GROUND-WATER FLOW IN A HEAVILY EXPLOITED BURIED CHANNEL AQUIFER, SOURIS RIVER BASIN, NORTH DAKOTA

By

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GROUND-WATER FLOW IN A HEAVILY EXPLOITED BURIED CHANNEL SYSTEM, SOURIS RIVER BASIN, NORTH DAKOTA

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PREFACE

While living in Costa Rica in 1983, I was motivated to pursue graduate studies in hydrogeology. In the "third world" I discovered the tremendous need for applied geological knowledge. In January of 1984 I came to OSU to begin graduate work. This thesis topic evolved out of my desire to combine practical hydrogeology with state-of-the art numerical computer simulation methods. In the summer of 1985 Dr. Pettyjohn suggested that I study the aquifer systems in the Minot area of North Dakota.

For much advice and technical support over the past three years I would like to gratefully thank Dr. Pettyjohn. Dr. Hounslow provided help in critical review of my thesis and for this I am thankful. Bill Horak and Scott Christenson of the U.S.G.S. Water Resources Division in Oklahoma City were able to spend a good deal of time with me and provide much needed advice on ground-water flow modeling with the McDonald Harbaugh Model.

Also my deeply felt thanks is extended to my parents, sister, and all of my friends in the Stillwater area for their support and encouragement.

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CHAPTER I

INTRODUCTION

Purpose

The purpose of this thesis research project is to study the three dimensional ground-water flow patterns in a heavily exploited buried channel aquifer. The long-term records of observation wells screened at multiple depths in the aquifer provide a unique opportunity to observe the effects of stress on the ground-water flow system over an extended period. In determining the ground-water flow patterns in three dimensions, the relationship and interaction between the Sundre aquifer, the overlying sand and gravel units, and the shallower Souris aquifer will be better understood.

Another purpose of this research is to test the conceptualized flow hypotheses with a digital computer model of the hydrologic system. The computer model is used to estimate the amount of leakage brought about by pumping, and to estimate the amount of pumped water derived from leakage as opposed to the amount obtained from storage within the Sundre aquifer. Also the model was used to estimate the maximum pumpage the aquifer can sustain at equilibrium.

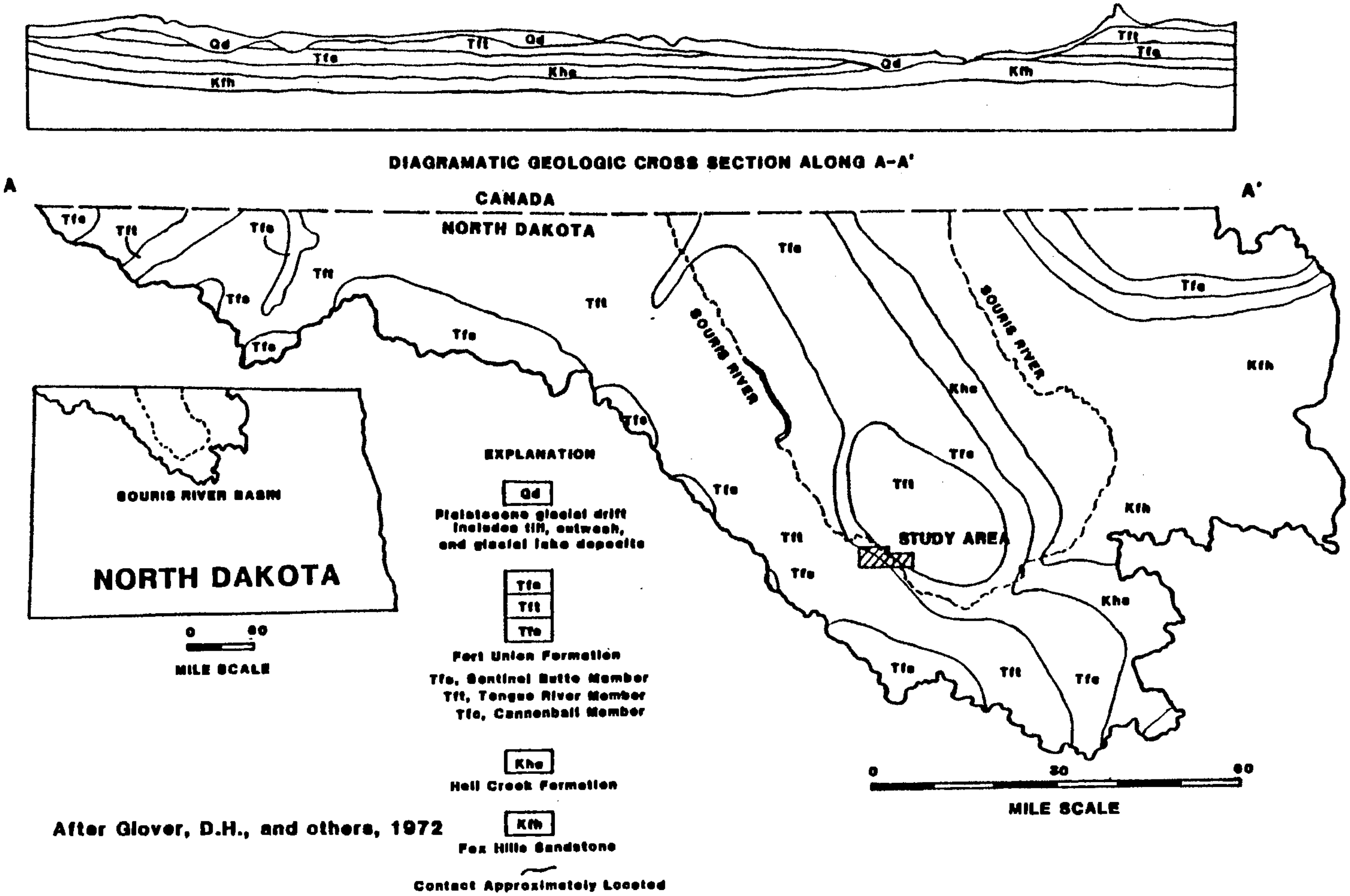
It is intended that this thesis research will aid in the understanding of factors governing ground-water flow in confined buried-channel aquifer systems that are experiencing heavy pumping stresses over extended periods. To date only a small percentage of the water resources in buried-channel aquifers of North Dakota have been developed. As these aquifer systems begin to play an ever increasing role in the water supply of the glaciated mid-continent region, the more their hydrogeologic properties need to be understood.

Physical Features and Climate of the Minot Area

Physical Features

The area of study lies just to the southeast of Minot, in the central part of Ward county (Fig. 1). It contains 21 square miles, about four of which include the Souris River floodplain.

The Souris River flows southeastward through Ward County and bisects the study area (Fig. 1). With its headwaters in Canada, the river has a gradient that is less than two feet per mile. The river channel ranges from eight to about 30 feet in width and the floodplain varies from one to three miles wide. The U.S.G.S. gaging station just upstream from Minot recorded an average annual discharge of 100,600 acre-feet for the period 1903 to 1963. However, the flow of the river is controlled almost entirely by the regulation of several dams upstream (Pettyjohn, 1967).



After Glover, D.H., and others, 1972

GENERALIZED GEOLOGIC MAP OF THE SOURIS RIVER BASIN

Figure 1. Geologic Map of the Souris River Basin

The upland areas are gently rolling hills that are composed of glacial drift. The hills are deeply disected near the Souris River floodplain. The floodplain itself is nearly flat with several oxbow lakes occurring near the river channel. The altitude of the land surface ranges from 1540 feet on the floodplain to over 1700 feet on the adjacent uplands.

Climate

The climate in north-central North Dakota is harsh, with winter temperatures down to -20 degrees F. and summer temperatures up to 100 degrees F. Average annual precipitation in the Minot area is about 16 inches, most of which originates from summer convective thunderstorms.

Previous Investigations and Sources of Data

Previous Investigations

Prior to the discovery of the Sundre buried-channel aquifer southeast of Minot in 1963 (Pettyjohn, 1967) all of the research concerning water resources in the Minot area focused on glacio-fluvial deposits in the Souris River valley and glacial drift in upland areas. Simpson (1929) described the general geology and ground-water occurrences in Ward County. This was the first scientific look at Minot's water supply since municipal wells went on line in 1916. Akin (1947) gave a more thorough treatment to the topic of ground-water conditions in the Minot area. He discussed the hydrologic properties of the sand and gravel valley fill within Minot, from which the city's water supplies were obtained.

The next study, LaRocque and others (1963), was conducted by the U.S.G.S. from 1945 - 1951 as part of a program for the development of water resources in the Missouri River Basin. Part of this study concerned the ground-water discharge into the Souris River. They estimated baseflow to the Souris River in five stretches between successive gaging stations. It was found that ground-water inflow per unit length of river is least in a stretch between Minot and Verendrye. This probably reflects induced infiltration of the Souris River in the vicinity of Minot, which was caused by well pumping.

In a two part report, Pettyjohn and Hills (1965), and Pettyjohn (1967), the geohydrology of the Souris River valley in the vicinity of Minot was again addressed. The first part was a summary of the basic data collected from 1963 to 1964 which included water well and test hole log descriptions, ground-water quality data, and a list and location of all wells and test holes in the studied area. Pettyjohn (1967) reports primarily on the hydrology and chemical quality of the Minot aquifer. However, in this report the presence of the Sundre buried channel was first identified; it was based on a single test hole (154N-82W-4aad). Also an attempt was made to define the boundary of the channel with topographic and outcrop information. Furthermore, Pettyjohn (1967) recommended (1) the drilling of additional test holes to define the dimensions of the Sundre buried channel and (2) an aquifer test of this deposit with a view towards augmenting Minot's municipal water supply at some future date.

Pettyjohn (1968), and Pettyjohn and Huthinson (1971), reported on the geology and ground-water resources of Renville and Ward counties. The first report consists of data on wells and test holes in the two counties, water-level measurements, and logs of test holes and selected wells. Also included are chemical analyses of ground-water samples. Pettyjohn and Hutchinson (1971) discussed the regional hydrogeology of the two county area. The history of Minot's ground-water usage is also discussed along with a brief description of the Sundre aquifer. This report was the result of a four year investigation of the availability, quantity, and quality of ground-water resources in Renville and Ward counties by the U.S.G.S. in cooperation with the North Dakota Geological Survey and the North Dakota State Water Commission.

The city of Minot published a report (Pettyjohn, 1970) predicting that an additional source of water, other than the Souris River and the Minot aquifer, would be needed for municipal supplies in the near future due to increasing demand. An aquifer test of the Sundre aquifer is described in detail in this report. Furthermore, Pettyjohn (1970) proposed a ground-water management plan for Minot. He recommended the drilling of pilot holes for determination of areas of maximum transmissivity in the Sundre aquifer, the initiation of a periodic water level measurement program prior to and continuing through the development of the Sundre aquifer, the consideration of injecting water in the Sundre aquifer for storage purposes, and the encouragement of farmers, ranchers, and industry to tap the Sundre aquifer.

In 1972 the "Souris-Red-Rainy River Basins Comprehensive Study" was released by the Souris-Red-Rainy River Basins Commission. The Appendices B, F, G, and H covering such topics as water resources, irrigation, water supply and public health, and water quality, were of value to this research although the major emphasis was on surface water. The Minot and Sundre aquifers were briefly mentioned in Appendix B. Water level declines in the Minot well field were noted and the exploration of the Sundre aquifer south east of Minot was reported.

Reeder (1978) described the drift aquifers of the Souris River Basin in a general sense and discussed the role of ground water in water resource management. He further described general considerations dealing with ground-water development, conservation, and management in the Souris, Red, and Rainey River basins.

In his report "Geology and Geotechnical Conditions of the Minot Area, North Dakota", Kehew (1983) described the stratigraphy and origin of the Pleistocene deposits of the study area. The Souris and Sundre aquifers are mentioned, but just in summary of Pettyjohn's work. Geotechnical conditions pertaining to future construction and waste disposal were also discussed.

Sources of Data

Most of the information used in this thesis research project came from the above sources. Dr. Pettyjohn supplied much of the basic data and many drillers logs from his personal records. Monthly reports of water levels in municipal and observation wells from Sept. 1967 to the present were kindly provided to Dr. Pettyjohn by the City of Minot. The Bismark office of the U.S.G.S. provided me with Souris River flow data. The North Dakota State Water Commission graciously provided local stream flow measurements in section 3, T154N-R82W three of the study area, water-level measurements in some recently drilled observation wells, and pumpage records for the Sundre well field.

Well Numbering System

The well-numbering system used in this report is illustrated in Figure 2. This system is based on the grid system used by the U.S. Bureau of Land Management. The first number in a well-location number indicates the township north of a base line in Arkansas. The second number denotes the range west of the fifth principal meridian. The third

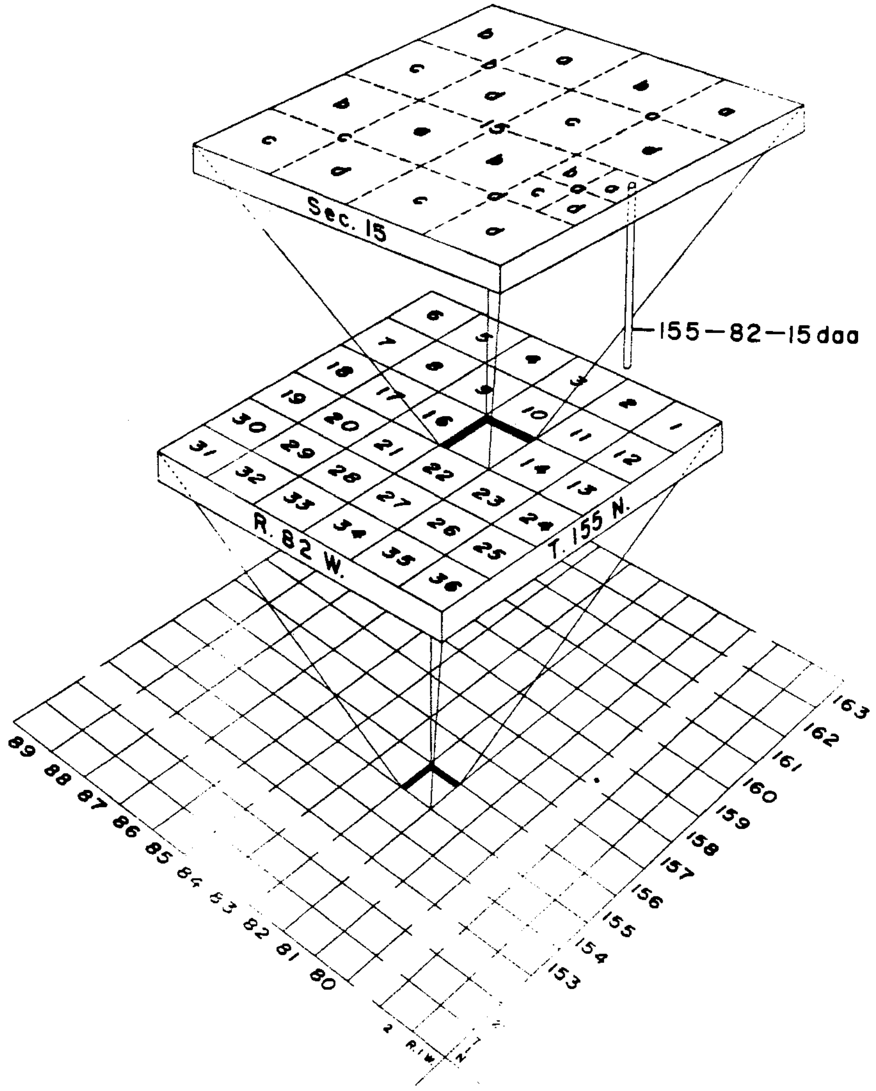


Figure 2. Well Numbering System

number indicates the section in which the well is located. The lowercase letters given after the section number indicate the position of the well within the section. The letter "a" refers to the northeast quarter; "b", the northwest quarter; "c", the southwest quarter; and "d", the southeast quarter. Succeeding letters refer to the quarter -quarter section and the quarter-quarter-quarter section. Observation wells, municipal wells, and cross-sections used in this study are shown in Figure 3.

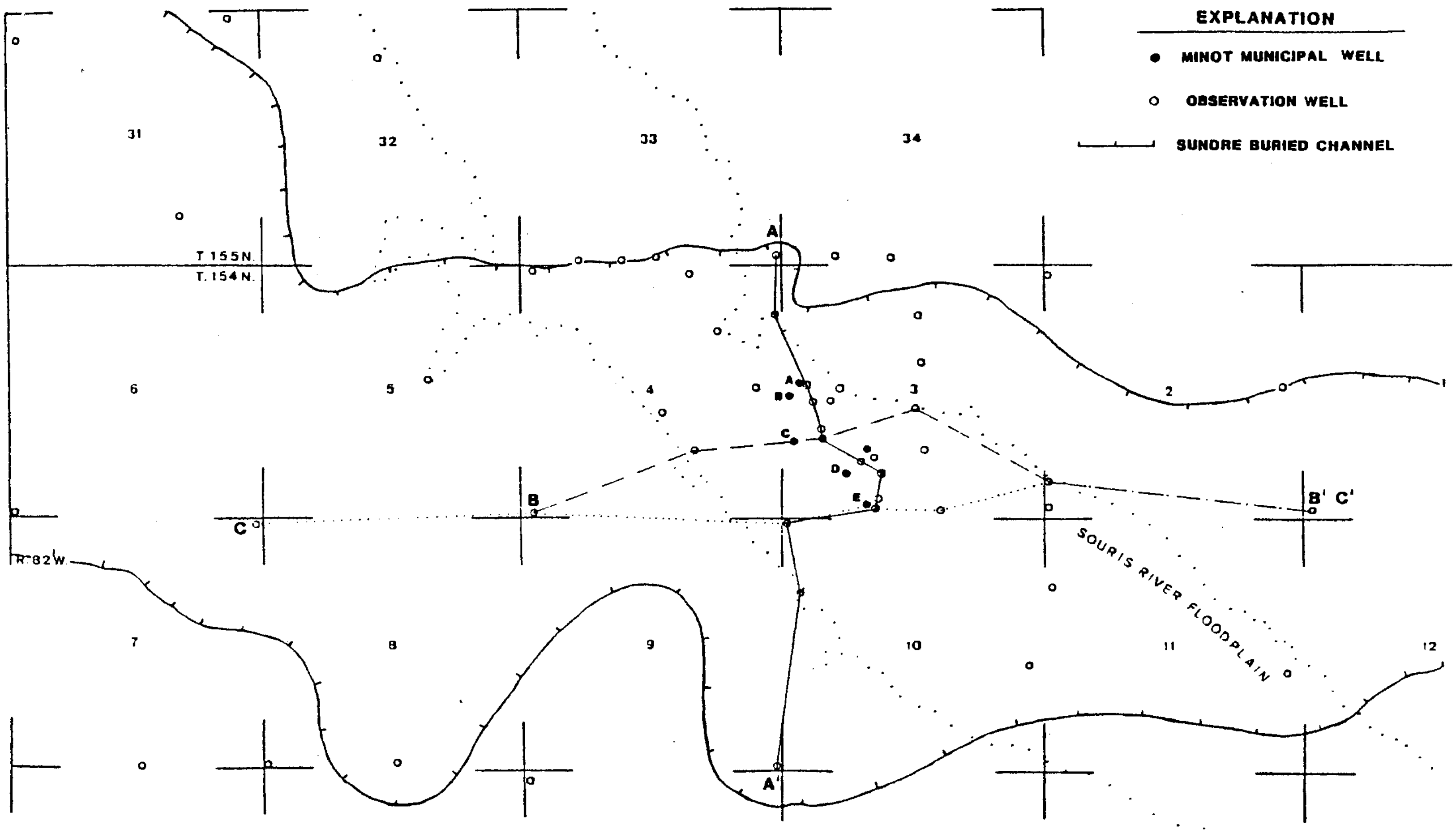


Figure 3. Well and Cross-Section Location Map

CHAPTER II

GEOLOGIC SETTING

Tertiary Deposits

The bedrock in the Minot area is the Fort Union Group of Tertiary age. This group is comprised of four formations, only two of which occur within the study area (Fig. 1). They are, in ascending order, the Cannonball Formation and the Tongue River Formation. The Cannonball Formation is marine in origin and consists of dark-gray sand, clay, and a few layers of thin nodular, fossiliferous limestone (Pettyjohn and Hutchinson, 1971). The Cannonball commonly contains brackish to saline water. Concentrations of dissolved solids and chloride increase away from the Souris River, thus indicating some dilution by river infiltration. The Tongue River Formation is a terestrial deposit of clay, silt, sandstone and numerous lignite beds (Pettyjohn and Hutchinson, 1971). The Tongue River contains a sodium bicarbonate-type water that is unusually soft owing to the large percentage of sodium relative to calcium. Lemke (1960) reported the total thickness of the Fort Union Group to be 655 feet at Section 9, T155N-R85W as determined from borehole cuttings of a dry hole drilled in 1923. The

Tongue River Formation crops out in many places along the Souris River valley (Pettyjohn and Huthinson, 1971).

