APPRAISAL OF THE WATER RESOURCES OF THE SKUNK CREEK AQUIFER IN MINNEHAHA COUNTY, SOUTH DAKOTA

By Grant L. Ohland

U.S. GEOLOGICAL SURVEY

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Huron, South Dakota
1990

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

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

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,234	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.06308	liter per second
inch	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

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = \frac{°F - 32}{1.8}$$

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

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ABSTRACT

The Skunk Creek aquifer in Minnehaha County, a major glacial outwash deposit in the Skunk Creek drainage basin, consists of a 30-square-mile shallow stream-connected sand and gravel aquifer in southeastern South Dakota. The aquifer thickness ranges from 1 to 74 feet. Average annual fluctuation of the water table is 2.5 feet. The water has an average dissolved-solids content of 620 milligrams per liter and is very hard, averaging 403 milligrams per liter calcium carbonate hardness.

A numerical model was developed and calibrated under steady-state and transient conditions. The model contained 484 active nodes each representing 0.0625 square mile (0.25 mile on a side). Hydraulic conductivities of the aquifer used in the model range from 10 to 400 feet per day and average specific yield is 20 percent. Recharge from infiltration of precipitation was estimated to be 6 inches per year or 24 percent of average annual precipitation. The maximum evapotranspiration rate was 32 inches per year and the evapotranspiration extinction depth for the model was 5 feet. The steady-state hydrologic budget was about 11,000 acre-feet per year. Recharge by precipitation was about 9,500 acre-feet and recharge from streams was about 1,100 acre-feet. Discharge by evapotranspiration was about 5,000 acre-feet and discharge to streams was about 5,700 acre-feet.

The model was tested under transient conditions by simulating actual hydrologic conditions for 1985. Average monthly conditions were used for each monthly model run. The 1985 transient hydrologic budget was 40,740 acre-feet. Recharge from precipitation and decrease in storage was 25 and 22 percent respectively and discharge by evapotranspiration, discharge to streams, and increase in storage was 11, 23, and 14 percent respectively. Recharge from streams, ground-water inflow, and pumpage amounted to 1.5 percent or less for each item.

The calibrated model was used to simulate the effects of two hypothetical hydrologic situations. The first situation was steady-state conditions to determine drawdown distribution and the volume of water that the aquifer was capable of producing using average hydrologic conditions for the period 1978 through 1985. The simulation resulted in a ground-water withdrawal of about 15,700 acre-feet per year from 19 additional wells pumping at a rate of 500 gallons per minute and 13 existing wells pumping at a combined average rate of 24 gallons per minute.

The second simulation involved 12 monthly transient simulations using 1985 hydrologic conditions at a pumping rate of 15,962 acre-feet per year. Comparison of the hydrologic budget to the 1985 pre-development budget indicated that the decreased water levels caused by increased pumpage resulted in decreased streamflow in Skunk Creek, decreased ground-water storage, and decreased evapotranspiration.

INTRODUCTION

The Skunk Creek drainage basin covers 613 mi^2 in southeastern South Dakota (fig. 1). Skunk Creek and its tributaries drain the entire basin, eventually joining the Big Sioux River near Sioux Falls. A major glacial outwash aquifer, called the Skunk Creek aquifer, is contained entirely within the basin and has an area of approximately 90 mi^2. The aquifer, part of the Big Sioux aquifer system, has been divided into three management units named the Southern Skunk Creek, Middle Skunk Creek, and Northern Skunk Creek based on hydrogeological divisions within the aquifer. The aquifer is a surficial valley-train glacial outwash deposit that consists predominantly of sand and gravel with minor amounts of silt and clay. The unconfined nature of the aquifer allows for a direct hydraulic connection with Skunk Creek and other surface-water bodies.

The study area consists of the Middle and Southern Skunk Creek management units which cover approximately 30 mi^2, contain about 96,000 acre-ft of water in storage, and extend from the southwest corner of Moody County southward through Minnehaha County to the City of Sioux Falls (fig. 1).

Water withdrawn from the aquifer is used largely for domestic and agricultural purposes. Additional development of the aquifer could result in water-level declines in some areas.

Purpose and Approach to the Study

The objectives of this study are to: (1) Describe the hydrogeological characteristics of the Skunk Creek aquifer; (2) characterize its hydrogeochemistry and the processes that influence the composition of the water; and (3) develop and calibrate a numerical (computer simulated) ground-water flow model for the aquifer under steady-state (equilibrium) and transient conditions. The model will be used as a management tool to predict the hydrologic effects of selected stresses applied to the hydrologic system.

This investigation was based on data from the the U.S. Geological Survey, South Dakota Geological Survey, and the South Dakota Department of Water and Natural Resources, Water Rights Division.

Geological data obtained from test-hole drilling were used to modify a previously constructed geologic map of surficial outwash deposits associated with the Skunk Creek valley. These test-hole data were also used to construct aquifer configuration maps, as well as geologic cross sections.

Data from the U.S. Geological Survey WATSTORE data base were used to evaluate the hydrogeochemistry of the aquifer. This data base contains quality of water analyses from irrigation, domestic, and public water supply sources, as well as from samples collected from streams and observation wells.

The numerical computer simulation of the aquifer was conducted using the U.S. Geological Survey modular ground-water flow model (McDonald and Harbaugh, 1984). Aquifer simulations included a steady-state simulation based on an 8-year period (1978-85), annual transient simulations (1982 and 1983), and monthly transient simulations for 1984 and 1985. Following model calibration under steady-state (equilibrium) and transient conditions, the model was used to simulate two hypothetical situations which applied additional stresses to the hydrologic system.

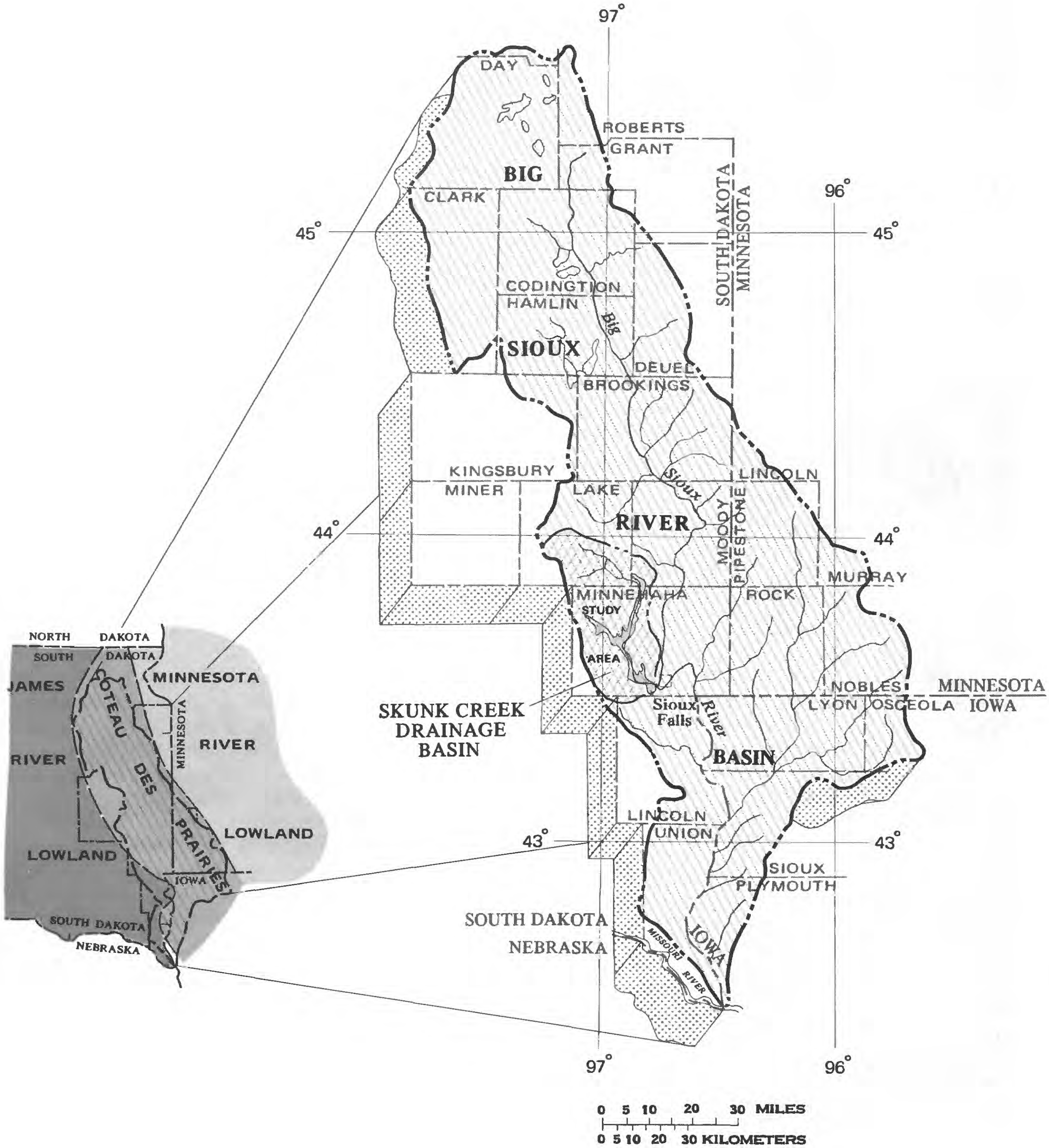

Figure 1.—Location of the Coteau des Prairies, Big Sioux River basin, Skunk Creek drainage basin, and the study area.

Previous Investigations

The first investigation of the outwash deposits associated with Skunk Creek was conducted by Rothrock and Newcomb (1926). The purpose of their study was to locate suitable quantities of easily accessible road gravel within Minnehaha County. They determined the extent of the Skunk Creek outwash by a topographic reconnaissance of the area. The suitability of the sand and gravel for use as road material was determined from numerous mechanical grain-size analyses of samples collected from active gravel pits.

Rothrock and Otton (1947) conducted a ground-water investigation of the Sioux Falls area which included the southern part of the Skunk Creek aquifer. Part I of their investigation describes the geology and hydrology of the area, whereas Part II includes data collected from shallow test drilling, porosity determinations, mechanical grain-size analyses, and determination of aquifer permeability by laboratory methods and in-situ aquifer testing. Laboratory determination of hydraulic conductivities for 14 samples collected at various depths ranged from 80 to 1,980 ft/d, and averaged 580 ft/d. An aquifer test conducted on a production well in a coarse gravel in the southern portion of the Skunk Creek aquifer resulted in a hydraulic conductivity of 1,335 ft/d. The analysis was based on the Theis graphical solution. Aquifer tests of six other nearby wells in the hydrologically similar Big Sioux aquifer resulted in hydraulic conductivities ranging from 320 to 1,070 ft/d.

The surficial geology of the study area was mapped by Steece (1959) and Tipton (1959). They defined two different ages of Wisconsin outwash deposits in the valley of Skunk Creek.

A hydrogeological investigation of the Skunk Creek drainage basin, including the Skunk Creek aquifer, was conducted by M. J. Ellis and D. G. Adolphson of the U.S. Geological Survey. Their investigation resulted in two publications. The first includes the results of shallow test-hole drilling used to determine the extent of the aquifer (Adolphson and Ellis, 1964). The second publication includes a map of the surficial glacial geology, geologic cross sections, as well as a brief description of the hydrogeology and hydrogeochemistry of the drainage basin (Ellis and Adolphson, 1965). Ellis and Adolphson (1965) stated that the three management units of the Skunk Creek aquifer are not hydraulically connected except by surface-water flow in Skunk Creek.

D. L. Iles (1983) conducted a study to determine ground-water resources in the vicinity of Sioux Falls and Brandon, South Dakota. The investigation included a general description of the hydrogeology and hydrogeochemistry of the southern portion of the Skunk Creek aquifer and described the hydraulic connection with the buried Wall Lake aquifer in the vicinity of Sioux Falls. Iles postulated that the hydraulic gradient in the Wall Lake aquifer resulted in discharge of poor quality water into the southern part of the Skunk Creek aquifer, resulting in generally poorer quality water in the vicinity of the Wall Lake discharge area.

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. 2).

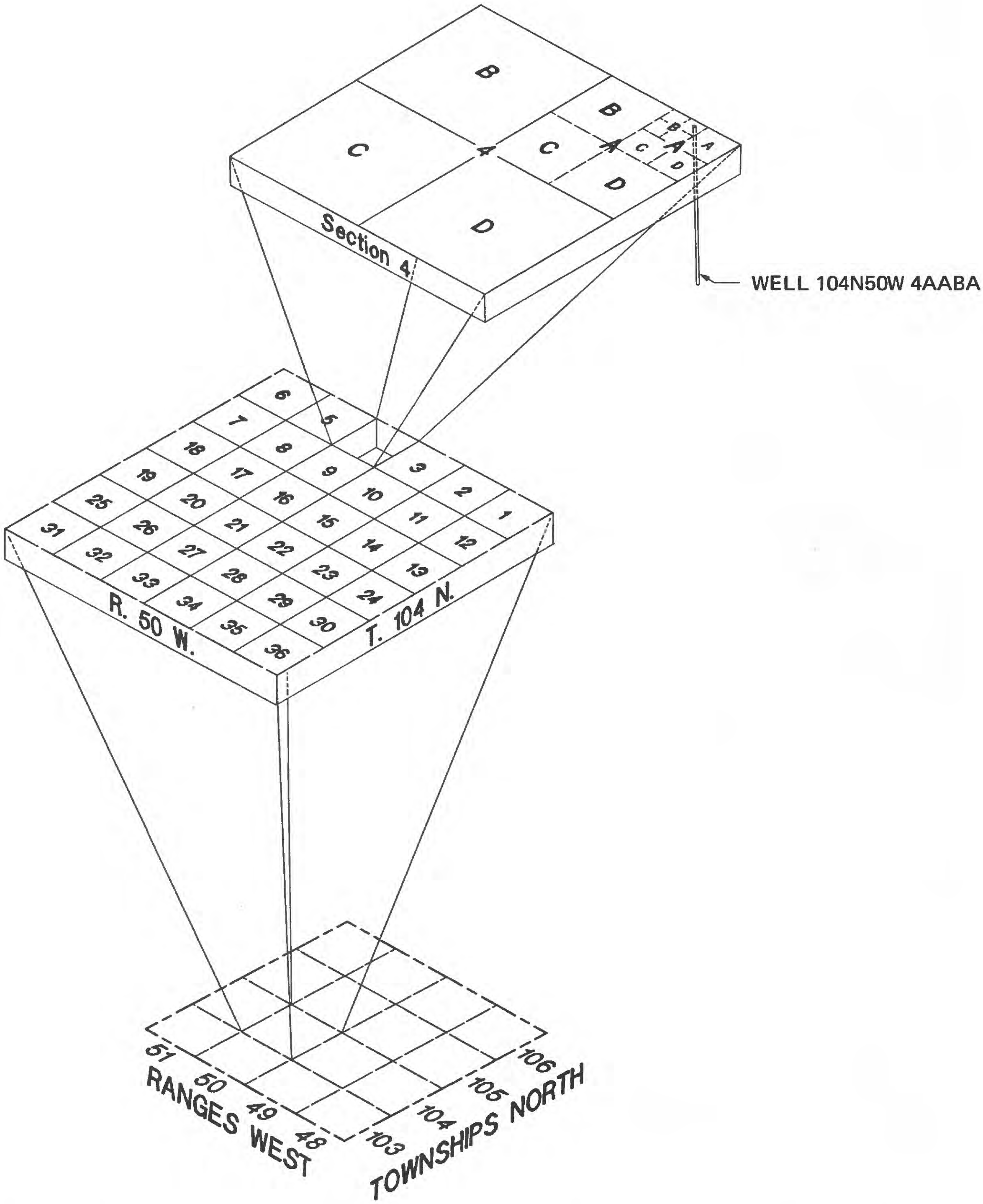

Figure 2.—Well-numbering diagram. The well number consists of township followed by "N", range followed by "W", and section number, followed by a maximum of four case letters that indicate, respectively, the 160, 40, 10, and 2½ acre tract in which the well is located.

Acknowledgments

I would like to express my thanks to Dr. Wayne Pettyjohn, Oklahoma State University, for his advice during the study and helpful review of this report and to Dr. Arthur Hounslow, Oklahoma State University, for his help in the interpretation of the hydrogeochemical aspects of this study.

Thanks are also due to the South Dakota Department of Water and Natural Resources, Water Rights and Geological Survey Divisions, for their contribution of data.

HYDROLOGIC SYSTEM

The Big Sioux River drainage basin has an area of approximately 9,000 mi^2 in eastern South Dakota, southwestern Minnesota, and northwestern Iowa (fig. 1). The Skunk Creek drainage basin (613 mi^2) is in the southern portion of the Big Sioux River basin in the Coteau des Prairies section of the Central Lowland physiographic province (fig. 1). Land surface elevations in the basin range from approximately 1,800 ft above sea level in the northern upland areas to about 1,400 ft in the southern part of the Skunk Creek valley (Ellis and Adolphson, 1965). The upland areas drain into the Skunk Creek valley, which extends from central Lake County to southern Minnehaha County where it joins the Big Sioux River valley. Skunk Creek, the major stream within the valley, begins at Lake Brant in southeastern Lake County and flows eastward and then southward eventually joining the Big Sioux River at Sioux Falls. Skunk Creek has an average gradient of approximately 5 ft/mi throughout its length of approximately 38 mi. The width of Skunk Creek valley ranges from one-quarter mile near Hartford to 2 mi west of Sioux Falls; the average width is approximately one mile. The largest tributary is West Branch Skunk Creek, which flows southeastward from western Minnehaha County joining Skunk Creek near Hartford.

The upland areas of the basin consist of a gently rolling topography east of the valley, whereas the remaining upland areas are characterized by small knobs and ridges that isolate undrained depressions forming small lakes and sloughs (Ellis and Adolphson, 1965).

The climate in the study area is sub-humid with a mean annual precipitation of about 25 inches. Maximum precipitation occurs during the growing season with approximately 75 percent of the annual precipitation occurring between April and September. Annual cumulative snowfall averages 40 inches, generally occurring between November and March (Spuhler and others, 1971). The mean annual temperature is about 46 °F, while temperature extremes commonly range from -20 °F in the winter months to near 100 °F in the summer.

Precipitation contributes approximately 817,300 acre-ft/yr of water to the Skunk Creek drainage basin (613 mi^2). Approximately 44,900 acre-ft/yr (1.4 in/yr) leaves the basin as streamflow. The remaining 772,400 acre-ft/yr (23.6 in/yr) consists of water added to ground water storage, to storage in ponds, sloughs, and lakes, and water loss by evapotranspiration.

Aquifer Distribution and Thickness

The Skunk Creek aquifer is composed of surficial glacial outwash deposits in the valleys of Skunk Creek and its major tributaries. The distribution and thickness of sand and gravel deposits associated with Skunk Creek are shown in figure 3. Geologic cross sections are shown in figures 4-9. The width of the aquifer is generally equivalent to the width of the flood plain ranging from approximately 0.25 to 2 mi.

