EFFECTS OF AGRICULTURAL IRRIGATION ON WATER RESOURCES IN THE ST. JOSEPH RIVER BASIN, INDIANA, AND IMPLICATIONS FOR AQUIFER YIELD

By James G. Peters and Danny E. Renn

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4273

Indianapolis, Indiana

1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information,
write to:

District Chief
U.S. Geological Survey
5957 Lakeside Boulevard
Indianapolis, Indiana 46278

Copies of this report
can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Bldg. 810
Box 25425
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

GLOSSARY

Water-resource terms are defined in the glossary and are in double quotes where first used in the text.

aquifer.--Part of the subsurface that is composed of permeable material that stores water that can be removed economically by pumping wells.

available drawdown.--The maximum depth the water level in an aquifer can be lowered before all the water in the aquifer is removed. In this report, available drawdown is assumed to be the altitude of the water level in a well before pumping minus the altitude of the bottom of the aquifer.

capture.--The increase in water flowing into an aquifer or the decrease in water flowing out of an aquifer in response to pumping from wells.

cone of depression.--A depression in the water surface around a pumping well that is caused by removing water stored in the aquifer.

conjunctive use.--The combined use of ground water and surface water that promotes the effective use of both.

consumptive use.--A use of water that makes it unavailable for reuse locally. Evaporation is an example of consumptive use.

drawdown.--The decline in the water level in an aquifer (or well) caused by pumping.

ground-water mining.--The removal of ground water from aquifer storage by pumping from wells. Mining occurs when the rate of withdrawal exceeds the rate of capture. When ground water is mined for extended periods of time, the water resource may be depleted.

ground-water seepage (to streams).--Water that discharges from aquifers by seeping through the streambed into the stream channel. Ground-water seepage is the main source of flow in streams, especially during periods of drought.

intercepted seepage (to streams).--That part of ground-water seepage that is captured by pumping. Intercepted seepage is a source of water for pumping and results in a reduction in streamflow.

irrigation potential (of soils).--A measure of the capability of a soil to produce larger crop yields in response to supplemental water applied to the soil. Soils that have the greatest irrigation potential have the largest increase in crop yields following irrigation.

optimal yield.--The volume of water that can be withdrawn from an aquifer system that represents the best compromise among all competing economic, social, and legal interests.

recharge (from precipitation).--The quantity of rainfall or snowmelt that percolates through the soil to the underlying aquifer.

safe yield.--The volume of water that can be withdrawn from an aquifer system such that all hydrologic constraints, as determined by water-resource managers, are fulfilled.

storage.--Water stored in the pore spaces of an aquifer.

streamflow reduction.--The decrease in streamflow that results from the pumping of either ground water or surface water.

sustained yield.--The volume of water that can be withdrawn indefinitely from an aquifer system without depleting the water supply.

underflow (in or out).--Ground water that flows into or out of an aquifer and remains completely underground.

CONVERSION FACTORS

For the convenience of readers who prefer to use metric (International System) units, conversion factors for inch-pound units used in this report are listed below:

Multiply	By	To obtain
acre	0.4047	hectare
billion gallons per day (bgd)	43.81	cubic meter per second
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
gallon per day (gal/d)	3.785	liter per day
inch (in.)	25.40	millimeter
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

The following term and abbreviation also is used in this report:

milligram per liter (mg/L)

EFFECTS OF AGRICULTURAL IRRIGATION ON WATER RESOURCES IN THE ST. JOSEPH RIVER BASIN, INDIANA, AND IMPLICATIONS FOR AQUIFER YIELD

By James G. Peters and Danny E. Renn

ABSTRACT

During the past decade, the acreage of irrigated agricultural land in Indiana has tripled, causing public concern about competition for water and resulting in several State laws for regulating water withdrawals. The St. Joseph River basin represents less than one-tenth of the area of the State, but it contains one-third of the State's irrigated land. Irrigated land in the basin is composed of permeable soils that are underlain by productive glacial aquifers.

A computer model was used to analyze the effects of maximum irrigation withdrawals on aquifer drawdown and streamflow in a 16.5-square-mile area of intensive irrigation. Simulation of maximum pumping resulted in predicted aquifer drawdowns of one-fourth of the total available drawdown. Flow in a nearby stream was decreased by 40 percent. Areas of most intensive irrigation in the basin also are areas that have productive aquifers and well-sustained streamflows.

Aquifer yield is based on the concept of capture--the volume of increased recharge to the aquifer or decreased discharge from the aquifer that results from pumping. The high rates of capture for aquifers in the basin supply ample water for present (1982) irrigation and for substantial future development.

INTRODUCTION

This report is part of a series of reports by the U.S. Geological Survey's Information Transfer Program. The report is designed for a non-technical audience that has minimal knowledge of hydrology. Those readers interested in more detailed explanations of the material discussed in the report are referred to the technical literature cited in the text.

Purpose and Scope

The purpose of this report is to describe, in nontechnical terms, the effects of pumping for irrigation on the water supply in the St. Joseph River basin. The geologic and hydrologic characteristics of the basin, as well as the distribution of irrigation, are presented. The effects of pumping for maximum irrigation are described by the changes to aquifer water levels and streamflow predicted by a computer model. A ground-water budget was used to identify the changes in the sources of recharge and discharge of water to the aquifer during pumping. The results of the analyses are discussed in terms of aquifer yield and its implications for water-resource management by State and local agencies.

National Perspective on Irrigation

During the past 30 years, agricultural production in the United States has increased dramatically. The reason for this increase is improvement in production per acre due, in large part, to irrigation. Although only one-seventh of the total cropland in the United States is irrigated, it produces one-fourth of the total crops (Frederick, 1982, p. 1).

Increased irrigation also has resulted in large increases in water use from ground- and surface-water sources (fig. 1). Between 1950 and 1980, water used for irrigation in the United States increased 69 percent, from 89 bgd (billion gallons per day) to 150 bgd. More importantly, by 1980, irrigation represented 80 percent of the total "consumptive use"[1] of the Nation's water (Solley and others, 1983, p. 16).

About 40 percent of the water used for irrigation is ground water pumped from "aquifers". The volume of ground water used for irrigation has increased from about 20 bgd in 1950 to 64 bgd in 1980 (Solley and others, 1983, p. 16). During 1980, 70 percent of all ground water withdrawn in the United States was used for irrigation (U.S. Geological Survey, 1984, p. 37).

These large withdrawals of ground water have caused large declines, "drawdowns", in aquifer water levels in many parts of the country. Ground-water pumping in the central part of California (fig. 2) has resulted in drawdowns of as much as 6 ft/yr (feet per year). Near coastal areas in California, drawdowns have been almost 200 feet during the past 30 years. In Arizona, drawdowns of 100 feet are common throughout the State and in some areas exceed 400 feet (U.S. Geological Survey, 1984, p. 85 and 92). In the High Plains, pumping has depleted as much as 50 percent of the water in the Ogallala aquifer throughout a 3,500-mi^2 (square mile) area (Luckey and others, 1981).

---

[1]Words defined in the Glossary are in double quotation marks when first used in the text.

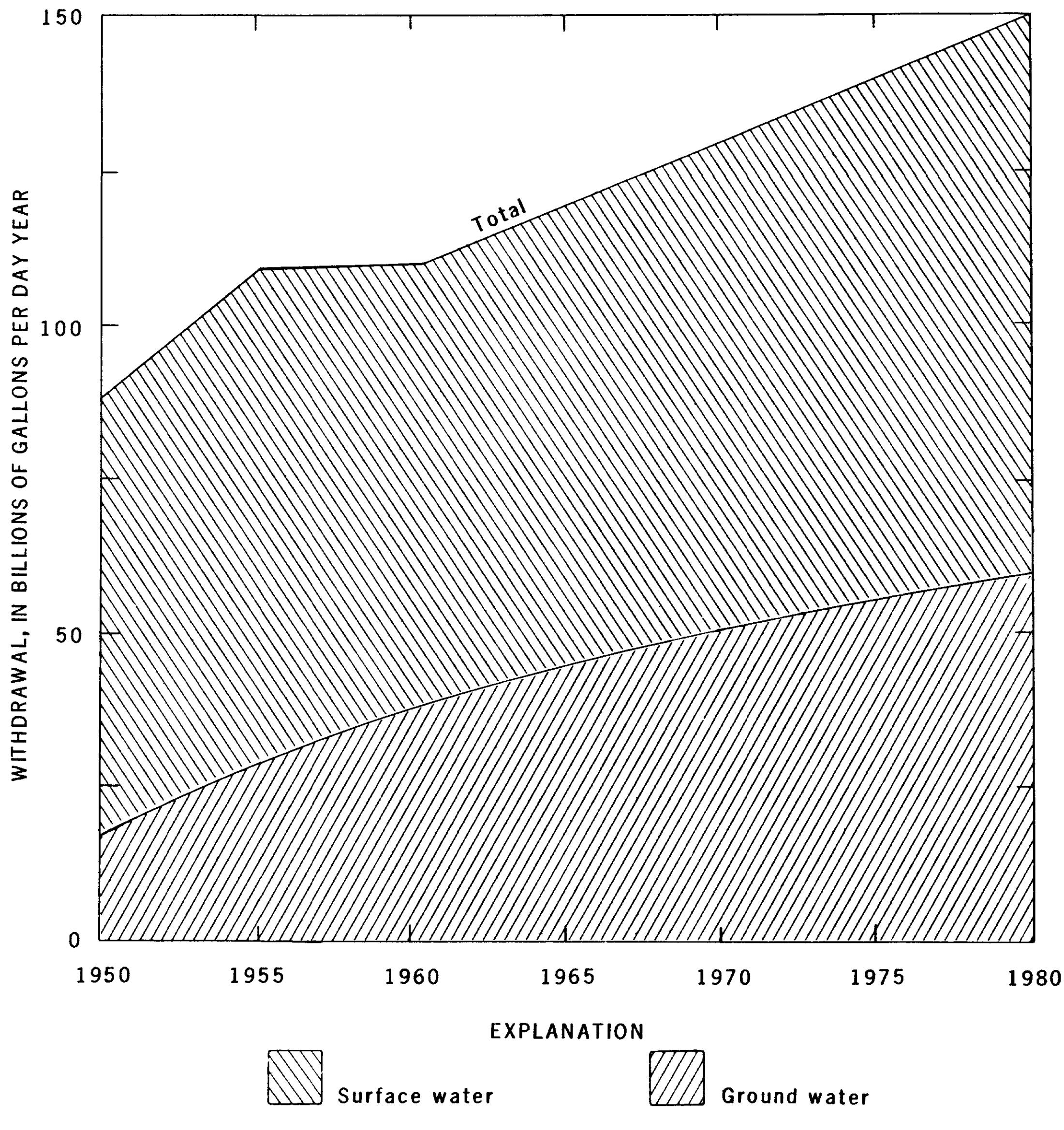


Figure 1.-- Withdrawals of water for irrigation in the United States, 1950-80. (modified from Solley and others, 1983).