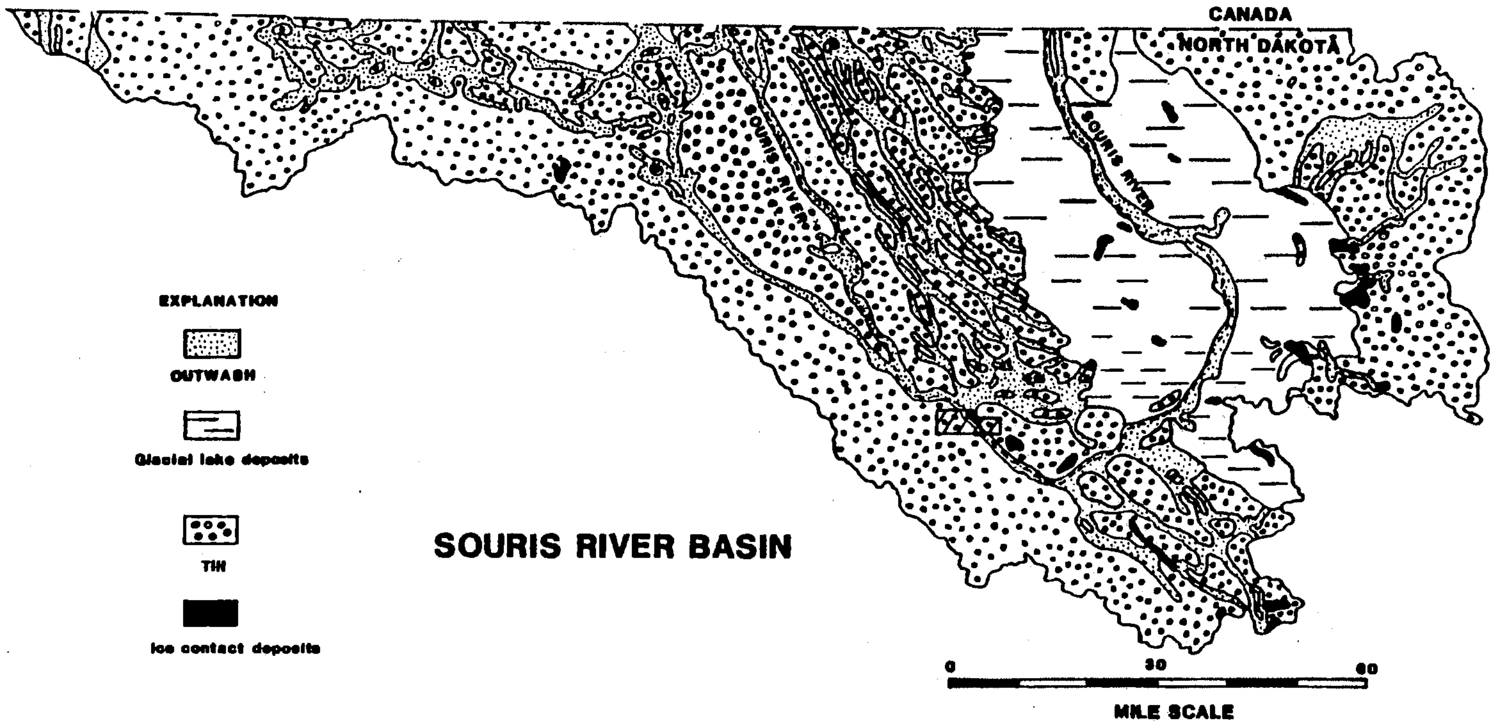
Within the Fort Union, fine-grained sandstone and lignite layers provide a source of water for wells and springs. Due to gas pressure and natural artesian pressure, flowing wells are common in the Fort Union, however yields are low (Pettyjohn and Hutchinson, 1971).

Quaternary Deposits

Glacial Drift

Pleistocene glacial deposits and Holocene alluvial deposits mantle most of the Fort Union in north-central North Dakota (Fig. 4). During the course of at least three major glaciations of the Pleistocene, up to 600 feet of drift was deposited (Pettyjohn and Hutchinson, 1971). These deposits primarily consist of ground moraine, end moraine, outwash, ice-contact deposits, and glacial lake deposits (Fig. 4). Ground moraine is the most prevelent deposit in the Minot area. This material, known as till, consists of a heterogeneous, unstratified mixture of clay, silt, sand, gravel, and larger rock fragments.

The remaining portion of the study area is underlain by outwash deposits carved into the ground moraine by glacial melt waters (Fig. 4). These deposits chiefly consist of sand and gravel and they cover large areas predominantly in the major river valleys, but also are locally extensive in some upland areas (Fig. 4). In the Souris River valley,



After Glover, D.H., and others, 1972

Figure 4. Glacial Geology Map of the Souris River Basin

outwash deposits reach thicknesses of as much as 150 feet (Pettyjohn and Hutchinson, 1971). Within the valley these deposits are overlain by a thin veneer of Holocene alluvial material. In regions of sufficient thickness and permeability, these outwash sands and gravels store large volumes of ground water, the Minot well field being a case in point.

Buried Valley Deposits

Prior to the Pleistocene, major river systems in North Dakota flowed north and northeast toward Hudson Bay. The pre-glacial land surface sloped to the northeast, however many valleys that have been cut into the bedrock trend normal to this slope, in a southeastward direction (Fig. 5). Bluemle (1972) describes these southeast-draining valleys as narrow with relatively steep sides. He also states that such a morphology is typical of glacial diversion trenches, which were located at the edge of glaciers and cut rapidly by tremendous amounts of water. These meltwater diversion trenches formed when glacial advances blocked pre-Pleistocene northeastward drainage (Bluemle, 1972). Each time glaciers advanced over the area, drainage patterns were changed drastically (Bluemle, 1972).

Outwash streams from these glacial episodes carved out a number of valleys in the Fort Union bedrock (NDSWC map, 1982). These valleys or channels have since been buried by drift from later glacial advances. They commonly are filled

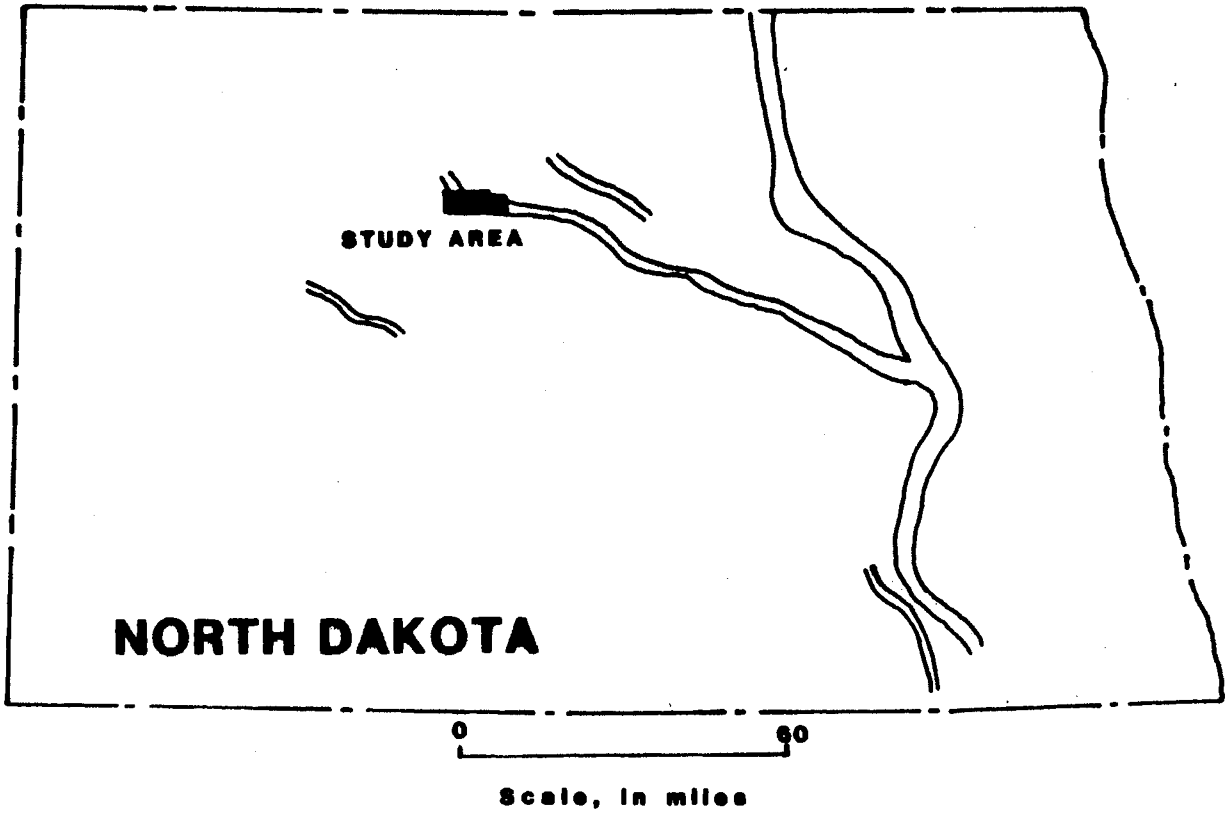


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Figure 5. Major Buried Valley Aquifers of North Dakota

with sand, gravel, and clay layers. In the Sundre channel such deposits reach thicknesses of up to 300 feet (Figs. 6-8). This buried valley has been traced over a hundred miles across north central North Dakota (North Dakota State Water Commission, 1982) (Fig. 5).

This hypothesis of buried-valley formation is supported by the observations of Dr. Wayne Pettyjohn. During the drilling of a Sundre test well in 1969, a split-spoon core of the aquifer material revealed till boulders mantled with gravel. This unusual lithology is thought to originate from a rapidly flowing ice-marginal stream which caused parts of the frozen banks (composed of till) to spall off into the water. The outer few inches of the till boulders then became partially melted by the water and as it rolled along the stream bed acquired gravel on its outer surface (Pettyjohn, personal communication, 1986). A stream flowing along a glacier margin could be supplied with sufficient quantities of frozen till for this to occur.

The stratigraphy of the Sundre buried valley is complex (Figs. 6-8). Clay layers, ranging in thickness from two to 70 feet, form discontinuous layers at various depths. Fine to coarse sand and gravel layers and lenses comprise the remainder of the valley fill. Locally, thicknesses of sand and gravel, uninterrupted by clay layers, may reach approximately 230 feet (Fig. 6). The complex spatial distribution of sediments in the Sundre aquifer probably reflects two or more depositional modes occurring through

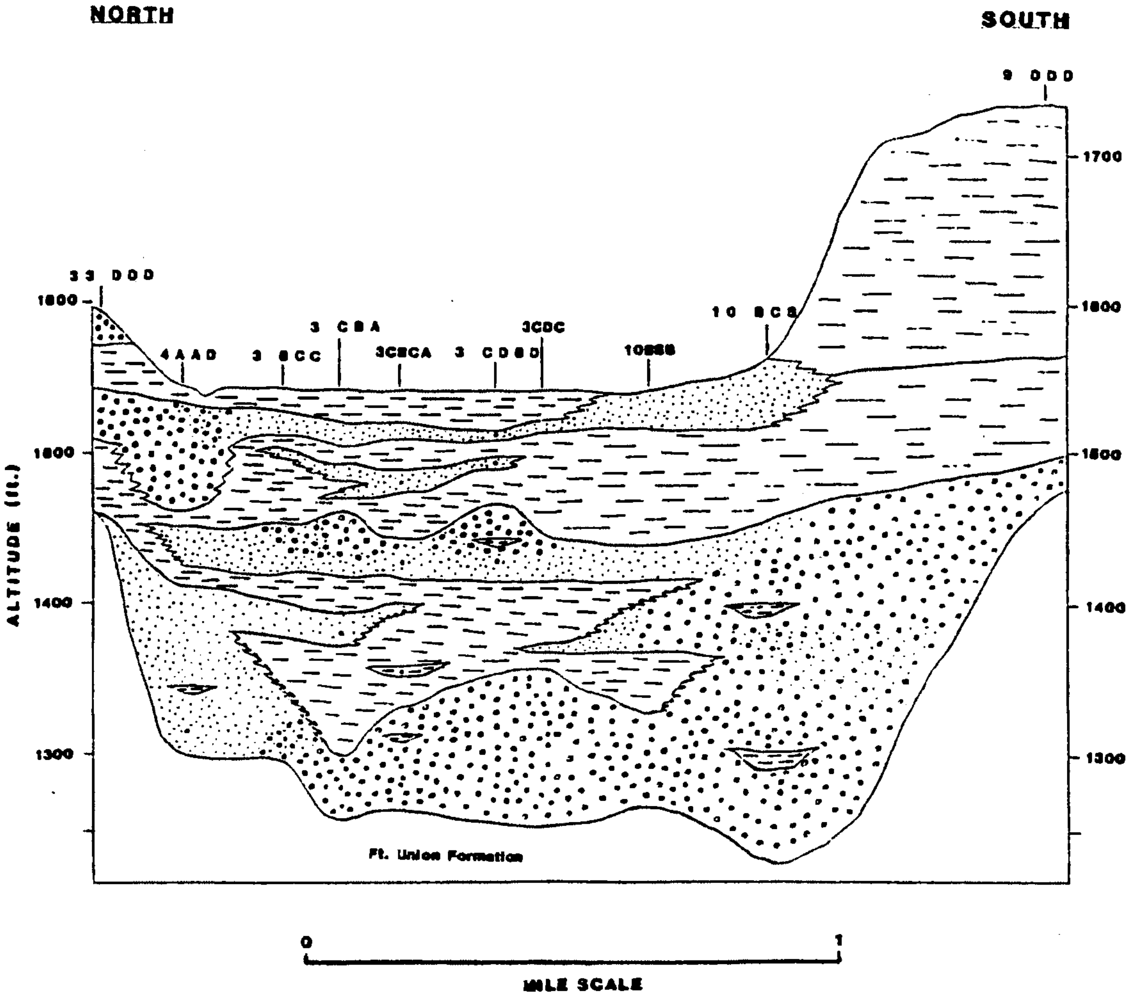

Figure 6. Lithologic Cross-Section A-A'

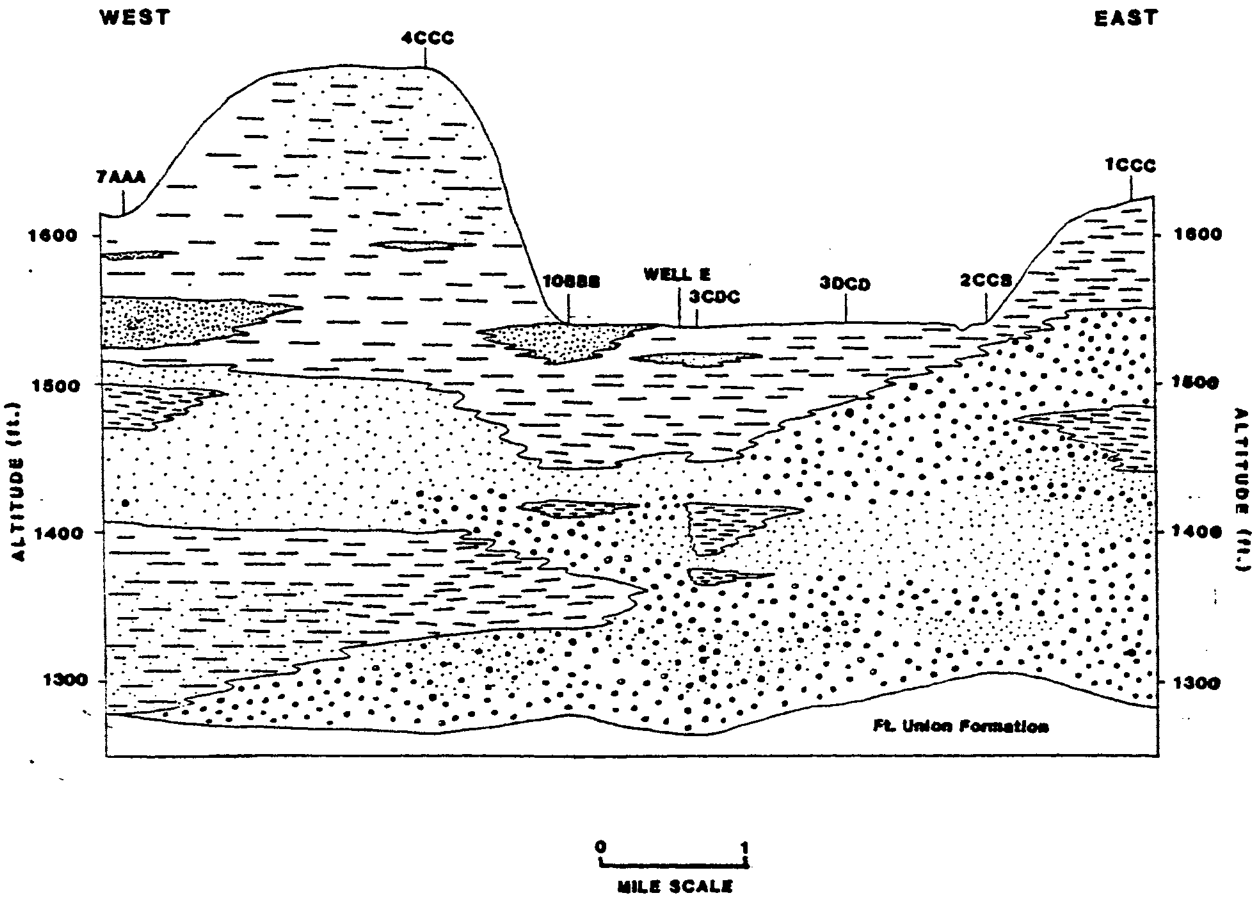

Figure 7. Lithologic Cross-Section B-B'

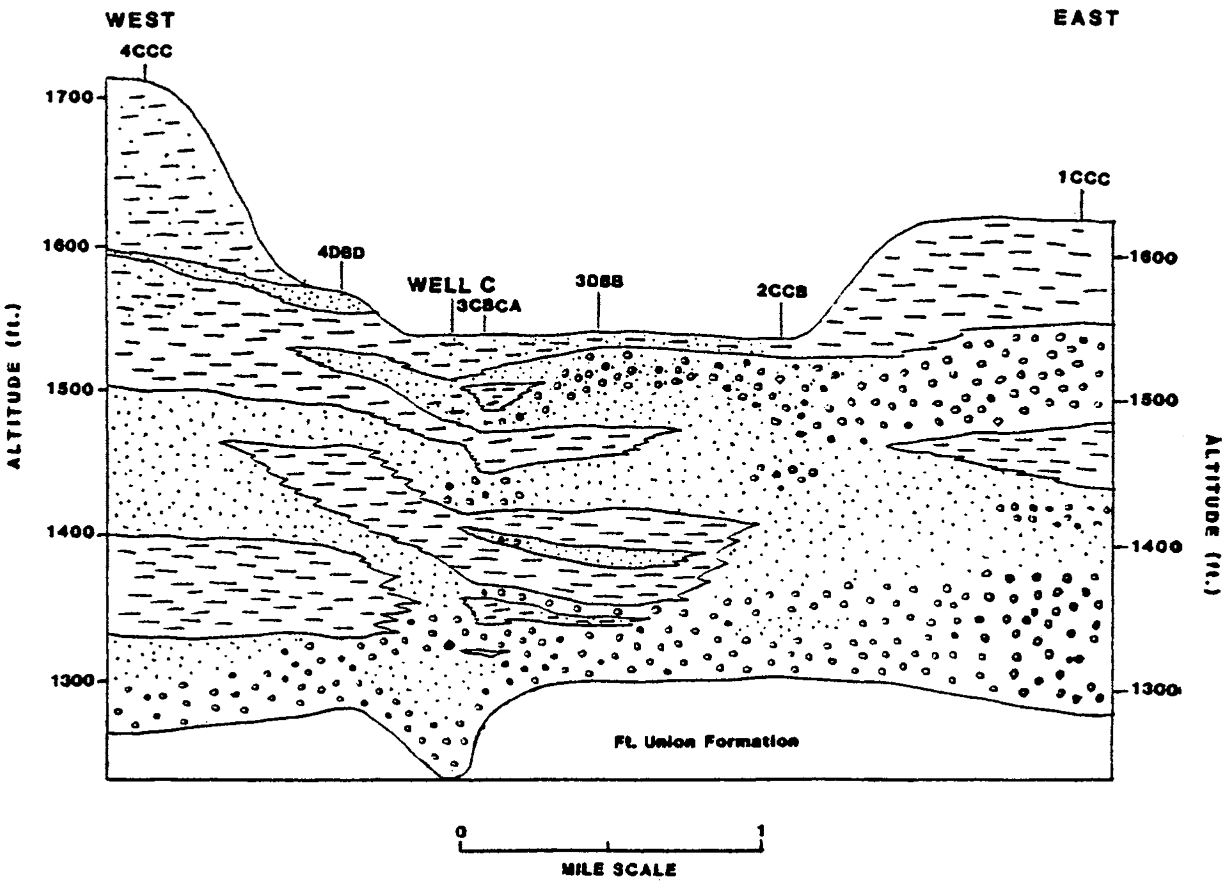

Figure 8. Lithologic Cross-Section C-C'

time. One kind of depositional environment would be the large-volume ice-marginal streams described above. Another depositional pattern would occur if the stream flow were blocked by an advancing glacier. In this case, silt and clay deposits would most likely result. Still another environment, could occur during interglacial periods which would consist of low-energy, anastomosing stream systems (Kehew, 1986). This oscillation of low-enery high-energy environments in association with glacial advances and retreats could have produced the complex stratigraphy of the Sundre aquifer. High-yielding aquifers occur where the coarse-grained material occurs at sufficient thicknesses and permeabilities.

CHAPTER III

HISTORY OF GROUND-WATER DEVELOPMENT IN THE MINOT AREA

Minot Aquifer

Major aquifers in the Minot area occur in the Pleistocene sediments of glacial and glacial-fluvial origin (Fig. 9). The glacial-fluvial sediments in the Minot area occur in the Souris River valley and its tributaries where sands and gravel deposits may reach thicknesses of up to 100 feet, but average about 40 feet (Pettyjohn, 1967). Aquifers in these deposits are named according to the reach of river in which they occur. Consequently, the Minot and Souris aquifers have different names even though they are stratigraphically equivalent and hydrologically connected (Fig. 9).

