A WATER RESOURCE APPRAISAL OF THE SKUNK CREEK AQUIFER IN MOODY AND MINNEHAHA COUNTIES, SOUTH DAKOTA

By

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Bachelor of Arts

University of Minnesota - Morris

Morris, Minnesota

1982

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1986

A WATER RESOURCE APPRAISAL OF THE SKUNK CREEK AQUIFER IN MOODY AND MINNEHAHA COUNTIES, SOUTH DAKOTA

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PREFACE

The water resources of the Skunk Creek aquifer in southeastern South Dakota were evaluated by investigating the hydrogeology and hydrogeochemistry of the glacial outwash deposits which comprise the aquifer. Geologic and hydrologic data were used to develop a numerical computer model to simulate ground-water flow in the aquifer. The model was used to predict the hydrologic effects of increased aquifer withdrawal under various hydrologic conditions.

I would like to express my thanks to Dr. Wayne Pettyjohn for serving as my major thesis advisor. The knowledge, advice, and inspiration that he has given me during my graduate work at Oklahoma State University is deeply appreciated.

I am very grateful to Neil Koch of the U.S. Geological Survey for proposing this project as my thesis topic and for serving on my graduate advisory committee. Special thanks for his advice and encouragement during my employment with the U.S. Geological Survey.

I would also like to express my gratitude to Dr. Arthur Hounslow for serving on my graduate committee. The geochemical principles he taught me during my graduate studies were very valuable in the interpretation of the hydrogeochemical aspects of this study.

Many thanks are due the U.S. Geological Survey - Water Resources Division in Huron, South Dakota for providing data and funding for this project. Special thanks to Don Hansen, Patrick Emmons, Rick Lindgren, and Herbert Bandelmann with the U.S. Geological Survey - South Dakota District Office for their contribution to various aspects of this study. I would also like to express my gratitude to Scott Christenson with the U.S. Geological Survey - Oklahoma District Office for his help and patience with the explanation of their computer system.

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.

Special recognition and appreciation go to my mother and father for their life-long guidance, support, and encouragement.

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INTRODUCTION

General Overview

The Skunk Creek - Lake Madison drainage basin covers 613 square miles in southeastern South Dakota (Figure 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 square miles. The aquifer has been divided into three management units named the Big Sioux Aquifer: South Skunk Creek, Middle Skunk Creek, and North Skunk Creek based on hydrogeological divisions within the aquifer. The aquifer is a surficial valley-train glacial outwash deposit consisting predominantly of sand and gravel with minor amounts of silt and clay. The unconfined nature of the aquifer allows for a direct hydrologic connection with Skunk Creek and other surface water bodies.

The study area consists of the Middle and South Skunk Creek management units which cover approximately 30 square miles and extend from the southwest corner of Moody County southward through Minnehaha County to the City of Sioux Falls (Figure 1).

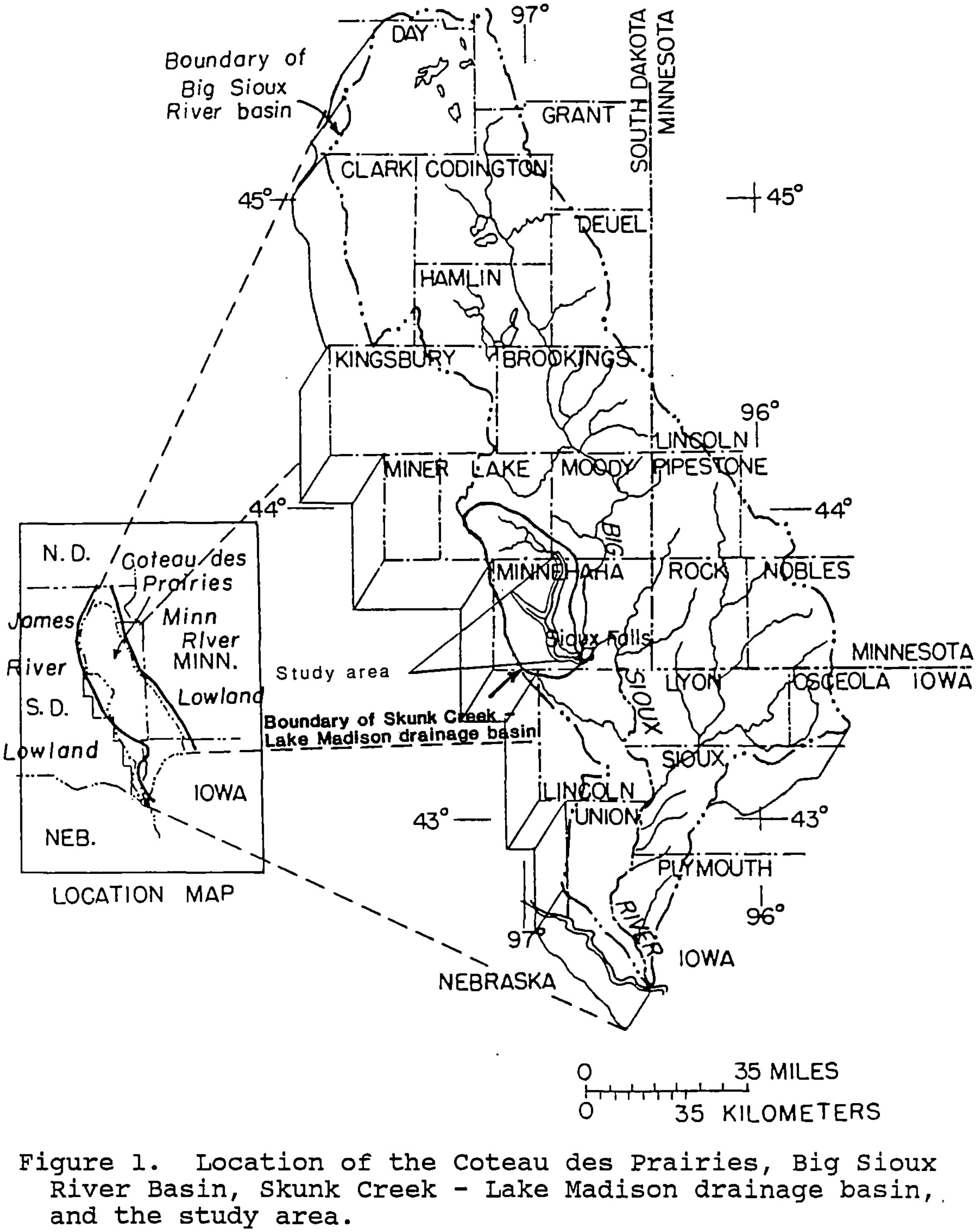

Figure 1. Location of the Coteau des Prairies, Big Sioux River Basin, Skunk Creek - Lake Madison drainage basin, and the study area.

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

Objectives

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.

Methods of Investigation

This investigation was based on data provided by 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 was 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. The geologic logs utilized for the cross-sections are shown in Appendix A.

Data from the U.S. Geological Survey WATSTORE data base was used to investigate 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 water quality data used for this study are shown in Appendices B and C.

The numerical computer simulation of the aquifer was conducted using the U.S. Geological Survey modular groundwater flow model (McDonald and Harbaugh, 1984). Aquifer simulations included a steady-state simulation based on a eight year period (1978 - 1985), 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 several hypothetical situations which applied additional stresses to the hydrologic system.

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 assessable 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 1980 feet/day (630 - 14800 gpd/ft^2), and averaged 580 feet/day (4370 gpd/ft^2). 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 1335 feet/day (10,000 gpd/ft^2). 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 1070 feet/day (2400 - 8000 gpd/ft^2).

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

A hydrogeological investigation of the Skunk Creek - Lake Madison 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 hydrologically connected except by surface water flow in Skunk Creek.

D.L. Iles (unpublished report, 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 hydrologic 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.

CHAPTER II

REGIONAL CHARACTERISTICS

Geography

The Big Sioux River drainage basin has an area of approximately 9000 square miles in southeastern South Dakota, southwestern Minnesota, and northwestern Iowa (Figure 1). The Skunk Creek - Lake Madison 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 (Figure 1). Land surface elevations in the basin range from approximately 1800 feet above sea level in the northern upland areas to about 1400 feet in the southern part of the Skunk Creek valley (Ellis and Adolphson, 1965). The upland areas drain into the Skunk Creek - Lake Madison 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 aprroximately five feet per mile through out its length of approximately 38 miles. The width of Skunk Creek valley ranges from one-quarter mile near Hartford to two miles 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 until joining Skunk Creek near Hartford.

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

Climate

The climate in the study area is sub-humid with a mean annual precipitation of approximately 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 degrees F. (Fahrenheit), while temperature extremes commonly range from -20 degrees F. in the winter months to near 100 degrees F. in the summer. The annual average number of days with temperatures below zero degrees F. is 34; temperatures drop below freezing an average of 174 days each year. Temperatures greater than 90 degrees F. can be expected about 25 times a year (Spuhler, and others, 1971).

Evapotranspiration

Evapotranspiration in the study area is assumed to occur only during the growing season for agricultural crops and other plants. Approximately 94 percent of the land in Minnehaha County is used for agricultural purposes; 81 percent is cropland and 13 percent is pasture land (U.S.D.A. -S.C.S., 1964). The remaining 6 percent, includes less than 1 percent woodlands, which generally occurs in the proximity of surface water bodies. Evapotranspiration is greatest in areas near lakes, ponds, and streams due to the occurrence of phreatophytic plants, such as various types of large trees.

Soils

The following general description of the soils in the study area concentrates on those soil associations that have developed on outwash deposits in the valley of Skunk Creek. Descriptions of the soil associations was obtained from a soil survey for Minnehaha County (U.S.D.A.-S.C.S., 1964). A soil survey for Moody County is not available, however soil types for the small portion of the study area in Moody County are assumed similar to those in adjacent areas of Minnehaha County.

Soil associations developed on the outwash deposits in the study area are the Luton - Dimmock and Fordville - Estelline associations.

The Luton - Dimmock association occurs on level to nearly level areas on the flood plain of Skunk Creek and its tributaries. These soils consist of clay and silty clay in the surface layer, with a clay and silty clay loam in the subsoil layers. The soils are poorly to moderately well drained and are generally non-calcareous near the surface, but become strongly calcareous at depth. Soil pH values range from 5.6 to 8.4 with a general increase in pH with depth.

The Fordville - Estelline soil association occurs on nearly level and gently sloping stream terraces and outwash plains. These soils are well drained and usually develop over sand and gravel alluvium. The surface layer is generally composed of silt loam and loam with subsoil layers being composed of silt loam to sand and gravel. These soils are generally non-calcareous near the surface, but become strongly calcareous at depth. Soil pH values, which generally increase with depth, range from 5.6 to 9.0.

Glacial Geology

The Skunk Creek - Lake Madison basin is mantled by glacial drift which ranges in age from Late Wisconsinian (youngest) to the Kansan (oldest) glacial stages of the Pleistocene period. The glacial deposits consist of end-moraine, ground-moraine, and outwash deposits overlying the bedrock surface. These deposits range from less than one foot to more than 250 feet in thickness.

The end-moraine deposits are composed predominantly of glacial till with localized lenses of sand and gravel. Glacial till is defined as a non-sorted, non-stratified deposit consisting of silt, sand, gravel, and boulder-sized rock fragments with a clay matrix. Clays within the till are typically of the smectite variety and were probably derived from the Pierre Shale. These deposits are of Late Wisconsinian age and typically form ridge-like topographic features (Ellis and Adolphson, 1965).

Ground-moraine deposits are composed mainly of glacial till with localized lenses of sand and gravel, as well as deposits of loess. These deposits range from Late Wisconsinian to Illinoian in age and occur predominantly east of the Lake Madison - Skunk Creek valley. Gently rolling topographic features with isolated depressions containing small lakes and sloughs are typical of ground-moraine deposits in the area (Ellis and Adolphson, 1965).

Outwash deposits are of glacio-fluvial origin and consist of poorly to well-sorted sand and gravel with small amounts of silt and clay. The majority of the outwash deposits in the study area lie in the Skunk Creek valley and are of Late Wisconsinian age (Ellis and Adolphson, 1965). The outwash deposits resulted from glacial meltwater runoff from a glacial lobe that advanced easterly from the James River lowland into western Minnehaha County (Rothrock and Otton, 1947). Glacial meltwater carrying a heavy sediment load flowed from the receding glacier eastward toward the Big Sioux River valley. However, the flow was diverted southward by the western side of a topographic high formed by morainal deposits of Kansan glacial age. Eventually the meltwater stream joined the Big Sioux River in southern Minnehaha County. Consequently, the Skunk Creek valley marks the eastern extent of the Wisconsinian glacial advance and contains significant thicknesses of sand and gravel (Rothrock and Otton, 1947).

Bedrock Geology

Bedrock in the study area consists of the Sioux Quartzite which forms a resistant structural high that is mantled by Pleistocene glacial deposits except where it crops out in Section 11, T.102 N., R.51 W..

The Sioux Quartzite is Precambrian in age and consists of fine textured, pink to red, silicified sandstone. The rock has a characteristic pink color due to its low iron content. It is very well cemented by silica, resulting in a primary porosity of less than 2 percent (Rothrock and Otton, 1947). Secondary porosity and permeability is significantly greater due to the ubiquitous nature of fractures within the rock (Rothrock and Otton, 1947). The rock unit may also contain conglomerate, siltstone, and shale members and is generally very resistant to erosion. Its thickness is believed to exceed 3000 feet (Flint, 1955).

CHAPTER III

HYDROGEOLOGY OF THE SKUNK CREEK AQUIFER

Hydrologic System

Precipitation contributes approximately 817,300 acre-ft/yr (25 in/yr) of water to the Skunk Creek - Lake Madison drainage basin (613 mi^2) annually. 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.

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 (Plate II). 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 North Skunk Creek and Wall Lake aquifers. Minor recharge originates as leakage from adjacent glacial till deposits. Natural discharge from the aquifer results from seepage to streams, evapotranspiration, and minor leakage to the Sioux Quartzite.

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 Plate I. The numbering system used to describe the locations of observation wells and test holes is shown in Figure 2. Geologic cross-sections are shown in Figures 3 - 8.

The outwash deposits, which range in thickness from less than 1 to 74 feet are underlain by glacial till or 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 (Plate I, Figures 2 and 3). The extent of this hydrologic connection is not fully understood due to the lack 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 existance of two hydrologic units in certain areas. An estimate of the flow from the Wall Lake aquifer to the Skunk Creek aquifer is approximately 471 acre-ft/yr.

The Skunk Creek aquifer consists of two separate masses of outwash separated by a bedrock high, composed of quartzite that crops out in Section 11, T.102 N., R.51 W. (Plate

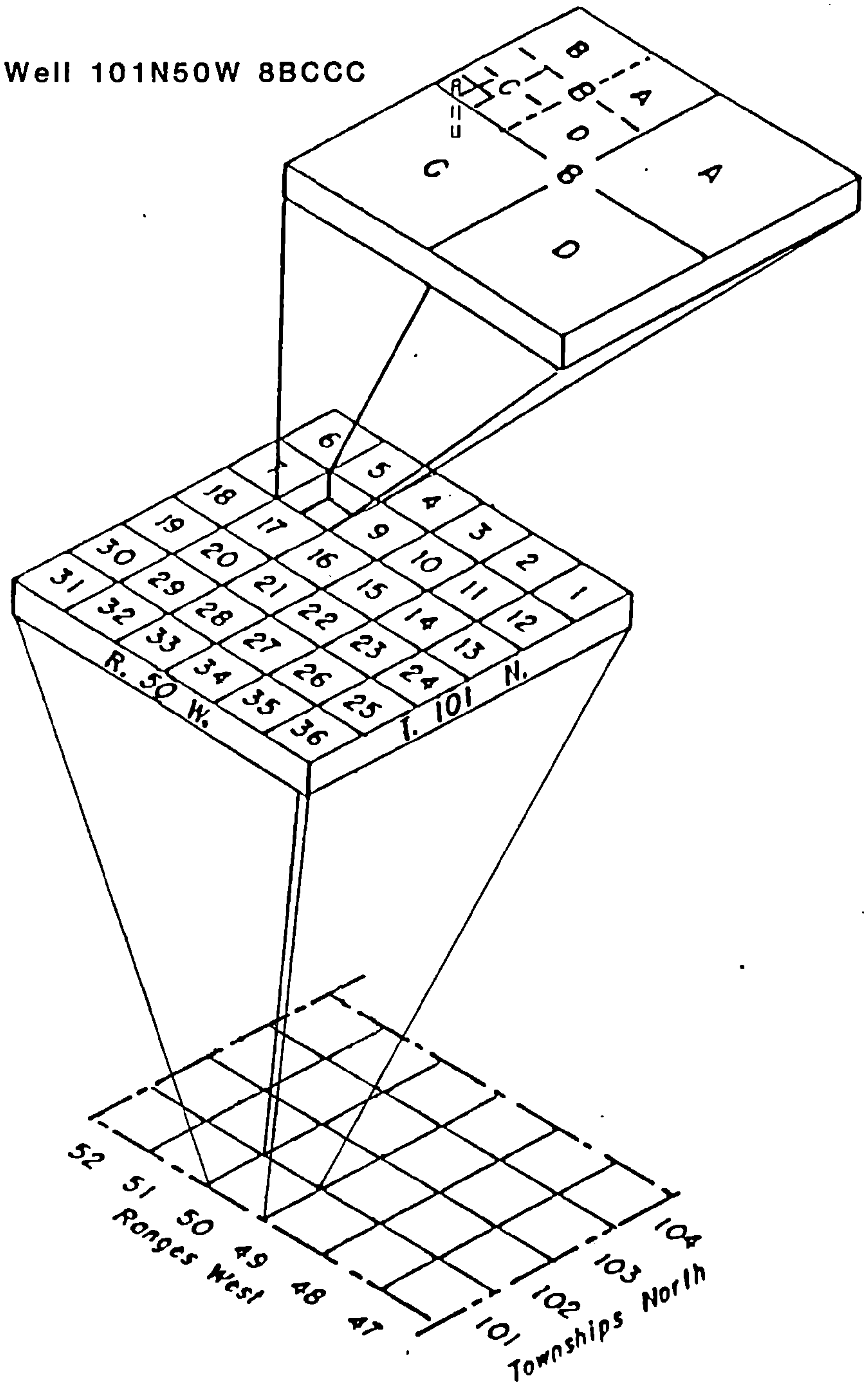

Figure 2. Well numbering diagram. The well number consists of township followed by "N", range followed by "W", and section number, followed by a maximum of four case letters that indicate, respectively, the 160, 40, 10, and $2^1/_2$ acre tract in which the well is located.