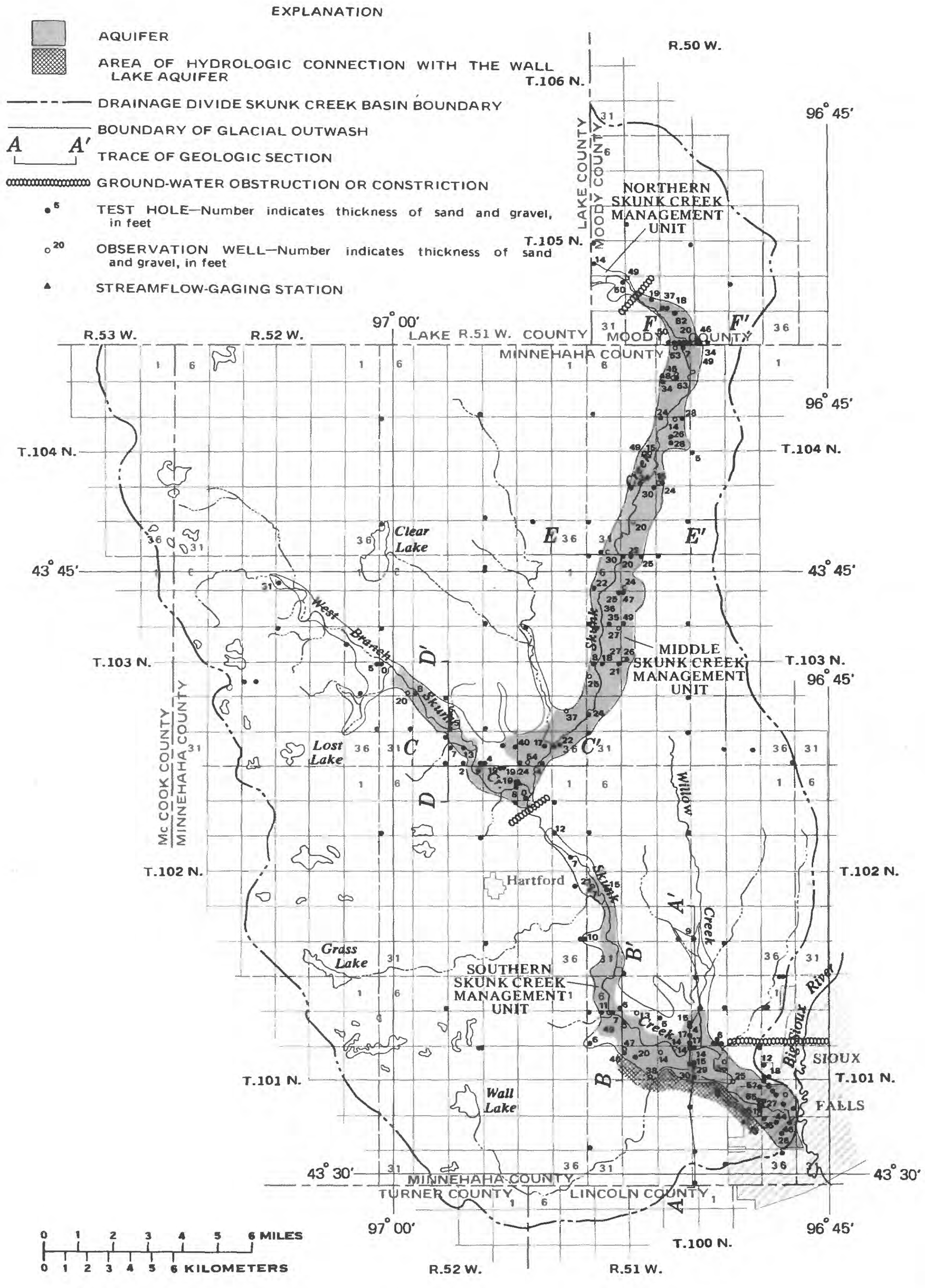

Figure 3.—Distribution and thickness of surficial glacial outwash deposits associated with Skunk Creek.

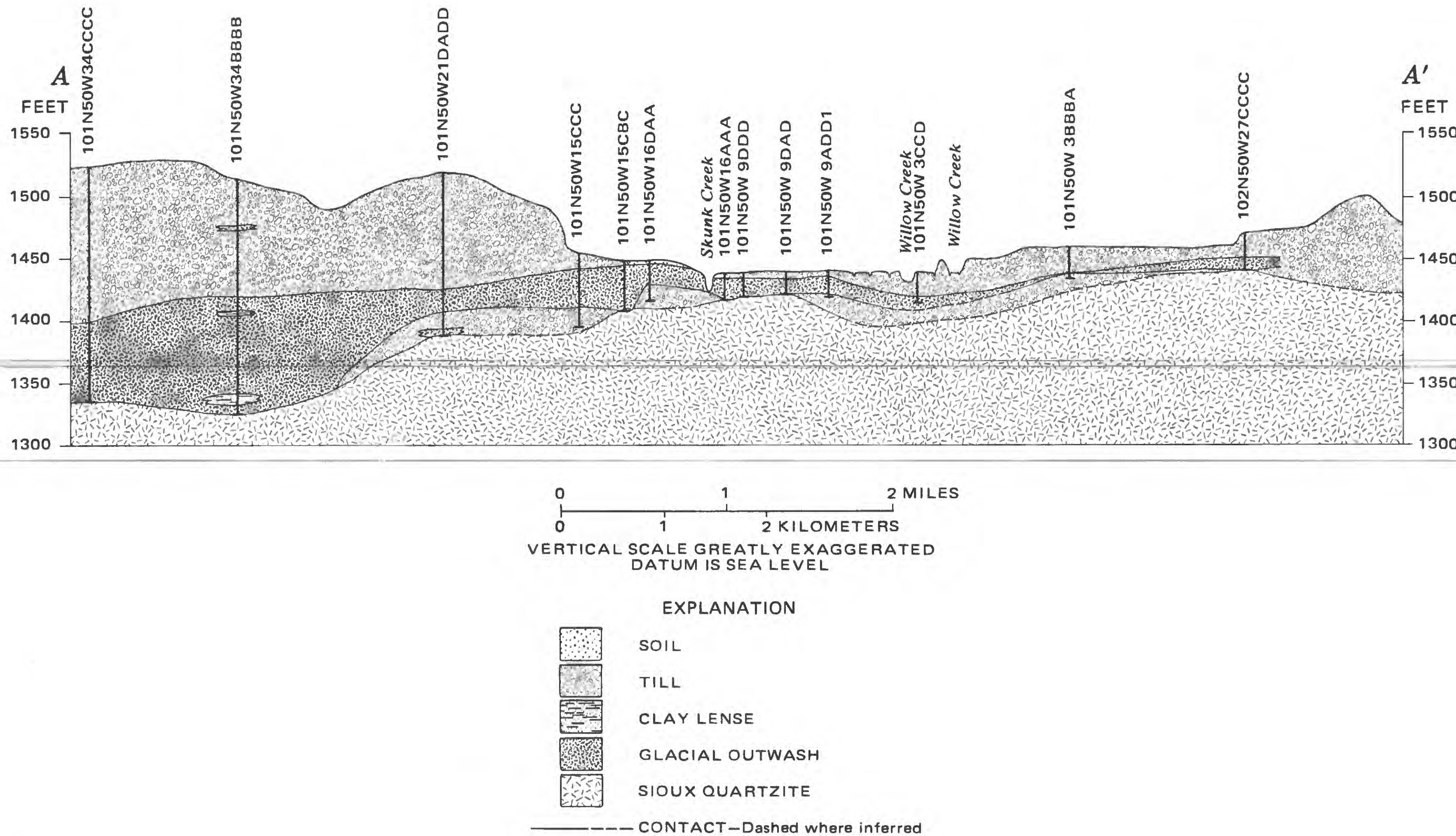

Figure 4.—Geologic cross section A-A′. (Trace of section is shown in figure 3.)

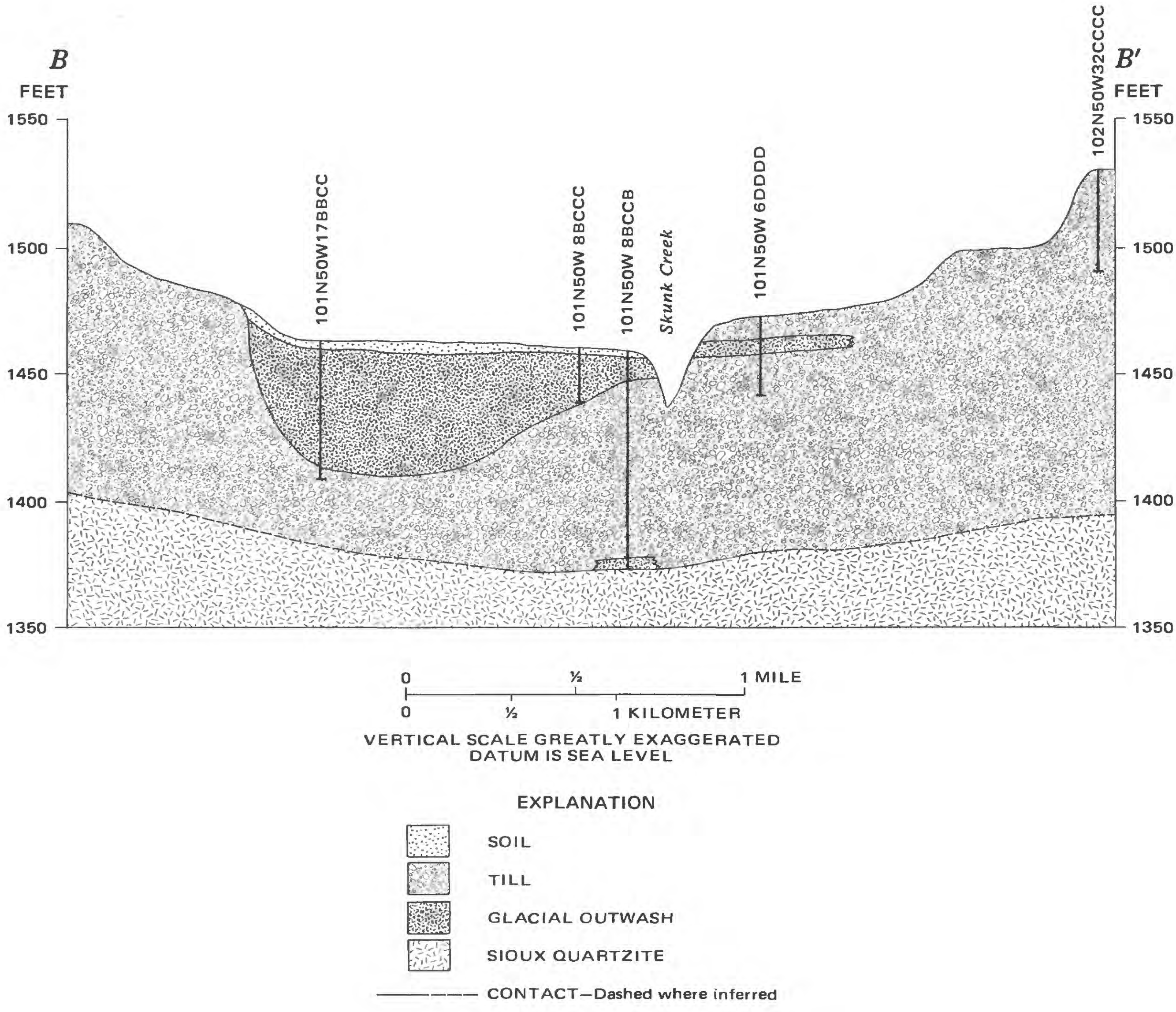

Figure 5.—Geologic cross section B-B′. (Trace of section is shown in figure 3.)

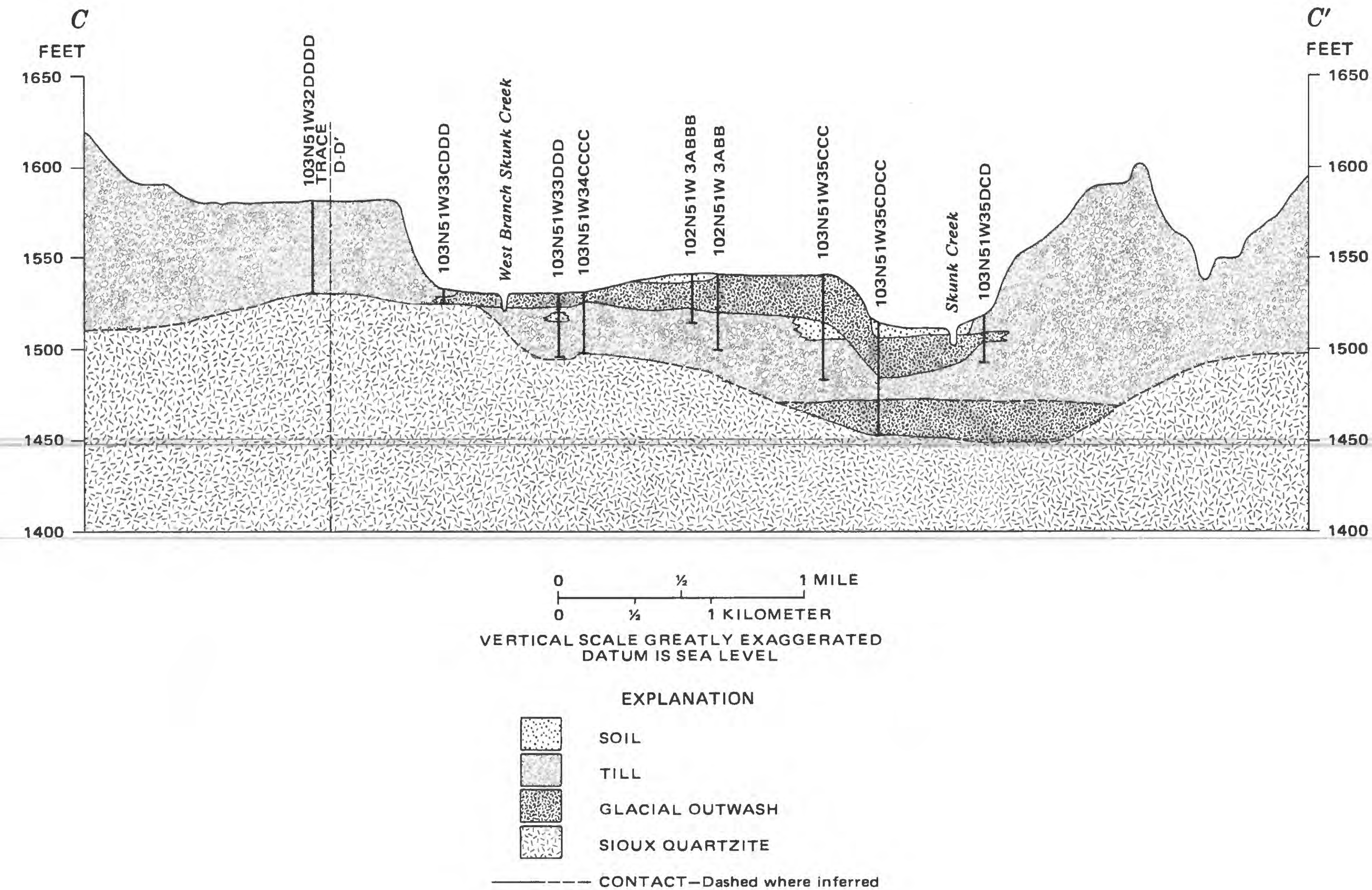

Figure 6.—Geologic cross section C-C′. (Trace of section is shown in figure 3.)

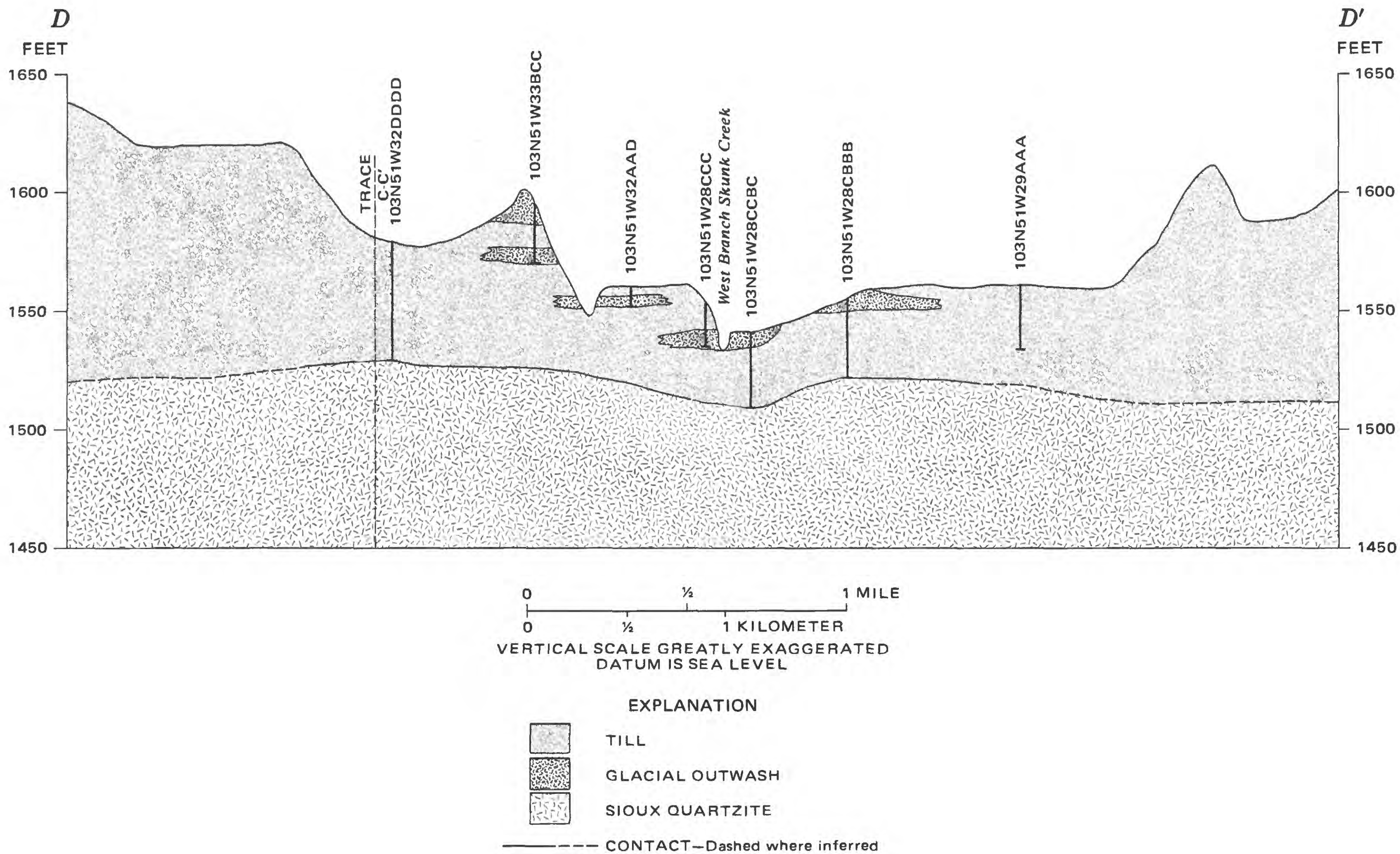

Figure 7.—Geologic cross section D-D′. (Trace of section is shown in figure 3.)

