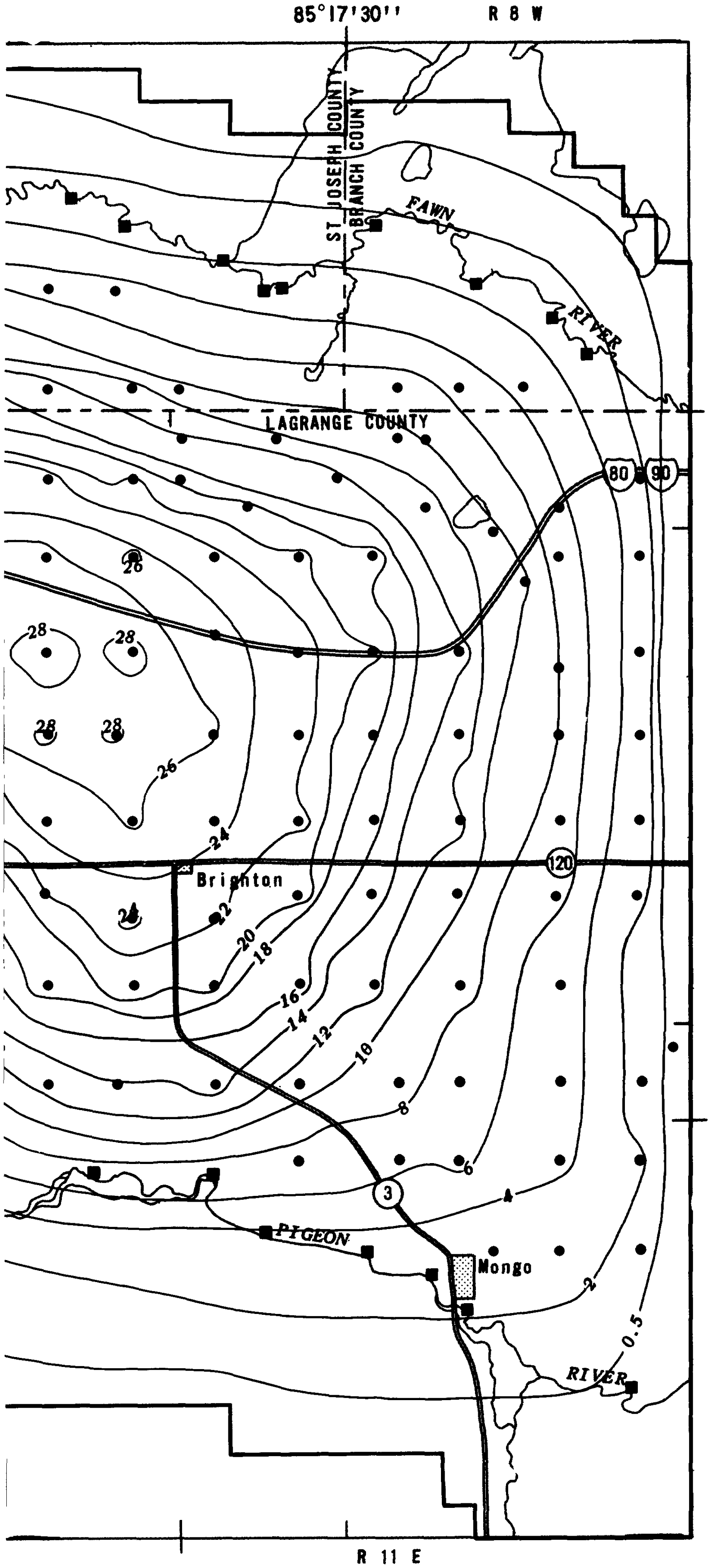


Figure 47.-- Drawdown in layer 2 for pumping-plan 4 with constant-head boundaries.



EXPLANATION

—2— LINE OF EQUAL DRAWDOWN, LAYER 2-- Intervals 1.5 and 2 feet

● SIMULATED WELL

■ SIMULATED SURFACE-WATER PUMP

▬ ACTIVE-NODE BOUNDARY

0 — 2 MILES

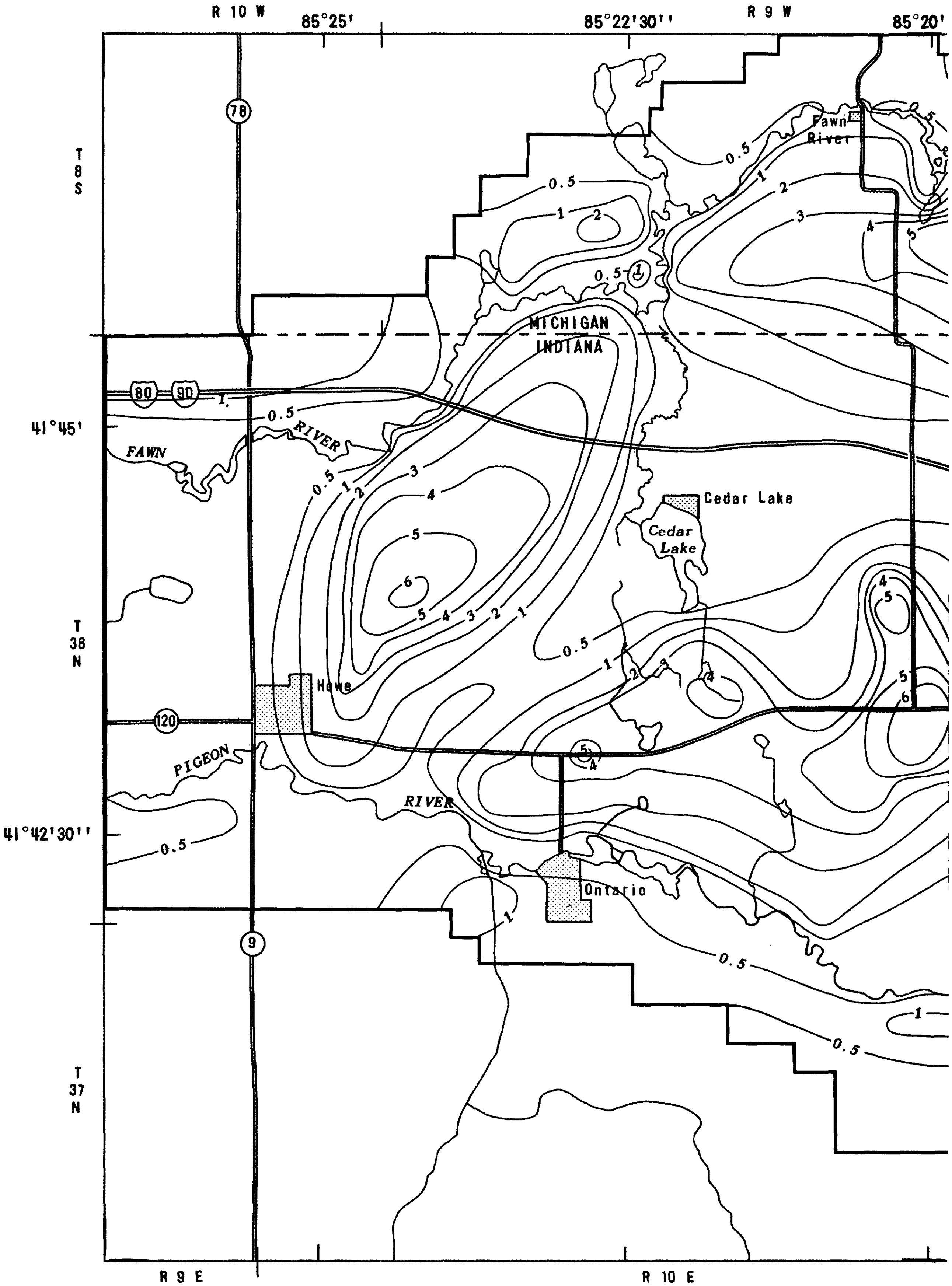
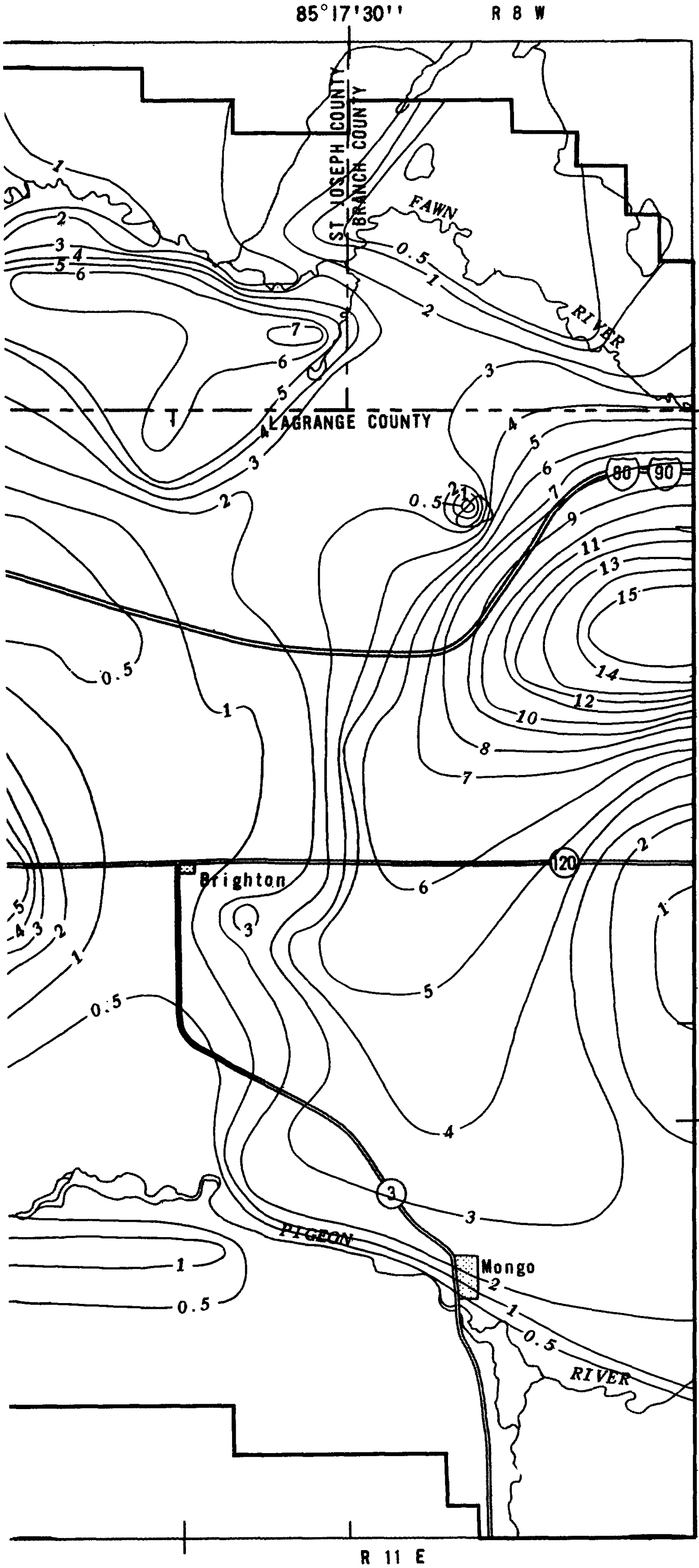