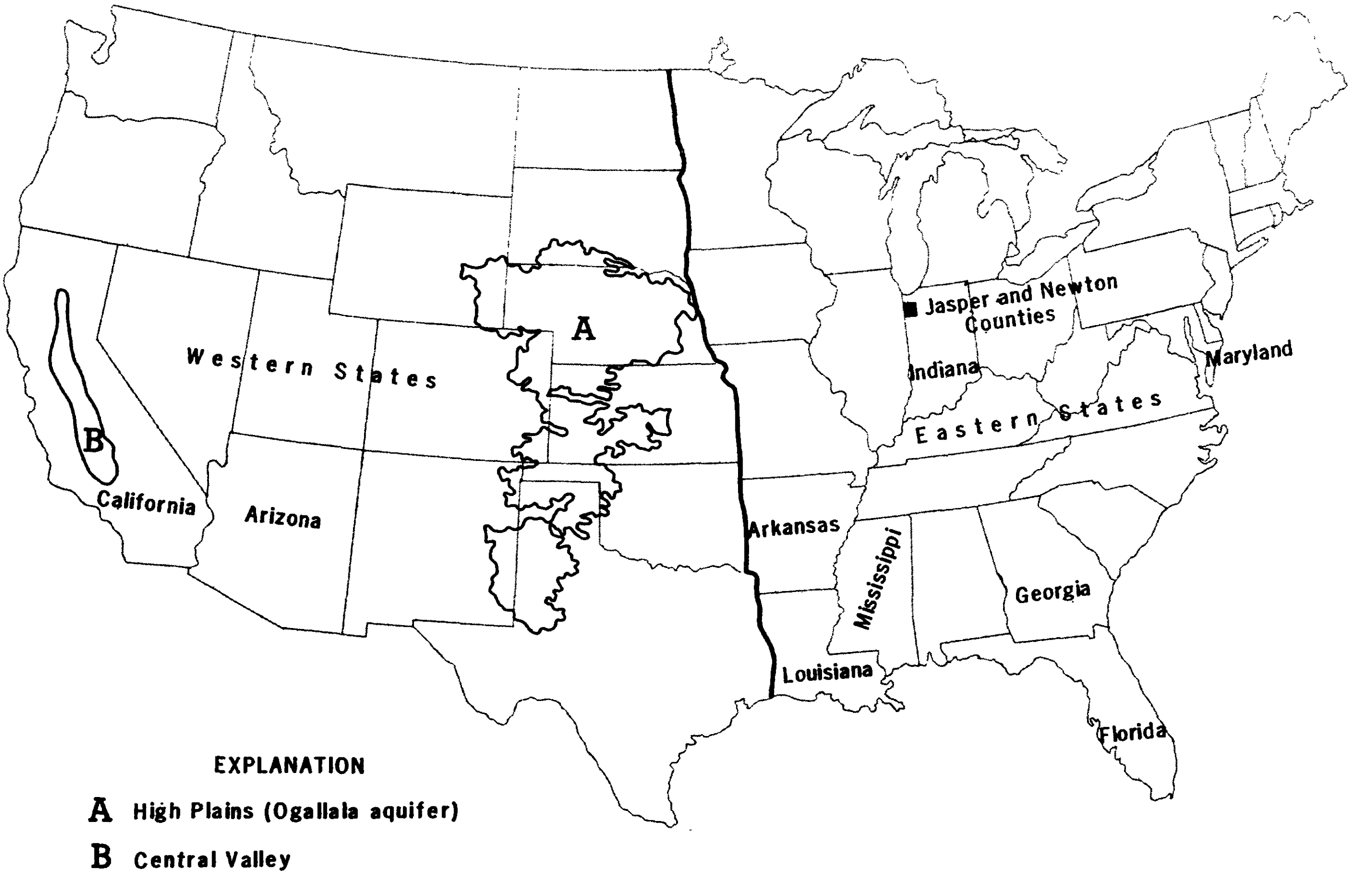


Figure 2.-- Selected areas of intensive irrigation from ground water in the continental United States.

Although about 90 percent of the irrigation in the United States is in 17 western States, the rate of increase in irrigation is much greater in the East (fig. 2). From 1970 to 1980, water used for irrigation in the West increased only 11 percent; while in the East, it more than doubled (Murray and Reeves, 1972; Solley and others, 1983). During 1980, 60 percent, or about 7,400 Mgal/d (million gallons per day), of water used for irrigation in the East was ground water (Solley and others 1983, p. 19). Large drawdowns resulting from ground-water pumping are common in many areas of the East, especially in the southeastern coastal States. For example, drawdowns of 180 ft resulting from irrigation have been reported in southwestern Louisiana. Irrigation also has resulted in notable drawdowns in Arkansas, Florida, Georgia, Maryland, and Mississippi (U.S. Geological Survey, 1984).

Indiana Perspective on Irrigation

Irrigation in Indiana has increased rapidly during the past decade, when the acreage of irrigated land tripled (fig. 3). A continued increase in the acreage of irrigated land is expected, because, during 1985, only about one-sixth of the State's land that is suitable for irrigation was being irrigated (Rolland Wheaton, Purdue University, written commun., 1985).

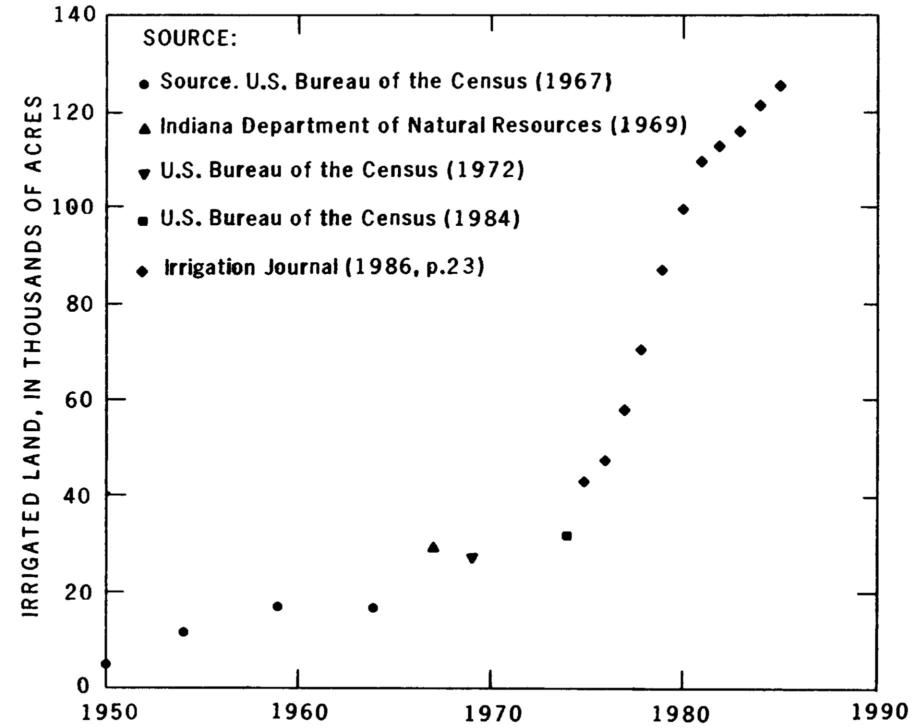


Figure 3.-- Irrigated land in Indiana, 1950-85.

During the past 5 years, public concern about irrigation in Indiana has increased mainly because of competition for water between irrigation and other uses in northwestern Indiana. In July 1981, a large corporation began irrigating 7,000 acres of cropland in Jasper and Newton Counties (fig. 2). Thirty-four irrigation wells pumped water from a limestone aquifer, and the resulting drawdown adversely affected water levels in as many as 130 private wells used for supplying water to households and livestock (Basch and Funkhouser, 1985, p. 1). During 1982, the Indiana General Assembly responded by passing the "Water Rights: Emergency Legislation" bill, which empowered the State to restrict pumping when nearby wells were affected adversely. However, this legislation applied only to Jasper and Newton Counties.

During the next 2 years, two more water laws were passed mainly because of concerns about irrigation. The first, the Water Resource Management Act (Indiana Code 13-2-6.1), passed in 1983, required that all users of water with the ability to withdraw at least 100,000 gal/d (gallons per day) to register their withdrawals with the Indiana Department of Natural Resources and provided for an assessment of the State's water resources. Additional legislation, passed in 1985, extended the scope of the "Water Rights: Emergency Regulation" bill to include the entire State.

Although public and political attention has been focused mainly on irrigation in Jasper and Newton Counties, the Indiana Department of Natural Resources has recognized that water-resource conflicts involving irrigation, as well as other uses of water, might occur in other drought-prone parts of Indiana as well. During the mid to late 1970's, irrigation in the St. Joseph River basin (fig. 4) had been increasing rapidly and, in 1980, at the request of the Indiana Department of Natural Resources, the U.S. Geological Survey began a 4-year study to determine what effects this rapid increase might have on the ground- and surface-water resources in the basin.

Acknowledgments

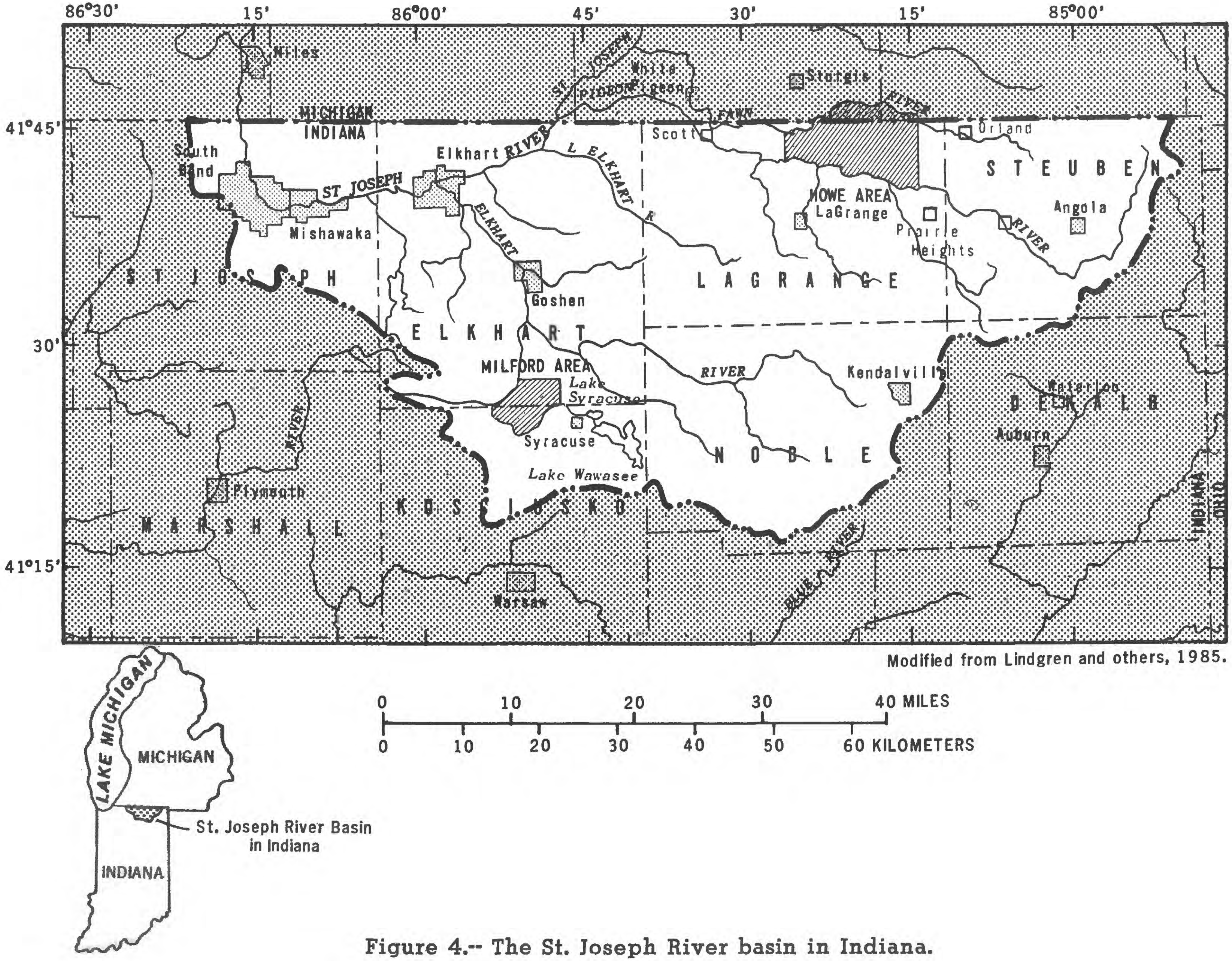
The Indiana Department of Natural Resources provided much of the information needed for the project on which this report is based. The Indiana Department of Natural Resources, Division of Water, updated an inventory of irrigation wells, provided driller's logs for high production wells, compiled land-use information, and delineated areas that have irrigable soils. The Division of Water also provided valuable suggestions and advice to the project staff at each stage of the project.

Dr. Daniel Wiersma, retired chairman of the Indiana Water Resources Research Center at Purdue University, and Dr. Rolland Wheaton, Agricultural Engineer at Purdue University, provided technical guidance in various aspects of agricultural irrigation. Dr. Wheaton wrote the calculator program for estimating requirements of water for irrigation.

Mike Jewett, Vic Virgil, and Dale Redding, the agricultural extension agents for Elkhart, Kosciusko, and Lagrange Counties, coordinated activities and meetings between the project staff and irrigators. Charles Phillips, of Phillips and Sons Irrigation Company[2], Bristol, and James Fizel, of J. and J. Irrigation Company, Lagrange, provided technical information about the irrigation systems. Many irrigators permitted the project staff to monitor their irrigation systems and to drill observation wells on their property. Several irrigators collected onsite data during the 1982 irrigation season. Without this support, much of the data collection would not have been possible.

---

[2]Use of trade names and firm names in this report is for identification or location purposes only and does not constitute endorsement of products by the U.S. Geological Survey, nor impute responsibility for any present or potential effects on the natural resources.