The Minot aquifer has been a source of water for the city since 1916. From this time until 1963 the aquifer supplied sufficient water for all municipal and small industrial needs (Pettyjohn, 1970). By the mid 1940's 11 industrial and municipal wells tapped the Minot aquifer (Akin, 1947). Since 1944 to the mid 1960's the annual

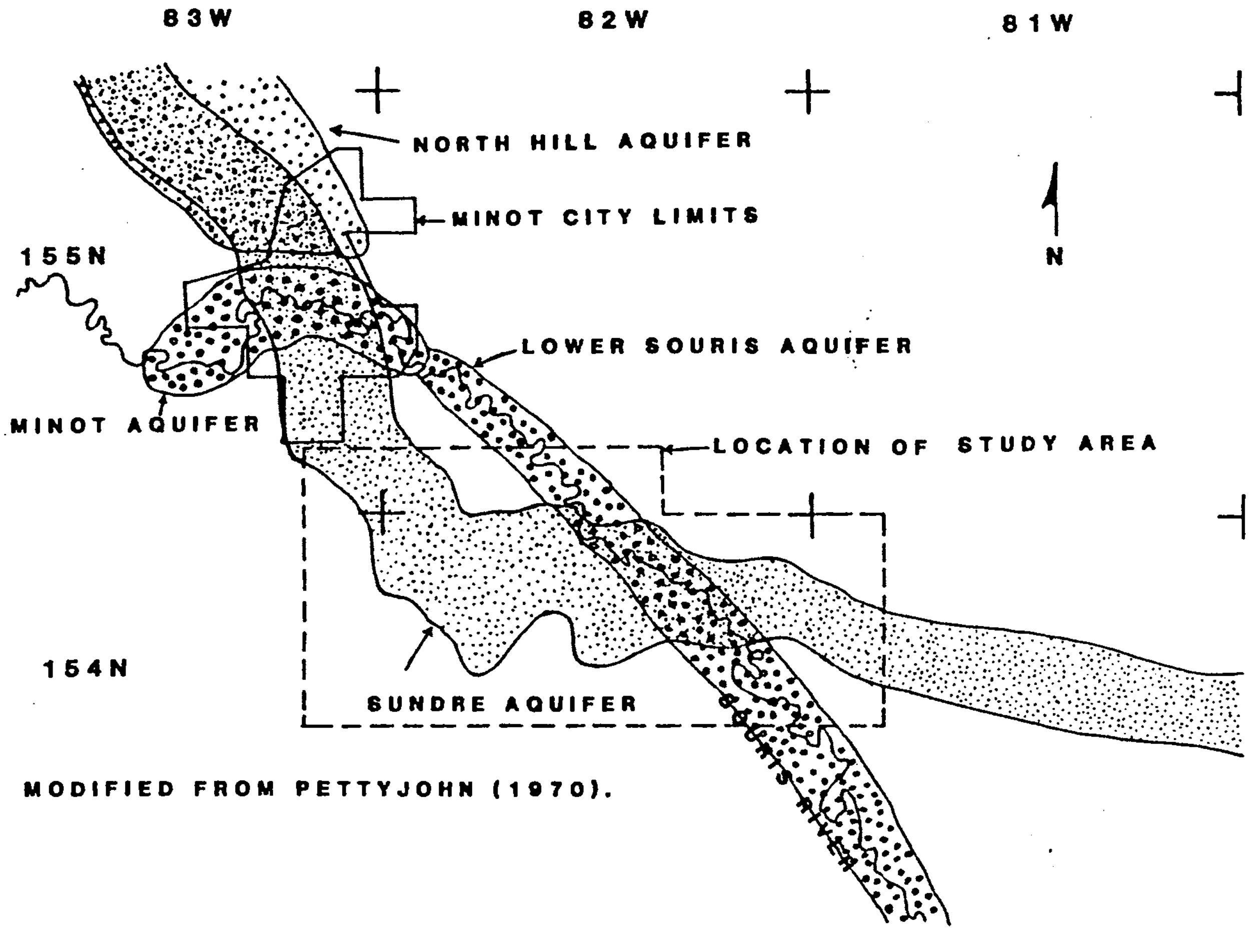

Figure 9. Major Aquifers in the Minot Area

withdrawal rate more than tripled. Ater eight more wells were installed in 1961, water levels in the aquifer were extensively lowered (Pettyjohn, 1970). This critical water shortage was mitigated by the establishment of an artificial recharge facility in 1965. This caused the trend of water level decline to be rapidly halted and reversed. However the amount of water recharged could still be depleted during the times of highest peak demand (Pettyjohn, 1970). At present about 70 percent of Minot's water supply is derived from ground-water sources. About half of that amount is pumped from the Minot aquifer and the remainder is obtained from the Sundre aquifer (Figs. 10-11).

Lower Souris Aquifer

The Lower Souris aquifer extends downstream from Minot for (Fig. 9). The sands and gravels that compose this aquifer range in thickness from 10 to 79 feet and are encountered at depths from 19 to 83 feet below the land surface (Pettyjohn, 1970). These deposits are generally confined to the Souris river floodplain and they may be locally discontinuous in places where clay-rich sediments predominate (Figs. 6-8). This aquifer supplies the baseflow to the Souris river. Water levels in this aquifer range from 10 to 13 feet below land surface.

Only one large-volume well taps the Lower Souris aquifer and it can produce 500 gpm. However this well, at the Bison Generating Plant, is seldom used. This aquifer

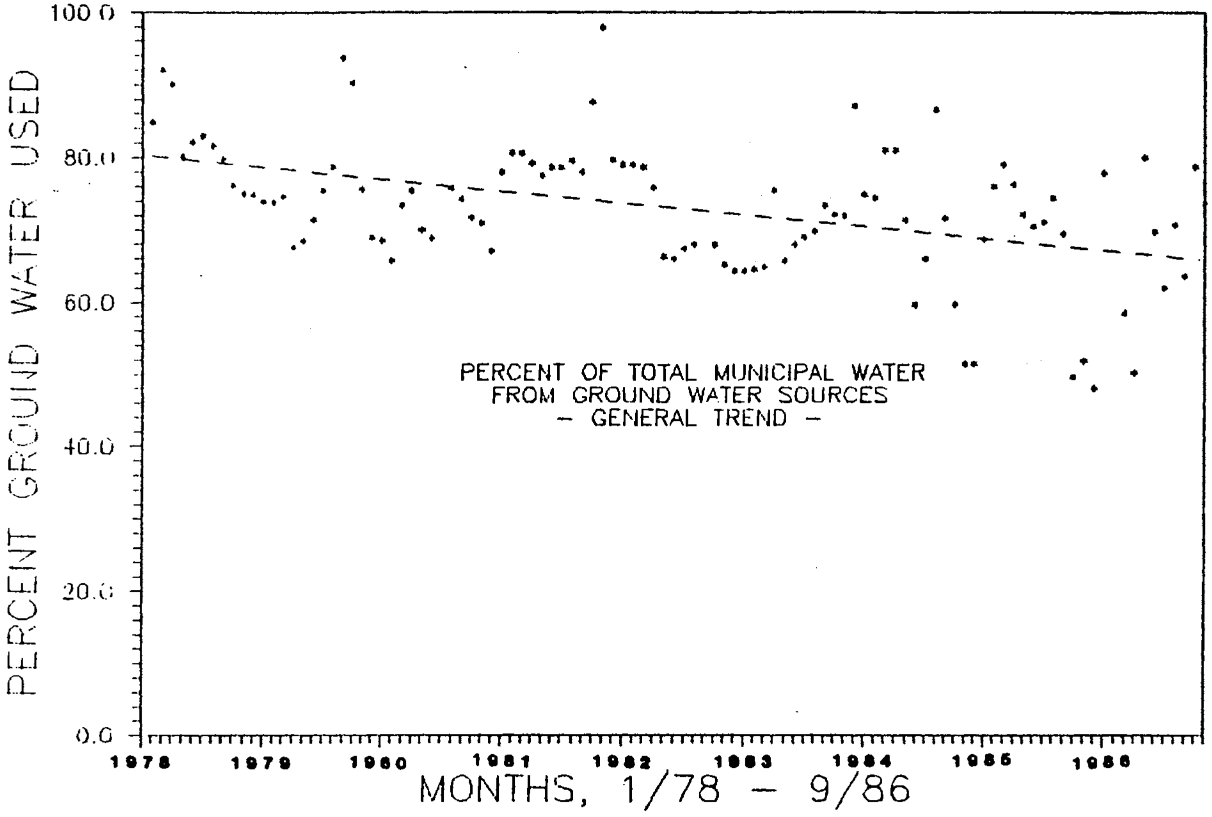

Figure 10. Percent of Total Water from Ground-Water Sources

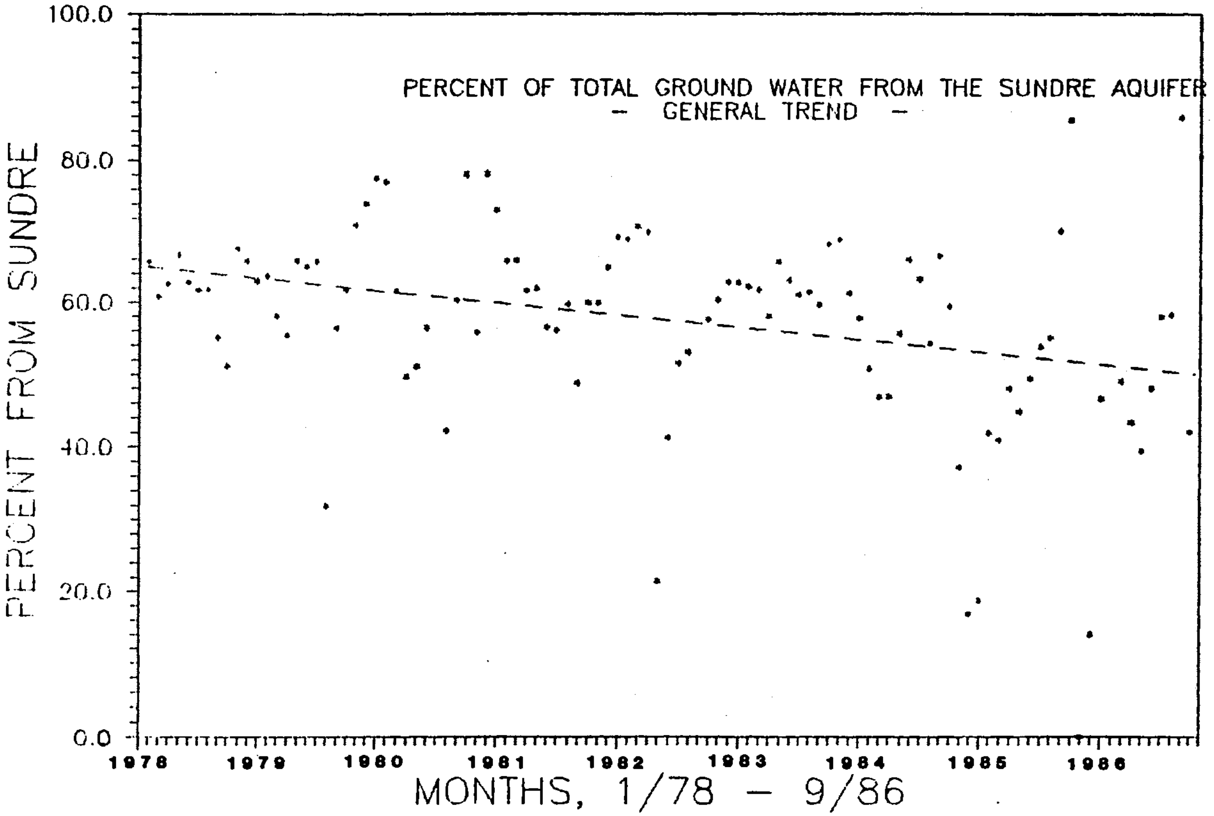

Figure 11. Percent of Ground-Water from Sundre Aquifer

has a large potential for development in many areas (Pettyjohn, 1970). More will be discussed about the hydrology of this aquifer in a later section.

Sundre Aquifer

The Sundre aquifer, the subject of this research, consists of glacial sand and gravel that is interbedded with clay. These deposits fill a buried channel carved in the bedrock (Fig. 9). The channel ranges from one to two miles in width and has been traced over 25 miles in Ward county and further across the state by test hole drilling (Pettyjohn, 1970). The maximum depth of the channel ranges from 300 to 350 feet below the surrounding bedrock surface and in places over 500 feet below land surface. The top of the aquifer reaches depths from 100 to 250 feet below land surface, the shallowest places being in the Souris river floodplain. Locally sand and gravel layers reach thicknesses of up to 230 feet uninterrupted by clay layers. Depth to water before well development took place ranged from about 12 feet on the floodplain to almost 200 feet on the uplands.

Minot municipal wells 5, 6, 9, and 10 penetrate the upper part of the Sundre aquifer within the city limit (Fig. 9). These wells are capable of pumping 1000 gpm with 8-hour specific capacities of approximately 156 gpm/ft (Pettyjohn, 1970). Eleven industrial and domestic wells produce from the Sundre at the south end of Minot, however the pumping rates are very low owing largely to well design and construction (Pettyjohn, 1970).

After a comprehensive aquifer test in 1969, five high-volume municipal wells were completed in the Sundre in 1975. These wells are located in the Souris River floodplain in the west and southwest parts of T154N-R82W-3 (Fig. 3). Wells D and E began producing in the summer of 1976 and wells A, B, and C were turned on in the summer of 1977. The greatest pumpage is derived from well D, which commonly discharges two to three times more than the other wells (Figs. 12-16). The average withdrawal rate of all wells combined is approximately .46 million cubic feet per day (3.4 mgd). The percent of ground water used by the city that comes from the Sundre aquifer is about 55 percent, ranging from a high of 65 percent in 1978 to a low of 50 percent in 1986 (Fig. 11). The amount of pumpage from each well varies widely from month to month (Figs. 12-16). This is due to water quality considerations, economic considerations, and seasonal fluctuations in demand.