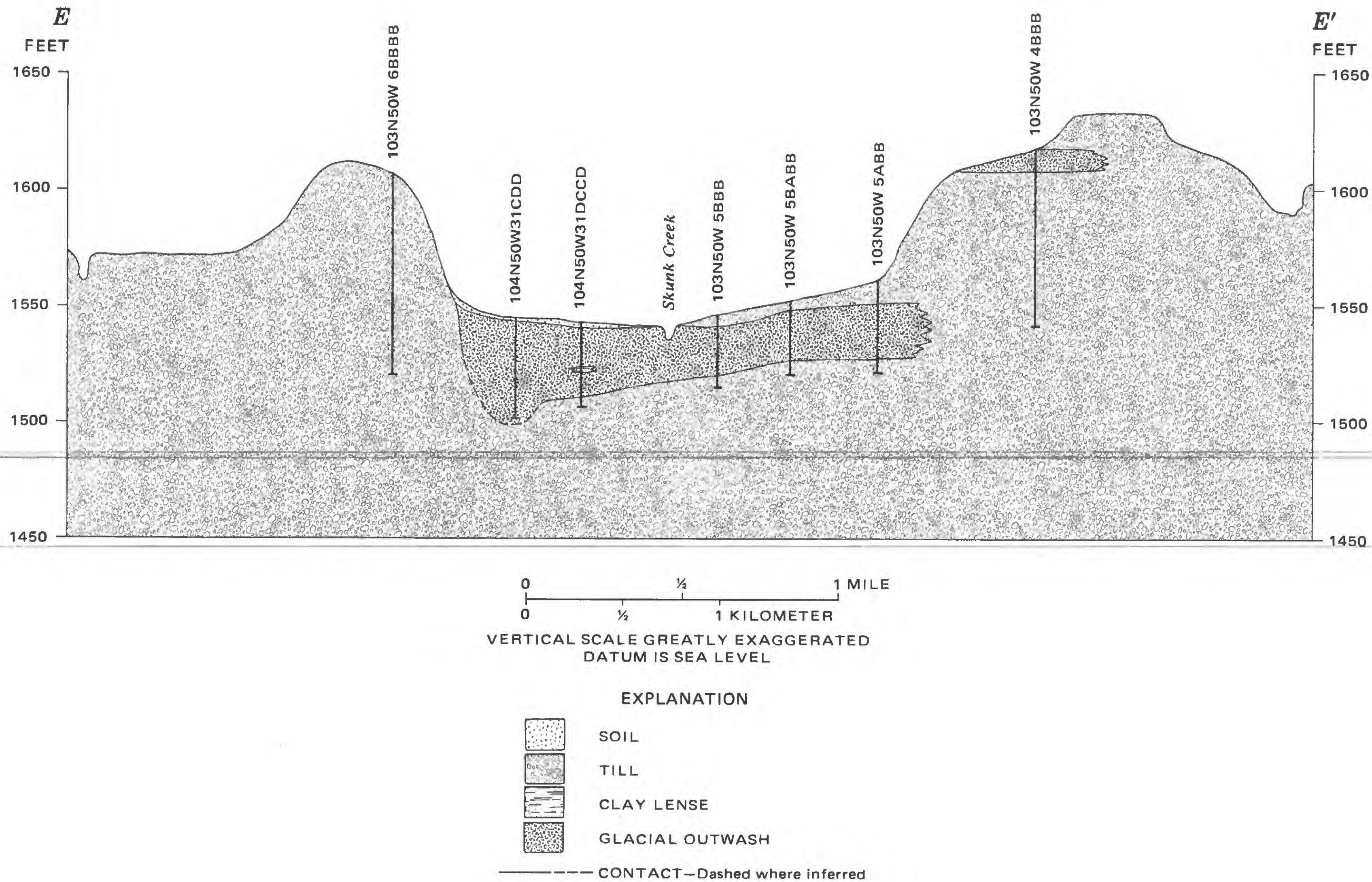

Figure 8.—Geologic cross section E-E′. (Trace of section is shown in figure 3.)

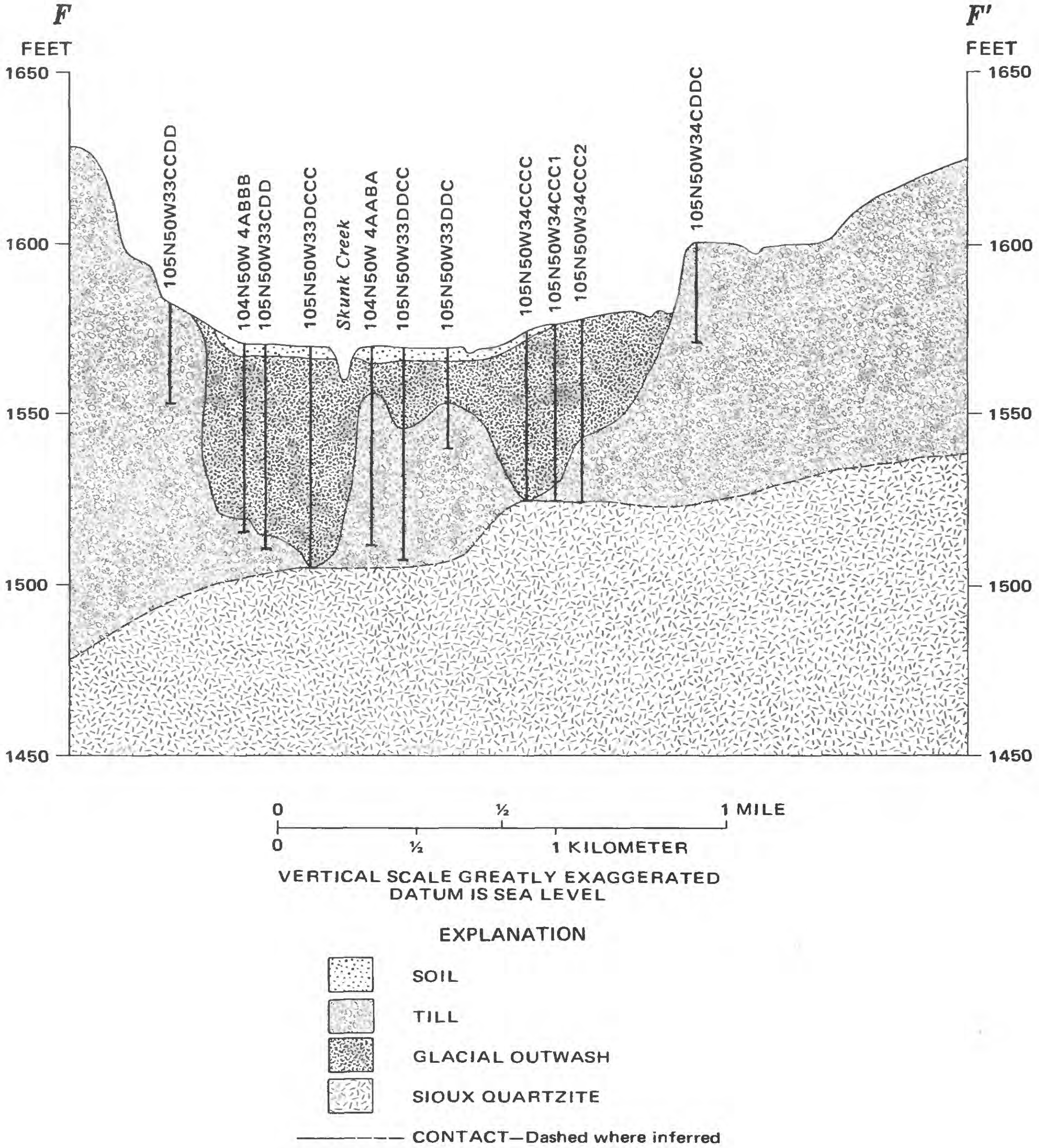

Figure 9.—Geologic cross section F-F'. (Trace of section is shown in figure 3.)

The outwash deposits, which range in thickness from less than 1 to 74 ft and average 25 ft are underlaid by glacial till or Precambrian Sioux Quartzite. Sand and gravel thicknesses are greatest in the vicinity of the connection with the Wall Lake aquifer in the southern portion of the study area (figs. 3 and 4). The extent of this hydraulic connection is not fully understood due to the paucity of test hole and potentiometric surface data. However, the northward hydraulic gradient in the Wall Lake aquifer indicates that discharge is occurring to the Skunk Creek aquifer. Recent test drilling in the Wall Lake aquifer indicates the possible existence of two hydrologic units in certain areas. The flow from the Wall Lake aquifer to the Skunk Creek aquifer is estimated at 470 acre-ft/yr.

The Skunk Creek aquifer is separated by a bedrock high, composed of quartzite that is exposed in Section 11, T. 102 N., R. 51 W. (fig. 3). Skunk Creek flows directly on this exposure where it has removed all outwash deposits from the bedrock surface. Consequently, the quartzite acts as a ground-water barrier in this area. The Sioux Quartzite also acts as a ground-water barrier in the northeast part of T. 101 N., R. 50 W. and inhibits flow from the Big Sioux aquifer into the southern end of the Skunk Creek aquifer.

Laterally discontinuous layers of outwash are common along the West Branch Skunk Creek (figs. 7 and 8). In some areas the base of the outwash deposits are above stream stage and ground water discharges through springs and seeps along stream banks. These deposits are not considered part of the Skunk Creek aquifer because ground-water storage is probably depleted during periods of little or no recharge.

In one area in the southern part of the aquifer, Skunk Creek has cut down through the outwash deposits and into the underlying till (fig. 5) resulting in a discontinuity in the hydraulic connection between the aquifer and the stream.

Aquifer Characteristics

The Skunk Creek aquifer is composed of glacial outwash consisting of limestone, dolomite, quartz, chalk, shale, granite, and minor amounts of gneiss, quartzite, and slate (Rothrock and Otton, 1947).

The aquifer material ranges from fine sand to coarse gravel that generally occurs as a poorly sorted mixture. Although some layers of well-sorted sand or gravel are present, their discontinuous nature makes correlation between nearby test holes difficult.

Hydraulic conductivity is defined as the volume of water that will move through a unit area of a porous medium for a given unit of time under a unit hydraulic gradient. Hydraulic conductivity is closely related to grain size as shown in table 1. Based on table 1, hydraulic conductivities of the aquifer are estimated to range from 70 to 2,000 ft/d. Aquifer test analyses and laboratory permeameter tests suggest that hydraulic conductivities range from about 80 to 1,980 ft/d (Rothrock and Otton, 1947).

Specific yield is defined as the ratio of the volume of water that will drain under the influence of gravity to the volume of saturated sediments. Specific yield determinations for the aquifer are not available, but Rothrock and Otton (1947) estimated it to be about 30 percent. Koch (1982) estimated the specific yield to be about 20 percent based on several aquifer tests in the nearby Big Sioux aquifer. For the purpose of storage and recharge calculations in this study, the average specific yield of the Skunk Creek aquifer is assumed to be 20 percent.

Table 1.--Relation between grain-size class and hydraulic conductivity in glacial drift

Grain size class	Range of hydraulic conductivity in glacial drift (feet per day)
Clay or silt	<20
Sand, very fine	10 - 80
Sand, fine	70 - 140
Sand, fine to medium	70 - 400
Sand, medium	130 - 400
Sand, fine to coarse	70 - 600
Sand, medium to coarse	130 - 800
Sand, coarse	400 - 1,000
Sand and gravel	400 - 1,200
Sand, coarse, and gravel	400 - 1,400
Gravel	800 - 2,000

From Koch (1980)

Ground-Water Recharge

Water recharged to the aquifer is from direct infiltration of precipitation, infiltration from surface-water bodies, such as streams, ponds, and sloughs, and underflow from the Northern Skunk Creek management unit and Wall Lake aquifers. Minor recharge originates as leakage from adjacent glacial till deposits. Water levels rise in response to periods of increased precipitation as shown in figure 10. Ground-water recharge mainly occurs in March, April, and May and is closely related to the spring runoff period. Recharge is minimal during the winter months when soil temperatures are below freezing. Water-level fluctuations are shown in the well hydrograph from observation well 104N50W4DCCC (fig. 10). Ground-water recharge was calculated for the study period from 1978 through 1985 using a well hydrograph technique and a stream hydrograph separation technique.

Well hydrograph analysis consisted of averaging the net rise in water levels measured in observation wells and multiplying by the specific yield. Analysis of water-level fluctuations in seven observation wells for 1978-85 resulted in an average annual net rise in water levels of 41.1 inches. Based on a specific yield of 0.20, the average annual effective recharge into the aquifer is about 5.9 inches or 24 percent of the average annual precipitation for the 8-year period. For example, the total net rise for the period of record for well 104N50W4DCCC (fig. 10) was 19.9 ft with an average annual net rise of 2.5 ft (30 inches) resulting in an average annual effective recharge of about 6 inches. Limitations of this method include error introduced in the determination of net water level rise due to the frequency of water-level measurements, inaccurate estimates of specific yield, and the effects of drawdown caused by nearby production wells.

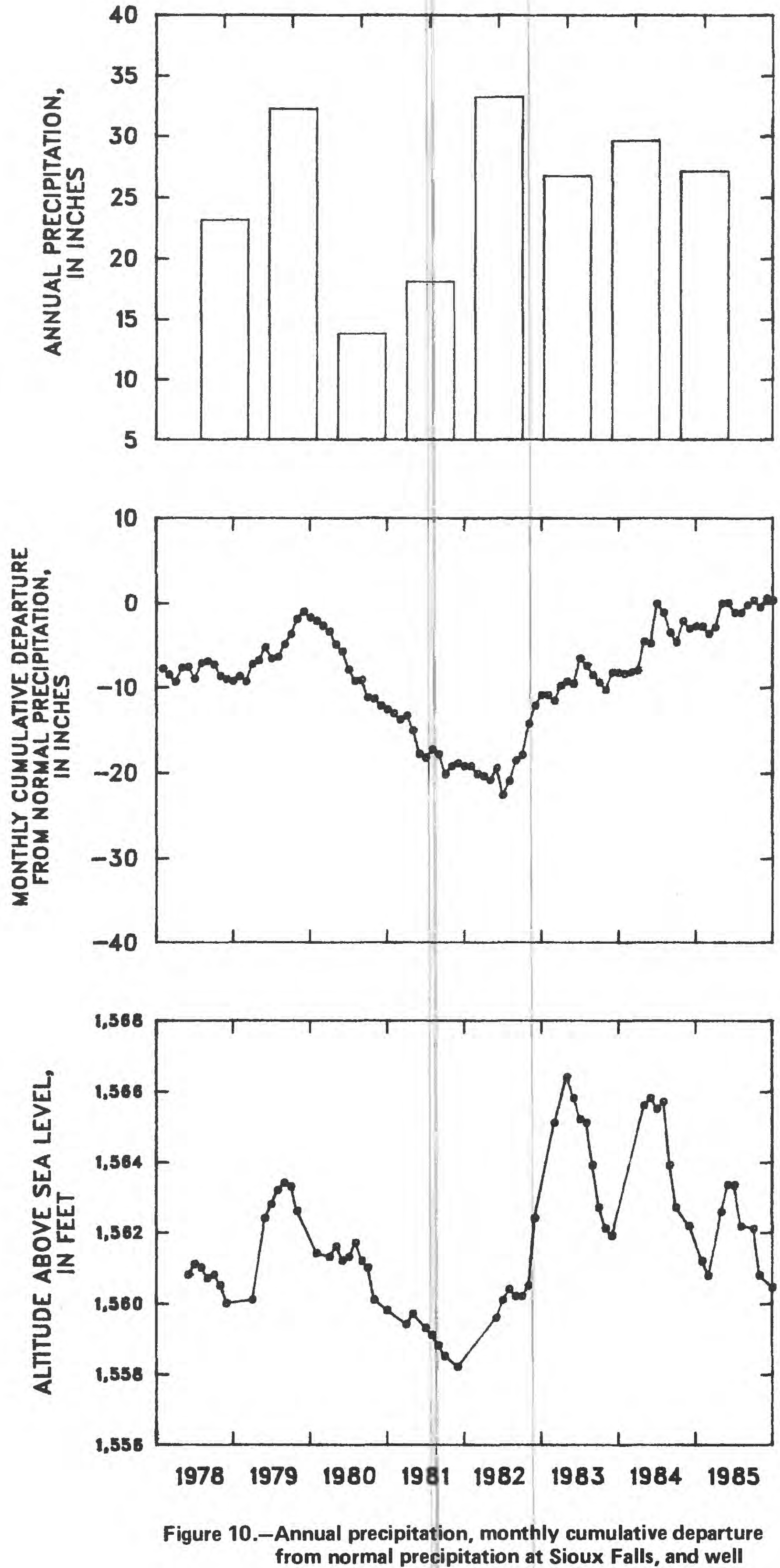

Figure 10.—Annual precipitation, monthly cumulative departure from normal precipitation at Sioux Falls, and well hydrograph for observation well 104N50W 4DCCC.

The stream hydrograph separation technique involves the separation of streamflow into ground water and surface water runoff components. Stream hydrograph separation was conducted with the use of computer code called RECHARGE, developed by Pettyjohn and Henning (1979). The RECHARGE program conducts stream hydrograph separation by three methods: (1) Fixed interval, (2) sliding interval, and (3) local minima. The comparison of ground-water recharge rates calculated from the different methods yielded similar results. Therefore, the results from the fixed interval method were used for the following discussion.

Stream hydrograph separations were conducted using daily streamflow discharge measurements from the gaging station on Skunk Creek at Sioux Falls for the water years 1978 through 1985. An example of a fixed interval hydrograph separation for 1985 is shown in figure 11. Ground-water recharge rates in the Skunk Creek drainage basin are shown in table 2. Recharge rates for the entire basin are considerably less than those calculated for the aquifer by well hydrograph analysis due to the variable permeability of the glacial deposits in the basin. Recharge from the low permeability glacial till eventually enters the high permeability outwash deposits and is subsequently discharged into streams as the ground-water runoff component of streamflow. The mean recharge rate from 1978 through 1985 (1.69 in/yr) multiplied by the area of the basin (613 mi^2) results in an average total volume of recharge of about 55,000 acre-ft/yr. Part of this volume of recharge is assumed to eventually enter the outwash deposits as underflow from the till. A volume of 55,000 acre-ft/yr over the area of the aquifer (90 mi^2) is equivalent to approximately 11 in/yr of recharge to the outwash. The reason for the discrepancy between calculated recharge by stream hydrograph separation and the well hydrograph method is not fully understood.

Table 2.--Summary of ground-water recharge rates in the Skunk Creek drainage basin based on a fixed interval streamflow hydrograph separation (1978-85)

Water year	Recharge rate (inch per year)	Total volume of recharge (acre-feet per year)	Percent of total streamflow	Annual precipitation (inch per year)
1978	0.62	20,407	48	27.07
1979	.94	30,579	47	28.32
1980	.35	11,435	63	17.21
1981	.02	797	71	15.74
1982	.32	10,510	34	27.19
1983	4.42	144,576	65	32.49
1984	5.25	171,706	59	28.87
1985	1.63	53,321	58	29.13
Mean	1.69	55,416	56	25.75

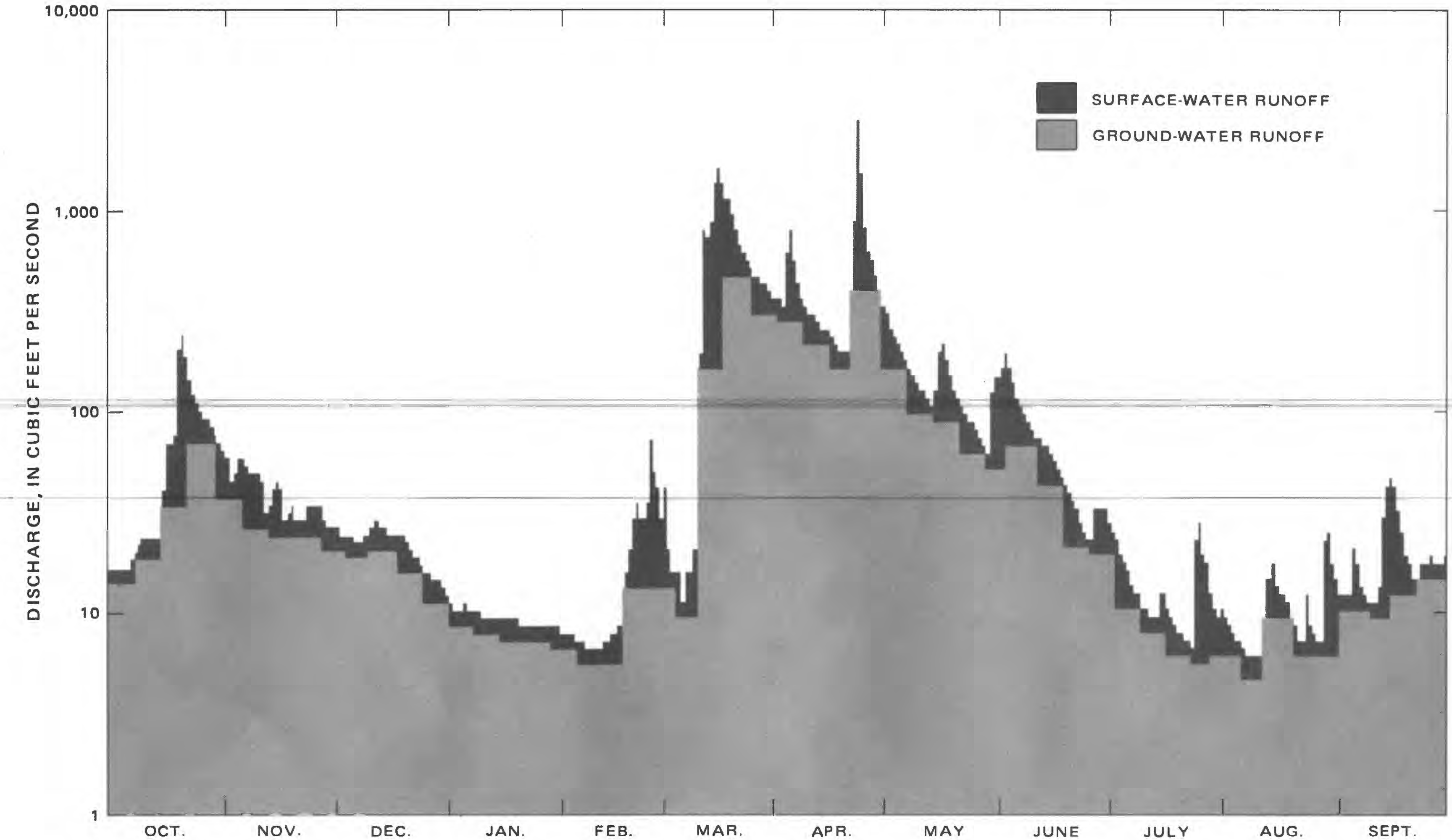

Figure 11.—Fixed interval streamflow hydrograph separation for Skunk Creek at Sioux Falls for water year 1985.

