A DIGITAL-COMPUTER MODEL OF THE BIG SIOUX AQUIFER IN MINNEHAHA COUNTY, SOUTH DAKOTA

By Neil C. Koch

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

For readers who may prefer to use metric units rather than inch-pound units, the conversion factors for the terms in this report are listed below:

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	1233.	cubic meter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	3.785	liter
million gallons per day (Mgal/d)	2.629	cubic meter per minute
gallon per day per square foot $(gal/d)/ft^2)$	0.041	meter per day
inch (in)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

DEFINITIONS

The geologic and hydrologic terms pertinent to this report are defined as follows:

Alluvium.--A general term for clay, silt, sand, gravel, or similar unconsolidated detrital material deposited during comparatively recent geologic time by a stream.

Aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow.--Sustained streamflow, consists mainly of ground-water discharge.

Drift.--A collective term applied to all rock material (clay, sand, gravel, and boulders) transported and deposited by glacial ice or meltwater issuing therefrom.

Evapotranspiration.--Water discharged to the atmosphere by evaporation from water surfaces and moist soil and by plant transpiration.

Ground water.--That part of subsurface water that is in the saturated zone.

Hydraulic conductivity.--The rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient at the prevailing kinematic viscosity.

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

Outwash.--A general term for silt, clay, sand, gravel, or boulders that have been washed, sorted, and subsequently deposited by water from melting glacial ice.

Potentiometric surface.--A surface that is defined by the levels to which water will rise in tightly cased wells.

Saturated zone.--Zone in which all voids are ideally filled with water. The water table is the upper limit of this zone, and the water in it is under pressure equal to or greater than atmospheric.

Specific yield.--The ratio of (1) the volume of water which saturated rock or soil will yield by gravity to (2) the volume of the rock or soil.

Steady-state flow.--When at any point in a flow field the magnitude and direction of the flow velocity as well as the hydraulic head are constant with time.

Storage coefficient.--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. In an unconfined aquifer, it is virtually equal to the specific yield.

Till.--An unsorted, unstratified mixture of clay, silt, sand, gravel, and boulders deposited by a glacier.

Transient flow.--When at any point in a flow field the magnitude or direction of the flow velocity changes with time.

Transmissivity.--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Water table.--That surface in an unconfined water body at which the pressure is atmospheric. Generally this is the upper surface of the zone of saturation, except where the surface is within relatively impermeable deposits or rocks.

A DIGITAL-COMPUTER MODEL OF THE BIG SIOUX

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ABSTRACT

The Big Sioux aquifer in the study area is a 36-square-mile, water-table aquifer hydraulically connected to the Big Sioux River. The aquifer commonly ranges from 20 to 50 feet in thickness, contains about 100,000 acre-feet of water in storage, and is bounded by relatively impermeable quartzite at Dell Rapids on the north and at Sioux Falls on the south.

Average annual water levels in the Big Sioux aquifer, average recharge, and average base-flow discharge in the Big Sioux River at Cliff Avenue, Sioux Falls, from 1970 through 1979 were used in the model. The model simulated water levels averaged 0.5 foot higher than the measured water levels in 50 wells.

The model was calibrated for transient conditions by simulating water levels and base flow for 1976. The water levels in 15 observation wells declined an average of 3.24 feet during 1976. The individual declines varied from 2.1 to 4.8 feet. The average difference between measured and computer-simulated water levels for these observation wells varied by month from 0.38 to 0.86 feet. The average of these monthly average differences for 1976 was 0.67 feet.

The calibrated model was used to simulate the effects of three hypothetical hydrologic situations. The first situation consisted of using 1976 monthly pumping rates, recharge, and evapotranspiration but having the Big Sioux River dry. Monthly pumping rates for 16 months beginning with October 1976 were used; individual monthly pumping rates were reused as needed. Storage started to be depleted in a node during the 6th month. During the 16th month the pumping rate had to be decreased by 40 percent from the actual pumping rate in order for the model to complete the monthly simulation without the storage being depleted at a node.

The second simulation consisted of a pumping rate of 44.4 cubic feet per second from 60 wells spaced throughout the aquifer under 1976 recharge, evapotranspiration, and stream-discharge conditions. More water was removed from storage and the river compared to the volume removed using the historic 1976 monthly pumping rates. The results of this simulation were that the aquifer could supply the additional water under 1976 hydrologic conditions.

The third situation consisted of the same conditions as the second except that recharge was zero and the Big Sioux River was dry downstream from Renner. After 18 monthly simulations, the pumping rate was decreased by 44 percent, to prevent pumping wells from depleting the aquifer, and at that rate 63 percent of the water being pumped was being replaced by water from the river.

INTRODUCTION

The Big Sioux River basin has an area of about 9,000 mi^2 in eastern South Dakota, southwestern Minnesota, and northwestern Iowa (fig. 1). The basin is about 210 mi long and 65 mi wide. The Big Sioux aquifer, a major glacial-drift aquifer, extends most of the length of the basin along the Big Sioux River and its tributaries. The study area (36 mi^2 of the aquifer) extends from Dell Rapids on the north, where the aquifer pinches out on quartzite, downstream to the city of Sioux Falls where again the aquifer pinches out on the quartzite (fig. 2).

The water resources of the Big Sioux River basin are being developed at an ever-increasing rate. During 1980 the city of Sioux Falls pumped about 13.6 Mgal/d (15,200 acre-ft) from shallow wells completed in the Big Sioux aquifer. By 2000, water use is expected to double. Irrigation and rural-water systems have been developed in the study area. The Big Sioux River is hydraulically connected with the Big Sioux aquifer. Lack of knowledge about the river-aquifer system could lead to overdevelopment of the water resources in some areas. This potential overdevelopment, in addition to causing local water-supply problems, could affect surface-water users downstream.

This is the second such study of the Big Sioux aquifer, the first being in Brookings, Hamlin, and Deuel Counties (Koch, 1980). This study was conducted by the U.S. Geological Survey in cooperation with the East Dakota Conservancy Sub-District, the South Dakota Department of Water and Natural Resources, and Minnehaha County.

Purpose and Approach of Study

The purpose of this study was to develop a predictive model of the ground-water system for use as a management tool. The model will be used by State and local officials in evaluating the effects of alternative methods of controlling or developing the ground-water resources of the Big Sioux aquifer in Minnehaha County.

The approach was to gather sufficient hydrologic data to develop a digital model. A digital model is a computer program that solves mathematical equations describing ground-water flow. The model numerically simulates the flow of water through the aquifer. The use of such a model helps to improve the understanding of the physical system. Once the model is calibrated under transient conditions, it can be used to predict the response of the aquifer system to man-induced stresses such as pumping and natural stresses such as drought. New plans for irrigation and other forms of water use proposed by State and local officials can be tested by changing the rates and distribution of withdrawal in the model. Such computer-model predictions can be rapidly produced.

The report describes: (1) The general ground-water system; (2) the digital model and how it was used and modified to simulate equilibrium or steady-state conditions based on averages determined from data for 1970-79; (3) how the model was used and modified to simulate measured water-level changes and base flow during 1976; and (4) an evaluation of the effects of three hypothetical hydrologic situations.

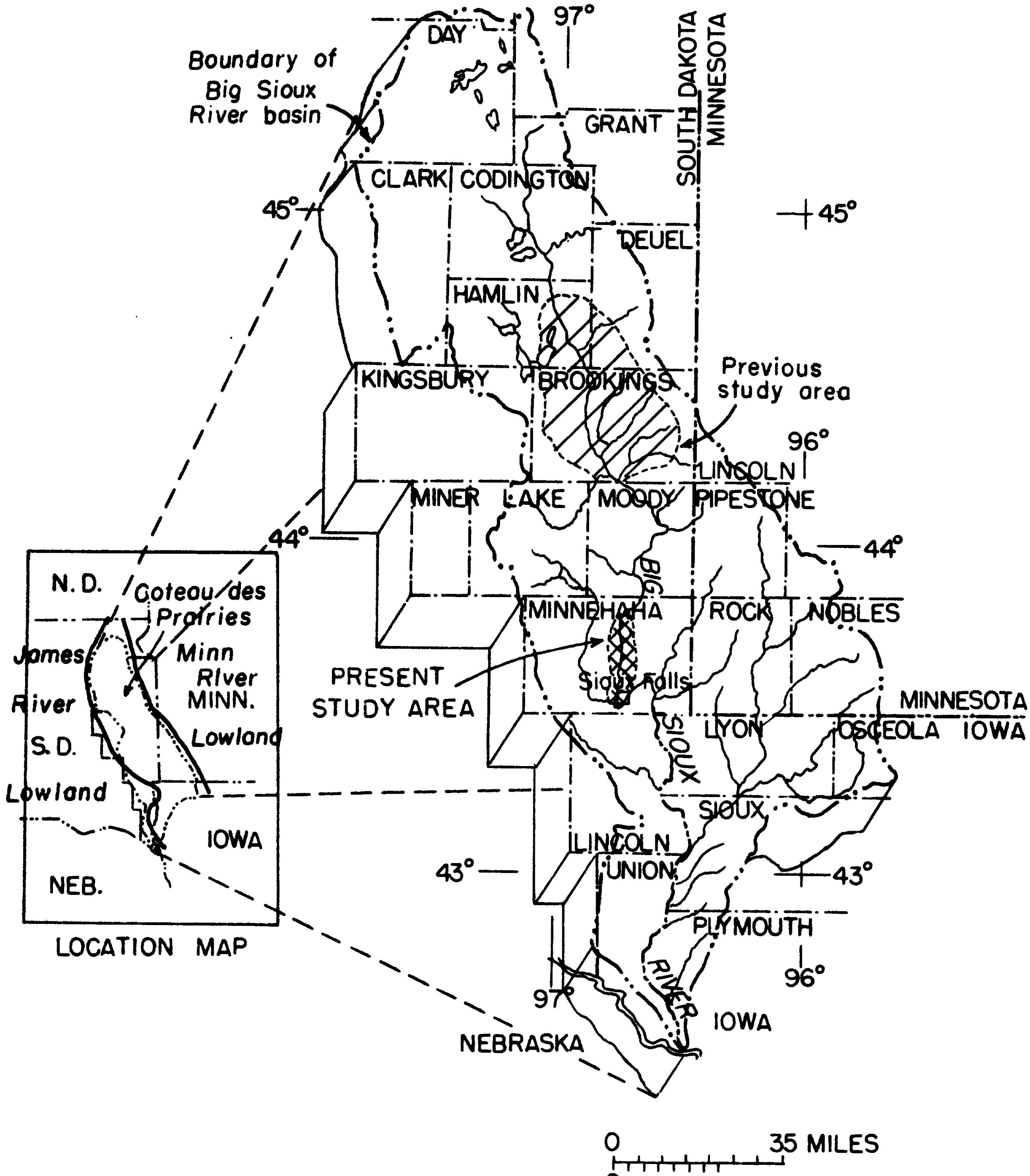


Figure 1.--Location of study area and Big Sioux River basin.

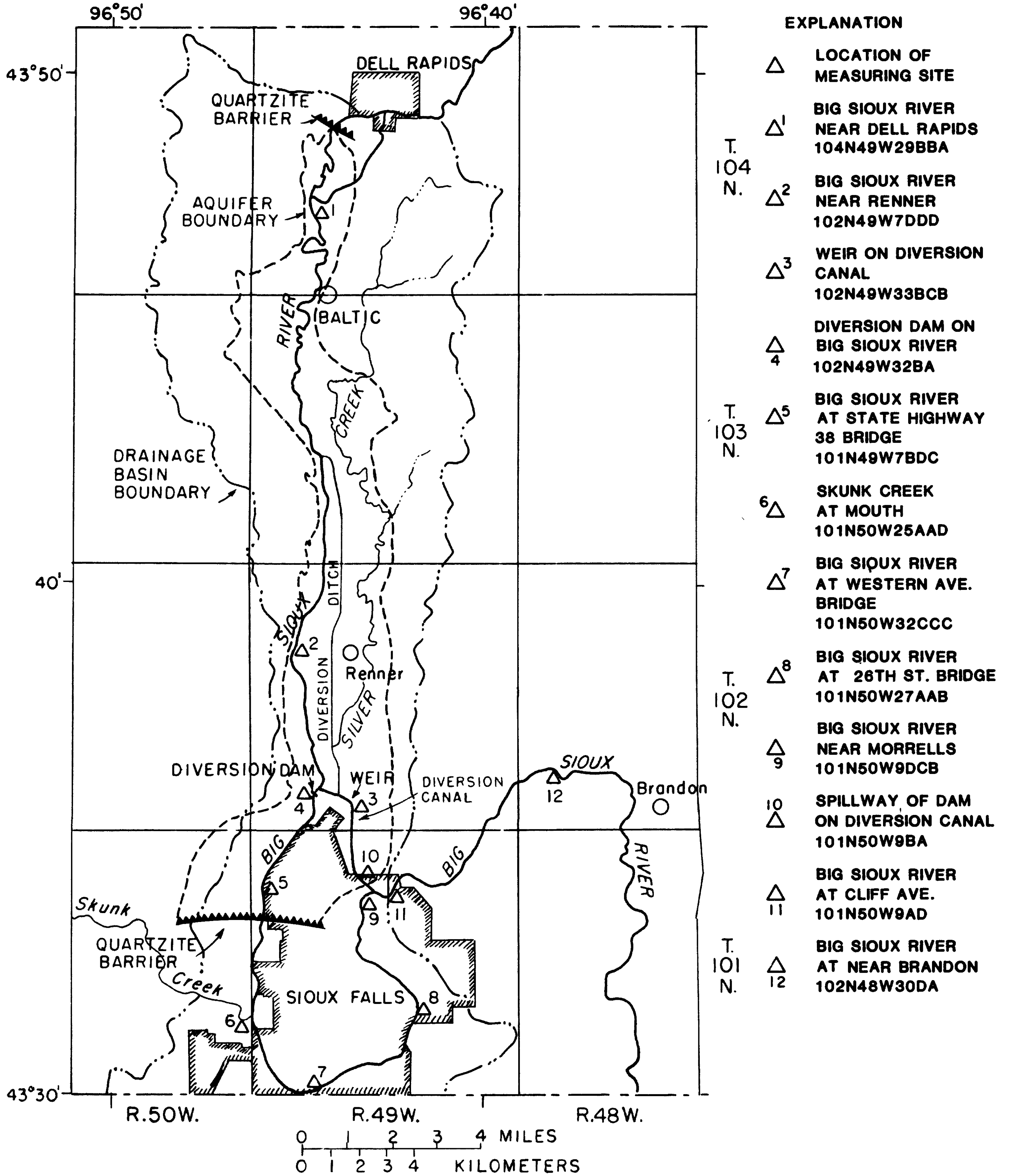


Figure 2.--Areal extent of the Big Sioux aquifer in the study area and location of discharge-measurement sites used to determine stream gain or loss.

Well-numbering System

The wells and test holes are numbered according to a system based on the Federal land-survey of eastern South Dakota (fig. 3).

Acknowledgments

Appreciation is expressed to the well drillers, sub-district, county, and municipal officials, and irrigators in the study area for their cooperation, help, and information provided. Special thanks are extended to Lester Hash, David Boone, and Douglas Moberly of the Sioux Falls Water Department who provided considerable water data.

GEOLOGY AND GEOGRAPHY

The entire project area is within the Coteau des Prairies, a highland plateau occurring between the Minnesota River lowland to the east and the James River lowland to the west. A topographic linearity nearly parallel to the scarp-like margins of the highland was formed by moraines developed along the lateral margins of two lobes of glacial ice held apart by the wedge-shaped bedrock highland between them.

The Big Sioux River is the only large stream that drains the Coteau des Prairies. The river's course, which approximates the central axis of the coteau, seems to have been developed during one of the glacial ages when glacial meltwater flowed southward, confined between the two glacier lobes that flanked the coteau. Most of the tributaries to the Big Sioux River flow from the east. Lakes, ponds, and marshes are more abundant west of the Big Sioux River than east of it.

The Coteau des Prairies is composed of bedrock formations and a mantle of unconsolidated glacial drift. In the study area the bedrock surface is the Sioux Quartzite of Precambrian age, which is overlain by as much as 200 ft of unconsolidated glacial drift.

The Big Sioux aquifer is an alluvium-mantled outwash which consists of silt, fine to coarse sand, and gravel. The aquifer overlies a relatively impermeable glacial till. The aquifer is bounded both on the north and on the south by the relatively impermeable Sioux Quartzite.

HYDROLOGIC SYSTEM

Water in the study area is found in surface streams, ponds, and in aquifers in glacial drift and fractures in the quartzite. Surface water, and the water in the glacial drift originate as precipitation in or north of the study area. The volume of precipitation, however, is much greater than the volume that runs off from the surface or is added to storage in surface- and ground-water reservoirs. Much of the precipitation is returned to the atmosphere by evapotranspiration, which decreases the volume of precipitation available for use in the area (table 1).

