Hydrogeology and Computer Simulation of the

Sundre Aquifer System

Ward and McHenry Counties, North Dakota

By
Steve W. Pusc

North Dakota Ground-Water Studies
Number 92 - Part II
North Dakota State Water Commission
Vernon Fahy, State Engineer

Prepared by the
North Dakota State Water Commission
In Cooperation with the
City of Minot, North Dakota

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INTRODUCTION

General statement

The city of Minot, North Dakota has historically had problems with an adequate water supply. Heavy long-term pumping of the Minot aquifer well field, from 1916 to 1963, resulted in over 70 feet of water level decline. This serious reduction of ground water in storage prompted a ground-water investigation to identify a solution to Minot's water supply problem (Pettyjohn, 1967). Test drilling done for Pettyjohn, 1967, led to the discovery of the high-yielding Sundre aquifer system. A subsequent investigation, conducted by the North Dakota State Water Commission (NDSWC) and United States Geological Survey (USGS) concluded that the Sundre aquifer had the potential to yield 6 million gallons per day (Pettyjohn, 1970). In 1974 and 1975, the city of Minot constructed five large capacity production wells which tap the Sundre aquifer system (Plate 1).

Aware of their past problems, the city of Minot contacted the NDSWC about a study to assess the reliability and long-term potential of the Sundre aquifer system. On June 20, 1983, the city of Minot entered into an agreement with the NDSWC whereby the NDSWC would conduct the first phase of a quantitative analysis of the Sundre aquifer system.

Purpose and objectives

The purpose of this report was to gain a better understanding of the hydrogeology and ground-water potential of the Sundre aquifer system. The general objective was to further define the geometry of the aquifer and the occurrence and movement of water through the aquifer system. Specific objectives were to:

1) develop a conceptual model of ground-water flow in the area.

2) evaluate the effects 10 years of pumping have had on ground-water flow systems in the area.

3) evaluate the hydraulic connection between the Souris River, Souris Valley aquifer and Sundre aquifer.

4) describe and interpret the quality of ground water both spatially and temporally.

5) develop a calibrated digital computer model to simulate ground- water flow in the area.

6) evaluate the sensitivity of the computer model.

7) evaluate the feasibility of utilizing the model as a predictive tool.

Description of study area

Location

The study area is located in the northwestern part of the Drift Prairie District of the Central Lowlands physiographic province of North Dakota (fig. 1). Specifically the area includes Township 155 North, Ranges 82 and 83 West; Township 154 North, Ranges 81, 82, and 83 West all in Ward County; and Township 154 North, Ranges 79 and 80 West in McHenry County (pl. 1).

Topography

The Sundre aquifer system study area is characterized by a broad, relatively flat Souris River floodplain with adjoining steep valley walls. Narrow, deep coulees, occupied by intermittent streams, cut into the steep valley walls (pl. 1).

Elevations range from 1520 to 1560 along the Souris River floodplain to 1900 feet in the southwest corner of the study area (pl. 1).

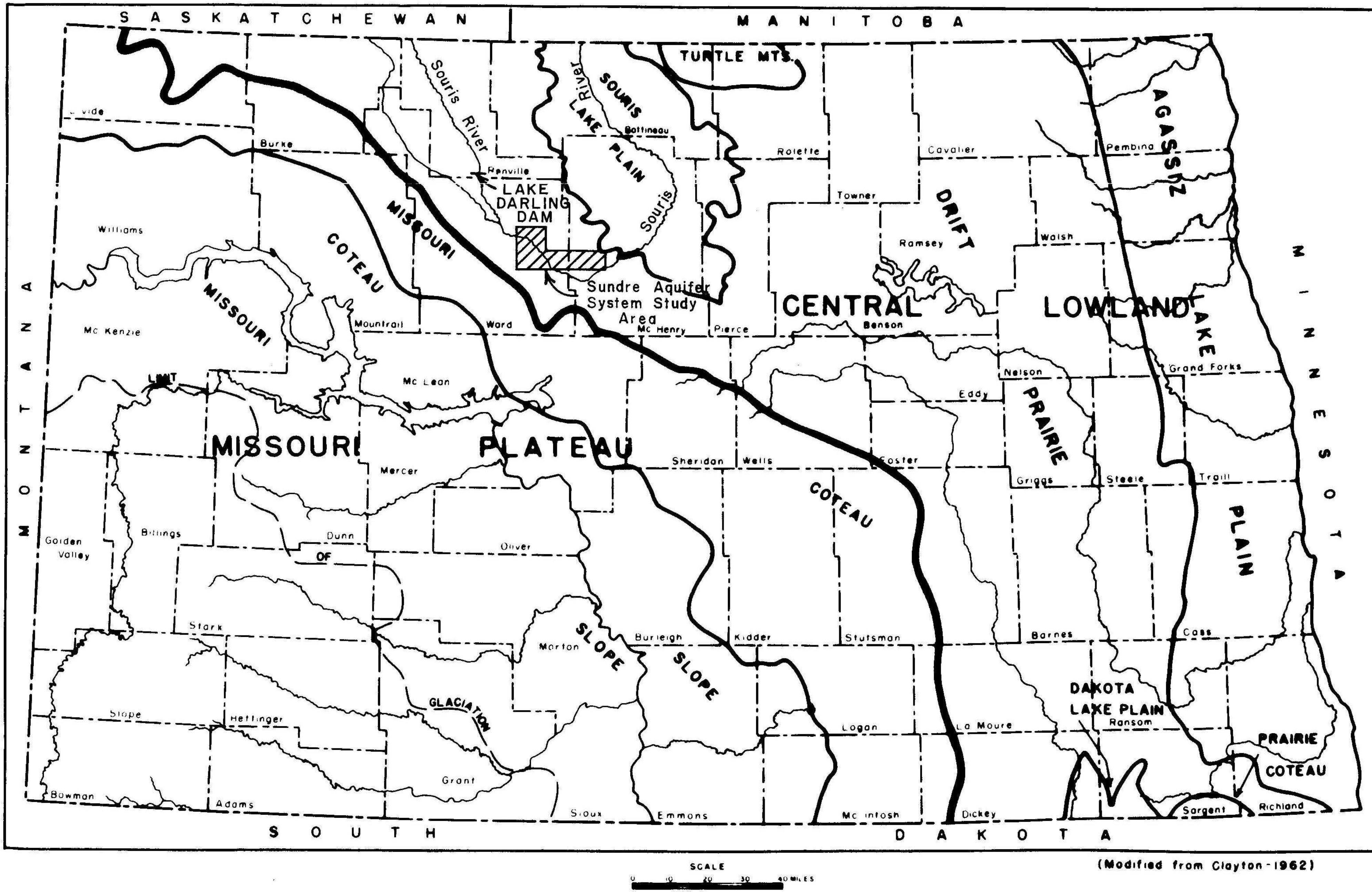


FIGURE 1. MAP SHOWING PHYSIOGRAPHIC PROVINCES OF NORTH DAKOTA AND LOCATION OF THE SUNDRE AQUIFER SYSTEM STUDY AREA

Previous investigations

The geology and ground-water resources of Ward County were first described by Simpson (1929). Simpson's report provides a discussion of early water supplies at Minot and also includes a brief inventory of private and municipal wells. Limited ground-water quality data from the Minot area were also presented. Andrews 1939, investigated the coal resources of the Minot area. Lemke, 1960, described in some detail the geology of the Souris River area.

Several reports pertaining specifically to the Minot area have been published. The first report to study in detail the geology and ground-water conditions in the Minot area was Akin, 1947. Akin's report presents an excellent historical account of Minot's surface water and ground-water supplies from 1900 to 1947. Bradley, 1963, briefly summarized the hydrogeology of the Souris River valley near Minot with special attention to the relationship of surface water to ground water. Pettyjohn, 1967, greatly refined the understanding of ground-water conditions in the Souris River valley near Minot and briefly discussed the newly discovered Sundre aquifer system.

In 1968 and 1969, the NDSWC conducted an investigation to define the ground-water potential of the Sundre aquifer. Using this data, Pettyjohn 1970 discussed the geometry, thickness, lithology, hydraulic properties, and water quality of the Sundre aquifer system.

A ground-water survey of Renville and Ward Counties was conducted on a cooperative basis by the NDSWC and the USGS. The report consists of three parts. Part I Geology, has not been completed. Part II, Basic Data, includes an inventory of test holes, well logs, water level measurements and chemical analyses (Pettyjohn, 1968A). Part III, Ground-Water Resources, includes a general evaluation of water yielding potential and chemical quality of major bedrock, glacial drift and alluvial aquifers in Renville and Ward Counties (Pettyjohn and Hutchinson, 1971). A general discussion of the location, areal extent, thickness, lithology, and water quality of the Sundre aquifer was included.

A ground-water survey of McHenry County was conducted on a cooperative basis with the NDSWC, North Dakota Geological Survey (NDGS) and USGS. The report consists of three parts. Part I Geology is a comprehensive investigation of the surficial geology and a general discussion of the subsurface geology (Bluemle, 1982). Part II, Basic Data, includes an inventory of test holes, well logs, water level measurements and chemical analyses (Randich, 1981A). Part III, Ground-Water Resources, presents a general evaluation of water yielding potential and chemical quality of major bedrock, glacial drift, and alluvial aquifers in McHenry County (Randich, 1981B). A general discussion of the location, areal extent, thickness, lithology and water quality of the New Rockford aquifer system (synonymous with part of the Sundre aquifer system) was included.

In 1983, Kehew completed a report entitled "Geology and Geotechnical Conditions of the Minot Area, North Dakota". Main emphasis of the report was to discuss geologic and hydrogeologic conditions affecting construction and waste disposal in the Minot area.

Methods of study

Hydrogeologic investigation of the Sundre aquifer system was accomplished by test drilling at 30 sites, installing 48 observation wells and measuring and recording depth to water in 86 observation wells. Additional data collected included: (1) measuring the level and discharge of the Souris River through the study area, (2) collecting and analyzing surface water and ground-water samples, and (3) recording water use from each of the five production wells completed in the Sundre aquifer system.

Test holes were drilled with a Failing 1250 forward mud rotary drilling rig owned by the NDSWC. Observation wells were constructed of either 1¼-inch or 2-inch polyvinyl chloride (pvc) or 2-inch steel casing with 3 or 6 foot pvc or steel screens.

Prior to this study, observation wells were installed by setting the desired length of casing and screen into the test hole, backwashing with fresh water and then collapsing the formation with air. The annulus was then filled with drill cuttings. New wells were subsequently slugged with a small quantity of fresh water and pumped (airlift) a minimum of 10 hours before collection of water samples and measurement of water levels.

Two (2) inch steel piezometers were constructed for this study by setting the desired length of casing and screen into the test hole, backwashing gently with fresh water and then sand (silica sand) packing around the screen. Bentonite pellets were immediately poured on top of the sand pack and the remainder of the hole was filled with drill cuttings.

Nests of piezometers were also constructed for this study. Construction of the piezometer nests involved the drilling of an initial deep test hole to determine the number of piezometers to be installed at a particular site. The initial deep test hole also served as the hole for the deep piezometer. First, the desired length of casing and screen were inserted into the test hole. Silica sand was then placed around the screen using a tremie pipe. After sand packing, the tremie pipe was lifted so that the bottom of the tremie pipe was above the top of the sand pack. Neat cement grout was then injected down the tremie pipe and upward in the annular space. This process continued until the grout overflowed around the casing at land surface. After the grout settled, additional grout was poured down the hole until the annular space was filled to land surface. The grout was allowed to "set" and then the piezometers were slugged with a small quantity of fresh water and pumped with air for development. Wells installed in the tills were not, however, slugged with fresh water. Subsequent piezometers were completed at each nest site by moving the drilling rig ahead 15 to 20 feet and drilling the next hole. As many as five piezometers were installed at various depths at the same site using this technique.

Samples of drill cuttings were collected and visually analyzed every five feet or whenever the lithology changed. Resistivity and spontaneous potential logs were run in most of the NDSWC test holes. Several of the deeper test holes near First and Second Larson Coulees were investigated using 16-64 normal, gamma ray, neutron and density logs. Copies of the geophysical logs are available for inspection in the office of the NDSWC. Locations of all test holes and observation wells are presented on plate 1. Pertinent data on each test hole is published in Pusc, 1987.

Depth to water measurements were recorded on a bi-monthly or monthly basis in a number of observation wells throughout the study area (Pusc, 1987). Inclement weather and poor road conditions prevented readings during a few of the winter months. Water levels in observation wells were monitored on a weekly basis during periods of heavy water use (late summer). Water levels were measured with steel tapes, electronic well sounders, continuous recorders and pressure gauges on flowing wells.

One continuous float type water level recorder was used to collect information for this study. The recorder was installed in October of 1976 on a large diameter well located at the south end of the Sundre well field at Township 154 North, Range 80 West, Section $3CDC_3$(pl. 1). This well also served as the pumping well during the 1969 Sundre aquifer test (Schmid, 1970).

Prior to this study, the discharge rate of each production well in the Sundre well field was estimated on the basis of the capacity of the pump installed in each well. Historically, reported annual water use from the Sundre aquifer was a total from all five production wells. Flow meters were not installed on each well due to the physical design of each well head.

Well discharge measurements were conducted for this study by pumping water from each well individually into a 30,000 gallon storage tank. The time required to fill a specific volume of the tank was measured and a discharge rate calculated. Tests were also conducted by pumping several wells at once. For more details and data on the production well discharge measurements, the reader is referred to Patch, 1985.

Data were also collected on the number of hours each production well was pumped. Data were recorded using digital readout (hour meters), vibrating and inductive time totalizers. Thus, by knowing the approximate pumping rate and hours pumped, a more accurate record of water pumped from each well over a given time period was obtained. Water use was also calculated using power consumption data for each well (Northern States Power, 1976-1985) and from NDSWC water use records.

Stage height of the Souris River was measured at two locations: (1) the south guardrail of the Saugstad Bridge (155-82-33DDCR), and (2) the south guardrail of the George E. Bell Bridge (154-82-24ABA2R) (pl. 1). Bi-monthly or monthly measurements were made with a weighted steel tape. Measurements were terminated shortly after winter freeze-up.

Sets of discharge and river stage measurements were obtained along the course of the Souris River to establish baseflow conditions (pl. 1). Measurements were obtained at five sites during October and November of 1985 using either a pygmy or double A current meter. A gage height reading was also obtained at each site to establish a stage-discharge relationship for the river. The release of water from Lake Darling and freeze-up of the Souris River eventually terminated the gain-loss monitoring. Unfortunately, both sets of discharge measurements were obtained when the river flow was greater than baseflow.

Water level and river stage data collected for this study were coupled with the existing data to determine: (1) the horizontal and/or vertical direction of ground-water movement, (2) aquifer response to natural recharge and/or discharge events, and (3) aquifer response to man-induced ground-water withdrawals.

Chemical analyses were conducted on water samples collected from selected observation wells and the Souris River. The water sampling procedure involved the collection of 250 millilitre (ml) of raw water, 250 ml of filtered water and 250 ml of filtered and acidified (nitric acid) water. Field measurements of specific conductance and water temperature were also made. Water temperature was, however, measured at land surface and does not represent an in situ temperature. The pH was measured in the lab. Water samples were obtained from domestic and city supply wells by using the existing pumps. State Water Commission observation wells were sampled using two methods: airlift and bailing. Airlift sampling was accomplished with a small diameter rubber hose attached to a portable air compressor. Sampling with a bailer involved the removal of at least two casing volumes of water by airlift and/or bailing techniques to introduce formation water into the well. After evacuating at least two casing volumes of water, a variable capacity point source bailer (pvc) was lowered to just above the bottom of the well screen. Bailing continued until enough water was secured for the sample. Water quality data are presented in Pusc, 1987.

Location numbering system

Wells and test holes presented on Plate 1 are numbered according to a system based on the location in the public land classification of the United States Bureau of Land Management (fig. 2). The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. Letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10 acre tract). For example, well 154-82-04ADD is in the SE¼SE¼NE¼ Section 4, Township 154 North, Range 82 West (Fig. 2). Consecutive terminal numerals are added if more than one well is located in a 10-acre tract.

Acknowledgements

The collection of data for this report was made possible by the cooperation of residents and officials of Ward and McHenry Counties who furnished essential information on wells, allowed the drilling of test holes on their property and permitted water level measurements and the collection of water samples. Mr.