Interactions Between Ground Water and Surface Water

The Skunk Creek aquifer is in hydraulic connection with streams in the study area resulting in gaining and losing stream conditions. Stream stage and the hydraulic conductivity of the streambed are the most important factors controlling the extent of the interaction between ground water and surface water. The hydraulic gradient in the Skunk Creek aquifer generally follows the southward slope of the surface drainage with localized flow towards Skunk Creek and its tributaries (fig. 12). Natural discharge from the aquifer results from seepage to streams, evapotranspiration, and minor leakage to the Sioux Quartzite.

Gaining stream conditions predominate when the localized hydraulic gradient in the aquifer is toward the stream (fig. 13B). Ground-water discharge to streams increases in response to lowering stream stages during periods of little or no precipitation (baseflow stage) in the late summer and winter months. Losing stream conditions occur when baseflow water levels in the aquifer are below stream stage (fig. 13A) or during periods of high stream stage following precipitation and/or snowmelt runoff (fig. 13C).

Measurements of streambed infiltration rates have not been conducted on the streams in the study area. However estimates for the nearby Big Sioux River were obtained from aquifer tests conducted on wells in the Big Sioux aquifer. Streambed infiltration rates ranged from 0.4 to 1.0 ft/d (Jorgensen and Ackroyd, 1973).

Koch (1982) states that this rapid rate of streambed infiltration can be maintained if the streambed is naturally scoured by spring runoff, however, streambed infiltration can be significantly decreased by deposition of fine sediment on the streambed, which occurs during periods of decreased streamflow.

The vertical hydraulic conductivity of the streambed can be calculated from infiltration rates using the following relation:

$$K_z = Im/\Delta h$$

where K_z = vertical hydraulic conductivity of the streambed (L/T);
I = streambed infiltration rate (L^3/T);
m = thickness of the streambed sediments (L); and
Δh = head difference between the stream stage and stream sediments (L/L).

The vertical hydraulic conductivity could not be calculated from the aforementioned infiltration rates because m and Δh are unknown. However, streambed vertical hydraulic conductivities are generally lower than infiltration rates because Δh is generally larger than m. Assuming a Δh of 4 ft and a streambed thickness of 2 ft the vertical hydraulic conductivity of the streambed in the Big Sioux River ranges from 0.2 to 0.5 ft/d based on the above infiltration rates.

Jorgensen and Ackroyd (1973) collected fine-grained, silty streambed material from a diversion canal on the Big Sioux River north of the City of Sioux Falls for laboratory analysis. Slower streamflow velocities in the diversion canal resulted in the deposition of a clayey silt, which had a vertical hydraulic conductivity of 0.01 ft/d (Jorgensen and Ackroyd, 1973). Streambed hydraulic conductivities for Skunk Creek are assumed to be less than those measured in the Big Sioux River due to smaller streamflow volumes and velocities resulting in the deposition of fine-grained sediments in the streambed. A plausible range of streambed hydraulic conductivities for Skunk Creek and its tributaries is 0.01 to 0.50 ft/d.

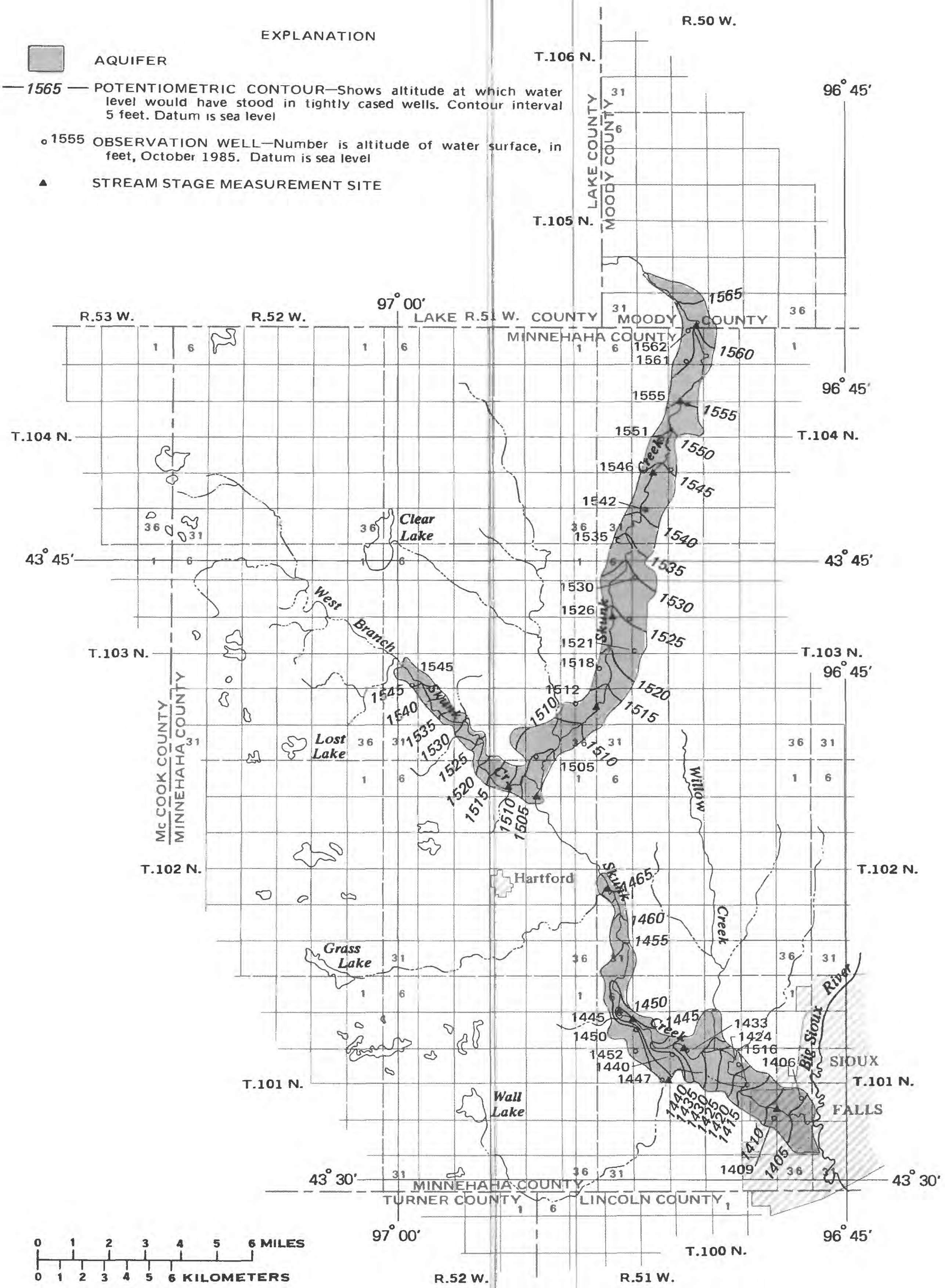

Figure 12.—Potentiometric surface of the Skunk Creek aquifer.

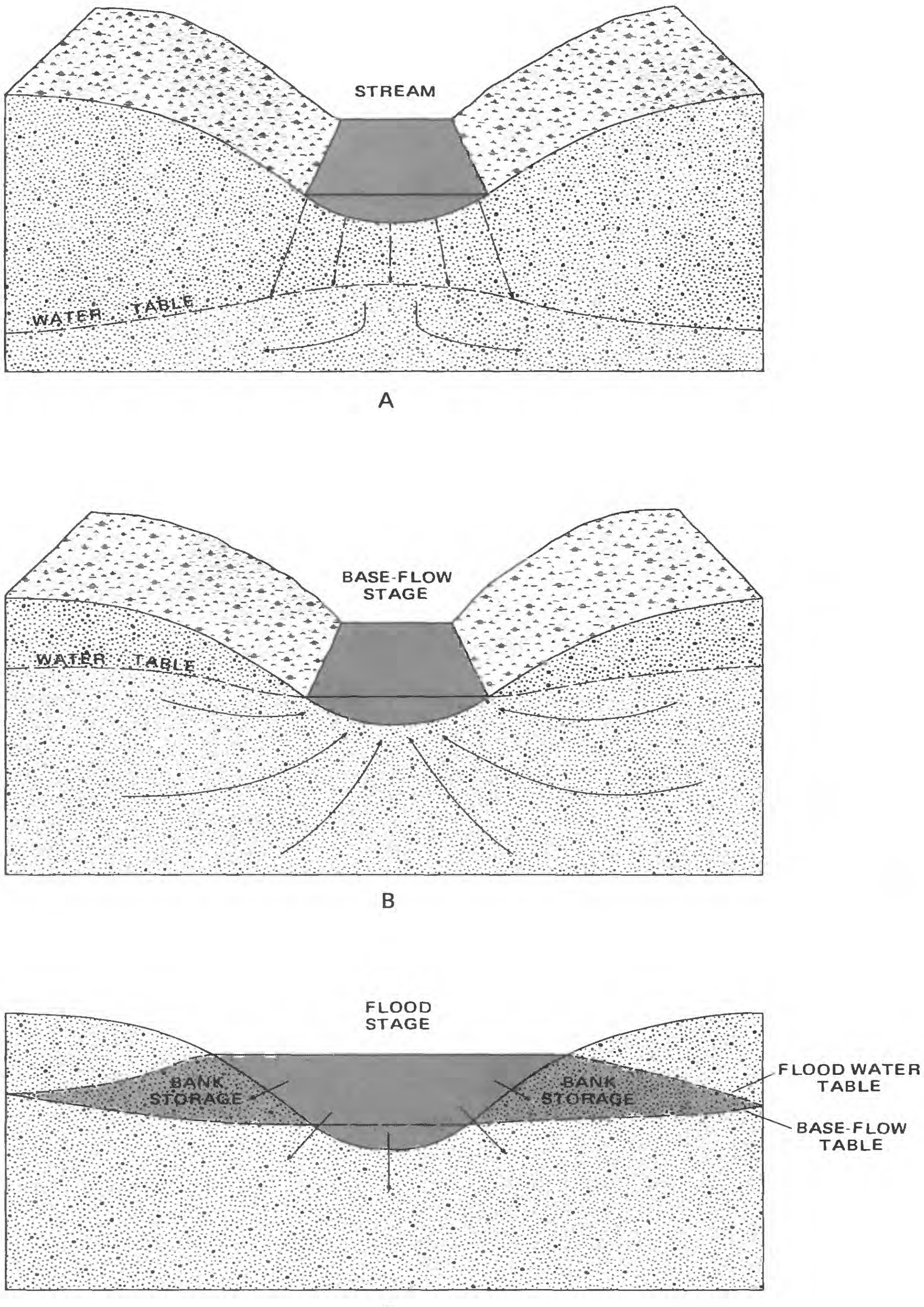

Figure 13.—Cross sections of gaining and losing streams. A. a losing stream; B. a gaining stream; C. a stream which is gaining during low flow periods but which may temporarily become a losing stream during flood stage. (From Fetter, 1988)

Water Quality

The Skunk Creek aquifer contains relatively potable water that is low in dissolved-solids content and is suitable for irrigation and public water supply use. The water has an average dissolved-solids content of 620 mg/L (milligrams per liter). It is very hard with an average carbonate hardness of 403 mg/L as $CaCO_3$ and $MgCO_3$. The range and mean concentrations for various chemical constituents for 43 ground-water analyses and 13 surface-water analyses are shown in tables 3 and 4. Concentrations of nitrate (NO_3 as N) are generally less than 1 mg/L, however, three values greater than 10 mg/L raise the mean value to 4 mg/L. Ground water with nitrate concentrations greater than 1 mg/L is generally associated with feedlot runoff or agricultural fertilizers.

The percent reacting values of common cations and anions for 43 ground-water samples and 13 surface-water samples were plotted on Piper diagrams (figs. 14 and 15). Ground-water samples were collected at 35 locations throughout the aquifer, whereas all surface-water samples were collected at the gaging station on Skunk Creek at Sioux Falls. The dissolved-solids content, dissolved sulfate concentration, and well depth for each sample location are shown in figure 16. Sulfate concentrations were largest in the vicinity of the hydraulic connection with the Wall Lake aquifer. No other spatial trends in the water quality of the aquifer were observed.

Ground-water samples were predominantly of the calcium-bicarbonate type. Surface-water samples taken from Skunk Creek at Sioux Falls contained predominantly calcium bicarbonate or calcium sulfate. Both ground water and surface water also contain significant concentrations of magnesium and small concentrations of sodium, potassium, and chloride.

Four of the ground-water samples were of the calcium-sulfate type. Of these four samples, three were collected near the hydraulic connection with the Wall Lake aquifer, which discharges calcium-sulfate water with a large dissolved-solids content to the Skunk Creek aquifer. Surface-water samples were collected at the gaging station on Skunk Creek at Sioux Falls downstream from the area of hydraulic connection with the Wall Lake aquifer. These samples contained a larger percentage of sulfate (fig. 15) and had a larger dissolved-solids content than water in the Skunk Creek aquifer due to the influence of ground-water mixing between the Skunk Creek and Wall Lake aquifers. Leakage from glacial till deposits into the aquifer also contributes small amounts of water with relatively large concentrations of sulfate and dissolved solids.

A statistical T-test analysis was conducted to determine the variance between the water quality of the Middle and Southern Skunk Creek management units. No significant hydrogeochemical difference between the two aquifer units was observed.

The chemical constituents of the water in the Skunk Creek aquifer are derived from water-mineral weathering reactions that act on glacial deposits and overlying soils. The dissolution of carbonate, sulfate, and silicate minerals contribute the dominant cations and anions in the ground water. The availability and solubility of minerals present in the aquifer and soil zone are important factors in the chemical evolution of the ground water (Freeze and Cherry, 1979).

Table 3.--Summary of chemical analyses of water from the Skunk Creek aquifer

[Chemical data obtained from the U.S. Geological Survey WATSTORE data base. Reported in milligrams per liter except as indicated]

Parameter	Number of samples	Minimum value	Maximum value	Mean value
Dissolved calcium	43	40	190	103
Dissolved magnesium	43	10	70	36
Dissolved sodium	43	2	57	16
Dissolved potassium	43	0	16	3
Dissolved chloride	43	0	66	16
Dissolved sulfate	42	20	500	129
Bicarbonate	41	120	427	316
Nitrate (as N)	28	0	53	4
Dissolved silica	8	18	30	25
Dissolved solids (sum of reported constituents)	41	216	1,188	620
Specific conductance (microsiemens per centimeter at 25 °C)	43	317	1,317	774
Hardness ($CaCO_3$ as Ca and Mg)	43	141	762	403
pH	43	7.0	8.2	7.5
Temperature (°C)	7	7.8	12.2	10.9

Table 4.--Summary of chemical analyses of surface water from Skunk Creek at Sioux Falls

[Chemical data obtained from the U.S. Geological Survey WATSTORE data base. Reported in milligrams per liter except as indicated]

Parameter	Number of samples	Minimum value	Maximum value	Mean value
Dissolved calcium	13	61	133	101
Dissolved magnesium	13	26	85	52
Dissolved sodium	13	15	65	33
Dissolved potassium	13	7	18	11
Dissolved chloride	13	8	58	25
Dissolved sulfate	13	150	490	279
Bicarbonate	13	157	354	282
Nitrate (as N)	6	.3	1	.6
Dissolved silica	13	2.2	25	10
Dissolved solids (sum of reported constituents)	13	442	1,150	848
Specific conductance (microsiemens per centimeter at 25 °C)	13	613	1,410	977
Hardness ($CaCO_3$ as Ca and Mg)	13	270	670	465
pH	13	7.6	8.3	7.9
Temperature (°C)	13	0	29	13

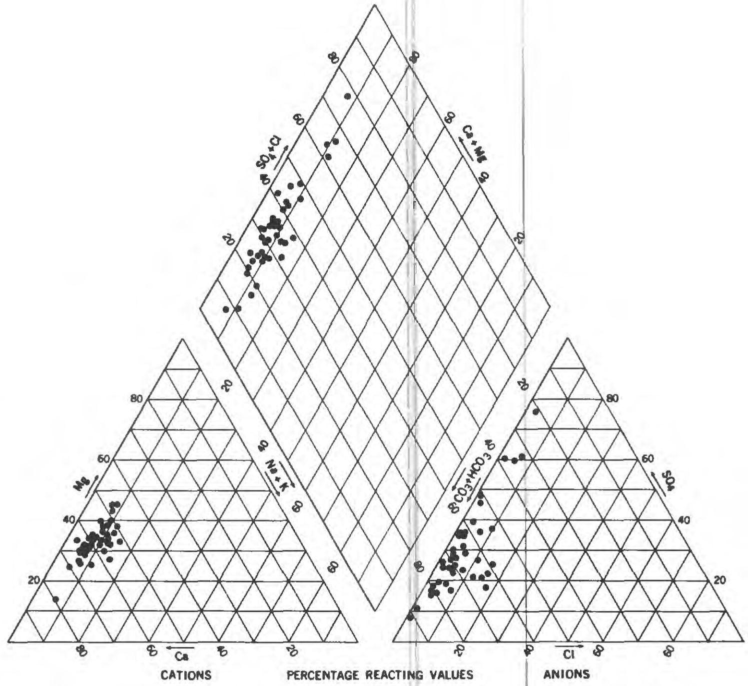

Figure 14.—Piper diagram of 43 water analyses from the Skunk Creek aquifer.

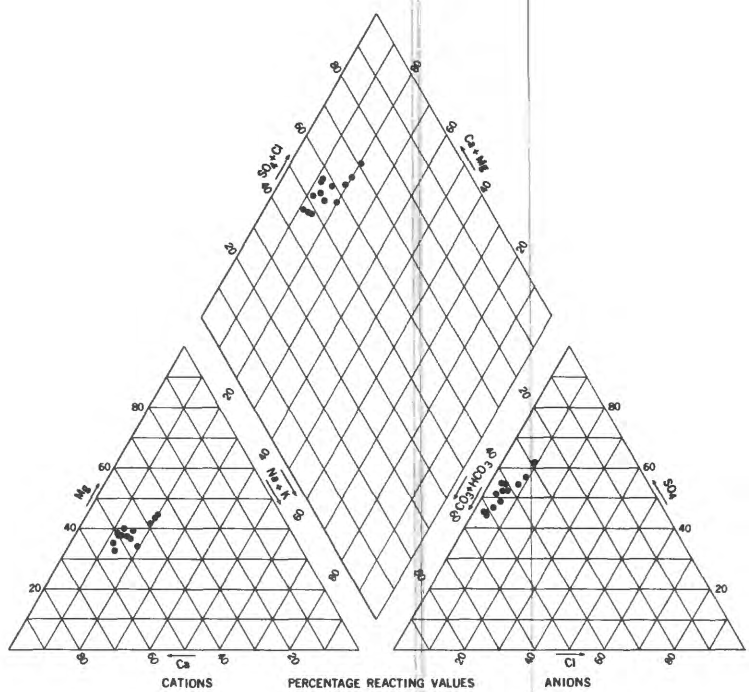

Figure 15.—Piper diagram of 13 water analyses from Skunk Creek at Sioux Falls.