Figure 48.-- Drawdown in layer 1 for pumping-plan 5 with constant-flux boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1--Intervals 0.5 and 1 foot

ACTIVE-NODE BOUNDARY

0 — 2 MILES

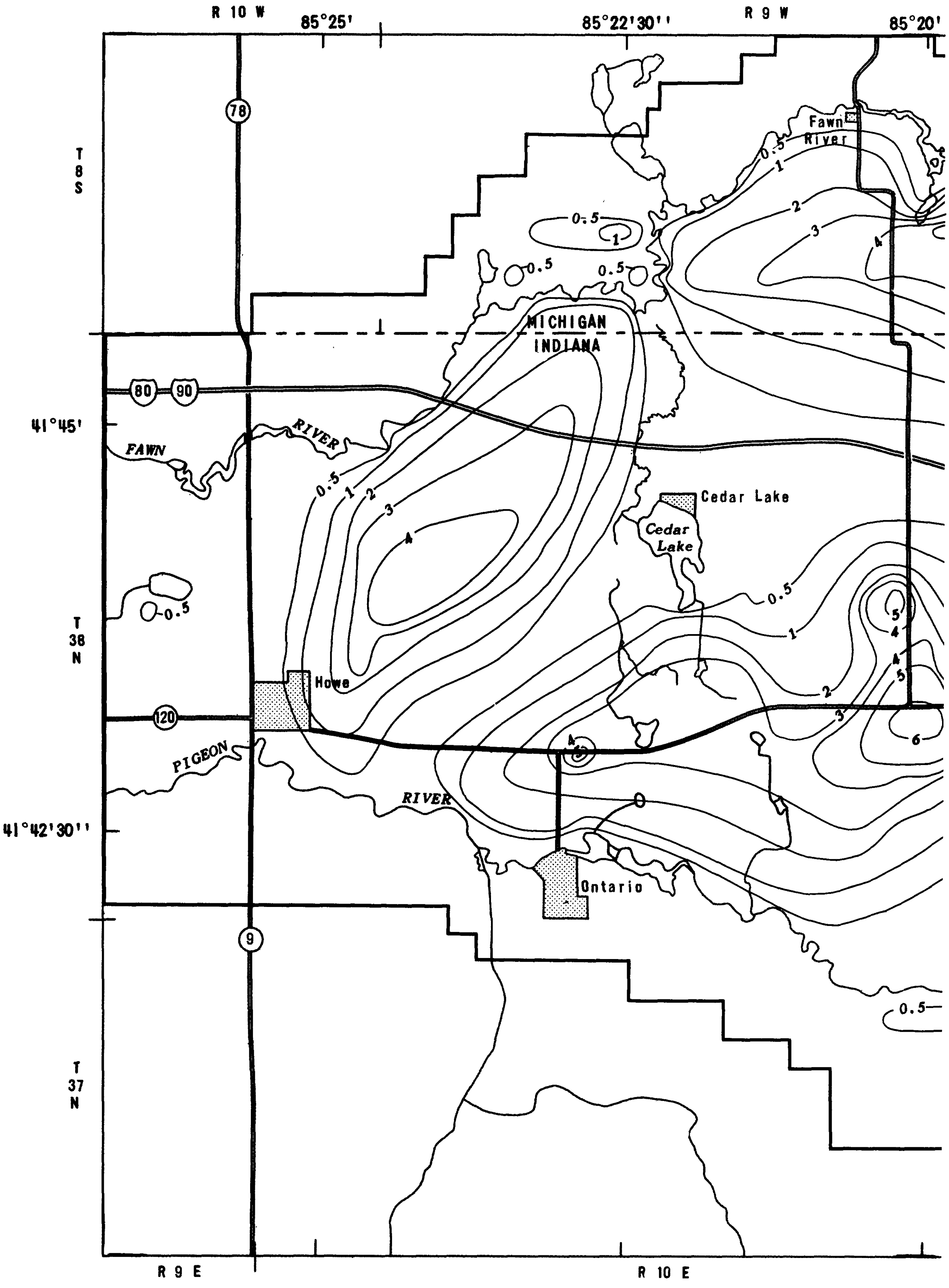
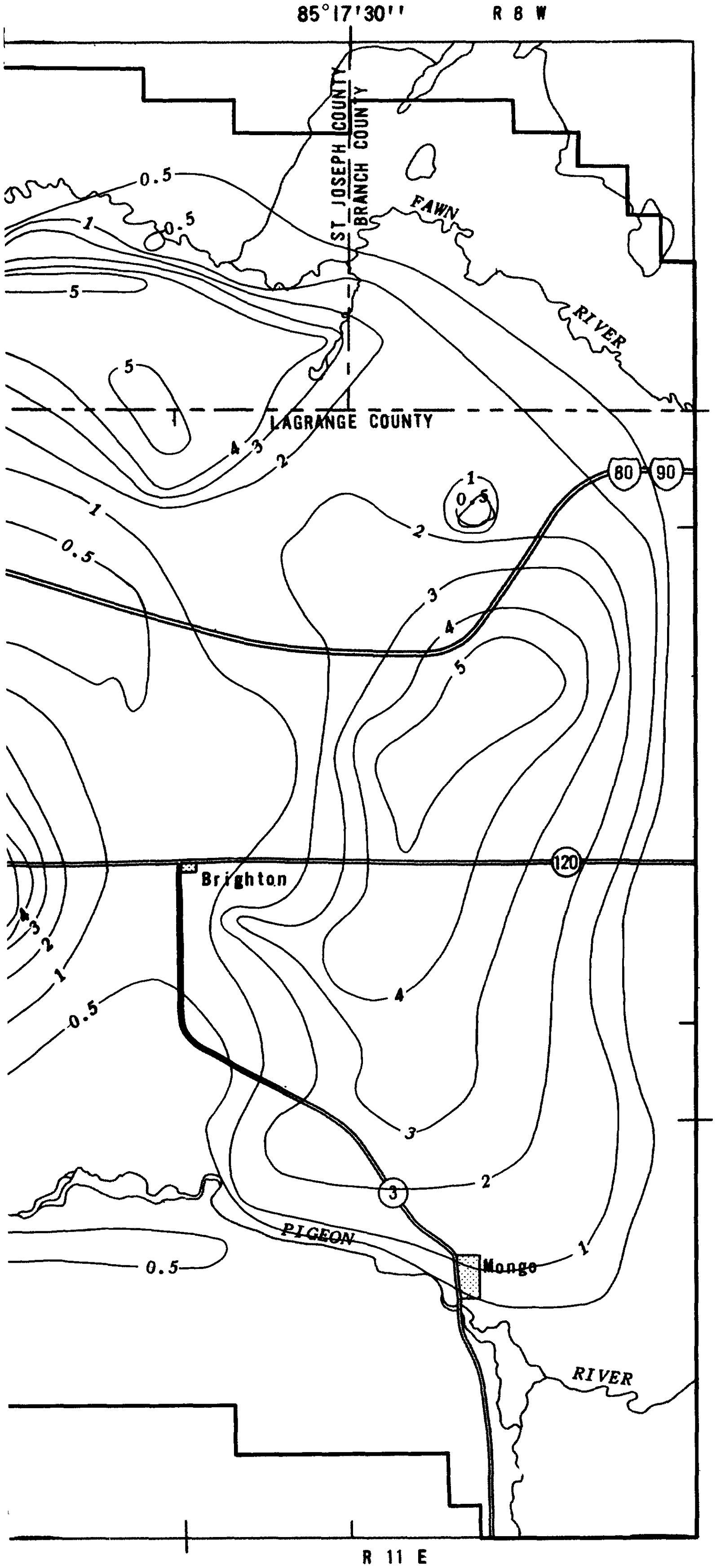