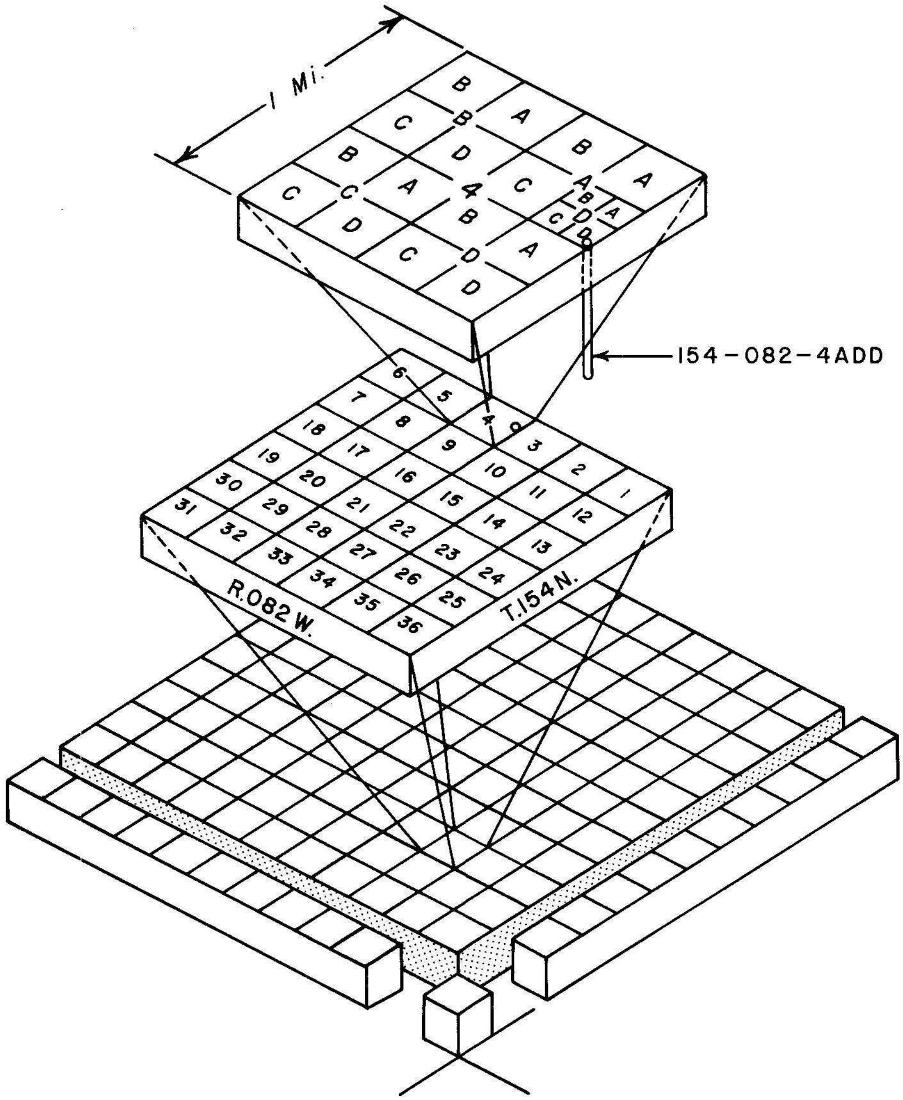


FIGURE 2. Location-numbering system.

Bob Schemp, City Manager of Minot; Lyle Weeks, Director of Public Works; Dan Reiter, Water/Waste Water Superintendent; Byron Thronson, Supervisor of Minot's water treatment plant and Jeff Boucher, Water Program Manager, deserve special mention for their cooperation. Particular recognition is due the following personnel of the North Dakota State Water Commission: C. E. Naplin, L. L. Froelich, A. E. Comeskey, M. O. Lindvig, G. L. Sunderland, Lewis Knutson, and G. J. Calheim for drilling and logging test holes and contributions to the understanding of the stratigraphy; G. O. Muri for chemical analyses of water samples and to M. H. Hove, K. K. Kunz, and M. B. Osborne for compiling the water level and quality files. Special thanks to J. C. Patch and R. L. Cline for writing hydrograph plotting programs for this report. Appreciation is also expressed to D. P. Ripley, R. B. Shaver, and R. L. Cline for their help with the computer simulation aspects of the report; to D. P. Ripley, R. B. Shaver and M. O. Lindvig for their critical review of the report and Toni Dally for typing multiple drafts of the report. Thanks to the private drilling companies that furnished well logs and other information used in this report. And, to my wife Collette for her support and encouragement throughout the duration of this project.

HYDROGEOLOGIC SETTING

Surficial geology

Surficial geologic materials overlying the study area are primarily a result of alluvial and glaciofluvial geologic processes (fig. 3). River sediment and glacial drift mantles most of the study area with the drift being the older and more dominant of the sediments (fig. 3). Historically, surficial units in the study area have been divided into two parts: the Oahe Formation and the Coleharbor Group (Clayton and others, 1980B).

The Oahe Formation includes all unconsolidated sediments deposited from the time of the last glaciation (10,000 years ago) to the present. These younger deposits include: 1) alluvial sediments (clay, silt, sand, and gravel) deposited along the floodplains of the Souris River and its major tributaries, 2) fine grained silt, clay, and sand deposited as alluvial fans at the confluence of the Souris River and its major tributaries, 3) landslide deposits which occur primarily along the Souris River valley wall, and 4) glacial collapse topography comprised of fine grained organic rich materials (fig. 3).

The depositional history of Oahe Formation sediments occurring in the Souris River valley is complex. Abandoned oxbows detected from air photos, topographic maps, and ground surveys indicate that the Souris River has changed courses several times throughout its history. Meandering of the river across its floodplain has resulted in fine grained backwater and overbank deposits in some areas, and coarser grained channel lag and terrace deposits in others. As the river changed course, these deposits were reworked and redeposited across the floodplain.

Unconsolidated sediments deposited during Pleistocene glaciation in North Dakota are assigned to the Coleharbor Group (Clayton, 1980B). These glacial

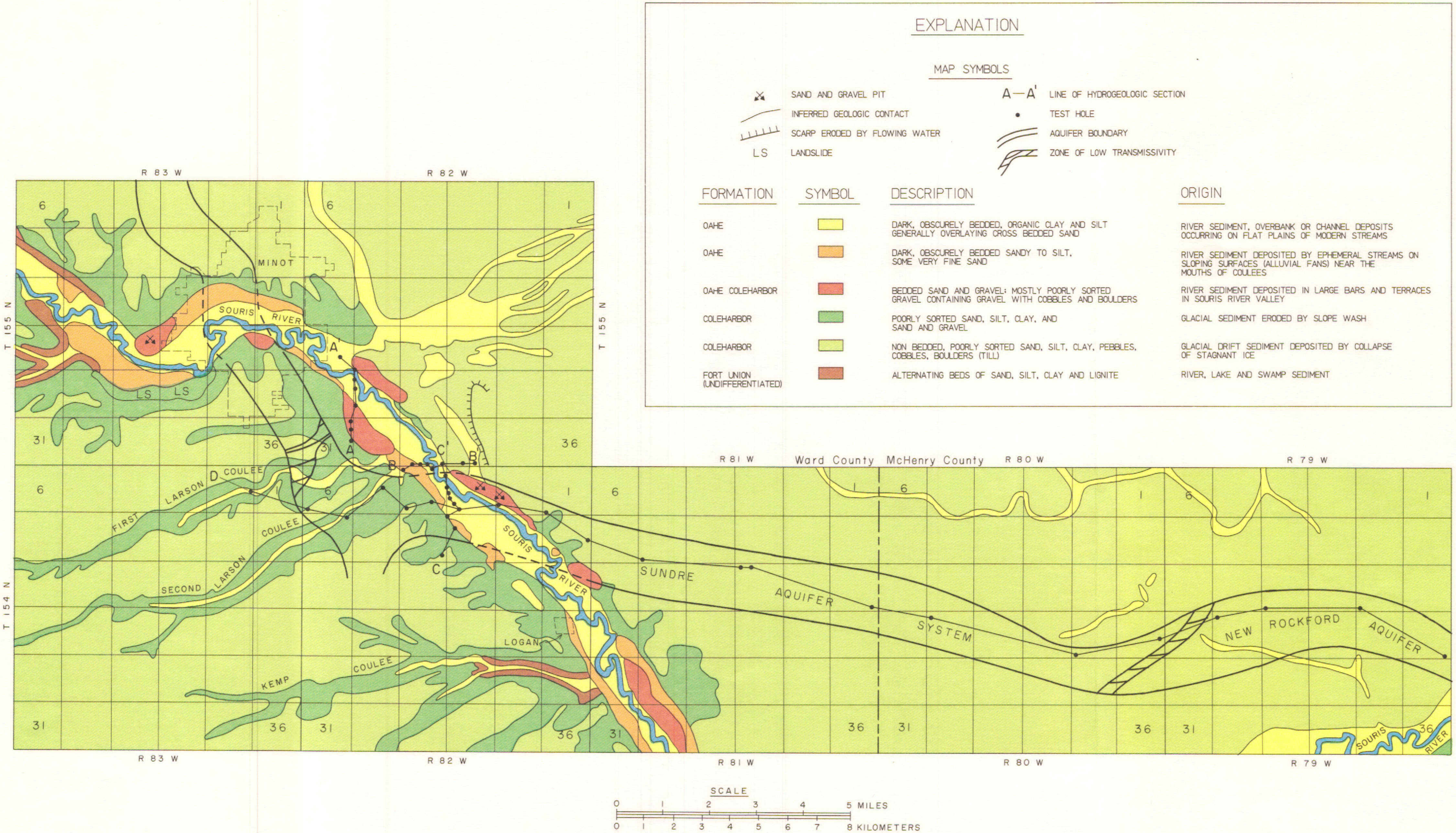


FIGURE 3. Generalized surfical geologic map of the Minot area, Ward and McHenry counties, North Dakota (modified from Kehew, 1983, Bluemle, 1982, Pettyjohn, 1967 and Lemke, 1960.)

sediments are composed primarily of poorly sorted, silty, sandy, pebbly clay (till), glaciofluvial sand and gravel, and lacustrine silt and clay. Abundant fragments of detrital lignite were encountered while drilling the Coleharbor Group sediments (Pusc, 1987). All of the study area, with the exception of the Souris River floodplain and its tributaries, is mantled by glacial till (fig. 3).

Bedrock deposits

The Fort Union Group, of Paleocene Age, unconformably underlies the Coleharbor Group in the study area. Fort Union Group sediments consist of four members, which in descending order of age are: 1) Bullion Creek, 2) Slope (formerly Tongue River, Clayton, 1980B), 3) Cannonball, and 4) Ludlow Members. Bedrock immediately underlying the study area trends primarily from Bullion Creek to Cannonball members. Bullion Creek and Slope members consist of alternating beds of brown silt, sand, clay, sandstone, and lignite. These sediments were deposited in low energy, river, lake, and swamp environments (Clayton, 1980B). The Cannonball member consists of alternating beds of olive-brown sand, shale, and sandstone which were deposited as marine shoreline and offshore sediments (Clayton, 1980B). Fort Union Group sediments outcrop along the walls of the Souris River just west of Minot and along Kemp Coulee south of Logan (fig. 3).

In reality, sediments of the Fort Union Group are very difficult to differentiate accurately by visual inspection of mud rotary drill hole cuttings. Thus, for this report, bedrock sediments immediately underlying the study area were classified as Fort Union, undifferentiated.

Presented in figure 4 is a structure contour map of the top of the Fort Union Formation. The most striking feature is a deep bedrock valley which trends

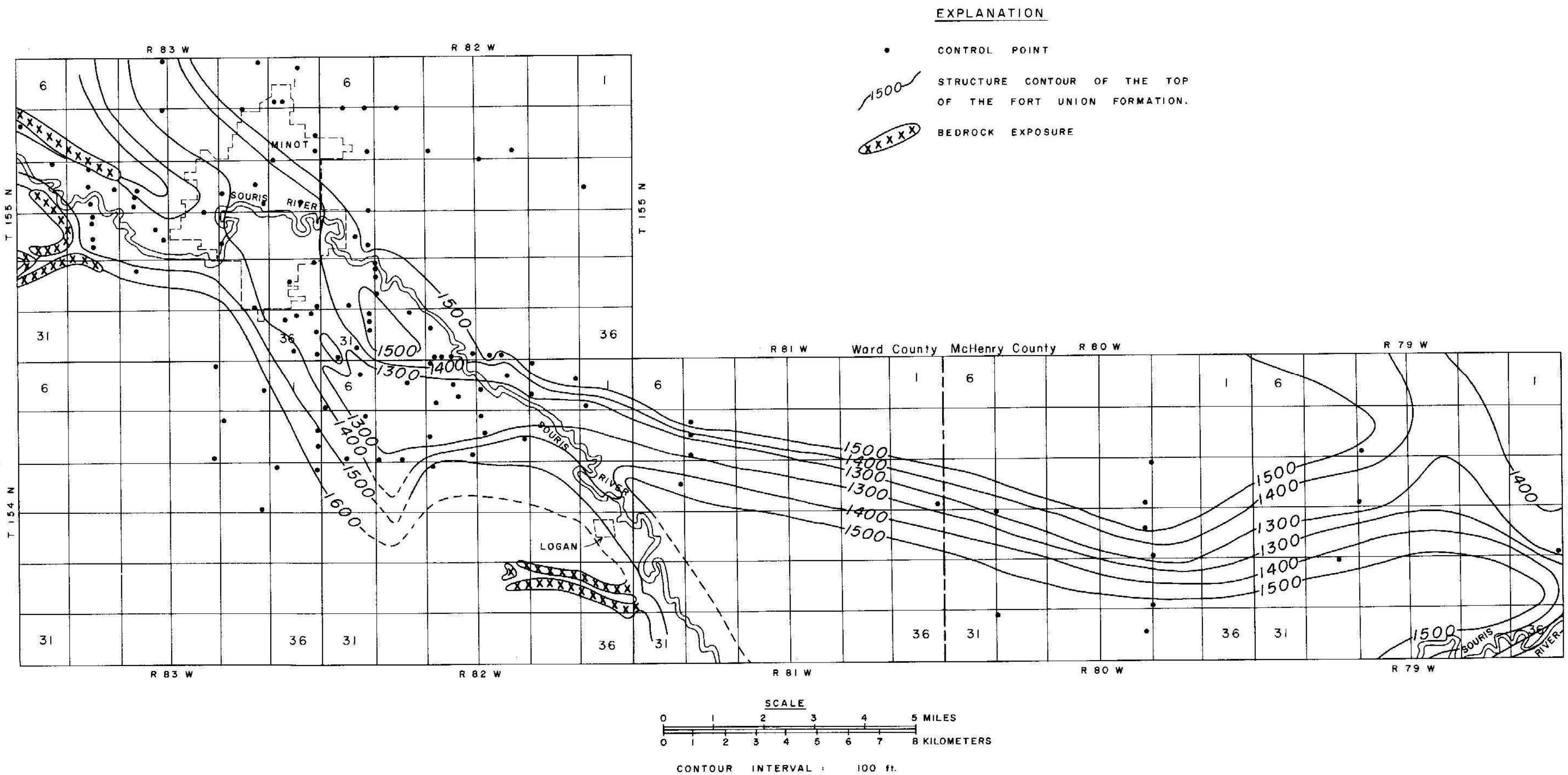


FIGURE 4. Structure contours of the top of the Fort Union Formation (undifferentiated).

from northwest to southeast. The valley is very steep walled suggesting rapid downcutting by glacial runoff. Width of the valley varies from 1 to 2 miles. Depth to bedrock ranges from 0 feet at the bedrock outcrops to 500 feet beneath the hills between first Larson and second Larson Coulees. It is within this bedrock valley that sand and gravel of the Sundre aquifer system were deposited.

Sandstone and lignite beds of the Fort Union Group yield small to moderate quantities of ground water to wells. Flowing wells completed in the Fort Union are common. One well completed by the NDSWC in 154-82-10CAC has 23-25 feet of head above land surface. Pettyjohn, 1967, speculates that "wells flow because of considerable amounts of dissolved gas in the water as well as artesian pressure." Many springs along the Souris River valley wall flow from the contact of a bed of Fort Union lignite with an underlying clay (Pettyjohn, 1971).