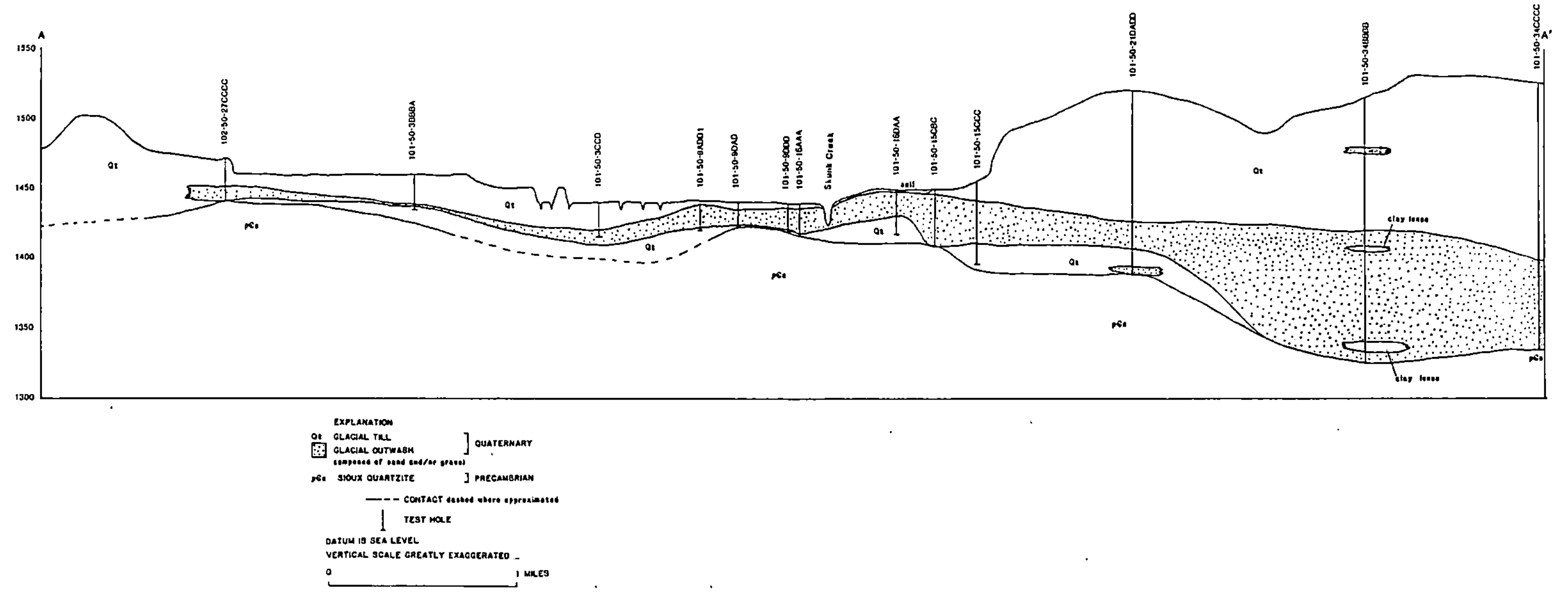

Figure 3. Geologic cross-section A - A'.

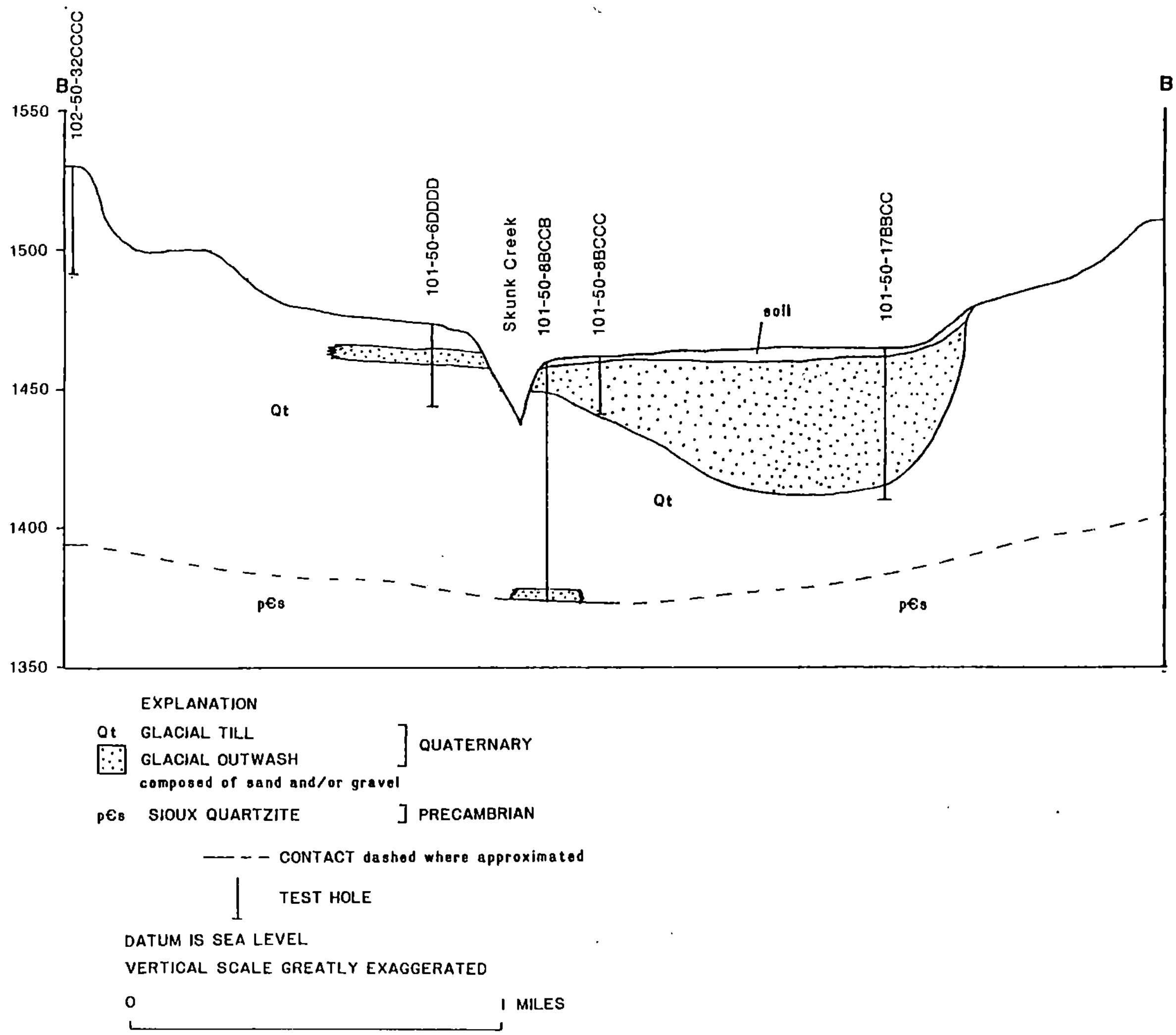

Figure 4. Geologic cross-section B - B'.

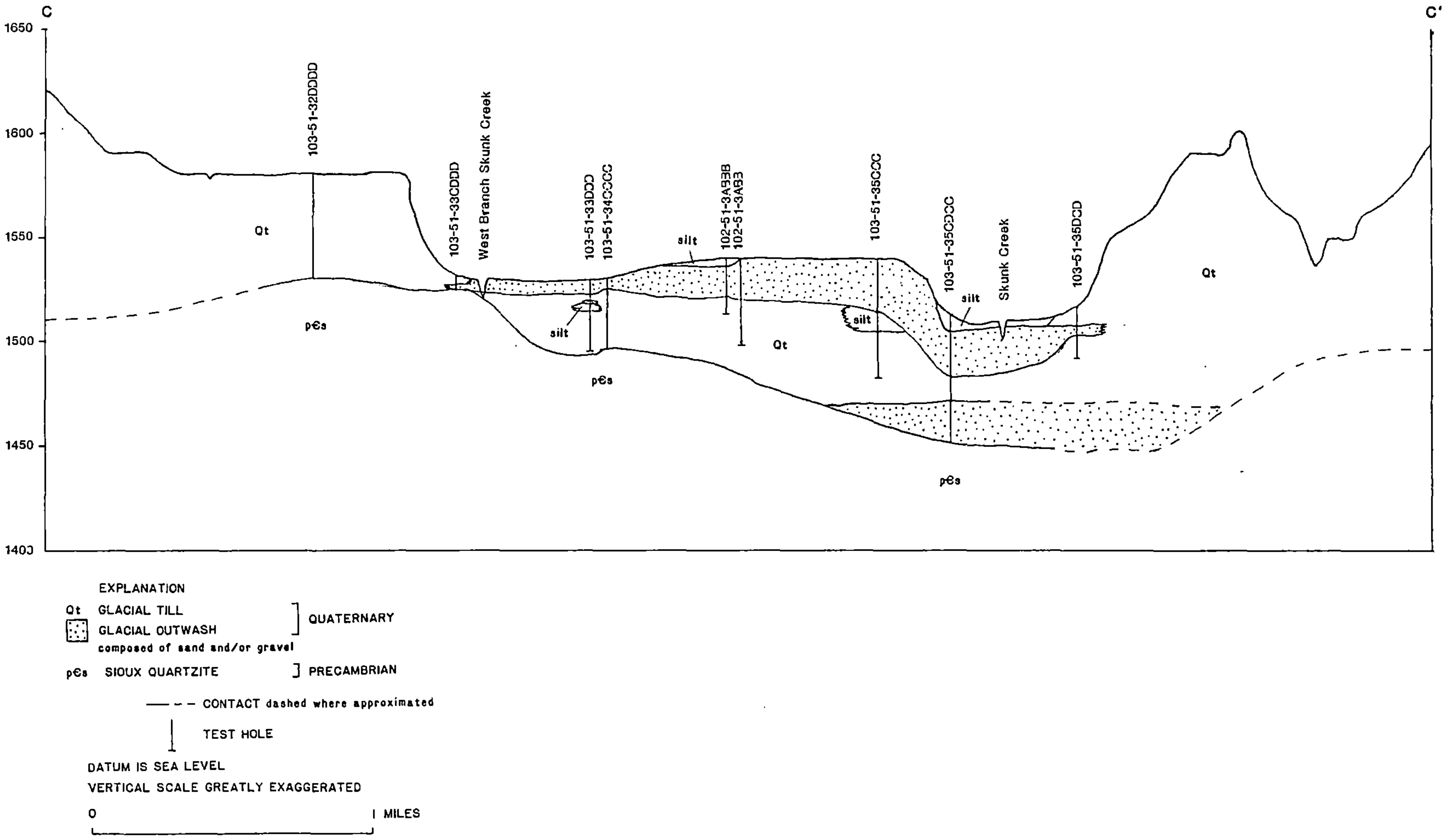

Figure 5. Geologic cross-section C - C'.

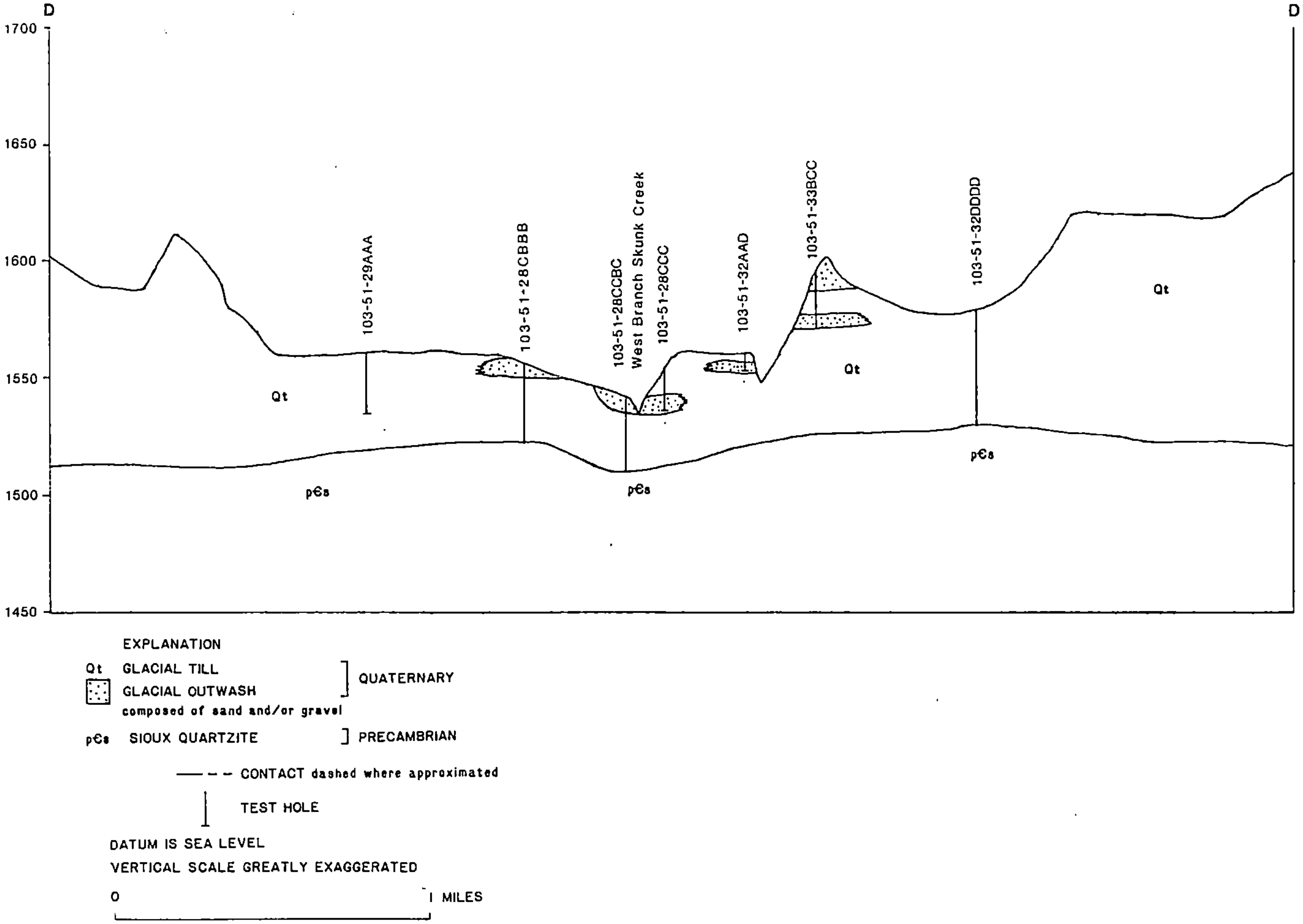

Figure 6. Geologic cross-section D - D'.