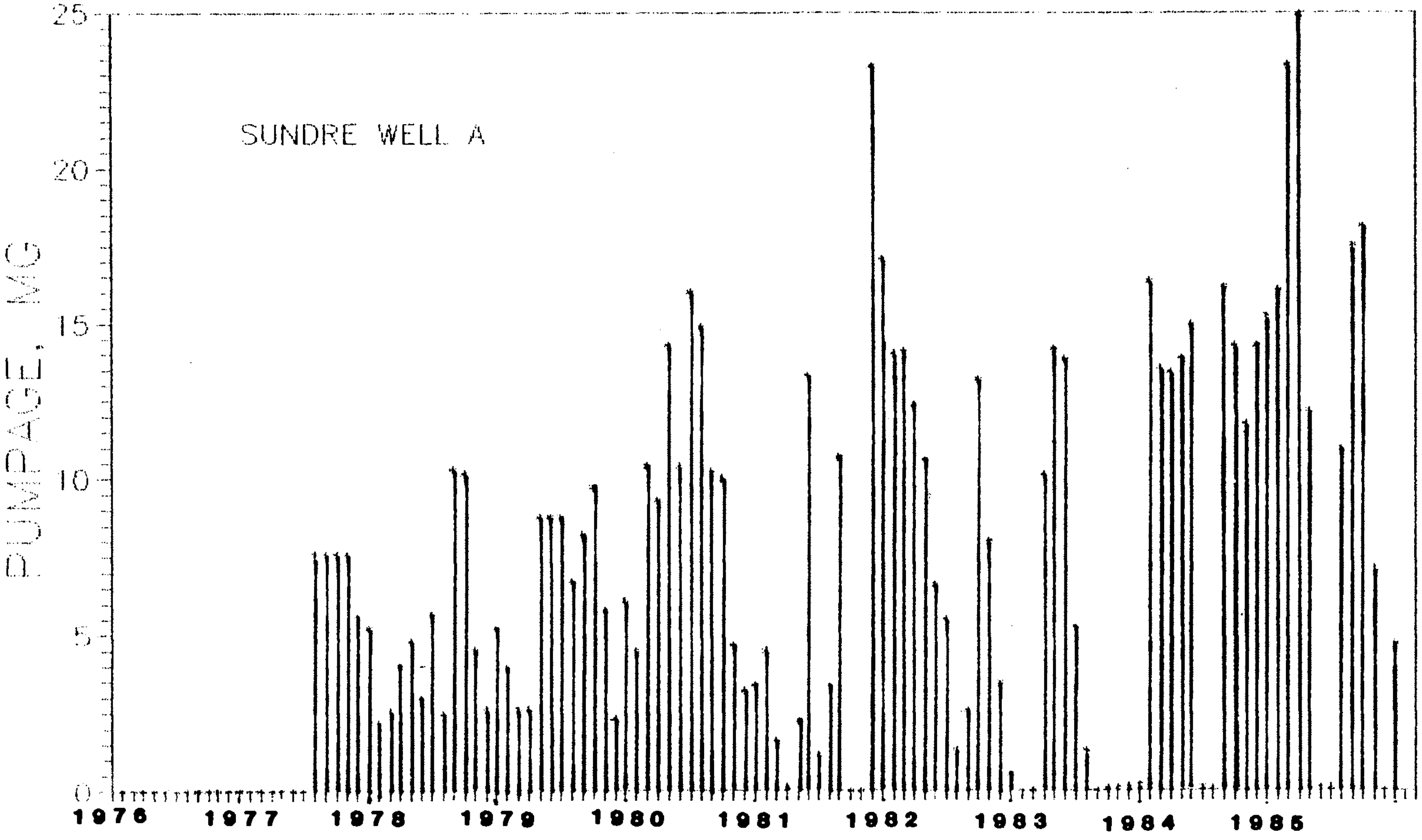

Figure 12. Well A Pumpage

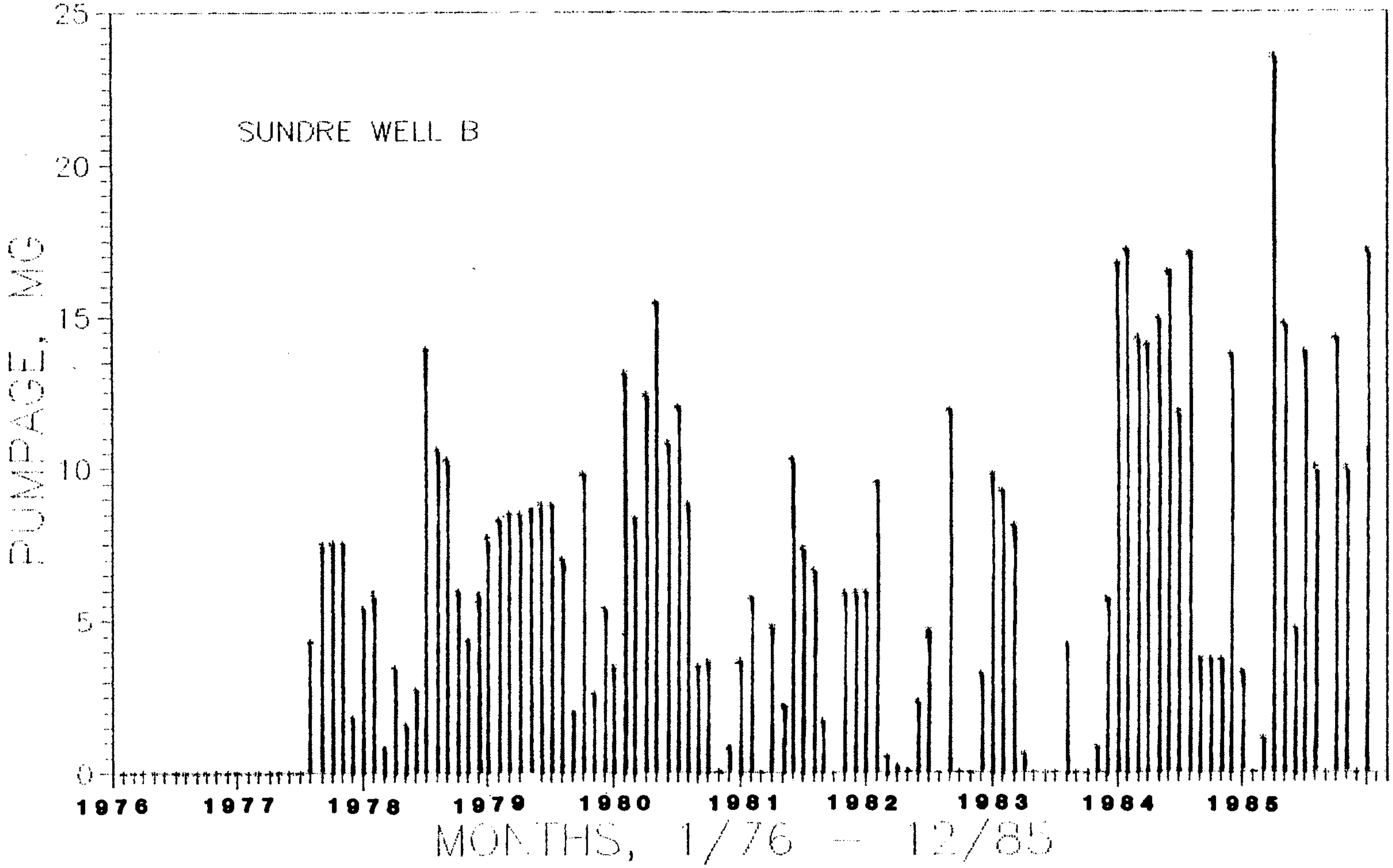

Figure 13. Well B Pumpage

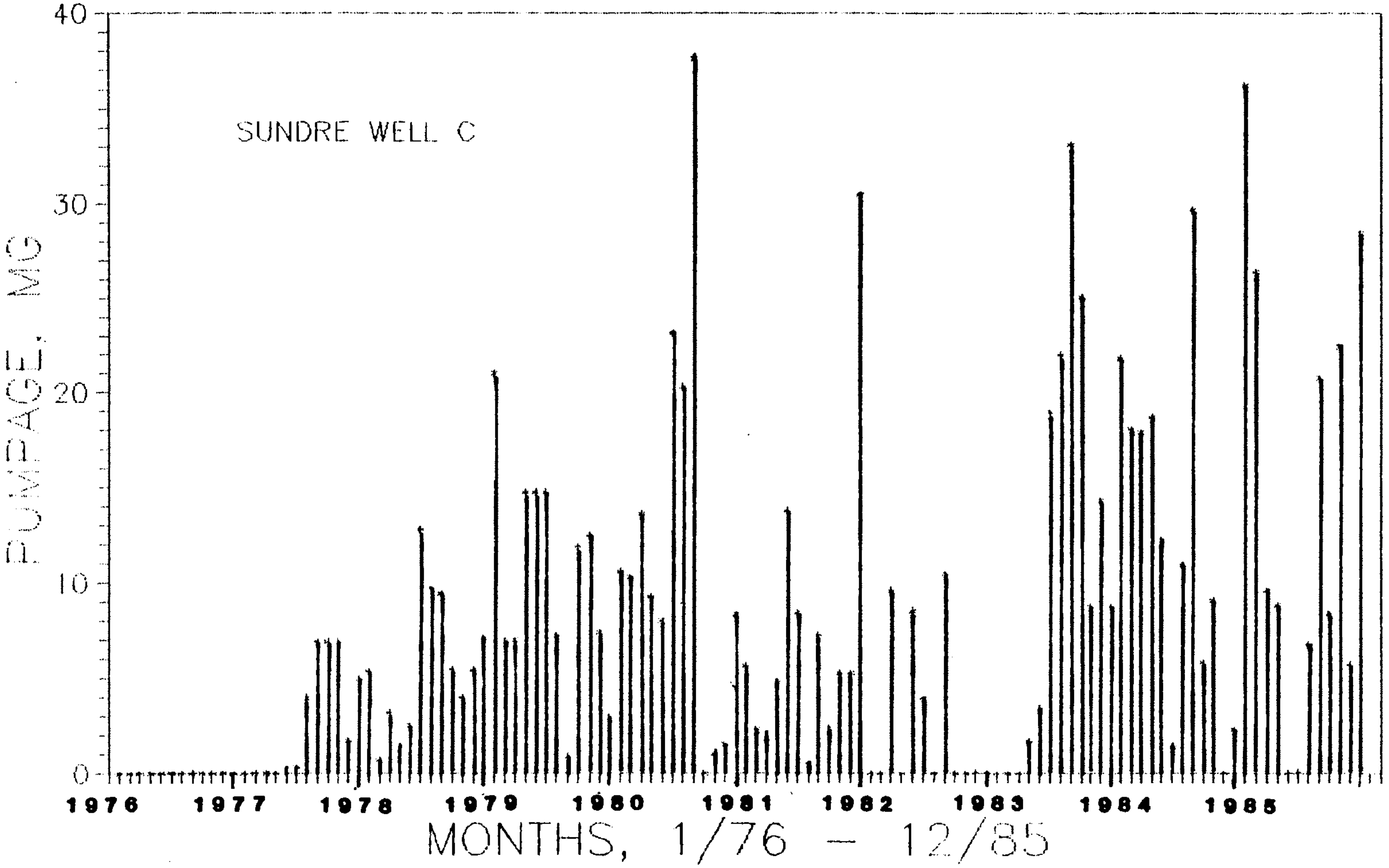

Figure 14. Well C Pumpage

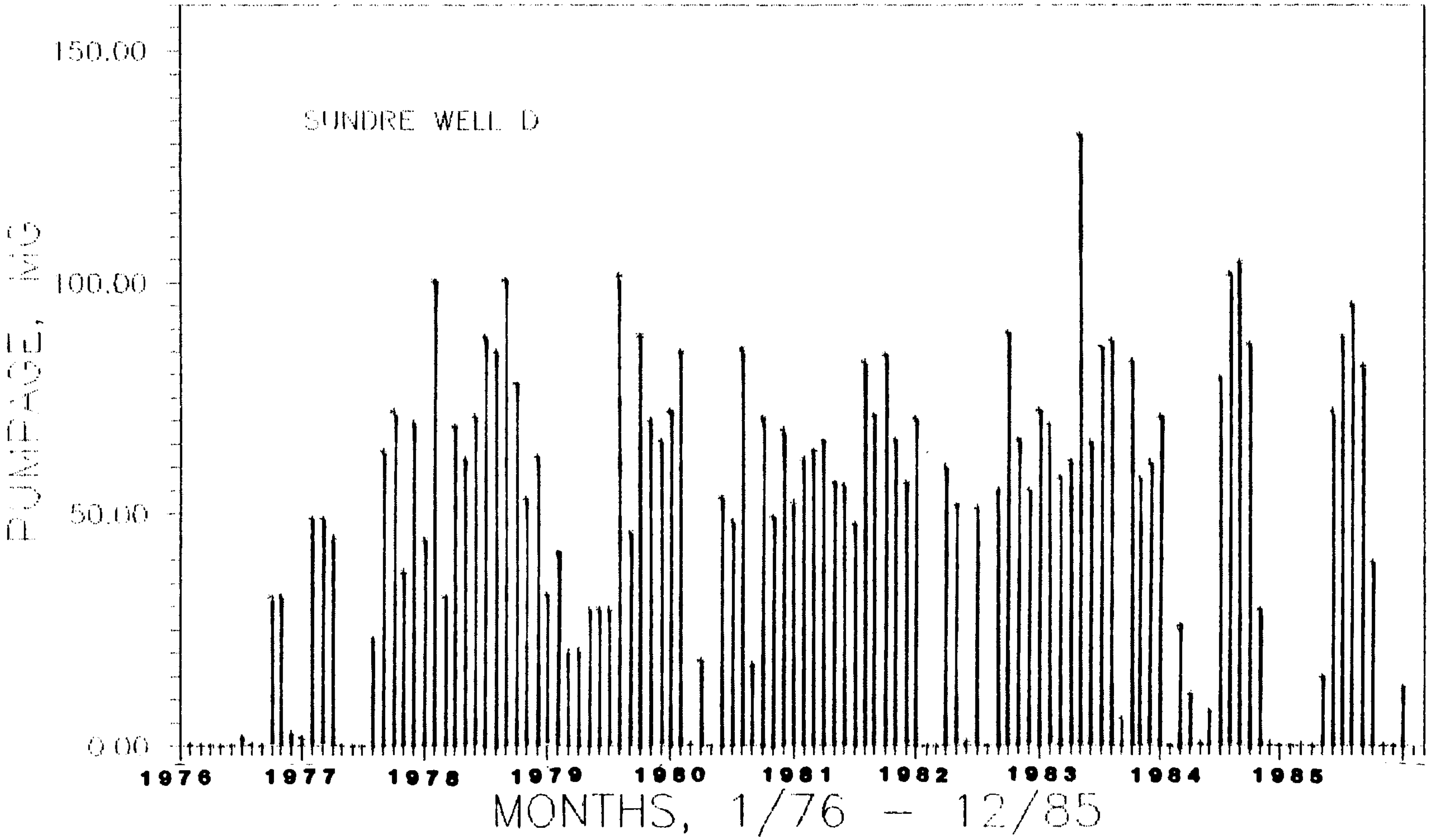

Figure 15. Well D Pumpage

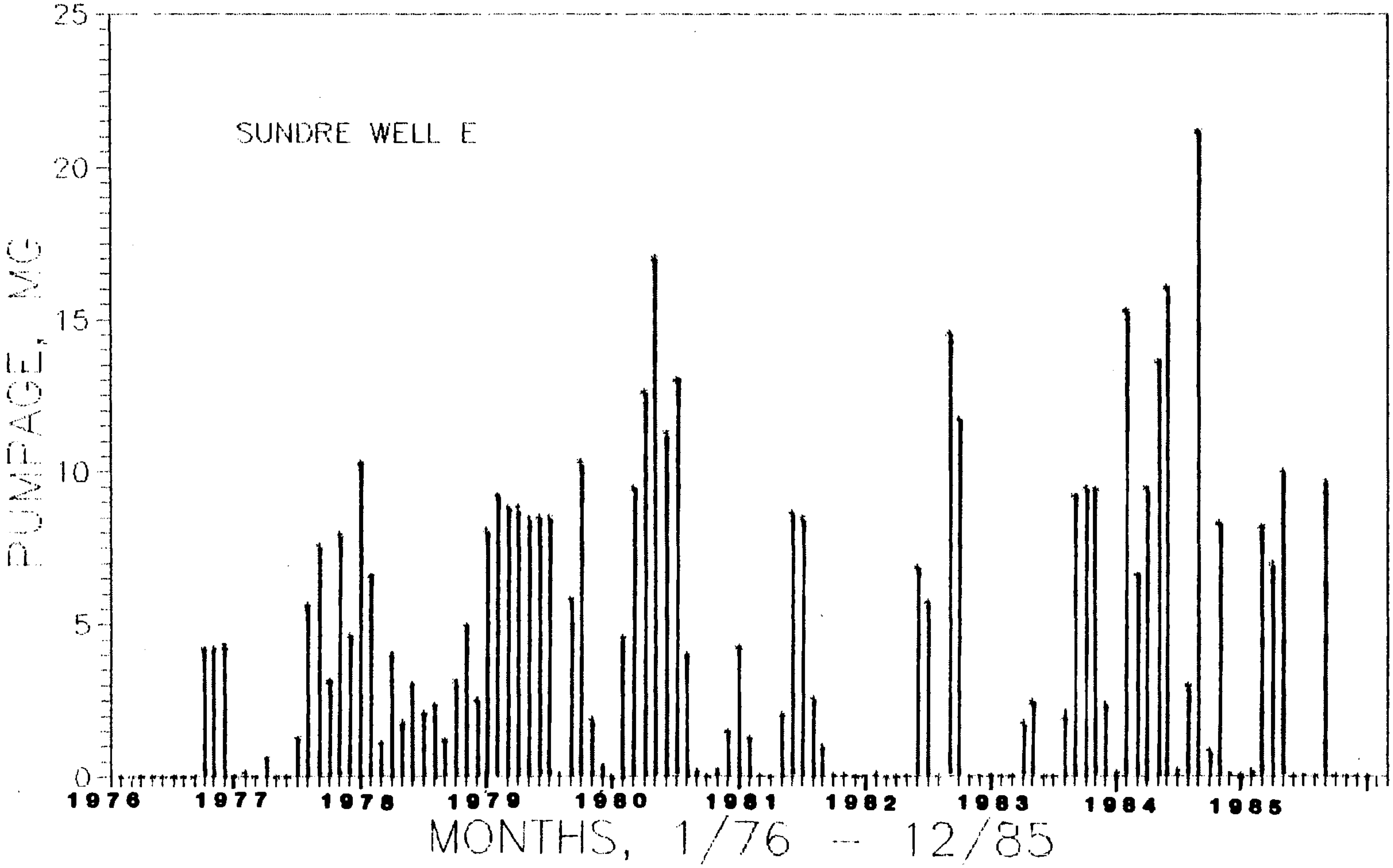

Figure 16. Well E Pumpage

CHAPTER IV

GROUND-WATER SYSTEM

Ground-water Occurrence and Movement

Ground-Water Occurrence

In the study area ground water is contained in multiple zones of sand and gravel. The stratigraphy of the Sundre and Lower Souris aquifers is very complex. The base of the Lower Souris aquifer is easily defined in the areas where it overlies bedrock. Where it overlies the Sundre aquifer the bottom is not distinct as it appears to grade into underlying deposits (Fig. 6). On the other hand, the two aquifers can be delineated on the basis of stratigraphy, and by observing water-level trends through time by means of hydrographs of well nests that are screened in several different stratigraphic intervals.

From the lithologic cross-sections, it appears that three sand and gravel units are fairly thick and extensive (Figs. 6-8). Two or three other similar units occur as locally developed lenses in clay units. The bedrock altitude in the Souris River floodplain on either side of the Sundre channel is approximately 1450 feet. Most likely

Lower Souris aquifer deposits do not occur lower than this elevation.

The hydrographs of well nests screened at different intervals within the system also may be used to distinguish the two aquifers. The pumping stress on the entire Sundre/Souris aquifer system effects the water level in each sand and gravel unit differently. Those units that are hydrologically connected will respond to the pumping stress in a similar manner.

For example, the hydrographs of well nest 3CBCA-154N-82W show the water levels at 240 feet and 175 feet responding identically to stress through time, as does the water level in the sands at 105 feet, although the latter are consistently about 2.5 feet higher than the water levels in the lower intervals (Fig. 17). The water level in the sediments at 56 feet however, show a far more stable trend although some similarities are evident (Fig. 17). The pumping stress has little, if any, effect on these shallower deposits. In view of the stratigraphy and hydrographs, the Lower Souris and Sundre aquifers are delineated as shown in Figure 18.

The depth to water in the Sundre aquifer ranges from 13 feet under the floodplain to over 200 feet beneath the uplands. The potentiometric surface is based on static water-level measurements taken prior to the Sundre aquifer test in 1969 (Plate 1). This was prior to development by municipal wells in this section of the Sundre aquifer,

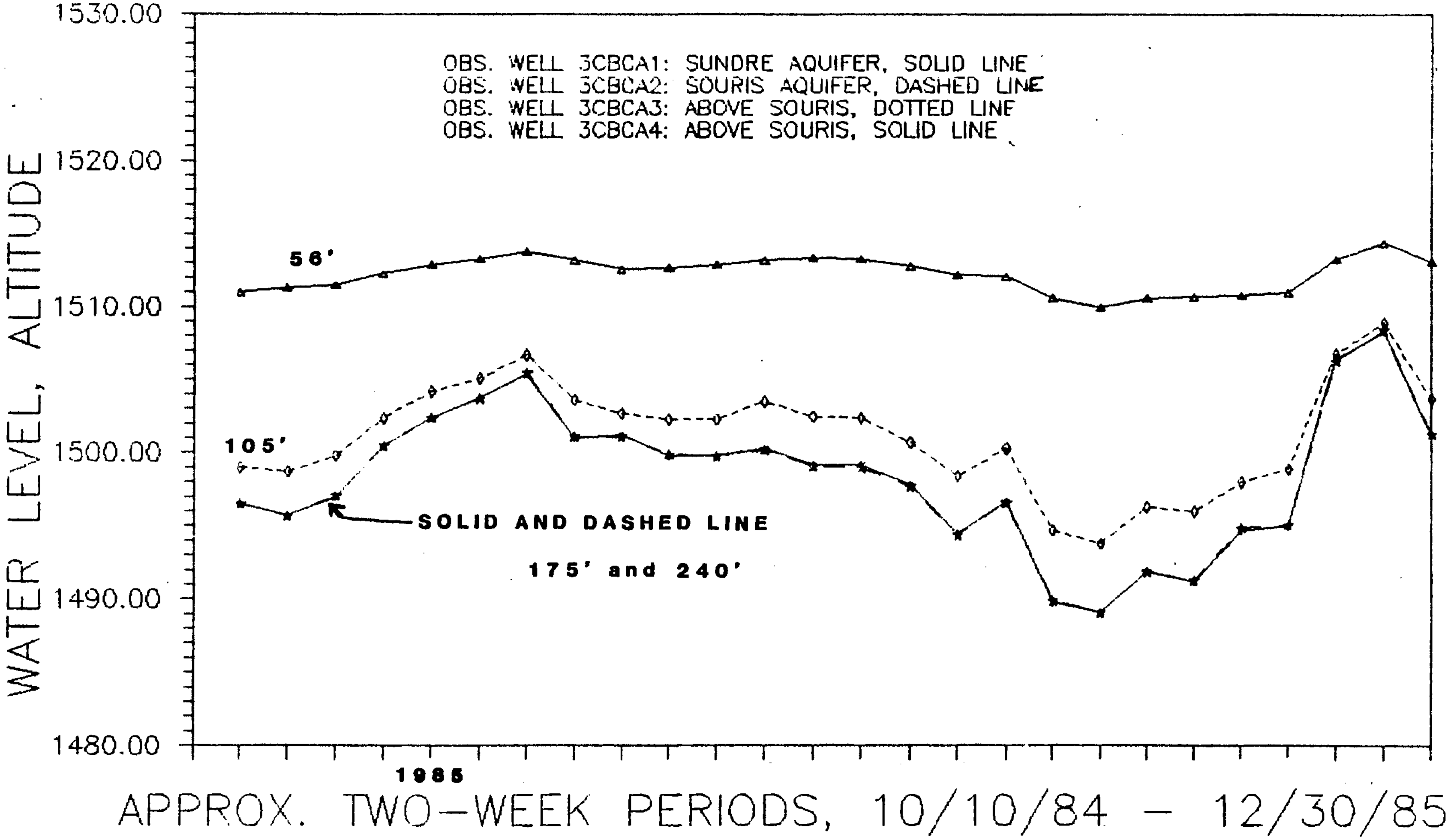

Figure 17. Hydrographs for Well Nest 3CBCA

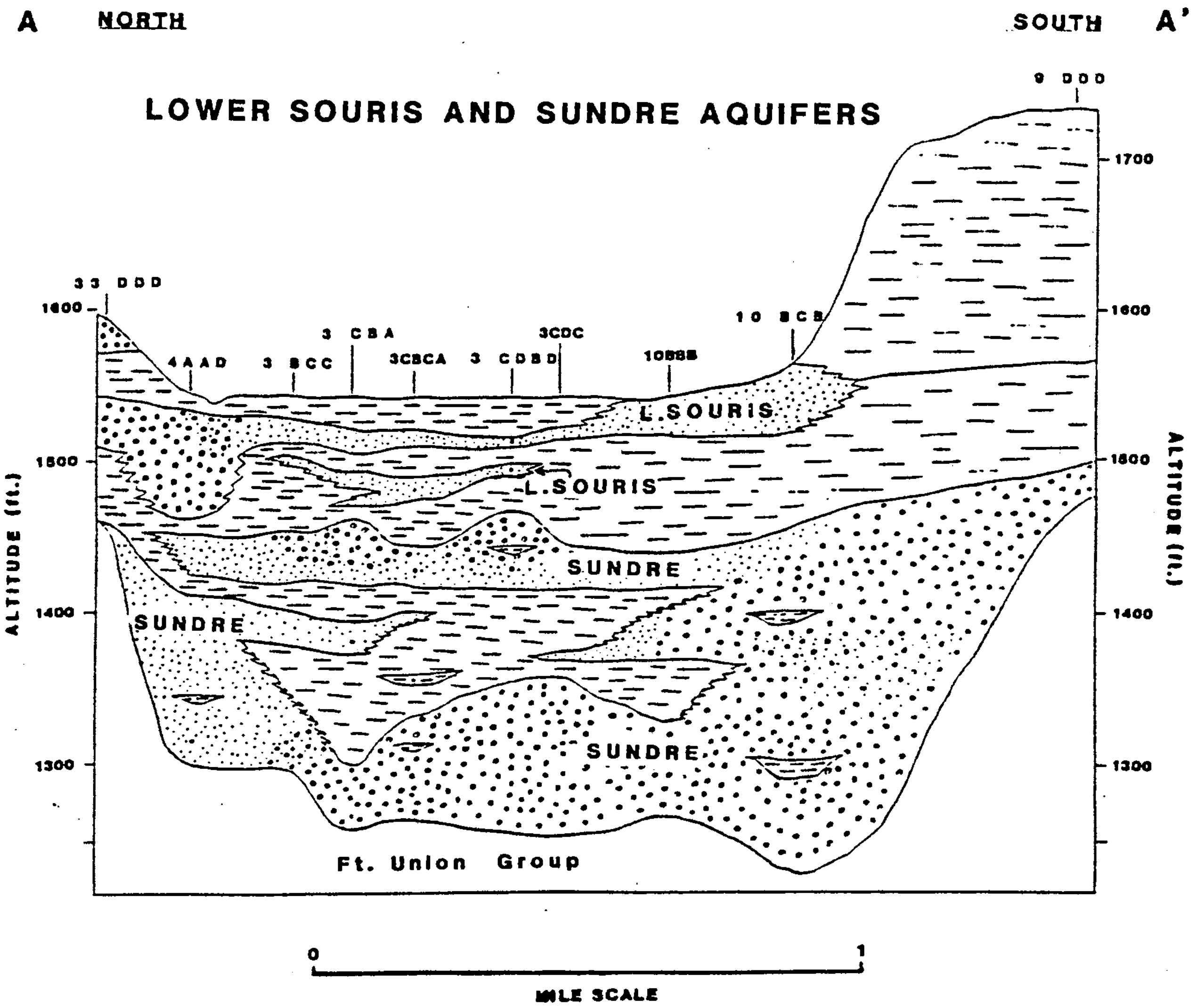

Figure 18. Delineation of Sundre and Lower Souris Aquifers

therefore steady-state conditions are represented.

Steady-State Flow Patterns

The regional hydraulic gradient in the Sundre channel is to the west-northwest. Ground water moves into the study area as underflow from the eastern extension of the Sundre channel. Ground water moves out of the study area as underflow through the northwest extension of the Sundre channel. Between the inflow and outflow points, the regional gradient is about 1 to 1.5 ft/mi.