Unconsolidated deposits

Introduction

A considerable thickness of multi-layered, unconsolidated sediments (clay, silt, sand, and gravel) occur from land surface down to bedrock within the study area. Sediments occurring in this horizon are composed primarily of glacial drift (Coleharbor Group) and recent stream alluvium (Oahe).

Thickness of the glacial drift ranges from 500+ feet near first and second Larson coulees to 0 feet at the bedrock outcrops. In the Souris River valley, the unconsolidated deposits vary from 100 feet just southeast of Minot to approximately 300 feet thick near the Sundre well field.

Souris Valley aquifer

Unconsolidated sediments within the Souris River valley consist of a complex sequence of interbedded clay, silt, sand, and gravel (fig. 5, hydrogeologic section A-A' and B-B'). The Souris Valley aquifer is here defined as all coarser grained

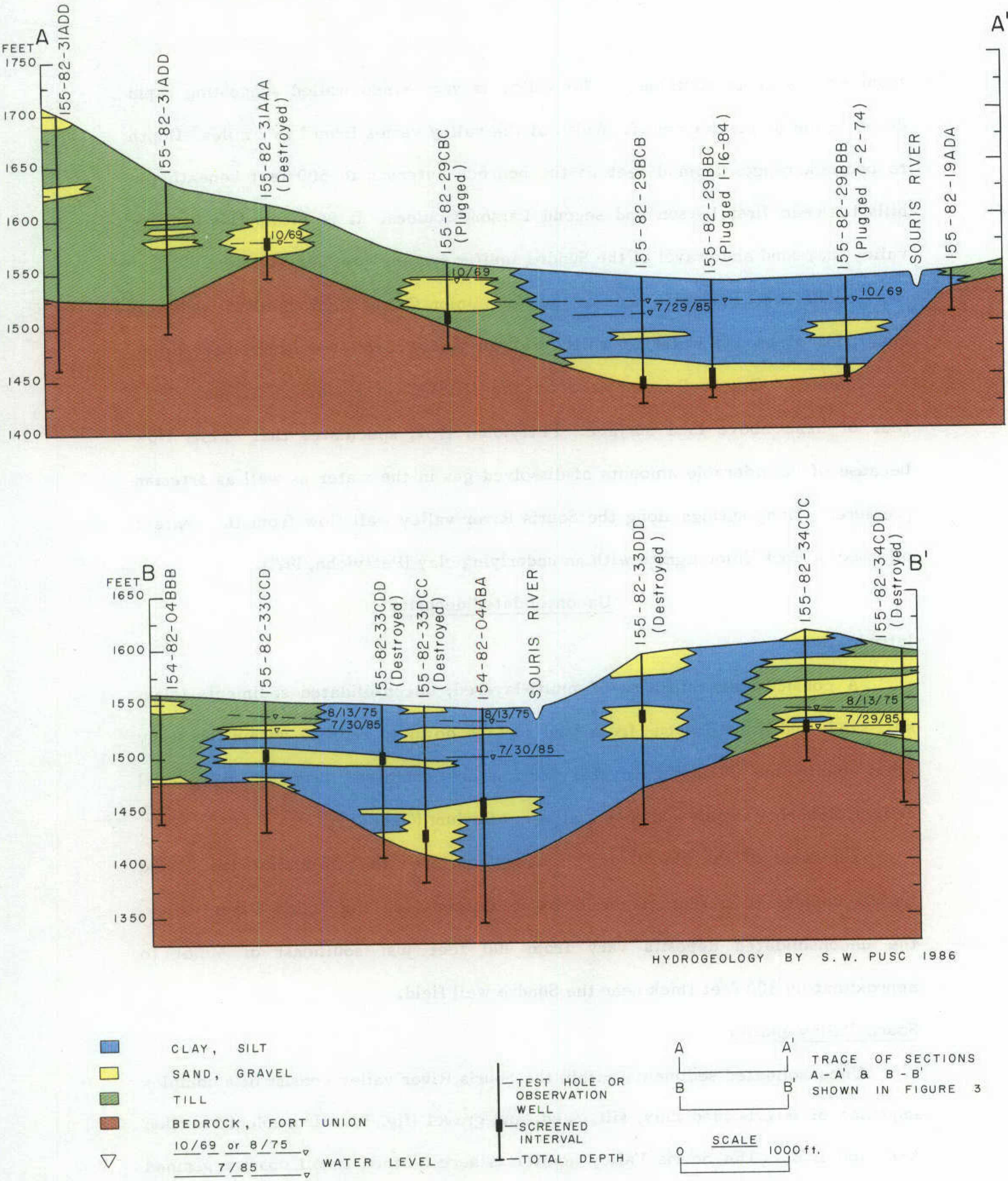


FIGURE 5. Hydrogeologic sections A-A' and B-B' showing the Souris Valley Aquifer.

sediments (i.e. sand and gravel) of the Oahe Formation which have been deposited within the Souris River valley (formerly Burlington, Minot and Lower Souris aquifers, Pettyjohn, 1967 and Pettyjohn and Hutchinson, 1971). The Souris Valley aquifer overlies the Sundre aquifer system at two locations in the study area (pl. 1). Locally, coarse sand, gravel, cobbles and boulders were encountered while drilling which resulted in a loss of circulation.

Sand and gravel intervals of the Souris Valley aquifer generally range from 5 to 90 feet thick and occur within the 1450 to 1550 elevation range (fig. 5). Ground water within the Souris Valley aquifer is under unconfined to confined conditions. Depth to the water table below land surface is commonly less than 5 feet.

The most significant aspect of the Souris Valley aquifer is that it provides a hydraulic connection between the Souris River and the Sundre aquifer system. As such, the Souris Valley aquifer plays an important role in regulating recharge to and discharge from the deeper Sundre aquifer. This report concentrates primarily on the area where the Souris Valley aquifer overlies the Sundre aquifer system in the vicinity of Minot's Sundre well field (pl. 1). The reader is referred to Pettyjohn (1967) and Pettyjohn and Hutchinson (1971) if more detail is needed on the Souris Valley aquifer in the vicinity of Minot (formerly Burlington, Minot, and lower Souris aquifers).

Sundre aquifer system

The Sundre aquifer system (formerly Northwest Buried Channel aquifer, South Hill aquifer and Sundre Buried channel aquifer, Pettyjohn and Hutchinson, 1971, and part of the New Rockford aquifer, Randich, 1981B) occupies a portion of a buried bedrock valley in the vicinity of Minot (fig. 4). The Sundre aquifer extends from northwest of the city of Minot, crosses beneath the Souris River valley at two locations, and continues east into McHenry County. In McHenry County, the Sundre aquifer system occupies the same bedrock valley as the New Rockford aquifer system, however, a transverse low-transmissivity barrier separates the aquifers into two hydrologic units.

The Sundre aquifer system consists of varying portions of fine to coarse sand to medium gravel with occasional interbeds of silt and clay (figs. 6 and 7). The sand and gravel is composed of varying amounts of Canadian shield silicates, carbonates, shales, and lignite. Alternating sequences of "choppy" and "smooth" drilling suggests that the sand and gravel is stratified. Test hole data indicates that the coarsest gravel is generally situated along the axis of the buried valley (Pusc, 1987).

In the Souris River floodplain, the Sundre aquifer is overlain by approximately 90 feet of interbedded clay, silt, sand, and gravel of the Souris Valley aquifer (fig. 6). To the east and west of the Souris River floodplain, the Sundre aquifer system is overlain by 15 to 50 feet of fluvial silt and clay which in turn is overlain by a considerable thickness of poorly sorted glacial till (fig. 7).

Depth to the top of the Sundre aquifer is dependent on location within the study area. Near first and second Larson Coulees, the top of the Sundre occurs 135 feet to 260 feet below land surface (fig. 7). On the Souris River floodplain the top of the Sundre aquifer is 70 to 90 feet below land surface (fig. 6). There are areas, however, where the Souris Valley and Sundre aquifers are one hydrologic unit. As such, no distinct depth to the top of the Sundre aquifer can be stated. East of the Souris River Valley the top of the Sundre aquifer occurs from 110 to 180 feet below land surface (fig. 7).

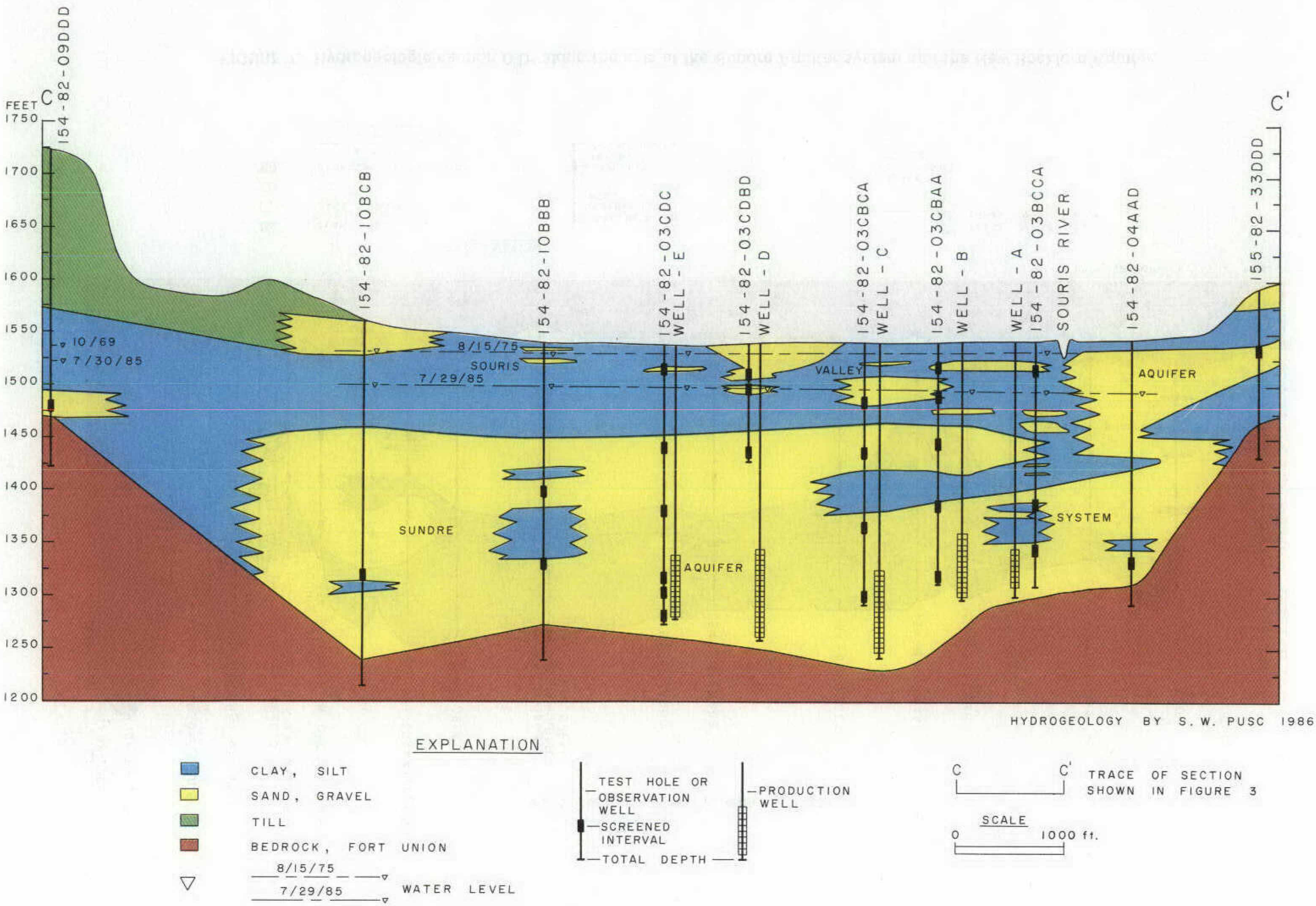


FIGURE 6.—Hydrogeologic section C-C' showing the Souris Valley aquifer and Sundre aquifer in the vicinity of Minot's Sundre well field.

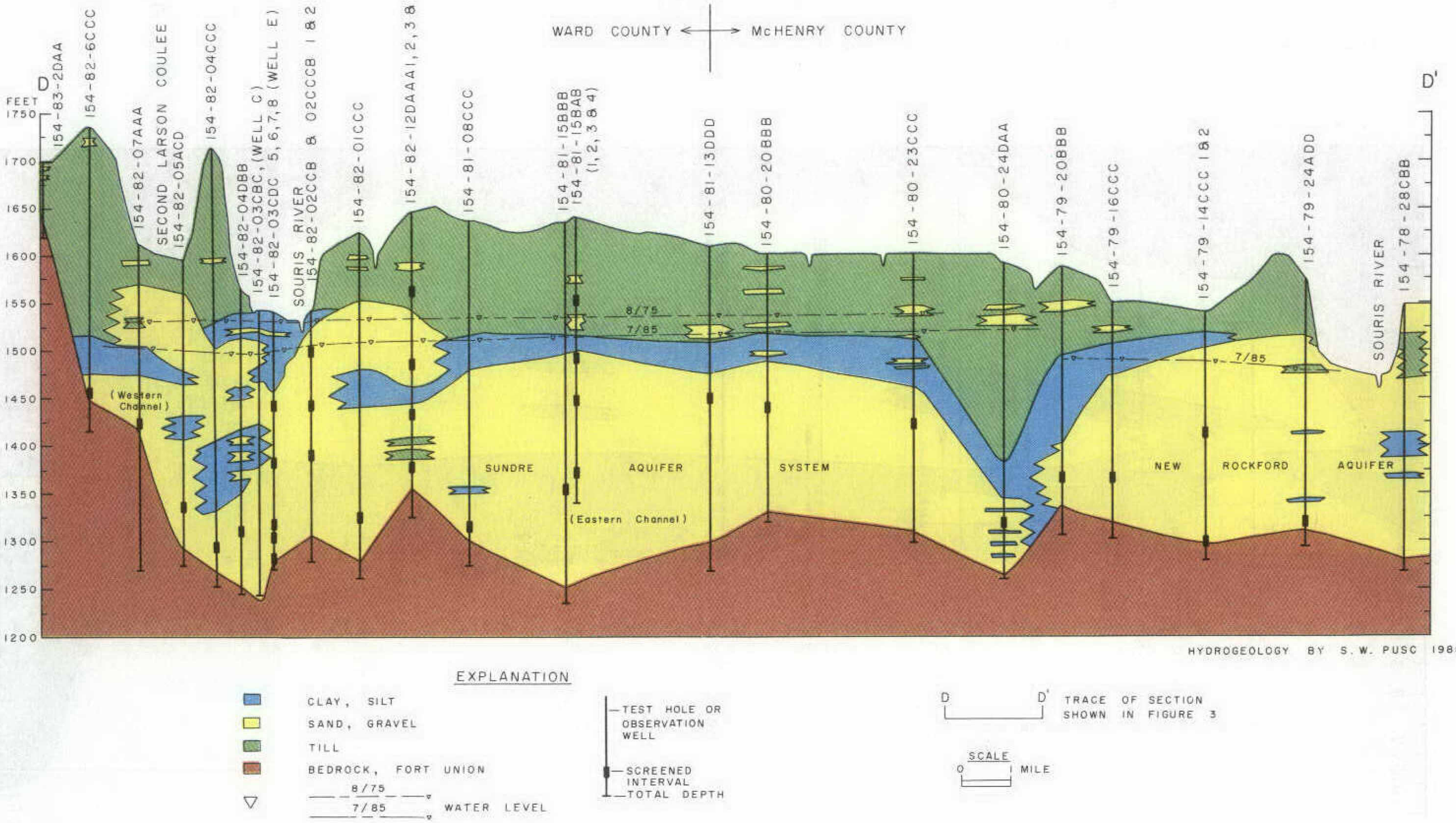


FIGURE 7. Hydrogeologic section D-D' along the axis of the Sundre Aquifer system and the New Rockford Aquifer.

Width of the Sundre aquifer ranges from 1 to 2 miles while the thickness varies from 30 feet thick in the western channel to 250 feet thick in the Souris River valley. In the Souris River valley, the Sundre aquifer generally occurs from 90 to 210 feet below land surface and averages 120 feet thick.

The eastern channel of the Sundre aquifer appears to be truncated by a low-transmissivity barrier southwest of Simcoe, North Dakota (fig. 7). The water level in 154-80-24DAA is 30 feet higher than water levels in any of the observation wells completed to the south and east of Simcoe. Therefore, this report considers the aquifer east of the barrier the New Rockford aquifer and the aquifer west of the barrier the Sundre aquifer.