Figure 49.-- Drawdown in layer 1 for pumping-plan 5 with constant-head boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1 -- Intervals 0.5 and 1 foot

ACTIVE-NODE BOUNDARY

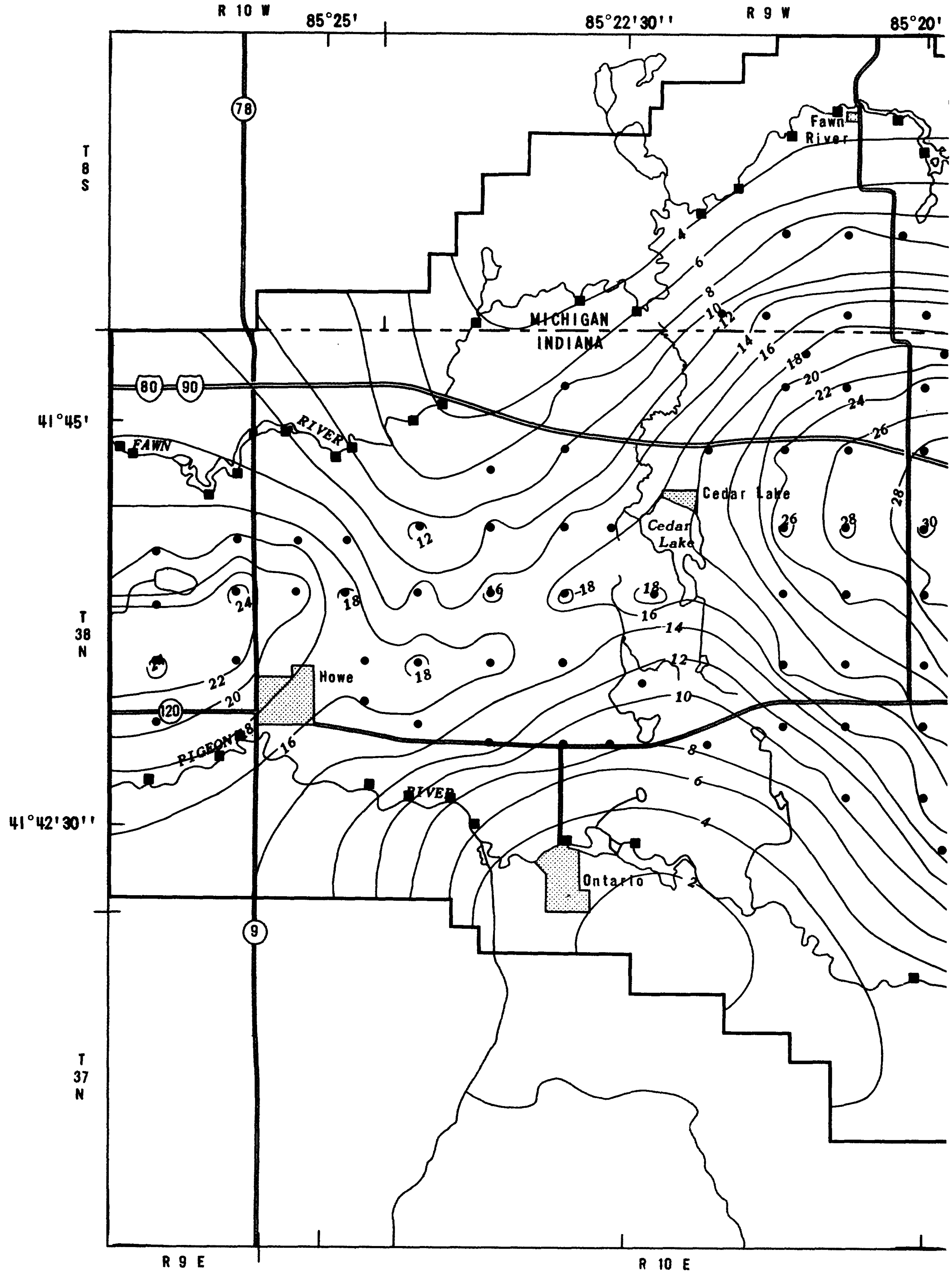
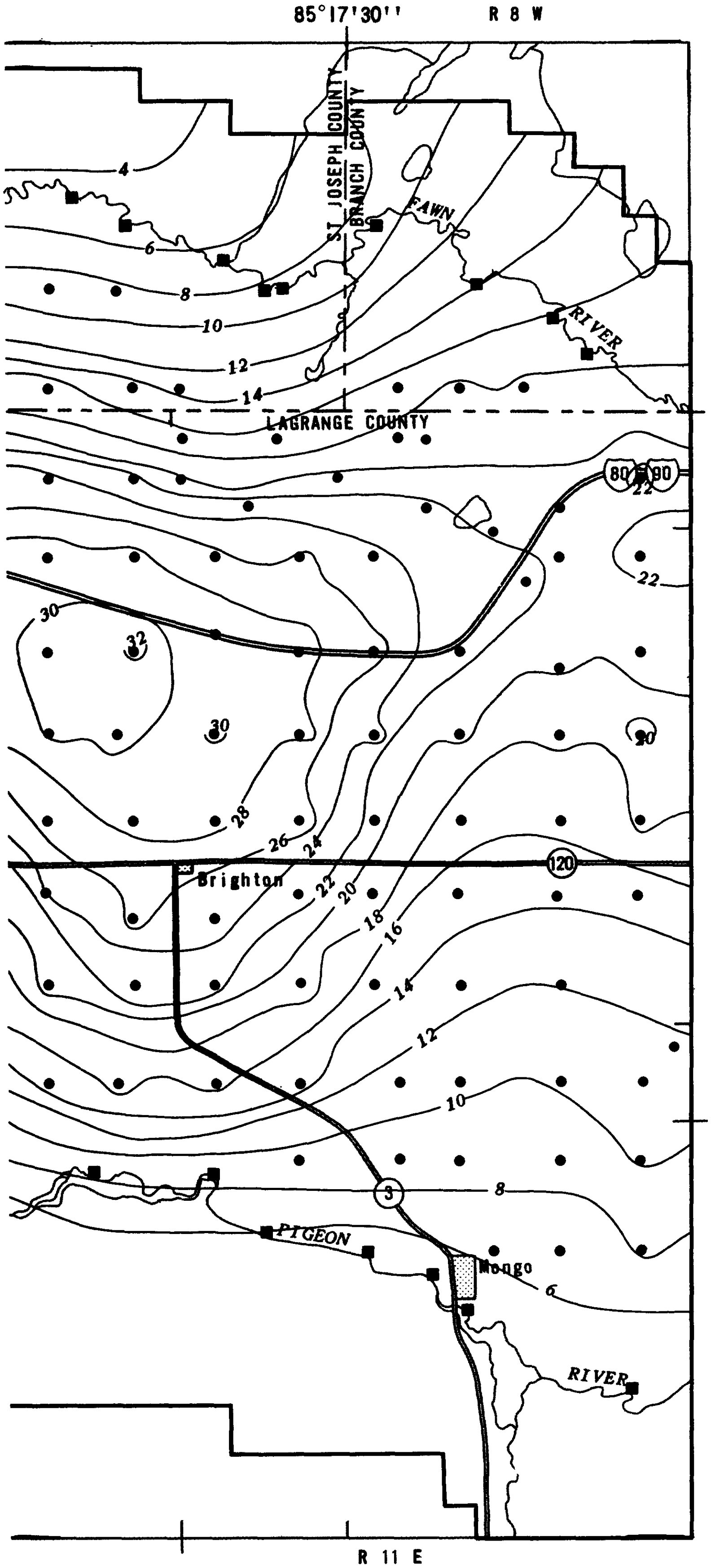


Figure 50.-- Drawdown in layer 2 for pumping plan 5 with constant-flux boundaries.