Under the Souris River floodplain in the study area, is a localized hydraulic mound that is about 3 feet higher than the regional gradient (Plate 1). This zone of higher head can also be seen in cross-section (Fig. 19). At first glance, one might assume that the mound is caused by leakage from above. However a hydologic cross-section of the vertical head distributions implies that this is not the case (Fig. 19). The top of the clay aquitard in the center of the Sundre aquifer is relatively flat while the base is undulating. Where the clay layer reaches its maximum thickness, the transmissivity of the underlying gravel is low relative to the surrounding aquifer. Hydrologic cross-sections of the Sundre aquifer show the regional flow longitudinally and transversely to the axis of the channel (Figs. 19 and 20). These cross-sections illustrate how flow lines diverge from regions of much lower transmissivity and converge on areas of higher transmissivity. Thus in the

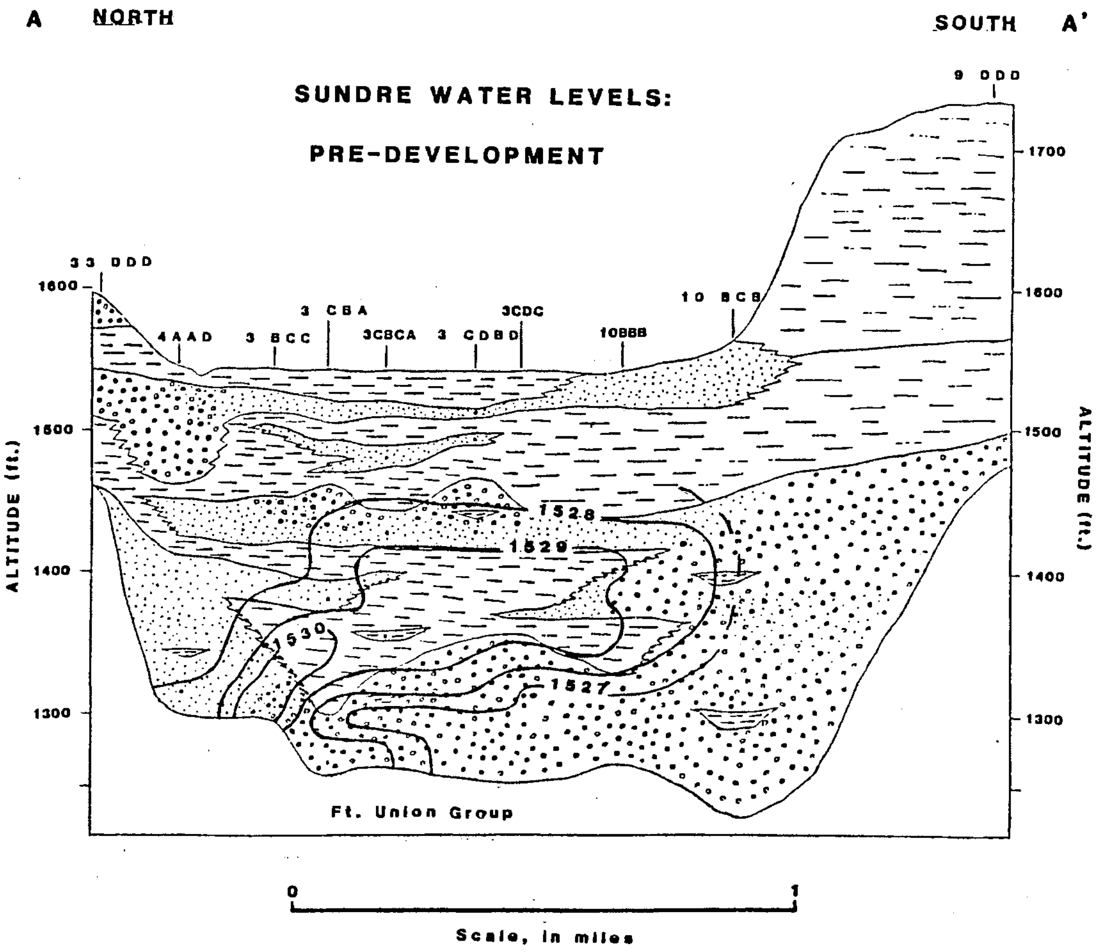

Figure 19. Pre-Development Hydrologic Cross-Section A-A'

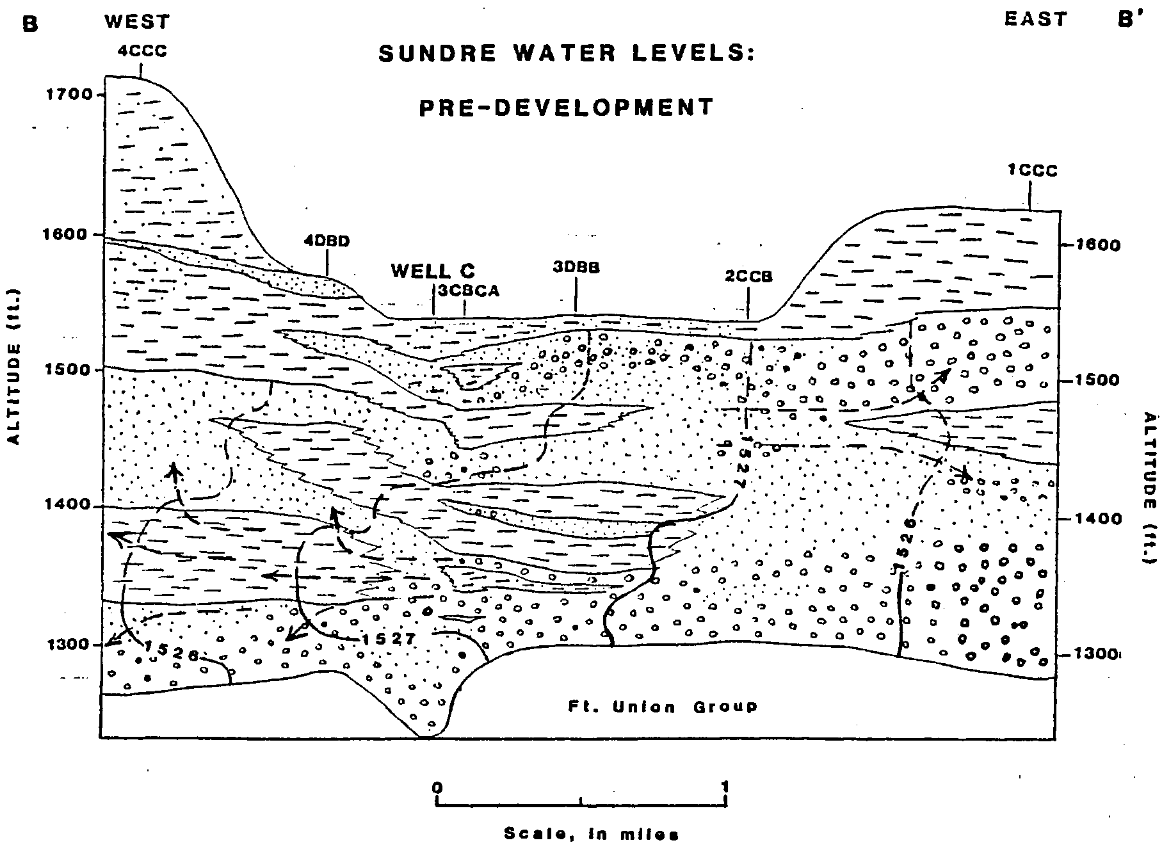

Figure 20. Pre-Development Hydrologic Cross-Section B-B'

piezometric profile, the water levels are higher for wells screened within the zone of lower transmissivity.

Hydraulic Characteristics of the Sundre Aquifer

The hydraulic characteristics of an aquifer include: saturated thickness, transmissivity, hydraulic conductivity, storativity, porosity, and rate of movement. These parameters affect the rate of ground-water flow, the amount of water in storage, and the rate and areal extent of water-level declines caused by pumpage. The hydraulic characteristics were estimated primarily from drill hole, observation well, and aquifer-test data.

Saturated Thickness

Since the Sundre aquifer is a confined system, the saturated thickness is equal to the sand and gravel thickness. The saturated thickness, in the center of the Sundre channel, in section 3-154N-82W exceeds 140 ft (Plate 2). The greatest thickness, 192 feet, was recorded in Well D. To the east and west of Section 3, the saturated thickness averages about 120 feet in the central part of the channel. The saturated thickness thins to zero feet at the boundaries of the buried channel. The municipal wells were drilled in the area of greatest known saturated thickness (Plate 2).

Transmissivity

The transmissivities of the Sundre aquifer were ascertained by an aquifer test in 1969 (Pettyjohn, 1970). The 12 inch-diameter production well was 220 feet deep and 50 feet of the aquifer were screened. The test lasted 15 days and the well was pumped at a rate of 1950 gpm during this time. Water levels were recorded in 37 observation wells and the production well. The distances between the observation wells and the production well ranged from 150 feet to 8.5 miles.

During the test, drawdowns were noted not only in the Sundre aquifer, but also in shallower sand and gravel units. This signifies that leakage occurs between the two aquifers when sufficient pumping stress is placed on the Sundre aquifer. Pettyjohn (1970) estimated that leakage occurred over an area of more than 28 square miles. However, the greatest amount is under the Souris River floodplain where the Souris and Sundre aquifers coincide. Induced infiltration from the Souris River recharges shallow outwash units, the Lower Souris aquifer, and eventually, the Sundre aquifer.

During the test, the cone of depression encountered many recharge and discharge (positive and negative) boundaries (Pettyjohn, 1970). The positive boundaries were caused by leakage from overlying units and areal changes in aquifer thickness or hydraulic conductivity. The negative boundaries were caused by the walls of the Sundre buried channel or by zones of lower hydraulic conductivity. Effective transmissivities range from 19,500 to 32,000 ft. squared/day. Because of the numerous boundaries encountered, the effective transmissivities were used in order to represent regional aquifer conditions. Plate 3 shows the transmissivity distribution within the Sundre Aquifer.

Hydraulic Conductivity

In the study area the sedimentary materials are, in order of decreasing hydraulic conductivity: gravel, sand, silt, and clay. These materials are interstratified throughout the aquifer, which makes the horizontal hydraulic conductivities substantially greater than the vertical hydraulic conductivities. Most observation wells in the area perforate the entire thickness of the Sundre aquifer. Therefore, the hydraulic conductivities could be estimated by dividing the transmissivity by the saturated thickness at each observation well. Calculated hydraulic conductivities ranged from less than 250 ft/day to over 800 ft/day locally. Values of 250 to 400 ft/day probably best represent the general aquifer conditions.

Storativity and Porosity

Storativities were also calculated with the 1969 aquifer test data (Pettyjohn, 1970). In the study area, storativities ranged from .0003 to .06. The higher values were recorded under or adjacent to the Souris River floodplain in an area of unconfined outwash. A reasonable representation of the storativity for the entire aquifer system is .0003 (Pettyjohn, 1970). An effective porosity of 20 percent was estimated as a general value throughout the aquifer and is based on published values for coarse sand and gravel materials (Fetter, 1980).

Rate of Flow

Ground-water in the Sundre aquifer system moves at rates of about .3 ft/day to 1 ft/day depending on the hydraulic conductivity and gradient. The following equation was used to estimate rates of ground-water movement:

$$v = \frac{KI}{n}$$

where

v = rate of movement, in feet per day;
K = hydraulic conductivity, in feet per day;
I = hydraulic gradient, dimensionless; and
n = effective porosity, in percent.

Hydraulic conductivities used in the equation ranged from 250 to 400 ft/day, hydraulic gradients ranged from 1.5 ft/mi., representing regional flow, to about 3 ft/mi. locally in Section 3, T154N-R82W.

Ground-Water Budget

Inflow

A ground-water budget is an accounting of the inflow to and outflow from the aquifer system and changes in ground-water storage. If inflow equals outflow and if the change in the volume of water in storage is zero, the aquifer is in equilibrium or steady-state condition. Equilibrium is reflected by the absence of long-term trends of water level change. If total inflow and outflow are not equal, the aquifer is in a nonequilibrium or transient condition, and the change in the volume of water in storage is reflected by changing water levels through time.

The primary inflow to the aquifer is underflow from eastern extension of the buried channel outside of the study area. The ground-water flow that enters through the buried channel to the east can be estimated with the following equation:

$$Q = KIA$$

where

Q = discharge, in cubic feet per day;
K = hydraulic conductivity, in feet per day;
I = hydraulic gradient (dimensionless); and
A = cross-section area of flow, in square feet.

Values for the variables in the equation were determined from a cross-section produced by the bedrock configuration map and from the steady-state hydraulic gradient (Plates 1 and 4). A value of 200 to 400 ft/d was used for the hydraulic conductivity. Underflow at the eastern boundary of the model was estimated to range from 21000 cubic feet/d to 42000 cubic feet/d. Because the overlying confining material is predominantly till that commonly exceeds 200 feet in thickness, direct recharge by precipitation is insignificant.

Outflow

Outflow from the aquifer occurs as underflow out of the northwest extension of the channel. Since the sand and gravel of high permeability thin in this portion of the aquifer, the outflow must balance the inflow by means of an increase of hydraulic gradient farther to the north and/or a greater cross-sectional area (Plate 4). Plate 4 indicates that the cross-sectional area is about twice that of the inflow region, however, due to sparce data, the hydraulic gradient cannot be determined accurately. It is assumed that the gradient increases at the outflow region due to pumpage from the Minot well field. Underflow out of the study area to the northwest is estimated to be the quantity of water equal to the steady-state inflow. Therefore, total underflow is within the range of 21,000 to 42,000 cubic feet/day.

Ground-Water Withdrawals

Significant withdrawal of ground water from the Sundre aquifer began in 1976 with the establishment of a municipal well field in Section 3, T154N-R82W. Of the total quantity of water used by the City of Minot from 1976 to 1985, 33 to 45 percent has come from the Sundre aquifer (Figs. 10-11). Since pumpage of the five municipal wells in the study area began in late 1976, a total of about 1.1 billion cubic feet

(8.3 billion gallons) have been withdrawn.

The stress on the aquifer caused by this pumpage has produced a elongated cone of depression (Figs. 21-23). The contours are not closed in order to indicate a greater extent of the cone. The altitude of the potentiometric surface within the cone has decreased with time. In the vicinity of pumping wells the water level has declined more than 30 feet from pre-development (1976) to late 1985. The hydraulic gradient from the outer margin to the center portion of the cone of depression is increasing with time (Figs. 21-23). This indicates that the cone is still expanding because equilibrium has not been achieved.

Superimposed upon the water level declines are peaks of relatively great magnitude. These have been correlated to events of high Souris River discharge (Fig. 24). The Souris River and the Sundre Aquifer are not directly hydaulically connected, yet these same peaks are seen in hydrographs up to three miles away from the river. The water-level peaks, therefore, result from river loading and do not represent change in storage in the Sundre Aquifer.

Leakage

Before pumping began, the Lower Souris aquifer and the deeper Sundre aquifer were probably at equilibrium as indicated by the two hydrographs in Figures 17 and 25. The hydrographs of well nest 3CBCA-154N-82W show that the lower three water-bearing intervals equilibrated when Well D was