Water level and test hole information also indicate that the western channel of the Sundre aquifer is truncated by a low-transmissivity barrier immediately southeast of Minot. Existence of these low transmissivity barriers means that the portion of the Sundre aquifer system from which Minot obtains its water is approximately 18 miles long (fig. 7).

Well yields from the Sundre aquifer range from 2-5 gpm from small diameter domestic wells to 2800 gpm from well "D" of the Minot well field. Drawdown and water level data indicate that the Sundre aquifer is a bounded, leaky-confined aquifer. Recharge to the Sundre aquifer is the result of leakage from two main sources; (1) the Souris Valley aquifer, which overlies the Sundre in the Souris River valley and (2) glacial drift and alluvial silt and clay deposits which overlie the Sundre aquifer east and west of the Souris River valley.

HYDROGEOLOGIC FLOW SYSTEMS

Introduction

Ground-water levels rise and fall in response to recharge to and discharge from the Sundre aquifer system. Factors affecting water levels in the Sundre aquifer system are: (1) stage elevation of the Souris River, (2) precipitation, (3) evapotranspiration, (4) barometric effects, (5) leakage from overlying and surrounding alluvial and/or glacial drift units, (6) leakage from bedrock sediments, (7) large scale ground-water withdrawals by the city of Minot and (8) small scale ground-water withdrawals by local residents.

Hydrographs and water level contour maps constructed from water level data were compared with factors that control fluctuations in water levels to determine the impact of each factor. Because of the large number of observation wells (86 wells) and dates of measurements, only hydrographs for representative wells and water level contour maps from representative dates are presented and discussed.

Souris River

The USGS has measured the discharge (Gage height) of the Souris River above Minot since 1903 (T155N, R83W, 17DBB, pl. 1). A summary of streamflow records and characteristics for the Souris River above Minot is presented in table 1.

Table 1. Streamflow Records and Characteristics, Souris River above Minot (from USGS, 1903-1985)

Total drainage area:	10,600 square miles
Gage Zero elevation: (above msl)	1545.75
Period of record:	May, 1903 to date
Maximum Flow Data	
Discharge:	12,000 cfs
Date:	April 20, 1904
Gage Height:	21.90
Minimum Flow Data	
Discharge:	0.0
Date:	In several years
Average Discharge:	168 cfs

Since 1936, discharge of the Souris River above Minot has been controlled by Lake Darling Dam (fig. 1). Prior to 1983, operation of Lake Darling was on a year-to-year basis. Due to channel improvements in Minot and other downstream urban centers, a general operating plan was developed in 1983 (International Souris River Board of Control, 1983).

Basically, operation of Lake Darling Dam involves releasing enough water from the dam to handle spring runoff while being assured of sufficient water to reach the Lake Darling summer conservation pool. Under normal operating conditions, maximum releases from the reservoir and thus maximum discharge (stage) of the Souris River above Minot occurs anytime from February through May (pl. 2). Infrequent and unpredictable events such as ice jams, rapid melting of snowpack or heavy local precipitation also contribute to higher river stages. In some years, there is no major spring runoff event (pl. 2). Releases from Lake Darling during the summer, fall and winter months depends on four criteria: (1) needs at the J. Clark Salyer National Wildlife Refuge downstream from Lake

Darling;(2) needs of the Eaton Flood Irrigation District at Towner; (3) coordinate releases with the city of Minot's waste water discharge into the river; and (4) for compliance to interim measures between Canada and the U. S. for minimum flow of the Souris River back into Canada (20 cfs, International Souris River Board of Control, 1983). In the summer, fall and winter months, the Souris River above Minot generally fluctuates 4 to 6 feet above datum (pl. 2).

Ground water flow systems under natural conditions

Vertical distribution of water levels

Detailed water levels were measured in the vertical at only one site (154-82-10BBB) prior to the fall of 1984. Other pairs of wells were in existence prior to fall 1984, however, inclement weather and poor access prevented detailed water level measurements during high recharge events. The vertical distribution of water levels is important to determine because knowledge of vertical ground-water movement (up or down) aids in determining recharge and discharge areas.

Presented in Figure 8 are pre-development hydrographs for the period 1970-1974 for observation wells 154-82-10BBB1 and 2. Note that water level elevations in the deeper well were generally higher than water level elevations in the shallower well. This head difference would provide the driving force by which ground water would move upward from the Sundre aquifer system, into the Souris Valley aquifer and finally discharge as evapotranspiration or Souris River flow. Limited data reveals that periods of high river stage temporarily reverse this relationship near the river, and recharge to the Souris Valley aquifer and Sundre Aquifer occurs (fig. 8, 1970).

Historic data is not available to document vertical ground-water gradients in the western and eastern channels of the Sundre aquifer system. However,

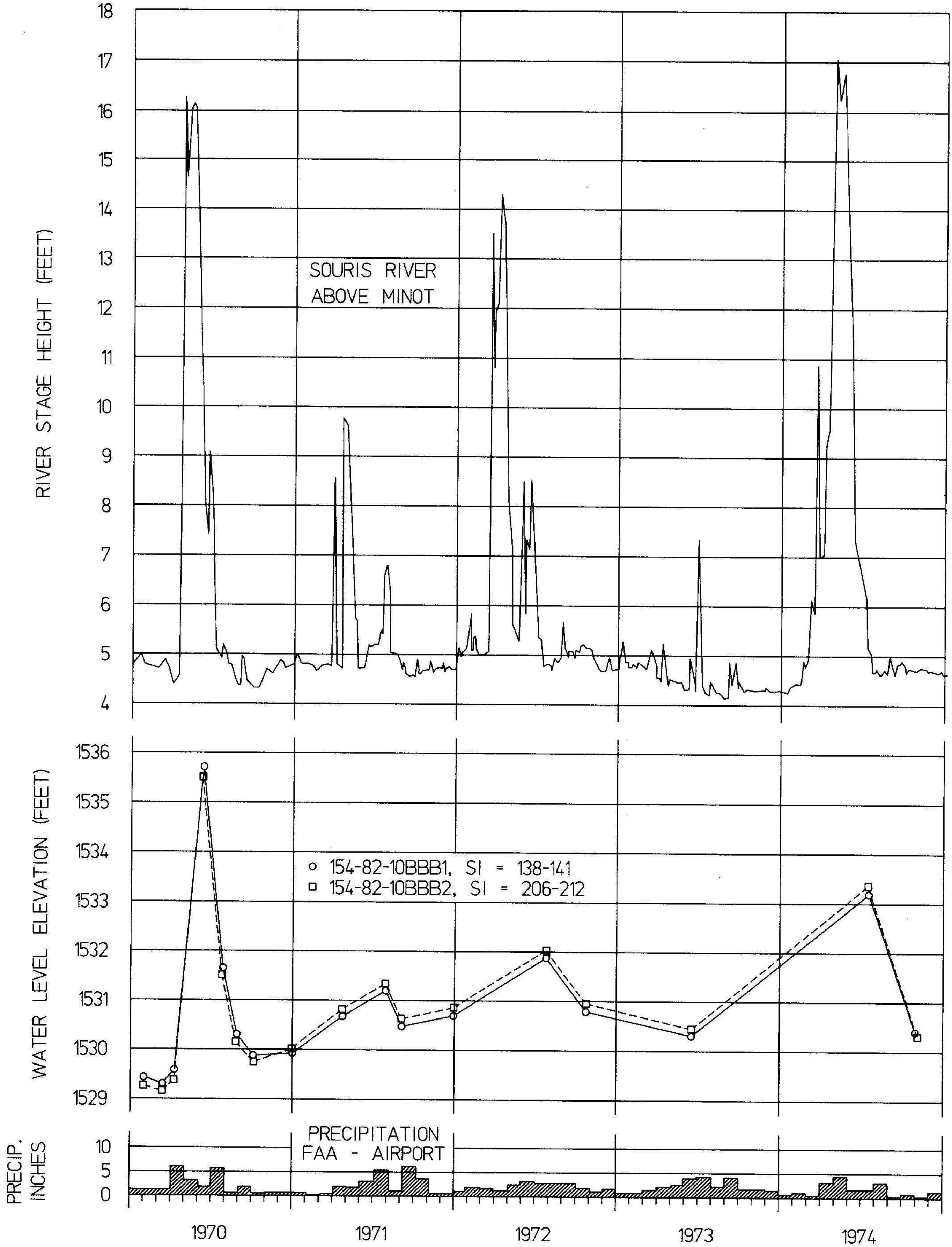


FIGURE 8. Hydrographs of water levels from observation wells 154-82-10BBB 1 & 2 versus gage height of the Souris River above Minot.

with the Souris River Valley acting predominately as a regional sink, the Sundre aquifer system to the east and west would act as a buried line sink. Thus, movement of ground water would be slowly downward through the overlying tills, into the Sundre aquifer, and lateral along the Sundre aquifer towards the Souris River valley. Discharge from the system occurred as evapotranspiration or Souris River flow.

Gain-loss stream measurements

Discharge measurements were obtained at four (4) sites along the Souris River from the USGS Gaging Station above Minot to just north of Logan on March 6, 1969 (USGS, 1969). A week earlier, personnel from the NDSWC visually inspected, and documented flow in the Souris River at two locations near Minot. Mean daily flow in the Souris River at the USGS Gage above Minot was below 2 ft^3/sec for six months prior to the March measurements (USGS, 1903-1985). Two months prior to the March 1969 measurements, flow in the river at the USGS gage above Minot was approximately .35 ft^3/sec. Therefore, these measurements and observations represent extreme low river flow (Table 2 and Figure 9) and probably most nearly represent natural baseflow conditions.

Table 2

Discharge Measurements and Visual Observations of Flow of the Souris River near Minot, North Dakota, February and March, 1969

Letter Designation	Location	Discharge
A	155-83-17DBB Souris River above Minot	0.38*
B	155-83-23CCC Minot water supply dam	0.00+, no water passing over dam
C	155-82-33DDC Saugstad bridge	0.00+ dry
D	154-82-03DBB	0.49*
E	154-82-03DAC	0.06*
F	154-82-11DAA	0.23*

*USGS, 1969
+Lindvig, 1969

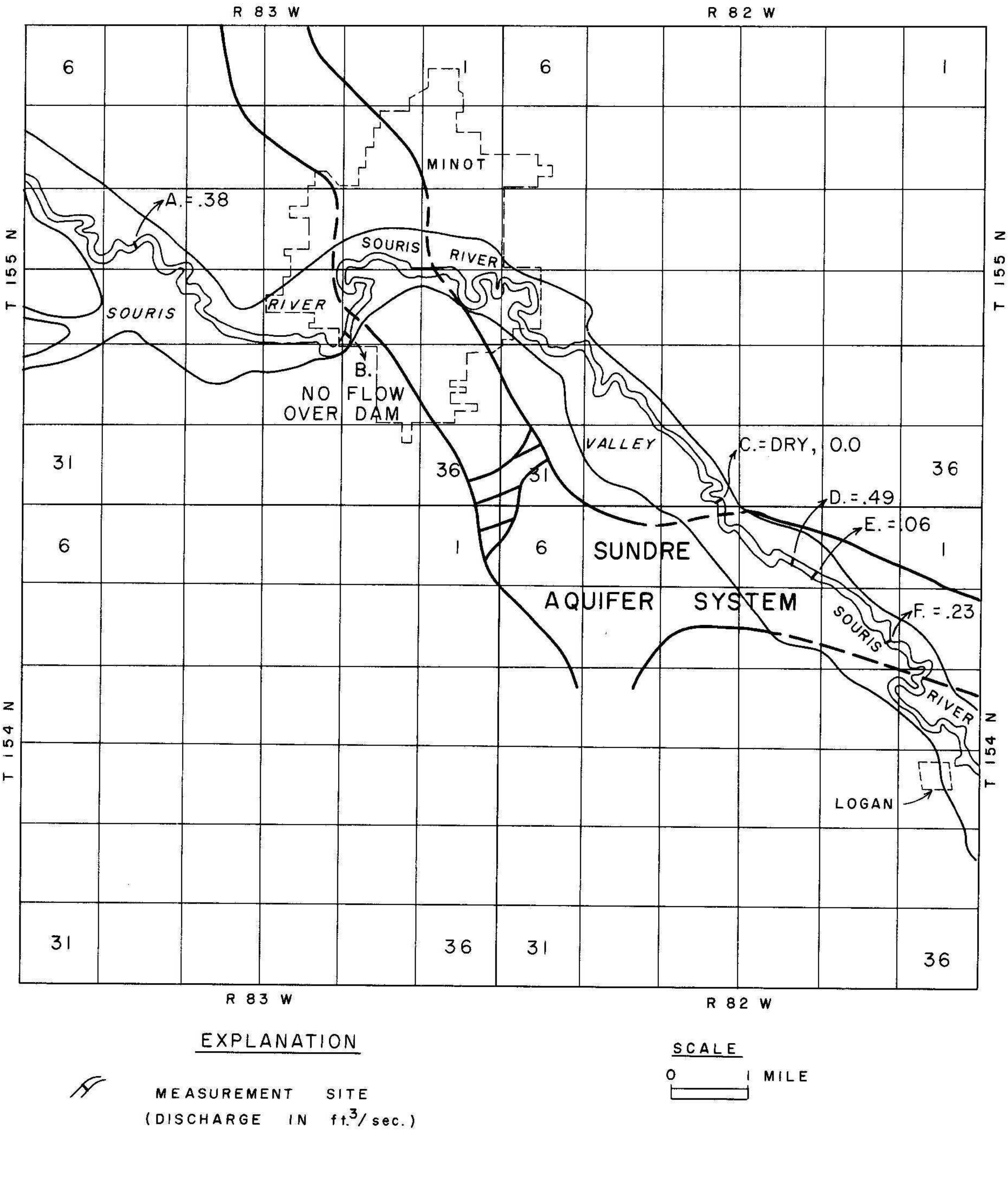


FIGURE 9. Discharge measurements and visual observations of flow of the Souris River, February and March, 1969.

"Roger (Schmid)and I followed the river from the Saugstad bridge to 154-82-11DAB. There are quite a number of springs in that reach of the river. There were also a few open spots where the water was moving and a gradual increase in flow could be noticed. I could not notice any flow at the Saugstad bridge and there was no water passing over the Minot supply dam." (fig. 9).

Measurements taken on March 6, 1969 indicate that stream discharge increases slightly to .5 ft^3/sec about one mile downstream from the Saugstad Bridge. Downstream from measurement site D, the flow in the river almost ceases (Table 2). Very low flow in the river during baseflow conditions indicates that only a small quantity of ground water actually discharges into the river during extremely low river flow conditions (less than 1 ft^3/sec.). Much of the water moving up from the Sundre aquifer to the Souris Valley aquifer at this time probably replaces water removed earlier by evapotranspiration.

Water level response to stage height of the Souris River

Presented in Figure 10 are 1969 through 1976 hydrographs from representative Sundre aquifer observation wells versus river stage of the Souris River above Minot. Generally, water levels in all the observation wells fluctuate directly with river stage. The spring rise in river stage causes a corresponding rise in water levels while a decline in river stage results in a decline in water levels. This suggests that the Souris River provides recharge to the Sundre aquifer and in turn, the Souris River receives discharge from the Sundre aquifer. Response of the water levels to the river, even at a distance of 8 miles (154-80-20BBB), reflects the confined nature of the aquifer system.