85°17'30''
R 8 W
ST JOSEPH COUNTY
BRANCH COUNTY
FAWN
RIVER
LAGRANGE COUNTY
80
90
120
Brighton
3
PIGEON
Mongo
RIVER
R 11 E
4
6
8
10
12
14
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22
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8
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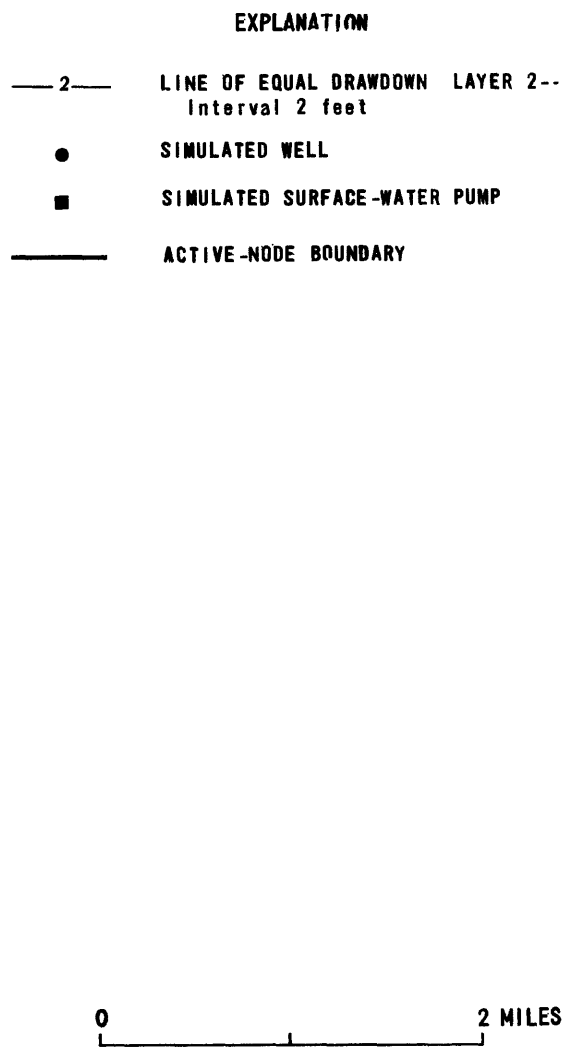

EXPLANATION
2 LINE OF EQUAL DRAWDOWN LAYER 2--
Interval 2 feet
SIMULATED WELL
SIMULATED SURFACE-WATER PUMP
ACTIVE-NODE BOUNDARY
0
2 MILES

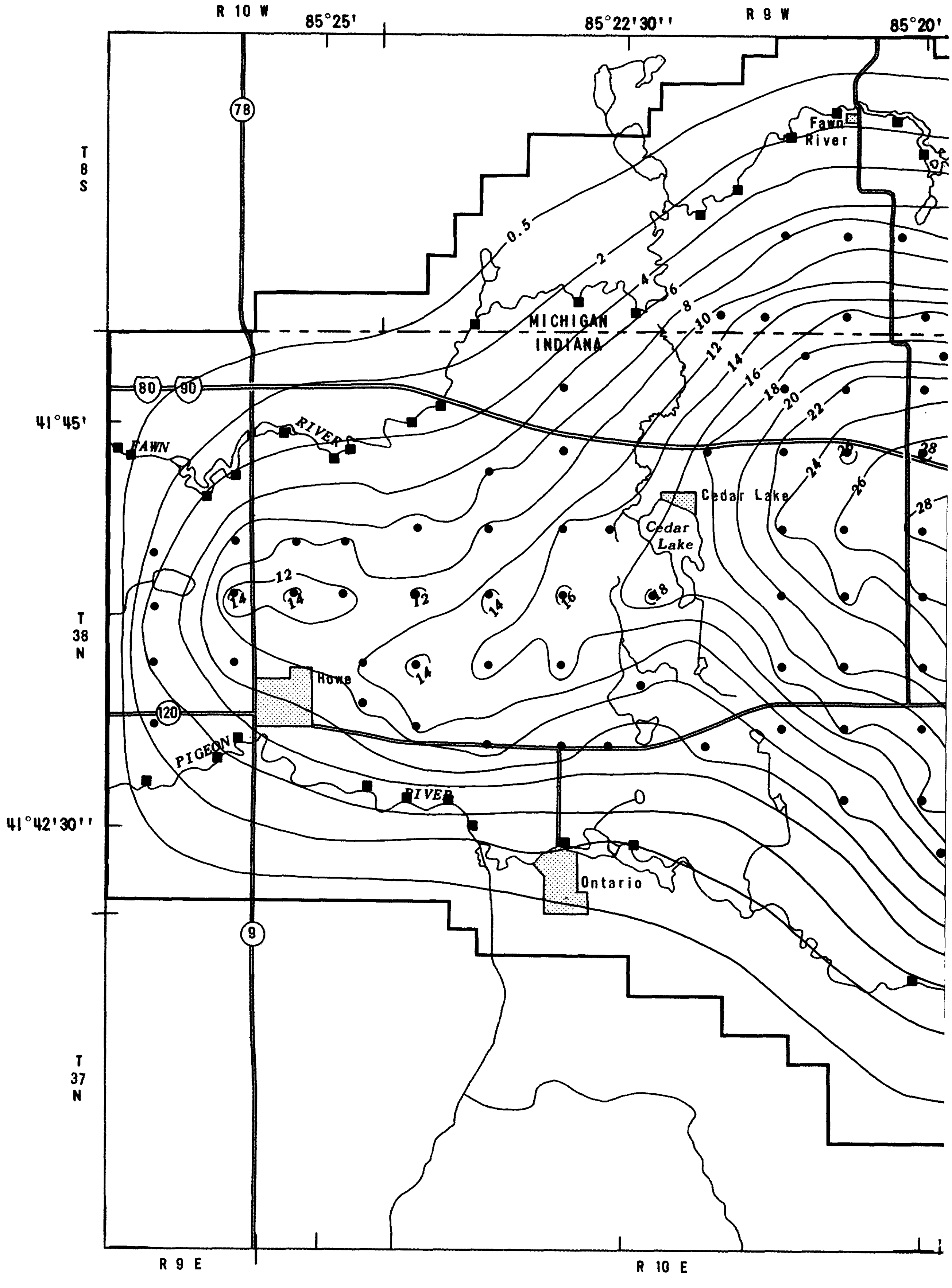
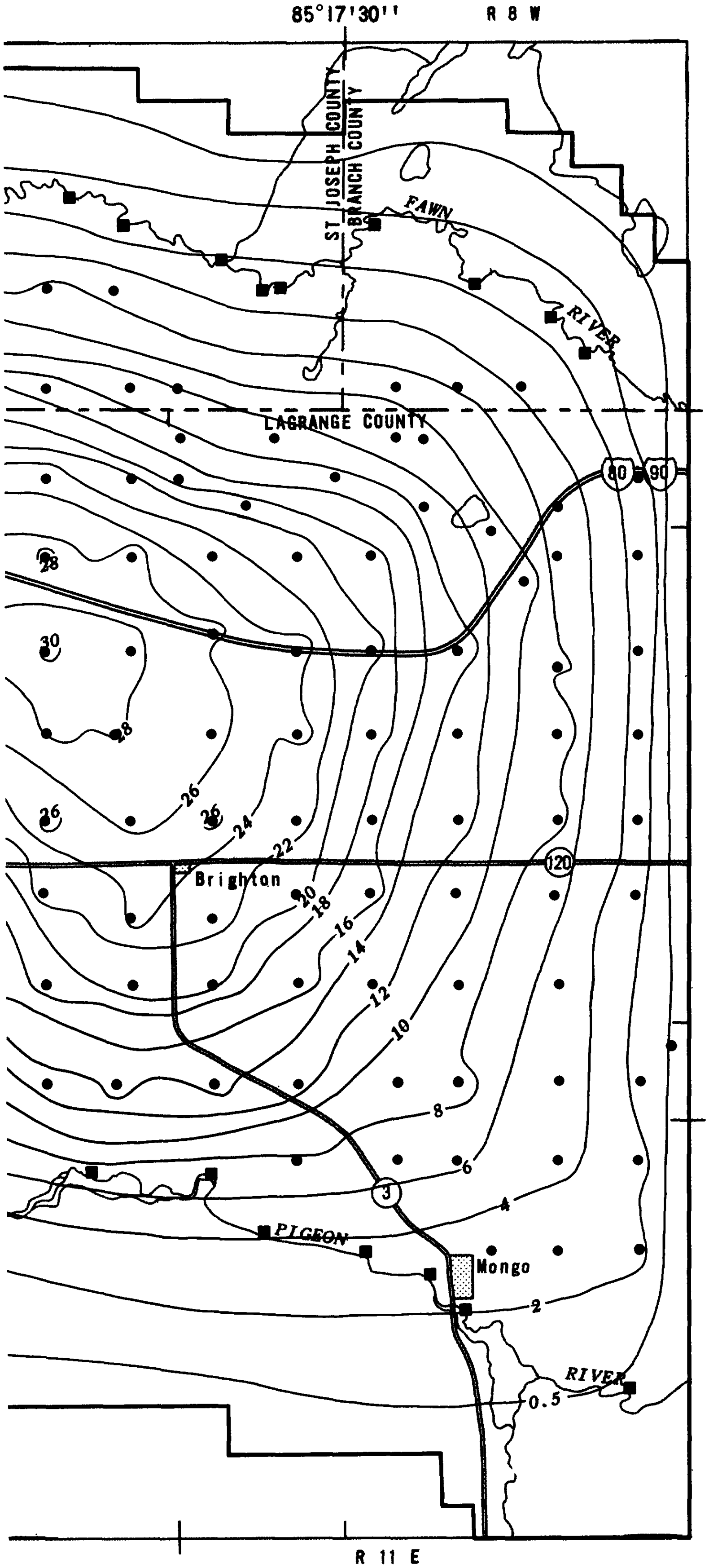


Figure 51.-- Drawdown in layer 2 for pumping-plan 5 with constant-head boundaries.