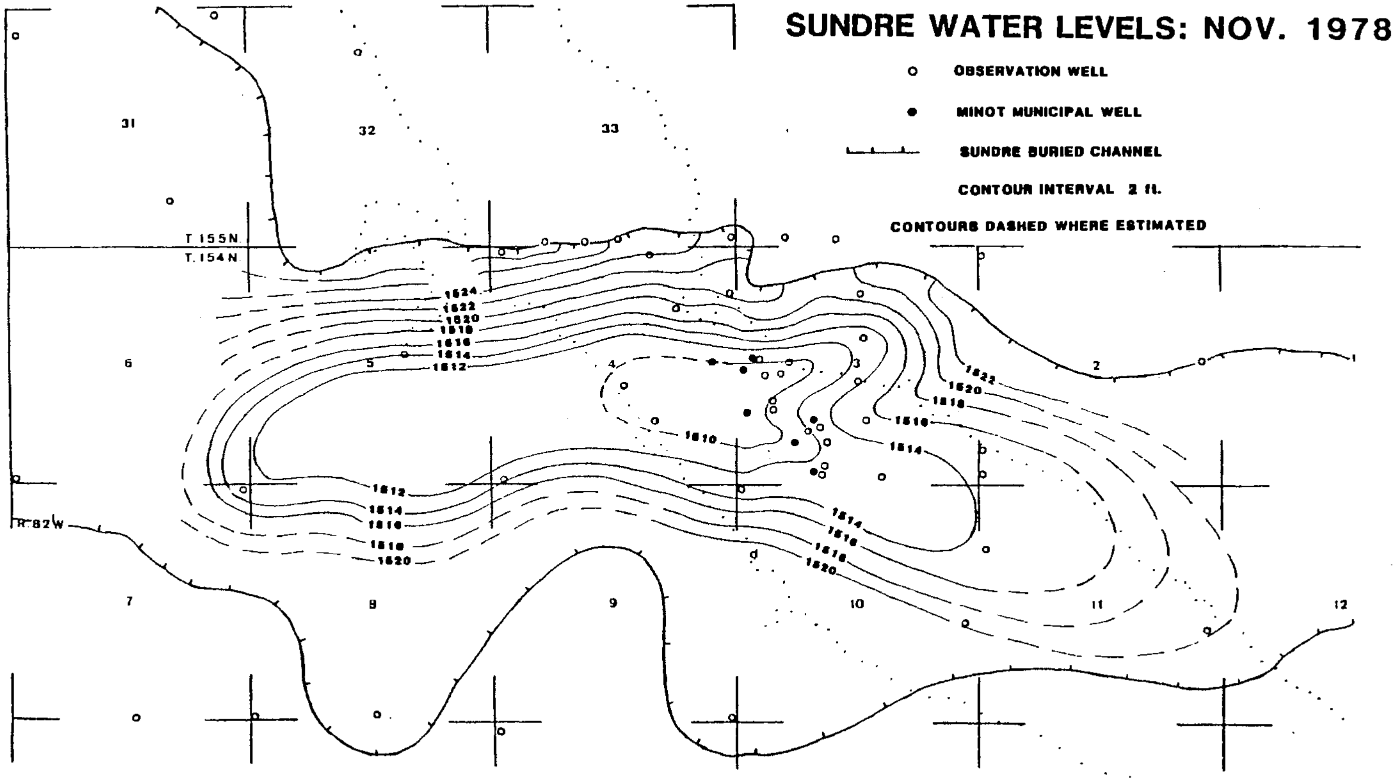

Figure 21. Sundre Water Levels: Nov. 1978

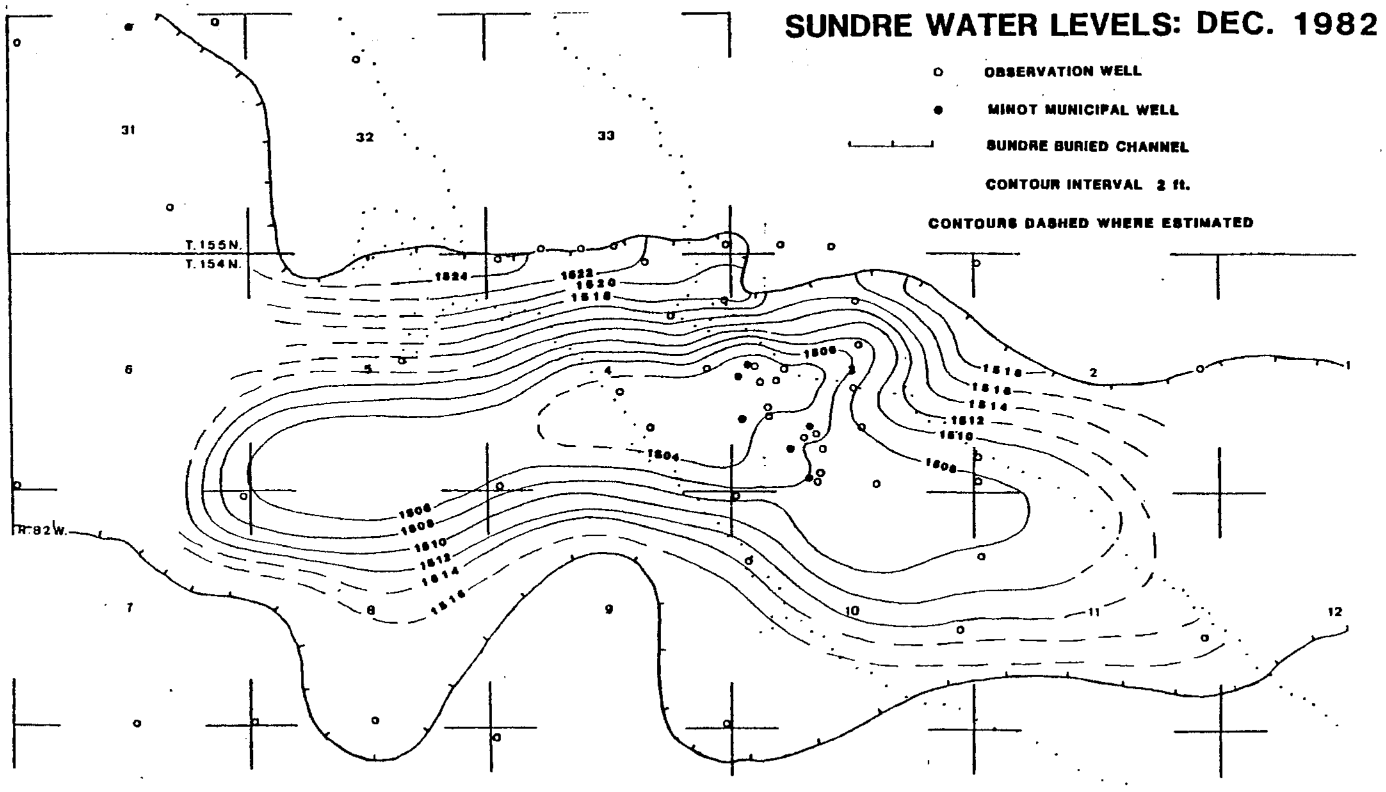

Figure 22. Sundre Water Levels: Dec. 1982

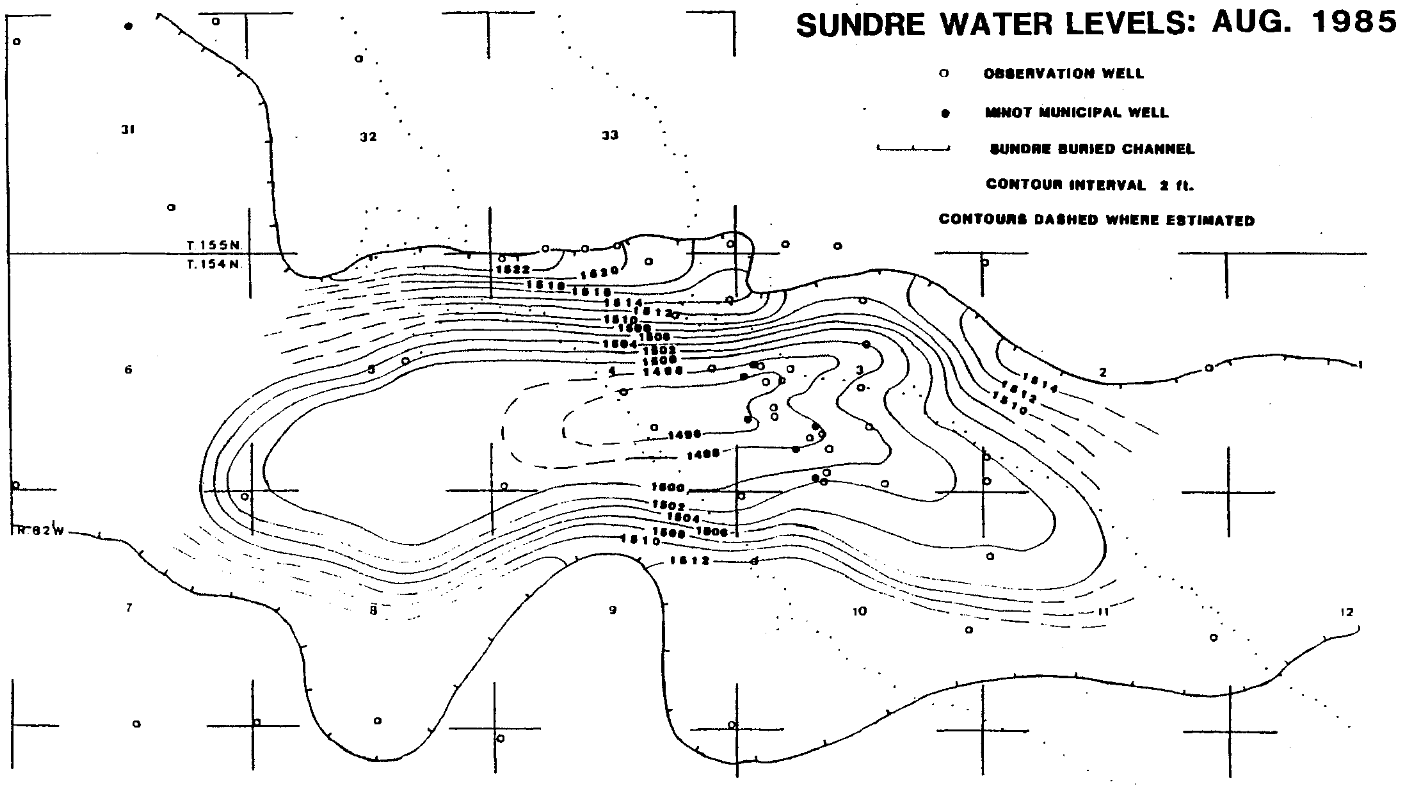

Figure 23. Sundre Water Levels: Aug. 1985

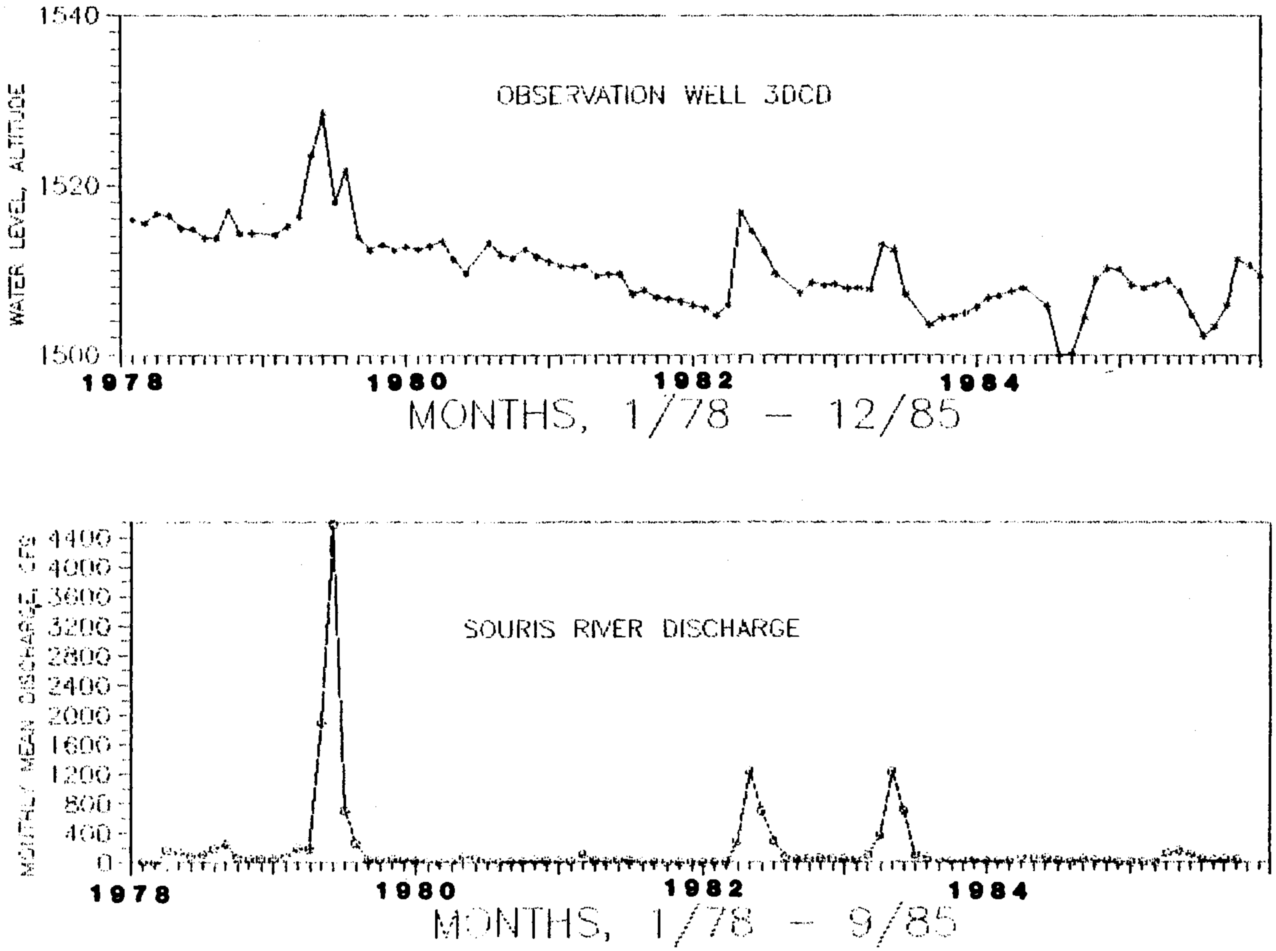

Figure 24. River Loading Events

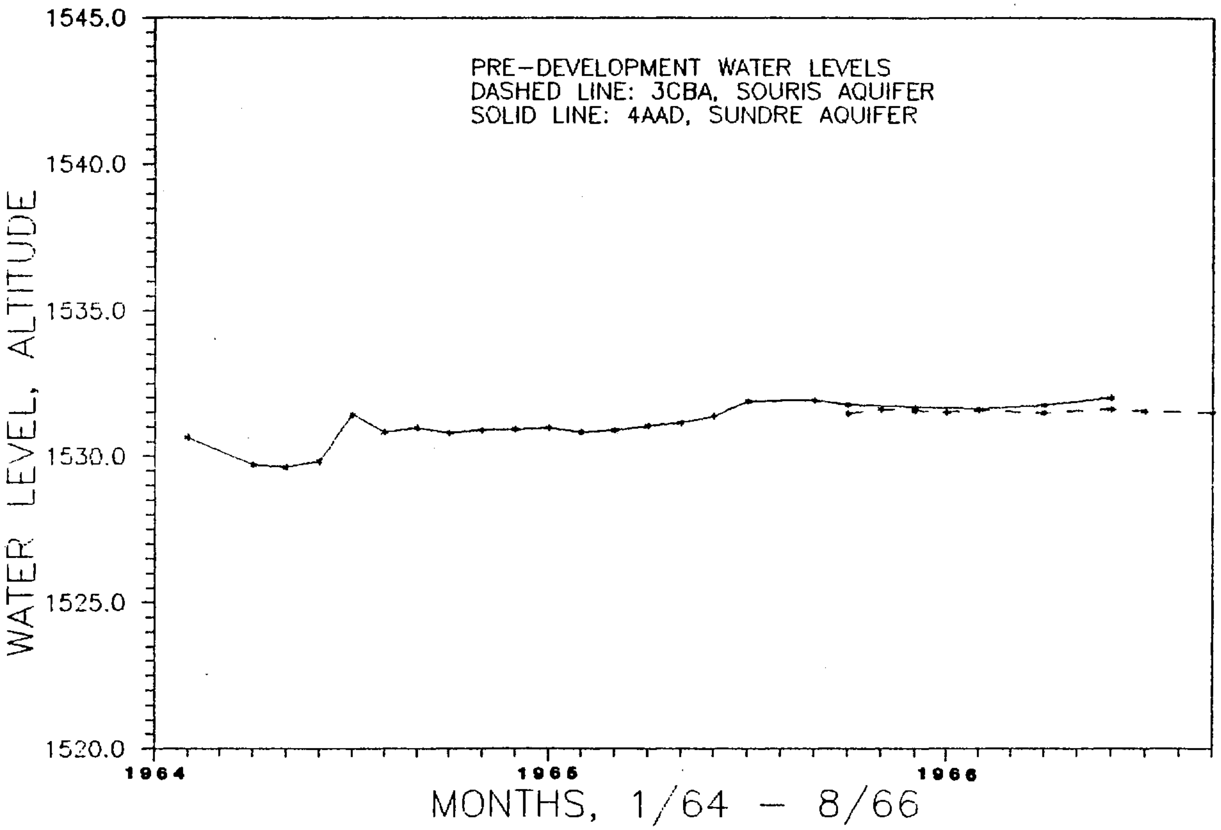

Figure 25. Pre-Development Hydrograph

shut off. Also the lower three water levels were approaching equilibrium with the shallowest water level during this time. The trend toward equilibration when stress is removed from the system indicates a lack of leakage during steady-state conditions. Hydrographs of wells 3CBA-154N-82W and 4AAD-154N-82W from 1964 - 1966 also indicate equilibrium conditions between the Sundre and Lower Souris aquifers (Fig. 25).

The decline of water levels in the Sundre aquifer has increased the head difference between the Sundre sand and gravel units and the overlying sand and gravel units in the Souris aquifer. The increasing head differential with time results in a increased leakage from the overlying water-bearing units. The head difference trend can be illustrated with hydrographs of well nests and with hydrologic cross-sections (Figs. 17, 26, and 27).

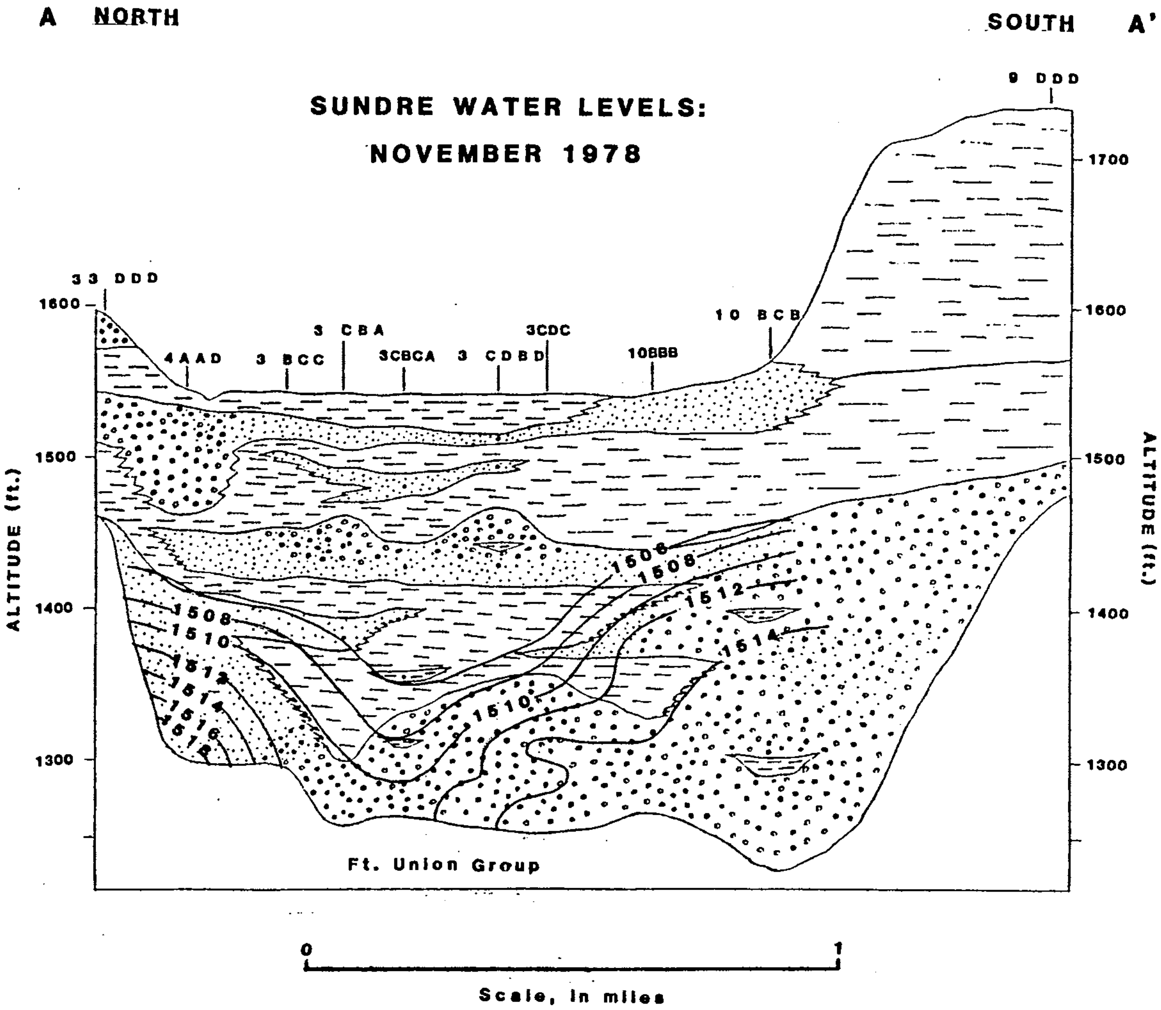

Figure 26. Hydrologic Cross-Section A-A' Nov. 1978

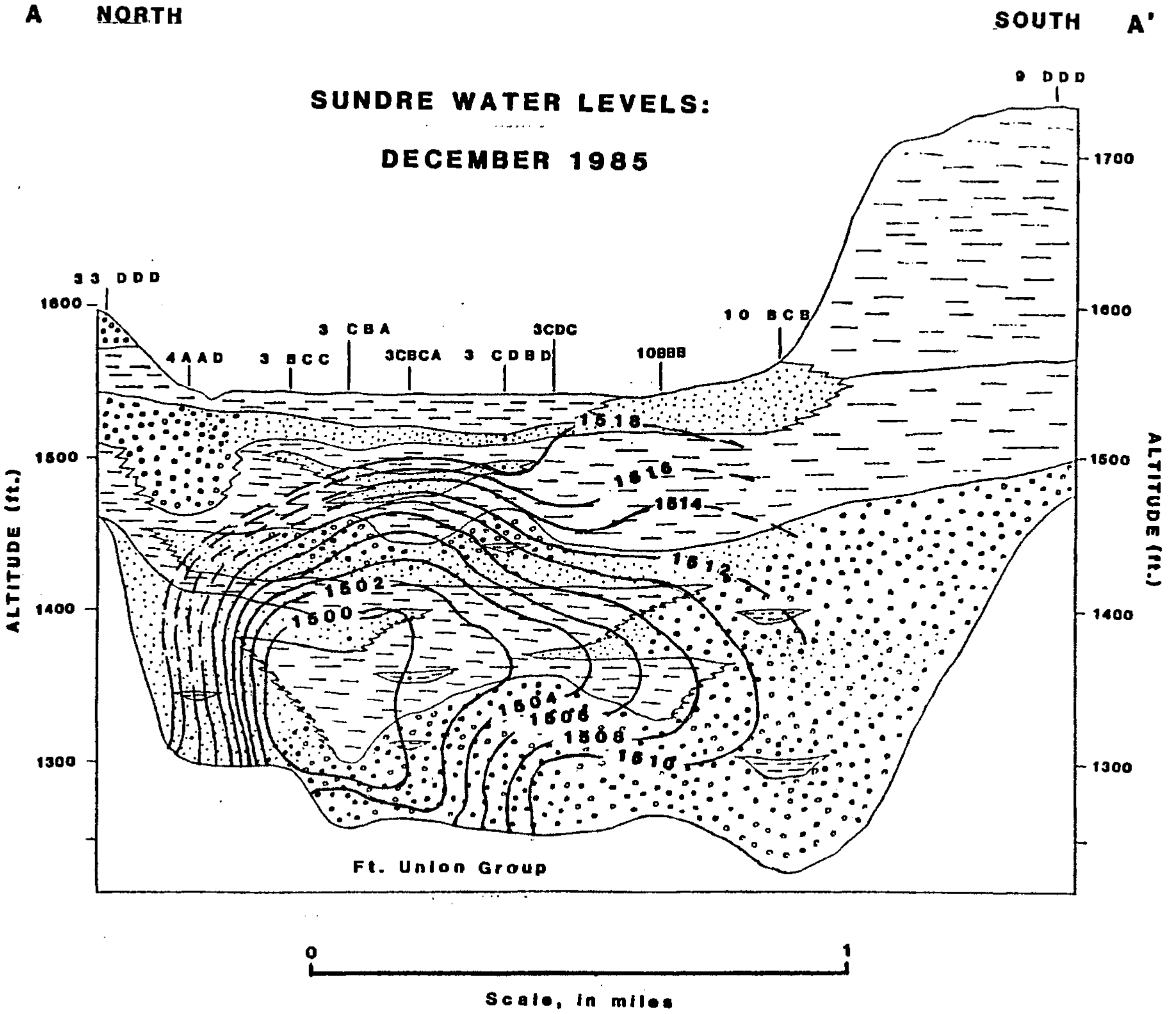

Figure 27. Hydrologic Cross-Section A-A' Dec. 1985

CHAPTER V.

SIMULATION OF GROUND-WATER FLOW

Model Development

Purpose

A ground-water flow model was developed for this study in order to mathematically synthesize the hydraulic characteristics of the Sundre aquifer and water-budget components for the overall ground-water system. Construction of a ground-water flow model is also a method of evaluating how well all hydrogeologic information is synthesized as a reasonable conceptualization of the actual ground-water system. In this study the model is used as a tool to evaluate rates of leakage through the overlying confining bed and to estimate the amount of pumped water derived from leakage as opposed to the amount obtained from storage within the Sundre aquifer. Also for management considerations, the model will be used to estimate the maximum pumpage the aquifer can sustain at equilibrium and the total amount of water that has been removed from storage since pumping began.

Description

A ground-water flow model is a group of mathematical equations that approximate ground-water flow through an aquifer with respect to the hydraulic characteristics of the aquifer and rates of inflow and outflow, whether they be from natural underflow or pumping stress. The flow model used in this study is called a "Modular Three-Dimensional Finite-Difference Ground-Water Flow Model" developed by McDonald and Harbaugh (1984) for the U.S. Geological Survey. A detailed discussion of the mathematics and theory behind the model development is outlined in their book. The model solves finite-difference approximations of the partial differential equations that govern two-dimensional ground-water flow. The aquifer is represented as a two-dimensional grid of square blocks. Each block in this simulation is 1320 feet by 1320 feet and 16 blocks comprise one square mile. Average hydrologic characteristics (transmissivity, storativity, and initial heads) for the entire square are assigned to a point or node in the center of block.