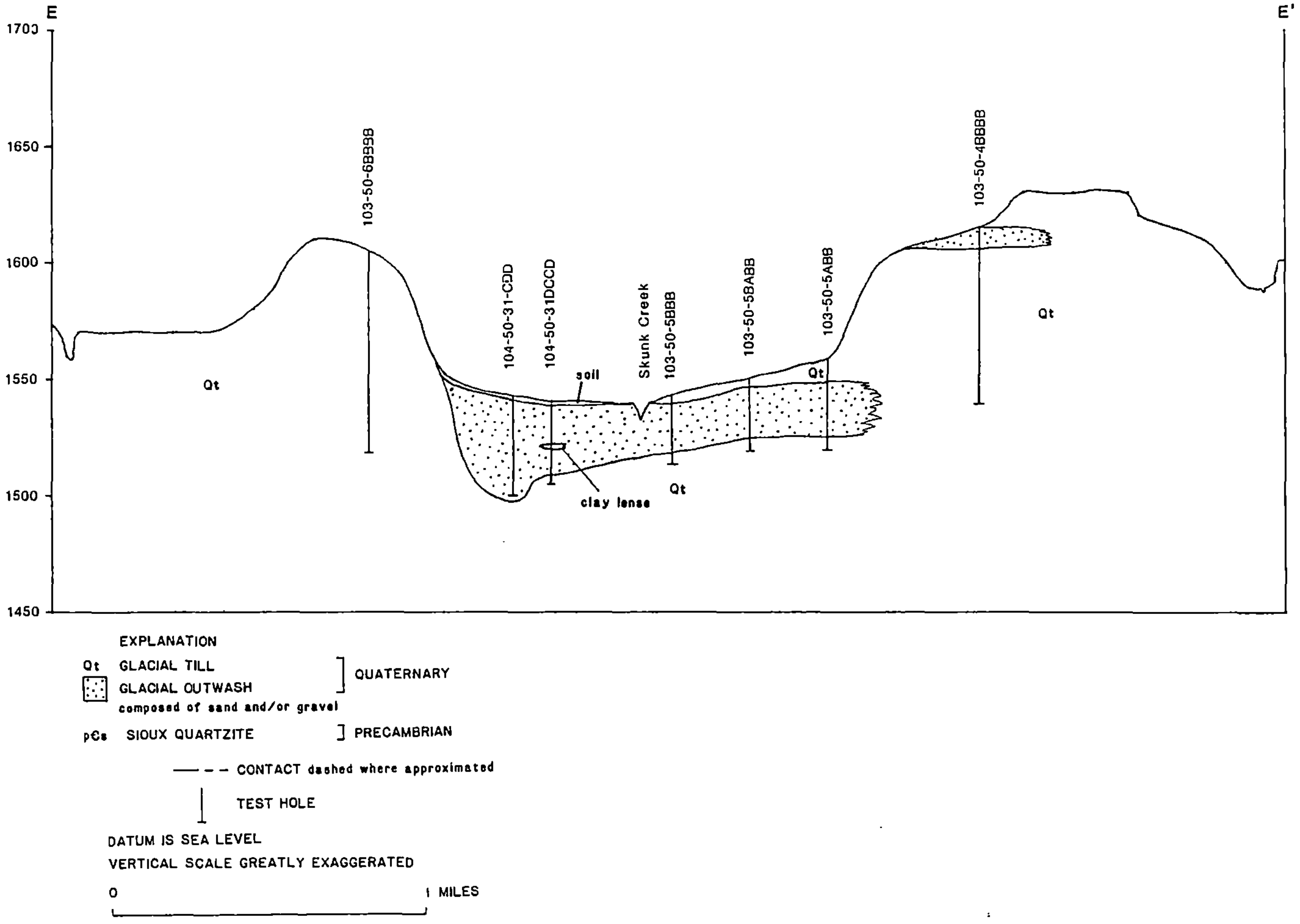

Figure 7. Geologic cross-section E - E'.

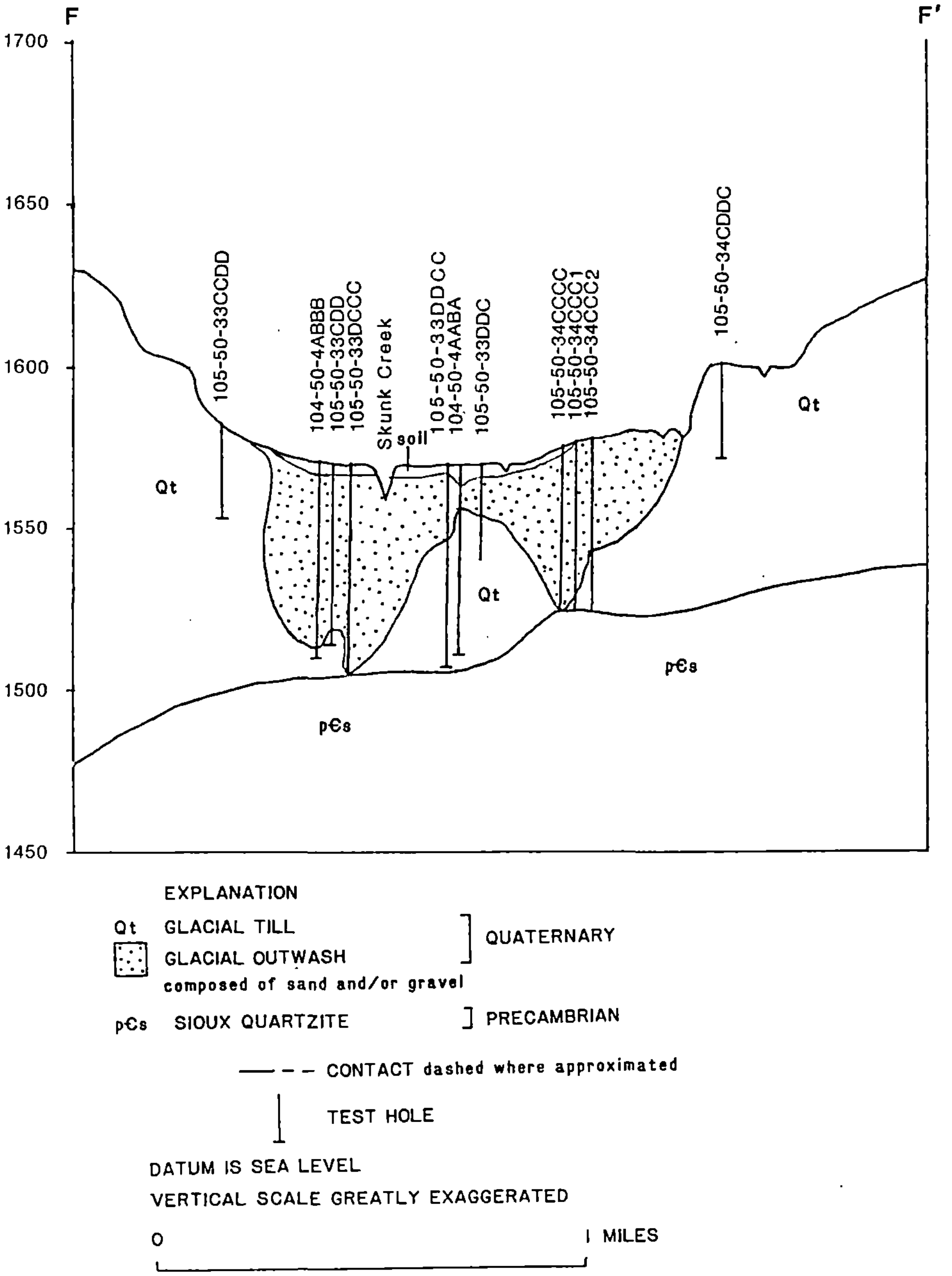

Figure 8. Geologic cross-section F - F'.

I). Skunk Creek flows directly on this outcrop where it has removed all outwash deposits from the bedrock surface. Consequently, the quartzite acts a ground-water barrier in this area.

The northern unit (Middle Skunk Creek management unit), north of the quartzite outcrop, lies along Skunk Creek and West Branch Skunk Creek. The southern unit (Southern Skunk Creek management unit), south of the quartzite outcrop, lies along Skunk Creek and southern Willow Creek. The width of the aquifer is generally equivalent to the width of the flood plain ranging from approximately .25 to 2 miles.

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 West Branch Skunk Creek (Figures 6 and 7). 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 downcut through the outwash deposits and into the underlying till (Figure 4) 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 porous media for a given unit of time under a unit hydraulic gradient. Hydraulic conductivity is closely related to grain size as shown in Table I. Based on Table I, hydraulic conductivities of the aquifer are estimated to range from 70 to 2000 feet/day (520 to 14960 gpd/ft^2). Aquifer test analyses and laboratory permeameter tests suggest that hydraulic conductivities range from about 80 to 1980 feet/day (630 to 14800 gpd/ft^2) (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 I

RELATIONSHIP BETWEEN GRAIN SIZE CLASS AND HYDRAULIC CONDUCTIVITY IN GLACIAL DRIFT

Grain Size Class	Range of hydraulic conductivity in glacial drift (feet/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 - 1000
Sand and gravel	400 - 1200
Sand, coarse, and gravel	400 - 1400
Gravel	800 - 2000

Modified from Koch (1980)

Ground-water Recharge

Recharge to the Skunk Creek aquifer occurs predominantly by the direct infiltration of precipitation through the soil zone, which varies from less than 1 to 5 feet in thickness. Water levels rise in response to periods of increased precipitation as shown in Figure 9. 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 104N50W04DCCC1 (Figure 9).

Ground-water recharge was calculated for the study period from 1978 through 1985 using two methods: i)a well hydrograph technique, and ii)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 - 1985 resulted in an average annual net rise in water levels of 41.1 inches. Based on a specific yield of .20, the average annual effective recharge into the aquifer is approximately 5.9 inches or approximately 24 percent of average annual precipitation for the eight year period. For example, the total net rise for the period of record for well 104N50W04-DCCC1 (Figure 9) was 19.9 feet with an average annual net rise of 2.5 feet (30 inches) resulting in an average annual effective recharge of approximately six 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.

The stream hydrograph separation technique involves

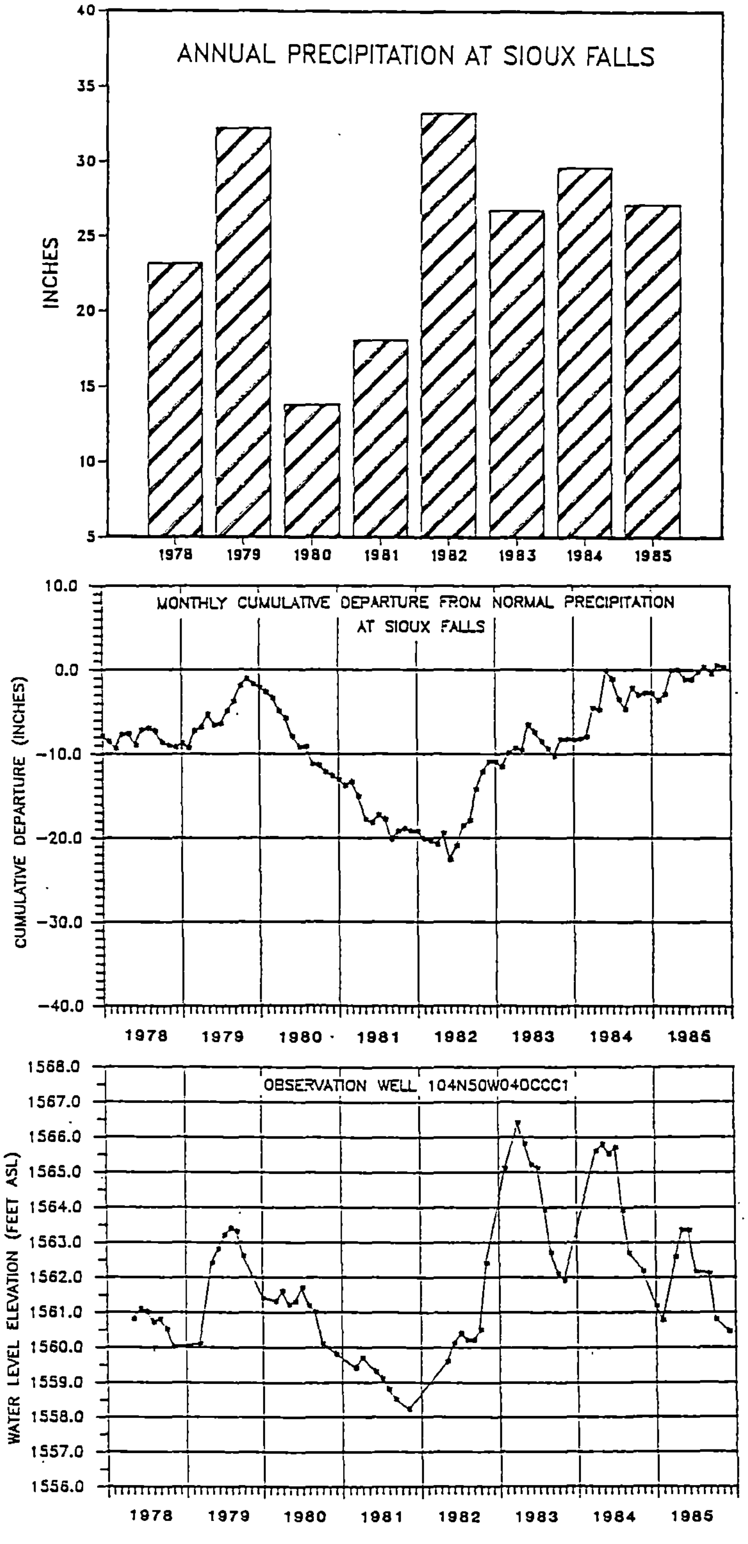

Figure 9. Annual precipitation, monthly cumulative departure from normal precipitation at Sioux Falls, and well hydrograph for observation well 104N50W04DCCC1.

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 10. Ground-water recharge rates in the Skunk Creek - Lake Madison drainage basin (613 mi^2) are shown in Table II. Recharge rates for the entire basin are considerably lower than those calculated for the aquifer by well hydrograph analysis due to the variable permeability of the glacial deposits in the basin. Recharge to the low permeability glacial till eventually enters the high permeability outwash deposits and is subsequently discharged into the stream 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 approximately 55000 acre-ft/yr. Part of this volume of recharge is assumed to eventually enter

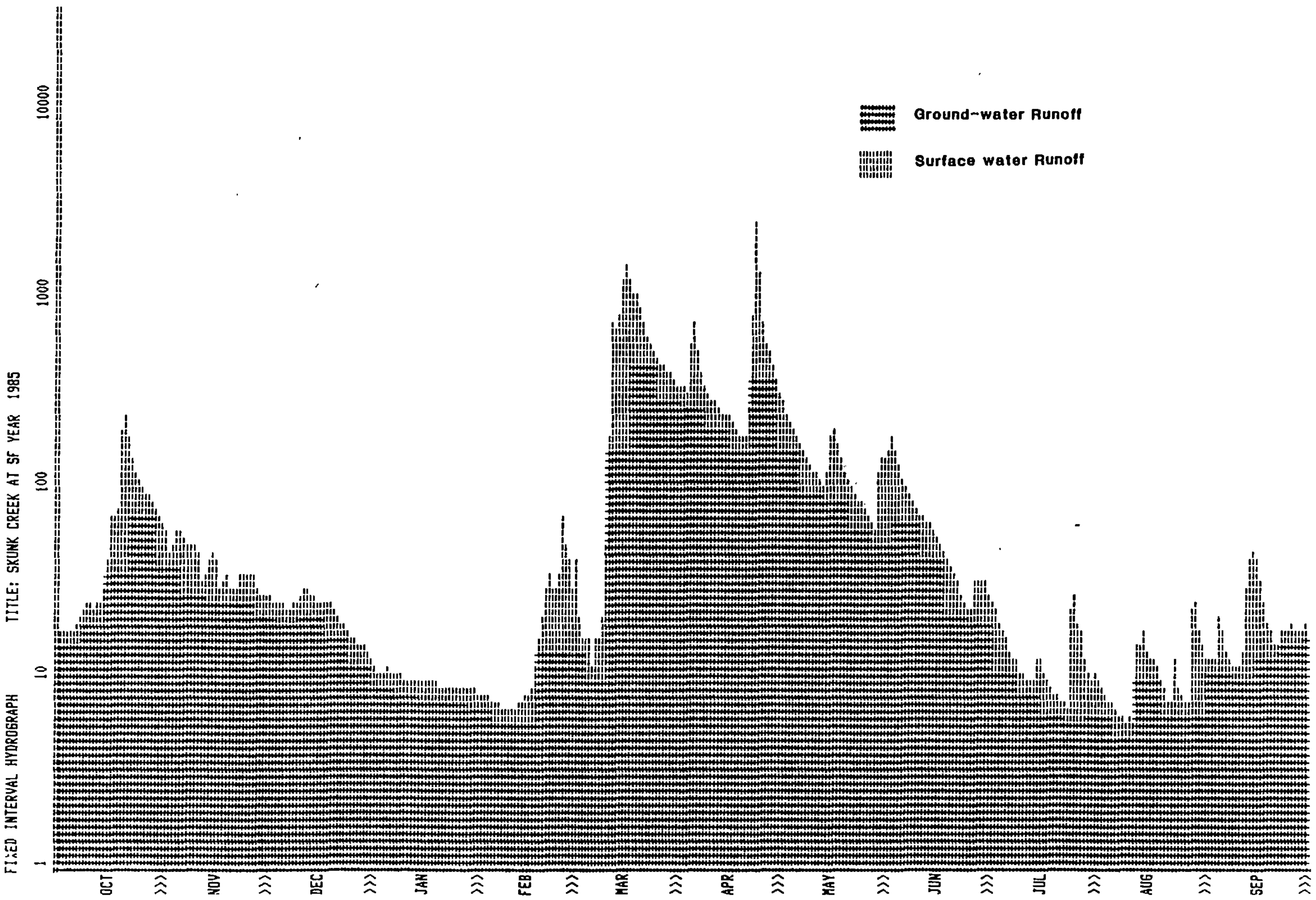

Figure 10. Fixed interval streamflow hydrograph separation for Skunk Creek at Sioux Falls (1985).

the outwash deposits as underflow from the till. A volume of 55000 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 II

SUMMARY OF GROUND-WATER RECHARGE RATES IN THE SKUNK CREEK - LAKE MADISON DRAINAGE BASIN BASED ON A FIXED INTERVAL STREAMFLOW HYDROGRAPH SEPARATION (1978 - 1985)

Water year	Recharge rate (in/yr)	Total volume of recharge (acre-ft/yr)	Percent of total streamflow	Annual precipitation for water year (in/yr)
1978	.62	20407	48	27.07
1979	.94	30579	47	28.32
1980	.35	11435	63	17.21
1981	.02	797	71	15.74
1982	.32	10510	34	27.19
1983	4.42	144576	65	32.49
1984	5.25	171706	59	28.87
1985	1.63	53321	58	29.13
Mean	1.69	55416	56	25.75

One possible explanation is the relatively short length of the streamflow data base utilized for the hydrograph separations. Recharge to the low permeability till deposits may take a number of years to reach Skunk Creek as ground-water runoff. Therefore a longer data base may provide a better estimate of actual recharge to the aquifer.