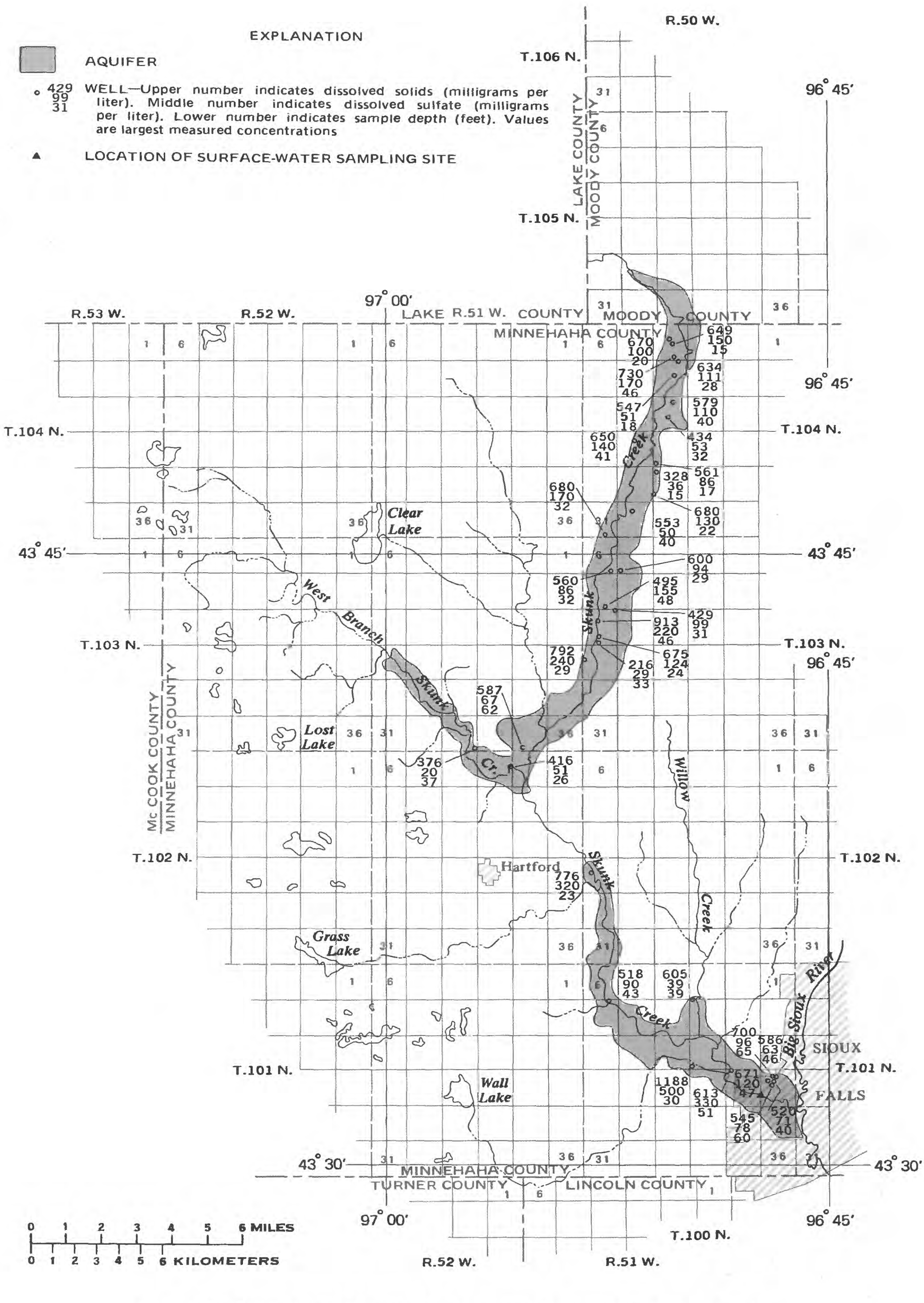

Figure 16.—Distribution of dissolved solids and sulfate in the Skunk Creek aquifer.

Table 5.--Summary of water saturation states with respect to various minerals

Sample location	Anhydrite	Gypsum	Aragonite	Calcite	Dolomite	Chalcedony	Quartz
101N50W 7AAB	-1.79	-1.45	0.26	0.56	0.85	0.15	0.69
101N50W 3CCC	-2.15	-1.77	.10	.21	.08	.30	.85
102N51W 3ADD	-2.08	-1.75	-.24	.05	-.09	.24	.77
103N50W18CDA	-1.58	-1.22	-.48	-.18	-.71	.34	.88
103N50W 7DCD	-1.50	-1.15	-.13	.17	-.17	.24	.77
103N51W33DDD	-2.56	-2.21	-.12	.17	.24	.34	.88
103N51W35CDCC	-1.85	-1.49	-.38	.07	-.55	.40	.95
104N50W 9ABA	-1.63	-1.23	-.35	.03	-.46	.43	.98

The saturation states of eight ground-water samples with respect to various common minerals are shown in table 5. The saturation states were calculated on only eight samples because of the limited availability of dissolved silica concentrations. The saturation indices were calculated using the WATEQF computer code developed by Plummer, Jones, and Truesdell (1976). The WATEQF program was designed to thermodynamically calculate the distribution of inorganic species in natural waters using ionic concentrations taken from chemical analyses and in-situ pH, redox potential, and temperature measurements. The program simulates low temperature geologic environments in which water-mineral chemical interactions are occurring. The water saturation index with respect to a particular mineral is defined by the following relation:

$$SI = \log IAP/Ksp$$

where SI = saturation index;
IAP = ion activity product; and
Ksp = solubility product.

Saturation indices greater than zero indicate that the water is supersaturated and that conditions are thermodynamically feasible for precipitation of a particular mineral. A saturation index equal to zero represents equilibrium conditions, whereas a saturation index less than zero indicates that the water is undersaturated and dissolution may occur.

Sulfate Mineral Dissolution

The dissolution of soluble sulfate minerals, such as gypsum, contribute the sulfate component and a portion of the calcium component of the water. Evidence for the dissolution of gypsum is shown by the linear relation between reacting values of calcium and sulfate (fig. 17). Despite the large solubility of gypsum, the water saturation indices show undersaturated conditions (dissolution) with respect to these minerals. This is possibly due to the limited availability of these minerals in the aquifer and soil zone.

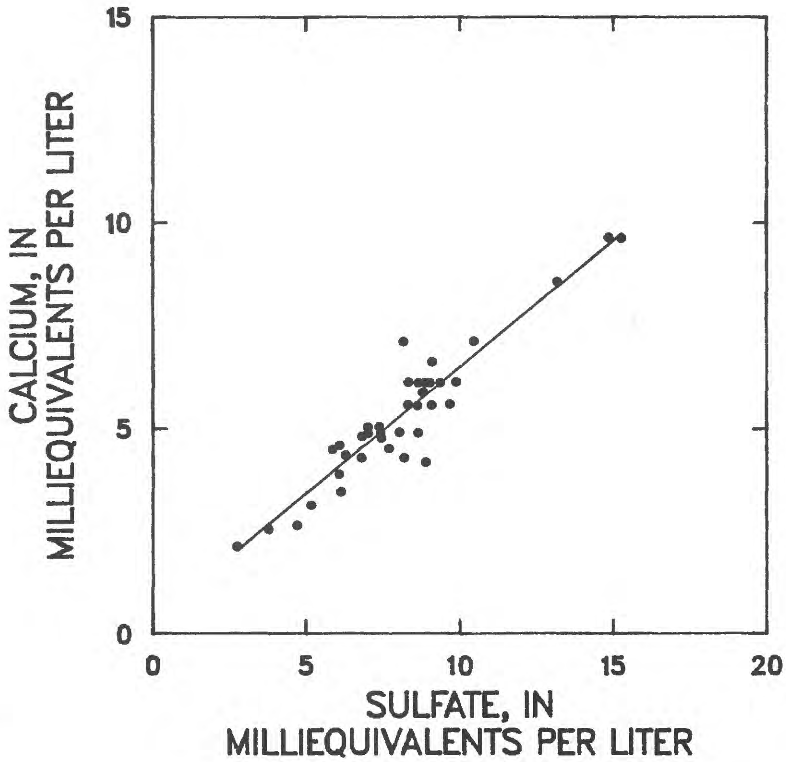

Figure 17.—Linear relation between reacting values of calcium and sulfate.

Carbonate Mineral Dissolution

The dissolution of carbonate minerals, such as calcite, aragonite, and dolomite, are responsible for the magnesium, bicarbonate, and a portion of the calcium present in the water. The linear relation between reacting values of residual calcium plus magnesium and bicarbonate is evidence for the dissolution of dolomite (fig. 18). Residual reacting values for calcium were obtained by assuming that all sulfate is derived from the dissolution of gypsum. Therefore, subtracting the sulfate reacting values (milliequivalent per liter) from the calcium reacting values yields the residual calcium available from other mineralogic sources. Four of the samples had no residual calcium and do not appear on figures 18 and 19. The lack of residual calcium is possibly due to cation exchange with smectitic clays or a cation-anion imbalance caused by sample analysis error.

A less prominent linear relation between residual calcium and bicarbonate (fig. 19) indicates that the dissolution of calcite and aragonite probably is less prominent. Saturation indices for aragonite, calcite, and dolomite are all at or near equilibrium. This indicates that carbonate minerals are undergoing dissolution and therefore contribute significant amounts of calcium, magnesium, and carbonate ions to the water.

The majority of the carbonate minerals probably is dissolved under open-system conditions in the soil zone and the upper part of the aquifer. Recharge water derived from precipitation is charged with atmospheric carbon dioxide resulting in the formation of carbonic acid. Carbon dioxide provided from the decay of organic matter and respiration by plant roots further enhances the formation of carbonic acid (Freeze and Cherry, 1979). The low pH (less than 7) of the recharge water results in rapid dissolution rates of carbonate minerals. The buffering capacity of the carbonate-dominated aquifer system appears to rapidly increase the pH of infiltrating waters. This is evidenced by the rapid increase in pH, with increasing depth in the soil zone.

Silicate Mineral Dissolution

The presence of silica in the ground water is indicative of the dissolution of silicate minerals present in igneous and metamorphic rock fragments in the outwash deposits (Hem, 1970). Dissolution of silicate minerals other than quartz and amorphous silica during the chemical evolution of the ground water has resulted in supersaturated (precipitation) conditions with respect to quartz and chalcedony (table 5). The dissolution of ferromagnesian silicate minerals probably contributes to the magnesium content of the water. The chemical weathering of quartz and amorphous silica generally does not increase the amount of silica present in ground water (Freeze and Cherry, 1979). Therefore, chemical weathering of the Sioux Quartzite probably does not contribute significant amounts of silica to the ground water.

MODEL DESCRIPTION AND DEVELOPMENT

A numerical computer model was used to simulate ground-water flow in the Skunk Creek aquifer. The model is based on a numerical representation of the previously discussed hydrologic and geologic characteristics of the Skunk Creek aquifer. The U.S. Geological Survey MODFLOW computer code developed by McDonald and Harbaugh (1984) was used to simulate ground-water flow by solving partial differential equations using finite-difference methods. The MODFLOW computer code, as the name implies, is a modular model with modules or packages to simulate well pumpage, river leakage, evapotranspiration, recharge, and subsurface drainage.

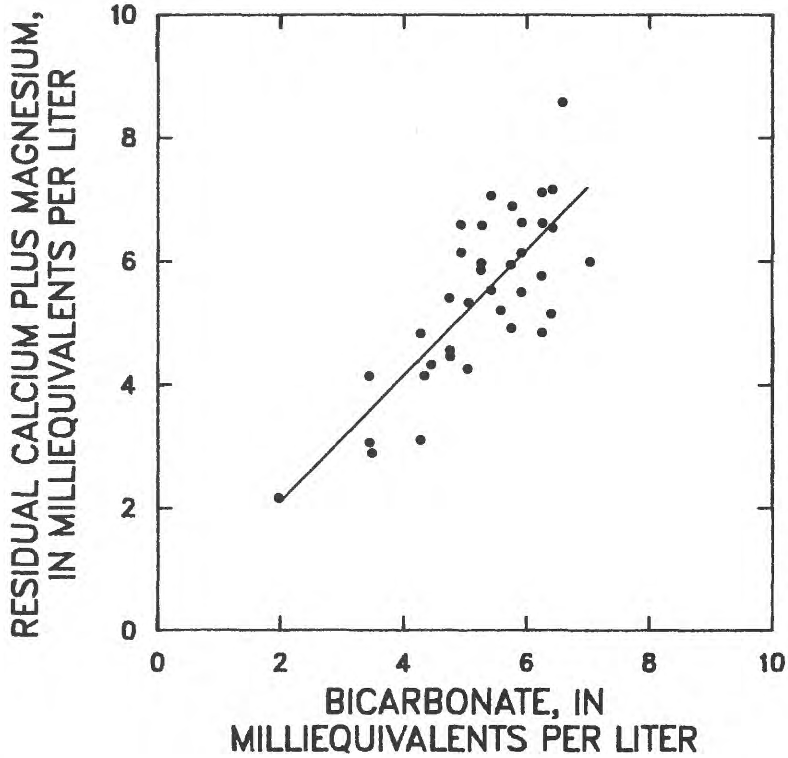

Figure 18.—Linear relation between reacting values of residual calcium plus magnesium and bicarbonate.

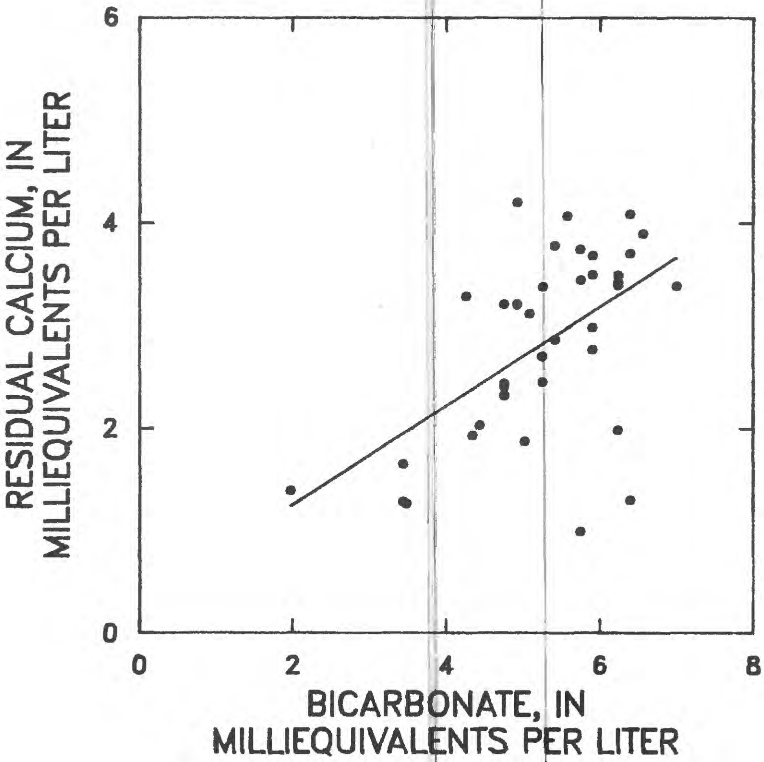

Figure 19.—Relation between reacting values of residual calcium and bicarbonate.

Model development consisted of preparing a base map of the study area illustrating the location of aquifer boundaries and streams. A grid of 64 columns and 100 rows was superimposed on the base map (fig. 20) with each cell in the grid 0.25 mi on a side. The center of each cell is referred to as a node. The model contains 484 active nodes each representing 0.0625 mi^2 of the aquifer. A numerical value for land surface elevation, aquifer base elevation, top of aquifer elevation, water-table elevation, recharge, evapotranspiration, storage, and aquifer hydraulic conductivity was assigned to each active node in the model. Grid cells outside the aquifer boundaries were defined as inactive and therefore act as no-flow boundaries.

River stage elevations represented in the model are based on stream stage-discharge relation and stream stage measurements taken at bridges throughout the study area. The MODFLOW computer code calculates the aquifer transmissivity for each node by subtracting the aquifer base elevation from the water-table elevation and multiplying the result by the hydraulic conductivity.

Model Assumptions

Development of the numerical model involved a number of hydrogeologic assumptions, which follow:

1) The aquifer material is isotropic and homogenous in each active node in the grid matrix.

2) Ground-water flow is laminar, horizontal, and two-dimensional.

3) The Skunk Creek aquifer is hydraulically connected to the Big Sioux River, Skunk Creek, and its tributaries.

4) The aquifer is unconfined (water table) except in the area of the hydraulic connection with the Wall Lake aquifer where the aquifer is confined (artesian) (fig. 21).

5) Recharge to the aquifer from the Wall Lake aquifer and the Northern Skunk Creek management unit is constant and does not fluctuate due to seasonal variations in hydraulic gradient.

6) Recharge to the aquifer occurs from the infiltration of precipitation, leakage from streams, and discharge from the Wall Lake and North Skunk Creek management unit aquifers.

7) Recharge to the aquifer occurs at equal rates in all areas of the aquifer that are unconfined.

8) No recharge to the aquifer occurs from the glacial till and the Sioux Quartzite.

9) Discharge from the aquifer results from ground-water runoff to streams, evapotranspiration, and irrigation pumpage.

10) Stream stage elevation remains constant for the time period of each model simulation.

11) Evapotranspiration is a linear function of depth below land surface. Evapotranspiration is greatest at land surface and decreases to zero at an assigned depth.

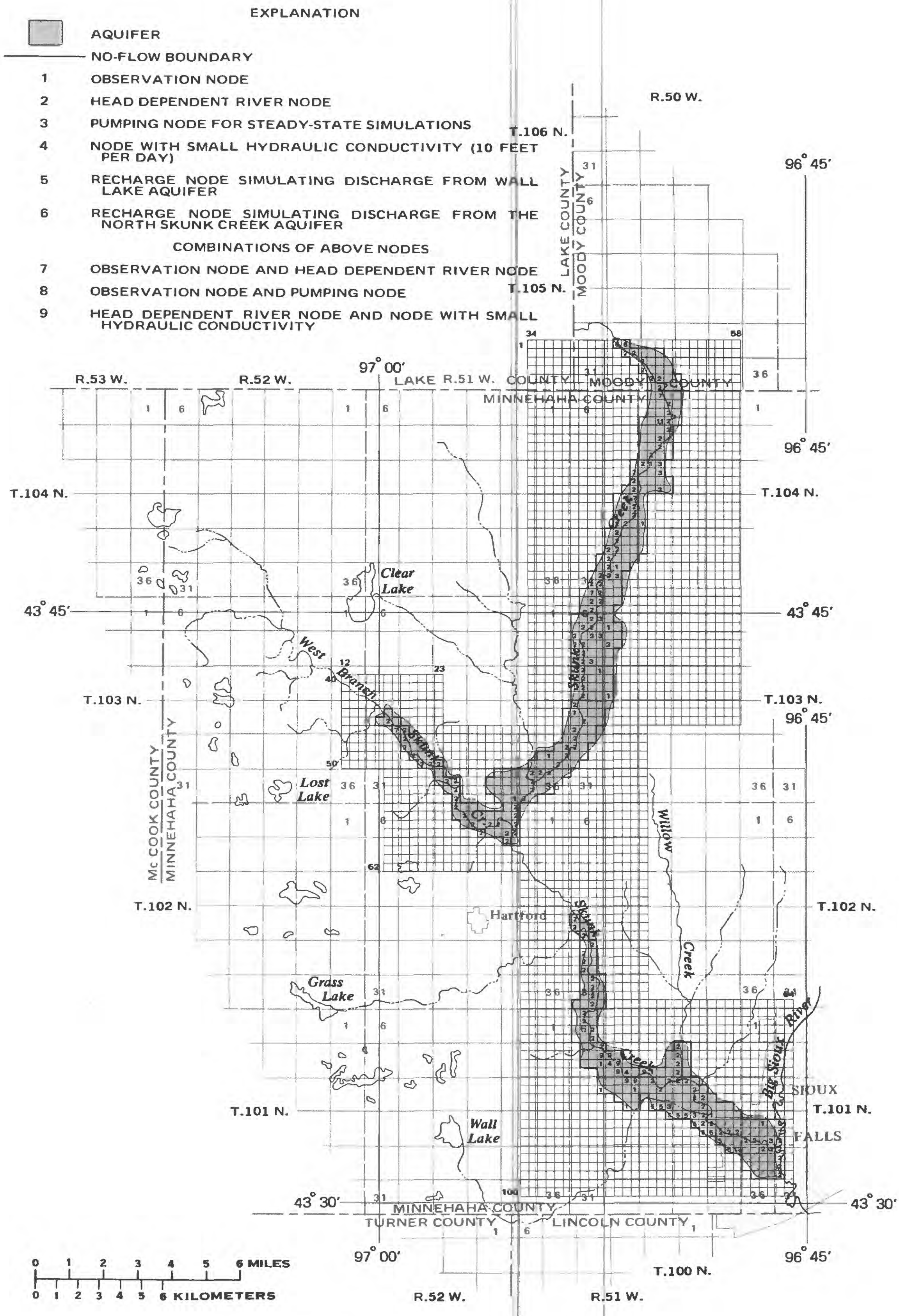

Figure 20.—Skunk Creek aquifer model area and model grid.