Assumptions

Any model is, at best, an approximation of the real hydrogeologic system because not all of the variations and complexities of the actual system can be included. Simplifying assumptions are required to manage the problem of simulating the actual conditions. The model analysis used in this study is based on the following assumptions:

1. All flow in the aquifer in confined, two-dimensional, and has no vertical component of flow except in areas under the Lower Souris aquifer where leakage takes place.
2. Flow across boundaries is perpendicular to the boundary.
3. The aquifer is homogeneous within each given block of the finite-difference grid.
4. There is no flow across the Sundre aquifer/bedrock interface.
5. Estimates of steady-state inflow and outflow are reasonable.
6. The averaged pumping rates used during the stress periods of calibration adequately represent the stress on the aquifer system.
7. Water-level contours shown in Plate 1 represent steady-state conditions prior to 1975 when the Sundre well field was developed.

Boundaries and Data Input

Boundaries

All model boundaries were established with respect to natural aquifer limits as defined by geologic interpretations of test hole and well log records (Fig. 28). The no-flow boundaries coincide with Sundre sand and gravel

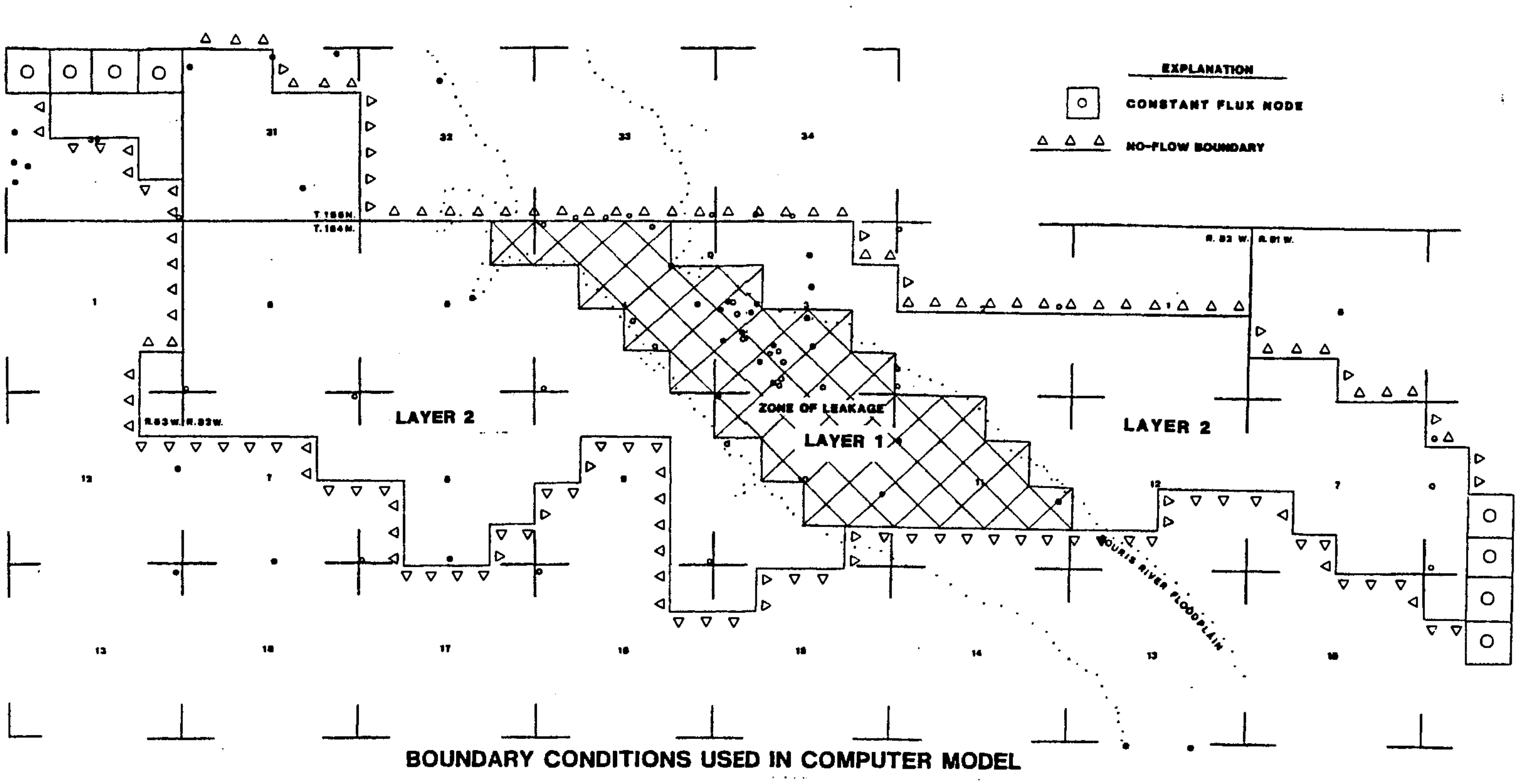

Figure 28. Model Boundary Conditions

pinchouts against the Fort Union bedrock. Constant-flux boundaries coincide with areas of underflow in the east, and areas of outflow in the northwest. The zone of leakage corresponds to the extent of the Lower Souris aquifer, which is confined to the floodplain of the Souris River (Fig. 28).

Data Input

Data input in the model include the hydrologic characteristics of the aquifer, such as transmissivity, storativity, and initial heads. Estimates of inflow and outflow were calculated using the Darcy equation and the regional pre-development (steady-state) potentiometric surface.

Calibration and development of the ground-water model used the estimated aquifer charcteristics and water-budget components. By trial-and -error process, the estimated parameters were adjusted until a reasonable simulation at each node was obtained. The calibration was done for steady-state conditions and transient conditions.

Calibration

Steady-State Analysis

The steady-state calibration procedure determined a reasonable distribution of transmissivity and boundary flux within the limits of the conceptualized hydrogeologic system. The slight mound in the pontentiametric surface in Section 3, T154N-R83W of the Sundre aquifer was not created during calibration because the aquifer parameters within each block are considered to be homogeneous and flow is assumed to be horizontal. Transmissivities and underflow values were adjusted accordingly within the ranges given in Chapter IV. A comparison of the measured pre-development water levels and the simulated levels can be seen in Plate 5. The difference between the measured steady-state water levels and the simulated water levels at each node in the modeled area ranged from 0 to 3 ft. and averaged about 2 ft.

Transient Analysis

Transient calibration was accomplished by adding storativity, pumpage, and time to the steady-state model. Ten stress periods were used in the transient-calibration phase. Pumpage for each year from 1976 through 1985 was converted to a rate of withdrawal for each period. In order to simulate leakage from the Lower Souris aquifer and shallower gravel units, another layer was added to the model. Constant heads were maintained in this upper layer throughout the simulation in order to provide the necessary leakage. The ground-water budget output at the end of each stress period provides a record of the amount of leakage taking place and the amount of water removed from or added to storage.

To calibrate the transient model, changes in water levels in observation wells located at various distances around the well field were recorded on an annual basis from

1978 to 1985. The water-level declines simulated by the computer model were matched to the observed water-level declines in the observation wells. This was done by adjusting vertical conductivity values and storativity values in the model. The observed and simulated water-level declines in three observation wells are shown in Figures 29 - 31.

The simulated water levels fluctuate much more than the observed water levels. This may be because the real ground-water system contributes more water from storage than does the simulated system. The divergences between the simulated and observed heads in 1978, 1979, and mid-1982 indicate that the simulated system is much more sensitive to pumpage variations than the real system. In 1985, the observed and simulated water levels for wells 2CCB and 7AAA diverge more than the water levels in well 3CDB (Figs. 29-31). This probably occurs because 2CCB and 7AAA are closer to the model boundaries where the regional flux may change through time. Changes in underflow into or out of the study area may occur through time due to changes in hydraulic gradient. Furthermore, changes in leakage rates could have occurred through time due to possible water-level changes in the Lower Souris aquifer.

Limitations of the Model

The model reasonably simulates observed water levels in the steady-state system of the Sundre aquifer and with less

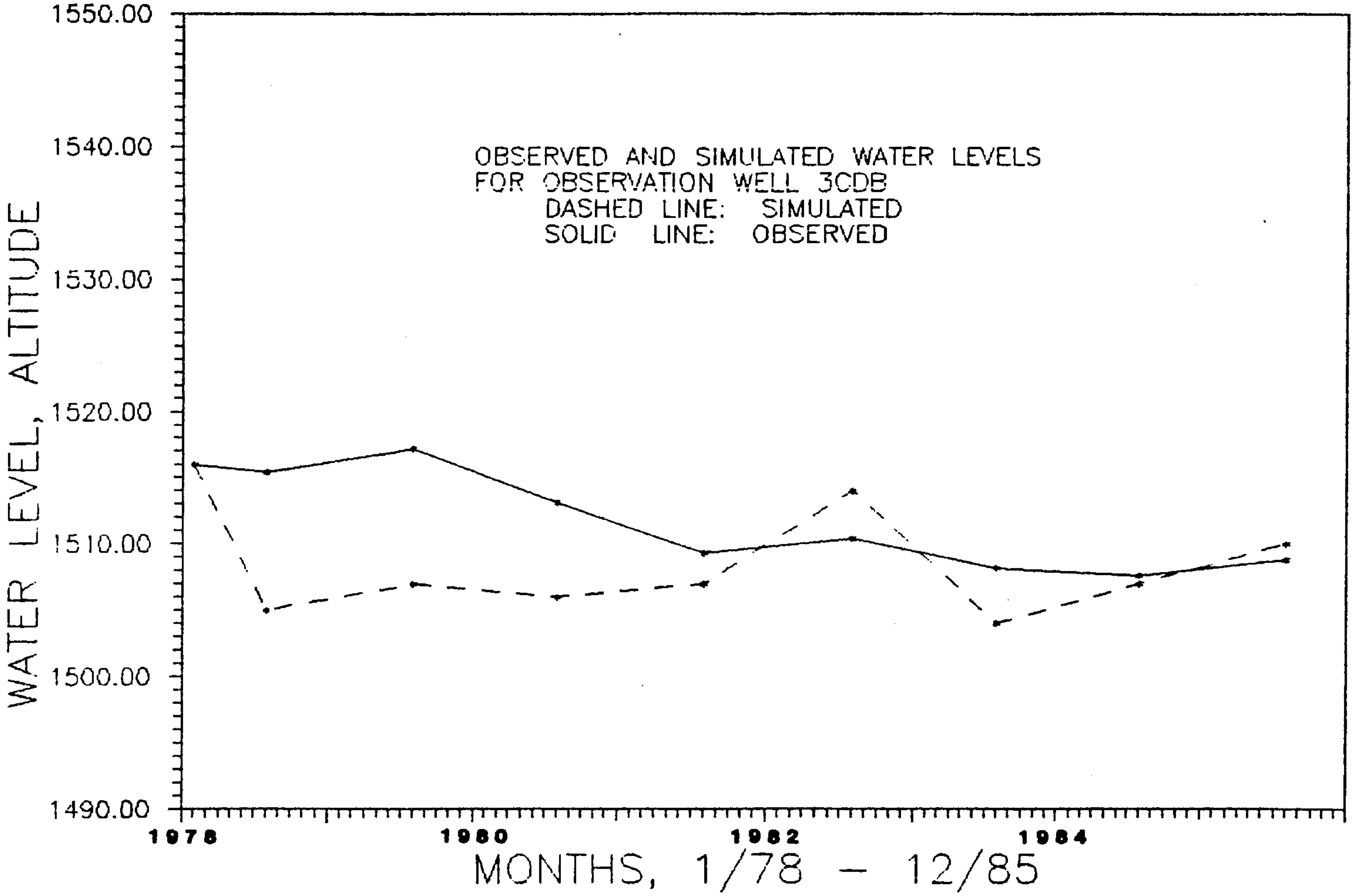

Figure 29. Transient Calibration for Well 3CDB

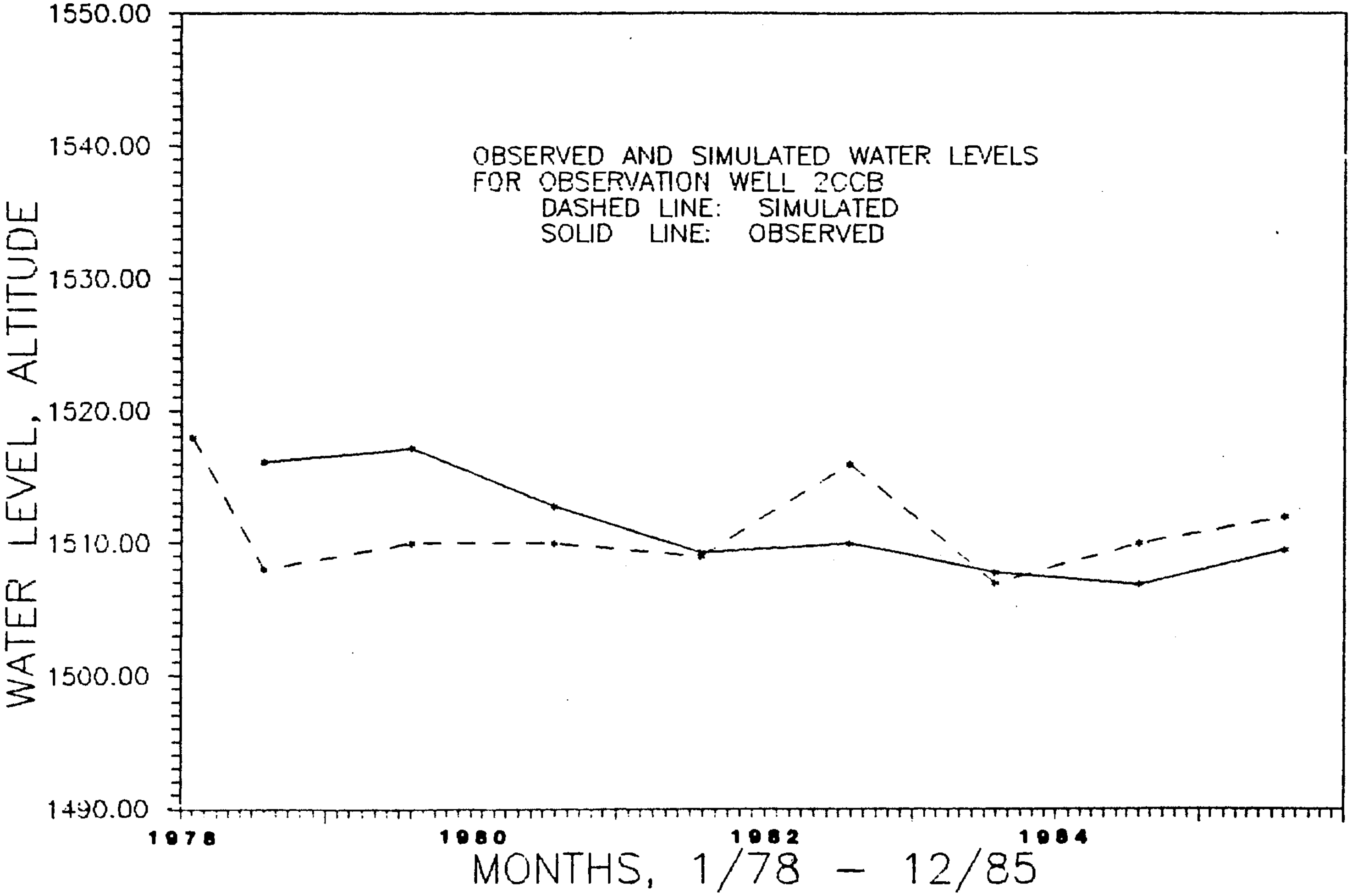

Figure 30. Transient Calibration for Well 2CCB

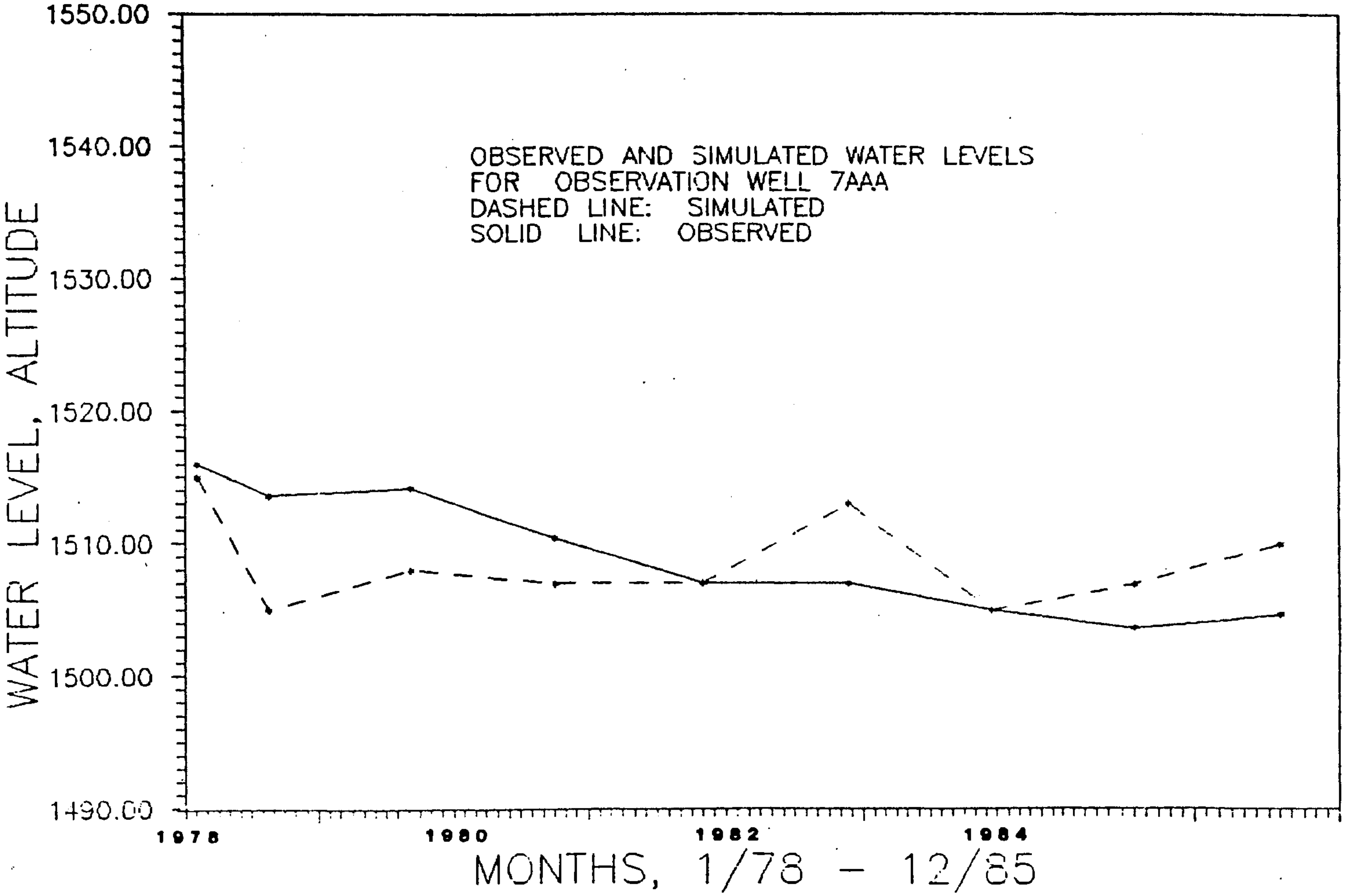

Figure 31. **Transient Calibration for Well 7AAA**

accuracy simulates water-level declines through time in response to pumpage. Projections of future water-level declines using this model, therefore, are not recommended. In order to increase the accuracy of the transient calibration, and subsequently to make the model more useful as a management tool, more long-term water-level data in the Lower Souris aquifer is needed. Such information could provide insight into possible changes in rates of leakage through time due to water-level changes in the Lower Souris aquifer.

Also recommended is the installation of additional monitoring wells in the northwest part of the study area and northwest of the study area. Collection of data from these wells would facilitate the understanding of the relationship between the cones of depression caused by Minot well field pumpage in T155N-R83W and by well field pumpage in the study area.

Results of Model Analysis

Leakage

As a result of variable rates of pumping stress imposed on the Sundre aquifer, leakage, in turn, has varied through time proportional to the rate of pumping. In each stress period leakage ranged from approximately 98 to 99% of pumpage. The cummulative budget for the ten stress periods indicates that of the approximately 1.2 billion cubic feet of water pumped from the Sundre, about 1.1 billion cubic feet (99.8%) was derived from leakage. The total amount of water removed from storage during the ten stress periods was 1.86 million cubic feet.

This very high contrast between the amount of pumped water derived from leakage and the amount from storage could be due to Lower Souris water level declines through time which were not accounted for in the model. A gradual decrease in Lower Souris water levels with time would also decrease or hold constant the rate of leakage, which would in turn increase the amount of water removed from storage by the model. With only the Sundre water levels decreasing, the rate of leakage increased through time as the head difference between the two aquifers increased.

Sustained Yield

In order to determine the sustained yield of the Sundre Aquifer, pumpage in the five municipal wells was increased as long as the water levels remained above the base of the clay aquitard capping the Sundre aquifer. For a conservative estimate of the sustained yield, steady-state conditions were employed so that there would be no loss of water from storage. The layer representing the Lower Souris aquifer provided leakage during the simulation. In establishing the relative pumpage rates for each of the five wells, proportions similar to historic trends were used. For example, Well D commonly discharges up to three times as much as the other wells combined.

The Sundre aquifer was capable of sustaining a maximum of 780,000 cubic feet per day (5.83 mgd) without adverse declines in water levels. This is approximately two times greater than the maximum pumpage of any stress period in the transient model. In portions of the aquifer that do not receive leakage from above, the sustained yield would probably be significantly less.