Recharge also results from the Souris River overflowing its banks and flooding the river valley during extremely high river discharge events (1969, 1970, 1974, 1975, and 1976). Flood events of this nature would increase both recharge

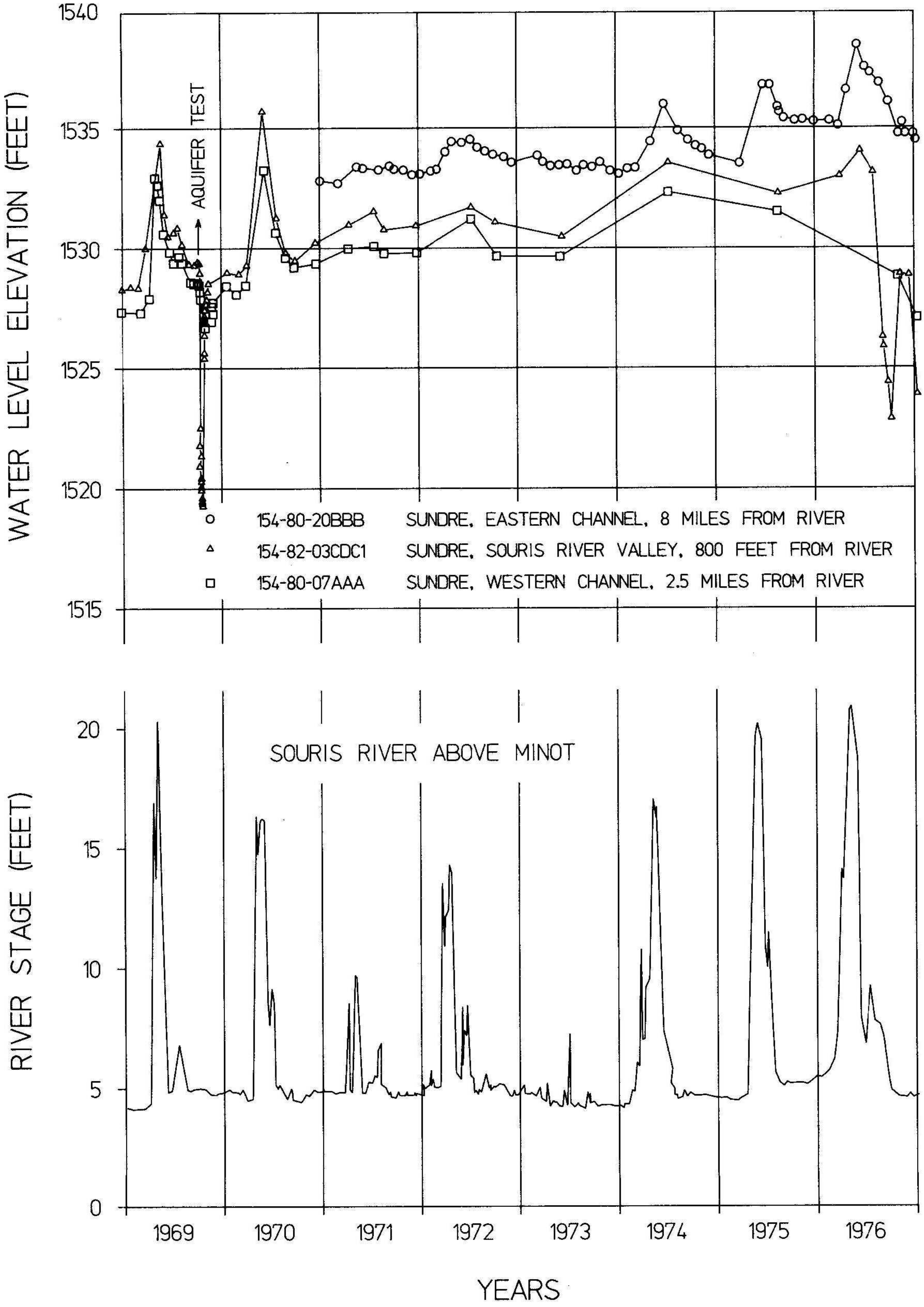


FIGURE 10. Hydrographs of water levels from representative Sundre Aquifer observation wells versus gage height of the Souris River above Minot (1969-1976).

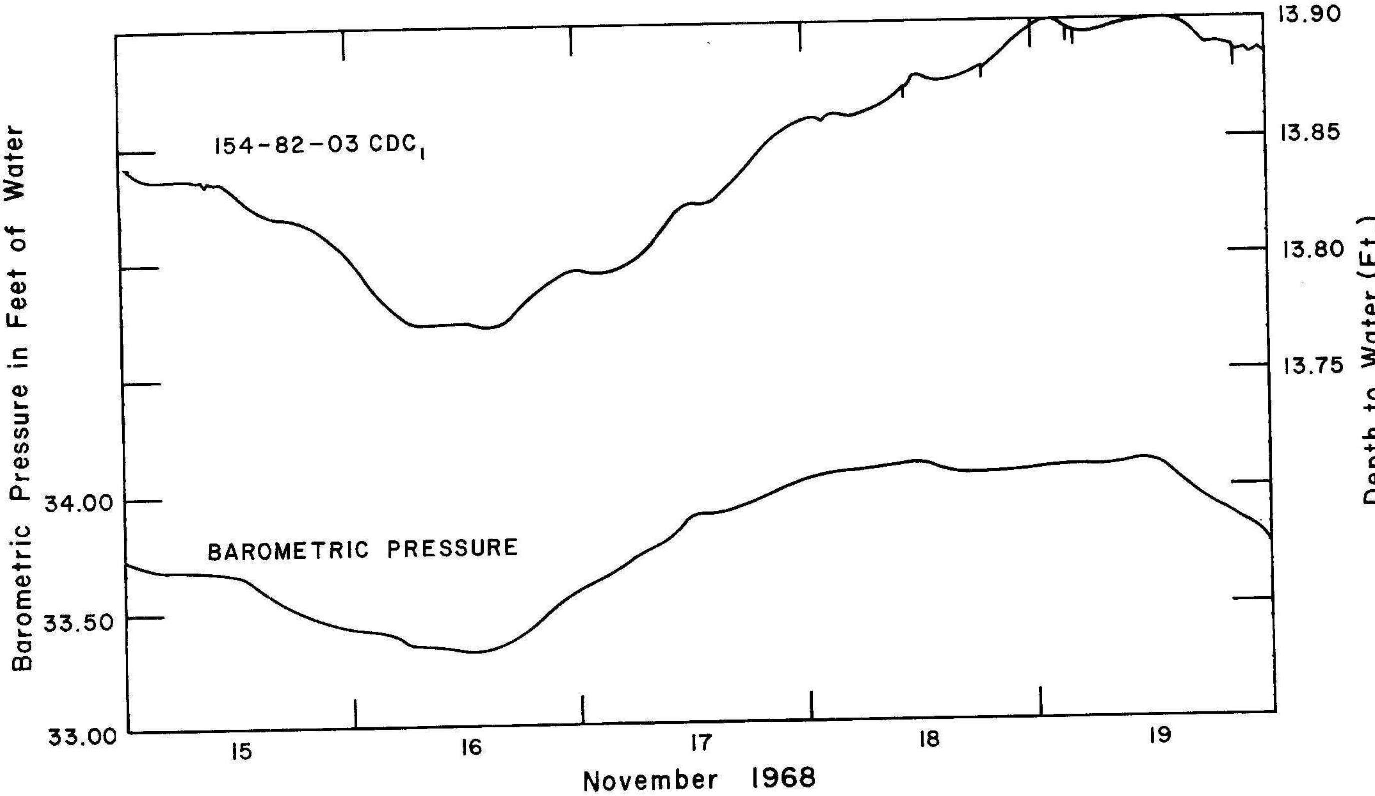
area and residence time, thereby increasing overall recharge for that particular high river stage event.

Barometric effects

Changes in barometric pressure produce subtle changes in ground-water levels in wells tapping the Sundre aquifer. Correlation of measured water levels with recorded barometric pressure changes is presented in Figure 11. Note that when the barometric pressure increases, the water level falls and vise versa. Barometric efficiencies (change in water level in feet/change in barometric pressure in feet of water) calculated from the data range from 10 to 15%. These percentages are consistent with an elastic unconsolidated aquifer such as the Sundre. With more rigid systems such as consolidated sandstone, the load change (barometric pressure) is borne by the water, resulting in a greater water level fluctuation and thus a higher barometric efficiency. Based on a barometric efficiency of 10-15%, a change in barometric pressure of one inch of mercury (equal to 1.13 feet of water) causes the water levels in the Sundre aquifer to rise or fall .15 feet. Thus, changes in barometric pressure have a minor effect on water levels.

Evapotranspiration

Evapotranspiration (ET) is a combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Natural discharge of water into the atmosphere by ET can cause a decline in ground-water levels. ET effects on the water table are generally strongest during daylight hours of the growing season (May-September).



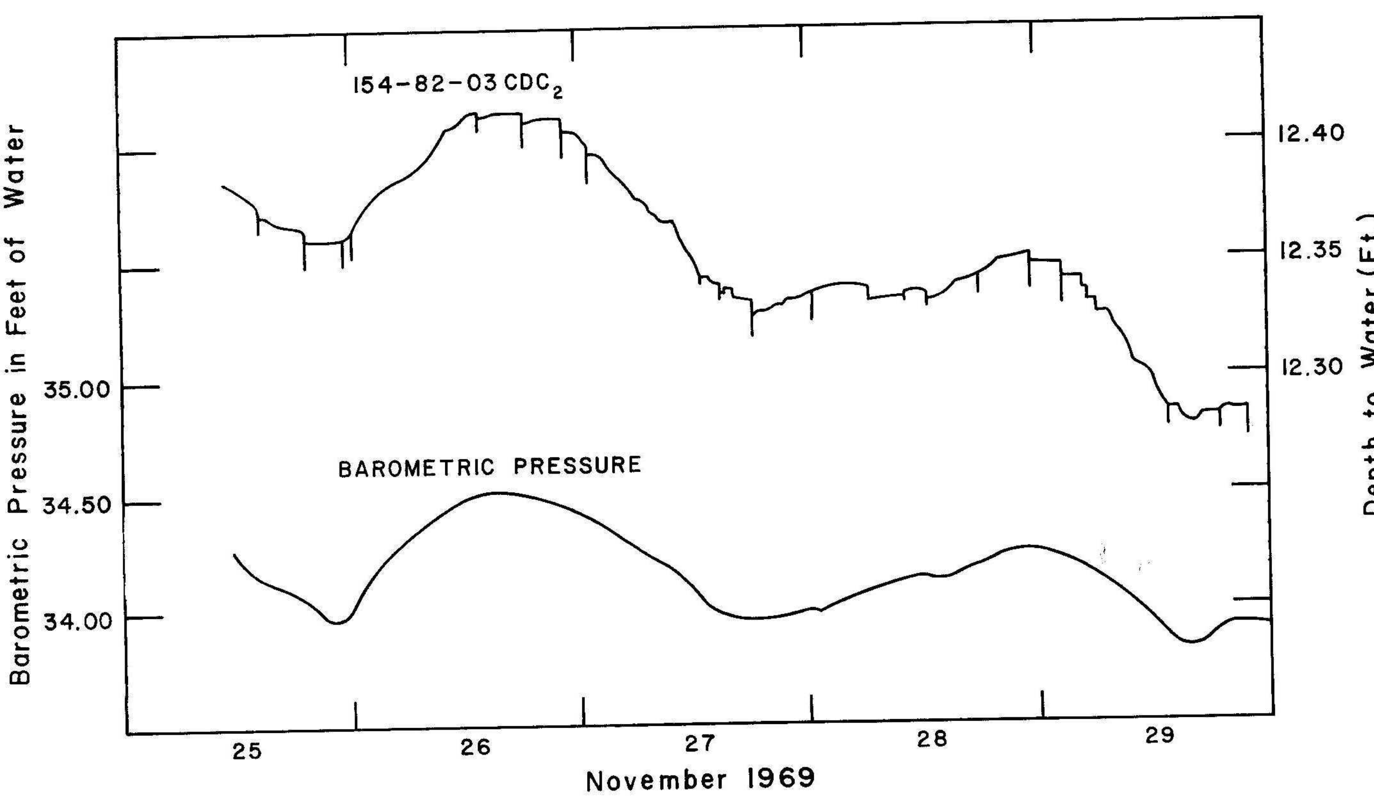


FIGURE 11. CORRELATION OF WATER LEVELS FROM OBSERVATION WELLS 154-82-03 CDC 1 AND 2 VERSUS BAROMETRIC PRESSURE

Before ground-water development, the water table in the Souris River Valley was close to land surface. Phreatophyte growth, such as cottonwoods, willows, etc. grew along the river and extracted water from the river valley during the growing season. Thus, ET was believed to be a major source of discharge from ground-water flow systems in the area. Unfortunately there is no data available to determine the magnitude to which ET depressed the water table in the Souris Valley aquifer, or to what degree that effect was transferred to the deeper Sundre aquifer system.

Precipitation

Recharge from precipitation occurs at varying rates throughout the study area. Unfortunately, data needed to determine areal recharge rates for the area are not available. However, relative rates of recharge can be estimated from the nature of the surficial geologic materials and slope of land surface. Glacial till, which overlies the east and west channels of the Sundre aquifer system, has a high percentage of clay and therefore is less permeable than the unconsolidated sand and gravel intervals of the Souris River valley. As a result of the differences in permeability and thickness, the rate of recharge is greater on the valley floor than on the adjoining till upland areas. Also, melting snowpack, heavy precipitation, and overbank flooding would tend to fill abandoned oxbows and depressions in the river valley. This ponding of water on the valley floor would increase both recharge area and residence time, thereby increasing overall recharge to the Souris Valley aquifer and underlying Sundre aquifer.

Ground-water movement

Ground-water movement in the Sundre aquifer system, prior to development of Minot's Sundre well field, is presented on Figure 12. Under low Souris River

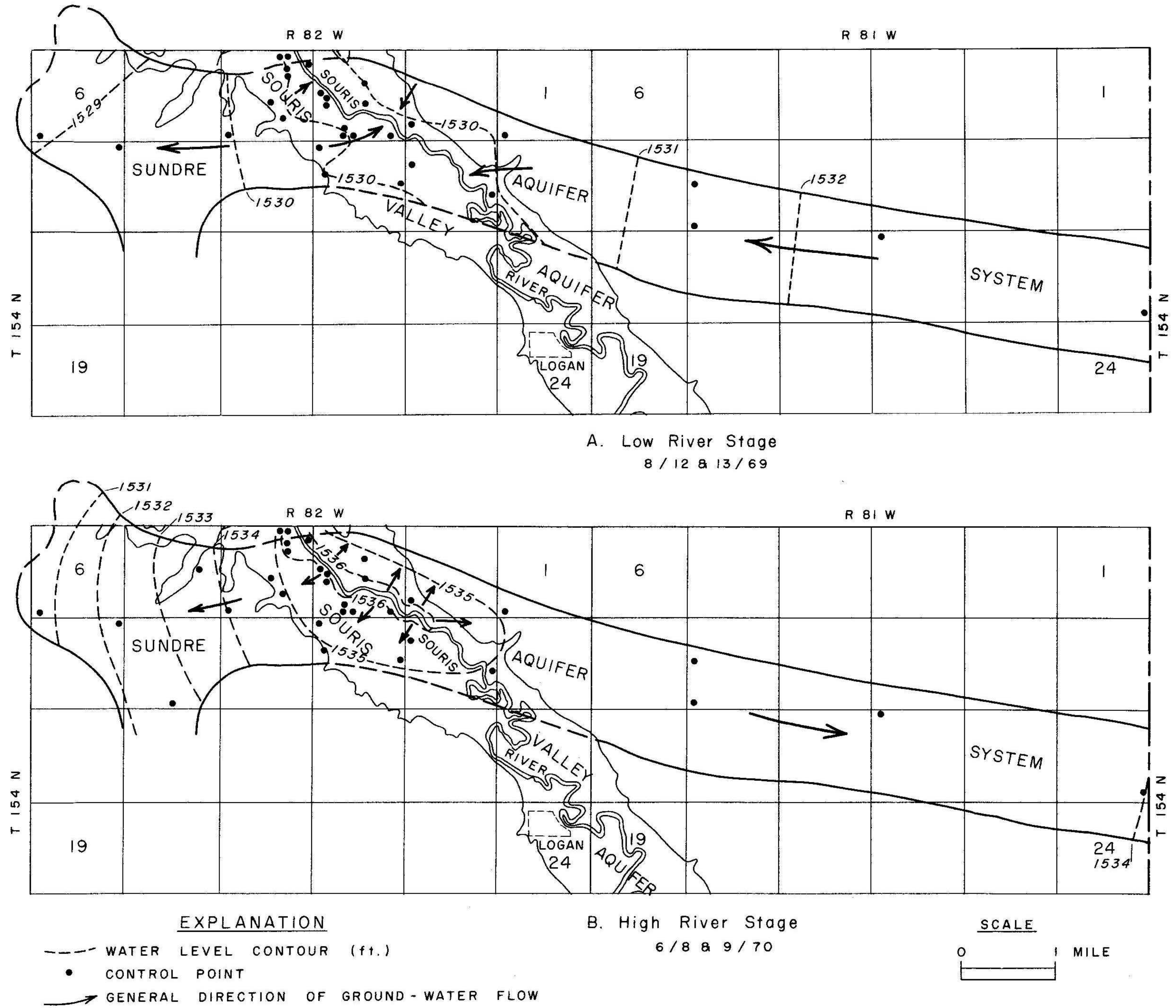


FIGURE 12. Potentiometric surface maps of the Sundre Aquifer System during low river stage of 8-12 & 8-13, 1969 (A) and high river stage of 6-8 & 6-9, 1970 (B).

flow conditions, ground-water flow was generally towards the Souris River (fig. 12-A). Water level elevations in August of 1969 were approximately 1532 feet in the eastern channel of the Sundre aquifer to just under to 1530 feet near the Souris River. The gradient established between wells 154-81-13DDD and 154-81-15BBB in the eastern channel of the Sundre aquifer, was a very flat .04 feet/mile (fig. 12-A). Near the Souris River valley (discharge area), the gradient steepened to .5 feet/mile. Gradients of between .04 to .5 feet/mile translate into estimated ground-water velocities (V) of between .004 ft/day (1.5 ft/year) to .05 ft/day (19.5 ft/year), (based on the Darcy relationship of $V = \frac{K(dh/dl)}{a}$ and assuming T = 34,000 ft^2/day, thickness = 200 feet and porosity of 30%). This indicates that under natural, low river stage conditions, ground water in the Sundre aquifer system moved very slowly towards the Souris River Valley.