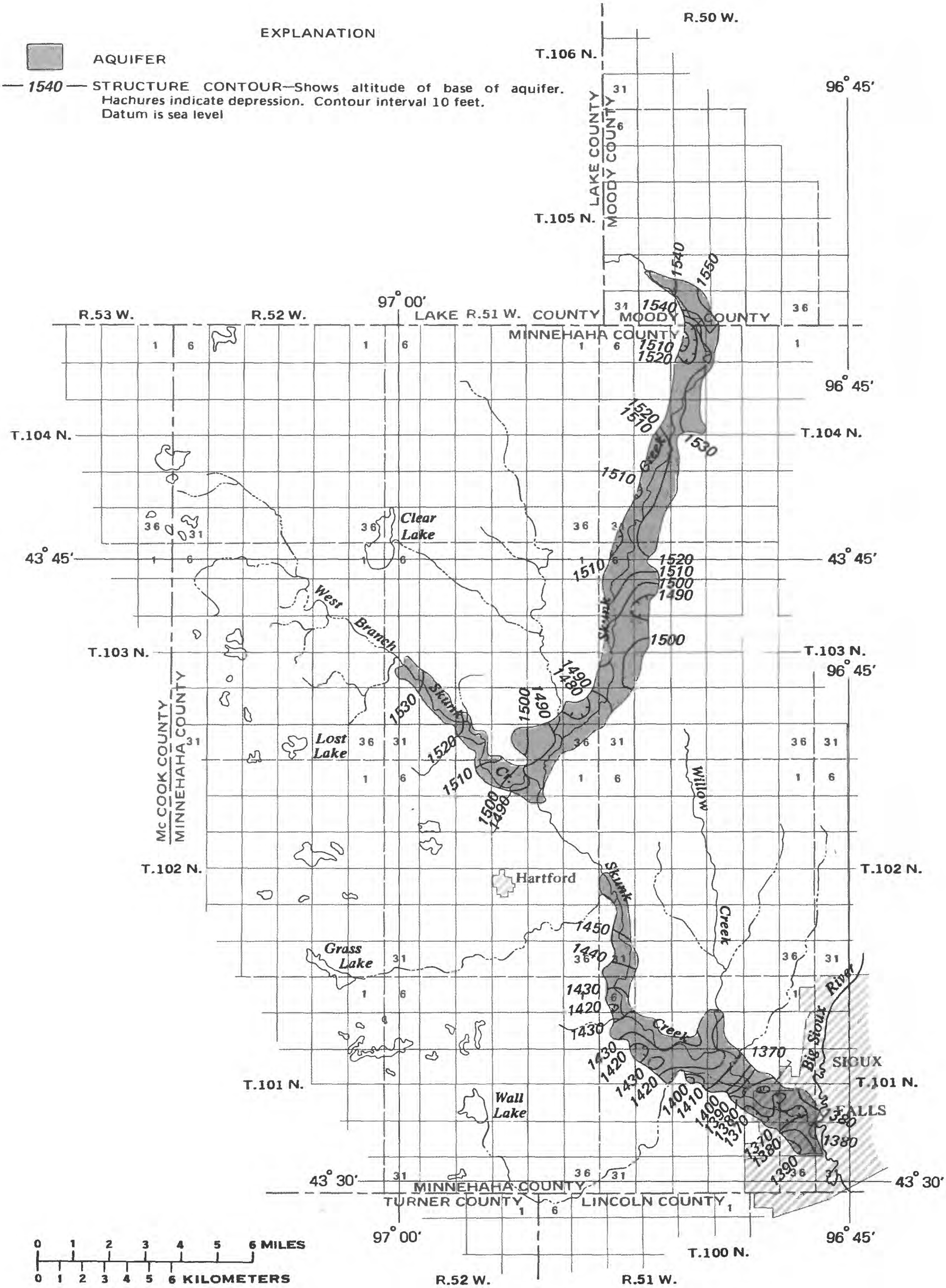

Figure 21.—Altitude of the base of the Skunk Creek aquifer.

12) Water withdrawn from the aquifer by pumpage does not return to the aquifer as recharge.

13) The aquifer transmissivity is head-dependent except in those nodes where the aquifer is confined.

Model Data

The following discussion describes the methods and values used to numerically represent the Skunk Creek aquifer in the model.

Land surface elevations for each node were obtained by superimposing a 0.25-mi grid over 7.5 minute U.S. Geological Survey topographic maps for the study area. The most frequently occurring elevation in each grid cell was used as the average land surface elevation in that particular model node.

The elevation of the bottom of the aquifer was determined from lithologic test-hole logs in the study area. The bottom of the aquifer was generally considered to be the first glacial till or bedrock surface encountered during drilling (excluding clay lenses). Nodal values for the aquifer base elevation were assigned on the basis of test-hole data for that node. Where test-hole data were unavailable, the aquifer bottom elevation was determined by interpolation from nearby test holes. In nodes where the aquifer bottom elevation varied considerably, known elevations were averaged to obtain the nodal value. Outwash deposits adjacent to streams with a bottom elevation above stream stage were generally excluded from the model area. These deposits were not considered as part of the aquifer due to their relative hydraulic separation from nearby streams. A contour map of the aquifer bottom elevations used in the model is shown in figure 21.

The top of the aquifer was represented in the unconfined Skunk Creek aquifer by land surface elevations. Numerical values assigned to represent the top of the aquifer are not used in calculations conducted by the MODFLOW computer code unless the aquifer is confined in that particular node. Available lithologic logs were used to assign top of aquifer elevations to the 10 nodes representing the hydraulic connection with the confined Wall Lake aquifer.

Hydraulic conductivities used in the model were based on grain-size determinations obtained from test-hole data (table 1). A plausible range of hydraulic conductivity for the outwash deposits which comprise the Skunk Creek aquifer is from 70 to 2,000 ft/d. Hydraulic conductivities represented in the model range from 10 to 400 ft/d with a constant value of 400 ft/d assigned to all nodes representing the unconfined Skunk Creek aquifer. A value of 300 ft/d was assigned to the 10 nodes that represent the hydraulic connection with the Wall Lake aquifer. A hydraulic conductivity of 10 ft/d was assigned to 9 nodes in which Skunk Creek has cut down through the aquifer into glacial till as illustrated in figure 6.

Storage terms assigned in the model consist of a specific yield of 0.20 and a storage coefficient of 0.001. A specific yield of 0.20 was assumed for the Skunk Creek aquifer as described in the section on "Aquifer Characteristics." The storage coefficient of 0.001 for the Wall Lake aquifer is an estimate based on values typically assigned to leaky, artesian aquifers (Heath, 1983). The MODFLOW computer code uses the designated storage coefficient value for those nodes in which the aquifer is confined and the assigned value for specific yield for unconfined conditions.

Recharge to the aquifer is represented in the model as occurring from infiltration of precipitation and discharge from the Wall Lake and Northern

Skunk Creek management unit aquifers. Recharge to the aquifer by precipitation was calculated using the well hydrograph technique described in the section on "Ground-Water Recharge."

Underflow from the Wall Lake and Northern Skunk Creek management unit aquifers was simulated using recharge wells along the boundaries where the aquifers interact. Recharge rates in these wells were set equivalent to the calculated flow across the aquifer interfaces, which were about 14 acre-ft/yr for the Northern Skunk Creek management unit aquifer and 470 acre-ft/yr for the Wall Lake aquifer.

Rivers in the study area were represented in the model by assigning a value for river stage, river bottom elevation, and river reach conductance for each river node in the river module of the MODFLOW computer code (fig. 20).

River stage elevation for each node along the length of the river was determined by interpolating between river stage measurement points. River stage was measured at three gaging stations and several bridges throughout the study area during 1985. River stage and discharge measurements are not available prior to 1985, except at the gaging station on Skunk Creek at Sioux Falls. Therefore, river stage elevations for simulations prior to 1985 were determined using 1985 river stage measurements that were adjusted using river stage-discharge rating tables for the gaging station on Skunk Creek at Sioux Falls. For example, river stage measurements taken on May 23, 1985, at a discharge rate of 90 ft^3/s were used for the steady-state simulation (1978-85 average monthly streamflow of 132 ft^3/s) with an adjustment factor of +0.28 ft.

The river bottom elevation was obtained by subtracting an estimated average river depth from the river stage elevation. Estimated river depth for the Big Sioux River is 4 ft, Skunk Creek is 3 ft, West Branch Skunk Creek is 2 ft, and Willow Creek is 2 ft.

The MODFLOW computer code requires a conductance term for each river reach (river node) in the river module. Conductance is calculated using the following relation:

$$C = KLW/M$$

where C = conductance of the river reach (L^3/T);
K = vertical hydraulic conductivity of the riverbed (L/T);
L = length of the river reach (L);
W = width of the river reach (L); and
M = thickness of the riverbed (L).

A riverbed hydraulic conductivity of 0.05 ft/d was used to calculate the conductance for Skunk Creek, West Branch Skunk Creek, and Willow Creek, whereas 0.5 ft/d was used for the Big Sioux River. These values are estimates based on the plausible range of riverbed hydraulic conductivity as previously discussed. The length of each river reach in each model node was measured on U.S. Geological Survey 7.5 minute topographic maps. Average estimated river width for the Big Sioux River is 80 ft, Skunk Creek is 40 ft, West Branch Skunk Creek is 25 ft, and Willow Creek is 20 ft. Riverbed thickness was assumed to be 1 ft for all river reaches.

The maximum potential evapotranspiration rate was set to 70 percent of the average Class A pan evaporation rates for various simulation periods. For example, the mean annual Class A pan evaporation for the period of 1978 through 1985 was 46 in/yr which was simulated using a maximum evapotranspiration rate of 70 percent of this value (32 in/yr). Seventy percent of Class A pan evaporation is approximately equal to the free-water surface evaporation as described by Farnsworth and Thompson (1982).

Evapotranspiration in the model was represented to an extinction depth of 5 ft below land surface. No evapotranspiration was simulated at depths greater than 5 ft due to the predominantly shallow rooted vegetation in the study area. The maximum potential evapotranspiration rate is provided to the model and the evapotranspiration is subsequently calculated for each node based on the depth to water below land surface. If the water table is below the extinction depth, no evapotranspiration is simulated for that node.

Discharge from the aquifer by pumpage was simulated using discharge wells in the appropriate model nodes (fig. 20). Withdrawal rates were based on average reported irrigation pumpage for the simulation period and were assumed constant throughout the time period represented in each model simulation.

MODEL CALIBRATION

Steady-State Condition

An aquifer is considered in a steady-state (equilibrium) condition when inflow to the aquifer equals outflow with no change in storage. Although water levels in the Skunk Creek aquifer fluctuate in response to precipitation, no long-term declines are evident (fig. 22), indicating that the aquifer is in a long-term steady-state (equilibrium) condition. In a steady-state model, the storage coefficient and specific yield are set equal to zero resulting in no change in aquifer storage. Calibration of the steady-state model was conducted using average hydrologic conditions from 1978 through 1985. The mean annual precipitation for this period was 25.5 inches which is slightly greater than the long-term average of 25.4 inches.

Average water levels, aquifer recharge, evapotranspiration, stream stage, stream baseflow, and irrigation well pumpage over the 8-year period were used for the steady-state calibration procedure.

Hydrologic parameters were adjusted within their plausible range as previously described. The model was considered calibrated when simulated ground-water discharge to streams was approximately equivalent to average baseflow conditions and a best fit between model simulated heads and observed water levels was obtained. The resulting potentiometric surface is shown in figure 23.

Hydraulic conductivity of the aquifer and riverbed were adjusted in the calibration procedure with variable results. Adjustments to aquifer hydraulic conductivity generally were ineffective in improving the agreement between simulated and observed water levels. However, in the area where Skunk Creek has cut down into glacial till (Section 8, T. 101 N., R. 50 W.), reducing the hydraulic conductivity from 400 to 10 ft/d significantly improved the agreement. Riverbed hydraulic conductivity was varied from 0.01 to 1.0 ft/d in Skunk Creek and from 0.1 to 1.0 ft/d in the Big Sioux River. The best agreement between simulated and observed water levels and simulated and observed ground-water discharge to streams was obtained using a riverbed hydraulic conductivity of 0.05 ft/d for Skunk Creek, West Branch Skunk Creek, and Willow Creek, and 0.5 ft/d for the Big Sioux River. Decreasing the riverbed hydraulic conductivity in the Big Sioux River caused simulated heads

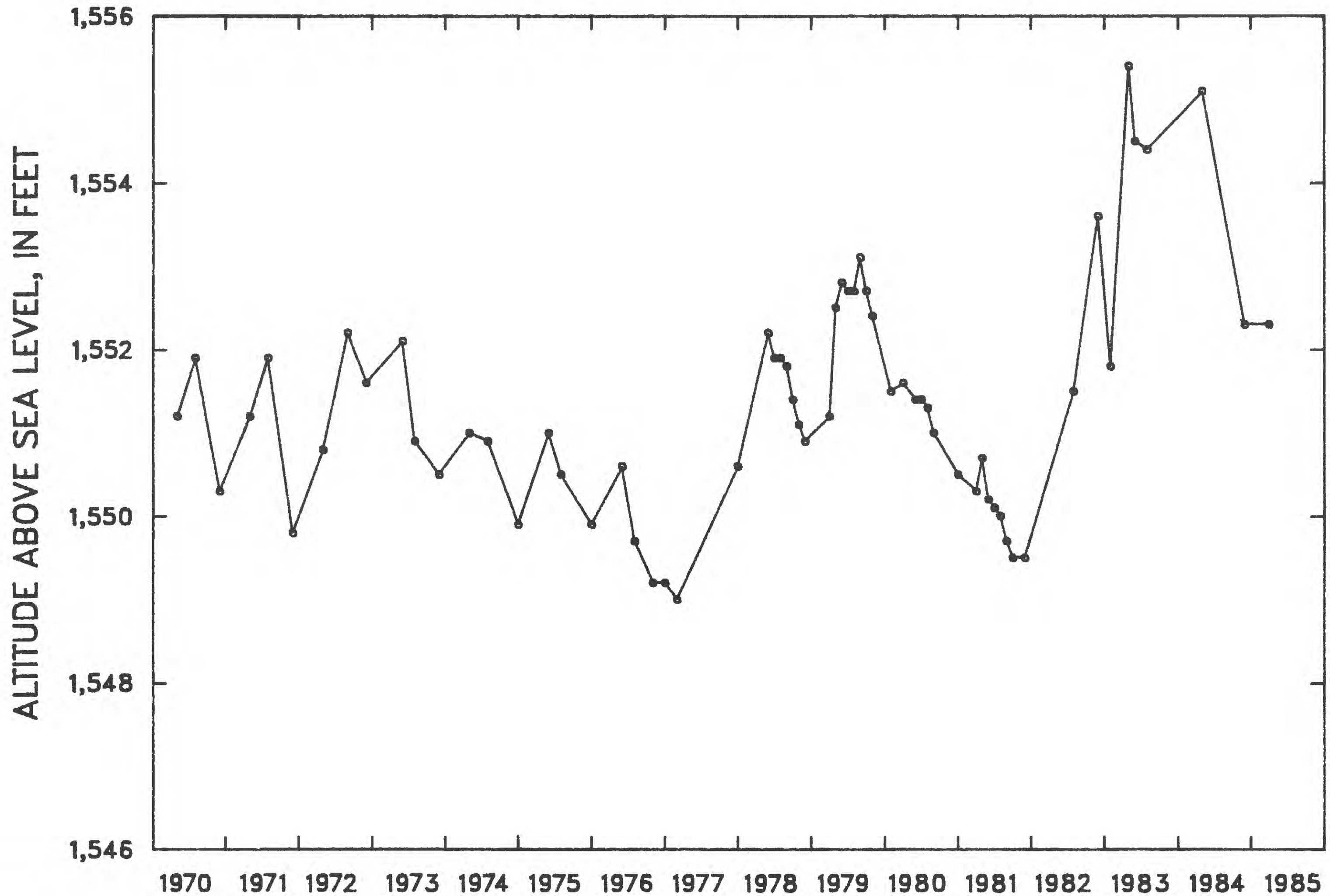

Figure 22.—Well hydrograph for observation well 104N50W20AABA.