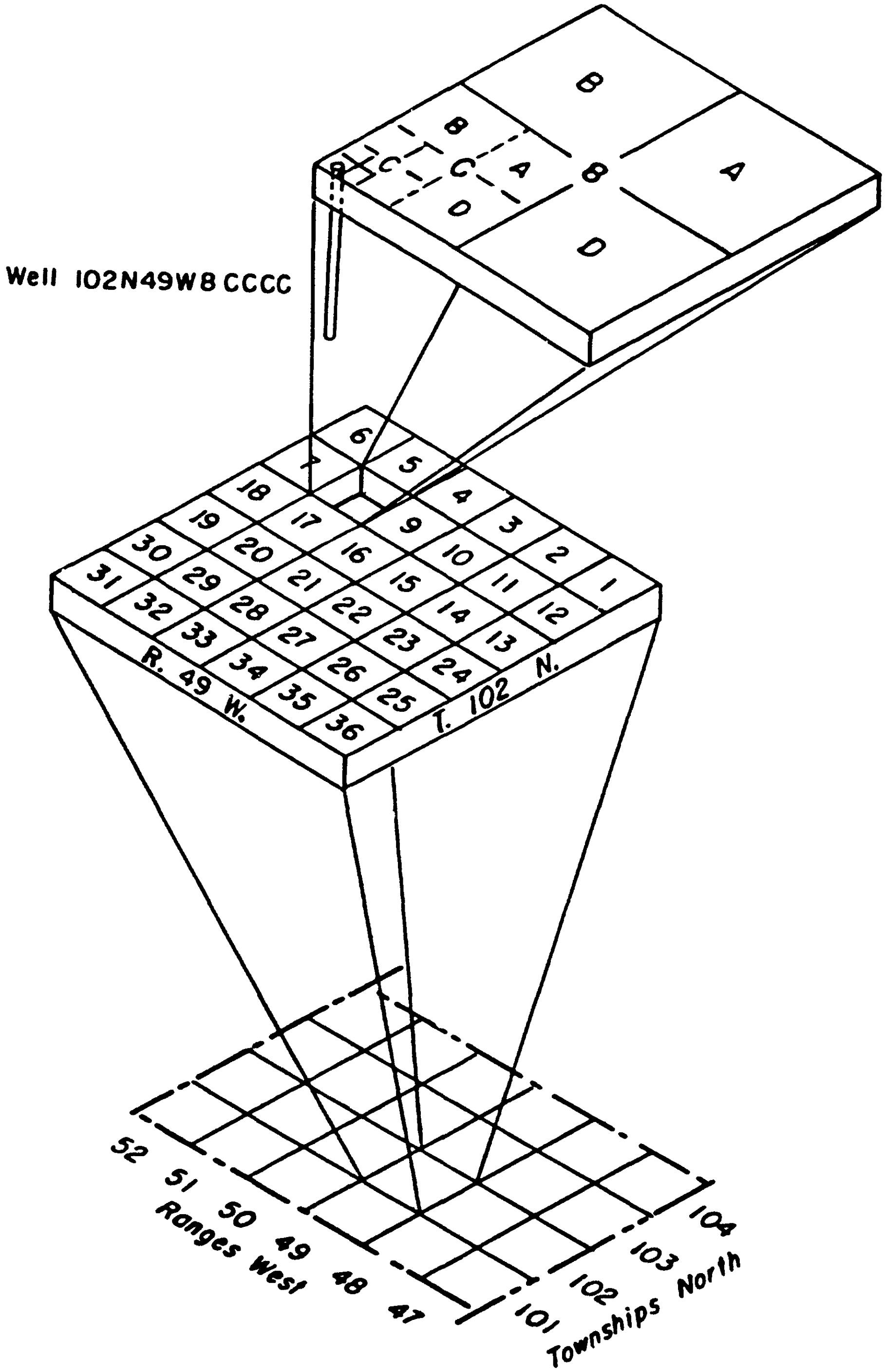


Figure 3.—Well-numbering diagram. The well number consists of township followed by "N," range followed by "W," and section number, followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2½-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same tract.

Table 1.--Hydrologic budget of the 130-square-mile drainage area between Dell Rapids and the Cliff Avenue streamflow-gaging station at Sioux Falls based on data from 1970-79

Budget component	Acre-feet per year	Percent
INFLOW		
Precipitation	174,400	45
Streamflow in Big Sioux River at Dell Rapids	176,800	45
Streamflow in Skunk Creek at Sioux Falls	27,200	7
Return flow from Sioux Falls water treatment plant to Big Sioux River	10,200	3
Total inflow	388,600	100
OUTFLOW		
Streamflow in Big Sioux River at Cliff Ave. in Sioux Falls	216,900 1/	56
Evapotranspiration	158,000	41
Sioux Falls pumpage	13,500	3
Irrigation pumpage	200	0.05
Total outflow	388,600	100

1/ Includes gain along Big Sioux River of 2,700 acre-feet per year.

Normal precipitation in the study area is about 25 inches (174,400 acre-ft) annually in the 130-mi^2 drainage area. Of this, about 2,700 acre-ft leaves the area as streamflow gain and 13,700 acre-ft is removed by pumpage. The remaining 158,000 acre-ft is used by vegetation and evaporated. By far the largest volume is assumed to leave the area by evapotranspiration.

The major shallow aquifer in the study area is a part of the Big Sioux aquifer which underlies the Big Sioux River valley. This 36-mi^2 part of the water-table aquifer commonly ranges from 20 to 50 ft in thickness and contains about 100,000 acre-ft of water in storage.

Recharge to the Big Sioux aquifer in the study area is by infiltration of precipitation, and seepage from the Big Sioux River. Natural discharge is by evapotranspiration and seepage to the Big Sioux River.

WATER-LEVEL FLUCTUATIONS

Ground-water levels fluctuate seasonally in response to changes in recharge or discharge (fig. 4). Water levels rise during the spring and early summer when recharge from percolation of snowmelt and spring rains is greater than discharge by pumping, subsurface outflow, and evapotranspiration. Conversely, water levels decline from mid-summer to fall or mid-winter when discharge is greater than recharge.

The volume of recharge and discharge represented by water-level fluctuations can be estimated if the physical properties of the aquifer are known. The volume of water associated with a change in water level can be determined by multiplying the specific yield of the aquifer by the water-level change. For example, the water-level fluctuations in well 102N49W32DBAC (fig. 4) show a maximum fluctuation of about 12 ft for the period of record and an average annual fluctuation of about 4.5 ft. The average annual fluctuation in 18 observation wells is 4.2 ft. Based on an estimated specific yield of 20 percent, the average annual fluctuation of 4.2 ft amounts to 10.1 inches of water. In the 36-mi^2 aquifer this is a storage change of 19,400 acre-ft.

AQUIFER CHARACTERISTICS

Aquifer Thickness

Thickness of sand and gravel in the aquifer is shown in figure 5. The saturated thickness of a water-table aquifer is a critical factor because it decreases in response to pumping, thus decreasing the yield from the aquifer. On the basis of well data, the aquifer ranges in thickness from 4 to 48 ft. The greatest measured thickness is near the weir on the diversion canal.

Transmissive and Storage Characteristics

The hydrologic characteristics of the aquifer can be determined from aquifer tests and model calibration. Transmissivity, the product of hydraulic conductivity and saturated aquifer thickness, is a measure of the capacity of an aquifer to transmit water. In general, the larger the transmissivity the smaller the drawdown will be for any given pumping rate. Storage coefficient is a measure of the capacity of an aquifer to store and release water.

GROUND-WATER AND SURFACE-WATER RELATIONSHIPS

Water in the Big Sioux aquifer is in hydraulic connection with the Big Sioux River in the study area. Jorgensen and Ackroyd (1973) determined from three aquifer tests that streambed infiltration ranged from 0.5 to 1.0 ft/d (4 to 7.4 (gal/d)/ft^2). This rapid rate of streambed infiltration of the Big Sioux River can be maintained where the streambed is naturally scoured annually during spring runoff. Where the river is dammed, fine sediment is deposited on the streambed (fig. 2), which restricts surface-water recharge to the aquifer and discharge from aquifer to stream. The weir on the diversion canal also traps fine sediment along the diversion canal. The fine sediment can be removed only by dredging.

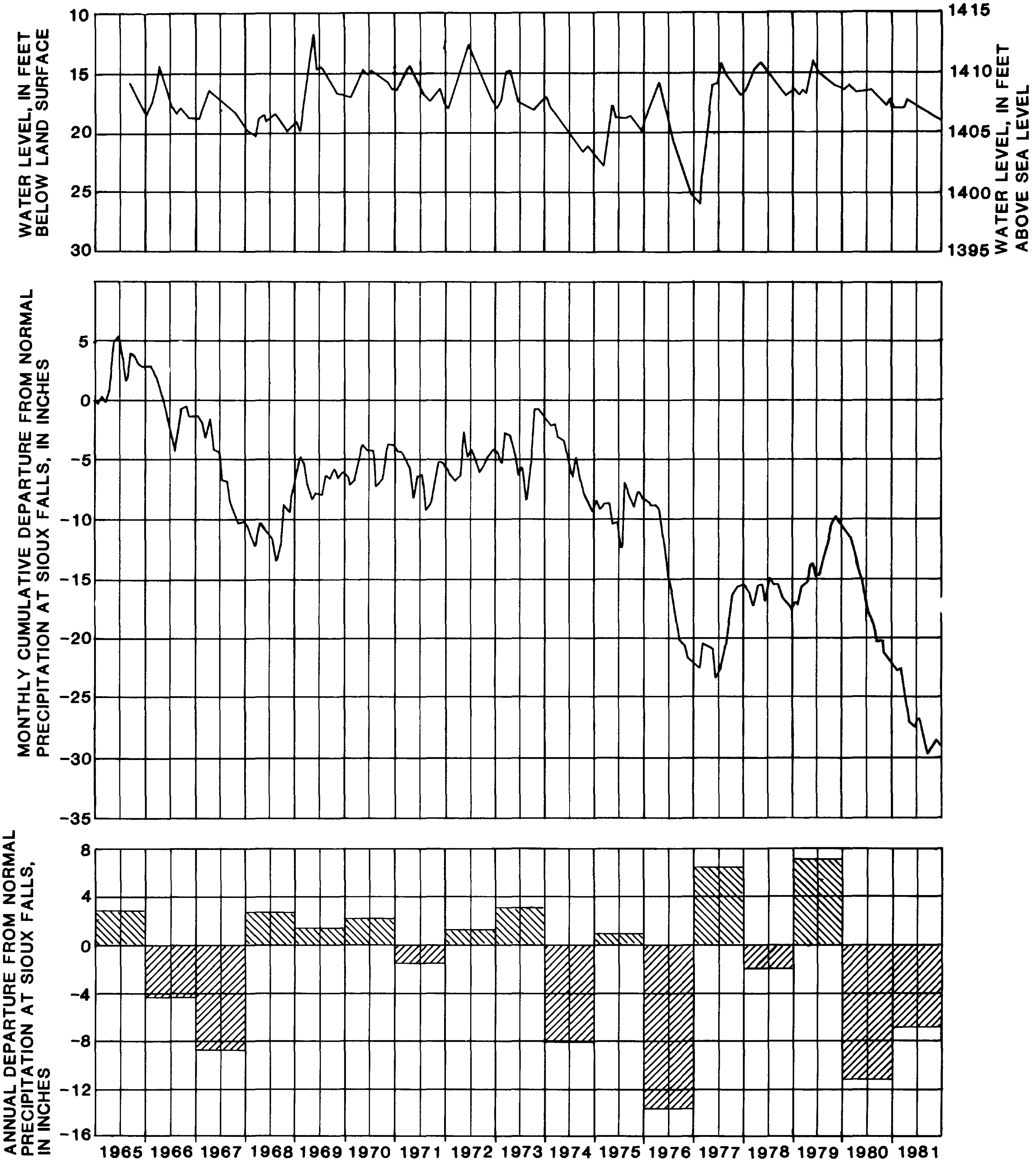
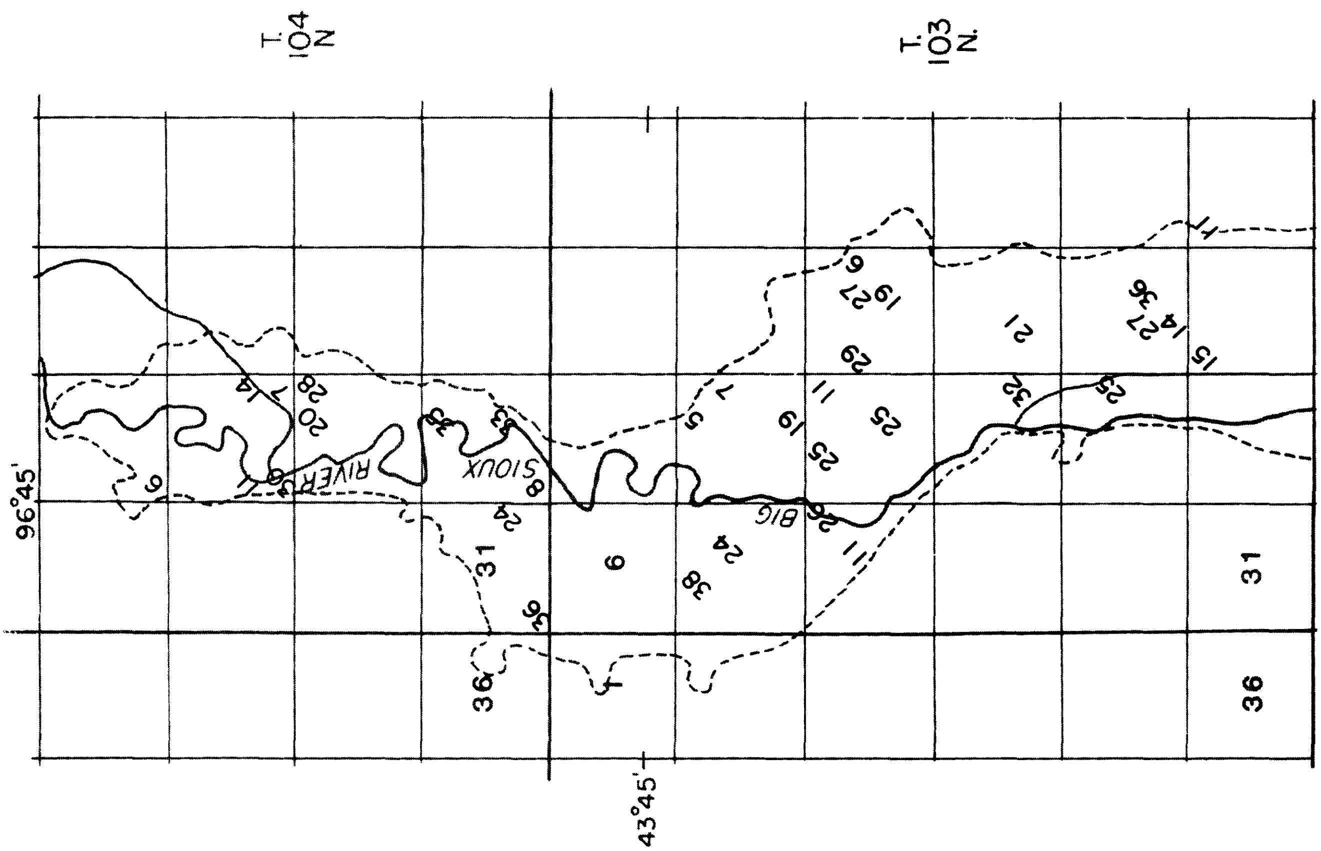


Figure 4.--Water-level fluctuations in well 102N49W32DBAC and monthly cumulative departure from normal precipitation and annual departure at Sioux Falls. (Base period for normal precipitation, 1931-60.)


T. 104 N.
T. 103 N.
96°45'
43°45'
BIG SIOUX RIVER

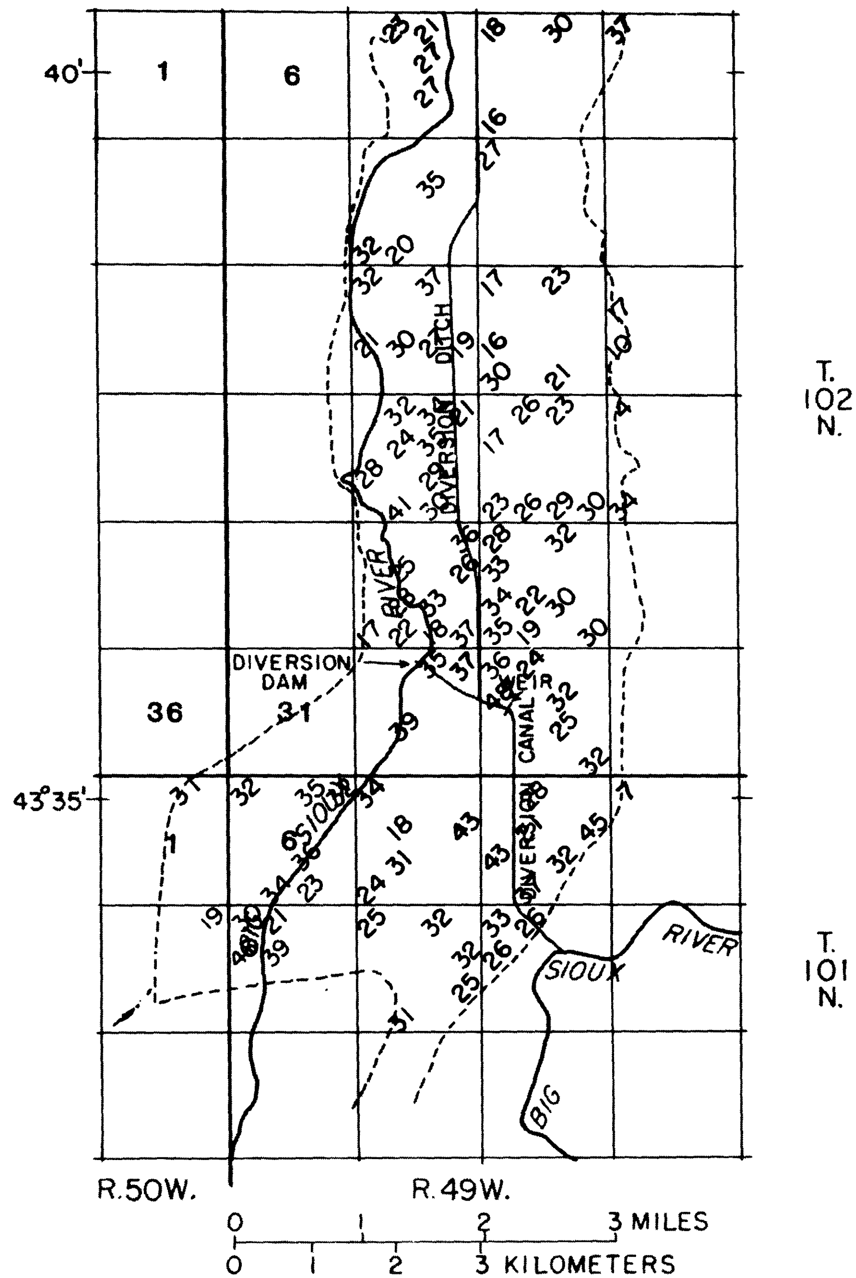


Figure 5.--Thickness of sand and gravel in the Big Sioux aquifer. Number is known thickness in feet from well data.