EXPLANATION

—2— LINE OF EQUAL DRAWDOWN, LAYER 2-- Intervals 1.5 and 2 feet

● SIMULATED WELL

■ SIMULATED SURFACE-WATER PUMP

▬ ACTIVE-NODE BOUNDARY

0 2 MILES

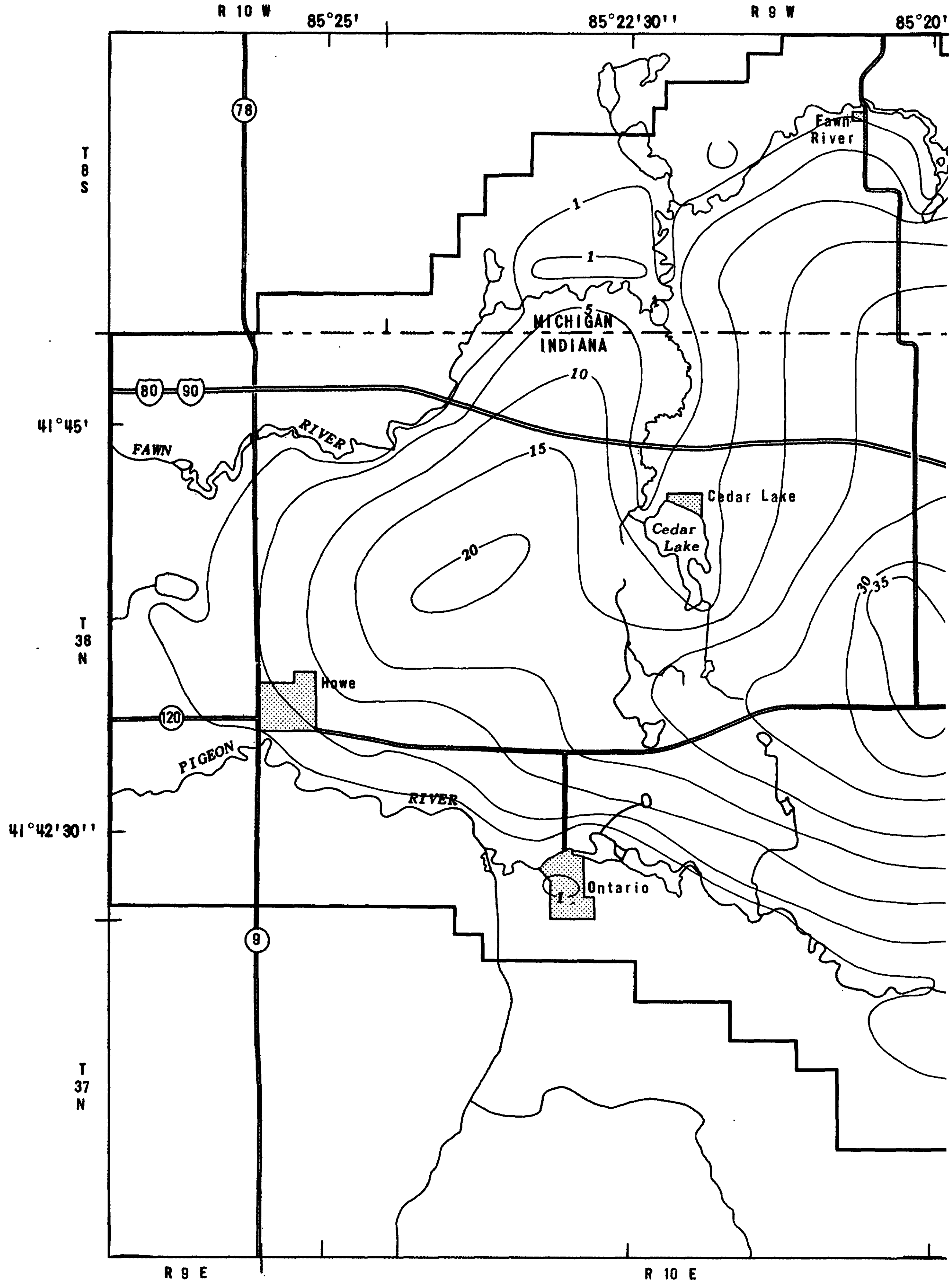
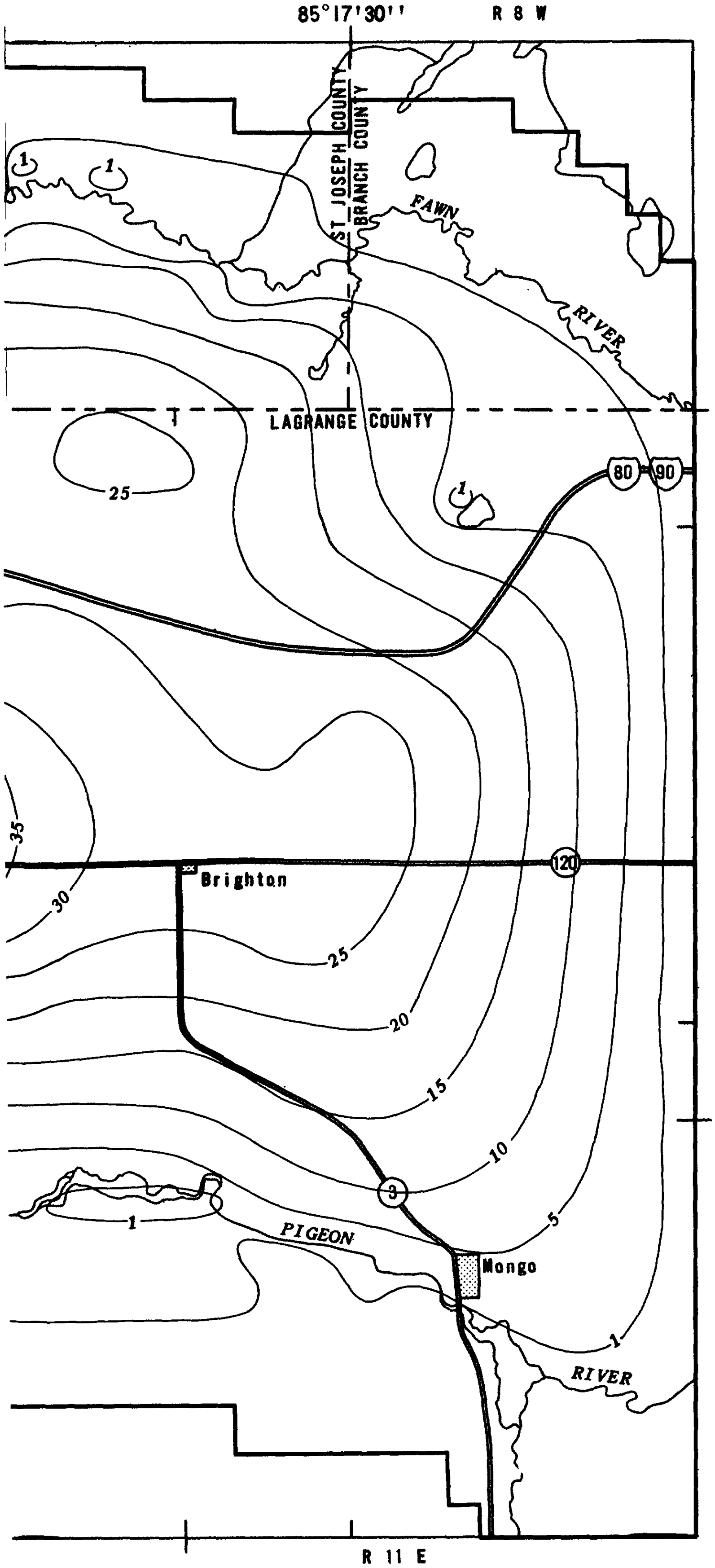


Figure 52.-- Drawdown in layer 1 for pumping-plan 6 with constant-head boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 1--Intervals 4 and 5 feet