Ground Water - Surface Water Interactions

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 ground water - surface water interaction.

Gaining stream conditions predominate when the localized hydraulic gradient in the aquifer is toward the stream (Figure 11B). 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 (Figure 11A) or during periods of high stream stage following precipitation and/or snow melt runoff (Figure 11C).

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 .4 to 1.0 ft/day (3.2 - 7.4 gpd/ft^2) (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 low discharge.

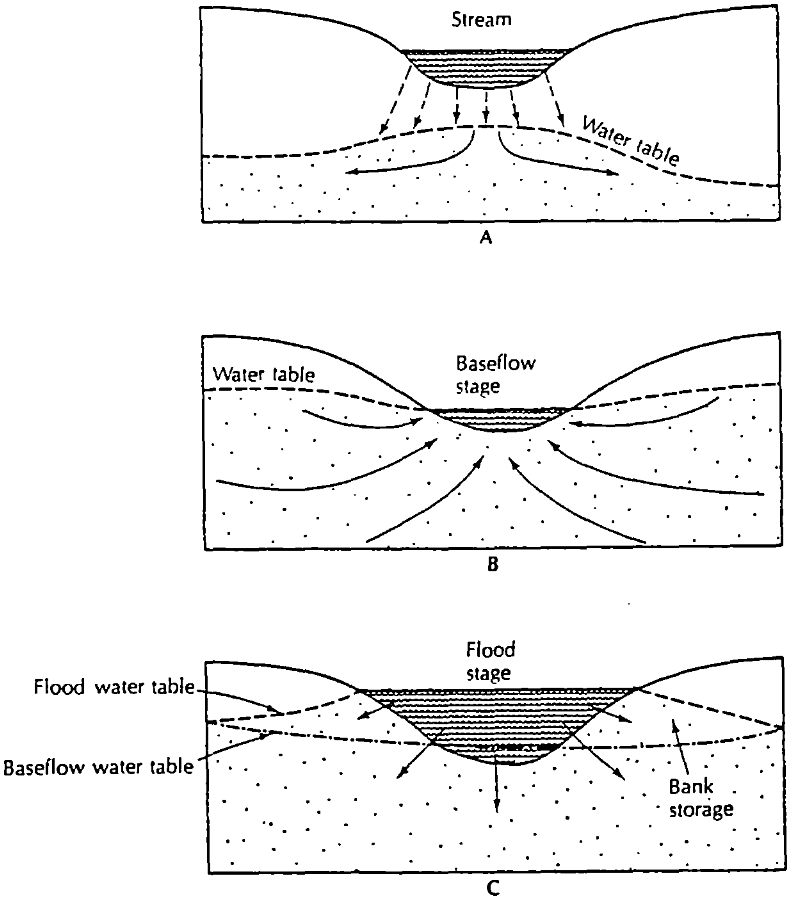

Figure 11. Cross-sections of gaining and losing streams. A. a losing stream; B. a gaining stream; C. a stream which is gaining during low flow periods but which may temporarily become a losing stream during flood stage. (From Fetter, 1980)

The vertical hydraulic conductivity of the streambed can be calculated from infiltration rates using the following relationship: $K_z = Im/\Delta h$

where: K_z = vertical hydraulic conductivity of the streambed
I = streambed infiltration rate
m = thickness of the streambed sediments
Δh = head difference between the stream stage and stream sediments

The vertical hydraulic conductivity could not be calculated from the aforementioned infiltration rates because m and h are unknown. However, streambed vertical hydraulic conductivities are generally lower than infiltration rates because Δh is generally larger than m. Assuming a Δh of four feet and a streambed thickness of two feet the vertical hydraulic conductivity of the streambed in the Big Sioux River ranges from .21 to .50 feet/day (1.6 - 3.7 gpd/ft^2) based on the above infiltration rates.

Jorgensen and Ackroyd (1973) conducted laboratory tests of a fine grained, silty streambed material collected from a diversion canal on the Big Sioux River north of the City of Sioux Falls. Lower streamflow velocities in the diversion canal resulted in the deposition of a clayey silt, which had a vertical hydraulic conductivity of .01 feet/day (.74 gpd/ft^2) (Jorgensen and Ackroyd, 1973). Streambed hydraulic conductivities for Skunk Creek are assumed to be lower than those measured in the Big Sioux River due to lower stream flow 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 .01 to .50 feet/day (.74 - 3.7 gpd/ft^2).

CHAPTER IV

HYDROGEOCHEMISTRY OF THE SKUNK CREEK AQUIFER

Water Quality

The Skunk Creek aquifer contains relatively good quality water which is of low 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. 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 III and IV. Concentrations of nitrate (NO_3 as N) are generally less than one mg/l, however three values greater than 10 mg/l raise the mean value to four mg/l. Ground water with high nitrate concentrations 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 (Figures 12 and 13). 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

TABLE III

SUMMARY OF CHEMICAL ANALYSES OF WATER FROM THE SKUNK CREEK AQUIFER

Parameter	Number of samples	Minimum value	Maximum value	Mean value
Dissolved calcium (mg/l)	43	40	190	103
Dissolved magnesium (mg/l)	43	10	70	36
Dissolved sodium (mg/l)	43	2	57	16
Dissolved potassium (mg/l)	43	0	16	3
Dissolved chloride (mg/l)	43	0	66	16
Dissolved sulfate (mg/l)	42	20	500	129
Bicarbonate (mg/l)	41	120	427	316
Nitrate (as N) (mg/l)	28	0	53	4
Dissolved Silica (mg/l)	8	18	30	25
Dissolved solids (mg/l, sum of reported constituents)	41	216	1188	620
Specific conductance (uMhos/cm)	43	317	1317	774
$CaCO_3$ Hardness (mg/l, as Ca and Mg)	43	141	762	403
pH	43	7.0	8.2	7.5
Temperature (degrees Celsius)	7	7.8	12.2	10.9

Chemical data obtained from the U.S. Geological Survey WATSTORE data base.

TABLE IV

SUMMARY OF CHEMICAL ANALYSES OF SURFACE WATER FROM SKUNK CREEK AT SIOUX FALLS

Parameter	Number of samples	Minimum value	Maximum value	Mean value
Dissolved calcium (mg/l)	13	61	133	101
Dissolved magnesium (mg/l)	13	26	85	52
Dissolved sodium (mg/l)	13	15	65	33
Dissolved potassium (mg/l)	13	7	18	11
Dissolved chloride (mg/l)	13	8	58	25
Dissolved sulfate (mg/l)	13	150	490	279
Bicarbonate (mg/l)	13	157	354	282
Nitrate (as N) (mg/l)	6	.3	1	.6
Dissolved Silica (mg/l)	13	2.2	25	10
Dissolved solids (mg/l, sum of reported constituents)	13	442	1150	848
Specific conductance (uMhos/cm)	13	613	1410	977
$CaCO_3$ Hardness (mg/l, as Ca and Mg)	13	270	670	465
pH	13	7.6	8.3	7.9
Temperature (degrees Celsius)	13	0	29	13

Chemical data obtained from the U.S. Geological Survey WATSTORE data base.

concentration, and well depth for each sample location are shown on Plate III. Sulfate concentrations were highest in the vicinity of the hydrologic 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, with calcium as the dominant cation and bicarbonate as the dominant anion. Surface water samples taken from Skunk Creek at Sioux Falls were of the calcium-bicarbonate or calcium-sulfate type. Both ground water and surface water also contain significant concentrations of magnesium and low 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 hydrologic connection with the Wall Lake aquifer, which discharges calcium-sulfate water of a high 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 hydrologic connection with the Wall Lake aquifer. These samples contained a higher percentage of sulfate (Figure 13) and had a higher 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 high concentrations of sulfate and dissolved solids.

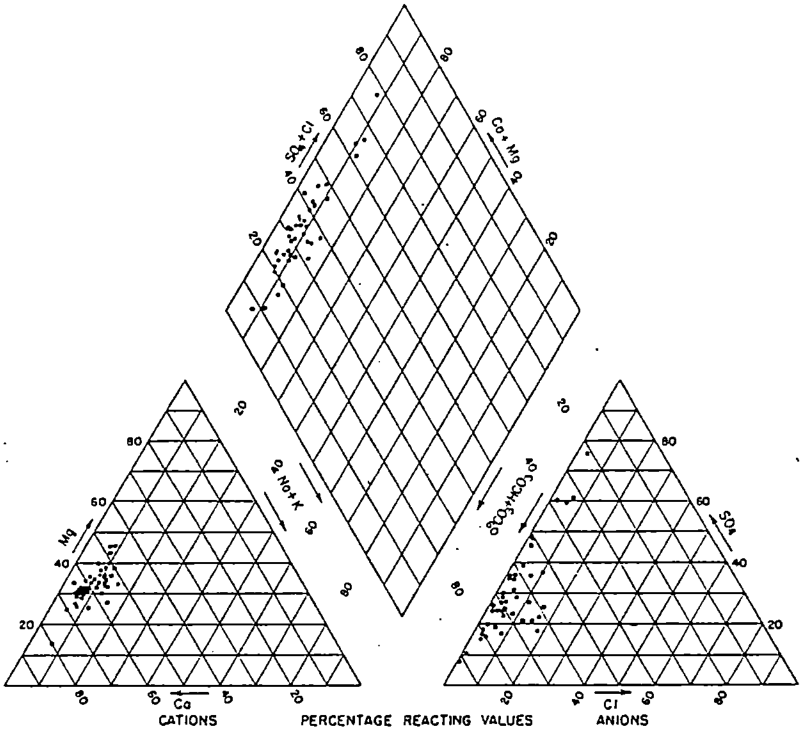

Figure 12. Piper diagram of 43 water analyses from the Skunk Creek aquifer.

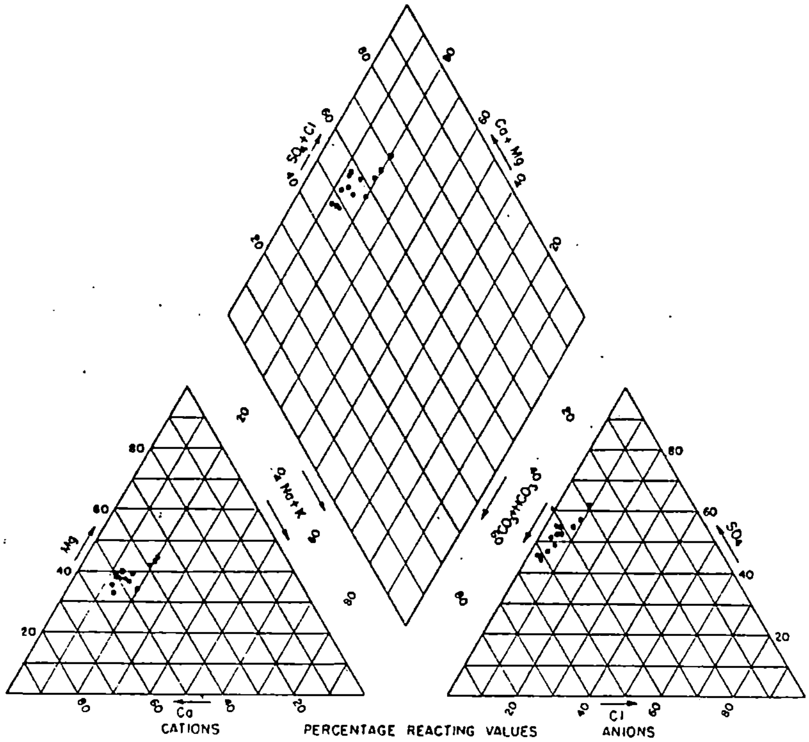

Figure 13. Piper diagram of 13 water analyses from Skunk Creek at Sioux Falls.

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

Origin of the Chemical Constituents in the Ground Water

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).

The saturation states of eight ground-water samples with respect to various common minerals are shown in Table V. 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

TABLE V

SUMMARY OF WATER SATURATION STATES WITH RESPECT TO VARIOUS MINERALS

Sample Location	Anhydrite	Gypsum	Aragonite	Calcite	Dolomite	Chalcedony	Quartz
101N50W07AAB	-1.79	-1.45	.26	.56	.85	.15	.69
101N50W03CCC	-2.15	-1.77	.10	.21	.08	.30	.85
102N51W03ADD	-2.08	-1.75	-.24	.05	-.09	.24	.77
103N50W18CDA	-1.58	-1.22	-.48	-.18	-.71	.34	.88
103N50W07DCD	-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
104N50W09ABA	-1.63	-1.23	-.35	.03	-.46	.43	.98

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 relationship:

SI = log IAP/Ksp where: SI= saturation index
IAP = ion activity product
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.

<u>Sulfate Mineral Dissolution</u>

The dissolution of highly soluble sulfate minerals, such as gypsum and anhydrite, contribute the sulfate component and a portion of the calcium component of the water. Evidence for the dissolution of gypsum and anhydrite is shown by the linear relationship between reacting values of calcium and sulfate (Figure 14). Despite the high solubility of gypsum and anhydrite, 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.

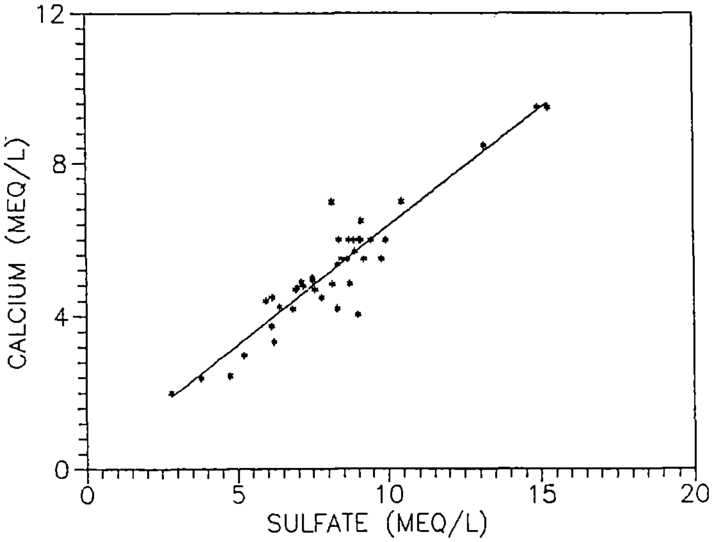

Figure 14. Scatter diagram illustrating the linear relationship between reacting values (meq/l) of calcium and sulfate.

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 relationship between reacting values of residual calcium plus magnesium and bicarbonate is evidence for the dissolution of dolomite (Figure 15). 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 (meq/l) from the calcium reacting values (meq/l) yields the residual calcium available from other mineralogic sources. Four of the samples had no residual calcium and do not appear on Figures 15 and 16. 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 relationship between residual calcium and bicarbonate (Figure 16) indicates that the dissolution of calcite and aragonite is probably 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 are probably 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 CO_2 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 high 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.