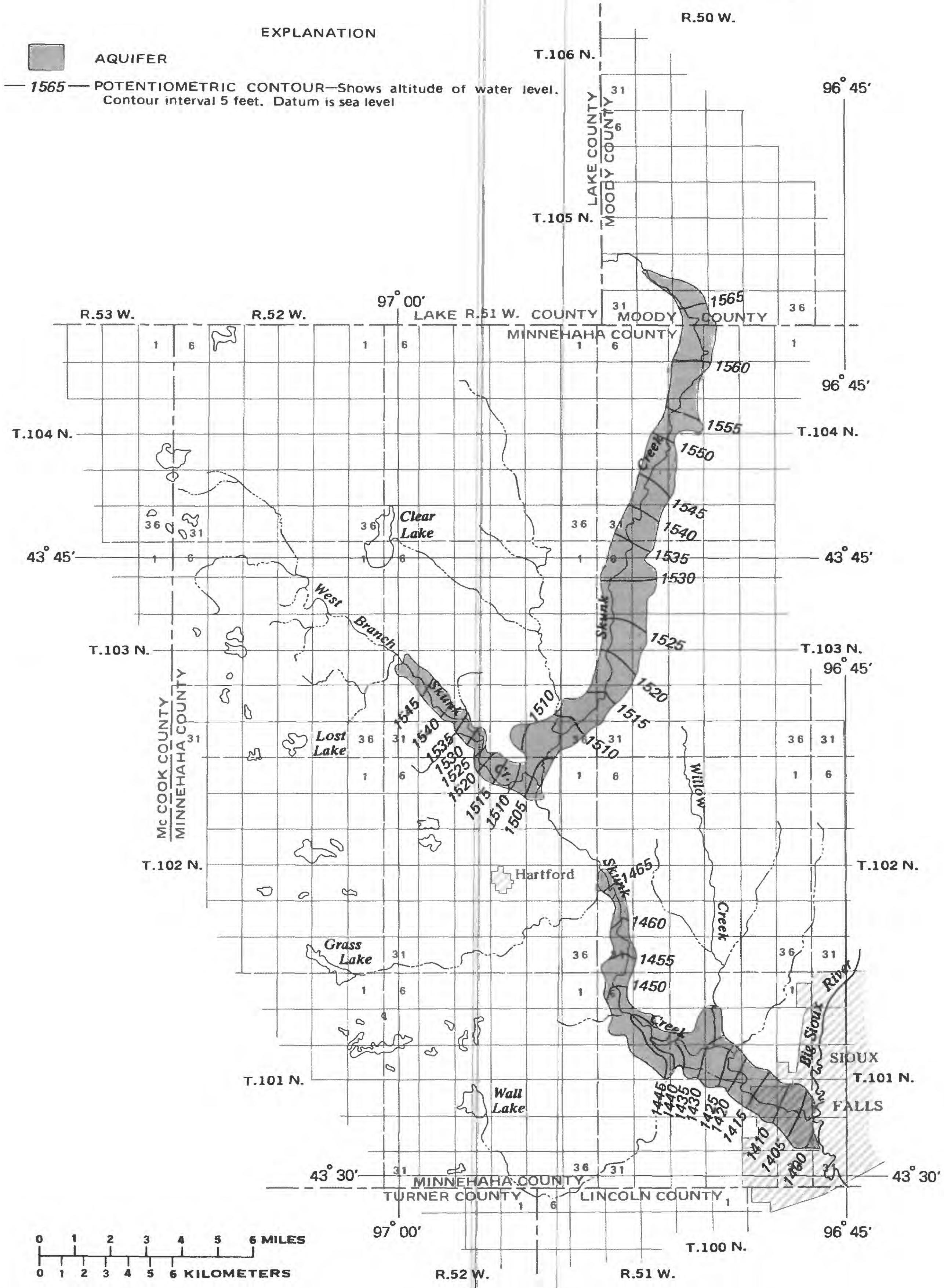

Figure 23.—Simulated steady-state potentiometric surface of the Skunk Creek aquifer.

to increase about 1 to 3 ft directly upgradient from the river. The best fit between model simulated heads and observed water levels was obtained using the following values for the hydrologic parameters:

Aquifer hydraulic conductivity:	10 - 400 ft/d
Streambed vertical hydraulic conductivity:	
Skunk Creek, West Branch Skunk Creek and Willow Creek:	0.05 ft/d
Big Sioux River:	0.5 ft/d
Recharge:	6.0 in/yr
Maximum evapotranspiration rate:	32 in/yr
Evapotranspiration extinction depth:	5 ft

The algebraic mean difference between model simulated heads and observed water levels was 0.03 ft and the absolute mean difference between model-simulated heads and observed water levels was 1.25 ft based on data from 26 observation wells. The algebraic mean difference between heads was obtained by the summation of positive or negative head differences and dividing by the number of observations (n = 26). Similarly, the absolute mean difference in heads was obtained by the summation of absolute head differences and dividing by 26. Water-level measurements taken from seven observation wells were available for the complete 1978-85 study period. Water-level measurements for an additional 19 wells were available from November 1984 to December 1985. To allow the use of all 26 wells for the calibration procedure, 1984-85 water-level measurements were corrected for the 1978-85 calibration period. The amount of water-level adjustment (-0.26 ft) was obtained by subtracting the difference between the November 1984 - December 1985 average water levels from the 1978-85 average water levels for the seven observation wells with a complete record.

The steady-state simulation provided a hydrologic budget (table 6) based on average hydrologic conditions from 1978 through 1985. Recharge to the aquifer by precipitation is the largest inflow component of the hydrologic budget, whereas ground-water recharge by streams comprises only 10 percent and inflow from the Wall Lake and Northern Skunk Creek management unit aquifers comprises only 4 percent of the inflow budget. Evapotranspiration and discharge to streams were the largest outflow components from the aquifer. Irrigation pumpage accounts for only 4 percent of the outflow.

Table 6.--Simulated steady-state hydrologic budget for the 30-square-mile aquifer

Budget component	Rate (acre-feet per year)	Percent
INFLOW		
Recharge by precipitation	9,506	86
Recharge from streams	1,086	10
Ground-water underflow	485	4
Total inflow	11,077	100
OUTFLOW		
Evapotranspiration	4,931	44
Discharge to streams	5,741	52
Irrigation pumpage	405	4
Total outflow	11,077	100

Steady-State Sensitivity Analysis

The sensitivity of the steady-state model was tested by varying aquifer hydraulic conductivity, riverbed hydraulic conductivity, recharge, evapotranspiration rate, and the evapotranspiration extinction depth. The computer-simulated heads that resulted from the sensitivity simulations were compared to observed water levels in 26 observation wells. The results are shown in table 7.

The model was most sensitive to changes in recharge and riverbed hydraulic conductivity. Increasing aquifer recharge by 50 percent (from 6 to 9 in/yr) caused the simulated heads to rise an average of 1.06 ft. Decreasing aquifer recharge by 50 percent (from 6 to 3 in/yr) caused water levels to drop an average of 1.23 ft. Increasing the riverbed hydraulic conductivity by 100 percent (from 0.05 to 0.5 ft/d to 0.1 to 1.0 ft/d) resulted in an average water-level decline of 0.19 ft, whereas a decrease of 90 percent (from 0.05 to 0.5 ft/d to 0.005 to 0.05 ft/d) caused simulated heads to rise an average of 1.58 ft.

The model was least sensitive to changes in aquifer hydraulic conductivity and maximum evapotranspiration rates. An increase in aquifer hydraulic conductivity by 30 percent caused simulated water levels to decline an average of 0.27 ft and an equivalent decrease resulted in an average water-level rise of 0.40 ft.

Transient Model Calibration

A transient model allows for water to be added or removed from aquifer storage in quantities that are related to the aquifer storage coefficient or specific yield. The model was tested under transient conditions by simulating actual hydrologic conditions for 1985. Average water levels, aquifer recharge, evapotranspiration, stream stage, and irrigation well pumpage for each month in 1985 were used for the transient model calibration procedure. Initial head conditions for the January 1985 simulation were obtained from a series of two annual and 12 monthly transient simulations prior to 1985. Annual simulations for 1982 and 1983, as well as monthly simulations for 1984, were conducted using average hydrologic conditions for each simulation period. Water levels derived from the steady-state solution were used as initial head conditions in the 1982 simulation and the simulated water levels for 1982 were used as the starting head conditions for the 1983 simulation. The monthly simulations for 1984 were conducted using the simulated water levels from the previous simulation as initial head conditions. Initial head conditions for the 1985 monthly simulations were established in the same manner with the heads from the December 1984 simulation used as the initial conditions for the January 1985 simulation.

Table 7.--Summary of sensitivity analysis results for the steady-state model

Adjusted hydrologic parameter	Increased (percent)	Decreased (percent)	Algebraic mean difference in water levels[1]	Absolute mean difference in water levels[2]	Average water level change from steady-state solution[3]
Steady-state solution	--	--	0.03	1.25	--
Recharge	25		.58	1.22	0.55
	50		1.09	1.43	1.06
		25	-.55	1.35	-.58
		50	-1.20	1.51	-1.23
Steambed hydraulic conductivity	50		-.13	1.23	-.16
	100		-.22	1.22	-.25
		50	.41	1.28	.38
		100	1.61	2.04	1.58
Aquifer hydraulic conductivity	10		-.07	1.26	-.10
	20		-.16	1.27	-.19
	30		-.24	1.29	-.27
		10	.14	1.23	.11
		20	.28	1.22	.25
		30	.43	1.23	.40
Maximum evapotranspiration rate	10		-.05	1.27	-.08
	20		-.11	1.29	-.14
	30		-.18	1.31	-.21
		10	.11	1.22	.08
		20	.20	1.21	.17
		30	.29	1.23	.26
Evapotranspiration extinction depth	50		-.48	1.40	-.51
		50	.51	1.30	.48

[1]Algebraic mean difference between model-simulated heads and observed water levels in 26 observation wells. Value obtained by the summation of positive or negative head differences and dividing by 26.

[2]Absolute mean difference between model-simulated heads and observed water levels in 26 observation wells. Value obtained by the summation of absolute head differences and dividing by 26.

[3]Average water-level change from steady-state water levels in 26 observation wells. Value obtained by subtracting the algebraic mean difference in water levels for the steady-state solution (0.03 foot) from the algebraic mean difference in water levels from the sensitivity simulations. A positive value indicates a rise in water levels and a negative value represents a water-level decline.

Table 8.--Comparison of monthly 1985 simulated and observed water levels

Month	Number of observations	Algebraic mean difference in water levels[1]	Absolute mean difference in water levels[2]
January	22	0.64	1.17
February	23	.72	1.28
March	18	.21	1.26
April	23	.71	1.35
May	23	.27	1.38
June	26	.31	1.45
July	25	.67	1.64
August	24	.67	1.51
September	24	.34	1.24
October	25	.31	1.10
November	--	--	--
December	25	.28	1.14
Annual average	--	.47	1.32

[1]Algebraic mean difference between model-simulated heads and observed water levels. Value obtained by the summation of positive and negative head differences and dividing by the number of observations.
[2]Absolute mean difference between model-simulated heads and observed water levels. Value obtained by the sumation of absolute head differences and dividing by the number of observations.

Water-level measurements from 26 observation wells were used to compare monthly 1985 simulated water levels to observed water levels (table 8). A comparison of simulated and measured water levels for 1985 for three observation wells in the aquifer is shown in figure 24. Simulated fluctuations in water levels were generally in agreement with observed fluctuations.

Simulated ground-water discharge to streams was compared with average observed increases in stream discharge between the gage near Chester, which lies near the headwaters of Skunk Creek and the gage on Skunk Creek at Sioux Falls for July and August of 1985. Spring and fall months in 1985 could not be compared because precipitation resulted in overland runoff masking the baseflow. Comparison of simulated and observed ground-water discharge to streams for the winter months was poor with simulated discharge significantly greater than observed. This was possibly related to frozen sediment along stream banks inhibiting ground-water discharge to streams or erroneous streamflow discharge measurements resulting from ice accumulations in stream channels. The simulated ground-water discharge to streams for July and August was 12.4 and 11.5 ft^3/s, respectively. The average observed increase in streamflow between the two gages during these months was 10.3 and 8.8 ft^3/s, respectively. The difference between observed and simulated ground-water discharge to streams was approximately 17 percent for July and 23 percent for August. These discrepancies are possibly due to unreported irrigation use from Skunk Creek, the averaging of streamflow gains over each month, and inaccuracies in the model stream representation.

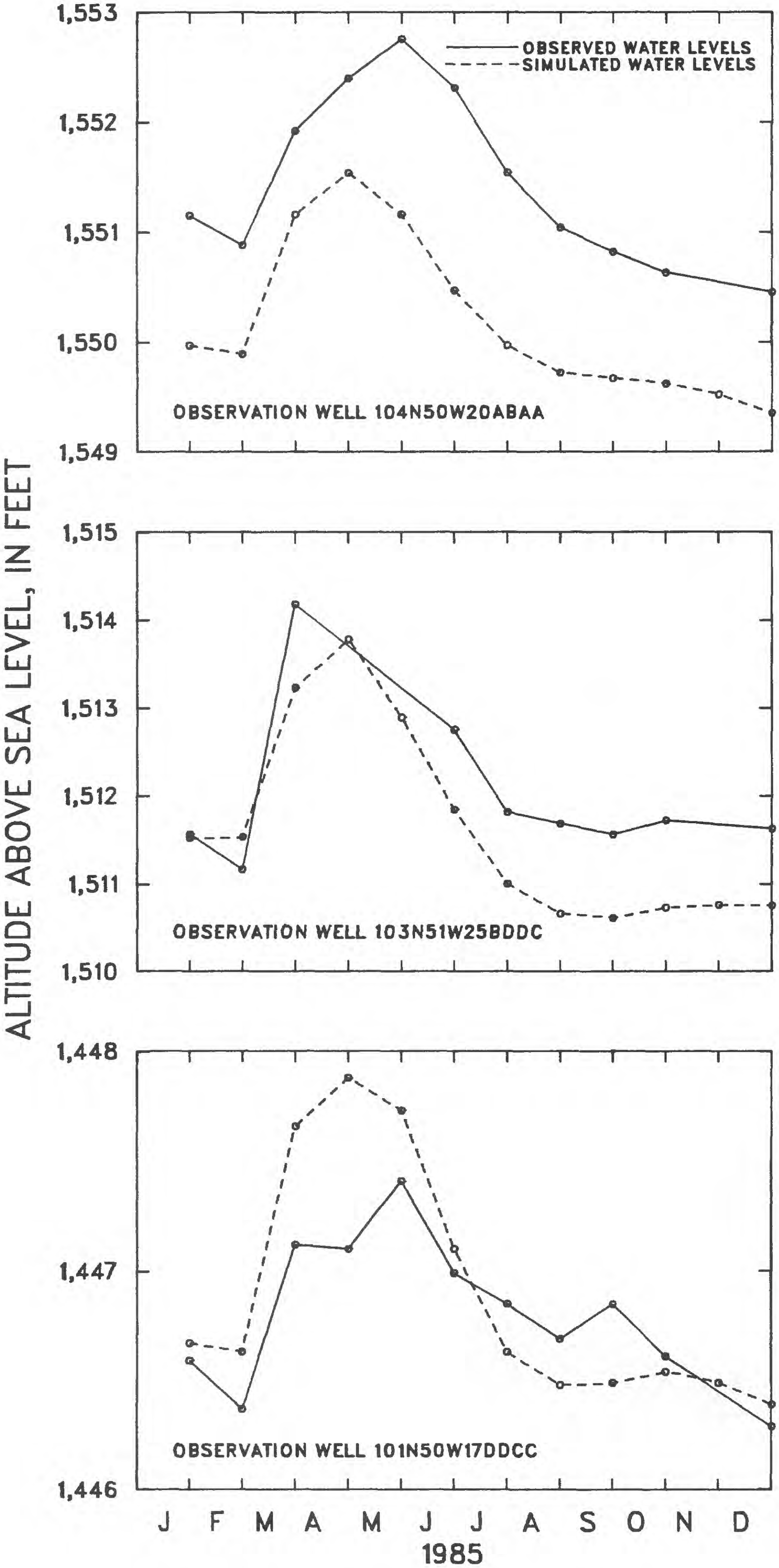

Figure 24.—Comparison of 1985 monthly observed and simulated water levels for 3 observation wells.

Monthly simulations for 1985 provided a simulated hydrologic budget for each month, which are summarized in table 9. The hydrologic budget equates water added to the aquifer (accretions) to water removed from the aquifer (depletions). A list of accretions and depletions for the Skunk Creek aquifer is as follows:

Accretions	Depletions
Recharge from precipitation	Evapotranspiration
Recharge from streams	Discharge to streams
Ground-water underflow	Pumpage
Decrease in ground-water storage	Increase in ground-water storage

A decrease in ground-water storage is considered an accretion because it is a source of water to the hydrologic budget.

Recharge by precipitation was the dominant source of water added to the aquifer during 1985, whereas ground-water discharge to streams was the major cause of depletion. Reported irrigation pumpage consisted of only 1.5 percent of the 1985 hydrologic budget.

MODEL APPLICATION

The model was used to analyze and predict the effects of two hypothetical hydrologic situations: (1) Increased withdrawal under steady-state conditions; and (2) increased withdrawal under 1985 transient hydrologic conditions.

The steady-state model was used for the first hypothetical situation to determine the distribution and volume of withdrawal that the aquifer is capable of sustaining under equilibrium conditions.

The second hypothetical situation involved the simulation of 1985 hydrologic conditions with increased withdrawal. This simulation provides an estimate of aquifer drawdown and production capabilities during 1985, when aquifer recharge (7.3 in/yr) was greater than the 1978-85 average of 6.0 in/yr.

Increased Withdrawal under Steady-State Conditions, Hypothetical Situation 1

The steady-state model was used to predict the effects of increased withdrawal under average hydrologic conditions for the period from 1978 through 1985. Increased withdrawal from the aquifer was simulated with the addition of 19 hypothetical wells to the existing 13 wells used in the steady-state simulation. A discharge rate of 500 gal/min from the 19 hypothetical wells was chosen to represent pumpages required for center pivot irrigation systems or other large production wells. The number and spacing of the discharge wells was determined by a trial and error approach until the model was able to reach new equilibrium conditions. The West Branch Skunk Creek area was not capable of supporting wells at a 500 gal/min discharge rate due to a lesser saturated thickness and restrictive aquifer boundary conditions.

Table 9.--Summary of simulated monthly hydrologic budgets for 1985

[Upper number is acre-feet (rounded); lower number is percentage]

Accretions (Sources of water)	January	February	March	April	May	June	July	August	September	October	November	December	Total
Recharge by	0	319	4,510	1,511	1,946	0	160	604	734	414	50	0	10,248
precipitation	0.0	19.9	48.4	47.4	34.7	0.0	3.8	17.8	29.8	21.7	3.3	0.0	25.2
Recharge from	6	7	107	43	60	61	25	25	26	20	23	14	417
streams	0.3	0.5	1.1	1.3	1.1	1.5	0.6	0.7	1.0	1.1	1.5	0.9	1.0
Ground-water	41	37	41	40	41	40	41	41	40	41	41	41	485
underflow	2.1	2.3	0.4	1.3	0.7	1.0	1.0	1.2	1.6	2.2	2.7	2.7	1.2
Decrease in	941	437	0	1	754	1,940	1,869	1,024	431	480	649	695	9,221
storage	47.6	27.3	0.0	0.0	13.5	47.5	44.6	30.2	17.5	25.1	42.5	46.4	22.6
Depletions (Consumption of water)													
Evapotranspiration	0	0	0	0	1,553	1,142	914	578	329	0	0	0	4,516
	0.0	0.0	0.0	0.0	27.7	28.0	21.8	17.1	13.4	0.0	0.0	0.0	11.1
Discharge to	987	779	449	506	893	809	972	904	794	785	713	732	9,323
streams	49.9	48.7	4.8	15.9	15.9	19.8	23.2	26.7	32.3	41.1	46.7	48.8	22.9
Pumpage	0	0	0	5	36	89	209	213	48	8	0	0	608
	0.0	0.0	0.0	0.2	0.6	2.2	5.0	6.3	1.9	0.4	0.0	0.0	1.5
Increase in	1	21	4,208	1,083	320	0	0	0	60	163	50	18	5,924
storage	0.1	1.3	45.2	34.0	5.7	0.0	0.0	0.0	2.4	8.5	3.3	1.2	14.5
Total	1,976	1,600	9,315	3,189	5,603	4,081	4,190	3,389	2,462	1,911	1,526	1,500	40,742
	100	100	100	100	100	100	100	100	100	100	100	100	100

The simulation resulted in a total ground-water withdrawal of 15,731 acre-ft/yr from a total of 32 discharging wells. The simulated drawdown in the aquifer measured from the previous steady-state potentiometric surface is shown in figure 25 and the hydrologic budget at new equilibrium conditions is shown in table 10. Drawdown ranging from 4 to 12 ft was greatest in the pumping nodes and decreased rapidly away from the pumping nodes as shown in figure 26. No drawdown was observed in the West Branch Skunk Creek area due to the lack of pumping in this area.

Comparison of the hydrologic budget with increased withdrawal (table 10), relative to the pre-development hydrologic budget (table 6), reveals that declining water levels induced by pumping resulted in a decrease in ground-water discharge to streams of 4,069 acre-ft/yr and an increase in recharge from streams of 7,565 acre-ft/yr. Evapotranspiration was decreased by 3,671 acre-ft/yr and pumpage from the aquifer was increased by 97 percent (15,326 acre-ft/yr).