Water levels in two wells in the western channel of the Sundre aquifer are unexpectedly lower than water levels in wells near the river (fig. 12-A). This is contrary to the conceptual model of the Souris River valley being the discharge area, with ground water moving toward it. Pettyjohn, 1971, speculated that:

> "large scale long term ground-water pumping by the city of Minot resulted in water level declines in these wells and a general direction of movement towards the central part of Minot."

It appears that, given enough time (50 years), the effects of pumping were able to pass through the low transmissivity barrier shown on Plate 1, and depress water levels in 154-82-06CCC and 07AAA.

Depicted in Figure 12-B is the movement of ground water in the Sundre aquifer system following high river stages of May 1970. Note that movement is now away from the river in all directions. This indicates that during high stage, the Souris River is a source of recharge to the Sundre aquifer system. Near the river, the gradient is 1 foot/mile while out in the far eastern channel, the gradient is a very flat .1 foot/mile away from the river. Note also the rather steep gradients away from the river in the western segment of the Sundre aquifer (1.6 feet/mile). This is probably due to decreased aquifer transmissivity (decrease of thickness and/or hydraulic conductivity) to the west.

In summary, ground-water flow in the area during natural low river flow conditions was downward through the overlying tills, into the eastern and western channels of the Sundre aquifer, lateral movement towards the Souris River valley, and finally upward movement from the Sundre aquifer into the Souris Valley aquifer. Discharge from the Souris Valley aquifer was to the Souris River and/or by evapotranspiration (fig. 13A).

During high river stage, ground-water movement was downward from the Souris River, through the Souris Valley aquifer, into the Sundre aquifer and finally lateral movement to the east and west in the Sundre aquifer (fig. 13B). Flat water level gradients coupled with reversals in ground-water movement resulted in long residence times for the ground water moving laterally along the eastern and western channels of the Sundre aquifer system. These conditions are conducive to the development of stagnation zones within the ground-water flow system.

Sundre aquifer test (1969)

Design and operation

A 15 day aquifer test was conducted on the Sundre aquifer system starting at 10:00 a.m. on October 20, 1969 and ending at 10:00 a.m. on November 3, 1969. The production well, located in Township 154 North, Range 82 West, Section $3CDC_3$, was constructed by C. A. Simpson and Son of Bisbee, North Dakota

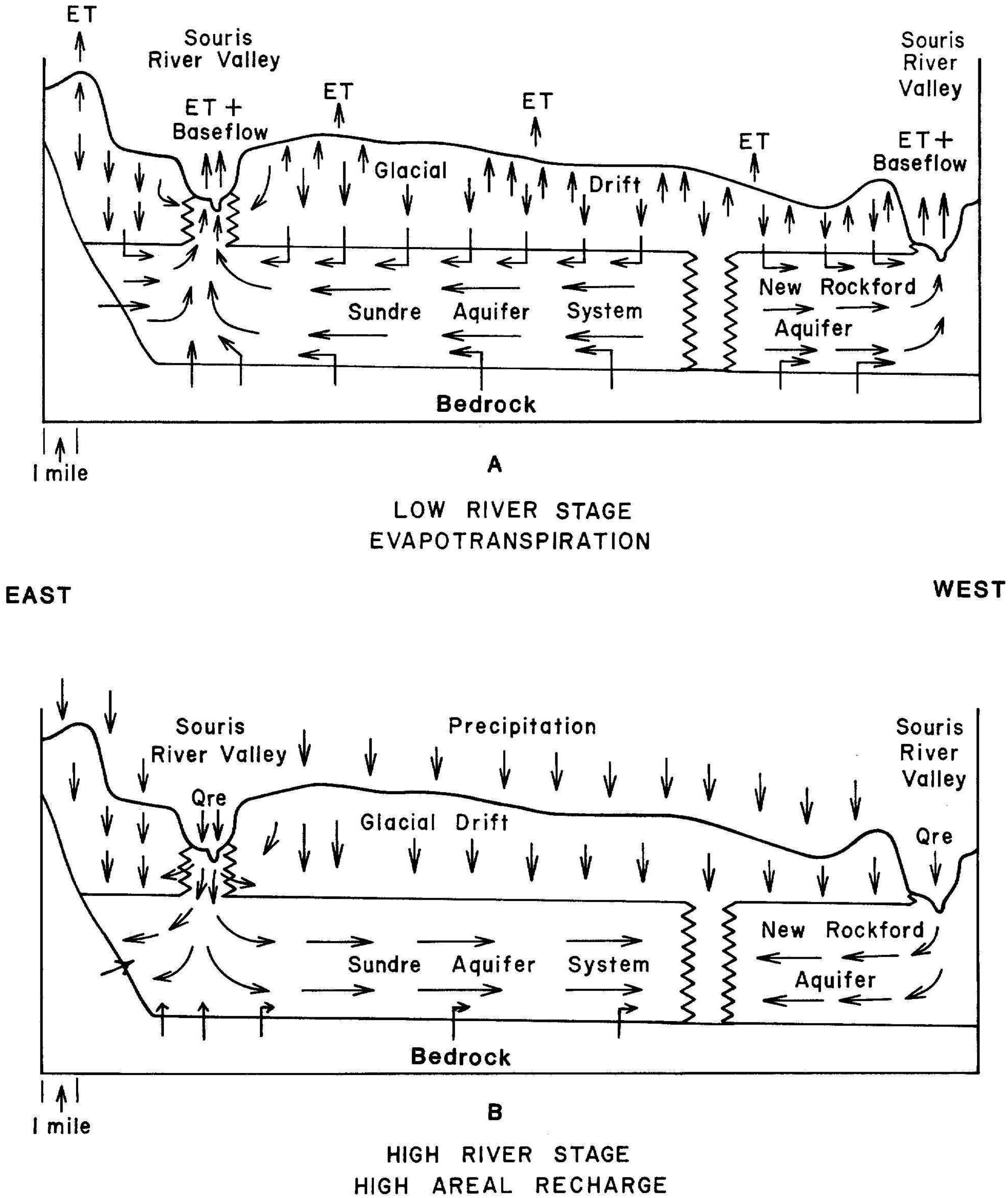


FIGURE 13. SCHEMATIC OF GROUND WATER FLOW IN THE SUNDRE AND SOURIS VALLEY AQUIFERS UNDER NATURAL CONDITIONS.

specifically for the test (fig. 14). The production well was constructed with 12-inch diameter steel casing from 0-170 feet, 35 slot screen from 170-195 feet and 25 slot screen from 195-220 feet. A deep well turbine pump powered by a 50 horsepower electric motor was used to pump the well. Twelve inch bowls were set at about 80 feet from land surface (Schmid, 1970).

Discharge rates were measured with a Cox flowmeter and recorded on a Barton circular chart recorder. A gate valve installed in the discharge pipe was used to hold the flow rate fairly constant. Discharge water was pumped through 250 feet of 10-inch irrigation pipe to a cooling lagoon at the Bison Power Plant (fig. 14). A constant discharge rate of 1950 gpm, with a variance of less than 1½% was maintained throughout most of the 15 day test. Maximum fluctuation in discharge occurred during the first 15 minutes when discharge varied from 1870 gpm to 1950 gpm.

During the aquifer test, a production well owned by the Bison Power Plant was in operation on October 29 from 12:30 p.m. (13,110 min.) to 15:00 p.m. (13,410 min.). The Bison Power Plant well is located approximately 900 feet north of the production well used for the Sundre aquifer test (fig. 14). The Bison well is 92 feet deep and constructed of 10-inch steel casing with 20 feet of gravel packed screen at the bottom. It appears that the Bison well is screened near the interface of the base of the Souris Valley aquifer and the top of the Sundre aquifer. Pumping of the Bison well was the only other significant ground-water withdrawal during the entire Sundre aquifer test. Drawdown data collected during the Sundre test indicate that pumping of the Bison well had very little effect on the test.

During the aquifer test, water level measurements were recorded in the

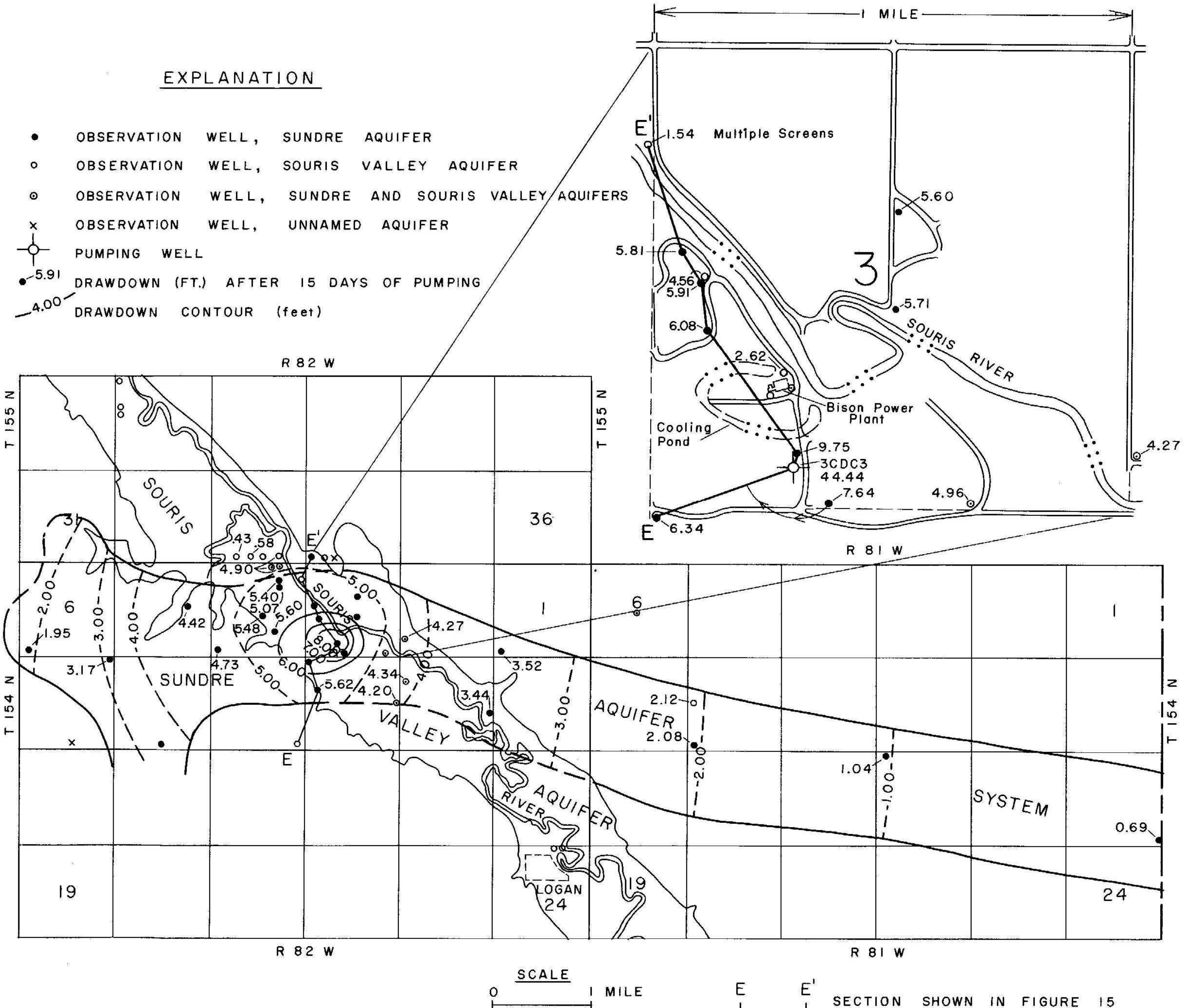


FIGURE 14. Location of observation wells measured during the Sundre Aquifer test of 10-20-69 to 11-03-69 and drawdown in the Sundre Aquifer System after pumping [well 154-82-03CDC3] at 1950 gpm for 15 days.

pumping well and 50 observation wells. A map showing the areal distribution of the observation wells in relation to the pumping well is presented in Figure 14. The location, radius from pumping well, screened interval, and methods used to measure each well are presented in Table 3. A hydrogeologic section through the aquifer test site is shown in Figure 15.

Water levels in the pumping well and 15 nearby observation wells, were measured with Keck water level sensors coupled to Stevens Type F recorders. The remainder of the observation wells and the production well were measured using chalked steel tapes. Observation wells ranged from 150 feet to almost 9 miles from the pumping well. Drawdown and recovery data from the test are available from the NDSWC, 900 E. Blvd., Bismarck, ND.

Water samples from the production well were collected at 11 different times during the test. Analyses of the 11 samples were completed at the State Water Commission water quality laboratory in Bismarck, North Dakota.

Response to pumping

The areal drawdown response in the Sundre aquifer system after test pumping well 154-82-3CDC$_3$ at 1950 gpm for 360 hours is illustrated in Figure 14. At the end of 360 hours of pumping, 44.44 feet of drawdown was measured in the pumping well, while only 9.75 feet of drawdown was measured in an observation well located 150 feet northeast of the pumping well. A water level response to pumping of 0.7 feet was measured at well 154-82-13DDD located 9 miles east of the pumping well (fig. 14). The greater drawdown in the western channel, as compared to an equal distance from the pumping well in the eastern channel, is a result of lower transmissivity (thickness and/or hydraulic conductivity) to the west coupled with leakage from the river to the north and east. Test drilling reveals that the aquifer

TABLE 3 - Observation Wells Monitored During the 1969 Aquifer Test of Sundre Aquifer System

Location	Radius from Pumping Well	Method of Measurement	Screened Interval	Aquifer Screened
154-82-3CDC$_3$ (pumping well)	0	T, C	170-220	Sun.
-3CDC$_1$	150	T	231-237	Sun.
-3CDC$_2$	500	T, C	217-223	Sun.
-3CDB$_2$	760	T, C	77-80	S.V.-Sun.
-3CDB$_3$	770	T	88-91	S.V.-Sun.
-3CAC	1440	T	81-84	S.V.
-10BBB$_1$	1600	T, C	138-141	Sun.
-10BBB$_2$	1620	T, C	206-212	Sun.
-3CBA$_4$	1760	T	148-151	Sun.
-3CBA$_3$	1810	T, C	257-263	Sun.
-3CBA$_1$	2000	T	?- 96	S.V.
-3DBB	2040	T, C	227-233	Sun.
-3DCD	2090	T	58-61	S.V.-Sun.
-3CBA$_2$	2270	T, C	231-237	Sun.
-10BCB	2530	T, C	238-241	Sun.
-3BCC	2800	T, C	217-223	Sun.
-3ACB	2950	T	208-214	Sun.
-4DBD	3300	T, C	246-252	Sun.
-2CCB	3700	T	97-100	Sun.
-4AAD	3900	T, C	*Multiple slots	S.V.-Sun.
-11BCB	4200	T	66-69	S.V.-Sun.
-4ACA$_2$	4300	T, C	102-105	S.V.-Sun.
-4ACA$_1$	4370	T, C	206-212	Sun.
-4DBB	4400	T, C	252-258	Sun.
155-82-34CDC	4600	T	86-89	S.V.
-34CDD	4700	T	70-73	S.V.
154-82-10DAA	5200	T	97-100	S.V.-Sun.
-9DDD	5200	T	239-242	?
-4ABA$_2$	5400	T	97-100	S.V.
-4ABA$_1$	5600	T	80-100	S.V.
-4CCC	6200	T	418-424	Sun.
155-82-33DCC	6300	T	117-120	S.V.
-33CDD	6700	T	47-52	S.V.
-33CCD	7200	T	46-49	S.V.
154-82-5ACD	8700	T	257-263	Sun.
-1CCC	9000	T	297-303	Sun.
-11DAA	9500	T, C	177-183	Sun.
-8DCC	11,000	T	367-373	?
-7AAA	12,000	T	187-193	Sun.
-7DCC	15,500	T	257-263	?
-24BAA	15,800	T	25-28	S.V.
155-82-29CBC	16,800	T	48-53	S.V.
154-82-6CCC	17,000	T	277-283	Sun.
-24ABA	17,000	T	30-32	Sun.
155-82-29BCB	17,700	T	100-103	S.V.
-29BBC	18,400	T	80-100	S.V.
-29BBB	19,200	T	90-93	S.V.
154-81-8BCC	20,000	T	258-261	Sun.
-8CCC	20,600	T	318-321	Sun.
-15BBB	31,300	T	278-281	Sun.
-13DDD	47,000	T	156-159	Sun.