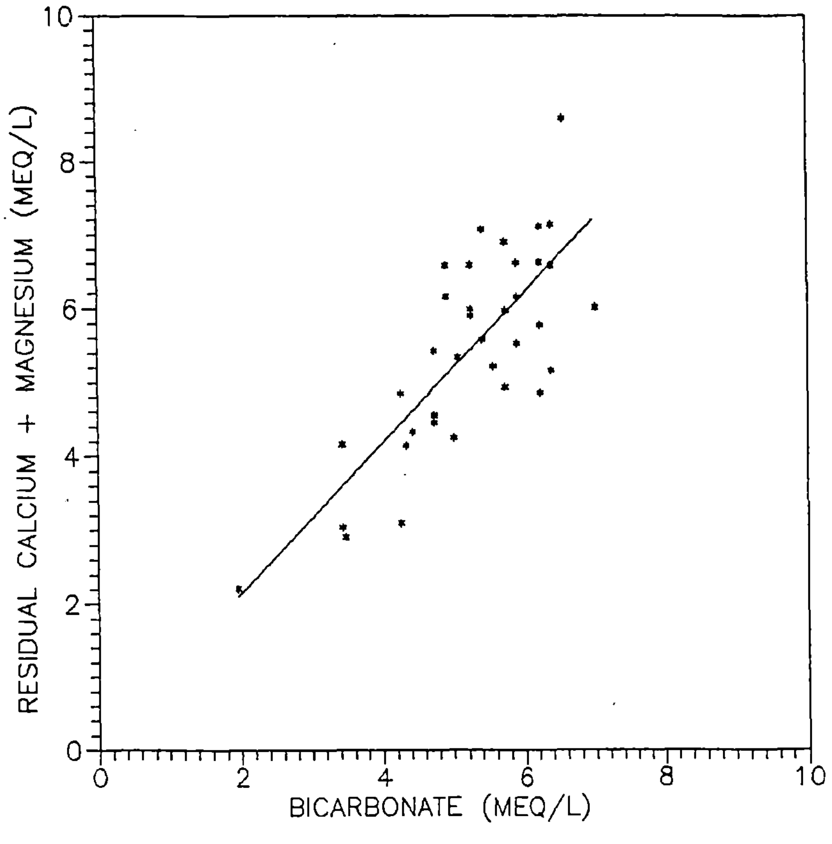

Figure 15. Scatter diagram illustrating the prominent linear relationship between reacting values (meq/l) of residual calcium plus magnesium and bicarbonate.

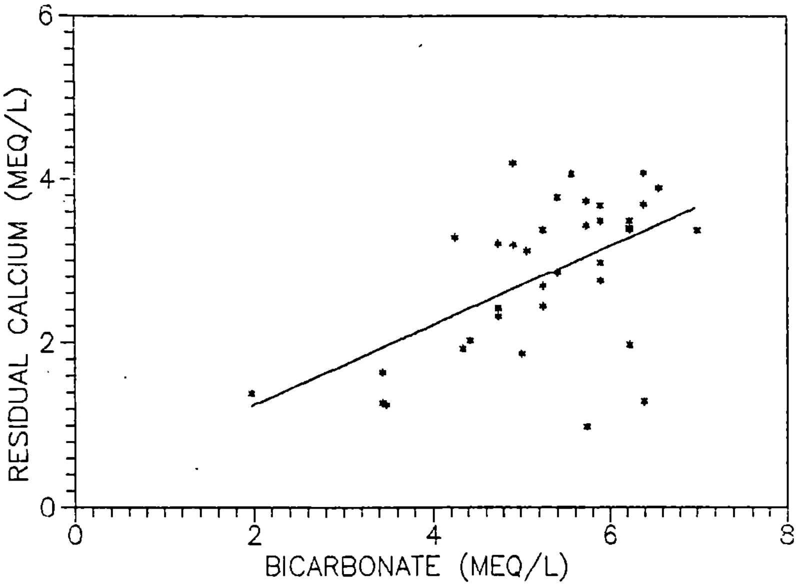

Figure 16. Scatter diagram illustrating the less prominent relationship between reacting values (meq/l) of residual calcium and bicarbonate.

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, 1973). 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 V). The dissolution of ferromagnesian silicate minerals probably contributes to the magnesium content of the water. The chemical weathering of quartz and amorphous silica does not generally increase the amount of silica present in ground water (Freeze and Cherry, 1979).

Therefore, chemical weathering of the Sioux Quartzite is not believed to contribute significant amounts of silica to the ground water.

CHAPTER V

NUMERICAL COMPUTER MODEL

Model Description

A numerical computer model was used to simulate ground-water flow in a hydrogeological setting analagous to 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.

Model Development

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 (Plate IV) with each cell in the grid .25 mile on a side. The center of each cell is referred to as a node. The model contains 484 active nodes each representing .0625 square miles 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 relationships and stream stage measurements taken at bridges through out 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 hydrologic 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 hydrologically connected to the Big Sioux River, Skunk Creek, and its tributaries.

4) The aquifer is unconfined (water table) except in the area of the hydrologic connection with the Wall Lake aquifer where the aquifer is confined (artesian) (Plate IV).

5) Recharge to the aquifer from the Wall Lake aquifer and the North Skunk Creek aquifer (northern model boundary) 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 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 a assigned depth.

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 Input Data

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

Land Surface Elevation

Land surface elevations for each node were obtained by superimposing a .25 mile grid over 7.5 minute U. S. Geological Survey topographic maps for the study area. The most frequently occurring elevation in the each grid cell was used as the average land surface elevation in that particular model node.

Elevation of the Aquifer Bottom

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 as 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 hydrologic separation from nearby streams. A contour map of the aquifer bottom elevations used in the model is shown on Plate V.

Top of Aquifer Elevation

Available lithologic logs were used to assign top of aquifer elevations to the 10 nodes representing the hydrologic connection with the semi-confined Wall Lake aquifer. 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.

Hydraulic Conductivity of the Aquifer

Hydraulic conductivities used in the model were based on grain-size determinations obtained from test hole data (Table I). A plausible range of hydraulic conductivity for the outwash deposits, which comprise the Skunk Creek aquifer is from 70 to 2000 feet/day (520 - 14960 gpd/ft^2). Hydraulic conductivities represented in the model range from 10 to 400 feet/day (70 - 2990 gpd/ft^2) with a constant value of 400 feet/day (2990 gpd/ft^2) assigned to all nodes representing the unconfined Skunk Creek aquifer. A value of 300 feet/day (2240 gpd/ft^2) was assigned to the 10 nodes that represent the hydrologic connection with the Wall Lake aquifer. A hydraulic conductivity of 10 feet/day (70 gpd/ft^2) was assigned to 9 nodes in which Skunk Creek has downcut through the aquifer into glacial till as illustrated in Figure 5.

Storage in the Aquifer

Storage terms assigned in the model consist of a specific yield of .20 and a storage coefficent of .001. A specific yield of .20 was assumed for the Skunk Creek aquifer as described in the previous section on "Aquifer Characteristics". The storage coefficient of .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

Recharge to the aquifer is represented in the model as occurring from infiltration of precipitation and discharge from the Wall Lake and North Skunk Creek (North Skunk Creek management unit) aquifers.

Recharge to the aquifer by precipitation was calculated using the well hydrograph technique previously described in the section on "Ground-water Recharge".

Underflow from the Wall Lake and North Skunk Creek aquifers was simulated by implementing 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 and 471 acre-ft/yr for the North Skunk Creek and Wall Lake aquifers, respectively.

River Representation

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 (Plate IV).

River stage elevation for each node along the length of the rivers was determined by interpolating between river stage measurement points. River stage was measured at three gaging stations and various 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 cfs were used for the steady-state simulation (1978 - 1985 average monthly streamflow of 132 cfs) with an adjustment factor of +0.28 feet.

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

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

$$C = KLW/M$$

where: C = conductance of the river reach
K = vertical hydraulic conductivity of the riverbed
L = length of the river reach
W = width of the river reach
M = thickness of the riverbed

A riverbed hydraulic conductivity of .05 feet/day (.4 gpd/ft^2) was used to calculate the conductance for Skunk Creek, West Branch Skunk Creek, and Willow Creek, whereas .5 feet/day (3.7 gpd/ft^2) was used for the Big Sioux River. These values are estimates based on the model calibration procedure and 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 widths for the Big Sioux River, Skunk Creek, West Branch Skunk Creek, and Willow Creek are 80, 40, 25, and 20 feet, respectively. Riverbed thickness was assumed to be 1 foot for all river reaches.

Evapotranspiration from the Aquifer

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 seventy 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 a depth of five feet below land surface. No evapotranspiration was simulated at depths greater than five feet due to the predominantly shallow rooted vegetation in the study area. The maximum potential evapotranspiration rate is input into 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.

Pumpage from the Aquifer

Discharge from the aquifer by pumpage was simulated using discharge wells in the appropriate model nodes (Plate IV). 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.

CHAPTER VI

MODEL CALIBRATION

Steady-State Model Calibration

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 (Figure 17), 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 eight 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

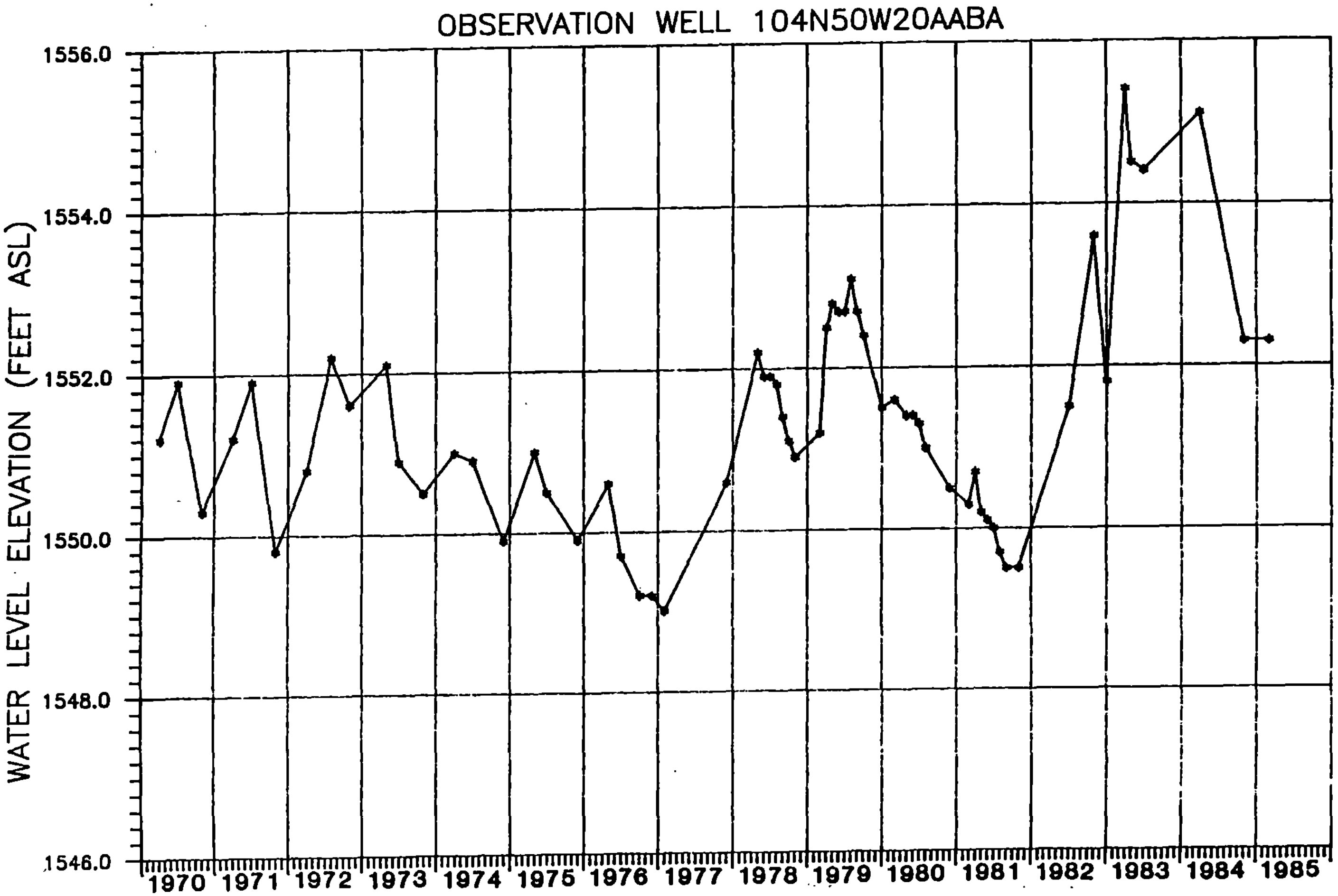

Figure 17. Long term well hydrograph for observation well 104N50W20AABA.

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 on Plate VI.

Hydraulic conductivity of the aquifer and riverbed were adjusted in the calibration procedure with variable results. Adjustments to aquifer hydraulic conductivity were generally ineffective in improving the match between simulated and observed water levels. However in the area where Skunk Creek has downcut into glacial till (Section 8, T.101 N., R.50 W.) reducing the hydraulic conductivity from 400 (2990 gpd/ft^2) to 10 feet/day (75 gpd/ft^2) significantly improved the head match. Riverbed hydraulic conductivity was varied from .01 to 1.0 feet/day (.07 - 7.5 gpd/ft^2) in Skunk Creek and from .1 to 1.0 feet/day (.7 - 7.5 gpd/ft^2) in the Big Sioux River. The closest match between simulated and observed water levels and simulated and observed groundwater discharge to streams was obtained using a riverbed hydraulic conductivity of .05 feet/day (.37 gpd/ft^2) for Skunk Creek, West Branch Skunk Creek, and Willow Creek, and .5 feet/day (3.7 gpd/ft^2) for the Big Sioux River. Decreasing the riverbed hydraulic conductivity in the Big Sioux River caused simulated heads to increase approximately 1 to 3 feet 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 feet/day
Streambed vertical hydraulic conductivity:
  Skunk Creek, West Branch Skunk Creek
    and Willow Creek: .05 feet/day
  Big Sioux River: .5 feet/day
Recharge: 6.0 inches/year
Maximum evapotranspiration rate: 32 inches/year
Evapotranspiration extinction depth: 5 feet

The algebraic mean difference between model simulated heads and observed water levels was .03 feet and the absolute mean difference between model simulated heads and observed water levels was 1.25 feet 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 - 1985 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 - 1985 water-level measurements were corrected for the 1978 - 1985 calibration period. The amount of water-level adjustment (-.26 feet) was obtained by subtracting the difference between the November 1984 - December 1985 average water levels from the 1978 - 1985 average water levels for the seven observation wells with a complete record.

Steady-State Hydrologic Budget

The steady-state simulation provided a hydrologic budget (Table VI) 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 and inflow from the Wall Lake and North Skunk Creek aquifers comprise only five and two percent of the budget, respectively. Evapotranspiration and discharge to streams were the largest outflow components from the aquifer. Irrigation pumpage accounts for only two percent of the total hydrologic budget.

TABLE VI

SIMULATED STEADY-STATE HYDROLOGIC BUDGET

Budget Component	Rate (acre-ft/yr.)	Percent
INFLOW:		
Recharge by precipitation	9506	43
Recharge from streams	1086	5
Ground-water underflow	485	2
Total Inflow	11077	
OUTFLOW:		
Evapotranspiration	4931	22
Discharge to streams	5741	26
Irrigation pumpage	405	2
Total Outflow	11077	

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 VII.

The model was most sensitive to changes in recharge and riverbed hydraulic conductivity. Increasing aquifer recharge by 50 percent (from 6 in/yr to 9 in/yr) caused the simulated heads to rise an average of 1.06 feet. Decreasing aquifer recharge by 50 percent (from 6 in/yr to 3 in/yr) caused water levels to drop an average of 1.23 feet. Increasing the riverbed hydraulic conductivity by 100 percent (from .05 - .5 feet/day to .1 - 1.0 feet/day) resulted in an average water-level decline of .19 feet, whereas a decrease of 90 percent (from .05 - .5 feet/day to .005 -.05 feet/day) caused simulated heads to rise an average of 1.58 feet. 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 .27 feet and an equivalent decrease resulted in an average water-level rise of .40 feet.

TABLE VII

SUMMARY OF SENSITIVITY ANALYSIS RESULTS FOR THE STEADY-STATE MODEL

Adjusted Hydrologic Parameter	Increased	Decreased	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	----	----	.03	1.25	----
Recharge	25 %		.58	1.22	.55
	50 %		1.09	1.43	1.06
		25 %	-.55	1.35	-.58
		50 %	-1.20	1.51	-1.23
Streambed 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 (.03 ft) 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.

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.

Water-level measurements from 26 observation wells were used to compare monthly 1985 simulated water levels to observed water levels (Table VIII).

TABLE VIII

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	.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.

A comparison of simulated and measured water levels for 1985 was made by plotting well hydrographs for three observation wells in the aquifer (Figure 18). This allows for a comparison of simulated and observed monthly fluctuations in water levels. 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. The simulated ground-water discharge to streams for July and August was 11.5 and 11.5 cfs, respectively. The average observed increase in streamflow between the two gages during these months was 10.4 and 8.8 cfs, respectively. The difference between observed and simulated ground-water discharge to streams was approximately 10 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.