In general the Big Sioux River between Dell Rapids and Renner (site 2, fig. 2) receives more water from the aquifer than is discharged to the aquifer. Conversely the Big Sioux River between Renner and the State Highway 38 bridge (site 5, fig. 2) discharges more water to the aquifer than it receives from the aquifer (Jorgensen and Ackroyd, 1973). In this area the stream is in the vicinity of the Sioux Falls well field (fig. 10). The water table has been lowered in the well field so that water moves from the stream to the aquifer. Seven low-flow seepage studies, three during the fall, two during late winter, and two during spring and early summer showed that at the time of five of these studies, there were stream gains between Dell Rapids and Renner and stream losses between Renner and the State Highway 38 bridge (fig. 2). During low flow, stream gain between Dell Rapids and Renner ranged from 10 to 26 percent of the streamflow (table 2), whereas the stream loss between Renner and the State Highway 38 bridge ranged from 61 to 95 percent of the streamflow.

The average annual base flow in the Big Sioux River between Dell Rapids and Cliff Ave. in Sioux Falls is 19 ft^3/s (13,700 acre-ft), based on streamflow records from 1970-79 (fig. 6). Of that volume, 14.1 ft^3/s (10,200 acre-ft) is treated water from the city of Sioux Falls which flows into the river. The remaining 4.9 ft^3/s (3,500 acre-ft) between Dell Rapids and Cliff Ave. is streamflow gain from ground-water and overland runoff.

The cumulative-stream-gain-or-loss graph (fig. 6) also may be used as a tool to show whether stream gain or loss is apparent or real (Koch, 1970). The stream loss is apparent during parts of 1970, 1972, 1978, and 1979. That is, during the 1 or 2 months after the month having the stream loss there will be a stream gain equaling the loss. The apparent gain or loss probably is the result of travel time in that a large volume of water passes only the upstream gaging station in the latter part of one month and does not pass the downstream gage until the following month. Longer periods of apparent gain or loss could be the result of bank storage. Conversely, if the months after a stream loss do not show an equal stream gain such as during 1973, 1974, 1975, 1976, and 1977, then the stream loss is real. The real stream loss is probably the result of the aquifer being recharged by the river during spring high flows. The large stream loss during the spring of 1973 is probably not as great as shown in figure 6. Streamflow records were incomplete for that period. Stream gains ranged from 7,200 to 12,700 acre-ft per year from 1970-77. Stream gains were 24,200 for 1978 and 36,400 for 1979 probably the result of greater-than-normal precipitation during 1977 and 1979.

DIGITAL MODEL

A digital model of an aquifer system solves mathematical equations describing ground-water flow. The two-dimensional model developed by Trescott, Pinder, and Larson (1976) used in this study uses a digital computer for numerically solving the partial differential equations for ground-water flow using finite-difference methods to calculate approximate solutions.

Table 2.—Streamflow discharges and gain or loss in the Big Sioux River

Site no.[1/]	Measurement sites	11-6-64			1-11-67			2-23-67			4-25-67			6-14-67			11-14-69			11-12-80		
		Discharge (cubic feet per second)[2/]	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge[3/]	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge	Discharge (cubic feet per second)	Gain (+) or loss (-) (cubic feet per second)	Percent of gain or loss of total discharge
1	Dell Rapids	19	—	—	7.8	—	—	10	—	—	175	—	—	110	—	—	73	—	—	37	—	—
2	Renner	22	+3	16	9.8	+2	26	11	+1	10	184	+9	5	114	+4	4	83	+10	14	32	-5	14
3	Weir on diverson canal	16	—	—	.35	—	—	.46	—	—	3.2	—	—	2.5	—	—	57	—	—	23	—	—
4	Dam on Big Sioux River	.68	—	—	4.7	—	—	6.5	—	—	177	—	—	114	—	—	5.9	—	—	5.4	—	—
	Diversion canal plus Dam	16.68	-5.3	24	5.05	-4.8	49	6.96	-4	36	180	-4	2	116	+2	2	62.9	-20	24	28.4	-3.6	11
5	State Highway 38 bridge	—	—	—	1.6	-3.1	66	.57	-5.9	91	163	-14	8	111	-3	3	.13	-5.8	98	3.5	-1.9	35
6	Mouth of Skunk Creek	.3	—	—	2.0	—	—	4	—	—	17	—	—	5.1	—	—	4	—	—	1.7	—	—
7	Western Ave. bridge	—	—	—	—	—	—	—	—	—	192	+12	7	121	+4.9	4	—	—	—	—	—	—
8	26th St. bridge	—	—	—	—	—	—	—	—	—	182	-10	5	126	+5	4	—	—	—	—	—	—
9	Morrells	—	—	—	6.4	+2.8	78	4.1	-0.47	10	182	—	—	110	-16	13	—	—	—	—	—	—
10	Spillway of dam on diversion canal	—	—	—	0	—	—	0.	—	—	1.5	—	—	2.5	—	—	—	—	—	—	—	—
11	Cliff Ave.	—	—	—	—	—	—	—	—	—	196	+12	6	128	+16	12	—	—	—	55	+27[4/]	96
12	Brandon	31	+14	84	35	+29	453	12	+7.9	193	202	+6	3	134	+6	4	67	+5.9	9	—	—	—

1/ Number refers to site location in figure 2.

2/ Cubic feet per second X 724 = acre-feet per year.

3/ Value is percent gain or loss between the site with the percent value and the upstream site divided by discharge of upstream site.

4/ To determine gain for Cliff Ave. subtract discharge at diversion canal, State Highway 38, and Skunk Creek from discharge at Cliff Ave.

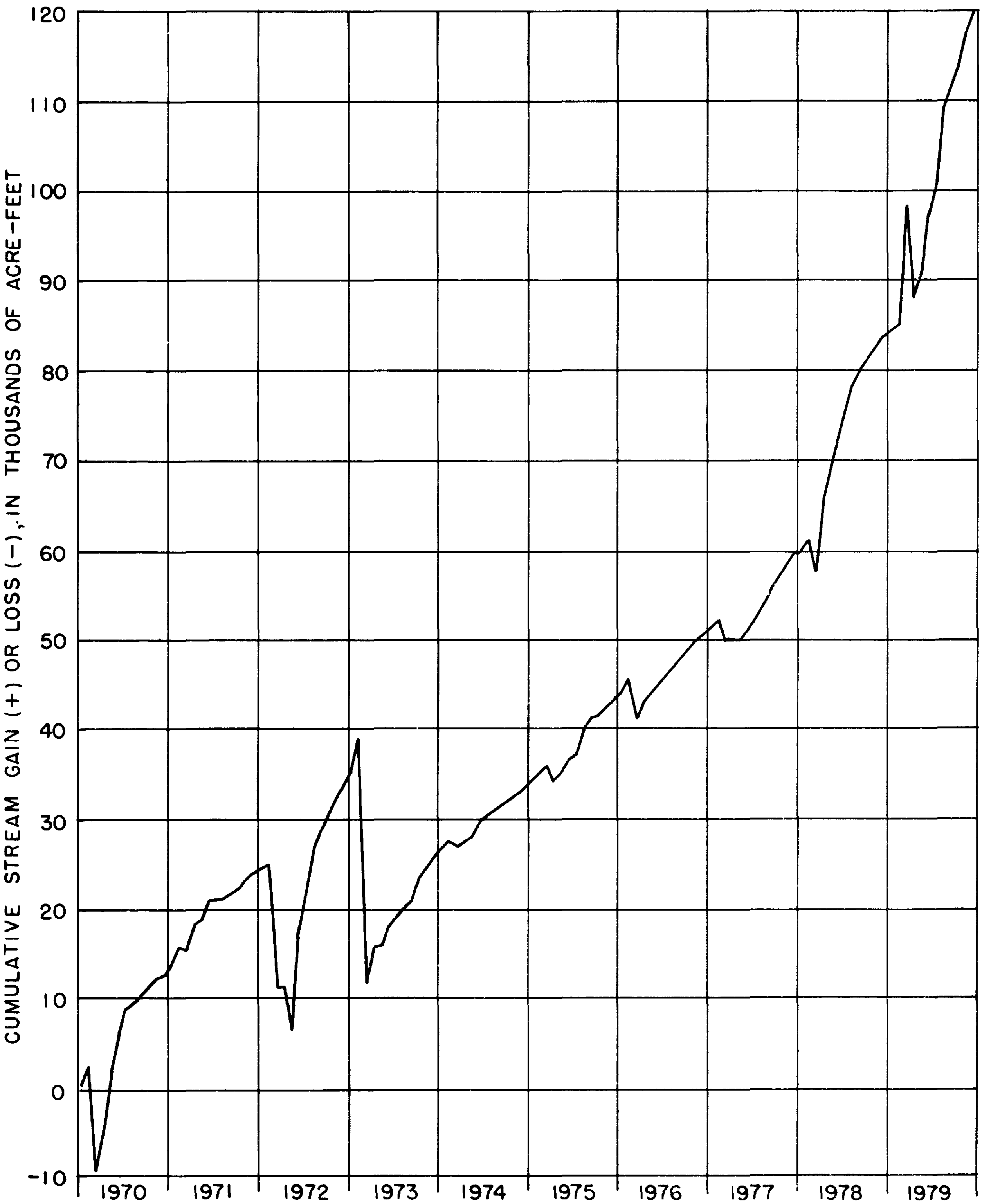


Figure 6.--Cumulative stream gain or loss in the Big Sioux River between Dell Rapids and Cliff Ave. streamflow-gaging station at Sioux Falls.

Model Development

A map of the project area was prepared showing the aquifer boundaries and stream locations (fig. 2). A 0.25-mi grid network was superimposed on the map (fig. 7). The network has 77 rows and 18 columns, a total of 585 cells overlying the aquifer. Each cell contains a node at its center. These nodes are points at which flow equations are evaluated even though the cell represents a volume of the aquifer through which flow is occurring. Data entered into the computer for each node are the altitude of the water table, the altitude of the bottom of the aquifer, the altitude of the land surface, the aquifer hydraulic conductivity, and the specific yield.

The model was developed based on existing hydrologic conditions. A number of simplifying assumptions were used in the model to make it possible to describe the aquifer mathematically.

The hydrologic assumptions used in the model of the Big Sioux aquifer are:

(1) The alluvium-mantled outwash aquifer is a single unconfined (water-table) aquifer.

(2) The aquifer is hydraulically connected to the Big Sioux River.

(3) The flow in the aquifer is horizontal.

(4) On the perimeter of and beneath the aquifer there are no-flow conditions.

(5) Recharge to the aquifer is from streamflow and infiltration of precipitation to the aquifer surface.

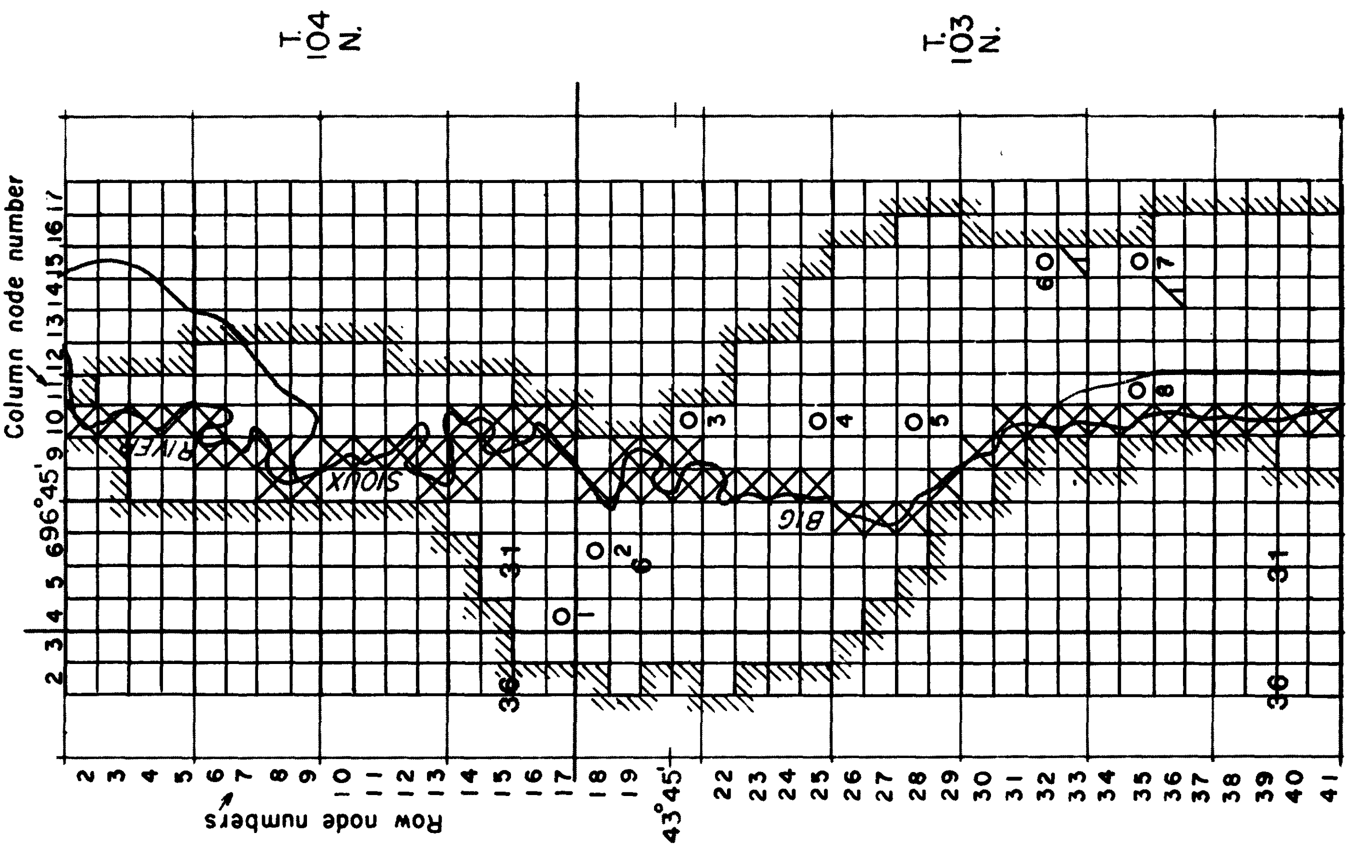
(6) Ground water is discharged by pumpage from wells, evapotranspiration, and flow to the Big Sioux River.

(7) The average stream stage remains constant throughout the steady-state simulation but under transient conditions, the stream stage is raised or lowered each month based on stream stage at Dell Rapids and the diversion dam. The constant hydraulic-head stream nodes are removed when the stream becomes dry.

(8) Evapotranspiration is a linear function of depth below land surface. Evapotranspiration is maximum at land surface and decreases linearly to zero at 5 ft below land surface.

(9) Return flow from irrigation is not modeled because the irrigation water applied is assumed to be entirely consumed by the crops.

(10) Transmissivity is hydraulic-head dependent.