—— ACTIVE-NODE BOUNDARY

0 2 MILES

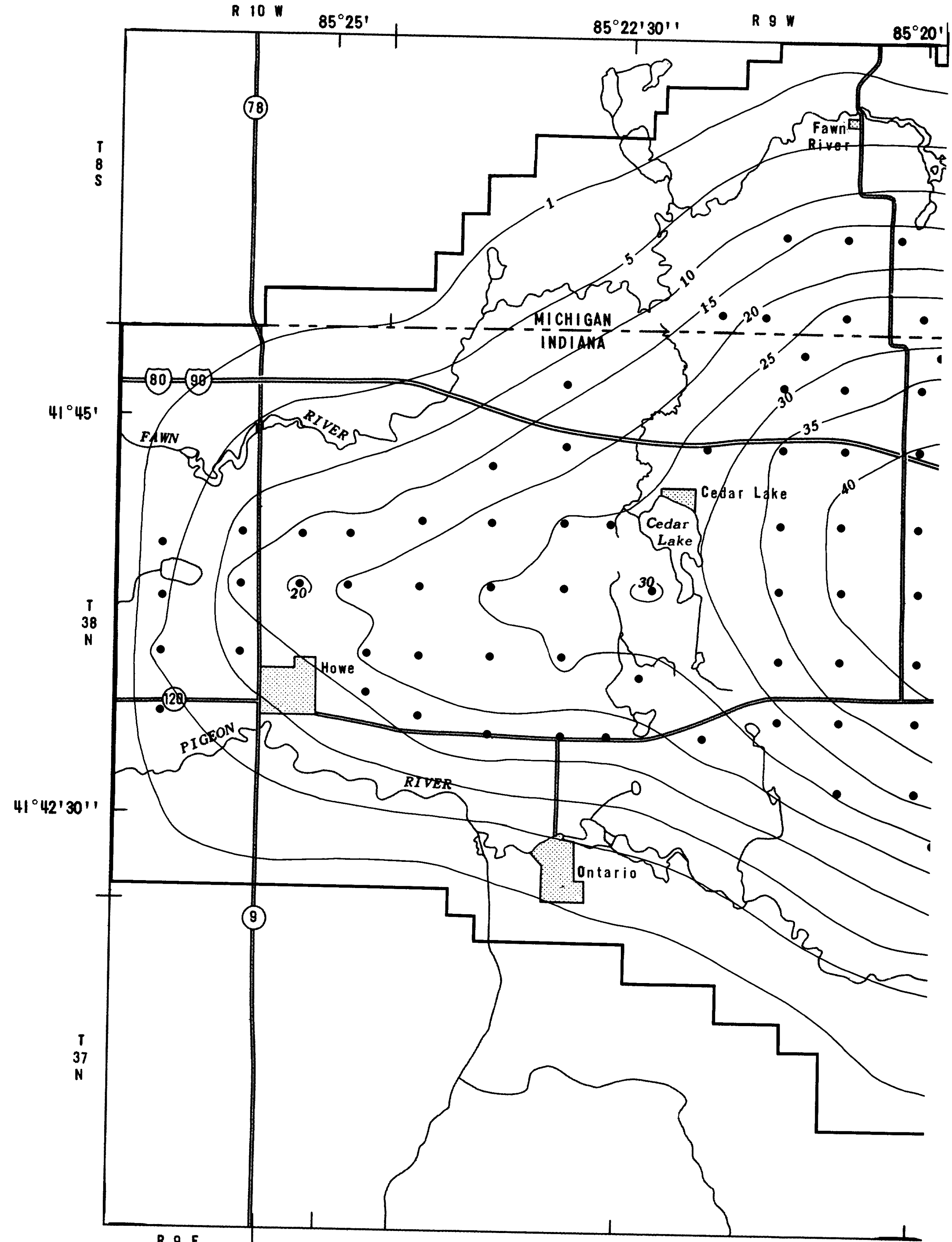
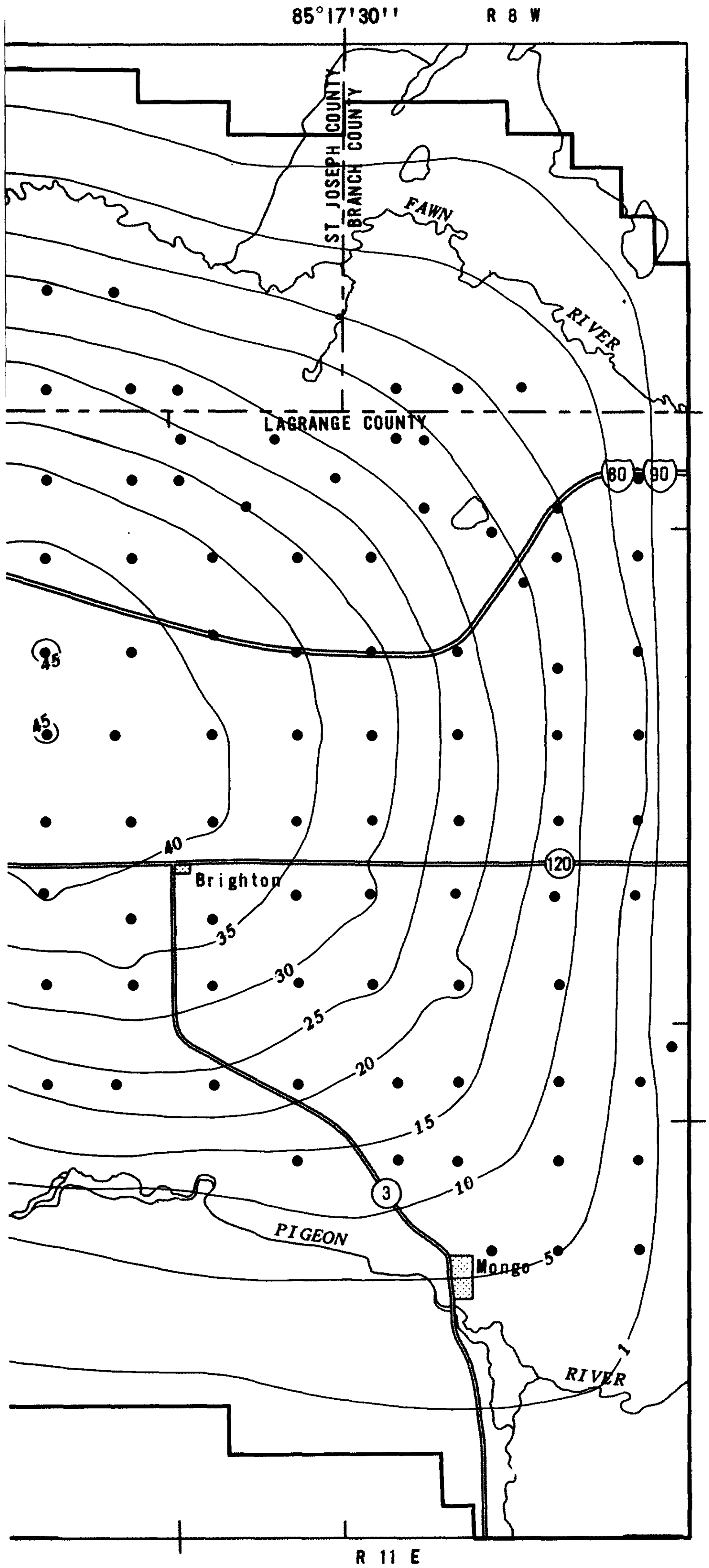


Figure 53.-- Drawdown in layer 2 for pumping-plan 6 with constant-head boundaries.



EXPLANATION

—1— LINE OF EQUAL DRAWDOWN, LAYER 2-- Intervals 4 and 5 feet

● SIMULATED WELL

▬ ACTIVE-NODE BOUNDARY

0 2 MILES

seasons were assumed to be the average flows during June, July, and August (a 3-month mean) that are equaled or exceeded 50 and 80 percent of the time. The flow-duration curve based only on data for June, July, and August (fig. 54) was used to evaluate the results of plans 2 through 5.

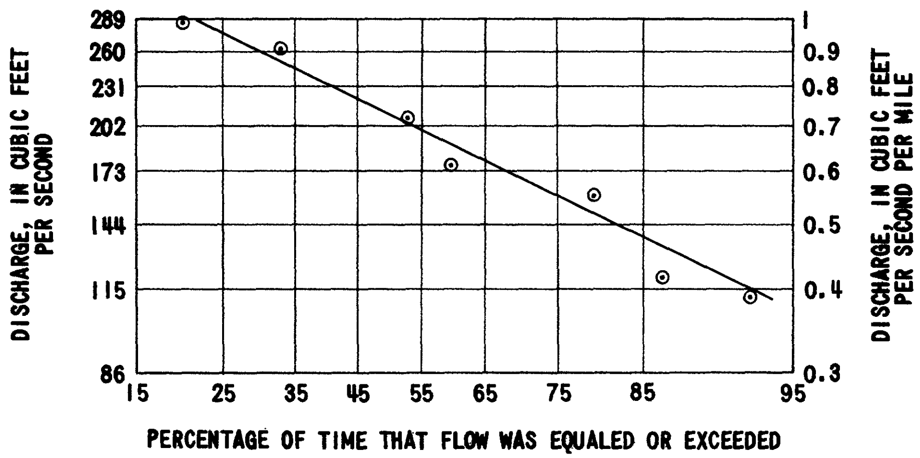


Figure 54.-- Flow duration of Pigeon River for average flows during June, July, and August.

Mean daily discharges for the entire year were used to develop a flow-duration curve to estimate flow in normal and dry years, which were assumed to be flows at 50- and 80-percent flow duration. This curve (fig. 55) was used to evaluate the results of long-term pumping (plan 6). A Q7,10 (7-day, 10-year recurrence interval) discharge for Pigeon River at the west end of the study area was estimated on the basis of drainage area from the Q7,10 flow at Pigeon River near Scott. This discharge, 69 ft^3/s, was set as the minimum streamflow allowed for the steady-state pumping simulation. The extremes of the flow-duration curves are not well defined and should be used with caution because the curves represent estimated discharge values for a period of record in which few extremes (high or low flows) were recorded.