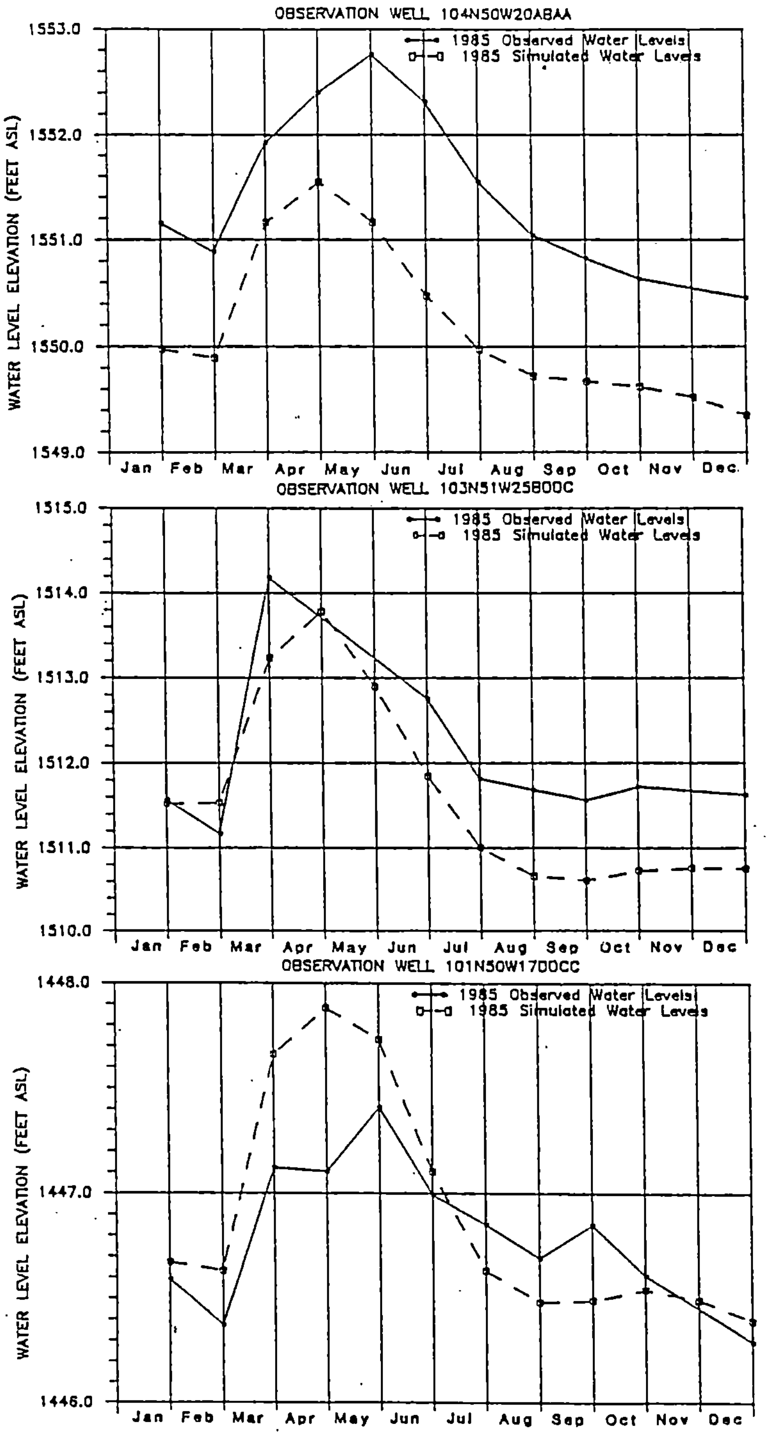

Figure 18. Comparison of 1985 monthly observed and simulated water levels for 3 observation wells.

Results of Monthly 1985 Transient Simulations

Monthly simulations for 1985, provided a simulated hydrologic budget for each month, which are summarized in Table IX. 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.

TABLE IX

SUMMARY OF SIMULATED MONTHLY HYDROLOGIC BUDGETS FOR 1985

Accretions (Sources of water)	January	February	March	April	May	June	July	August	September	October	November	December	Total
Recharge by Precipitation	0	319	4510	1511	1946	0	160	604	734	414	50	0	10248
	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 Streams	6	7	107	43	60	61	25	25	26	20	23	14	417
	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 Underflow	41	37	41	40	41	40	41	41	40	41	41	41	485
	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 Storage	941	437	0	1	754	1940	1869	1024	431	480	649	695	9221
	47.6	27.3	0.0	.0	13.5	47.5	44.6	30.2	17.5	25.1	42.5	46.4	22.6
Depeletions (Consumption of water)													
Evapotranspiration	0	0	0	0	1553	1142	914	578	329	0	0	0	4516
	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 Streams	987	779	449	506	893	809	972	904	794	785	713	732	9323
	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
Irrigation 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 Storage	1	21	4208	1083	320	0	0	0	60	163	50	18	5924
	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	1976	1600	9315	3189	5603	4081	4190	3389	2462	1911	1526	1500	40742
	100	100	100	100	100	100	100	100	100	100	100	100	100

Upper number is acre-ft (rounded); lower number is percentage

CHAPTER VII

MODEL APPLICATION

Simulation of Hypothetical Hydrologic Situations

The model was used to analyze and predict the effects of three hypothetical hydrologic situations: 1) increased withdrawal under steady-state conditions, 2) increased withdrawal under 1985 transient hydrologic conditions, and 3) increased withdrawal under severe drought conditions (no recharge).

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 1978-1985 average of 6.0 in/yr.

The third hypothetical situation was conducted to evaluate the aquifer's response to severe drought conditions with no recharge from precipitation or leakage from streams.

Hypothetical Situation I, Increased Withdrawal under Steady-State Conditions

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 gpm was chosen for discharge nodes 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 gpm discharge rate due to a lesser saturated thickness and aquifer boundary conditions.

The simulation resulted in a total ground-water withdrawal of 15731 acre-ft/yr from a total of 32 discharge wells. The simulated aquifer drawdown measured from the previous steady-state potentiometric surface is shown on Plate VII and the hydrologic budget at new equilibrium conditions is shown in Table X. Drawdown was greatest in the pumping nodes ranging from 4 to 12 feet and decreased rapidly away from the pumping nodes as shown in Figure 19. 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 X), relative to the pre-development hydrologic budget (Table VI), reveals that declining water levels induced by pumping resulted in a decrease in ground-water discharge to streams of 4069 acre-ft/yr and a increase in recharge from streams of 7565 acre-ft/yr. Evapotranspiration was decreased by 3671 acre-ft/yr and pumpage from the aquifer was increased by 97 percent (15326 acre-ft/yr).

The volume of water produced from each hypothetical well could supply a population of approximately 4300 persons based on a U.S. Geological Survey estimated consumption rate of 166 gallons/day/person (Pettyjohn, personal comm.) The total volume from the 19 hypothetical wells could supply a population of approximately 81,000 persons.

TABLE X

SUMMARY OF SIMULATED HYDROLOGIC BUDGET FOR HYPOTHETICAL SITUATION I

Budget Component	Rate (acre-ft/yr.)	Percent
INFLOW:		
Recharge by precipitation	9527	25.5
Recharge from streams	8651	23.2
Ground-water underflow	485	1.3
Total Inflow	18663	
OUTFLOW:		
Evapotranspiration	1260	3.4
Discharge to streams	1672	4.5
Pumpage	15731	42.1
Total Outflow	18663	100.0

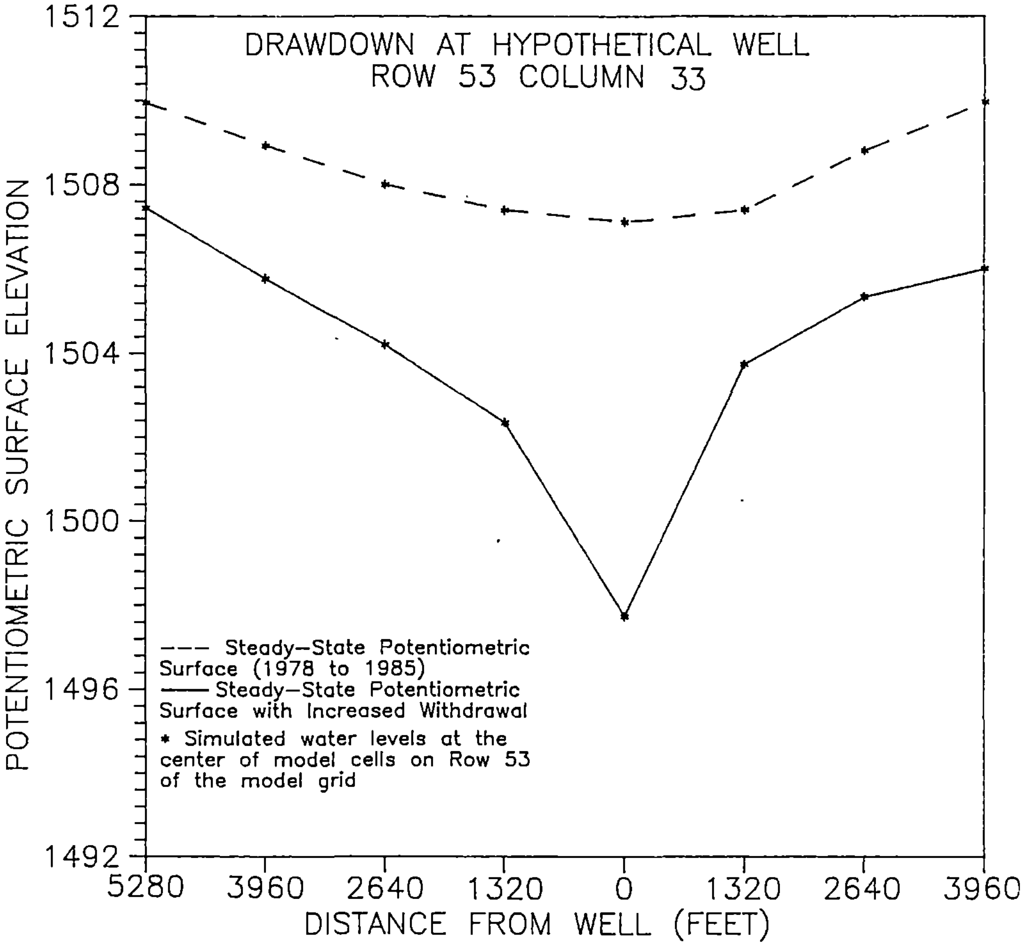

Figure 19. Distance-drawdown plot for hypothetical well (Row 53, Column 33) at a pumping rate of 500 gpm, Hypothetical Situation I.

Hypothetical Situation II, Increased Withdrawal under 1985 Transient Conditions

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. The same 19 discharge wells used in Hypothetical Situation I (Plate VIII) 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 II are shown in Table XI. Comparison of the hydrologic budget in Table XI, to the 1985 pre-development budget (Table IX), indicates that the declining water levels brought about by increased withdrawal caused an increase in recharge from streams (2325 acre-ft/yr) and decreases in ground-water discharge to streams (3953 acre-ft/yr), ground-water storage (5250 acre-ft/yr), and evapotranspiration (1990 acre-ft/yr). Simulated pumpage for this simulation represents an increase of 15354 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 (Plate VIII). Drawdown was greatest in the discharge nodes, ranging from 5 to 8 feet. No

TABLE XI

SUMMARY OF SIMULATED MONTHLY HYDROLOGIC BUDGETS FOR HYPOTHETICAL SITUATION II

Accretions (Sources of water)	January	February	March	April	May	June	July	August	September	October	November	December	Total
Recharge by Precipitation	0	319	4510	1511	1946	0	160	604	734	414	50	0	10248
	0.0	9.3	45.3	38.2	31.8	0.0	3.1	13.2	19.5	12.1	1.5	0.0	18.3
Recharge from Streams	38	62	426	372	203	202	145	176	223	264	320	311	2742
	0.9	1.8	4.3	9.4	3.3	4.1	2.8	3.9	5.9	7.8	9.9	9.8	4.9
Ground-water Underflow	41	37	41	40	41	40	41	41	40	41	41	41	485
	1.0	1.1	0.4	1.0	0.7	0.8	0.8	0.9	1.1	1.2	1.3	1.3	0.9
Decrease in Storage	2035	1300	0	57	867	2225	2214	1466	881	986	1200	1240	14471
	48.1	37.8	0.0	1.4	14.2	45.1	43.2	32.0	23.4	28.9	37.2	38.9	25.9
Evapotranspiration	0	0	0	0	989	663	469	266	139	0	0	0	2526
	0.0	0.0	0.0	0.0	16.2	13.4	9.2	5.8	3.7	0.0	0.0	0.0	4.5
Discharge to Streams	813	544	277	286	531	457	580	506	414	363	304	295	5370
	19.2	15.8	2.8	7.2	8.7	9.3	11.3	11.1	11.0	10.6	9.4	9.2	9.6
Pumpage	1300	1172	1302	1265	1337	1348	1511	1515	1305	1308	1301	1298	15962
	30.8	34.1	13.1	31.9	21.9	27.3	29.5	33.1	34.7	38.3	40.4	40.8	28.6
Increase in Storage	0	1	3399	429	200	0	0	0	20	35	5	0	4089
	0.0	.0	34.1	10.8	3.3	0.0	0.0	0.0	0.5	1.0	0.2	0.0	7.3
Total	4227	3435	9955	3960	6114	4935	5120	4574	3756	3411	3221	3185	55893
	100	100	100	100	100	100	100	100	100	100	100	100	100

Upper number is acre-ft (rounded); lower number is percentage

drawdown occurred in the unstressed areas, such as in the region of West Branch Skunk Creek.

Total ground-water withdrawals for this simulation of 15962 acre-ft/yr will supply a population of approximately 81,000 persons based on a estimated consumptive water use of 166 gallons/day/person.

Hypothetical Situation III, Increased Withdrawal under Severe Drought Conditions

The aquifer was further stressed in the third hypothetical hydrologic situation by simulating increased ground-water withdrawal under severe drought conditions. This was accomplished by modifing the 1985 transient model to simulate increased pumpage and no recharge to the aquifer by precipitation and leakage from streams. Increased ground-water withdrawal was simulated using the same 19 hypothetical discharge wells utilized in Hypothetical Situation II. As in the previous simulation, these wells were used in addition to the 1 to 10 wells simulating monthly reported irrigation pumpage in 1985. Dry stream conditions and no recharge to the aquifer by precipitation were simulated by inactivating the recharge and river modules in the MODFLOW code.

A withdrawal rate for each of the 19 hypothetical discharge wells of 500 gpm resulted in dry nodes in several areas of the aquifer during the October simulation. Withdrawal rates for all of the 19 wells were decreased to 400 gpm and the 12 monthly simulations were completed with no dry nodes.

Monthly hydrologic budgets for this hypothetical situation are shown in Table XII. Total pumpage from the aquifer for the 12 monthly simulations was 12893 acre-ft/yr. The pre-development 1985 hydrologic budget (Table IX) shows a net decrease in aquifer storage of only 9221 acre-ft/yr, whereas 14150 acre-ft/yr was removed from aquifer storage in this simulation. The additional 4929 acre-ft/yr removed from aquifer storage represents the effects of a 95 percent (12285 acre-ft/yr) increase in pumpage under severe drought conditions (no recharge).

A cumulative aquifer drawdown map for this hypothetical situation is shown on Plate IX. Drawdowns, calculated from the January 1985 initial head conditions, were greatest in the discharge nodes, ranging from 1 to 9 feet. No drawdown occurred in the area of West Branch Skunk Creek or near the southern model boundary (near Sioux Falls) due to the absence of the Big Sioux River, which receives large quantities of ground-water discharge from the southern end of the aquifer.

The volume of water supplied by each of the hypothetical wells during drought conditions could support a population of approximately 3400 persons based on estimated consumptive use of 166 gallons/day/person. The cumulative volume from all 19 wells could support a population of approximately 64000 persons.

TABLE XII

SUMMARY OF SIMULATED MONTHLY HYDROLOGIC BUDGETS FOR HYPOTHETICAL SITUATION III

Accretions (Sources of water)	January	February	March	April	May	June	July	August	September	October	November	December	Total
Ground-water	41	37	41	40	41	40	41	41	40	41	41	41	485
Underflow	1.7	1.8	1.9	1.9	1.3	1.4	1.4	1.5	1.7	1.9	2.0	2.0	1.7
Decrease in	1156	990	1070	1016	1530	1398	1470	1358	1100	1039	1015	1008	14150
Storage	48.3	48.2	48.1	48.1	48.7	48.6	48.6	48.5	48.3	48.1	48.0	48.0	48.3
Depletions (Consumption of water)													
Evapotranspiration	0	0	0	0	473	327	249	134	62	0	0	0	1245
	0.0	0.0	0.0	0.0	15.1	11.4	8.2	4.8	2.7	0.0	0.0	0.0	4.3
Pumpage	1042	939	1041	1012	1076	1097	1251	1256	1054	1046	1039	1040	12893
	43.5	45.7	46.8	47.9	34.2	38.1	41.4	44.9	46.3	48.4	49.2	49.5	44.0
Increase in	156	89	70	45	22	14	11	10	23	34	17	10	501
Storage	6.5	4.3	3.2	2.1	0.7	0.5	0.4	0.4	1.0	1.6	0.8	0.5	1.7
Total	2395	2055	2222	2113	3142	2876	3022	2799	2279	2160	2112	2099	29274
	100	100	100	100	100	100	100	100	100	100	100	100	100

Upper number is acre-ft (rounded); lower number is percentage

Model Limitations

The hydrologic system represented in this model is analagous to the Skunk Creek aquifer, but 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 .0625 square mile model cell. This model should not be used to determine well spacing or well field withdrawal rates on a localized, site specific basis due to error induced by the .25 mile model grid spacing.

The model is based on estimates of average recharge, hydraulic conductivity, and other hydrologic parameters which may result in a misrepresentation of the aquifer.