Modified from Lindgren and others, 1985.

Figure 4.-- The St. Joseph River basin in Indiana.

BASIN DESCRIPTION

The drainage basin of the St. Joseph River includes 4,680 mi^2 of southern Michigan and northern Indiana and drains into Lake Michigan. The Indiana part is 1,698 mi^2 in area (Hoggatt, 1975, p. 186) and includes all or part of seven counties: St. Joseph, Elkhart, Lagrange, Steuben, Dekalb, Noble, and Kosciusko (fig. 4). For the remainder of the report, "the basin" refers only to the Indiana part of the St. Joseph River basin. (Another St. Joseph River in northeastern Indiana is not discussed in this report.) Crompton and others (1986) provide a summary of basin characteristics, and much of the information in this section is from that reference.

Nearly three-quarters of the land area in the basin (1,234 mi^2) is agricultural. About 85 percent of the agricultural land is used for growing crops--mostly corn and soybeans (U.S. Bureau of the Census, 1984). The remaining one-quarter of the land area comprises forests, lakes and associated wetlands, and urban areas. The major population centers, in order of decreasing size, are South Bend, Mishawaka, Elkhart, Goshen, and Angola.

Geology

The basin is in a part of Indiana that was covered by thick sheets of ice during several glacial periods, the most recent of which, the Wisconsin glacial period, ended about 10,000 years ago. Before glaciation, a surface of shale bedrock formed a broad lowland plain throughout most of the area; however, pre-glacial rivers had eroded several steep-sided valleys in the bedrock, the deepest of which is in northwestern Elkhart County (Gray, 1982). As the glaciers advanced southward out of Canada, they moved huge quantities of surface material with them; some of this material formed ridges, or moraines, along the edges of the glaciers. Moraines are composed mainly of till--a mixture of clay, sand, gravel, and boulders. Today, remnants of these moraines from the Wisconsin glacial period form upland areas along the southeastern edge of the basin (fig. 5).

As the glaciers melted, streams were formed, which carried large quantities of clay, sand, and gravel away from the glacier. This material was deposited in meandering stream channels, forming thick deposits called outwash. Today, these outwash deposits are found in lowland areas, such as in the valley along the Elkhart River (fig. 5).

The thickness of the glacial deposits that overlie the bedrock ranges from about 30 feet near Mishawaka to more than 500 feet in a bedrock valley near Elkhart. Most of the basin is covered with deposits 200 to 350 feet in thickness (Wayne, 1956, p. 31).

A simplified representation of the surficial geology indicating areas that are predominantly till or outwash is shown in figure 5. Locally, the composition of the glacial deposits can differ greatly. In areas shown as till, numerous pockets of sand and gravel can be found, and in areas shown as outwash, discontinuous layers of clay are common.

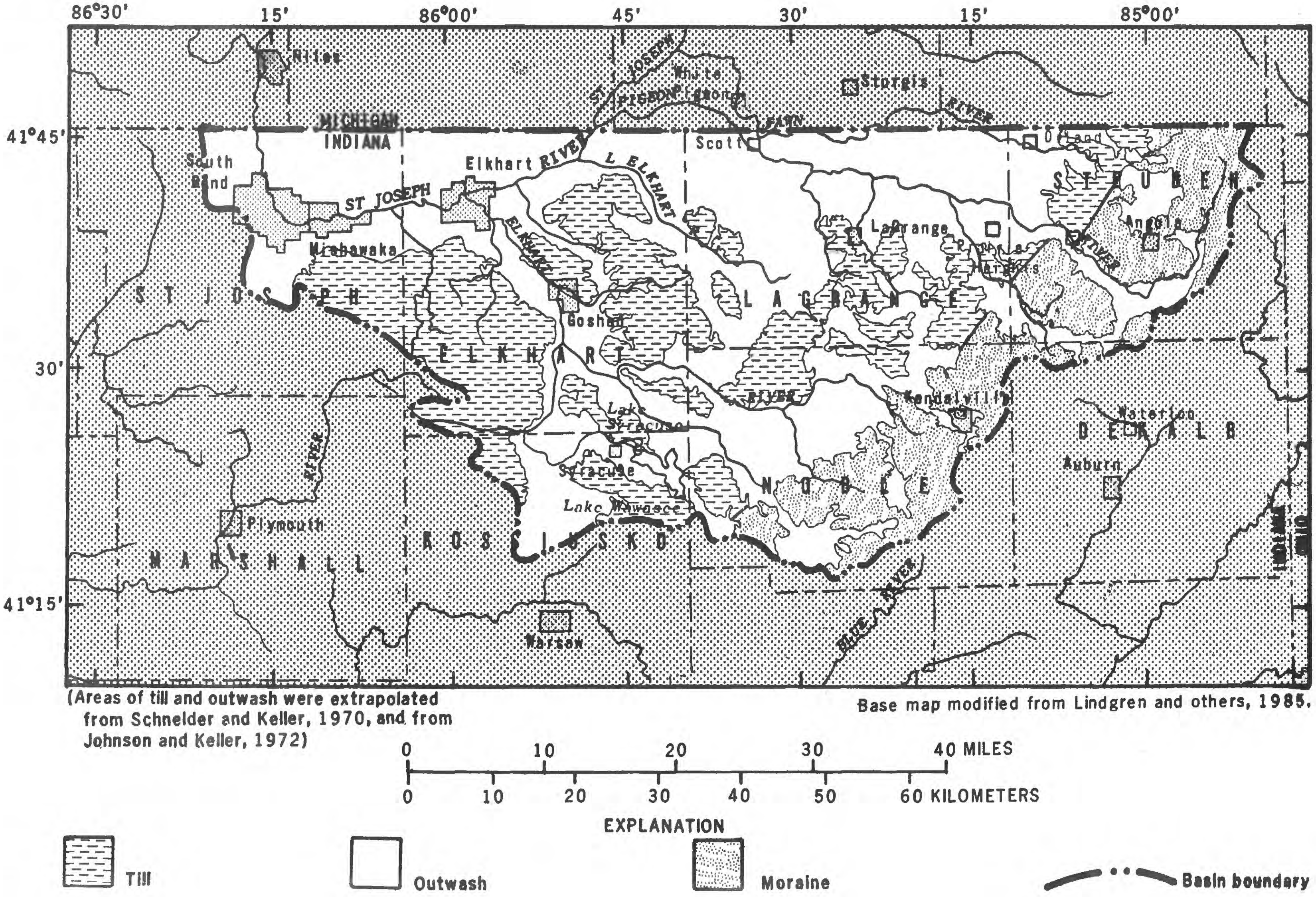


Figure 5.-- Surficial geology of the St. Joseph River basin in Indiana.

The soils that developed from glacial material can be divided into two general classes--sandy soils and clayey soils. Sandy soils developed primarily on outwash and are highly permeable and droughty. These soils have a high or very high "irrigation potential"; that is, crop yields from these soils are increased sufficiently by supplemental water to make irrigation profitable during most years. Examples are the Plainfield, Oshtemo, and Shipshe soils (U.S. Soil Conservation Service, 1977). Clayey soils developed primarily on till and are heavy, poorly drained loam soils that have a large clay and silt content. These soils have a low irrigation potential. Examples are the Miami and Crosier soils (U.S. Soil Conservation Service, 1977).

Hydrology

On the average, the basin receives about 35 inches of precipitation a year from rainfall and snowmelt. Of this, 24 inches evaporates from the surface or is transpired by plants (evapotranspiration) and 11 inches leaves the basin as streamflow runoff (Reussow and Rohne, 1975).

The headwaters of the St. Joseph River are in south-central Michigan. The river flows southwest into Elkhart County, Indiana, and then north into Michigan near South Bend in St. Joseph County, Indiana (fig. 4). The river discharges into Lake Michigan at Benton Harbor, Michigan. Major tributaries to the St. Joseph River that drain parts of Indiana are the Elkhart River, Little Elkhart River, Pigeon River, and Fawn River.

Streams in the St. Joseph River basin, when compared to streams in central and southern Indiana, generally have higher low flows and lower peak flows. The narrower range of variability in streamflow results from two factors: (1) the highly permeable outwash deposits over which many of the streams flow, and (2) the large number of lakes and wetlands through which the streams flow. During periods of rainfall or snowmelt, the streamflow runoff is delayed by rapid rates of percolation into the ground-water system and by temporary surface storage in lakes and wetlands. These factors cause lower peak flows. During periods of no rain, stored water is released slowly to the stream channels. This results in higher low flows. Thus, many streams in the basin provide a reliable supply of water throughout the year.

More than any other area of the State, the basin is characterized by its many natural lakes of glacial origin. Schneider (1966, p. 53) states that the lakes and peat bogs may number in the thousands. Most are small, although at least 150 lakes have storage capacities of more than 32 million gallons or surface areas more than 50 acres, or both (Governor's Water Resources Study Commission, 1980, p. 191-193). Lake Wawasee, in Kosciusko County, is the largest natural lake in the basin and also in the State (Indiana Stream Pollution Control Board, 1980, p. 1). Most of the lakes are along the southern and eastern parts of the basin in till areas. These areas also are the headwaters for the major tributaries to the St. Joseph River in Indiana.

The basin has some of the State's most productive aquifers, which are formed in outwash (sand and gravel) deposits along meltwater channels and in the lowlands between moraines. These aquifers primarily are in northern Elkhart, Lagrange, and St. Joseph Counties; in northeastern Kosciusko County; and northeastern Noble County, where sand and gravel deposits of 200 feet are common. Potential individual well yields are as much as 3 Mgal/d (Governor's Water Resources Study Commission, 1980). Water from precipitation that percolates down to the outwash aquifers (recharge) averages about 11 inches per year (in/yr) and can be as much as 25 in/yr (Pettijohn, 1968). Most of the recharge to the ground-water system discharges to streams and lakes and represents about 80 percent of the average streamflow runoff from the basin (Reussow and Rohne, 1975).

Regional (deep) ground-water flow is toward the St. Joseph River. Shallower ground-water flow generally is toward nearby streams, wetlands, and lakes, although local variations in geology can noticeably alter ground-water flow paths (Bailey and others, 1985; Lindgren and others, 1985).

Water Use

All public and private drinking water in the basin is obtained from wells that tap the highly productive aquifer systems in the basin. South Bend Public Utility, the largest single user of ground water, withdrew an average of 25 Mgal/d during 1985 (James Hebenstreit, Indiana Department of Natural Resources, oral commun., 1986). Total withdrawal for all public supplies averaged 44 Mgal/d during 1980 (Indiana Department of Natural Resources, 1982a); whereas, during the same year, withdrawals for domestic and livestock use averaged 15 Mgal/d (Indiana Department of Natural Resources, 1982b).

Most industries in the basin purchase water from public utilities, although many of the largest industries are self-supplied. The self-supplied withdrawals primarily are from wells; however, several industries in Elkhart and St. Joseph Counties withdraw water from the St. Joseph River (Governor's Water Resources Study Commission, 1980, p. 177).

Water is used for power generation to operate coal-fired steam turbines at one powerplant and hydro-electric generators at four other powerplants. The coal-fired plant at South Bend uses about 160 Mgal/d from the St. Joseph River to generate as much as 250 megawatts (MW) of electricity (Governor's Water Resources Study Commission, 1980, p. 177). The four hydro-electric powerplants--one each on the St. Joseph and Elkhart Rivers and two on the Fawn River--have a combined capacity of 12 MW (John Fisher, Lawson-Fisher Associates, oral commun., 1985).

Agricultural irrigation probably is the largest consumptive use of water in the basin. During 1982, an estimated 40,660 acres were irrigated (U.S. Bureau of the Census, 1984), which would require an estimated withdrawal of as much as 87 Mgal/d during the irrigation season (June through August) and normal rainfall.

EFFECTS OF IRRIGATION

The St. Joseph River basin is one of the most intensively irrigated areas in Indiana. Although it represents less than one-tenth of the area of the State, it contains nearly one-third of the irrigated land (U.S. Bureau of the Census, 1984). Between 1967 and 1982, irrigated land in the basin increased from about 3,000 acres to more than 40,000 acres (fig. 6), a thirteen-fold increase. Increases in irrigated land are expected to continue because only about one-fourth of the land that could respond favorably to irrigation is currently irrigated (Rolland Wheaton, Purdue University, written commun., 1984). Most irrigation wells are located in areas of outwash; therefore, the areas of the basin that have soils that respond best to irrigation generally are the areas that also have the most productive aquifers.