T. 104 N.
T. 103 N.
Column node number
Row node numbers
96°45'
43°45'
BIG SIOUX RIVER

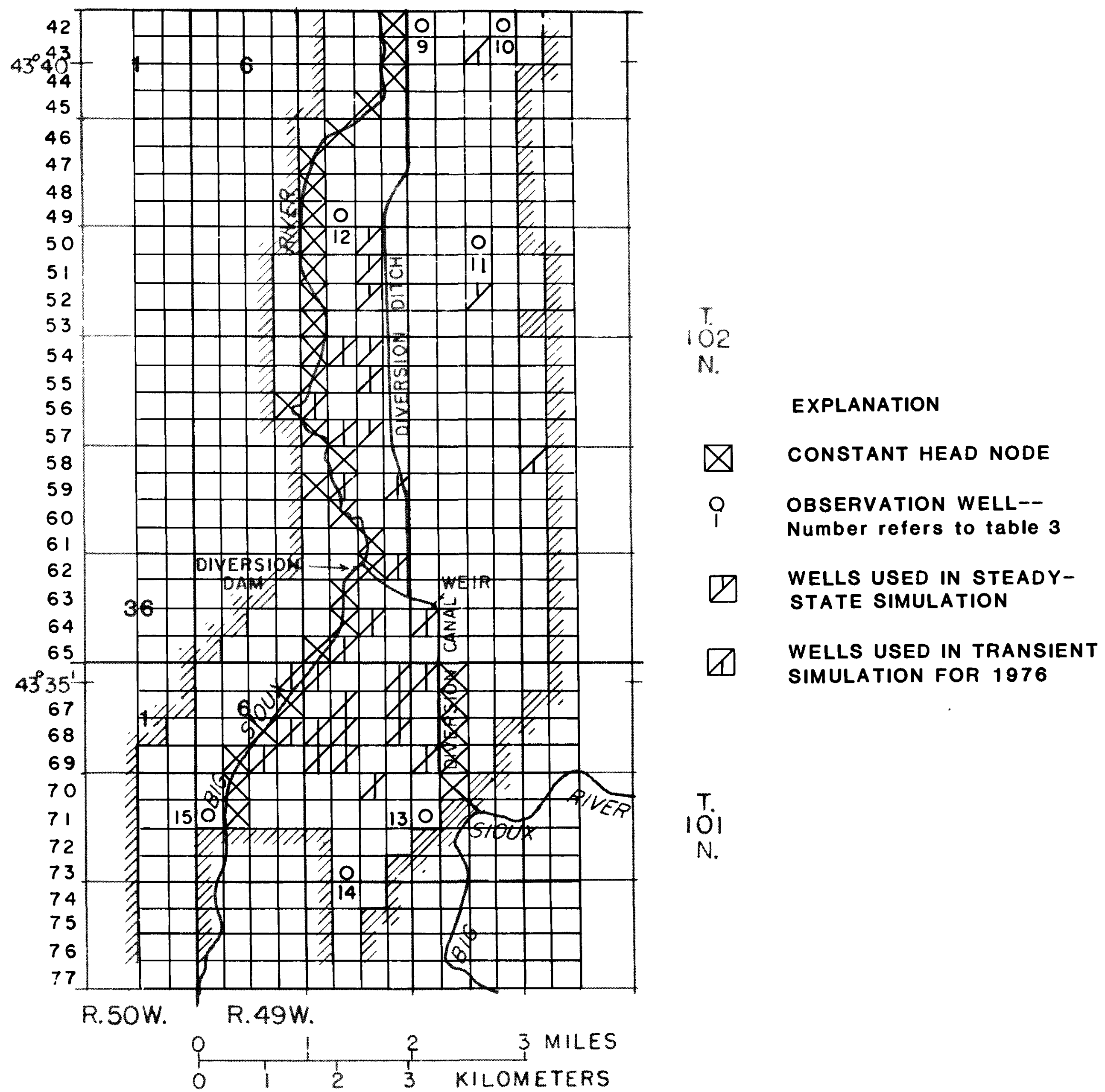


Figure 7.--Location of aquifer model area, pumping wells used in model simulations, and constant head nodes and observation wells used for calibration of the steady-state and transient simulations.

Calibration of the Equilibrium Model

The model was calibrated under equilibrium (steady-state) conditions before it was calibrated under transient conditions or used to predict the effects of development. Equilibrium conditions were assumed to be the average water levels from 1970 through 1979. The hydraulic-conductivity values ranged from 200 to 400 ft/d which is equivalent to the hydraulic conductivity of fine to coarse sand (Koch, 1980). Average pumpage was determined by using the 10-year average for municipal pumpage at Sioux Falls and irrigation pumpage (fig. 8). Altitude of the land surface was determined from topographic maps. Altitude of the bottom of the aquifer was determined using driller's logs (fig. 9). Evapotranspiration was assumed to be maximum (33 in/yr based on average annual lake evaporation) where ground-water levels were at the land surface, such as in lakes and streams. Depths greater than 5 ft were not used for evapotranspiration because these depths resulted in an unreasonably large stream loss because of increased flow from the stream to the aquifer. An average annual recharge rate of 7.6 in/yr was determined by totaling the amount of water-level rise from observation wells from 1967-78. Average annual recharge was then calculated using 18 observation wells. This value is conservative in that at certain times recharge may be less than discharge and the hydrograph will not show a water-level rise. Several modifications were made by changing hydraulic conductivity and recharge to obtain the best fit between computer-simulated water levels and measured water levels. The best fit (fig. 10) was obtained by decreasing the recharge rate by 9 percent to 6.9 in/yr and increasing the hydraulic conductivity by 100 ft/d in rows 1-55, and 50 ft/d in rows 56-77. This resulted in values for most nodes of 300 or 400 ft/d. These values are within the hydraulic conductivity range determined from driller's logs. Computer-simulated equilibrium conditions in the Big Sioux aquifer prior to ground-water withdrawals are shown in figure 11. Note that throughout most of the aquifer the pre-withdrawal water surface is within 1 or 2 ft of the steady-state water surface (fig. 10) except in the well field at Sioux Falls where the steady-state water surface is 6 to 9 ft below the pre-withdrawal water surface.

The accuracy of the steady-state model (fig. 10) was determined by comparing the absolute error between the altitude of the measured water levels and the altitude of the computer-simulated water levels. This was done by adding the differences from 50 wells, even if the computer-simulated value was higher or lower than the measured value, and dividing by the number of wells. The average absolute difference between the measured and simulated water levels was 0.8 ft. For 1970-79, on which the steady-state calibration was based, water levels in wells fluctuated a maximum of 11.6 ft. If all computer-simulated values that are higher than the measured values are added and all lower values are subtracted, the computer-simulated values averaged 0.5 ft higher than the measured values.

Comparison of measured and computer-simulated stream gain or loss between Dell Rapids and Cliff Ave. at Sioux Falls shows that there was a stream gain of 2,700 acre-ft/yr (3.7 ft^3/s) based on measured data (table 1), a stream loss of 2,600 acre-ft/yr (3.6 ft^3/s) based on computer-simulated data (p. 26), and a stream gain of 10,300 acre-ft/yr (14.2 ft^3/s) based on the same computer-simulated data without any pumpage (p. 27). Based on the calculated 5-day average (1970-79) of streamflow at Dell Rapids, Skunk Creek, and Cliff Ave., there was a stream gain of 13,800 acre-ft/yr (19 ft^3/s), however, because treated water from Sioux Falls was returned to the river upstream

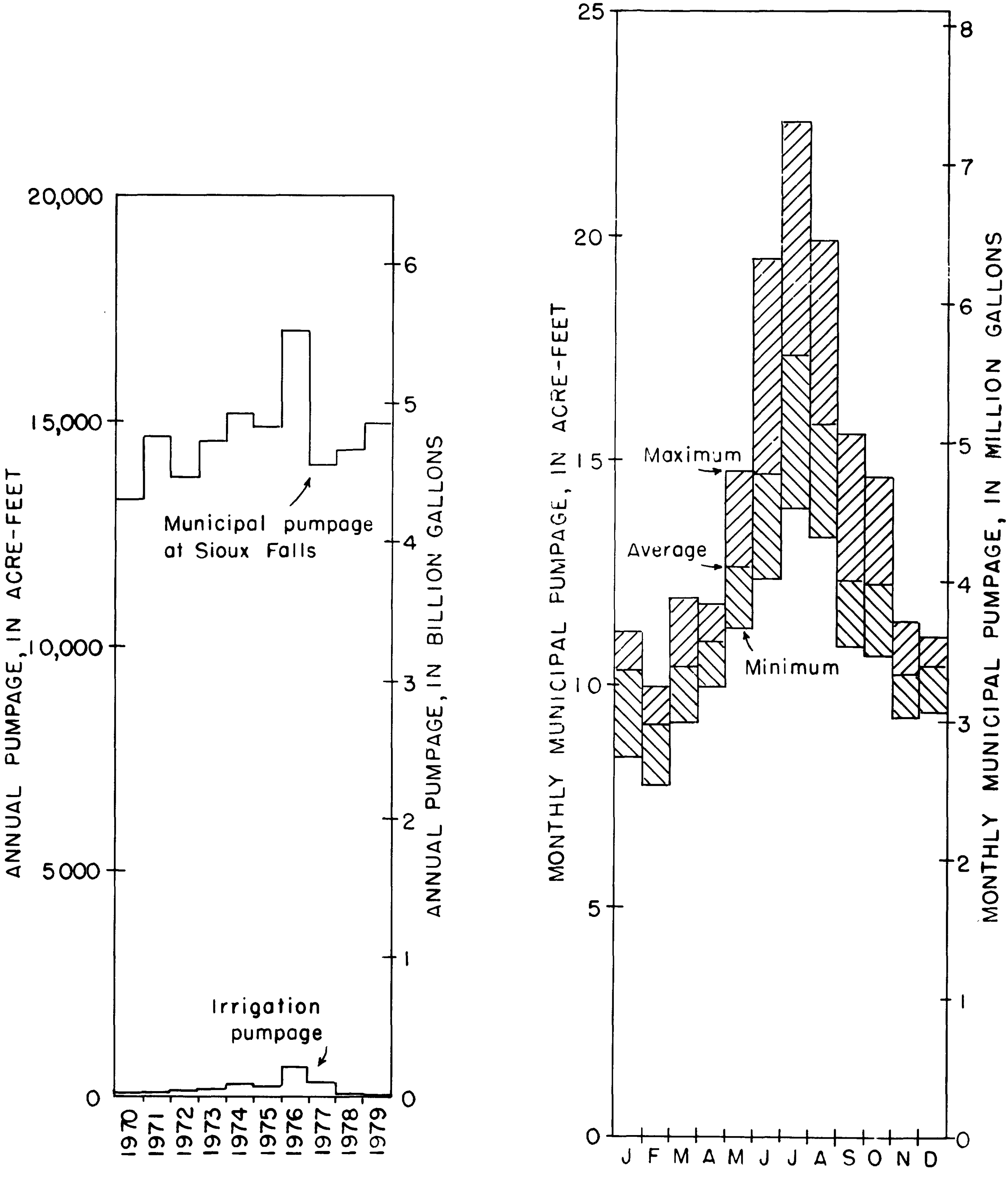
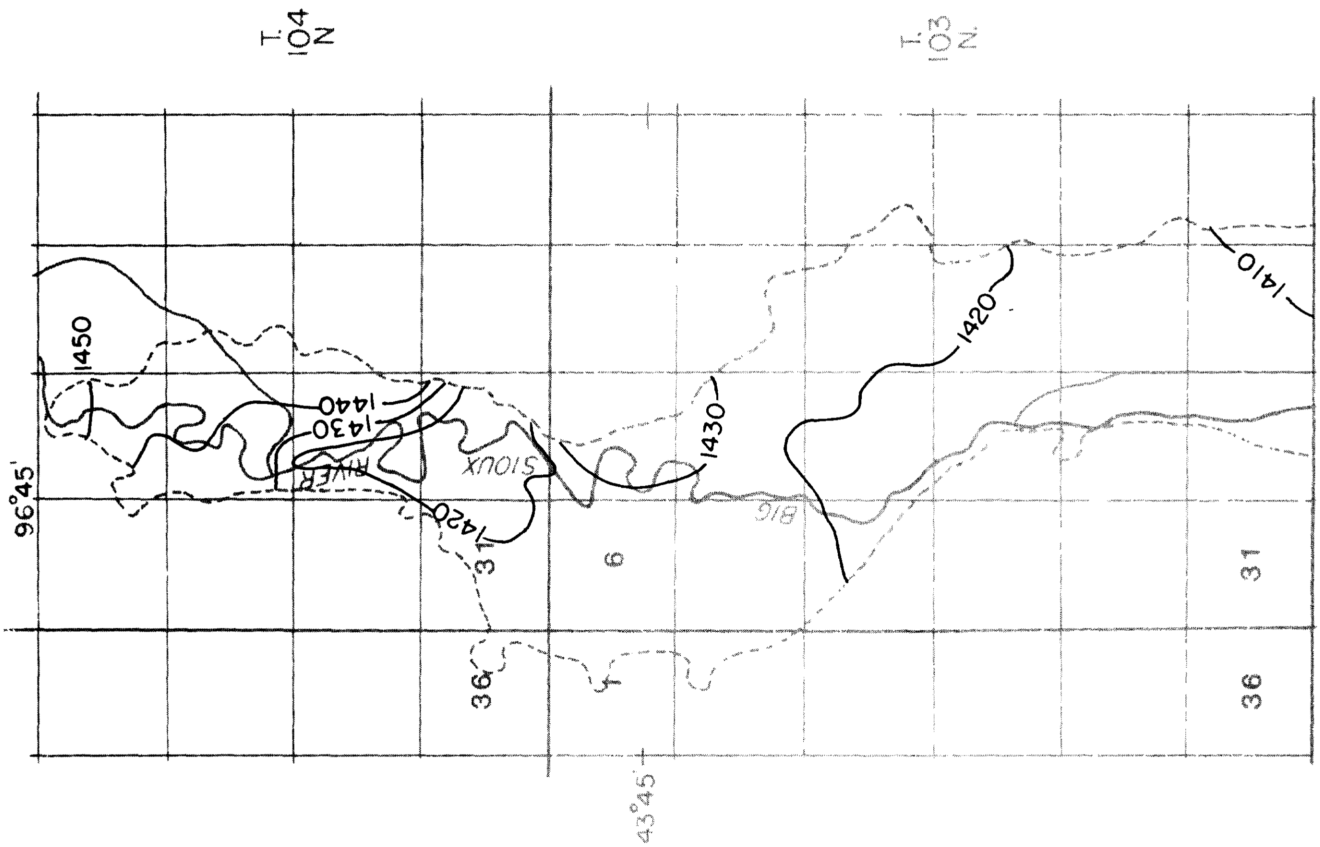