Aquifer production volumes predicted by the model are only estimates and should be used with caution. For example, the removal of the river module in the third hypothetical situation causes a water level rise in the downgradient portions of the model despite increased pumpage. This occurs because there is no ground-water discharge to streams represented in the model causing water levels to rise behind the downgradient no-flow boundaries.

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 and/or aquifer development near the boundaries. Aquifer drawdowns predicted by hypothetical situations could be misleading if heads at the recharge well nodes were to change due to future development (withdrawal).

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The Skunk Creek aquifer, a major glacial outwash deposit in the Skunk Creek - Lake Madison drainage basin is composed of a variable mixture of sand and gravel mantling glacial till and the Sioux Quartzite in the study area (30 mi^2).

Normal precipitation in the basin averages approximately 25 inches/year (817,300 acre-ft/yr) with approximately 44,900 acre-ft/yr leaving the basin as streamflow. The remaining 772,400 acre-ft/yr consists of water added to ground-water storage, to storage in ponds, sloughs, and lakes, and water loss by evapotranspiration.

The water quality of the Skunk Creek aquifer is relatively good with an average dissolved solids content of 620 mg/l. The water is very hard with an average $CaCO_3$ hardness of 403 mg/l.

A numerical computer model was developed and calibrated under steady-state and transient conditions. Average hydrologic conditions for a eight 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 .21 to .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 three 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 15731 acre-ft/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 15962 acre-ft/year with drawdown ranging from 0 to 8 feet.

The third hypothetical situation was conducted to determine the effect of increased pumpage under severe drought conditions (no recharge). This simulation used the same 19 hypothetical discharge wells as Hypothetical Situation II, however pumpage rates of 500 gpm for each well, resulted in dry nodes in some areas of the model. Therefore, well pumpage rates were decreased to 400 gpm for the 12 monthly simulations, resulting in a total withdrawal of 12893 acre-ft/year. Simulated drawdown ranged from 0 to 8 feet, with no dry nodes in the model.

Conclusions

Based on the 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 approximately six inches/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 hydrologically connected to the Wall Lake aquifer. Underflow from the Wall Lake aquifer effects 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 is generally 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 gpm.

9) The aquifer will reach steady-state (equilibrium) conditions with a total withdrawal rate of 15731 acre-ft/year, based on average hydrologic conditions from 1978 through 1985. This total withdrawal rate is from 19 hypothetical wells and 13 wells simulating 1978 - 1985 reported irrigation pumpage.

10) Based on simulated 1985 hydrologic conditions, the aquifer is capable of producing 15962 acre-ft/year for a 12 month period from 19 hypothetical wells and 1 to 10 wells simulating reported 1985 irrigation pumpage.

11) Based on simulated severe drought conditions (no recharge), the aquifer is capable of sustaining a total withdrawal rate of 12893 acre-ft/year for a 12 month period. This withdrawal rate is from 19 hypothetical wells in addition to the 1 to 10 wells simulating reported 1985 irrigation well pumpage.

12) Based on 1978 through 1985 average hydrologic

conditions the aquifer is capable of supplying water to a population of approximately 81,000 persons.

Recommendations

The Skunk Creek aquifer is an easily accessable source of large volumes of relatively good quality water. The water resources of the aquifer are virtually undeveloped, except for some relatively minor irrigation use. Further development of the aquifer as a water supply for municipalities, rural water distribution systems, and irrigation is recommended.

Aquifer development in the vicinity of the hydrologic connection with the Wall Lake aquifer should be avoided until the extent of the connection is better understood. Drawdown caused by pumpage may increase the flow of poor quality water from the Wall Lake aquifer causing degradation of the water quality in the Skunk Creek aquifer.

Further investigation of recharge to the aquifer from glacial till deposits is needed to establish a better understanding of the hydrologic system in the Skunk Creek-Lake Madison drainage basin. The collection of potentiometric surface data and insitu determination of hydraulic conductivities for till deposits would allow for more accurate quantification of recharge to the till and subsequent underflow to the Skunk Creek aquifer.

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APPENDICES

APPENDIX A

GEOLOGIC LOGS

Location: 101N50W 3BBBA
County: Minnehaha
Land Surface Elevation: 1458

Depth	Lithology
0 - 1	Topsoil, black
1 - 22	Clay, yellow-brown to gray, silty (till)
22 - 23	Sand with clay, saturated
23 - 25	Clay, dark gray, shaly, saturated
25	Rock, could not penetrate

Location: 101N50W 3CCD
County: Minnehaha
Land Surface Elevation: 1445

Depth	Lithology
0 - 4	Soil
4 - 14	Clay, tan - gray, silty
14 - 19	Clay, gray, silty
19 - 24	Sand, medium, silty

Location: 101N50W 6DDD
County: Minnehaha
Land Surface Elevation: 1473

Depth	Lithology
0 - 2	Soil
2 - 8	Clay, sandy
8 - 14	Sand, fine, sandy
14 - 29	Till, gray

Location: 101N50W 8BCCB
County: Minnehaha
Land Surface Elevation: 1462

Depth	Lithology
0 - 3	Soil
3 - 13	Sand and gravel, medium sand to fine gravel
13 - 85	Clay, tan to gray, silty
85 - 88	Sand with clay, medium

Location: 101N50W 8BCCC
County: Minnehaha
Land Surface Elevation: 1463

Depth	Lithology
0 - 4	Clay, yellow-brown, silty, pebbly (till)
4 - 21	Sand and gravel, medium to coarse, rocky
21	Rock, could not penetrate

Location: 101N50W 9ADD1
County: Minnehaha
Land Surface Elevation: 1443

Depth	Lithology
0 - 3	Soil and clay, brown, silty
3 - 5	Sand and fine gravel, reddish
5 - 10	Sand, medium, and fine gravel
10 - 18	Gravel, fine, clean
18 - 19	Clay, brown, silty, with small pebbles

Location: 101N50W 9DAD
County: Minnehaha
Land Surface Elevation: 1443

Depth	Lithology
0 - 6	Soil and clay, brown, silty
6 - 17	Gravel, coarse
17	Quartzite

Location: 101N50W 9DDD
County: Minnehaha
Land Surface Elevation: 1447

Depth	Lithology
0 - 1	Soil
1 - 3	Sand, fine to medium
3 - 9	Sand, medium to coarse, and fine to coarse gravel
9 - 18	Sand, medium to coarse, and fine gravel
18	Boulder

Location: 101N50W15CBC
County: Minnehaha
Land Surface Elevation: 1440

Depth	Lithology
0 - 3	Soil and loam
3 - 5	Sand and gravel, rust colored
5 - 10	Gravel, fine to medium, clean
10 - 15	Sand, fine to medium, gray
15 - 20	No sample
20 - 23	Clay, dark-gray

Location: 101N50W15CCC
County: Minnehaha
Land Surface Elevation: 1456

Depth	Lithology
0 - 4	Till, sandy
4 - 9	Till, gray, gravelly
9 - 14	Till, brown
14 - 29	Sand, fine to medium, silty
29 - 34	Sand, medium to coarse
34 - 44	Sand, medium
44 - 59	Till, tan

Location: 101N50W16AAA
County: Minnehaha
Land Surface Elevation: 1447

Depth	Lithology
0 - 4	Clay, tan, medium sand, and fine gravel
4 - 18	Sand, coarse, and fine gravel
18 - 22	Till, tan
22	Quartzite

Location: 101N50W16DAA
County: Minnehaha
Land Surface Elevation: 1454

Depth	Lithology
0 - 1	Soil
1 - 18	Sand, coarse, and coarse gravel; unsorted
18 - 32	Till, brown

Location: 101N50W17BBCC
County: Minnehaha
Land Surface Elevation: 1465

Depth	Lithology
0 - 3	Silt, dark-brown, sandy
3 - 23	Sand and gravel
23 - 43	Sand and gravel, fine sand to coarse gravel
43 - 46	Clay, dark-gray, silty, sandy, pebbly (till)

Location: 101N50W21DADD
County: Minnehaha
Land Surface Elevation: 1520

Depth	Lithology
0 - 93	Glacial till
93 -113	Sand
113 - 126	Glacial till
126 - 132	Sandy clay
132	Quartzite

Note: Detailed geologic log not available, log obtained from personel communication with Dennis Tomhave (July, 1986).

Location: 101N50W34CCCC
County: Minnehaha
Land Surface Elevation: 1522

Depth	Lithology
0 - 2	Topsoil
2 - 5	Clay, light-gray
5 - 15	Clay, yellow, silty, sandy, pebbly (till)
15 - 28	Clay, yellow, silty, pebbly (till)
28 - 60	Clay, gray, silty, pebbly; with thin sand and gravel layers in spots (till)
60 - 75	Clay, yellow-brown, silty, sandy, pebbly (till)
75 - 85	Clay, gray, silty, pebbly (till)
85 - 126	Clay, yellow-brown, silty, sandy, pebbly (till)
126 - 142	Sand, medium to coarse
142 - 190	Sand and gravel, medium sand to coarse gravel
190 - 193	Quartzite, pink; hard (Sioux Quartzite)

Location: 101N50W34BBBB
County: Minnehaha
Land Surface Elevation: 1510

Depth	Lithology
0 - 2	Clay, tan, silty
2 - 12	Clay, tan, silty, sandy (till)
12 - 16	Clay, gray-brown, silty, sandy, gravelly (till)
16 - 21	Clay, medium-gray, silty, sandy (till)
21 - 22	Rock
22 - 35	Clay, medium-gray, silty, sandy (till)
35 - 40	Sand (?), medium to coarse
40 - 95	Clay, medium-gray, silty, sandy, gravelly; hard layers at 45, 49, 55, and 89 feet (till)
95 - 106	Sand, medium to coarse, with coal pebbles
106 - 110	Clay (?)
110 - 150	Gravel, medium to coarse, with coal pebbles
150 - 174	Gravel, medium to coarse, with coal pebbles, some clay (?)
174 - 181	Clay (?), sandy
181 - 190	Gravel, medium to coarse, with coal pebbles
190 - 191	Quartzite, pink; there was actually only a few inches of penetration achieved (Sioux Quartzite)

Location: 102N50W27CCCC
County: Minnehaha
Land Surface Elevation: 1475

Depth	Lithology
0 - 14	Clay, brown
14 - 19	Clay, gray, silty, pebbly (till)
19 - 28	Sand and gravel, medium sand to coarse gravel
28 - 29	Quartzite; hard (Sioux Quartzite)

Location: 102N50W32CCCC
County: Minnehaha
Land Surface Elevation: 1529

Depth	Lithology
0 - 1	Topsoil, brown, clayey
1 - 36	Clay, brown with some gray streaks after about 12 feet, silty, sandy, pebbly (till)

Location: 102N51W 3ABB
County: Minnehaha
Land Surface Elevation: 1540

Depth	Lithology
0 - 1	Soil
1 - 8	Sand, coarse, and gravel
8 - 20	Sand, medium to coarse
20 - 42	Clay, gray, silty, sandy (till)

Location: 102N51W 3ABBB
County: Minnehaha
Land Surface Elevation: 1540

Depth	Lithology
0 - 4	Clay, yellow-brown, silty, pebbly (till)
4 - 23	Sand, medium to coarse; dry

Location: 103N50W 4BBBB
County: Minnehaha
Land Surface Elevation: 1612

Depth	Lithology
0 - 9	Sand, brown, silty
9 - 20	Clay, gray and light-brown, mottled, silty, pebbly, very soft (till)
20 - 48	Clay, brown, silty, sandy, pebbly; stiffer than interval from 9 to 20 feet (till)
48 - 76	Clay, grayish-pinkish brown, silty, sandy, pebbly (till)

Location: 103N50W 5ABB
County: Minnehaha
Land Surface Elevation: 1558

Depth	Lithology
0 - 4	Soil
4 - 10	Clay, tan, sandy
10 - 12	Sand, coarse
12 - 14	Medium sand and gravel
14 - 24	Sand, medium to coarse, silty
24 - 29	Sand, coarse
29 - 34	Till, tan
34 - 39	Till, brown

Location: 103N50W 5BBB
County: Minnehaha
Land Surface Elevation: 1545

Depth	Lithology
0 - 4	Clay, silty
4 - 9	Sand, silty
9 - 14	Sand, medium to coarse, silty
14 - 24	Sand, coarse, and fine gravel
24 - 29	Till, tan

Location: 103N50W 5BABB
County: Minnehaha
Land Surface Elevation: 1550

Depth	Lithology
0 - 3	Topsoil, brown, silty, sandy
3 - 7	Sand and gravel, fine sand to fine gravel, very silty
7 - 25	Sand and gravel, fine sand to fine gravel
25 - 36	Clay, yellow, silty, sandy, pebbly (till)

Location: 103N50W 6BBBB
County: Minnehaha
Land Surface Elevation: 1604

Depth	Lithology
0 - 1	Topsoil, brown
1 - 60	Clay, light-brown and light-gray, mottled, silty, pebbly (till)
60 - 86	Clay, pinkish-brown, silty, sandy, pebbly (till)

Location: 103N51W28CBBB
County: Minnehaha
Land Surface Elevation: 1552

Depth	Lithology
0 - 1	Topsoil, brown
1 - 7	Sand and gravel, fine sand to coarse gravel, slightly silty
7 - 31	Clay, yellow, silty, sandy, pebbly; fairly stiff (till)
31 - 32	Quartzite, pink; hard, there was actually only a few inches of penetration achieved (Sioux Quartzite)

Location: 103N51W28CCBC
County: Minnehaha
Land Surface Elevation: 1540

Depth	Lithology
0 - 2	Topsoil, black
2 - 5	Clay, yellow-brown, silty, pebbly (till)
5 - 10	Sand and gravel; some clay
10 - 17	Clay, yellow-brown, silty, pebbly (till)

Location: 103N51W28CCC
County: Minnehaha
Land Surface Elevation: 1550

Depth	Lithology
0 - 9	Clay, silty
9 - 14	Sand, medium to coarse, silty
14 - 17	Gravel, fine to coarse
17	Boulder

Location: 103N51W29AAA
County: Minnehaha
Land Surface Elevation: 1563

Depth	Lithology
0 - 1	Soil
1 - 3	Clay, gravelly (till?)
3 - 5	Clay, sandy
5 - 8	Clay, gravelly
8 - 27	Clay, sandy

Location: 103N51W32AAD
County: Minnehaha
Land Surface Elevation: 1530

Depth	Lithology
0 - 3	Soil
3 - 6	Gravel, very coarse

Location: 103N51W32DDDD
County: Minnehaha
Land Surface Elevation: 1579

Depth	Lithology
0 - 2	Topsoil, brown, sandy
2 - 22	Clay, yellow, silty, sandy, pebbly (till)
22 - 27	Clay, yellow and gray, mottled, silty, sandy, pebbly; very soft (till)
27 - 49	Clay, yellow and gray, mottled, silty, sandy, pebbly, stiffer than interval from 22 to 27 feet
49 - 50	Quartzite, pink; hard, there was actually only a few inches of penetration achieved (Sioux Quartzite)

Location: 103N51W33BCC
County: Minnehaha
Land Surface Elevation: 1545

Depth	Lithology
0 - 1	Soil
1 - 3	Sand, brown, silty
3 - 8	Sand and gravel, brown
8 - 18	Till, brown, moist
18 - 24.6	Sand, brown, silty, moist

Location: 103N51W33CDDD
County: Minnehaha
Land Surface Elevation: 1530

Depth	Lithology
0 - 1	Topsoil, black
1 - 4	Clay, yellow-brown, silty, pebbly (till)
4 - 6	Sand and gravel; hard rock at 6 feet could not penetrate (Quartzite?)