The effects of irrigation on the ground- and surface-water systems were studied in two areas of the basin; one in Elkhart and Kosciusko Counties near Milford, and the other in Lagrange County near Howe (fig. 4). Details of the study in these two areas are described by Bailey and others (1985), Lindgren and others (1985), and Peters (1987). The effects were similar in both areas; therefore, only the work done in the Milford area is described in this report.

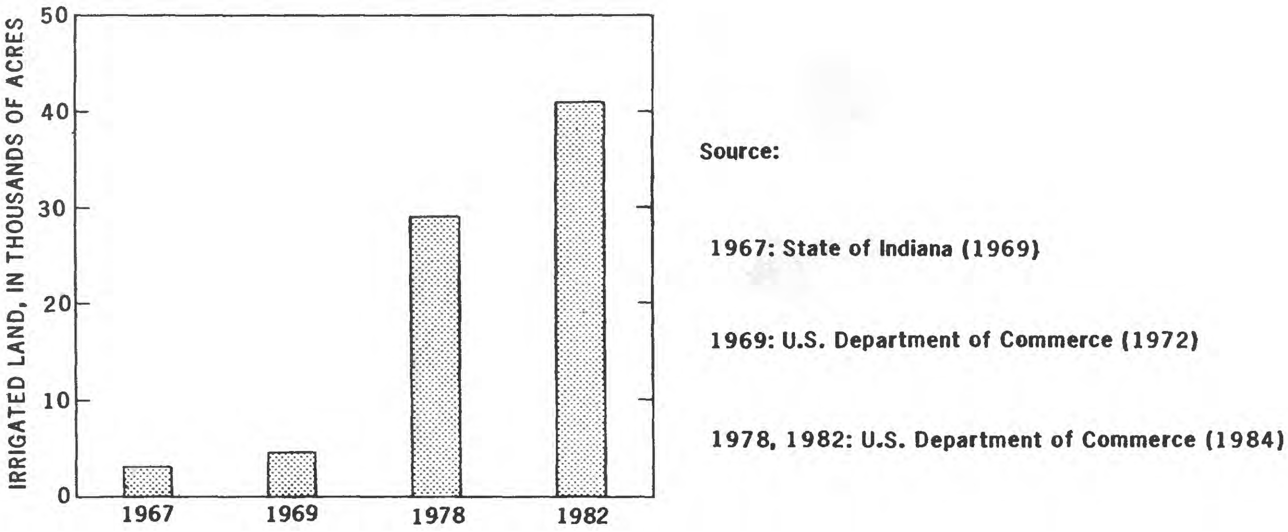


Figure 6.-- Irrigated land in the St. Joseph River basin in Indiana, 1967-82.

The Milford area (fig. 7) is 16.5 mi^2 and is covered with as much as 400 feet of glacial deposits. Near the surface, these deposits are composed mostly of outwash and till (fig. 8). The outwash deposits are composed mostly of sand and gravel and have interspersed layers of clay. These deposits form a productive aquifer system that provides all the ground water used in the area. The sandy soils, which developed on the outwash, have a significant potential for irrigation. The clayey soils, which developed on the till, have a limited potential for irrigation (Chelf, 1983). The clay layers and their effects on ground-water flow are not discussed in this report. Although included in the analysis, the effects of clay are complex and their description is beyond the scope of this report. A detailed description of the hydrogeology of the area is included in Lindgren and others (1985).

The three streams in the area are Turkey Creek, Preston Miles ditch, and Kieffer ditch. Because Turkey Creek and Preston Miles ditch flow over the outwash deposits, they have highly permeable streambeds. A large percentage of their flow is from ground water that seeps into the stream channels. Kieffer ditch flows over till deposits in its headwaters, so that, compared to Preston Miles ditch, a larger percentage of its flow is from overland runoff.

A computer model commonly is used to simulate the effects of different pumping plans on water supply. The model used for the Milford area is described by Lindgren and others (1985), and much of the information in the remainder of this section is from this reference.

The Milford model was used to predict the effects of several different irrigation pumping plans on the water resources of the area. One of these plans is discussed in this section. The plan simulates the effect of pumping the maximum volume of water that might be used for future irrigation--that is, the effect of irrigating all suitable land during a dry season. To simulate this situation, the following assumptions were made: (1) Based on soil permeability and current land use, as much as 3,225 acres (30 percent of the area) would be suitable for irrigation; (2) the maximum size of a parcel of land irrigated by a single pump would be 160 acres and the minimum area would be 40 acres; (3) irrigable land within 0.5 mile of Turkey Creek would be irrigated with water withdrawn directly from the creek; all other irrigable land would be irrigated by wells (fig. 9); and (4) during a dry season, 9.7 inches of irrigation water would be needed to supplement rainfall. To fulfill these assumptions, 26 wells and 12 surface-water pumps would need to pump continuously for 36.8 days.

Usually, irrigation systems operate intermittently throughout the summer and independently of each other. However, for the model simulation, all systems were assumed to operate continuously and at the same time. This assumption produced the largest simulated effect on water levels and streamflow for a specific volume of pumpage. Also, irrigation was assumed to be 100-percent efficient, and no water percolated back to the water table.

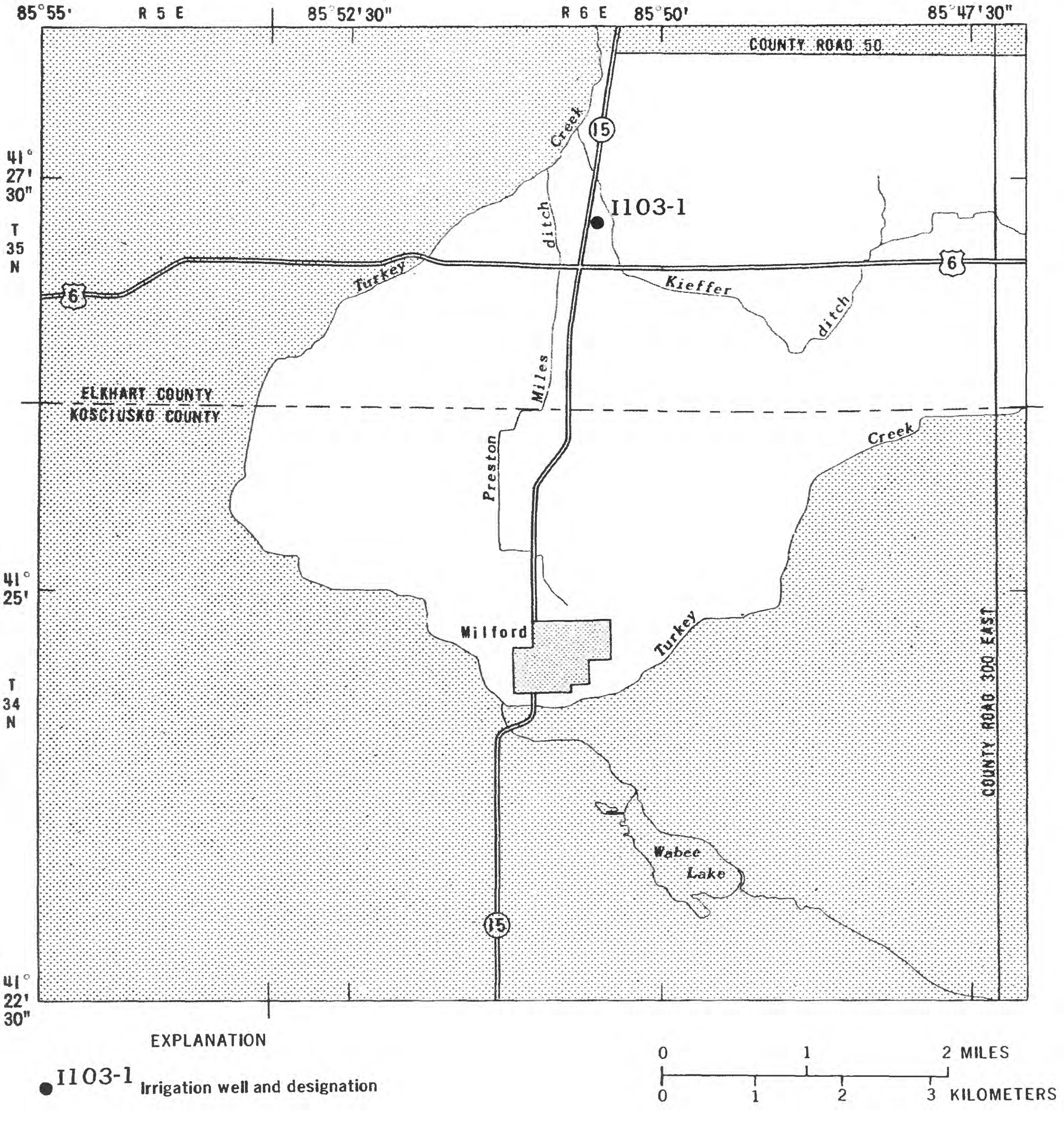


Figure 7.-- Milford area, Elkhart and Kosciusko Counties.

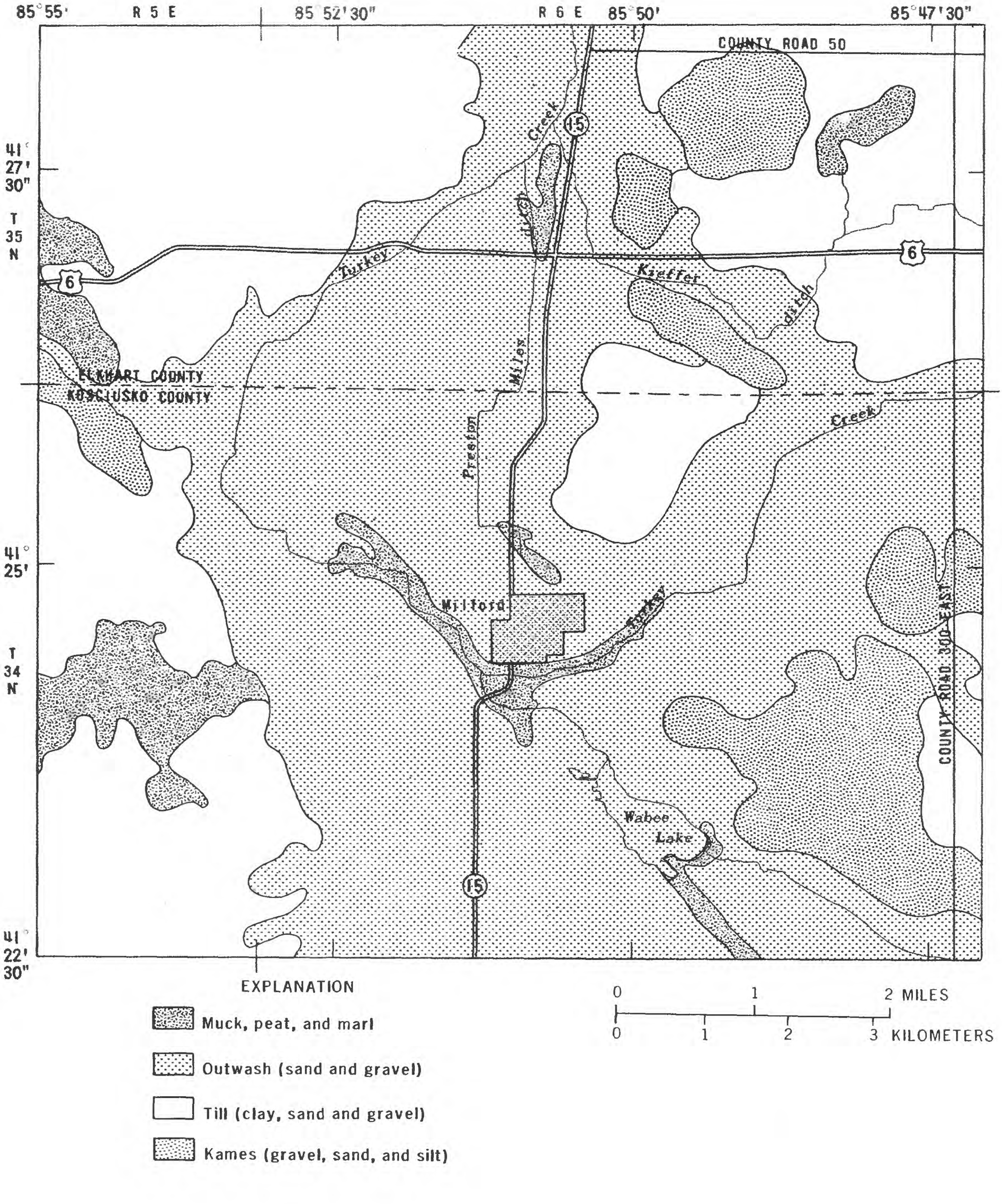


Figure 8.-- Surficial geology of the Milford area.