Table 10.--Summary of simulated hydrologic budget for hypothetical situation 1

Budget component	Rate (acre-feet per year)	Percent
INFLOW		
Recharge by precipitation	9,527	51
Recharge from streams	8,651	46
Ground-water underflow	485	3
Total inflow	18,663	100
OUTFLOW		
Evapotranspiration	1,260	7
Discharge to streams	1,672	9
Pumpage	15,731	84
Total outflow	18,663	100

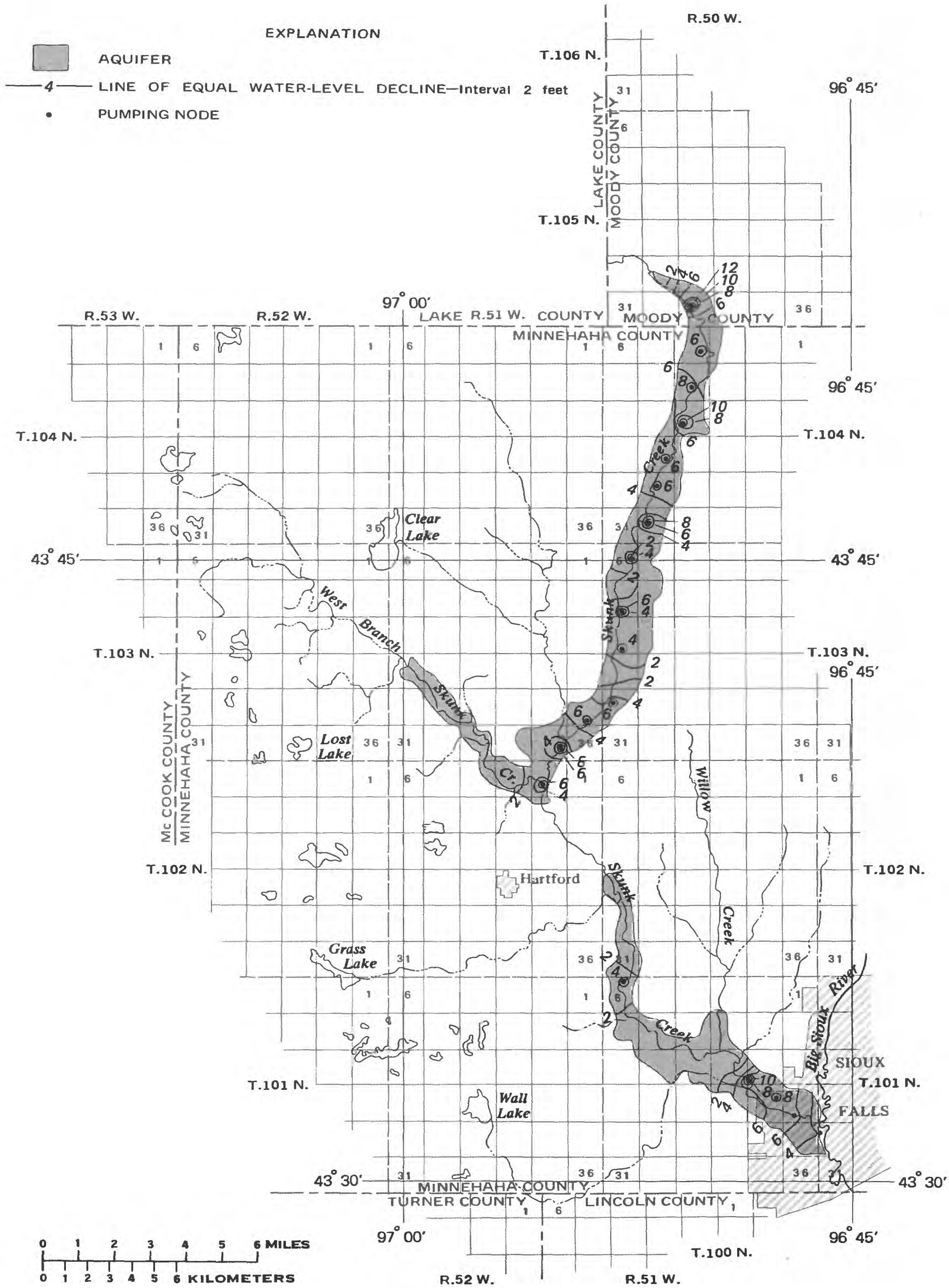

Figure 25.—Simulated steady-state drawdown for Skunk Creek aquifer, hypothetical situation 1.

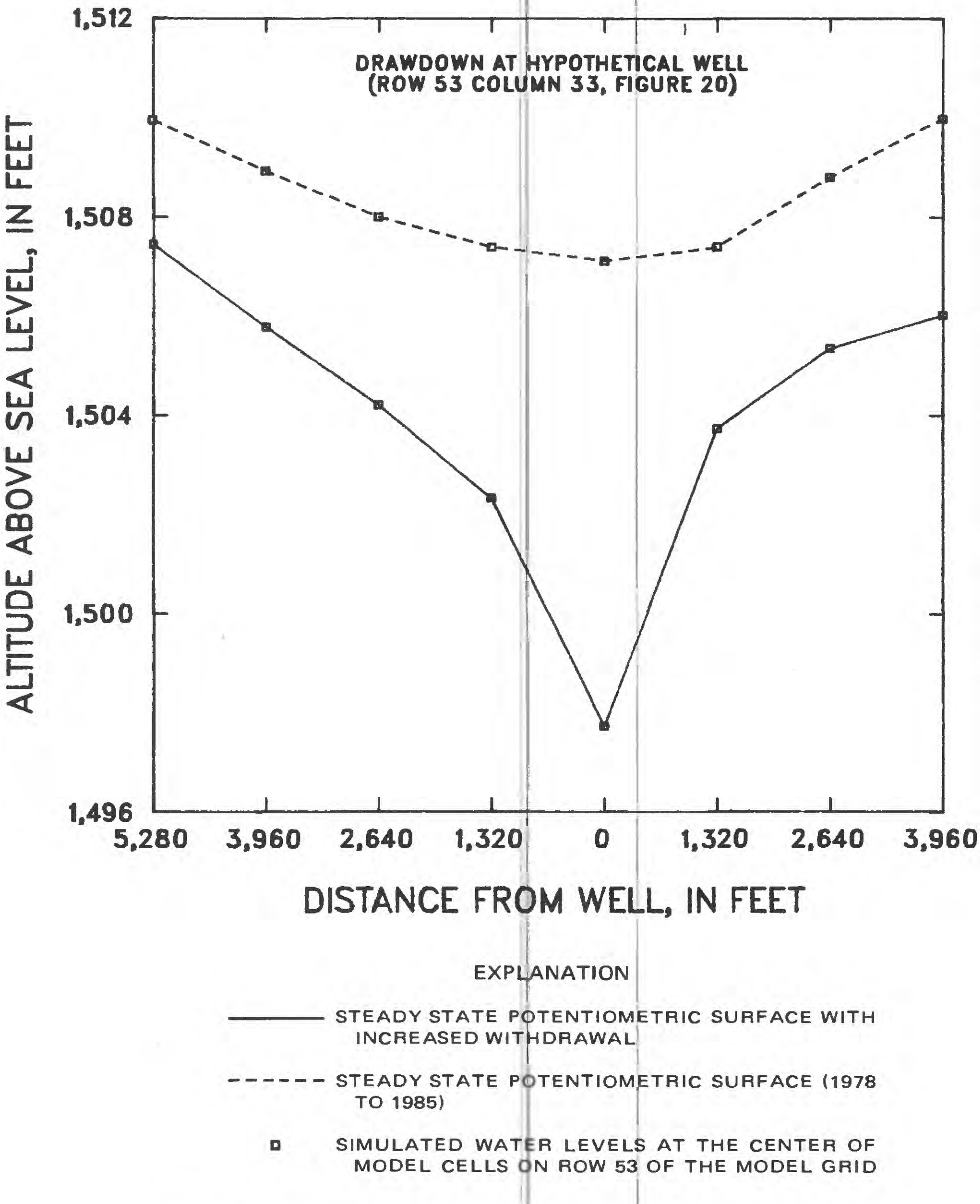

Figure 26.—Distance-drawdown plot for hypothetical well at a pumping rate of 500 gallons per minute, hypothetical situation I.

Increased Withdrawal under 1985 Transient Conditions, Hypothetical Situation 2

The second hypothetical hydrologic situation involved increasing ground-water withdrawal rates using 1985 hydrologic conditions. The 12 monthly transient simulations used for the transient calibration procedure were modified to simulate increased ground-water withdrawal of 15,962 acre-ft/yr. The same 19 discharge wells used in hypothetical situation 1 (fig. 27) were used to simulate increased withdrawal. These wells were used in addition to the 1 to 10 wells simulating monthly reported irrigation pumpage in 1985.

Simulated monthly hydrologic budgets for hypothetical situation 2 are shown in table 11. Comparison of the hydrologic budget in table 11, to the 1985 pre-development budget (table 9), indicates that the declining water levels brought about by increased withdrawal caused an increase in recharge from streams (2,325 acre-ft/yr) and decreases in ground-water discharge to streams (3,953 acre-ft/yr), ground-water storage (5,250 acre-ft/yr), and evapotranspiration (1,990 acre-ft/yr). Simulated pumpage for this simulation represents an increase of 15,354 acre-ft/yr or a 96 percent increase over reported irrigation pumpage for 1985.

Cumulative aquifer drawdowns for the 12 monthly simulations were measured from the initial head conditions for the January simulation (fig. 27). Drawdown was greatest in the discharge nodes, ranging from 5 to 8 ft. No drawdown occurred in the unstressed areas, such as in the region of West Branch Skunk Creek.

MODEL LIMITATIONS

The hydrologic system represented in this model is analogous to the Skunk Creek aquifer, however, the model has inherent limitations owing to approximations of hydrologic and geologic data. The model requires the numerical representation of the aquifer, which implies that all hydrologic and geologic parameters are equal throughout each 0.0625-mi^2 model cell. This model should not be used to determine well spacing or well field withdrawal rates on a localized, site specific basis because of error induced by the 0.25-mi model grid spacing. Furthermore, the model is based on estimates of average recharge, hydraulic conductivity, and other hydrologic parameters that may result in a misrepresentation of the aquifer.

Aquifer production volumes predicted by the model are only estimates and need to be used with caution. The use of constant flux recharge wells for the simulation of underflow from the Wall Lake and North Skunk Creek aquifers at the northern and southern model boundaries assumes the hydraulic gradient does not change due to water-level fluctuations caused by seasonal climatic changes or aquifer development near the boundaries. Drawdowns in the aquifer predicted by hypothetical situations could be misleading if heads at the recharge well nodes were to change as a result of future withdrawals.

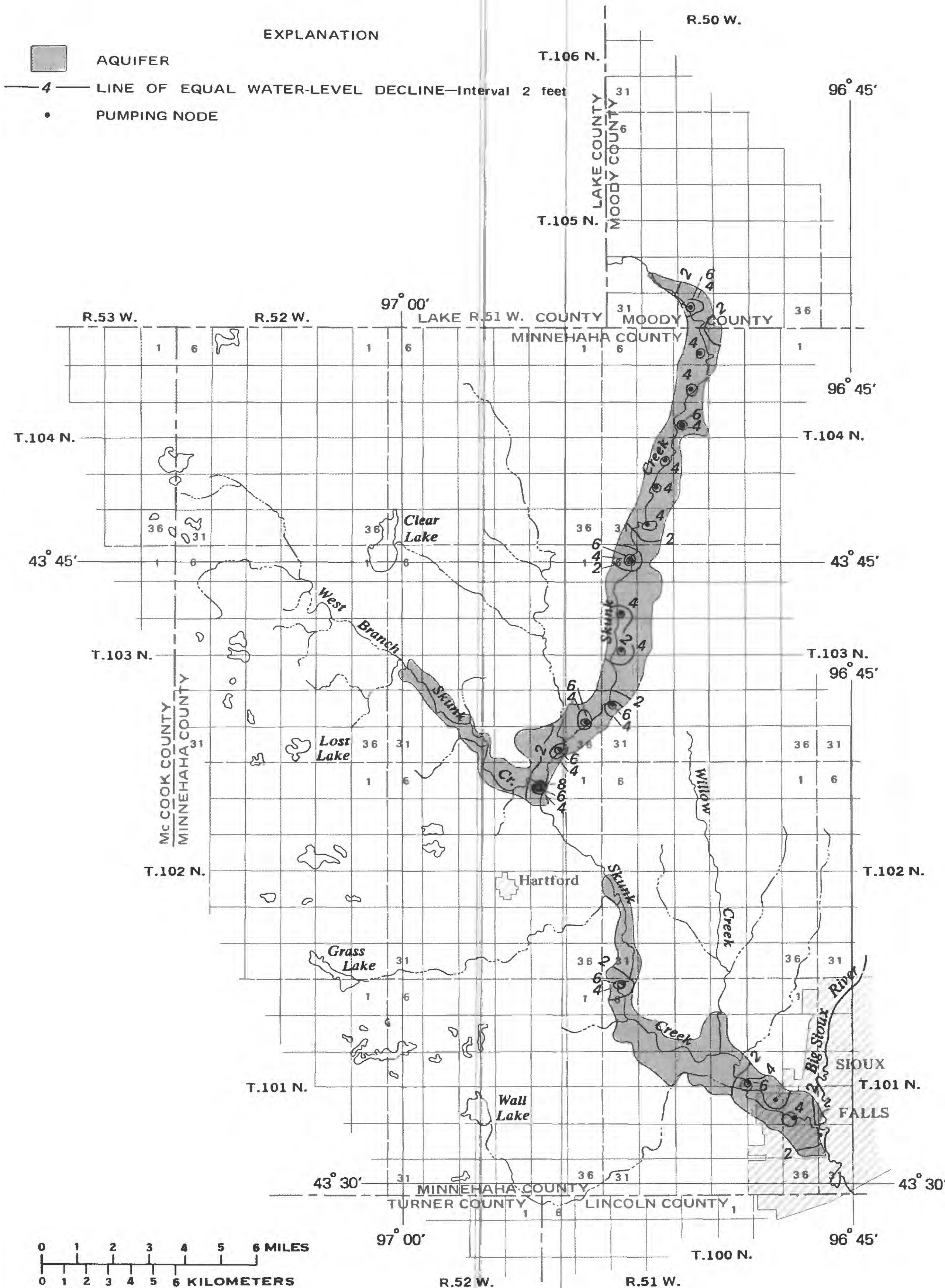

Figure 27.—Simulated drawdown for Skunk Creek aquifer after 12 months of pumping (1985), hypothetical situation 2.

Table 11.--Monthly simulated hydrologic budgets for hypothetical situation 2

[Upper number is acre-feet (rounded); lower number is percentage]

Accretions (Sources of water)	January	February	March	April	May	June	July	August	September	October	November	December	Total
Recharge by precipitation	0 0.0	319 9.3	4,510 45.3	1,511 38.2	1,946 31.8	0 0.0	160 3.1	604 13.2	734 19.5	414 12.1	50 1.5	0 0.0	10,248 18.3
Recharge from streams	38 0.9	62 1.8	426 4.3	372 9.4	203 3.3	202 4.1	145 2.8	176 3.9	223 5.9	264 7.8	320 9.9	311 9.8	2,742 4.9
Ground-water underflow	41 1.0	37 1.1	41 0.4	40 1.0	41 0.7	40 0.8	41 0.8	41 0.9	40 1.1	41 1.2	41 1.3	41 1.3	485 0.9
Decrease in storage	2,035 48.1	1,300 37.8	0 0.0	57 1.4	867 14.2	2,225 45.1	2,214 43.2	1,466 32.0	881 23.4	986 28.9	1,200 37.2	1,240 38.9	14,471 25.9
Depletions (Consumption of water)													
Evapotranspiration	0 0.0	0 0.0	0 0.0	0 0.0	989 16.2	663 13.4	469 9.2	266 5.8	139 3.7	0 0.0	0 0.0	0 0.0	2,526 4.5
Discharge to streams	813 19.2	544 15.8	277 2.8	286 7.2	531 8.7	457 9.3	580 11.3	506 11.1	414 11.0	363 10.6	304 9.4	295 9.2	5,370 9.6
Pumpage	1,300 30.8	1,172 34.1	1,302 13.1	1,265 31.9	1,337 21.9	1,348 27.3	1,511 29.5	1,515 33.1	1,305 34.7	1,308 38.3	1,301 40.4	1,298 40.8	15,962 28.6
Increase in storage	0 0.0	1 0.0	3,399 34.1	429 10.8	200 3.3	0 0.0	0 0.0	0 0.0	20 0.5	35 1.0	5 0.2	0 0.0	4,089 7.3
Total	4,227 100	3,435 100	9,955 100	3,960 100	6,114 100	4,935 100	5,120 100	4,574 100	3,756 100	3,411 100	3,221 100	3,185 100	55,893 100

SUMMARY AND CONCLUSIONS

The Skunk Creek aquifer, a major glacial outwash deposit in the Skunk Creek drainage basin is composed of a variable mixture of sand and gravel mantling glacial till and the Sioux Quartzite in the study area (30 square miles). Normal precipitation in the basin averages approximately 25 inches per year (817,300 acre-feet per year) with approximately 44,900 acre-feet per year leaving the basin as streamflow. The remaining 772,400 acre-feet per year consists of water temporarily added to ground-water storage, to storage in ponds, sloughs, lakes, and the soil, and ultimately lost to evapotranspiration.

The water quality of the Skunk Creek aquifer is suitable for most uses. The water has an average dissolved-solids content of 620 milligrams per liter. The water is very hard with an average calcium carbonate hardness of 403 milligrams per liter.

A numerical computer model was developed and calibrated under steady-state and transient conditions. Average hydrologic conditions for an 8-year period (1978 through 1985) were used to calibrate the steady-state model. The mean absolute difference between simulated and observed water levels for 26 observation wells was 1.25 feet. The transient model was calibrated on a monthly basis using hydrologic data from 1985. Simulated monthly water levels averaged from 0.21 to 0.71 feet higher than the measured water levels in 26 observation wells. The absolute mean difference between simulated and measured water levels for each month ranged from 1.10 to 1.64 feet.

A sensitivity analysis of the steady-state model indicated that simulated water levels were most sensitive to changes in aquifer recharge and the hydraulic conductivity of the streambed. The model was least sensitive to the hydraulic conductivity of the aquifer and the evapotranspiration rate.

The model was subsequently used to evaluate the effects of two hypothetical hydrologic situations on water levels in the aquifer. The first hypothetical situation simulated increased pumpage under (1978 through 1985) steady-state conditions. Total pumpage from 19 hypothetical wells and 13 pre-existing wells was 15,731 acre-feet per year, resulting in water-level declines ranging from 0 to 12 feet.

The second hypothetical situation evaluated the effects of increased pumpage under 1985 transient conditions. Total aquifer withdrawal from the 19 hypothetical wells and pre-existing wells was 15,962 acre-feet per year with drawdown ranging from 0 to 8 feet.

On the basis of results of this study, the following conclusions may be made:

1) Recharge to the aquifer occurs from infiltration of precipitation, underflow from the Wall Lake and North Skunk Creek aquifers, and leakage from streams and glacial till deposits.

2) Average annual recharge to the aquifer was about 6 inches per year from 1978 through 1985.

3) Natural discharge from the aquifer results from evapotranspiration, ground-water discharge to streams, and possible discharge to the Sioux Quartzite.

4) The Skunk Creek aquifer is hydraulically connected to the Wall Lake aquifer. Underflow from the Wall Lake aquifer affects the chemical quality of the water in the Skunk Creek aquifer downgradient from the discharge area.

5) Water in the aquifer is very hard, generally of the calcium-bicarbonate type, relatively low in dissolved solids, and is generally suitable for irrigation and public water supply use.

6) The chemical constituents in the ground water are derived primarily from the dissolution of sulfate, carbonate, and silicate minerals.

7) Increased pumpage from the aquifer generally is offset in the hydrologic system by decreased evapotranspiration and ground-water discharge to streams.

8) The West Branch Skunk Creek region of the aquifer appears to be incapable of sustaining well yields of 400 to 500 gallons per minute.

9) The model successfully simulated steady-state (equilibrium) conditions with a total withdrawal rate of 15,731 acre-feet per year, based on average hydrologic conditions from 1978 through 1985. This total withdrawal rate is from 19 hypothetical wells and 13 wells simulating 1978-85 reported irrigation pumpage.

10) On the basis of simulated 1985 hydrologic conditions, the aquifer is capable of producing 15,962 acre-feet per year for a 12-month period from 19 hypothetical wells and 1 to 10 wells simulating reported 1985 irrigation pumpage.

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