Figure 8. -- Annual and monthly maximum, minimum, and average municipal pumpage at Sioux Falls and annual irrigation pumpage from 1970-79.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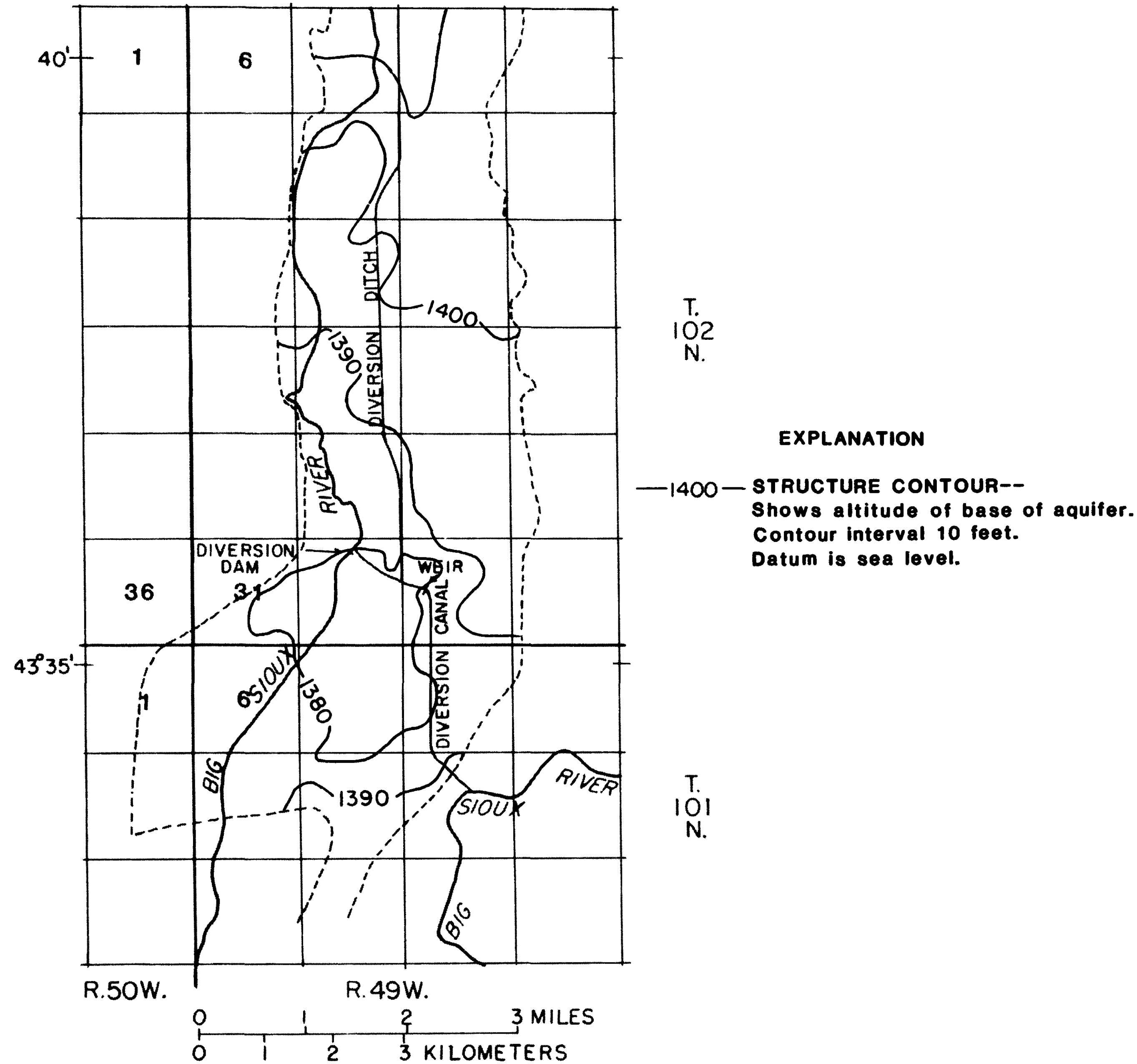
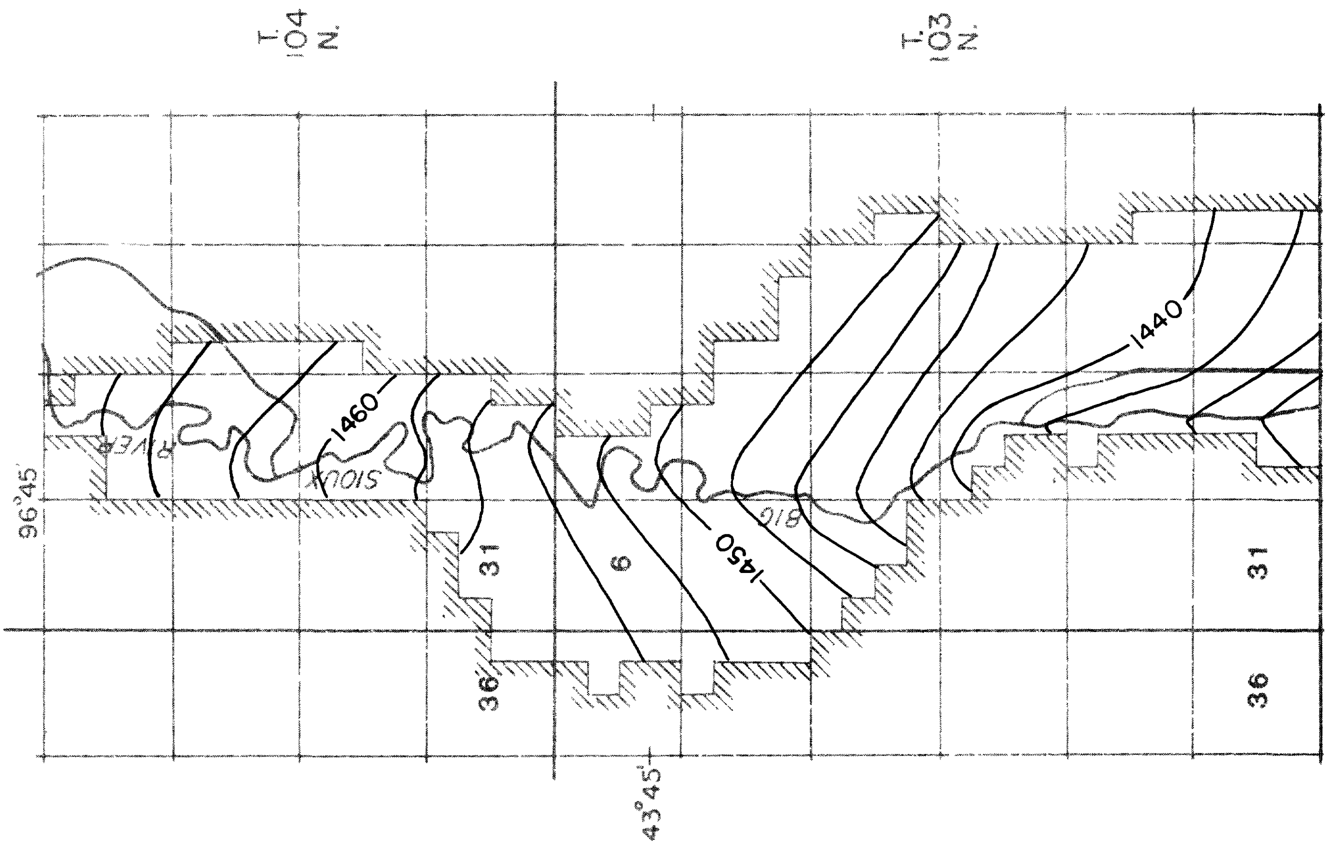


Figure 9.--Altitude of base of the Big Sioux aquifer.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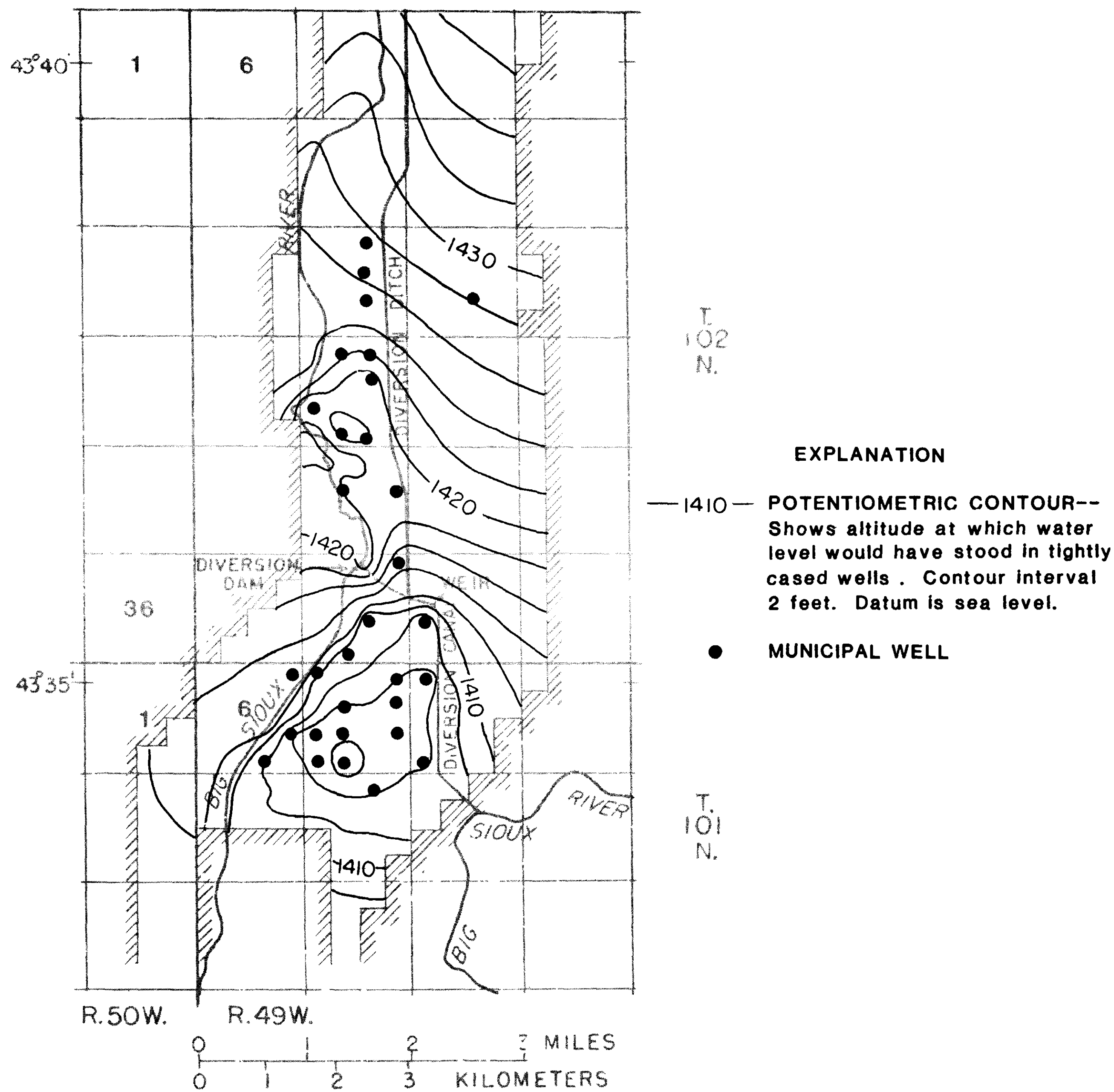
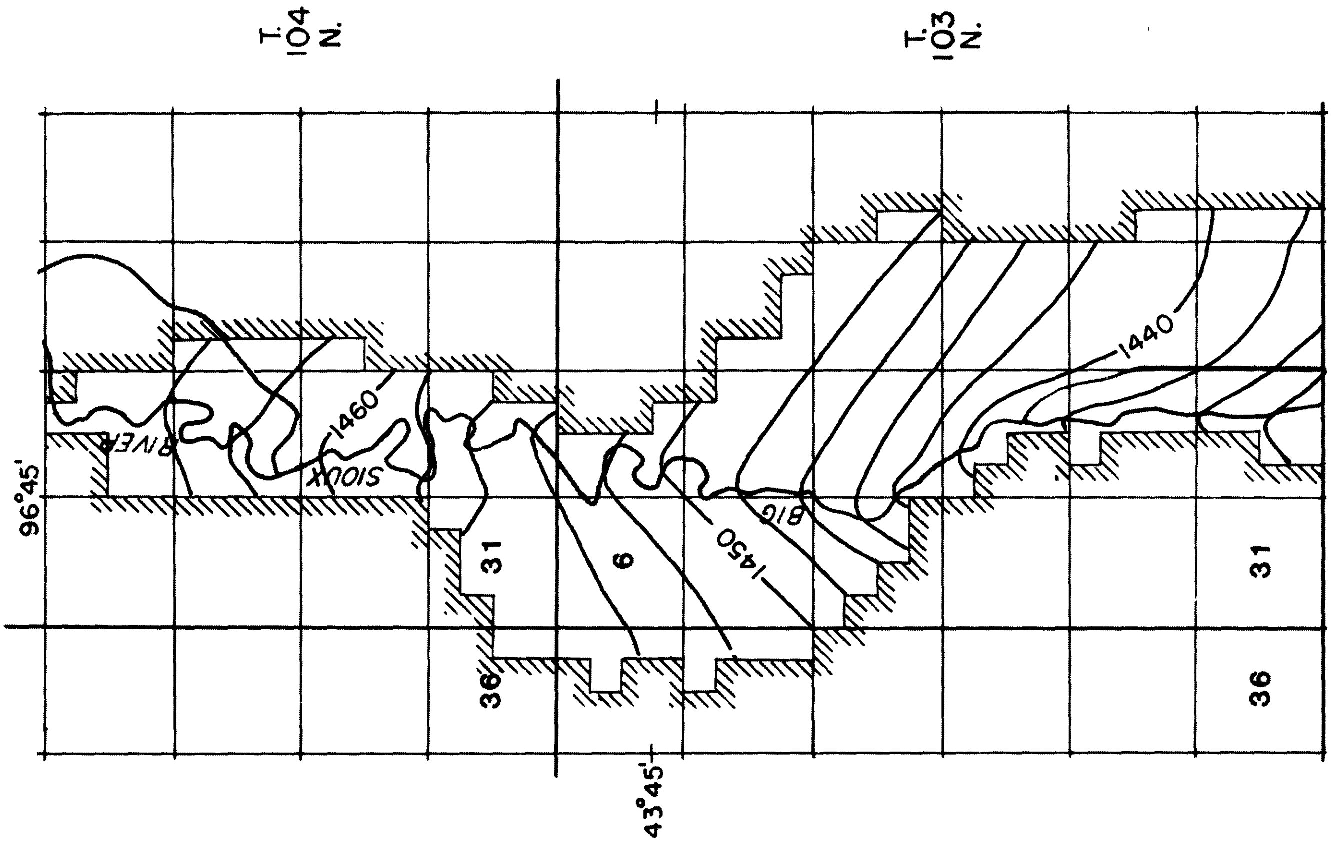


Figure 10.--Computer-simulated water levels under steady-state conditions based on average hydrologic conditions from 1970-79.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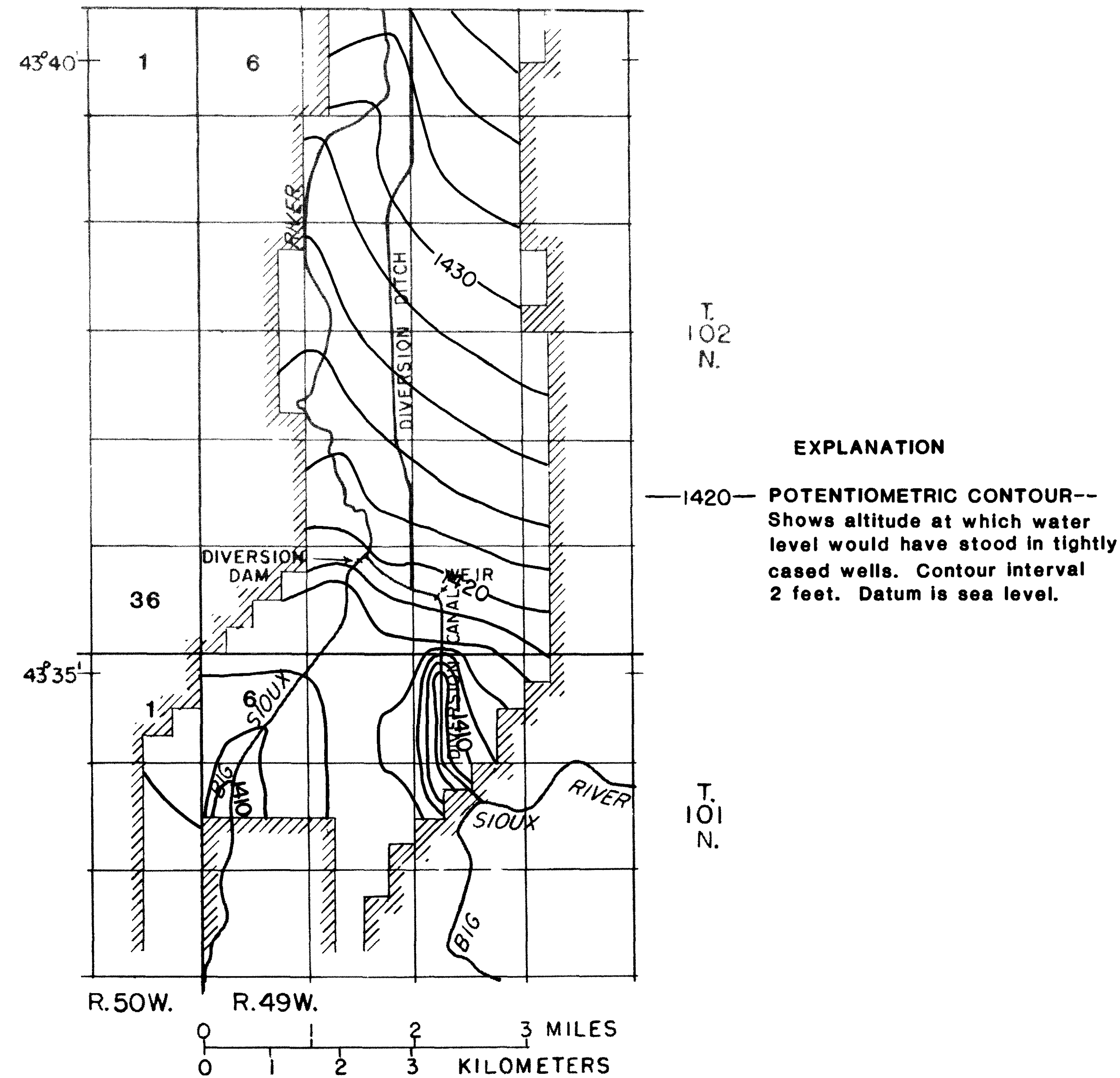


Figure 11.--Computer-simulated water levels under steady-state conditions prior to ground-water withdrawals.

from Cliff Ave., an adjustment was made to determine true stream gain or loss. Sioux Falls pumped an average (1970-79) of 13,500 acre-ft/yr (18.6 ft^3/s) (table 1) each year. Of that amount an estimated 25 percent (3,400 acre-ft/yr or 4.7 ft^3/s) was used for lawn irrigation and was not returned to the river, which leaves a 3,500 acre-ft/yr (4.9 ft^3/s) stream gain (see p. 12). These differences can't be compared for accuracy because the error in streamflow measurement (5 percent of the flow) is within the differences between the measured and computer-simulated values.

Simulated Hydrologic Budget

A hydrologic budget of computer-simulated flow rates at equilibrium associated with the various components of the Big Sioux aquifer for a model area of about 36 mi^2 are shown below:

Budget component	Flow rates, acre-feet per year	Percent
INFLOW		
Recharge to the aquifer from precipitation	11,600	53
Recharge to the aquifer from the stream	10,400	47
Total inflow	22,000	100
OUTFLOW		
Discharge from the aquifer to the stream	7,800	35
Evapotranspiration from the aquifer	600	3
Pumpage		
Sioux Falls	13,500	61
Irrigation	200	1
Total outflow	22,100	100

A hydrologic budget of computer-simulated flow rates at predevelopment (no pumpage) under equilibrium conditions is shown below. Note that compared to the previous budget which included ground-water pumpage, evapotranspiration was larger because the water levels were higher and recharge to the aquifer from streams was much smaller.