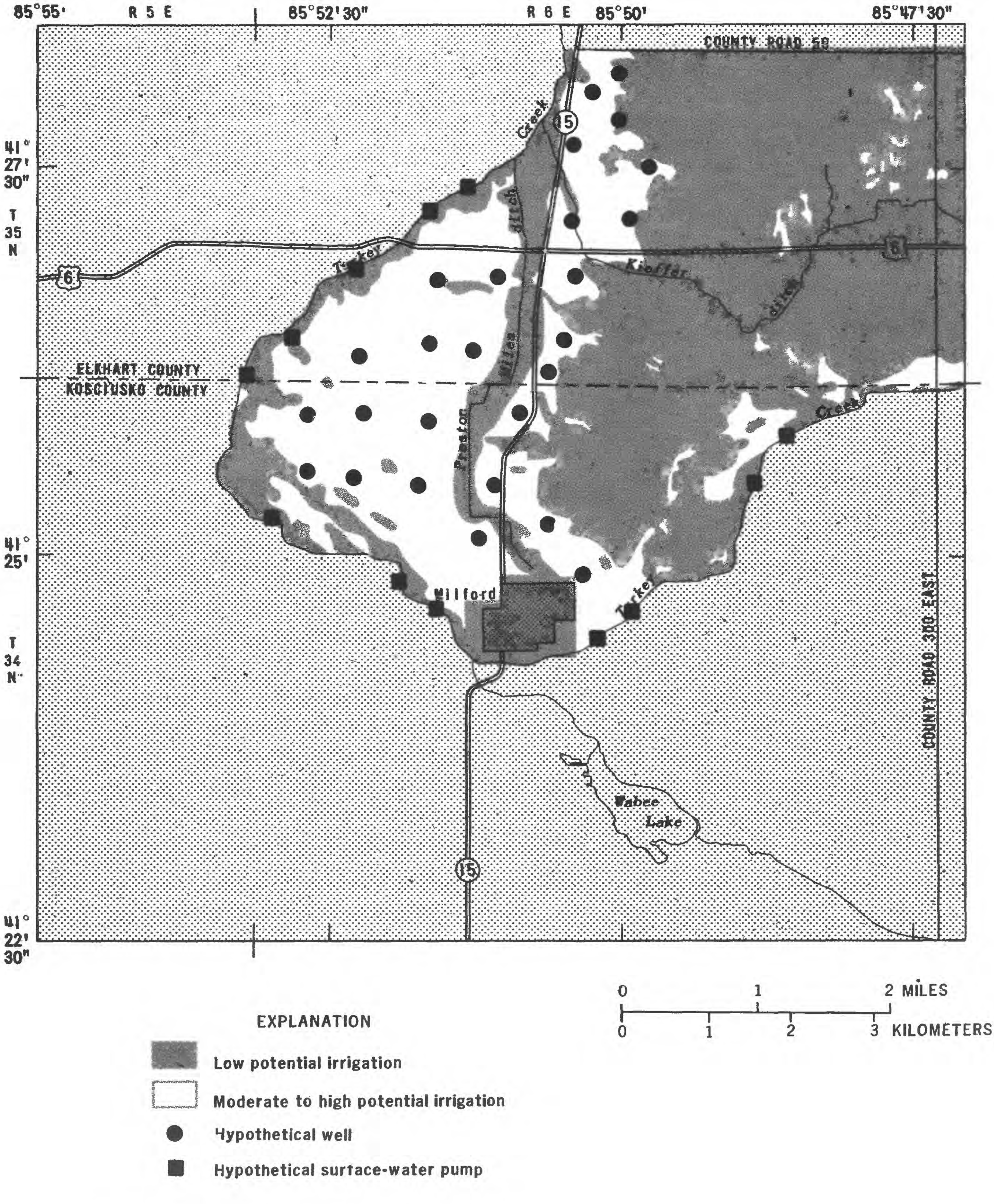


Figure 9.-- Areas of potential irrigation and locations of hypothetical ground- and surface-water pumps, Milford area.

Ground-Water Levels

When wells are not being pumped, the water surface in the aquifer is almost flat. However, when a well begins pumping, the water surface around the well begins to decline. The decline, or drawdown, is relatively large near the well and decreases at greater distances from the well, forming an inverted cone called a "cone of depression" (fig. 10). As pumping continues, drawdown increases, and the cone of depression extends farther from the well.

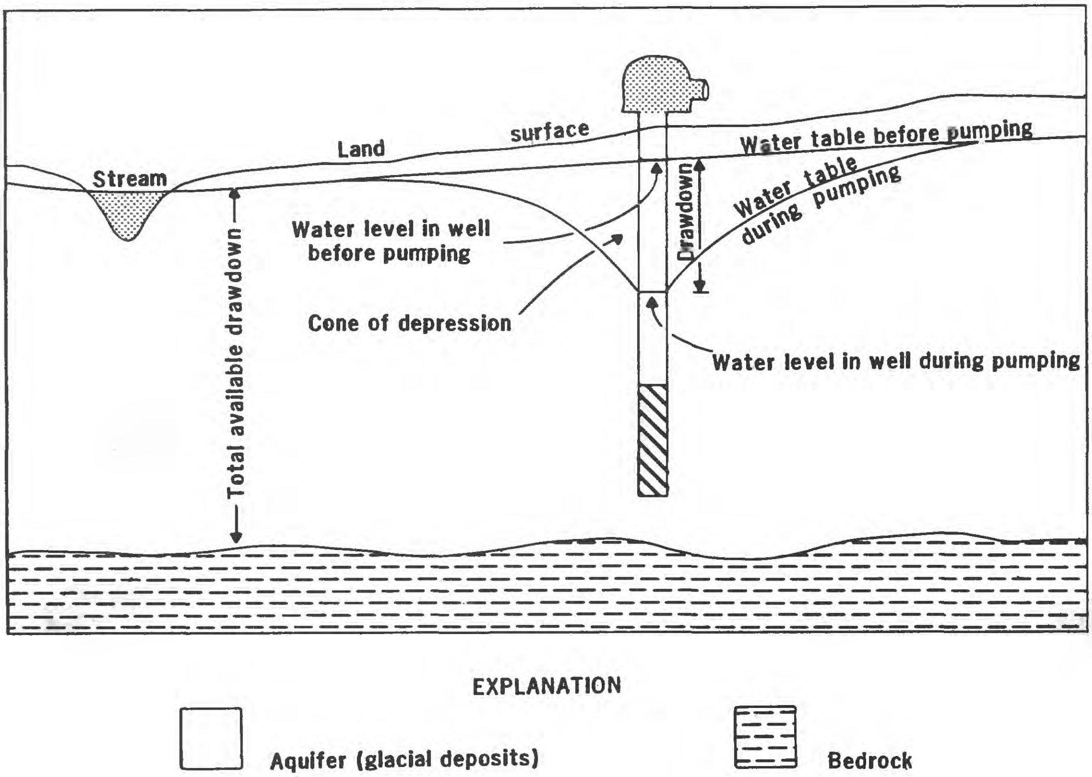


Figure 10.-- A vertical section through an aquifer showing water levels before and during pumping.

For maximum irrigation pumping, the simulated drawdown pattern in the aquifer is shown in figure 11. The drawdown contours indicate cones of depression around each of the pumping wells. The greatest drawdown, 20.7 feet, was predicted for a well west of Preston Miles ditch. Maximum drawdowns usually occur in areas where pumping wells are close together because the drawdown from one pumping well is added to the drawdown from the other well.

The predicted drawdown can be compared to the "available drawdown" to assess the effect of pumping. Total available drawdown is the altitude of the water level in a well before pumping, minus the altitude of the bottom of the aquifer (fig. 10). In the area where the maximum predicted drawdown is 16.9 feet, the total available drawdown, limited by clay layers, would be 83 feet. Thus, the maximum predicted drawdown would be about one-fourth of the largest possible drawdown in the aquifer.

Drawdown can be an important factor in evaluating pumping because of the possible adverse effects on production from nearby wells. The predicted drawdown from irrigation withdrawals in the Milford area is much less than total available drawdown, even during periods of intense pumping for irrigation.

Ground-Water Budget

An important factor in understanding the effect of pumping on water resources is to determine the source of the water for pumping or, stated differently, to determine what would have happened to the water if pumping had not occurred. A method for making these determinations is to compare ground-water budgets during periods with and without pumping. When preparing a ground-water budget, the sources and discharges of water to and from the aquifers are identified, and the magnitude of the sources and discharges are measured or estimated.

A ground-water budget for the Milford area was prepared for a period of no irrigation pumping (fig. 12). Sources of water to the aquifer in the study area include "underflow in", which is ground water that flows into the aquifers from outside the area, and "recharge from precipitation", which is that part of rainfall and snowmelt that flows downward through the unsaturated material to the aquifer. Discharges of water from the aquifer include "underflow out" of the area and "ground-water seepage to streams".

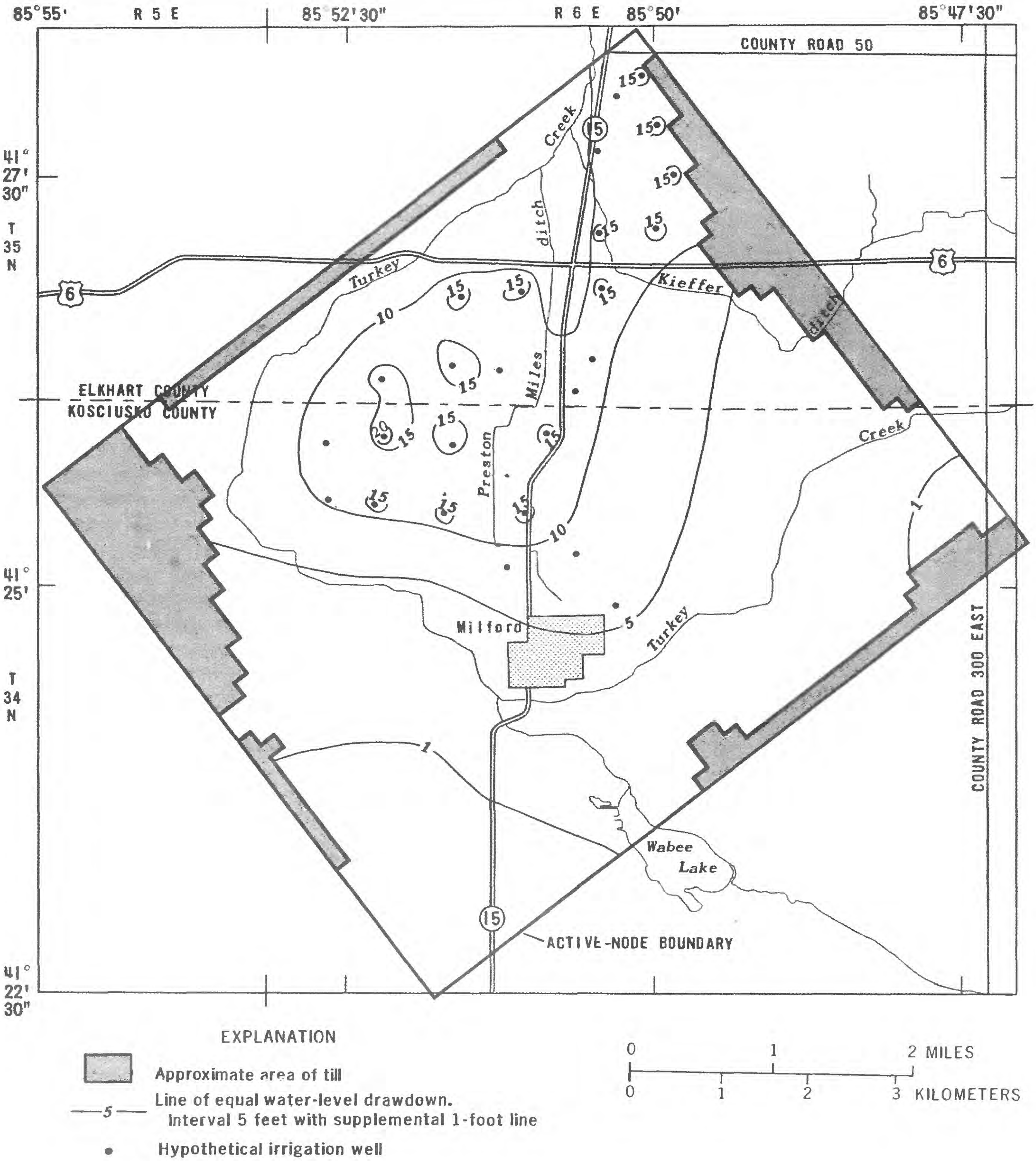


Figure 11.-- Aquifer drawdown calculated by the computer model, Milford area.