Conclusions

Since the Sundre Aquifer was developed in 1976, it has supplied the City of Minot with about 55% of its water. Water levels in the Sundre Aquifer have declined through time due to the very large pumping stress. Leakage from the shallower Lower Souris Aquifer has played a major role in the ground-water system. A computer model analysis of this aquifer system has shown that 1.1 billion cubic feet of water has leaked into the Sundre Aquifer from above. This is about 98% of the total water removed from the Sundre Aquifer. Also with the computer model, the sustained yield of the Sundre Aquifer is estimated at 780,000 cubic feet per day for areas underlying the Lower Souris Aquifer.

REFERENCES CITED

Akin, P. D., 1947, Geology and ground-water conditions at Minot North Dakota: North Dakota Geology Survey Ground Water Studies, no. 6, 99 pp.

Bluemle, J. P., 1972, Pleistocene drainage development in North Dakota: Geological Society of America Bulletin, v. 83, pp. 2189-2194.

Glover, D. H., and others, 1972, Water resources, Appendix B of Souris-Red-Rainy Basins Comprehensive Study: Souris-Red-Rainy Basins Commission, v. 4, 110 pp.

Kehew, A. E., 1983, Geology and geotechnical conditions of the Minot area, North Dakota: Report of Investigation No. 73, North Dakota Geological Survey, 35 pp.

Kehew, A. E., 1986, Depositional environments of buried-valley aquifers of North Dakota: Ground Water, v. 24, n. 6, pp. 728-734.

Lindvig, M. O., and Schmid, R. W., 1982, Progress map showing major glacial drift aquifers in North Dakota and estimatedpotential yields: North Dakota State Water Commission, 1 sheet, scale 1:1568800.

LaRocque, G. A., Swenson, H. A., and Greenman, D. W., 1963, Tables of hydrologic data, Crosby-Mohall area, North Dakota: U.S. Geological Survey open-file report, 508 pp.

McDonald, M., and Harbaugh, A. W., 1984, A modular three dimensional finite-difference ground-water flow model: U. S. Geological Survey, 500 pp.

Pettyjohn, W.A., 1967, Geohydrology of the Souris River valley in the vicinity of Minot, North Dakota: U.S. Geological Survey Water-Supply Paper 1844, 53 pp.

Pettyjohn, W.A., 1968, Geology and ground-water resources of Renville and Ward counties, Part 2 - ground-water basic data: North Dakota Geological Survey Bulletin 50 (North Dakota State Water Commission Conty Ground-Water Studies 11), 302 pp.

Pettyjohn, W.A., 1970, Preliminary report on the ground-water conditions in the vicinity of Minot, North Dakota: City of Minot, North Dakota, 36 pp.

Pettyjohn, W. A., and Hills, D. W., 1965, Geohydrology of the Souris River valley in the vicinity of Minot, North Dakota;Ground water basic data: North Dakota State Water Commission, Ground Water Studies, no. 65, 89 pp.

Pettyjohn, W. A., and Hutchinson, R. D., 1971, Ground-water resources of Renville and Ward Counties: North Dakota Geological Survey Bulletin 50, Part 3, 100 pp.

Reeder, H. O., 1978, Summary appraisals of the nation's ground-water resources - Souris-Red-Rainy region: U.S. Geological Survey Professional Paper 813-K, 25 pp.

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Education: Graduated from Enid High School, Enid, Oklahoma, in May, 1979; recieved Bachelor of Science Degree in Geology from Beloit College in August, 1983; completed requirements for the Master of Science degree at Oklahoma State University in May, 1987.

Professional Experience: Geologist, Big Four Petroleum Company, January, 1984, to October, 1986.

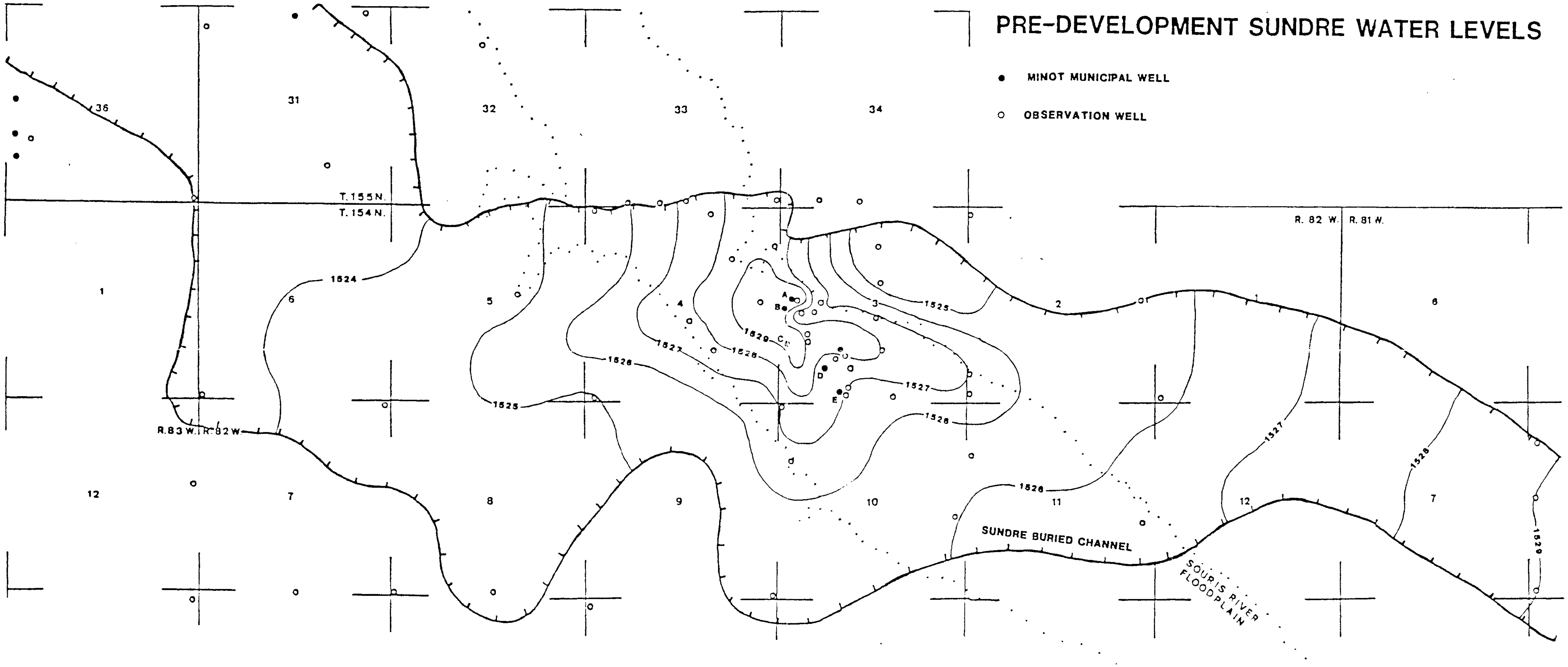
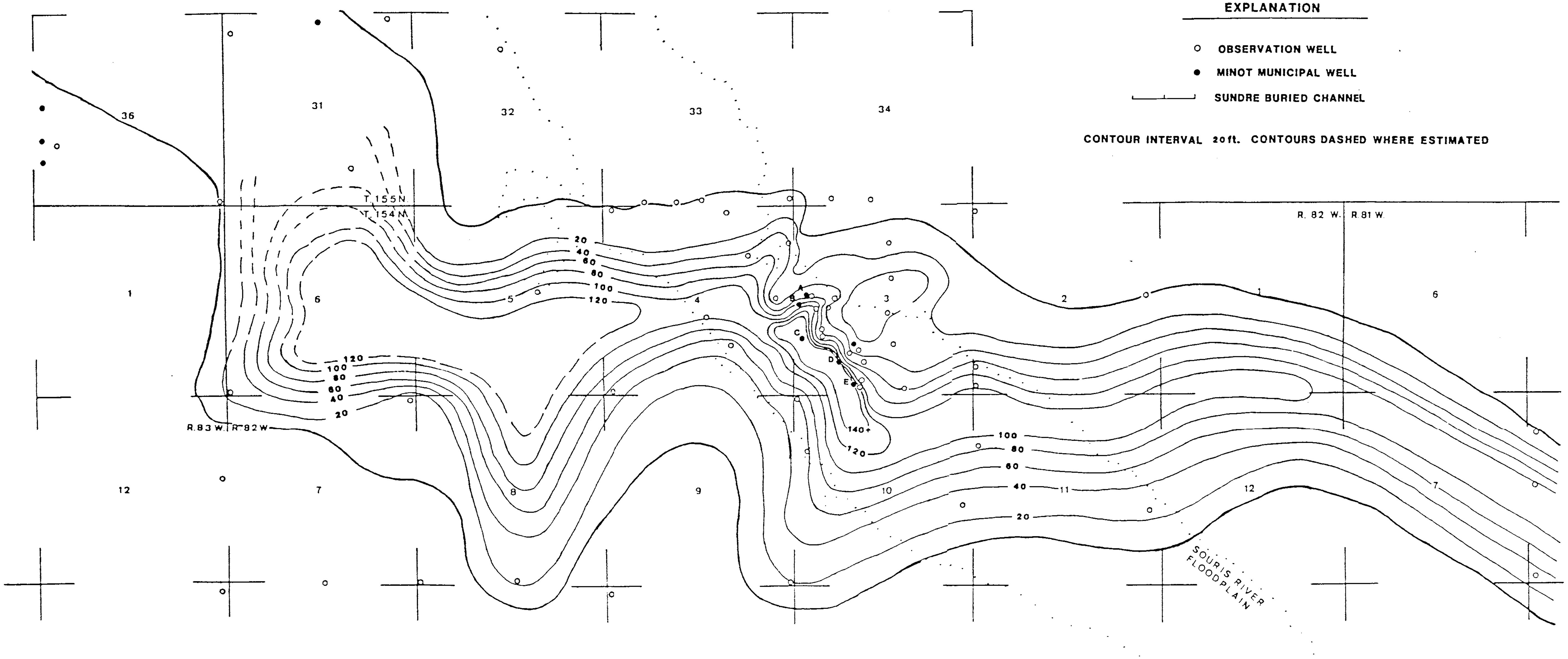
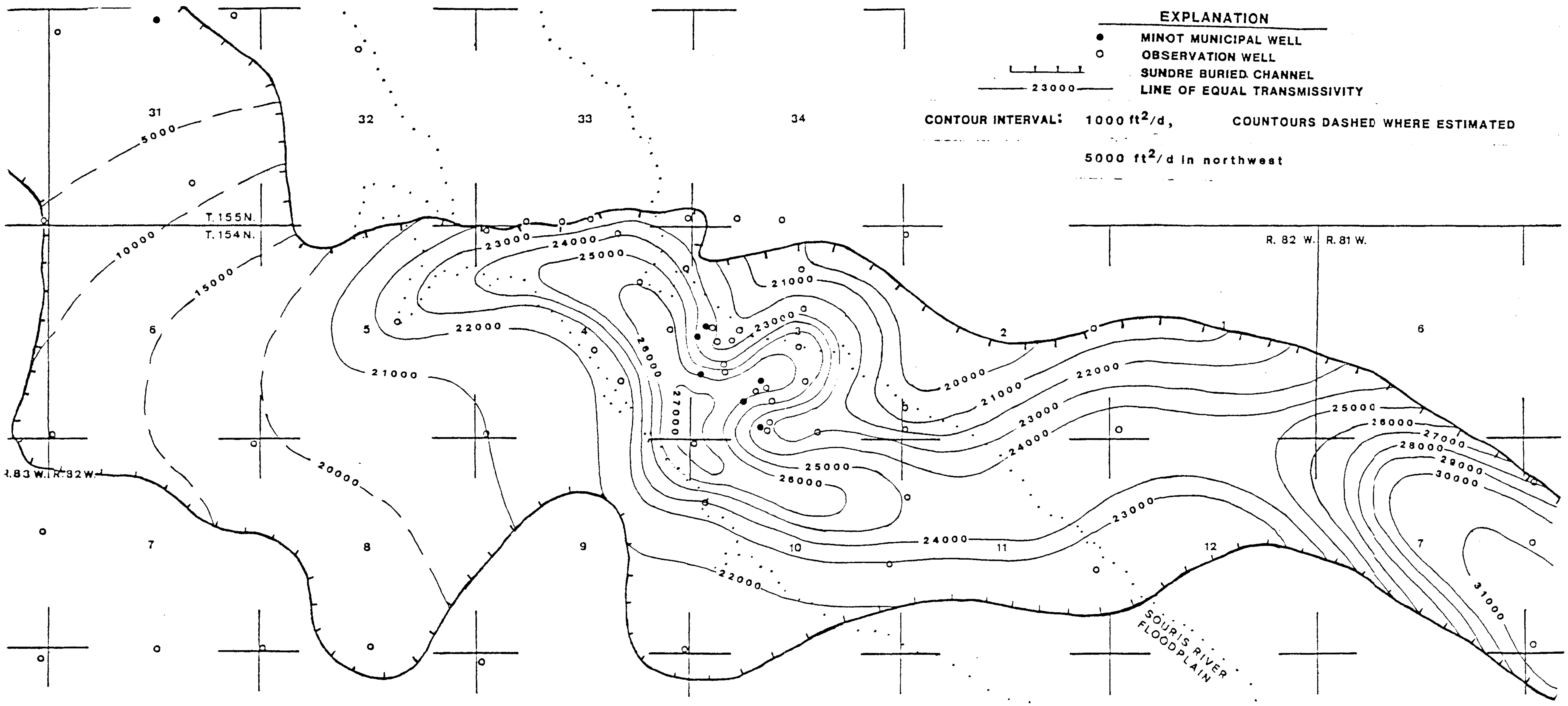

PRE-DEVELOPMENT SUNDRE WATER LEVELS
● MINOT MUNICIPAL WELL
○ OBSERVATION WELL
36
31
32
33
34
T.155N.
T.154N.
R.82 W. R.81 W.
1
6
5
4
3
2
6
A
B
C
D
E
1524
1525
1526
1527
1528
1529
R.83 W. R.82 W.
12
7
8
9
10
11
12
7
SUNDRE BURIED CHANNEL
SOURIS RIVER FLOODPLAIN

PLATE 1



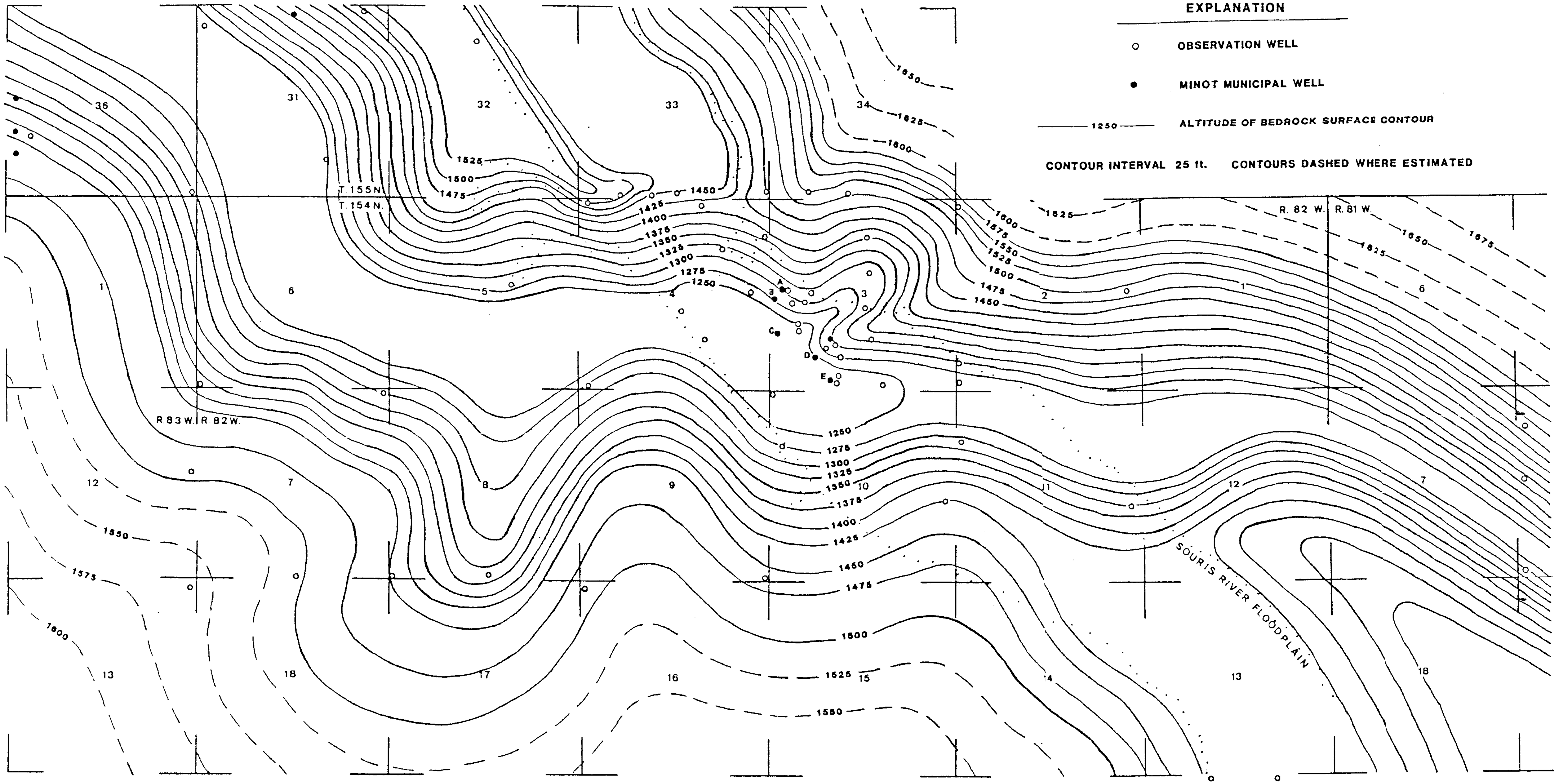
THICKNESS MAP OF GRAVEL AND COARSE SAND WITHIN THE SUNDRE BURIED-CHANNEL AQUIFER

PLATE 2



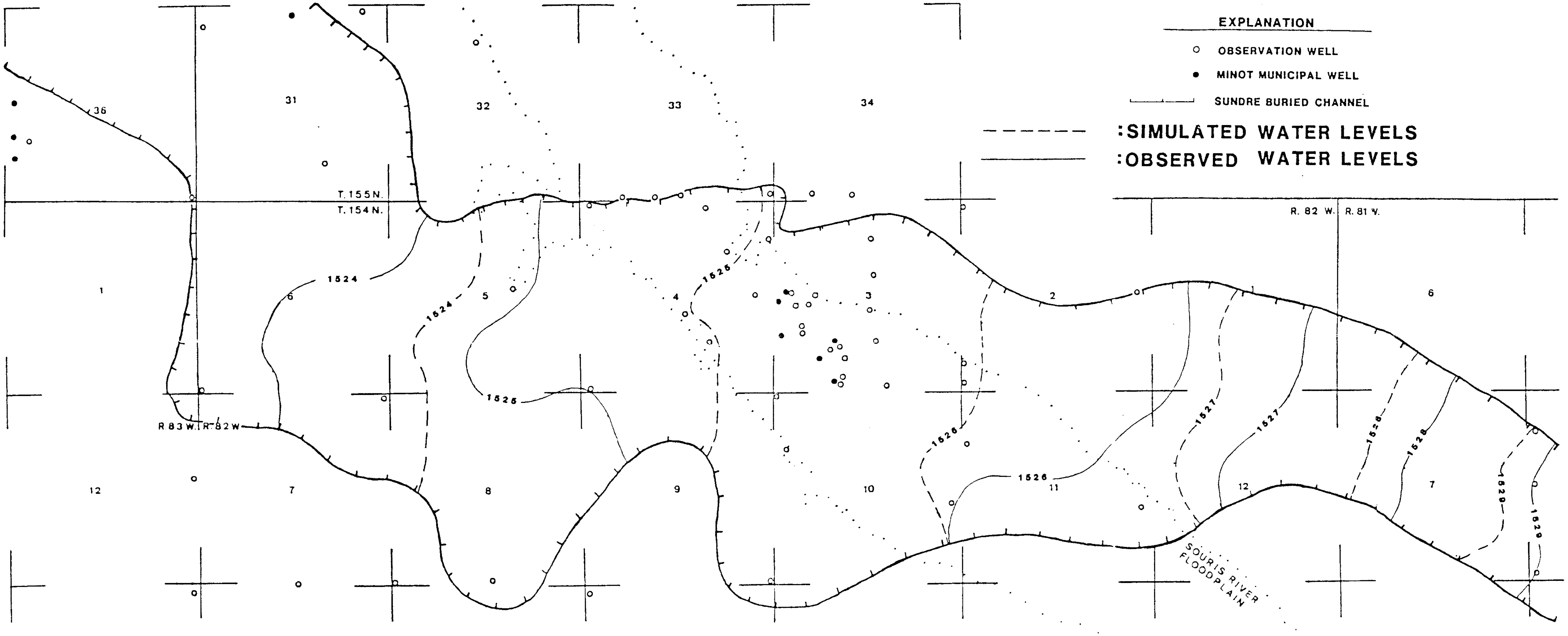
TRANSMISSIVITY OF THE SUNDRE AQUIFER

PLATE 3



BEDROCK CONFIGURATION OF THE STUDY AREA

PLATE 4



OBSERVED AND SIMULATED WATER LEVELS : STEADY-STATE

PLATE 5