Budget component	Flow rates, acre-feet per year	Percent
INFLOW		
Recharge to the aquifer from precipitation	11,600	89
Recharge to the aquifer from the streams	1,400	11
Total inflow	13,000	100
OUTFLOW		
Discharge from the aquifer to the stream	11,700	90
Evapotranspiration from the aquifer	1,300	10
Total outflow	13,000	100

Calibration of the Transient Model

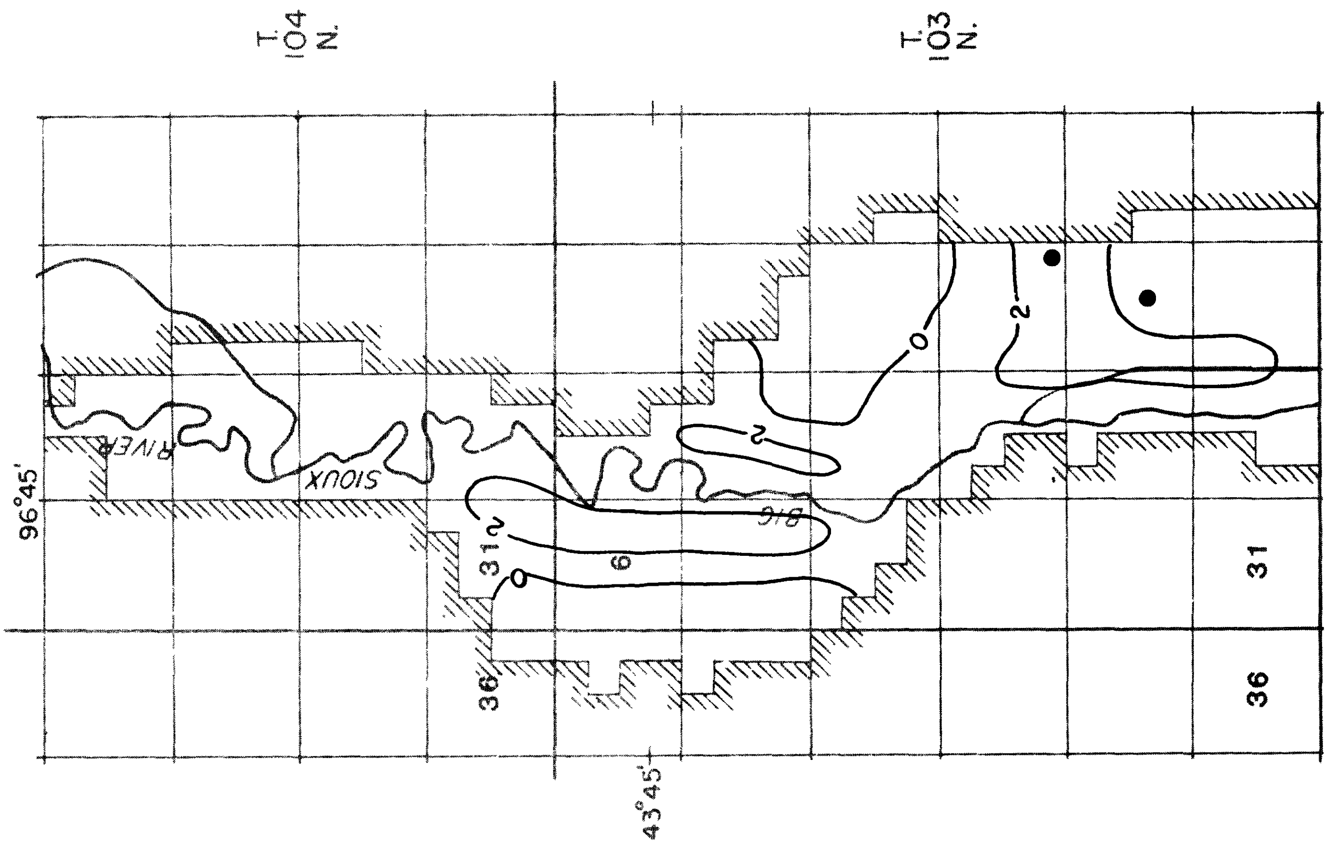
To use the digital model as a predictive tool, the model needs to be able to simulate past hydrologic conditions. Hydrologic conditions for each month during 1976 were used for verification of the model because a severe drought produced major water-level declines and the lack of precipitation enabled the transient calibration to be made without using recharge after May. The recharge values used from January through May 1976 were calculated based on averaging the rise in water level in 18 observation wells. A value of 20 percent was used for specific yield. Maximum evapotranspiration values were determined by using monthly pan-evaporation data from the National Weather Service at Sioux Falls. The January 1976 water levels were used as the starting hydraulic heads.

Water-level declines in the Big Sioux aquifer between January and December 1976 generally were less than 2 ft except in the Sioux Falls city well field where drawdowns were as much as 15 ft (fig. 12). Pumpage from the aquifer during 1976 was 17,500 acre-ft (5.66 billion gallons).

Measured water levels are compared with computer-simulated water levels in tables 3 and 4. Accuracy by observation well ranged from 43 to 97 percent (table 3). The 15 observation wells had an average accuracy during 1976 of 79 percent. Hydrographs of measured versus computer-simulated water level in three wells ranging in accuracy from 64 to 89 percent are shown in figure 13.

Table 3.--Comparison between changes in measured and computer-simulated water levels in 15 observation wells, 1976

Well number (fig. 7)	Local number	Location number	Change in water level, 1976: Measured value (feet)	Change in water level, 1976: Computer-simulated value (feet)	Percent difference between measured and computer-simulated value
1	S-24	104N49W31CCC	3.6	1.93	54
2	H-3	103N49W 6ABB	3.26	2.1	64
3	SPH-1	103N49W 5DCC	2.7	2.77	97
4	G-2	103N49W 8DCC	3.0	2.01	67
5	S-25	103N49W17DBB	2.6	2.25	87
6	SPF-3	103N49W21DABB	2.2	2.95	75
7	SPF-2	103N49W28ADD	3.3	2.95	89
8	SPF-1	103N49W29ADC	2.5	3.1	81
9	E-3	102N49W 4BBB	3.2	2.55	80
10	E-1	102N49W 4AAA	4.8	2.08	43
11	SPD-1	102N49W16ABB	2.1	2.2	95
12	D-4	102N49W 8CCC	4.7	3.15	67
13	S-29	101N49W 9BCB	3.2	4.5	71
14	NC	101N49W 8CDAD	4.7	2.0	43
15	RS	101N49W 7BCBC	2.7	1.9	70
	Average		3.24	2.56	79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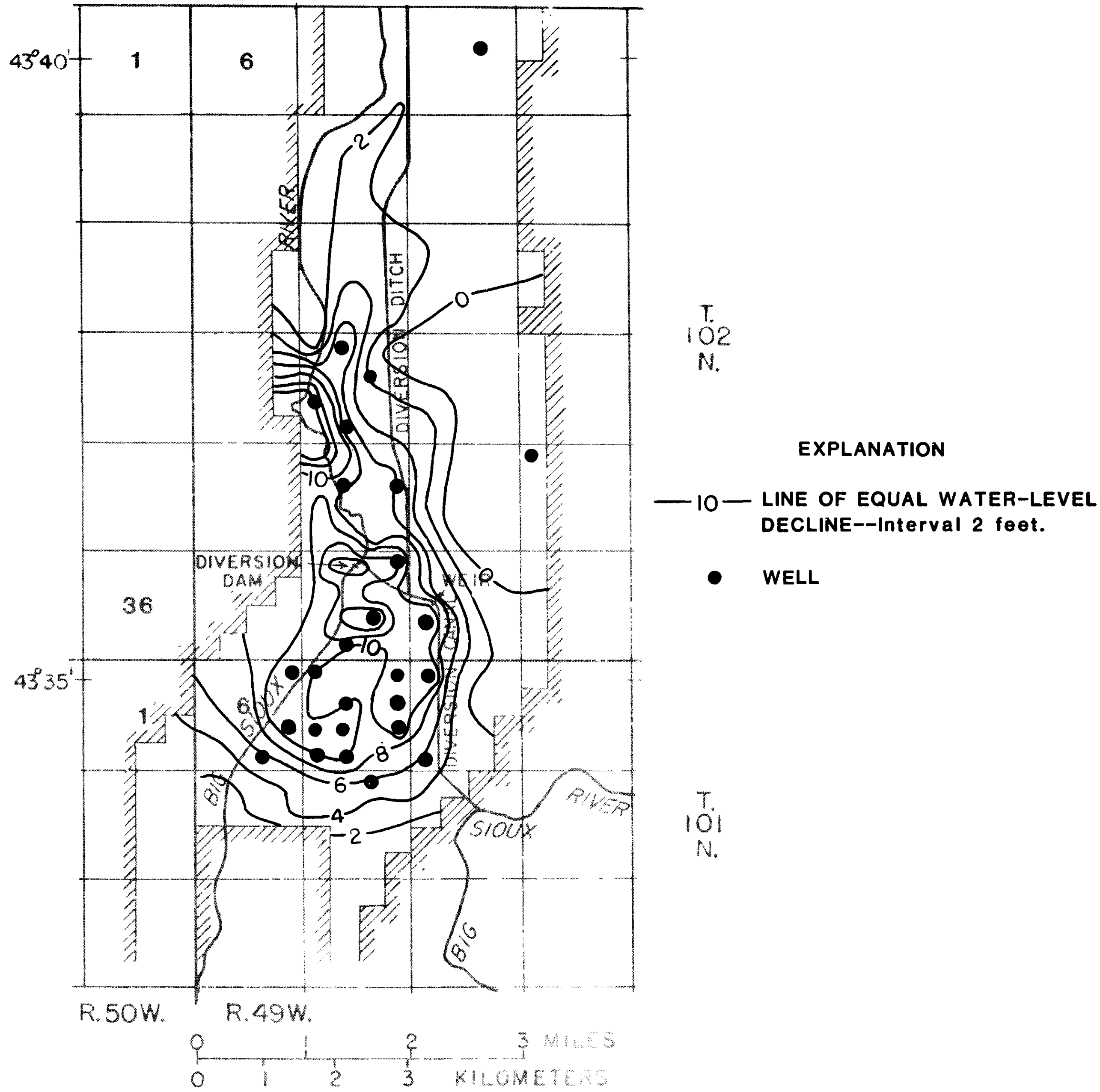


Figure 12.--Computer-simulated drawdown in the Big Sioux aquifer after simulating hydrologic conditions during 1976.

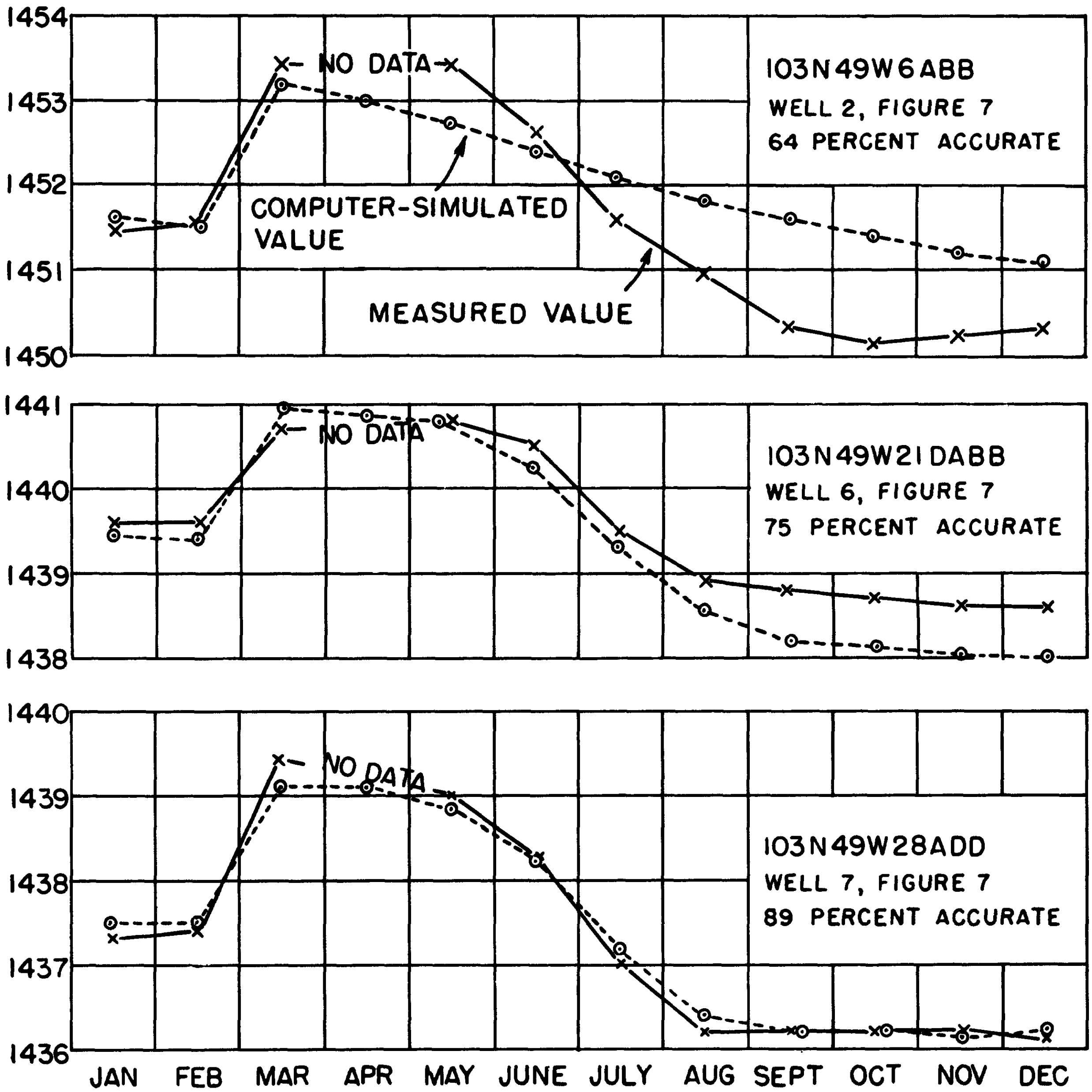


Figure 13.--Comparison of computer-simulated and measured water levels in three wells completed in the Big Sioux aquifer, 1976.

A hydrologic budget equates accretions to the water supply to depletions of the water supply. A budget equation states that inflow minus outflow equals change in storage. A general equation of the hydrologic budget for the Big Sioux aquifer may be written:

> Precipitation + surface-water inflow + decrease in ground-water storage = surface-water outflow + evapotranspiration + increase in ground-water storage + pumpage.

During 1976 pumpage was the biggest single item on the depletion side of the budget (table 5). This was offset mostly by surface-water recharge to the aquifer from January through June and ground-water discharge from storage from July through December. The one exception was during March when the biggest item was precipitation and snowmelt going into ground-water storage.

Table 4.--Summary by month during 1976 of differences between measured and computer-simulated water levels in 15 observation wells

	Average of the value of the difference between computer-simulated and measured water levels1/ (feet)	Average of the absolute value of the difference between computer-simulated and measured water levels2/ (feet)
January	-0.22	0.38
February	-.37	.54
March	-.09	.72
April	--	--
May	-.33	.65
June	-.29	.55
July	.17	.49
August	.38	.72
September	.45	.82
October	.43	.84
November	.35	.82
Decmeber	.26	.86
Annual average	.07	.67

1/ Derived by adding when computer-simulated value was higher than measured value (positive number) and subtracting when computer-simulated value was lower than measured value (negative number).

2/ The absolute value of a number is the number without its associated sign. For example, the absolute value of 4 and -4 are the same.

Table 5.--Computer-simulated monthly changes in the water supply of the Big Sioux aquifer during 1976. Upper number is acre-feet (rounded); lower number is percentage

	January	February	March	April	May	June	July	August	September	October	November	December	Total
SOURCES OF WATER (Accretions)													
Recharge from precipitation	440 11	470 16	6,880 44	390 10	390 9	-- --	-- --	-- --	-- --	-- --	-- --	-- --	8,570 14
Recharge to aquifer from streams	830 21	900 31	880 6	820 21	970 21	1,100 20	180 3	20 0.4	-- --	250 6	260 9	260 9	6,470 11
Discharge from storage	720 18	100 3	-- --	770 19	940 20	1,650 30	2,600 47	2,520 50	1,760 50	1,720 44	1,240 41	1,180 41	15,200 25
CONSUMPTION OF WATER (Depletions)													
Discharge from aquifer to stream	940 24	500 17	660 4	810 20	750 16	640 12	480 9	85 2	-- --	460 12	360 12	340 12	6,020 10
Evapotranspiration from aquifer	-- --	-- --	-- --	-- --	54 1	43 0.8	35 0.6	350 7	240 7	6 0.2	-- --	-- --	730 1
Pumpage	1,050 26	970 33	1,070 7	1,170 30	1,500 33	2,070 38	2,270 41	2,110 41	1,520 43	1,510 38	1,140 38	1,110 38	17,500 29
Recharge to storage	-- --	-- --	6,020 39	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	6,020 10
Total	3,980 100	2,940 100	15,510 100	3,960 100	4,600 100	5,500 100	5,570 100	5,080 100	3,520 100	3,950 100	3,000 100	2,890 100	60,500 100

ANALYSIS OF HYPOTHETICAL HYDROLOGIC SITUATIONS

The calibrated model was used to study effects of three hypothetical hydrologic situations. Equilibrium recharge-discharge relationships will change depending on volume and location of ground-water withdrawals and natural recharge to and discharge from the aquifer. Water levels decline as ground water is withdrawn. Because of declines, water may be released from storage, may be diverted from discharge to streams or evapotranspiration, or may be obtained as recharge from streams. If larger withdrawals continue and do not exceed inflow to the aquifer, a new equilibrium will eventually occur (or recharge and discharge will approach equilibrium).