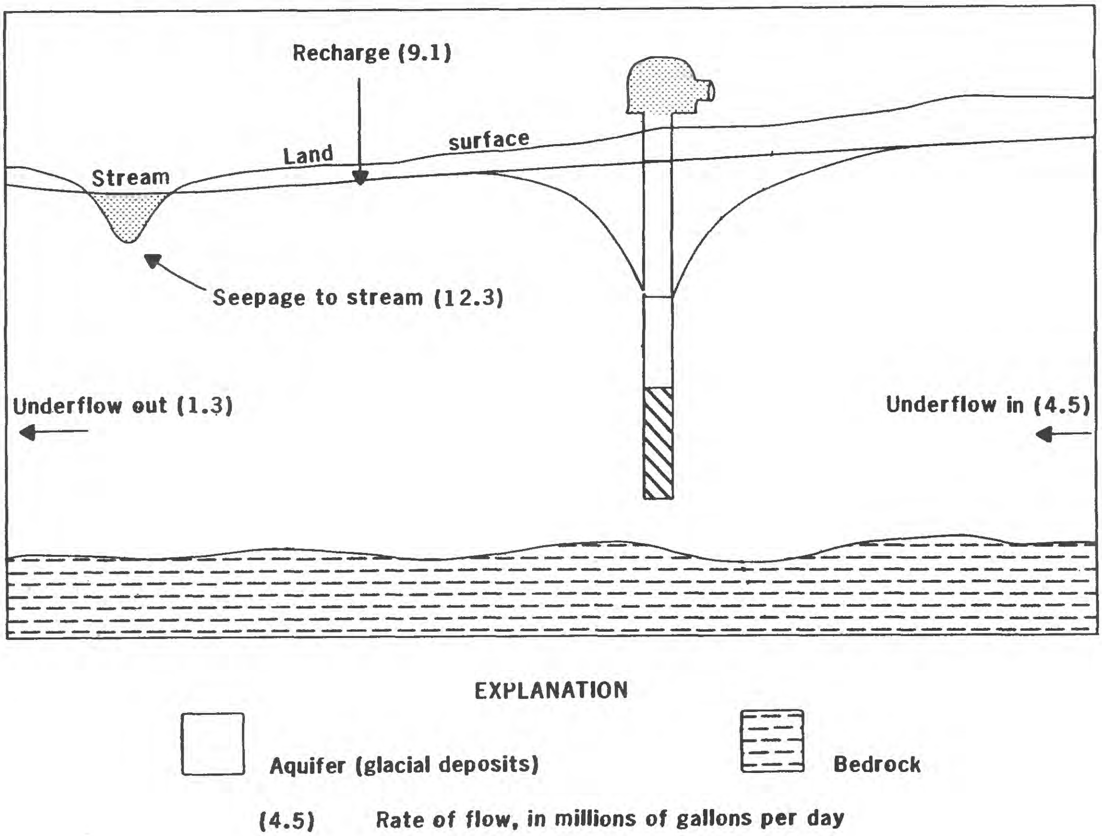


Figure 12.-- Ground-water budget for a period of no irrigation pumping, Milford area.

The largest source of water to the ground-water system was recharge from precipitation, 9.1 Mgal/d. The largest source of discharge was seepage to streams, 12.3 Mgal/d. The sources of water to the aquifer always must equal the discharges, because the actual volume of water does not change. Using the information in figure 12, the ground-water budget for the Milford area, when no water is pumped, is as follows:

Sources		Discharges	
9.1	Recharge	1.3	Underflow out
+4.5	Underflow in	+12.3	Seepage to streams
13.6	Total	13.6	Total

[All values are in million gallons per day.]

Ground-water pumping results in a new discharge to the system. Because sources and discharges always must be equal, other discharges decrease and(or) sources increase during pumping to maintain a balance in the water budget. For example, when pumping begins, water is removed from aquifer "storage" causing drawdown, as discussed in the "Ground-water level" section. Water removed from storage represents a new source in the water budget. As pumping continues, water that eventually would have seeped into streams is intercepted by pumping. This intercepted seepage is another source in the budget.

The ground-water budget for maximum irrigation pumping is shown in figure 13. The model predicts that pumping 16.8 Mgal/d for 36.8 days would result in water being removed from storage at the rate of 11.0 Mgal/d. Ground-water seepage to streams would decrease from 12.3 to 6.5 Mgal/d. Thus, during maximum irrigation, the ground-water budget for the Milford area would be:

Sources		Discharges	
(9.1)	Recharge	(1.3)	Underflow out
(4.5)	Underflow in	6.5	Seepage to streams
+11.0	Removal from storage	+16.8	Pumpage
24.6	Total	24.6	Total

[All values are in million gallons per day; numbers in parentheses are the same before and during pumping.]

By using this water-budget information, one can determine the sources of the water that was pumped from the wells. The rates of recharge and underflow do not change appreciably during pumping and, therefore, do not indicate additional sources of water. Ground-water seepage to streams decreased from 12.3 Mgal/d (before pumping) to 6.5 Mgal/d (during pumping). The difference between these two values (5.8 Mgal/d) is ground-water seepage that was intercepted by pumping; that is, water that was pumped from the wells but that would have seeped to streams if pumping had not occurred. Water removed from aquifer storage provided 11.0 Mgal/d to pumping. Therefore, the 16.8 Mgal/d pumped from the wells was supplied by "intercepted seepage to streams" and by aquifer storage. Expressed as an equation, this relation is written as follows:

$$\underset{\text{(intercepted seepage)}}{5.8\text{ Mgal/d}} + \underset{\text{(removal from aquifer storage)}}{11.0\text{ Mgal/d}} = \underset{\text{(pumping)}}{16.8\text{ Mgal/d.}}$$

Both of the sources of water for pumping have important consequences for water management. Water removed from storage may cause excessive drawdown, which limits aquifer production and may cause withdrawal problems for nearby wells. Intercepted ground-water seepage to streams reduces natural streamflow and may result in competition for water among users downstream from the irrigation pumping. The ways in which irrigation pumping reduces streamflow are discussed in the "Streamflow Reduction" section, which follows.

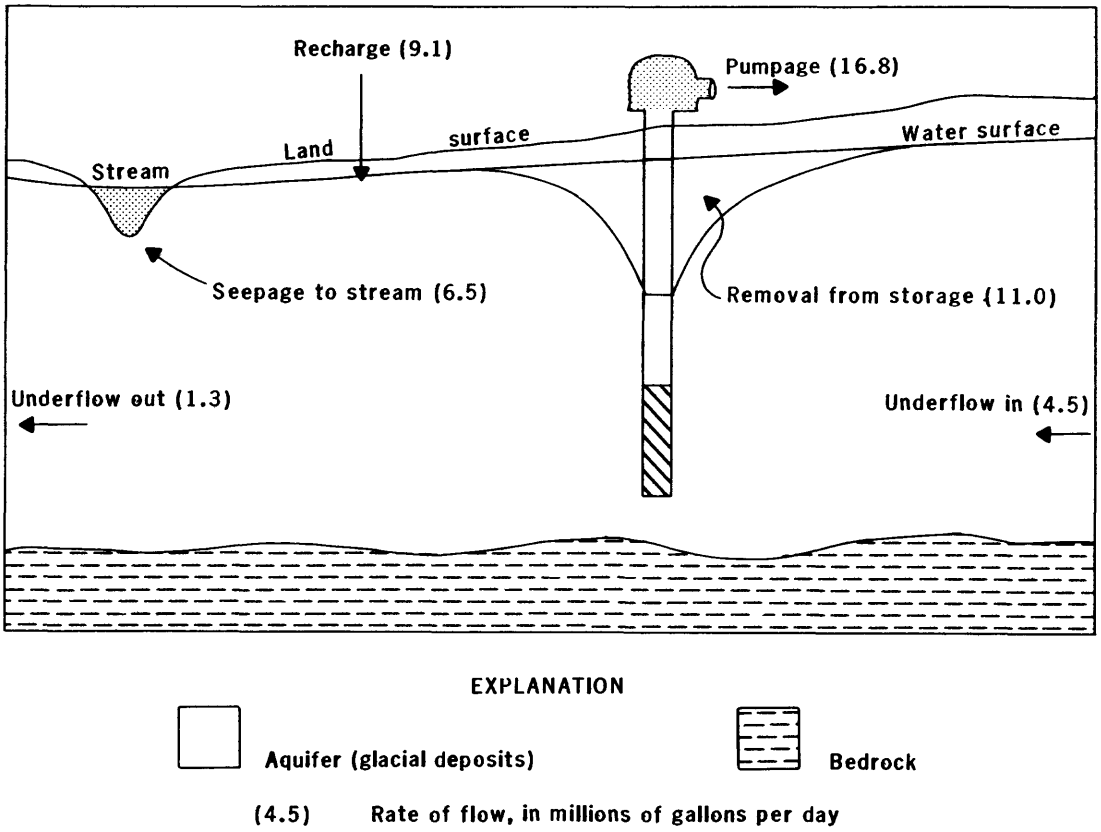


Figure 13.-- Ground-water budget for maximum irrigation pumping, Milford area.

Streamflow Reduction

In the "Ground-Water Budget" section, a comparison of the ground-water budgets for nonpumping and pumping periods showed that pumping from wells intercepts some of the ground-water that seeps into streams and thereby reduces streamflow. This section answers the questions:

How long does it take for pumping to reduce streamflow?
How long does the reduction last?
How large is the reduction?

The effects of ground-water pumping on streamflow can be demonstrated by examining the "streamflow reduction" that results from pumping a well located near a small stream. Using a procedure developed by Jenkins (1970), the authors estimated the streamflow in Kieffer ditch during and after one day of pumping from well I103-1 (fig. 7). Several hours after pumping begins, flow in Kieffer ditch starts to decline (fig. 14). The flow continues to decline several hours after pumping stops, and then begins to increase. By the tenth day, flow in Kieffer ditch is approaching natural flow as the effects of pumping diminish.

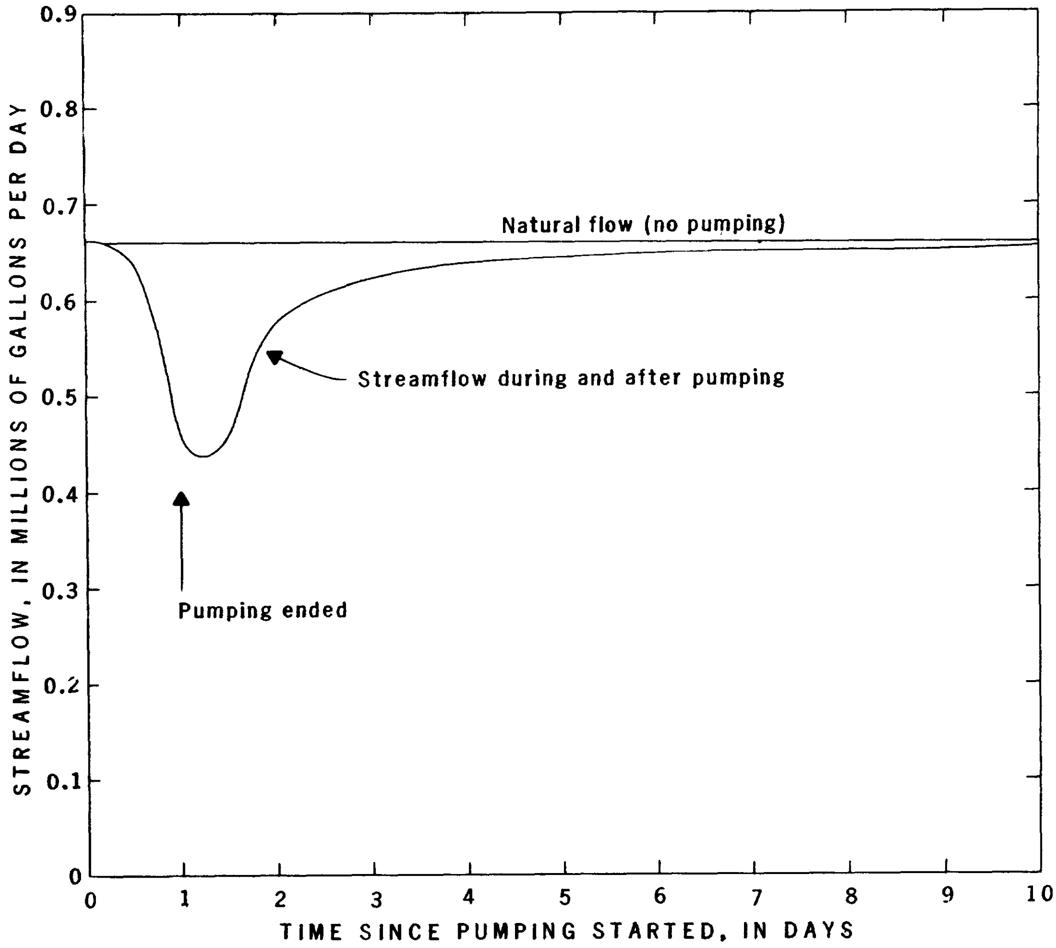


Figure 14.-- Predicted streamflow in Kieffer ditch and the effect of pumping from well I103-1, Milford area.