Streambed seepage and streamflow for each pumping plan are summarized on table 12. Calculations were made only for Pigeon River. Flow-duration curves for Fawn River could not be developed because the flow is regulated by dams. Thus, flow calculations of the type in table 12 were not done for Fawn River.

The gains and losses of water of each pumping plan are compared to those of the calibrated steady-state model in table 13. Recharge is not compared because it is a constant source.

The components of the water budget of each pumping plan, as percentages of total water in the system, are summarized in table 14.

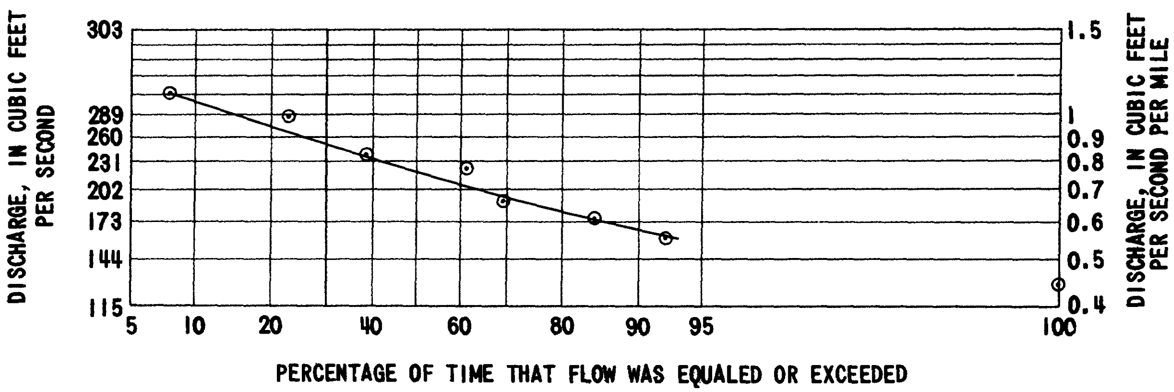


Figure 55.-- Flow duration of Pigeon River for mean-annual flows.

Plan 1.--The distribution of pumps supplying water to crops during 1982 was simulated with plan 1. Pumping rates and volumes measured in 1982 were duplicated in this plan but the actual on-and-off sequence of individual wells was not. As a result of all wells pumping at the same time, simulated drawdowns were greater than those observed during 1982.

Maximum water-level declines were 4 ft in layer 1 and 14 ft in layers 2 and 3. The extent of water-level declines in layers 1 and 2, for constant-flux boundaries, are shown in figures 38 and 39. The pattern of drawdown for constant-head boundaries is similar to that for constant-flux boundaries, but there is no water-level decline at the boundaries. Recovery was not simulated, but water levels near the pumping wells rapidly recovered to prepumping levels during 1982.

Water is induced from layer 1, aquifer storage, and streams (table 13). Aquifer storage is 37 percent of the water budget (table 14). Ground-water seepage to the streams was 7 ft^3/s (9 percent) less than in the steady-state calibration. For short-term pumping (one irrigational season) most of the water is from storage rather than from water intercepted before it reaches the streams. Eighty-seven percent of the water for irrigational pumping is from storage and 10 percent is induced from streams. (These percentages do not total 100 because of a slight mass-balance error in the simulation.)

Plans 2 and 3.--The current distribution of pumps supplying water to crops during hypothetical normal and dry seasons was simulated with pumping plans 2 and 3. The extent and the magnitude of drawdown caused by pumping in plan 2 (figs. 40 and 41) is slightly greater than that from plan 1 (figs. 38 and 39). For plan 2, maximum drawdown in layer 1 is 6 ft and in layer 2 is 15 ft. Drawdown in layer 1 corresponds to those areas that are not underlain by clay (fig. 9). Much of layer 1, including the Cedar Lake area, is protected from drawdown by the clay between layers 1 and 2. The extent and the magnitude of drawdown caused by pumping in plan 3 (figs. 42 and 43) is slightly greater than

Table 12.--Changes of flow in Pigeon River attributed to simulated pumping

Plan	Boundary CF = constant flux CH = constant head	Calibrated net seepage (ft^3/s)	Simulated net seepage (ft^3/s)	Simulated irrigational pumping from stream (ft^3/s)	Streamflow reduction (ft^3/s)	Natural streamflow[1] (ft^3/s)	Simulated net streamflow (ft^3/s)
1	CF	38	35	5	8	156	148
	CH	39	38	5	6	156	150
2	CF	38	33	5	10	211	201
	CH	39	35	5	9	211	202
3	CF	38	32	5	11	150	139
	CH	39	38	5	6	150	144
4	CF	38	23	15	30	211	181
	CH	39	33	15	21	211	190
5	CF	38	21	15	32	150	118
	CH	39	30	15	24	150	126
6	CH	39	-1	0	40	219	179
						179	139

[1]Flow for plan 1 is from table 6; for plans 2 and 3, from figure 54; and for plan 6, from figure 55.

Table 13.--Net gains and losses in the calibrated model and pumping simulations

Simulation	Boundary CF = constant flux CH = constant head	Net flux through leakage layers (ft^3/s) into:			Net flux from aquifer storage (ft^3/s)	Net flux through boundaries (ft^3/s)	Net seepage to streams[2] (ft^3/s)
		Layer 1[1]	Layer 2	Layer 3[1]			
Calibrated model	CH	33	12	-2	0	42	78
	CF	32	12	-2	0	42	78
Plan 1	CH	-18	53	-2	52	54	74
	CF	-29	58	-2	60	42	71
Plan 2	CH	-20	55	-3	51	57	71
	CF	-33	61	-2	61	42	68
Plan 3	CH	-19	54	-3	49	58	70
	CF	-33	60	-2	59	42	66
Plan 4	CH	-109	132	-6	117	106	58
	CF	-169	177	-2	166	42	43
Plan 5	CH	-106	129	-6	110	109	54
	CF	-169	176	-2	160	42	37
Plan 6	CH	-63	77	-8	0	162	-3

[1]A negative number indicates loss from the aquifer.
[2]A negative number means loss from the stream.

Table 14.--Water budgets for pumping plans [all data, except totals, are in percent]

Pumping plan	Boundary CF = Constant flux CH = Constant head	Sources						Discharges						
		Storage	Constant flux	Constant-head flux	Areal recharge	River seepage	Total water (ft^3/s)	Storage	Constant flux	Constant-head flux	Wells	River seepage	Drains	Total water (ft^3/s)
1	CF	37	35	--	24	4	165	0	10	--	42	47	1	167
	CH	31	--	42	23	4	169	0	--	10	42	47	1	170
2	CF	37	35	--	23	5	166	0	9	--	45	45	1	167
	CH	30	--	43	23	4	170	0	--	9	45	45	1	171
3	CF	36	35	--	24	5	164	0	10	--	45	44	1	165
	CH	29	--	44	23	4	169	0	--	9	44	46	1	169
4	CF	61	21	--	14	4	274	0	6	--	74	19	1	275
	CH	41	--	41	14	4	282	0	--	4	72	23	1	283
5	CF	60	22	--	14	4	269	0	5	--	76	18	1	270
	CH	40	--	43	14	3	279	0	--	3	73	23	1	280
6	CH	0	--	71	17	12	237	0	--	3	86	11	0	237

those in plan 2. In plan 3, the maximum drawdown in layer 1 is 7 ft and in layer 2 is 15 ft. As in plan 1, drawdowns in plans 2 and 3 are greater than those that would occur if pumping were intermittent.

Water is induced from layer 1, aquifer storage, and streams in both pumping plans (table 13). Flow duration of remaining streamflow in a normal year (plan 2) would be about 54 percent and in a dry year (plan 3) would be about 83 percent (table 12 and fig. 54). The water budget for both plans (table 14) is similar to that of plan 1.

Plans 4 and 5.--The effects of maximum potential irrigational pumping for crops during hypothetical normal and dry seasons where simulated with pumping plans 4 and 5. The extent and magnitude of drawdown in layer 1 caused by pumping-plan 4 and constant-flux boundaries (fig. 44) where significantly greater than those for plan 4 and constant-head boundaries (fig. 45). Drawdown was concentrated where there was no clay between layers 1 and 2. Maximum drawdown in layer 1 was 14 ft for constant-flux boundaries and 5 ft for constant-head boundaries.

Maximum drawdown in layer 2 was 30 ft for constant-flux boundaries and 29 ft for constant-head boundaries. The patterns of drawdown for the two boundaries were similar, but the extent was restricted in the simulation for constant-heads because there is no drawdown at the boundaries (fig. 47). Drawdown at the east and west constant-flux boundaries was due to the proximity of simulated pumping (fig. 46).

Extent and magnitude of drawdown caused by pumping in plan 5 (figs. 48-51) was slightly greater than that caused by plan 4 because pumping was longer. Maximum drawdown in layer 1 was 15 ft for constant-flux boundaries and 6 ft for constant-head boundaries. Maximum drawdown in layer 2 was 32 ft for constant-flux and 30 ft for constant-head boundaries.