Location: 103N51W33DDD
County: Minnehaha
Land Surface Elevation: 1534

Depth	Lithology
0 - 2	Soil
2 - 7	Sand, coarse, and coarse gravel
7 - 10	Clay, brown, silty
10 - 11	Gravel, coarse
11 - 15	Silt, brown, sandy
15 - 37	Till, brown

Location: 103N51W34CCCC
County: Minnehaha
Land Surface Elevation: 1531

Depth	Lithology
0 - 1	Topsoil, brown
1 - 5	Sand and gravel, fine sand to fine gravel, slightly silty
5 - 13	Clay, yellow, silty, sandy, pebbly (till)
13 - 32	Clay, yellow and light-gray, mottled, silty, sandy, pebbly (till)
32 - 33	Quartzite, pink; hard, there was actually only a few inches of penetration achieved (Sioux Quartzite)

Location: 103N51W35CCC
County: Minnehaha
Land Surface Elevation: 1540

Depth	Lithology
0 - 2	Soil
1 - 7	Sand, coarse, and fine gravel
7 - 15	Sand, fine to medium, and fine gravel
15 - 26	Sand, very fine, brown, clayey
26 - 35	Silt, gray, fine sand
35 - 53	Clay, gray, silty
53 - 57	Till, gray

Location: 103N51W35CDCC
County: Minnehaha
Land Surface Elevation: 1510

Depth	Lithology
0 - 8	Loam
8 - 9	Gravel
9 - 28	Sand, fine
28 - 42	Clay, yellow
42 - 62	Sand, fine
62	Quartzite

Location: 103N51W35DCD
County: Minnehaha
Land Surface Elevation: 1514

Depth	Lithology
0 - 3	Soil
3 - 10	Clay, sandy
10 - 11	Gravel and coarse sand
11 - 14	Sand, coarse
14 - 25	Clay and silt, sandy

Location: 104N50W 4ABBB
County: Minnehaha
Land Surface Elevation: 1569

Depth	Lithology
0 - 2	Topsoil, black
2 - 4	Clay, gray, silty, pebbly (till)
4 - 57	Sand and gravel, medium to coarse
57 - 59	Clay, yellow, silty, pebbly (till)

Location: 104N50W 4AABA
County: Minnehaha
Land Surface Elevation: 1573

Depth	Lithology
0 - 7	Silt, black; organic
7 - 14	Gravel, coarse
14 - 57	Silt, yellow and olive, mottled, pebbly, clayey (till)?
57 - 58	Quartzite, pink

Location: 104N50W31CDD
County: Minnehaha
Land Surface Elevation: 1542

Depth	Lithology
0 - 2	Soil
2 - 4	Sand, medium, and fine gravel
4 - 14	Sand, medium
14 - 19	Sand, medium to coarse
19 - 24	Sand, coarse
24 - 43	Sand, medium to coarse

Location: 104N50W31DCCD
County: Minnehaha
Land Surface Elevation: 1538

Depth	Lithology
0 - 2	Topsoil, black
2 - 18	Gravel, coarse, sandy, subrounded
18 - 20	Clay, yellow
20 - 32	Gravel, coarse, sandy, rounded
32 - 35	Clay, gray-brown, silty (till)

Location: 105N50W33CCDD
County: Moody
Land Surface Elevation: 1585

Depth	Lithology
0 - 4	Silt, light-brown, fine, dry (topsoil)
4 - 28	Clay, brown, silty, sandy (till)

Location: 105N50W33CDD
County: Moody
Land Surface Elevation: 1565

Depth	Lithology
0 - 1	Topsoil
1 - 4	Sand, medium to coarse
4 - 9	Sand and gravel, medium sand, coarse gravel
9 - 14	Gravel, fine to coarse
14 - 19	Sand and gravel, coarse sand, medium gravel
19 - 44	Sand and gravel, coarse sand, medium gravel
44 - 51	Sand, medium to coarse
51 - 56	Till

Location: 105N50W33DCCC
County: Moody
Land Surface Elevation: 1568

Depth	Lithology
0 - 3	Clay, black, silty, pebbly, moist (topsoil)
3 - 33	Sand, reddish-brown, fine to coarse
33 - 65	Sand, gray, silty
65 - 66	Quartzite; very hard, there was actually only a few inches of penetration in this interval

Location: 105N50W33DDCC
County: Moody
Land Surface Elevation: 1570

Depth	Lithology
0 - 3	Clay, black, silty (topsoil)
3 - 23	Sand, reddish-brown, coarse, pebbly, clayey
23 - 45	Clay, gray, silty, sandy; saturated
45 - 62	Clay, light-brown, silty, sandy; saturated (till)
62 - 63	Quartzite; hard, there was actually only a few inches of penetration in this interval

Location: 105N50W33DDC
County: Moody
Land Surface Elevation: 1574

Depth	Lithology
0 - 4	Topsoil
4 - 9	Sand, silty
9 - 16	Sand and gravel, coarse sand and medium gravel
16 - 29	Till, gray

Location: 105N50W34CCC1
County: Moody
Land Surface Elevation: 1575

Depth	Lithology
0 - 1	Topsoil, black
1 - 5	Sand, reddish-brown, fine to medium; some small pebbles
5 - 10	Sand and gravel, reddish-brown fine to coarse sand, fine to coarse gravel
10 - 12	Sand, fine to medium
12 - 35	Sand and gravel, fine to coarse sand, fine gravel
35 - 47	Sand, brown, fine, clayey
47 - 52	Till, brown
52 - 53	Quartzite

Location: 105N50W34CCC2
County: Moody
Land Surface Elevation: 1580

Depth	Lithology
0 - 1	Topsoil, black
1 - 5	Sand, fine to coarse, pebbly
5 - 10	Sand, fine to medium
10 - 35	Gravel, fine
35 - 53	Till, gray
53 - 54	Quartzite

Location: 105N50W34CCCC
County: Moody
Land Surface Elevation: 1572

Depth	Lithology
0 - 3	Silt, brown, fine, dry (topsoil)
3 - 23	Sand, reddish-brown, fine, silty, pebbly; moist
23 - 51	Sand, grayish-brown, very silty, pebbly; saturated
51 - 52	Quartzite; very hard, there was actually only a few inches of penetration in this interval

APPENDIX B

GROUND WATER CHEMICAL DATA

LOCATION	DATE	DEPTH	CA	MG	NA	K
101-50-24BDCC	08-30-79	60.0	85.0	26.0	8.7	2.4
	10-05-81	60.0	95.0	27.0	7.2	2.7
101-50-24BDAD	08-30-79	40.0	85.0	26.0	8.9	2.5
	10-05-81	40.0	94.0	27.0	6.8	2.7
101-50-24BADD	08-30-79	46.0	85.0	26.0	8.7	2.5
	10-05-81	46.0	100.0	30.0	9.1	3.1
101-50-24BCAA	08-30-79	47.0	120.0	38.0	2.3	3.9
	10-05-81	47.0	120.0	35.0	34.0	4.7
101-50-24BAD	08-30-79	65.0	110.0	38.0	25.0	3.2
	10-05-81	65.0	120.0	37.0	27.0	3.4
101-50-23BBBA	09-08-80	51.0	84.0	50.0	16.0	3.0
101-50-15DDD	01-26-77	30.0	190.0	70.0	42.0	5.0
	11-05-81	30.0	190.0	66.0	37.0	5.6
101-50-7AAB	09-28-60	43.0	75.0	29.0	9.7	6.6
101-50-3CCC	12-08-61	39.0	84.0	32.0	19.0	1.6
102-50-19BCCD	08-14-78	22.9	110.0	52.0	25.0	5.0
102-51-3ADD	09-27-60	26.0	60.0	27.0	6.6	2.2
103-51-33DDD	09-26-60	37.0	49.0	28.0	7.2	1.6
103-50-18CDA	12-07-61	24.0	107.0	36.0	13.0	16.0
103-50-7DCD	09-26-60	48.0	90.0	20.0	7.4	8.3
104-50-9ABA	12-06-61	28.0	114.0	39.0	15.0	3.4
103-51-35CDCC	12-11-58	62.0	96.0	29.0	9.9	3.5
	10-02-69	20.3	130.0	32.0	57.0	2.0
103-50-19CDDD	04-15-77	33.0	40.0	10.0	4.0	6.0
103-50-19BCCC	08-14-78	29.1	120.0	48.0	24.0	3.0
103-50-18DAB	01-26-77	60.0	140.0	42.0	19.0	2.0
103-50-18BDAD	00-00-76	46.0	81.0	60.0	20.0	2.0
	11-28-78	46.0	170.0	57.0	19.0	2.0
103-50-18AAAA	08-14-78	30.9	67.0	35.0	12.0	2.0
103-50-5CCCC	11-19-76	29.0	99.0	31.0	12.0	1.0
103-50-6DDCC	01-24-78	32.0	120.0	29.0	12.0	2.0
104-50-31DCCD	08-14-78	31.9	120.0	42.0	14.0	5.0
104-50-32BDA	11-19-76	40.0	98.0	27.0	11.0	2.0
104-50-28CCCA	02-14-77	22.0	94.0	35.0	33.0	2.0
104-50-28B	07-11-77	15.0	48.0	17.0	11.0	1.0
104-50-21CCCC	08-14-78	17.4	90.0	40.0	16.0	3.0
104-50-20BDDA	12-19-77	41.0	140.0	14.0	12.0	2.0
104-50-16CAB	10-16-81	32.0	88.0	19.0	7.0	1.0
104-50-16ABCC	08-02-76	40.0	110.0	36.0	13.0	0.0
104-50-9ACCC	11-19-76	18.0	97.0	40.0	22.0	1.0
104-50-4DCCC	08-14-78	45.7	97.0	47.0	18.0	5.0
104-50-4DBB	11-19-76	15.0	120.0	33.0	11.0	1.0
104-50-4	07-11-77	20.0	110.0	45.0	17.0	2.0

Chemical data obtained from the U.S. Geological Survey WATSTORE data base.

LOCATION	DATE	CL	SO4	HCO3	TDS	HRDNESS
101-50-24BDCC	08-30-79	5.4	88.0	290.0	505.5	319.0
	10-05-81	25.0	78.0	310.0	544.9	348.1
101-50-24BDAD	08-30-79	5.6	92.0	290.0	510.0	319.0
	10-05-81	29.0	71.0	290.0	520.5	345.6
101-50-24BADD	08-30-79	5.6	87.0	290.0	504.8	319.0
	10-05-81	21.0	63.0	360.0	586.2	372.9
101-50-24BCAA	08-30-79	54.0	120.0	360.0	698.2	455.7
	10-05-81	61.0	110.0	390.0	754.7	443.4
101-50-24BAD	08-30-79	48.0	96.0	380.0	700.2	430.8
	10-05-81	66.0	91.0	390.0	734.4	451.6
101-50-23BBBA	09-08-80	10.0	330.0	120.0	613.0	415.3
101-50-15DDD	01-26-77	41.0	500.0	340.0	1188.0	762.0
	11-05-81	30.0	460.0	350.0	1138.6	745.5
101-50-7AAB	09-28-60	2.2	90.0	306.0	518.5	306.4
101-50-3CCC	12-08-61	1.9	39.0	427.0	604.5	341.2
102-50-19BCCD	08-14-78	4.0	320.0	260.0	776.0	488.4
102-51-3ADD	09-27-60	4.4	51.0	265.0	416.2	260.8
103-51-33DDD	09-26-60	0.0	20.0	270.0	375.8	237.4
103-50-18CDA	12-07-61	19.0	124.0	360.0	675.0	415.1
103-50-7DCD	09-26-60	2.0	155.0	212.0	494.7	306.8
104-50-9ABA	12-06-61	32.0	111.0	320.0	634.4	444.9
103-51-35CDCC	12-11-58	1.7	67.0	380.0	587.1	358.8
	10-02-69	5.0	63.0			456.0
103-50-19CDDD	04-15-77	7.0	29.0	120.0	216.0	140.9
103-50-19BCCC	08-14-78	7.0	240.0	350.0	792.0	496.9
103-50-18DAB	01-26-77	28.0	170.0	350.0	751.0	522.1
103-50-18BDAD	00-00-76	13.0				448.9
	11-28-78	45.0	220.0	400.0	913.0	658.6
103-50-18AAAA	08-14-78	4.0	99.0	210.0	429.0	311.1
103-50-5CCCC	11-19-76	3.0	94.0	360.0	600.0	374.5
103-50-6DDCC	01-24-78	11.0	86.0	300.0	560.0	418.7
104-50-31DCCD	08-14-78	9.0	170.0	320.0	680.0	472.2
104-50-32BDA	11-19-76	10.0	55.0	350.0	553.0	355.6
104-50-28CCCA	02-14-77	6.0	130.0	380.0	680.0	378.5
104-50-28B	07-11-77	5.0	36.0	210.0	328.0	189.7
104-50-21CCCC	08-14-78	6.0	86.0	320.0	561.0	389.1
104-50-20BDDA	12-19-77	2.0	140.0	340.0	650.0	406.9
104-50-16CAB	10-16-81	6.0	53.0	260.0	434.0	297.7
104-50-16ABCC	08-02-76	10.0	110.0	300.0	579.0	422.5
104-50-9ACCC	11-19-76	6.0	51.0	330.0	547.0	406.6
104-50-4DCCC	08-14-78	3.0	170.0	390.0	730.0	435.4
104-50-4DBB	11-19-76	4.0	150.0	330.0	649.0	435.1
104-50-4	07-11-77	16.0	100.0	380.0	670.0	459.6

LOCATION	DATE	COND	PH	NO3-N	TEMP	SILICA
101-50-24BDCC	08-30-79	610.0	7.5	0.10		
	10-05-81	694.0	7.8	0.10		
101-50-24BDAD	08-30-79	610.0	7.4	0.10		
	10-05-81	714.0	7.4	3.40		
101-50-24BADD	08-30-79	610.0	7.4	0.20		
	10-05-81	734.0	7.6	0.10		
101-50-24BCAA	08-30-79	900.0	7.4	1.90		
	10-05-81	979.0	7.5	0.80		
101-50-24BAD	08-30-79	900.0	7.4	2.70		
	10-05-81	969.0	7.5	1.60		
101-50-23BBBA	09-08-80	850.0	8.1	0.94		
101-50-15DDD	01-26-77	1350.0	7.3	1.90		
	11-05-81	1370.0	7.3	9.00		
101-50-7AAB	09-28-60	612.0	7.9	0.00	12.2	18.0
101-50-3CCC	12-08-61	706.0	7.4	3.10	8.9	23.0
102-50-19BCCD	08-14-78	946.0	7.7	0.27		
102-51-3ADD	09-27-60	477.0	7.5	0.20	13.3	23.0
103-51-33DDD	09-26-60	460.0	7.7	13.00	12.2	28.0
103-50-18CDA	12-07-61	830.0	7.0	4.90	10.0	26.0
103-50-7DCD	09-26-60	602.0	7.6	0.00	12.2	22.0
104-50-9ABA	12-06-61	899.0	7.2	53.00	7.8	30.0
103-51-35CDCC	12-11-58	661.0	7.1	0.10		30.0
	10-02-69	665.0	8.0	0.00		
103-50-19CDDD	04-15-77	317.0	7.4			
103-50-19BCCC	08-14-78	1020.0	7.4	0.14		
103-50-18DAB	01-26-77	866.0	7.5			
103-50-18BDAD	00-00-76	1090.0	7.7			
	11-28-78	1060.0	7.2			
103-50-18AAAA	08-14-78	682.0	7.7	0		
103-50-5CCCC	11-19-76	664.0	7.4			
103-50-6DDCC	01-24-78	662.0	7.8			
104-50-31DCCD	08-14-78	850.0	7.7	0.3		
104-50-32BDA	11-19-76	700.0	7.4			
104-50-28CCCA	02-14-77	818.0	7.4			
104-50-28B	07-11-77	429.0	7.7			
104-50-21CCCC	08-14-78	676.0	7.9	21.5		
104-50-20BDDA	12-19-77	699.0	7.7			
104-50-16CAB	10-16-81	580.0	7.6			
104-50-16ABCC	08-02-76	769.0	7.2			
104-50-9ACCC	11-19-76	777.0	8.2			
104-50-4DCCC	08-14-78	850.0	8.0	0.07		
104-50-4DBB	11-19-76	723.0	7.6			
104-50-4	07-11-77	931.0	7.3			

APPENDIX C

SURFACE WATER CHEMICAL DATA

DATE	DISCHARGE	CA	MG	NA	K
07-14-70	13	133	57	54	17
10-12-71	4.7	78	39	18	7.4
04-08-71	46	81	34	15	10
06-16-71	23	95	47	25	12
11-03-71	3.9	100	47	20	7
04-25-72	22	110	53	26	10
06-28-72	64	130	82	65	14
10-18-72	8.8	110	58	33	9.9
04-25-73	7.7	130	85	65	18
06-21-73	8.2	97	68	51	14
12-03-73	6.8	120	56	27	7.4
03-08-74	23	67	26	15	7.8
06-07-74	63	61	29	18	6.9

DATE	CL	SO4	HCO3	TDS	HARDNESS
07-14-70	36	352	354	1003.0	565
10-12-71	12	180	260	594.4	350
04-08-71	7.7	170	236	553.7	340
06-16-71	12	220	318	729.0	430
11-03-71	11	270	260	715.0	440
04-25-72	17	290	326	832.0	490
06-28-72	55	420	376	1142.0	660
10-18-72	27	280	329	846.9	510
04-25-73	58	490	304	1150.0	670
06-21-73	41	350	253	874.0	520
12-03-73	22	290	304	826.4	530
03-08-74	11	150	189	465.8	270
06-07-74	10	160	157	441.9	270

DATE	COND	PH	NO3-N	TEMP	SILICA
07-14-70	1190	8.1	0.48	26	11
10-12-71	728	8	0.9	8.5	10
04-08-71	716	7.5		12.5	11
06-16-71	916	7.4		29	25
11-03-71	879	7.8		4.4	10
04-25-72	1000	8.3		9.9	3.8
06-28-72	1400	8.1		21.2	12
10-18-72	1040	7.6		4	15
04-25-73	1410	8.3		8.4	2.2
06-21-73	1130	8.1		18.4	6.3
12-03-73	1040	8.3	0.28	0	9.9
03-08-74	613	8	0.68	3	9.5
06-07-74	638	7.6	0.73	22	9.1

Chemical data obtained from the U.S. Geological Survey WATSTORE data base.

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VITA

Grant Lawrence Ohland

Candidate for the Degree of

Master of Science

Thesis: A WATER RESOURCE APPRAISAL OF THE SKUNK CREEK AQUIFER IN MOODY AND MINNEHAHA COUNTIES, SOUTH DAKOTA

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Biographical:

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