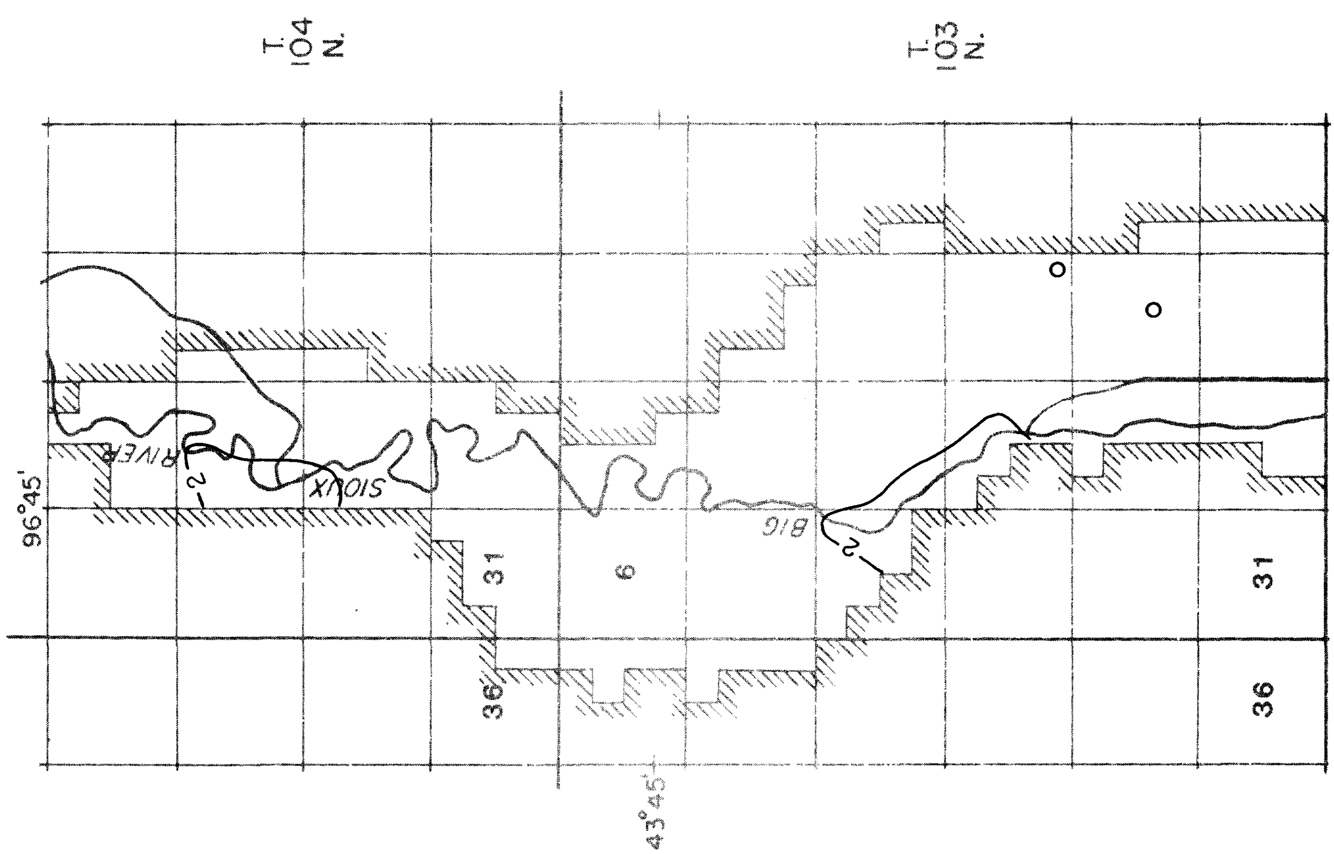
Development of the aquifer can be evaluated under several conditions: (1) Withdrawals can be increased and transient simulations made under normal hydrologic conditions as were determined by calculating averages based on 1970-79 data. These simulations would use a recharge rate of 6.9 inches per year and assume that flow occurs along the entire reach of the Big Sioux River. (2) Withdrawals can be increased and transient simulations made under the 1976 drought conditions. This would allow recharge at a limited rate only through May and result in the Big Sioux River being dry at the end of August. (3) Withdrawals can be increased and transient simulations made under maximum drought conditions. This would not allow for any recharge and no streamflow. (4) Use a combination of the above. The following table shows what assumptions and hydrologic conditions were used to see how the aquifer would be affected under three hypothetical hydrologic situations.

Hydrologic condition	Hypothetical hydrologic situation		
	1	2	3
	Simulation with a dry river	Simulation with increased withdrawal	Simulation with increased withdrawal and drought conditions
INFLOW			
Recharge from precipitation	1976 rate	1976 rate	No.
Recharge to aquifer from stream	No	Yes	Yes, from row 1-54. No, downstream from row 54.
OUTFLOW			
Discharge from aquifer to stream	No	Yes	Yes, from row 1-54. No, downstream from row 54.
Evapotranspiration from aquifer	1976 rate	1976 rate	No.
Pumpage rate	1976 monthly rate	44.4 cubic feet per second	44.4 cubic feet per second.
Number of pumping wells	26	60	60
STARTING WATER-LEVEL CONDITIONS	Oct. 1, 1976	Jan. 1, 1976	Dec. 31 of simulation 2.
NUMBER OF MONTHLY COMPUTER SIMULATIONS	16	12	18

Simulation With a Dry River

To evaluate the effects of pumping from the aquifer under extreme drought conditions, 1976 pumpage rates were used under conditions simulating a dry Big Sioux River. Transient simulations were made using 16 month-long pumping periods starting with October 1976 and reusing individual monthly pumping rates as needed, and using recharge, evapotranspiration, and pumpage rates for 1976. From October 1976 through February all wells continued to pump. During March, pumping stopped after a pumping well caused storage to be depleted at a node. The model is set to terminate calculations when the value representing storage is zero in a node. The pumping rate for that well was decreased by one-half and the March simulation was repeated. Computer simulations from April to January continued to have the pumping stopped after a pumping well caused storage to be depleted at a nodal area. The following table shows the percent decrease in the pumping rate used in order to complete the simulation. Drawdown in the aquifer and the location of wells that caused storage to be depleted in a node are shown in figure 14.

Month	Initial pumping rate (cubic feet per second)	Decreased pumping rate (cubic feet per second)	Percent decreased
1976			
October	24.5	24.5	0
November	19.2	19.2	0
December	18.0	18.0	0
1976			
January	17.2	17.2	0
February	16.9	16.9	0
March	17.5	15.9	9
April	19.6	18.2	8
May	24.4	20.0	18
June	34.8	31.7	9
July	36.9	31.4	15
August	34.3	28.3	17
September	25.6	20.1	21
October	24.5	19.5	20
November	19.2	14.6	24
December	18.0	15.2	15
1976			
January	17.2	10.4	40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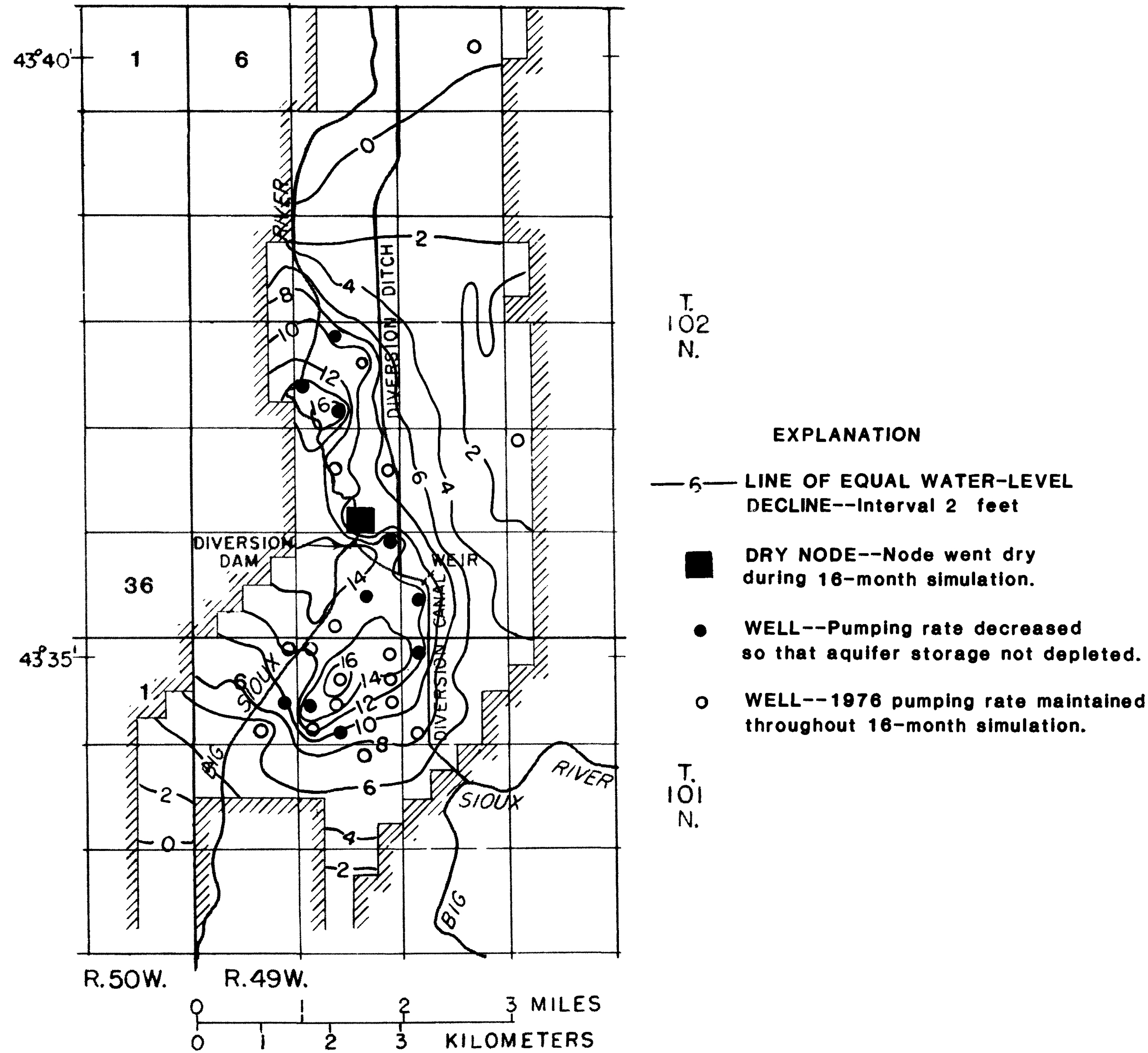


Figure 14.--Computer-simulated drawdown after 16 months of pumping under 1976 hydrologic conditions except for a dry river.

Simulation With Increased Withdrawal

To evaluate the effects of increased pumpage from the aquifer, new wells were spaced throughout the aquifer and withdrawal rates totaling 32,200 acre-ft/yr (44.4 ft^3/s) were established so that an equilibrium condition could be reached. The hydrologic budget at equilibrium is shown in table 6 and the potentiometric surface of the aquifer is shown in figure 15.

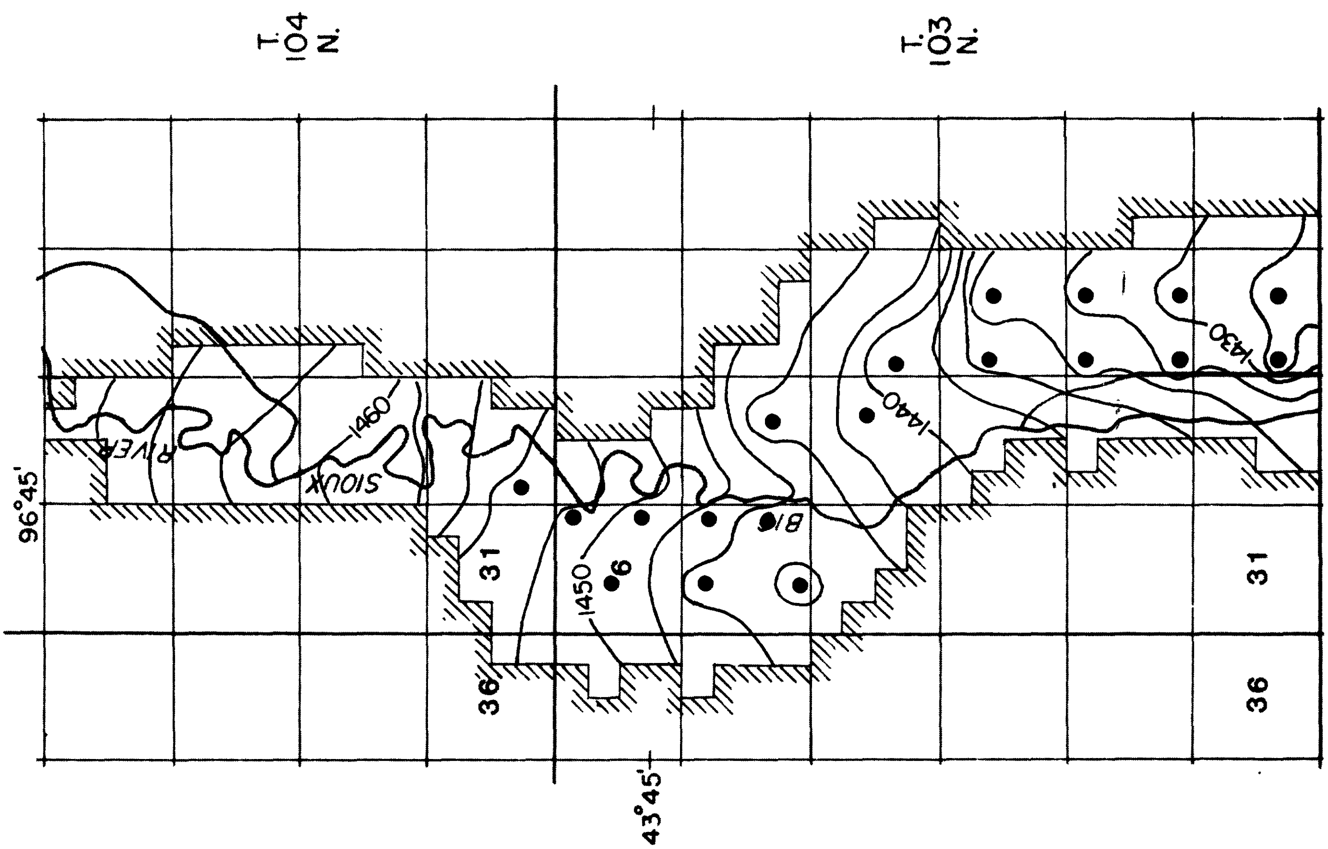
Table 6.—Computer-simulated hydrologic budget at equilibrium using average conditions based on 1970-79 data under an increased pumping rate of 44.4 cubic feet per second from 60 wells

Budget component	Acre-feet	Percent
INFLOW		
Recharge from precipitation	11,600	33
Recharge to aquifer from streams	23,700	67
Total inflow	35,300	100
OUTFLOW		
Discharge from aquifer to streams	2,830	8
Evapotranspiration from aquifer	310	0.9
Pumpage	32,200	91
Total outflow	35,340	100

Using the same well spacing and pumping rates established for the previous (equilibrium) simulation, 12 monthly simulations beginning with January were made under 1976 recharge, evapotranspiration, and stream-stage conditions (see p. 28). The monthly hydrologic budget is shown in table 7. Note the increased volume of water removed from storage and the river compared to the volume removed under 1976 monthly pumping rates (table 5). The drawdown between January and December is shown in figure 16.