Several important points about the effects of ground-water pumping on streamflow are illustrated on figure 14. Reduction in flow is delayed after pumping starts, and recovery of flow is delayed after pumping stops. These delays are due, in part, to the slow movement of ground water compared to that of surface water. Several hours are needed for the cone of depression around the well to extend to the stream when pumping starts, and a similar amount of time is needed for the effects to begin reversing when pumping stops.

Also, after pumping stops, the cone of depression around the pumping well begins to "fill up" with water, and water levels around the well return to pre-pumping levels. Thus, the water that temporarily was removed from aquifer storage during pumping is eventually replaced by water that would have seeped to the stream if pumping had not occurred. The result of this replacement is that the volume of water pumped from the well eventually equals the total reduction in streamflow. This fact is important to water managers who may need to allocate the flow in streams among several different users.

In many parts of the basin, cropland near streams is irrigated by pumping water directly from the stream channel. The combined effects of ground- and surface-water withdrawals on streamflow are illustrated by comparing the flow in Turkey Creek during a period with no irrigation pumping to the flow that results from pumping all wells and surface-water pumps needed for maximum irrigation. The information used to simulate pumping for maximum irrigation is presented in table 1. During a dry period before irrigation starts, flow in Turkey Creek is 25.8 Mgal/d (table 2), based on long-term streamflow records. As pumping begins, the withdrawals by surface-water pumps reduce streamflow immediately by an amount equal to the combined rate of pumping, 6.5 Mgal/d. By the end of the pumping period, streamflow reduction due to pumping from wells equals 4.3 Mgal/d. The resulting flow in Turkey Creek would be reduced to 15.0 Mgal/d.

Because withdrawals for irrigation in the Milford area are from ground- and surface-water, the magnitude and timing of both types of withdrawals need to be considered in estimating streamflow. Also, the magnitude of natural flow in the stream, relative to the magnitude of the reduction in streamflow, is often the most significant factor in evaluating the effects of pumping on streamflow. The flow in Turkey Creek is adequately maintained by ground-water seepage throughout the year, so maximum pumping for irrigation in the Milford area probably would reduce flow in the creek by less than 50 percent, even during dry periods.

In the Milford area, as in other areas of the basin, the largest withdrawals of ground-water are for irrigation during the summer. However, other uses of ground water require withdrawals year-round. For aquifers in which withdrawals continue for long periods of time, the rate at which water is removed from storage approaches zero, and the rate of streamflow reduction approaches the rate of pumping. When this condition occurs, drawdown stops, and the hydrologic system reaches a new equilibrium, in which water levels remain constant. The concept of equilibrium in ground-water systems is important when determining rates of withdrawal that can be maintained for long periods of time without depleting the supply of ground water. This concept and its consequences for water management are described in the "Implications for Aquifer Yields" section, which follows.

Table 1.--Conditions for simulating pumping for maximum irrigation, Milford area

[Modified from Lindgren and others, 1985; Mgal, million gallons; Mgal/d, million gallons per day]

Application					Number of		Rate of pumping (Mgal/d)	
Depth[1] (inches)	Ground water (Mgal)	Surface water (Mgal)	Irrigated land (acres)	Duration of continuous pumping (days)	Wells	Surface water pumps	Ground water	Surface water
9.7	618	238	3,225	36.8	26	12	16.8	6.5

[1]The depth of water applied uniformly over the irrigated land.

Table 2.--Predicted streamflow in Turkey Creek resulting from ground- and surface-water pumping for maximum irrigation, Milford area

Pumping condition	Natural streamflow[1] (Mgal/d)	Streamflow reduction (Mgal/d)		Net streamflow[4] (Mgal/d)
		Wells[2]	Surface-water pumps[3]	
No pumping	25.8	0	0	25.8
Maximum pumping	25.8	4.3	6.5	15.0

[1]A comparatively low streamflow that is exceeded 80 percent of the time and used to simulate flow during a dry period.
[2]Streamflow reduction by wells is the decrease in natural seepage to streams caused by ground-water pumping.
[3]Streamflow reduction by surface-water pumps is the water pumped directly from the stream channel.
[4]Net streamflow is natural streamflow minus streamflow reduction from wells and surface-water pumps.

IMPLICATIONS FOR AQUIFER YIELDS

Water withdrawals for current (1982) irrigation in the Milford area, as in other parts of the basin, have had only limited effect on the water resources (Lindgren and others, 1985). Possible withdrawals for future development are expected to have greater effects. But, will these effects be significant when compared to other existing or anticipated uses of water? This question cannot be answered by hydrologists alone, because it involves many nonhydrologic factors that can be dealt with only by water-resource managers. This section discusses the hydrologic and nonhydrologic factors as they might apply to water resources in the Milford area and, presumably, to other parts of the basin.

A major concern to resource managers is the quantity of water available for use. Providing direct estimates of water yield is not a simple matter because alternative development plans may change potential yield. These plans are based on many hydrologic, economic, and social factors. The number of alternatives is almost limitless. Several concepts for dealing with alternative management options have been suggested; the most common are "sustained yield", "safe yield", and "optimal yield" (U.S. Water Resources Council, 1980). Before discussing the three concepts of yield, the principle on which these concepts are based needs to be explained.

Under natural conditions, before ground-water pumping, aquifers are in a state of equilibrium. Natural sources of water to aquifers equal natural discharges of water from the aquifer. Pumping by wells results in a new discharge, which is balanced by increased recharge to the aquifer and(or) decreased discharge from the aquifer. These changes in flow to and from the aquifer are referred to as "capture" because they represent water captured by pumping.

When the rate of pumping exceeds the rate of capture, water is removed from aquifer storage. The progressive removal of water from storage is "ground-water mining". If ground-water mining continues long enough, the water resource becomes depleted. Currently, ground water is not being depleted in the basin, because potential rate of capture exceeds the rate of pumping.

Sustained Yield

Water-resource managers generally are interested in a maximum rate of pumping in which the level of development is balanced by capture. This level of development is called sustained yield and represents the maximum rate of withdrawal that can be sustained year after year.

Sustained yield depends only on capture, and not on the natural recharge or discharge that occurred before development. As Bredehoeft and Young (1970) point out, ground-water development can cause major changes to the recharge-discharge relationship and this changed relation (capture), rather than the natural relation, controls yield.

In the Milford area, recharge from precipitation and underflow are assumed to be constant; therefore, the only source of capture is reduction in streamflow. Reduction in streamflow from ground-water pumping can be in two forms: (1) If the rate of pumping is less than the rate of natural ground-water seepage to streams, only part of the seepage is intercepted, and the remainder becomes streamflow (this case was described in the section "Streamflow Reduction"); and (2) if the rate of pumping is greater than the rate of seepage, the direction of ground-water flow near the stream is reversed, and water begins to seep from the stream to the aquifer (fig. 15). Theoretically, this reverse seepage could increase until all flow in the stream recharges the aquifer, and streamflow ceases. For example, to simulate a dry year for maximum irrigation in the Milford area, flow in Turkey Creek was assumed to be 25.8 Mgal/d (table 2), which represents the theoretical sustained yield for the area. The combined rate of pumping for the 26 wells and 12 surface-water pumps was 23.3 Mgal/d (table 1) or 2.5 Mgal/d less than the sustained yield. Therefore, during periods of maximum pumping, the predicted flow in Turkey Creek would be 2.5 Mgal/d.

The concept of sustained yield is limited because it is based only on water availability and the consequences of sustained-yield pumping are extreme. Pumping at the rate of sustained yield can deplete streamflow and cause large water-level declines in the aquifer. Because of this limitation, sustained yield often has been replaced by safe yield.

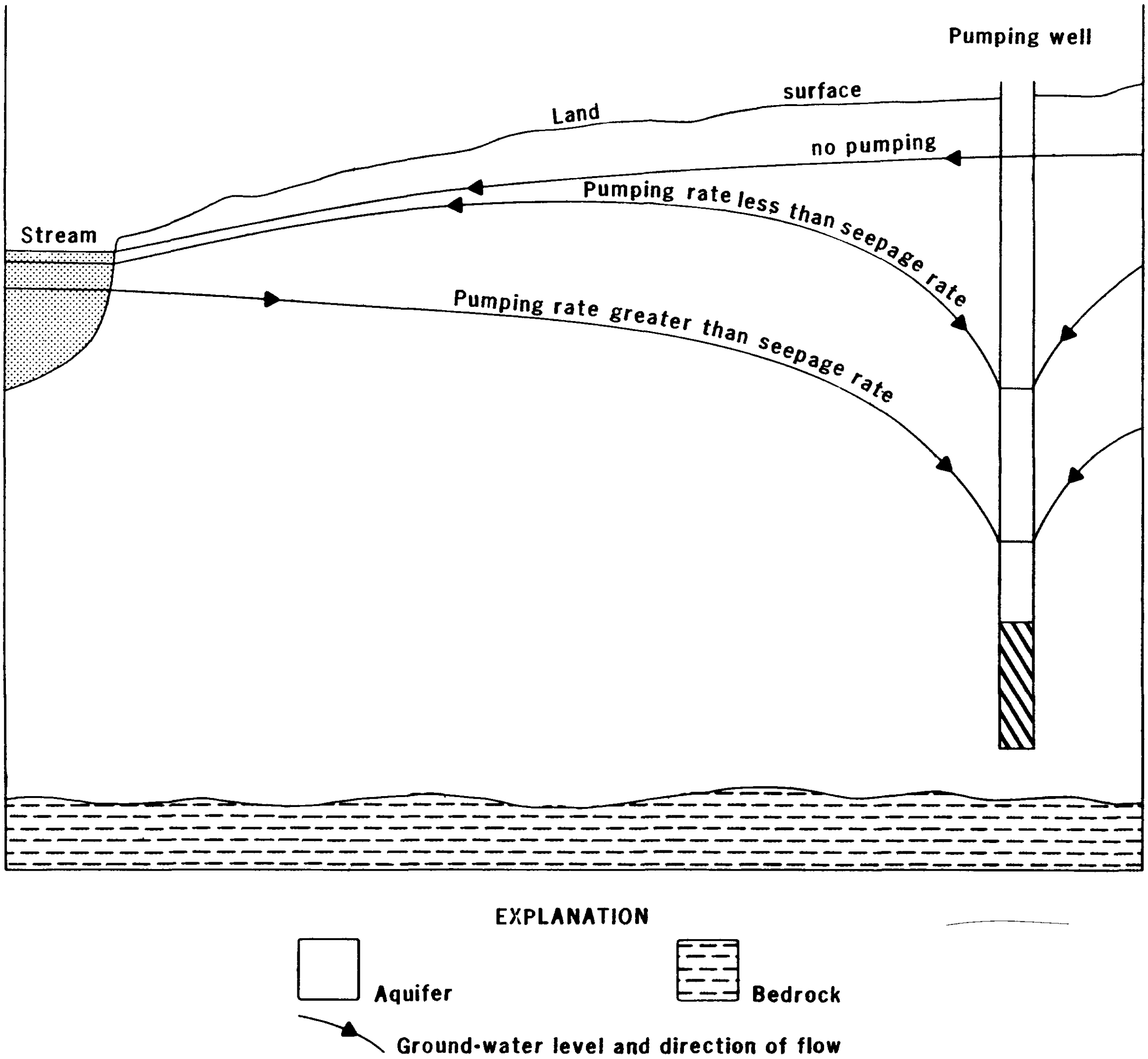


Figure 15.-- Ground-water levels and direction of flow in response to pumping from a well near a stream.