Total: 50 obs., 1 PW
T: measured with chalked steel tape
C: continuous recorder installed on well
*: data unreliable, well screened in more than one aquifer
Sun: Sundre aquifer
S.V.: Souris Valley

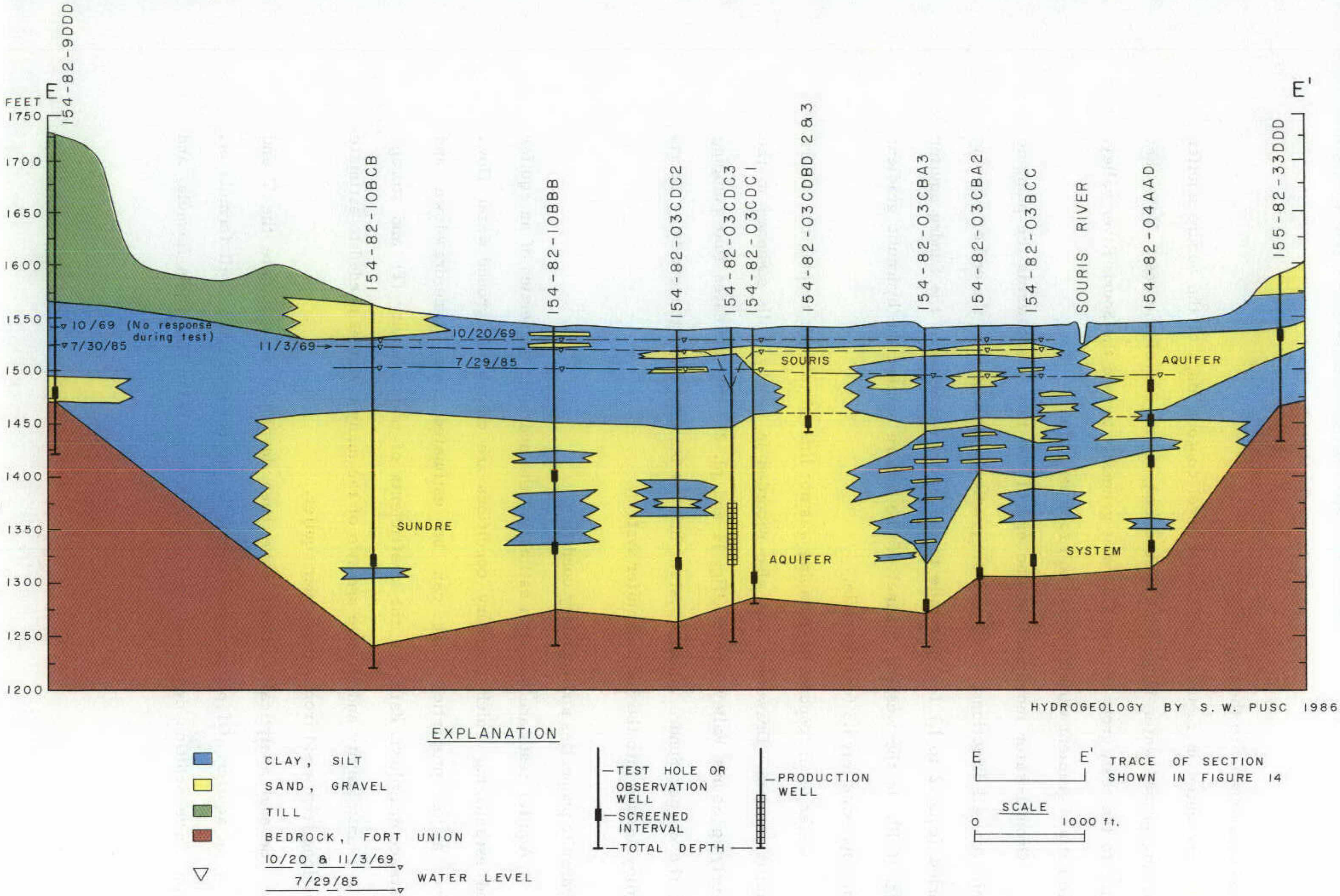


FIGURE 15. Hydrogeologic section E-E' of the Souris Valley Aquifer and Sundre Aquifer showing the drawdown recorded in selected observation wells monitored during the 1969 aquifer test.

thins considerably to the west (fig. 7).

Presented in Figure 16 are water level contour maps of the Sundre aquifer showing ground-water movement before and at the end of the test. Note that prior to the test, ground-water flow was generally toward the Souris River valley. The natural gradient varied from .5 to 1 foot per mile.

Ground-water movement at the end of the test was towards the pumping well from all directions. The hydraulic gradient established at the end of pumping varied from .2 to 1.7 feet per mile in the eastern channel of the Sundre aquifer (fig. 16-B). In the western channel of the Sundre aquifer the hydraulic gradient was approximately 1.5 feet per mile.

Water level response to pumping was not limited to wells tapping the Sundre aquifer system. Drawdown was also recorded in nearby wells screened in the overlying Souris Valley aquifer (fig. 14 and pl. 2). This indicates that pumping of the deeper Sundre aquifer system induces leakage from the overlying Souris Valley aquifer into the Sundre aquifer system.

Hydraulic properties and boundary conditions

Aquifer tests are useful in estimating the hydraulic properties of an aquifer and establishing which boundary conditions are controlling ground-water flow. Two major properties that can be estimated from time-drawdown and distance-drawdown data are the coefficients of transmissivity (T) and storage (S). Transmissivity and storage are two of the many variables needed to estimate the long term yield from a particular aquifer.

Several analytical methods have been developed to calculate the T and S of an aquifer. Of primary importance is the nonequilibrium well formula or, type curve solution developed by C. V. Theis in 1935. The Theis formula, and

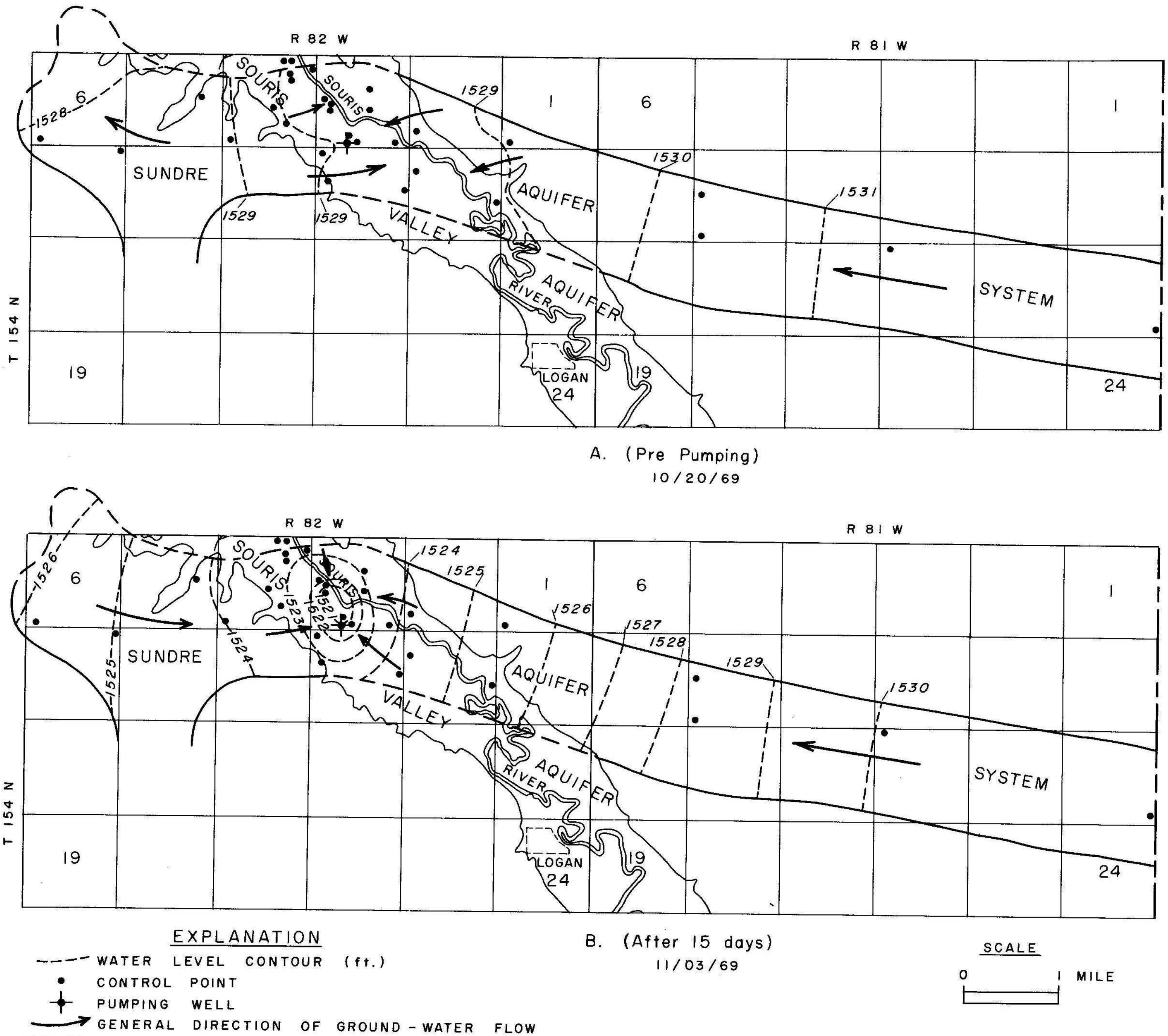


FIGURE 16. Potentiometric surface maps of the Sundre Aquifer System prior to the 1969 aquifer test (A) and after pumping well 154-82-03CDC3 for 15 days at 1950 gpm (B.)

several modified versions developed since, describe the relationship of drawdown to: transmissivity (T), storage coefficient (S), time (t), distance (r) and discharge (Q). The derivation and limiting assumptions of the Theis equation are presented in many references (Theis, 1935, Lohman, 1972, and Freeze and Cherry, 1979).

One of the major drawbacks of the Theis method is the limiting assumption of no leakage of water from overlying aquitards. If leakage is taking place, less drawdown will be measured in an observation well. Application of the Theis and Jacob methods to time-drawdown data impacted by leakage, results in the calculation of a larger than actual transmissivity.

The Theis equation also assumes that the aquifer is homogeneous, isotropic and infinite in areal extent. If the cone of depression around a pumping well intercepts a zone of low transmissivity, the infinite aquifer assumption is violated. After such a zone is encountered, not as much water is available to the pumping well and consequently water levels around the pumping well will decline at a faster rate than if the aquifer were infinite. If a barrier boundary is encountered during a test, the drawdown versus time (t) curve will deviate above the Theis curve. Application of the Theis and Jacob methods to time-drawdown data impacted by one or more barriers results in the calculation of a smaller than actual transmissivity.

Inspection of the drawdown versus log time data plot for the two closest observation wells indicates that both leakage and barrier boundaries affected the drawdown response (fig. 17). From 0 to 15 minutes, discharge was not constant and thus no conclusions on boundary conditions can be made. Within the 15 to 400 minute time interval the rate of change of drawdown with respect to the log of time decreases (curve flattens) indicating the impact of leakage. After

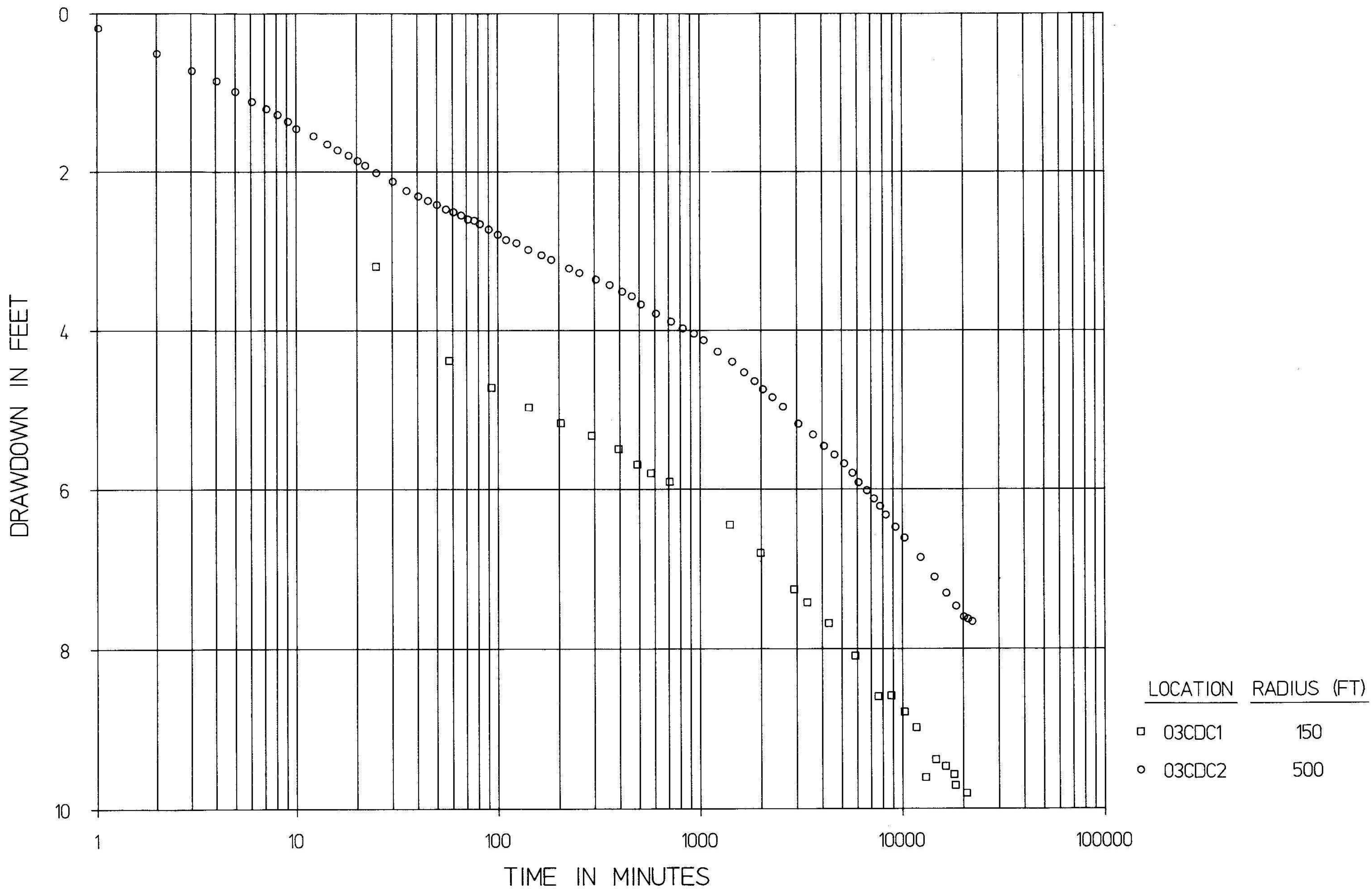


FIGURE 17. Semi-log plot of drawdown versus time for observation wells 154-82-03CD 1 & 2 during the 1969 Sundre Aquifer test.