Because pumping is considerably greater in plans 4 and 5 than in plans 1 through 3, more water is induced from the streams by plans 4 and 5. However, streamflow is still protected by additional removal of water from aquifer storage (table 13). Loss of water from layer 1 through leakage is also greater because of intense pumping from layer 2 (table 13). About 60 percent more water is induced through the boundaries in the simulations with constant-head boundaries than with constant-flux boundaries. This difference is probably unrealistically high, but the opposite end of the range is unrealistically low because some additional flow would be induced through the boundaries by real pumping. Streamflow would be reduced (table 12 and fig. 54) to 60- to 64-percent flow duration in a normal year (plan 4) and 89- to 92-percent in a dry year (plan 5). The water budgets of both plans are similar (table 14), but the percentage distributions of the components of sources and discharges differ significantly from those of plans 1 through 3.

Plan 6.--Steady-state drawdowns and reductions in streamflow caused by year-round pumping of the same well distribution and pumping rate (202.8 ft^3/s) used in plans 4 and 5 were simulated in pumping plan 6. This magnitude of pumping for such an extended period may never be realized but was simulated to test the response of the hydrologic system to a heavy stress. The authors assumed that none of the water pumped from the system returned to the system.

Only constant-head boundaries were used in plan 6 because the constant-flux simulation would not reach a mathematically stable solution. A steady-state solution with constant-flux boundaries would have been possible only if pumping had been significantly reduced. The amount of water induced through the constant-head boundaries may be a high estimate, but the restriction imposed on flux through the boundaries by the constant-flux simulation was unrealistic for the amount of stress on the system. There is no drawdown at the boundaries because of the constant heads so the drawdown shown is the least that would be expected. However, results for constant-head boundaries are probably closer to the real solution at steady state than constant-flux boundaries.

Maximum drawdown in layer 1 is 38 ft. This drawdown is not only much greater than drawdowns in plans 4 and 5, but its areal extent is also greater (fig. 52). Drawdown is a maximum in areas where there is no clay between layers 1 and 2 but is significant in all areas of layer 1. Drawdown in the Cedar Lake area and the surrounding wetlands is as much as 15 ft in areas underlain by clay and as much as 20 ft in area where clay is absent. Wetlands simulated by drains in the model are dry. Maximum water-level declines in layer 2 (46 ft) are concentrated under the areas confined by a clay layer (fig. 53).

Most of the water induced into layer 2 by pumping is flow across model boundaries (table 13). More water is induced from streamflow than was induced in the transient simulations (table 13) and streamflow in Pigeon River would be reduced to 82- percent flow duration in a normal year (fig. 55 and table 12). The flow duration for a dry year would be about 97 percent if the curve in figure 55 were extended in a straight line. The data do not allow a reliable extension beyond about 92 percent, so, for less flow, the result is a rough estimate of flow duration. Use of the flow-duration curve probably results in high estimates because the curve is based on mean-annual rather than mean-daily flow. The $Q_{7,10}$ estimated for the Howe area, 69 ft^3/s, does not fit on the curve because of the high estimates.

If less water could be induced to flow across the boundaries than is indicated in the simulation (plan 6), then more water would be induced from the streams. Because 97-percent flow duration is probably a high estimate, any additional water induced from the streams would result in flows nearing the $Q_{7,10}$ limitation on minimum streamflow.

SUMMARY AND CONCLUSIONS

The glacial-drift aquifer system in the Howe area, Lagrange County, is primarily outwash sand and gravel but contains numerous clay deposits of variable thickness and extent. Three aquifers can be distinguished on the basis of the distribution of clay layers and vertical changes in the hydraulic conductivity of the outwash at depth. These aquifers are hydraulically connected regionally but are confined by clay deposits locally. Aquifer 1 is a water-table aquifer in most of the area. Its characteristics include an average hydraulic conductivity of 220 ft/d, a saturated thickness ranging from 10 to 60 ft, and a transmissivity ranging from 5,000 to 16,000 ft^2/d. Aquifers 1 and 2 are separated by a clay layer ranging from zero to 50 ft in thickness.

Average hydraulic conductivity of aquifer 2 is 360 ft/d, and its saturated thickness ranges from 50 to 110 ft. Transmissivity of the aquifer ranges from 5,000 to 35,000 ft^2/d. Aquifers 2 and 3 are not separated by a clay layer but are distinguished by an increase in clay content of the outwash with depth. The average hydraulic conductivity of aquifer 3 was estimated to be 25 ft/d. Saturated thickness of the aquifer ranges from zero to 200 ft, and its transmissivity ranges from zero to 5,000 ft^2/d.

Fawn and Pigeon Rivers are hydraulically connected to the ground-water system. Discharge is nearly uniform because of consistent ground-water seepage and gradual release of runoff through lakes and wetlands.

The major use of water is irrigation. In 1982, 692 Mgal were pumped from ground water (mainly from aquifer 2) and 211 Mgal, from surface water for irrigation. These two volumes were 64 percent of all the water used in 1982.

A three-layer digital model was constructed to simulate steady-state flow in the three aquifers. The model was calibrated to ground-water levels and to ground-water discharge to streams measured in autumn 1982. Thirty-seven percent of the inflow to the system is recharge, 56 percent is model-calculated ground-water inflow at the model boundaries, and 7 percent is leakage from streams. Fifteen percent of the outflow from the system is ground-water outflow at the model boundaries, 83 percent is seepage to streams and wetlands, and 2 percent is pumpage (nonirrigational).

The digital model is a good representation of the ground-water flow system and its response to stresses, but it is not a unique interpretation of the outwash. In general, the model probably simulates greater drawdown in response to pumping than that due to actual pumping. The model is not reliable for predicting drawdown in a particular node because the hydraulic properties were averaged and interpreted from a scant set of site-specific data.

Five pumping plans simulated various amounts of irrigational pumping and a sixth plan simulated year-round, high pumping rates. The effects of pumping the same volume of water as was pumped during 1982 were assessed by pumping-plan 1. The effects of potential increases in irrigation from aquifer 2 and from surface-water sources were assessed by pumping plans 2 through 5. The current irrigational distribution was simulated in plans 2 and 3 with pumping rates that would supply water in a normal and in a dry year. Pumpage on all irrigable land in a normal and in a dry year was simulated in plans 4 and 5. These five plans were transient simulations for one irrigational season. The same well distribution that was simulated in plans 4 and 5, but with pumping continuing to steady state, was simulated in plan 6. This plan was used as a general assessment of the effects of large amounts of pumping over the long term.

Maximum water-level declines for plan 1 were 4 ft in aquifer 1 and 14 ft in aquifers 2 and 3. Simulated drawdowns were generally greater than that observed during 1982, but areas of simulated maximum drawdown were generally of small areal extent. Drawdown in the Cedar Lake area and the surrounding wetlands was less than 0.5 ft. Model-calculated ground-water seepage to the streams was reduced by 7 ft^3/s (9 percent) from that in the steady-state calibration. Most of the water induced by pumping was from aquifer storage rather than from the streams during the pumping period.

Extent and magnitude of drawdown resulting from pumping plans 2 and 3 were only slightly greater than those for plan 1. Ground-water seepage to streams was reduced only slightly because water was induced from aquifer storage.

The effects of plans 4 and 5 on water levels were greater than those of plans 1 through 3 because pumpage was greater. Maximum simulated drawdowns for plan 4 were 14 ft in aquifer 1, 30 ft in aquifer 2, and 31 ft in aquifer 3. Maximum drawdowns for plan 5 were 15 ft in aquifer 1, 32 ft in aquifer 2, and 31 ft in aquifer 3. Loss of ground-water seepage to streams was 2 to 3 times that of plans 2 and 3, but most of the water was induced from aquifer storage.

The pumping rate from aquifer 2 in plan 6 was the same as in plans 4 and 5 but was for a steady-state simulation. However, water-level declines and loss from streamflow were greater than in plans 4 and 5 because no storage term is simulated in the steady-state simulation. Simulated drawdown in aquifer 1 was 38 ft, in aquifer 2, 46 ft, and in aquifer 3, 45 ft. Rate of induction of water from streams was 82 ft^3/s, or nearly 4 times the rate in plan 5, the transient simulation with maximum pumpage. Although the wetlands and Cedar Lake were virtually unaffected by pumping simulated in plans 1 through 5, pumping in plan 6 did affect those areas. Simulated water-level declines in aquifer 1 in those areas were as much as 15 ft where clay underlies the aquifer and as much as 20 ft, where clay is absent.

Transient simulations indicate that large amounts of pumping from aquifer 2 over short periods of time (such as the irrigational season) have a small effect on the aquifer water levels, streamflow, lakes, and wetlands, because water is induced from aquifer storage. Large amounts of pumping near the model boundaries would also induce water from outside the area. Lakes and wetlands are additionally protected from excessive drawdown by the clay layer between aquifers 1 and 2. The system would probably recover to normal between irrigational seasons. The effect of continuous heavy pumping on the hydrologic system over several years, however, would be much greater than that of pumping during the irrigational season.

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