Safe Yield

Safe yield is the quantity of water that can be withdrawn from an aquifer without causing an undesirable result. What constitutes an undesirable result is defined by the resource manager and can be one, or a combination of several factors, such as high costs of production, saltwater intrusion, land subsidence, excessive drawdown, or other adverse environmental consequences.

Calculating a safe yield for an aquifer system requires that potentially undesirable consequences of pumping be identified and that rates of pumping be determined that would avoid these consequences. For example, the resource manager might determine that, if water levels in an aquifer dropped 20 feet below normal, many domestic wells in the area would cease to produce adequate water. The manager might also conclude that, if flow in a nearby stream was less than 10 Mgal/d, important fish habitat would be jeopardized. To avoid these undesirable consequences, the manager would want to know what rate of pumping would be possible without causing drawdown that exceeded 20 feet or causing streamflow to decrease to less than 10 Mgal/d. By using a computer model or other suitable analytical tool, pumping at different rates would be simulated until the safe yield--the maximum rate that would not violate the pre-established criteria--was determined.

The safe yield probably would change from year to year, depending on changing hydrologic conditions. During a dry period when natural streamflow declined to 10 Mgal/d, the safe yield would be very small and probably limited by a minimum-streamflow criterion. During periods of higher streamflow, safe yield would be higher and would probably be limited by a maximum-drawdown criterion. Thus, the determination of safe yield involves avoiding each of several possible undesirable results in a changing hydrologic environment.

The concept of safe yield generally is adequate in most areas where water is plentiful. However, many resource managers recognize the need for a more comprehensive yield concept that incorporates not only hydrologic factors, but also includes social, economic, and legal factors as well--a concept referred to as optimal yield.

Optimal Yield

Freeze and Cherry (1979, p. 364-365) describe optimal yield as follows:

> From an optimization viewpoint, ground water has value only by virtue of its use, and the optimal yield must be determined by the selection of the optimal ground-water management scheme from a set of possible alternative schemes. The optimal scheme is the one that best meets a set of economic and(or) social objectives associated with the uses to which the water is to be put. In some cases and at some points in time, consideration of the present and future cost and benefits may lead to optimal yields that involve mining ground water, perhaps even to depletion. In other situations, optimal yields may reflect the need for complete conservation. Most often, the optimal ground-water development lies somewhere between these extremes.

The purpose of establishing an optimal yield is to ensure that the water resource is developed in a way that provides maximum social benefit at acceptable cost. Decisions about what constitutes maximum social benefit and acceptable cost are made by resource managers. A hydrologist can help in this evaluation process, but the decisions are based, in large measure, on non-hydrologic considerations. Any discussion of these decisions as they might relate to the basin is beyond the scope of this report. However, a brief discussion of some of the considerations for making these decisions and a brief description of the process used to determine an optimal yield are appropriate.

The first step in determining an optimal yield is to define all the significant factors that affect development of the water resources. For the Milford area, these factors might include, but certainly would not be limited to, the combined use of ground water and surface water (conjunctive use), the relative importance of different uses of water, the cost of producing water for alternative purposes, anticipated increases in all uses of water, anticipated changes in population and land use, and water-quality considerations. After all significant factors have been identified, acceptable criteria are suggested for each factor.

The next step is to devise and evaluate various alternative plans for meeting the criteria. For example, the resource manager might determine that, during periods of low streamflow, water withdrawals should be from ground water; and, during periods of high streamflow, withdrawals should be from streams. This conjunctive use of ground- and surface-water would help ensure that an established minimum streamflow would be maintained during periods of drought and provide for aquifer recharge during periods of high precipitation.

To evaluate alternative plans, an optimization procedure is used that results in a measure of how well each plan meets the resource-development criteria. The optimization procedure is an iterative process in which plans are evaluated, initial criteria are changed, and a second set of plans are devised and evaluated. The procedure continues until a suitable plan is found that balances the various factors by their importance, thereby providing optimum benefits at acceptable costs. A thorough review of the development of optimization procedures was done by Domenico (1972).

All concepts of yield are based solely or, in part, on the principle of continuity, which requires that long-term withdrawals of ground water be limited by capture if ground-water mining is to be avoided. In the Milford area, as in other irrigated parts of the basin, potential rates of capture are high compared with present rates of withdrawal. Hydrologic information from this study indicates that substantial increase in ground-water development is possible before depletion of the water would occur.

SUMMARY AND CONCLUSIONS

As in other parts of the country, the irrigated agricultural land in Indiana has increased substantially during the past decade. This increase is expected to continue. Public concern about competition for water between irrigators and other users has resulted in several new laws that established the State's authority to regulate water withdrawals.

The St. Joseph River basin is one of the most intensively irrigated parts of the State. Highly permeable, sandy soils that cover much of the basin require irrigation for large crop yields. The thick glacial aquifers that lie beneath these sandy soils provide water for irrigation from wells and sustain flow in streams from which additional irrigation water is pumped. Thus, the areas of the basin that have soils that respond best to irrigation are those areas that have productive aquifers and well-sustained streamflows.

The results of studies in two intensively irrigated parts of the basin are very similar and probably are indicative of the effects of irrigation in other parts of the basin as well. Water for irrigation is withdrawn from highly productive glacial aquifers or from streams and ponds fed by these aquifers. Pumping occurs mainly during a 3-month period (June through August). Drawdown of aquifer water levels greater than 10 feet is confined to areas near pumping wells. Pumping initially results in removal of water from aquifer storage and subsequently results in interception of ground-water discharge to streams. Because withdrawals for irrigation are seasonal, water is removed only temporarily from aquifer storage. After pumping stops, all water removed from storage is replaced by water that would have discharged to streams if pumping had not occurred. Thus, the volume of water pumped for irrigation eventually results in an equal reduction in streamflow volume. However, the volume of water withdrawn for irrigation is small compared to the volume of water available for withdrawal. In general, irrigated areas in the basin have ample supplies of ground and surface water to support present needs and substantial future growth.

This favorable relation between need and supply does not occur in all areas of the State. In two northwestern counties, Jasper and Newton, irrigation from fractured limestone has caused drawdowns large enough to affect the water supply of nearby domestic wells. The contrast between pumping from outwash and pumping from bedrock demonstrates that similar hydrologic stress can result in dissimilar effects when applied to differing hydrologic systems. The contrast illustrates the need to account for differences in hydrogeology when developing statewide water-management policies.

To determine acceptable water-withdrawal rates for prolonged periods of time, the adverse effects of withdrawals on the water resources need to be defined by the water-resource manager. Estimates of water yield that will avoid these adverse effects then can be made by the hydrologist. Although several definitions of yield exist, they are all based on the concept of capture--increased sources of water to aquifers or decreased discharges of water from aquifers that result from pumping. When the rate of pumping is less than or equal to the rate of capture, pumping can continue indefinitely without depleting the water supply. When the rate of pumping exceeds the rate of capture for prolonged periods of time, ground-water mining can deplete the water supply. Within the basin, the short pumping periods and potentially high rates of capture make depletion of the water resources from irrigation highly unlikely.

REFERENCES CITED

Bailey, Z.C., Greeman, T.K., and Crompton E.J., 1985, Hydrologic effects of ground- and surface-water withdrawals in the Howe area, Lagrange County, Indiana: U.S. Geological Survey Water-Resources Investigations Report 85-4163, 130 p.

Basch, M.E., and Funkhouser, R.V., 1985, Irrigation impacts on ground-water levels in Jasper and Newton Counties, Indiana, 1981-1984: Indianapolis, Indiana Department of Natural Resources Water Resource Assessment 85-1, 109 p.

Bredehoeft, J.D., and Young, R.A., 1970, The temporal allocation of groundwater--A simulation approach: Water Resources Research, v. 6, no. 1, p. 3-21.

Chelf, D.F., 1983, The irrigation potential of the Milford and Howe study areas: Indianapolis, Indiana Department of Natural Resources, Division of Water, 26 p.

Crompton, E.J., and others, 1986, Review of the hydrologic data-collection network in the St. Joseph River basin, Indiana: U.S. Geological Survey Water-Resources Investigations Report 86-4157, 51 p.

Domenico, P.A., 1972, Concepts and models in groundwater hydrology: New York, McGraw-Hill, 405 p.

Frederick, K.D., 1982, Water for western agriculture: Washington D.C., Resources for the Future, Inc., 241 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Governor's Water Resource Study Commission [Clark, G.D., ed.], 1980, The Indiana water resource--Availability, uses, and needs: Indianapolis, Indiana Department of Natural Resources, 508 p.

Gray, H.H., 1982, Map of Indiana showing topography of the bedrock surface: Bloomington, Indiana Geological Survey Miscellaneous Map 35 and 36, scale 1:500,000, 2 sheets.

Hoggatt, R.E., 1975, Drainage area of Indiana streams: Indianapolis, Indiana Department of Natural Resources, Division of Water, 231 p.

Indiana Department of Natural Resources, 1969, Indiana agricultural irrigation in 1967: Indianapolis, 27 p.

Indiana Department of Natural Resources, 1982a, The 1980 survey of public water supply utilities in Indiana: Indianapolis, Division of Water, 77 p.

———1982b, The survey of domestic self-supplied and livestock water uses in Indiana: Indianapolis, Division of Water, 20 p.

Indiana Stream Pollution Control Board, 1980, Indiana lake classification system and management plan: Indianapolis, Indiana State Board of Health, 178 p.

Irrigation Journal, 1986, Irrigation survey for 1985: January-February, p. 21-25.

Jenkins, C.T., 1970, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 4, chap. D1, 17 p.

Johnson, G.H., and Keller, S.J., 1972, Regional geological map no. 8, Fort Wayne sheet, part B: Bloomington, Indiana Department of Natural Resources, Geological Survey, scale 1:250,000, 1 sheet.

Lindgren, H.A., Peters, J.G., Cohen, D.A., and Crompton, E.J., 1985, Hydrologic effects of ground- and surface-water withdrawals in the Milford area, Elkhart and Kosciusko Counties, Indiana: U.S. Geological Survey Water-Resource Investigations Report 85-4166, 75 p.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-652, scale 1:2,500,000, 2 sheets.

Murray, C.R., and Reeves, E.B., 1972, Estimated use of water in the United States in 1970: U.S. Geological Survey Circular 676, 37 p.

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

Pettijohn, R.A., 1968, Reconnaissance of the ground-water resources of the St. Joseph River basin in Indiana--Appendix to the State water plan: Indianapolis, Indiana Department of Natural Resources, Division of Water, 32 p.

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

Schneider, A.F., 1966, Physiography, _in_ Lindsey, A. A., ed., Natural features of Indiana--Symposium, 1966 [Indiana sesquicentennial volume, 1816-1966]: Indiana Academy of Science and Indiana State Library, p. 40-56.

Schneider, A.F., and Keller, S.J., 1970, Regional geological map no. 4, Chicago sheet: Bloomington, Indiana Department of Natural Resources, Geological Survey, scale 1:250,000, 1 sheet.

Solley, W.B., Chase, E.B., and Mann, W.B., IV, 1983, Estimated use of water in the United States in 1980: U.S. Geological Survey Circular 1001, 56 p.

U.S. Bureau of the Census, 1967, 1964 United States census of agriculture--Indiana: U.S. Department of Commerce, v. 1, part II, variable pagination.

———1972, 1969 United States census of agriculture--Indiana: U.S. Department of Commerce, v. 1, part II, section 2, variable pagination.

———1984, 1982 United States census of agriculture--Indiana: U.S. Department of Commerce, v. 1, part 14, variable pagination.

U.S. Geological Survey, 1984, National water summary 1983--Hydrologic events and issues: U.S. Geological Survey Water-Supply Paper 2250, 243 p.

U.S. Soil Conservation Service, 1977, Soil associations of Indiana: scale 1:500,000, 1 sheet.

U.S. Water Resources Council, 1980, Essentials of ground-water hydrology pertinent to water-resources planning (revised): Washington, D.C., Hydrology Committee Bulletin 16, 38 p.

Wayne, W.J., 1956, Thickness of drift and bedrock physiography of Indiana north of the Wisconsin glacial boundary: Bloomington, Indiana Geological Survey Report of Progress no. 7, 70 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1988—543-952/62144