Table 7.—Computer-simulated monthly changes in the water supply of the Big Sioux aquifer under 1976 conditions with a withdrawal rate of 44.4 cubic feet per second from 60 wells. Upper number is acre-feet (rounded); lower number is percentage

	January	February	March	April	May	June	July	August	September	October	November	December	Total
SOURCES OF WATER (Accretions)													
Recharge from precipitation	440 6	470 8	6,880 42	390 6	390 6	— —	— —	— —	— —	— —	— —	— —	8,570 10
Recharge to aquifer from streams	970 14	1,140 20	1,230 8	1,120 18	1,230 19	1,260 21	340 6	24 0.4	— —	540 9	590 11	650 11	9,100 11
Discharge from storage	2,100 30	1,300 22	— —	1,650 26	1,580 25	1,740 29	2,600 44	2,970 50	2,730 50	2,330 41	2,160 39	2,180 39	23,000 29
CONSUMPTION OF WATER (Depletions)													
Discharge from aquifer to stream	790 11	360 6	450 3	520 8	440 7	350 6	200 3	85 1	— —	140 2	110 2	100 2	3,500 4
Evapotranspiration from aquifer	— —	— —	— —	— —	17 0.3	11 0.2	7 0.1	180 3	86 2	— —	— —	— —	300 0.4
Pumpage	2,730 39	2,560 44	2,730 17	2,640 42	2,730 43	2,640 44	2,730 47	2,730 46	2,640 48	2,730 48	2,640 48	2,730 48	32,000 40
Recharge to storage	— —	— —	4,920 30	— —	— —	— —	— —	— —	— —	— —	— —	— —	4,900 6
Total	7,030 100	5,830 100	16,210 100	6,320 100	6,390 100	6,000 100	5,880 100	5,990 100	5,460 100	5,740 100	5,500 100	5,660 100	82,000 100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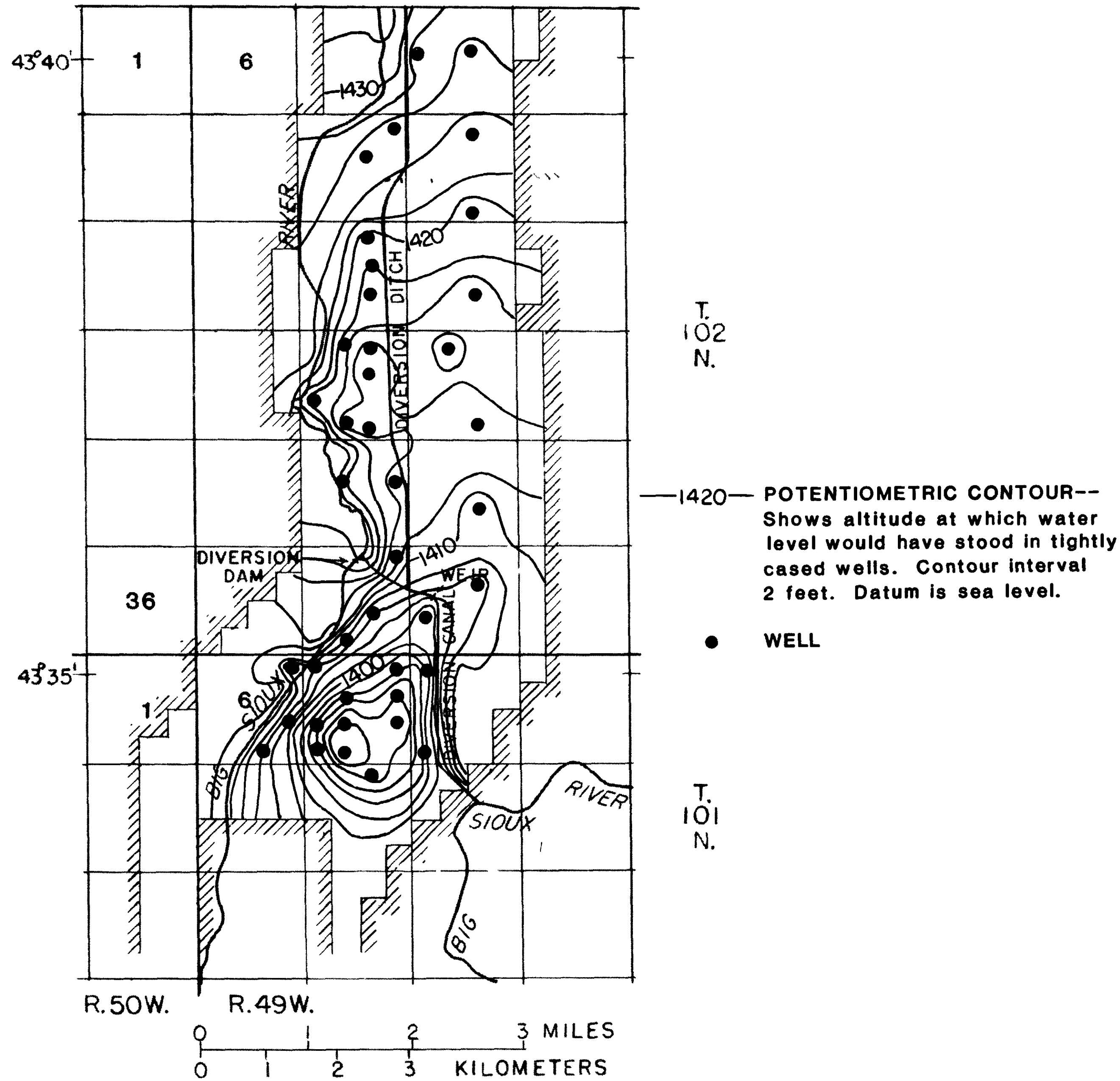
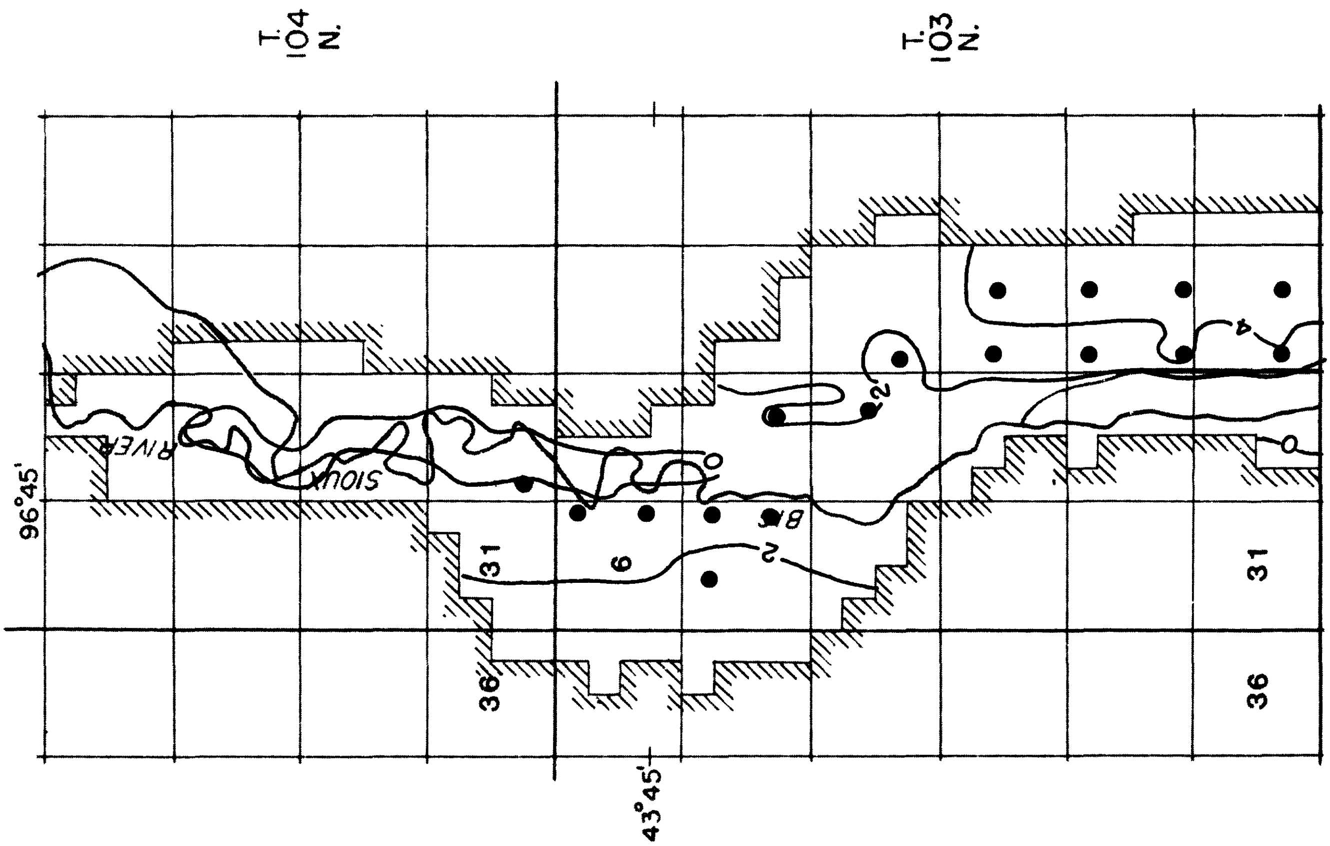


Figure 15.--Computer-simulated water levels after 1 year of pumping under 1976 hydrologic conditions and a pumping rate of 44.4 cubic feet per second from 60 wells.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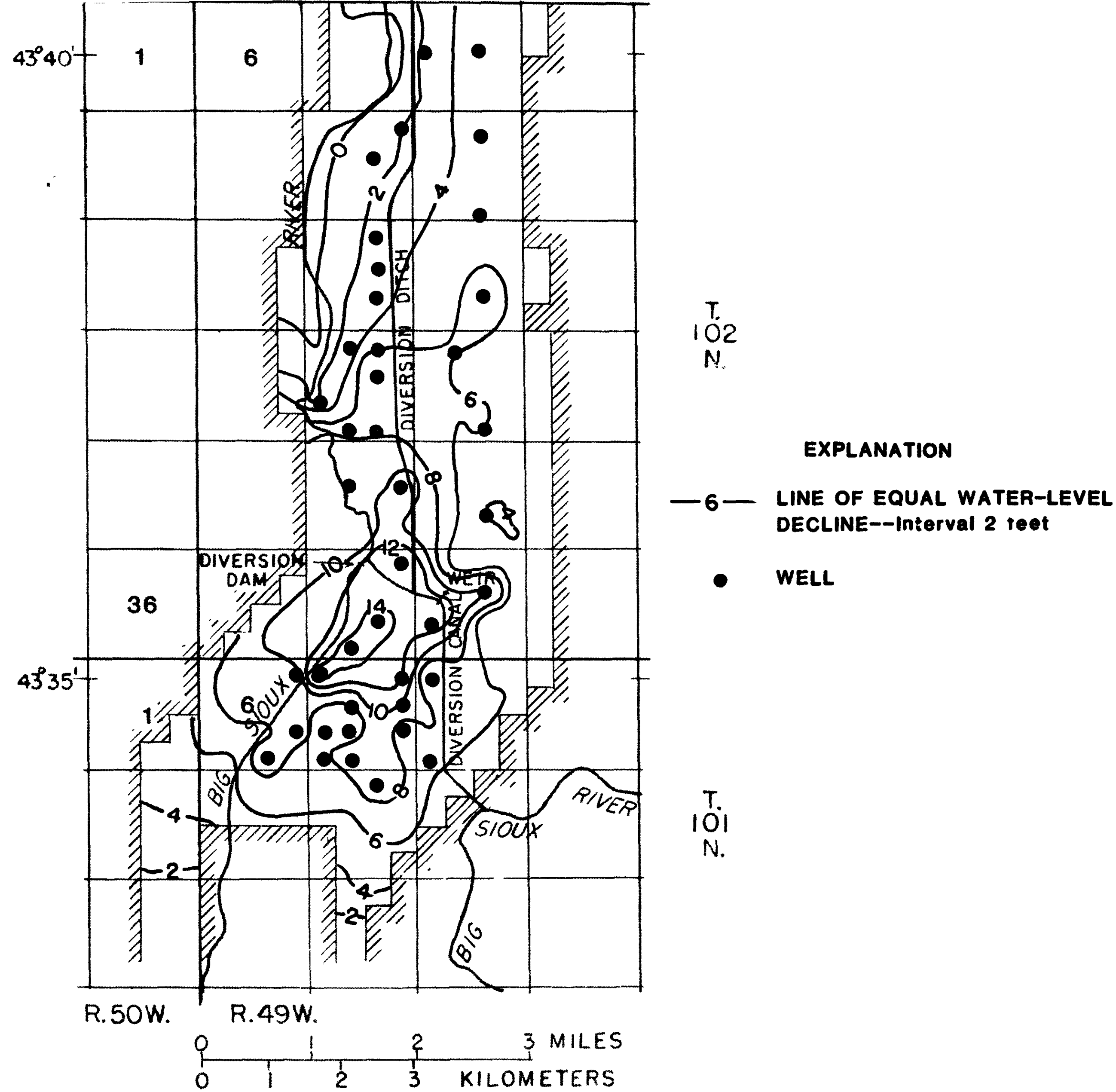

Figure 16.--Computer-simulated drawdown after 1 year of pumping under 1976 hydrologic conditions and a pumping rate of 44.4 cubic feet per second from 60 wells.

Simulation With Increased Withdrawal Under Extreme Drought Conditions

To evaluate the effects of the increased withdrawal rate totaling 32,200 acre-ft/yr (44.4 ft^3/s) under drier conditions than occurred during 1976, monthly simulations were made with no recharge and the Big Sioux River dry downstream from row 54. Starting water-level conditions were the hydraulic-head conditions at the end of the December simulation (p. 40 and table 7). Pumping wells depleted at least one node starting with the March simulation and almost every month thereafter. The percent decrease in the pumping rate of 44.4 ft^3/s in order to complete the monthly simulation is shown in table 8. After 18 monthly simulations the pumping rate had to be decreased by 44 percent and at that rate 63 percent of the water pumped was recharging the aquifer from the river.

Table 8.--Monthly computer simulations showing percentage of decreased pumping rate less than the starting rate of 44.4 cubic feet per second and percentage of the water pumped that is recharging the aquifer from the river

Month	Decreased pumping rate (cubic feet per second)	Percent decreased	Percent of water pumped that is recharging the aquifer from the river
January	44.4	0	22
February	44.4	0	24
March	44.0	0.9	25
April	41.6	6	28
May	39.9	10	31
June	37.8	15	33
July	34.4	22	38
August	32.5	27	41
September	31.2	30	44
October	30.0	32	47
November	29.6	33	48
December	29.1	34	50
January	27.6	38	53
February	27.6	38	54
March	27.6	38	55
April	26.6	40	57
May	25.6	42	60
June	24.8	44	63

SUMMARY

The Big Sioux aquifer, an alluvium-mantled outwash, in the study area is a 36-square-mile water-table aquifer hydraulically connected to the Big Sioux River. Normal precipitation in the 130-square-mile drainage area is about 25 inches (174,400 acre-feet) annually. Of this amount, 2,700 acre-feet leaves the area as streamflow gain, 13,700 acre-feet is removed by pumpage, and 158,000 acre-feet is removed by evapotranspiration.

Seven low-flow seepage studies were made, three during the fall, two during late winter, and two during spring and early summer. Most of these studies showed stream gains in the Big Sioux River between Dell Rapids and Renner and stream losses between Renner and Sioux Falls.

A digital computer model was calibrated under equilibrium and transient conditions. Average conditions were determined for hydraulic head, pumpage, and recharge for 1970-79. To achieve the best fit under equilibrium conditions, hydraulic conductivity and recharge were slightly modified by decreasing recharge by 9 percent to 6.9 inches per year and increasing hydraulic conductivity by 100 feet per day in rows 1-55 and 50 feet per day in rows 56-77. Fifty wells were used to compare the measured water levels with the computer-simulated water levels. The average absolute difference between the measured and simulated water levels was 0.8 ft. For 1970-79, on which the steady-state calibration was based, water levels in wells fluctuated a maximum of 11.6 ft. If all computer-simulated values that are higher than the measured values are added and all lower values are subtracted, the computer-simulated values averaged 0.5 ft higher than the measured values.

The transient calibration was made for 1976 at monthly intervals. A severe drought during 1976 produced major water-level declines and the lack of precipitation enabled the model calibration to be made without using a recharge factor after May. Between January and December 1976 there was a drawdown of less than 2 feet except in the Sioux Falls city well field where drawdown was as much as 15 feet. The water levels in 15 observation wells declined an average of 3.24 feet during 1976. The individual declines varied from 2.1 to 4.8 feet. The average difference between measured and computer-simulated water levels for these observation wells varied by month from 0.38 to 0.86 feet. The average of these monthly average differences for 1976 was 0.67 feet.

A general equation of the hydrologic budget for the Big Sioux aquifer may be written:

> Precipitation + surface-water inflow + decrease in ground-water storage = surface-water outflow + evapotranspiration + increase in ground-water storage + pumpage.

During 1976 the biggest single item on the depletion side of the budget was pumpage. This was offset mostly by surface-water recharge to the aquifer from January through June and ground-water discharge from storage from July through December. The one exception was in March when the biggest item was precipitation going into ground-water storage.

After the computer model was calibrated it was used to see how the aquifer would be effected under three hypothetical hydrologic situations. To evaluate the effects of pumping from the aquifer under extreme drought conditions, 1976 pumpage rates were used with a dry Big Sioux River. All pumping wells continued to operate for 5 months. During the 6th month a pumping well caused storage to be depleted at a node. The pumping rate for that well was decreased by one-half and the monthly simulation was repeated. During the simulation of the 16th month the total pumping rate had to be decreased by 40 percent in order to complete the monthly simulation.

To see how the aquifer would be affected by increased pumpage, 60 wells were spaced throughout the aquifer and withdrawal rates were established so that an equilibrium condition could be reached. This pumping rate of 44.4 cubic feet per second was used in transient simulations under different hydrologic conditions. The increased pumping rate was simulated under 1976 conditions. An increased volume of water was removed from storage and the river compared to the volume removed with 1976 pumping conditions. Another simulation was made with no recharge and a dry streambed downstream from row 54. After 3 months wells started depleting a nodal area. During the 18th month the pumping rate was decreased by 44 percent and at that rate 63 percent of the water was recharging the aquifer from the river.

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