400 minutes of pumping, until the end of the test, the rate of change of drawdown with respect to the log of time increases (curve steepens) indicating the impact of barrier boundaries.

Another technique for determining boundary conditions and hydraulic properties is to plot drawdown data from an aquifer test versus t/r^2 (time/radius squared) on logarithmic paper. If the aquifer is homogeneous, isotropic, infinite in areal extent and discharge is held constant, the data plots for all the observation wells should overlap along a single continuous curve called the Theis curve (Riley, 1971). If the drawdown plots from the individual wells do not all fall on the same curve, one or more boundary conditions is probably affecting the response. As stated by Riley (1971):

> "If the drawdown at a given value of t/r^2 diminishes with distance from the pumped well there is a strong possibility that results are being influenced by leakage."

If significant leakage exists, data obtained from wells at increased radii will fall lower and lower on the t/r^2 graph.

Under leaky conditions, additional boundaries encountered by the cone of depression will distort the drawdown versus t/r^2 curves causing subsequent data to deviate from the Hantush leaky type curves, (Lohman, 1972). If a barrier boundary is encountered, the data points will deviate upward reflecting a decrease in the supply of water to the pumping well. If a recharge boundary is encountered, the data points will deviate below the Hantush leaky type curves indicating an increase in the supply of water to the pumping well.

Presented in Figures 18 and 19 are logarithmic plots of drawdown versus t/r^2 for 7 nearby observation wells monitored during the 1969 pumping test. Note that for small values of t/r^2, the data points for all the observation wells fall

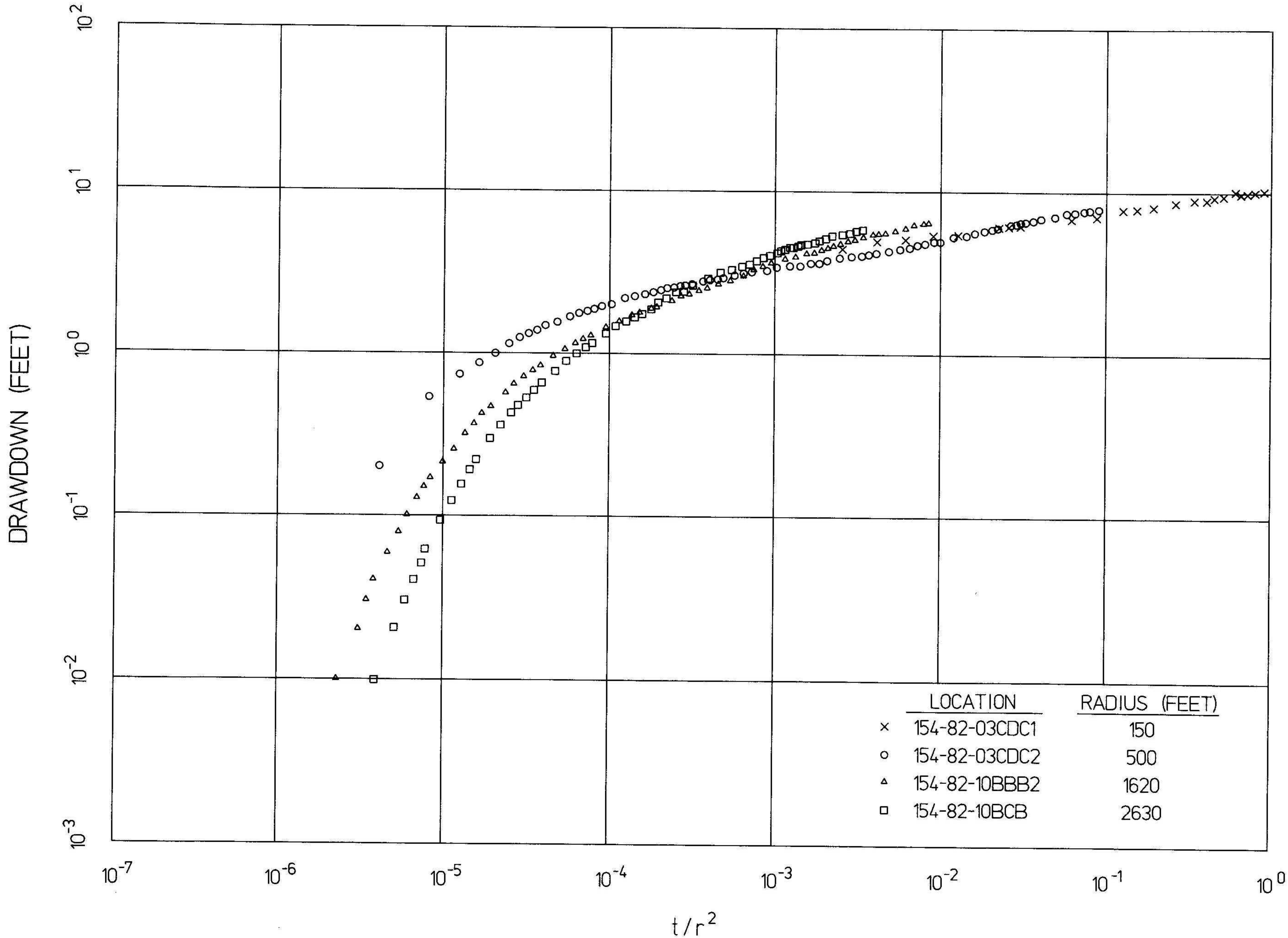


FIGURE 18. Logarithmic plots of drawdown versus t/r² for 4 observation wells monitored during the 1969 Sundre Aquifer test.

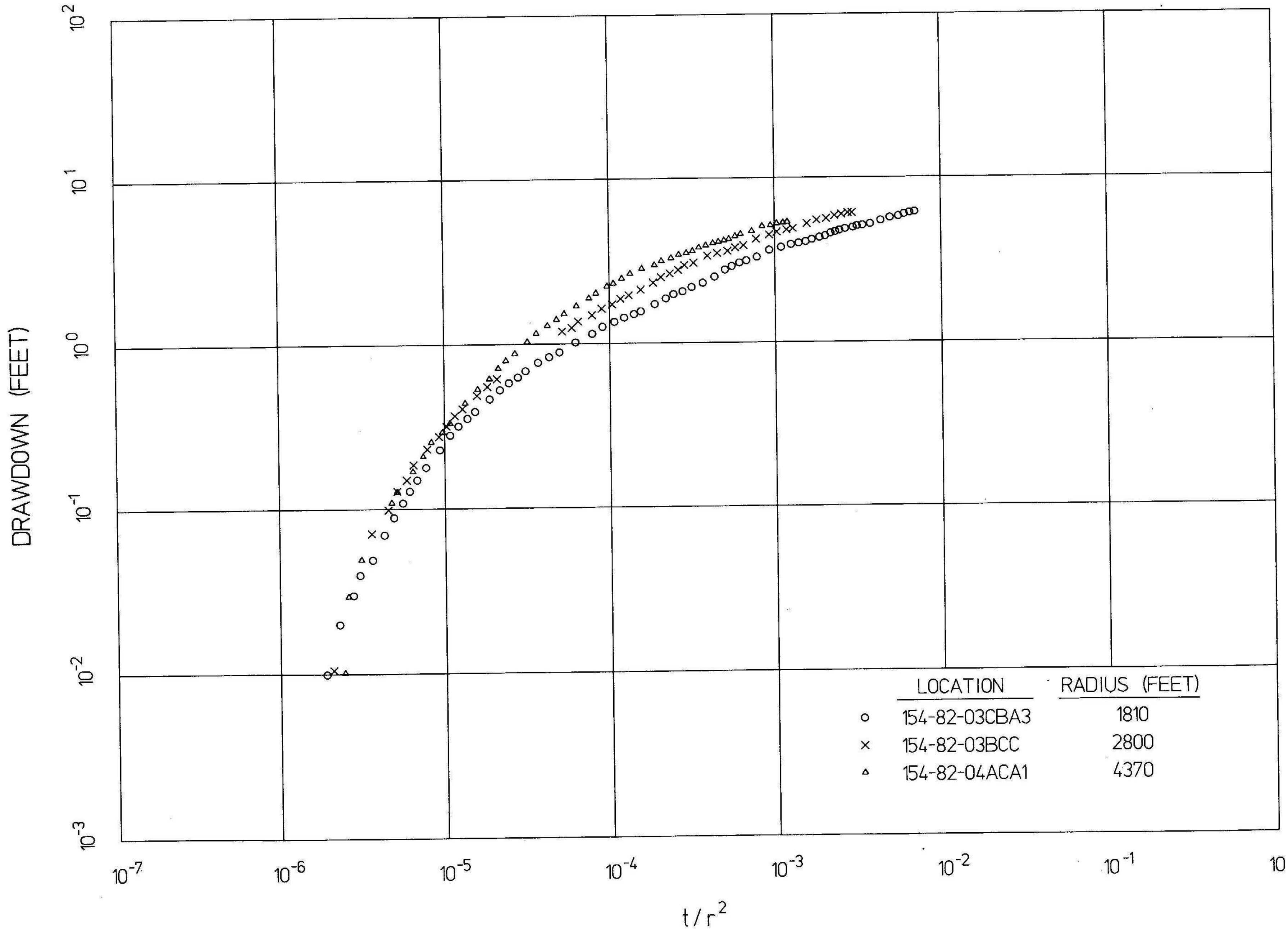


FIGURE 19. Logarithmic plots of drawdown versus t/r^2 for 3 observation wells monitored during the 1969 Sundre Aquifer test.

below the drawdown curve of the closest observation well to the pumping well (fig. 18 and 19). This suggests that leakage from overlying sediments is reducing the drawdown in these wells. Also note that all the drawdown curves begin to deviate upward and eventually cross the drawdown curve for the wells with smaller radii from the pumping well. This indicates that barrier boundaries, encountered by the cone of depression, are causing more drawdown in the observation wells than would be expected if the aquifer was infinite.

Also note that the theory of drawdown data from wells at ever increasing radii plotting ever lower on the graph, only holds true for wells with smaller radii (fig. 18 and 19). Such a situation indicates a departure from radial symmetry around the pumping well. Non-radial flow around the pumping well would result from directional differences in transmissivity and/or barrier boundaries. As stated by Riley 1971:

> "For this reason, the composite t/r^2 plot whose importance in diagnosis of leaky conditions which has already been emphasized, is also useful as an indicator of anistropy."

Drawdown data from the 1969 aquifer test indicate that the Sundre aquifer is a leaky, confined system with numerous barrier boundaries. It appears that the barrier boundaries are of such magnitude that they overcome the effects of leakage and eventually control the drawdown response.

Analytical techniques used to estimate the aquifer properties of transmissivity (T) and storage (S) are all based on an idealized aquifer system. Test drilling and aquifer testing has shown that the Sundre aquifer system is far from ideal in meeting the 'textbook' assumptions. Most of the limiting assumptions inherent in the analytical techniques are violated to one degree or another. There are, however, techniques which can be applied to calculate aquifer coefficients even when some of the assumptions are violated.

Presented in Figure 20 is a suite of distance-drawdown data plots for selected times after pumping began during the 1969 aquifer test. Note that for all times selected, the slope of the straight-line, distance-drawdown, data plots between the two close-in wells remains relatively constant with time (fig. 20). Barrier boundaries have little impact on altering the slope of the straight-line distance-drawdown data plot. As a result, aquifer transmissivity calculated will be close to its true value (Anon, 1966). However, the straight-line distance-drawdown data plots will be shifted upward due to leakage or downward due to the impact of barrier boundaries. Thus, an extension of the line to zero drawdown gives erroneous value for R^o (radius of zero drawdown), which makes the calculated value of storage coefficient too small (barrier boundaries) or too large (leakage). Values of transmissivity (T) calculated from the semi-log distance-drawdown data plots using the Jacob equation range from 33,000 ft^2/day to 36,000 ft^2/day. Storage coefficient (S) ranges from 1×10^{-3} to 2×10^{-3}.

Ground-water flow systems after development

Vertical distribution of water levels

Water levels were measured in the vertical at nine (9) multiple piezometer sites during the course of this study. Six (6) sites are located in the Souris River floodplain near Minot's Sundre well field, two (2) sites are located in the eastern channel of the Sundre aquifer and one (1) site is located in the western channel of the Sundre aquifer (pl. 1).

Presented in Figures 21 through 26 are hydrographs of water levels obtained from piezometer nests located in the Souris River floodplain. Presented in Figure 6 is a hydrogeologic section which includes the flood plain piezometer nest data. Generally, at all of the multiple piezometer sites there is a decreasing water

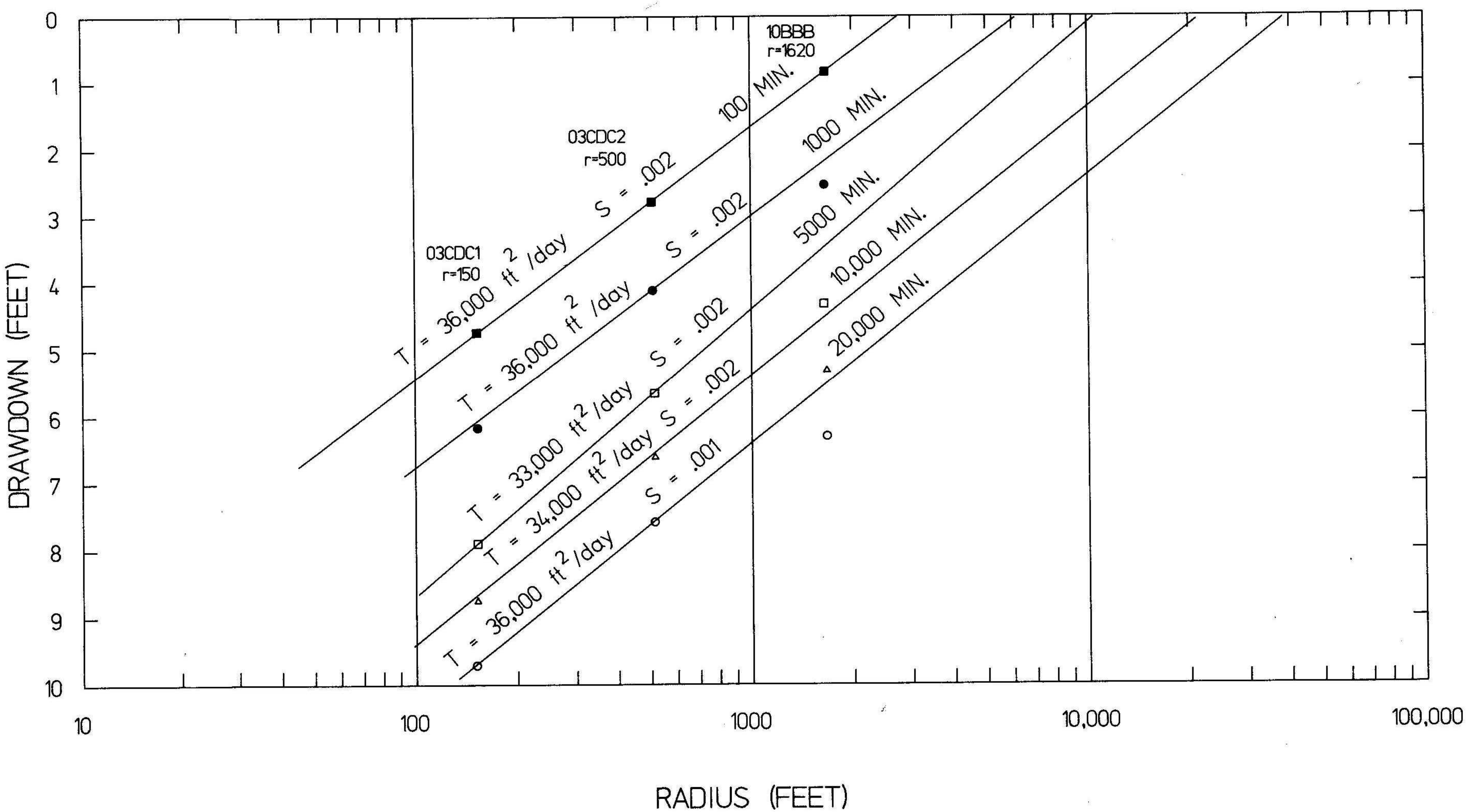


FIGURE 20. Semi-log plot of drawdown versus radius for the 1969 Sundre Aquifer test.

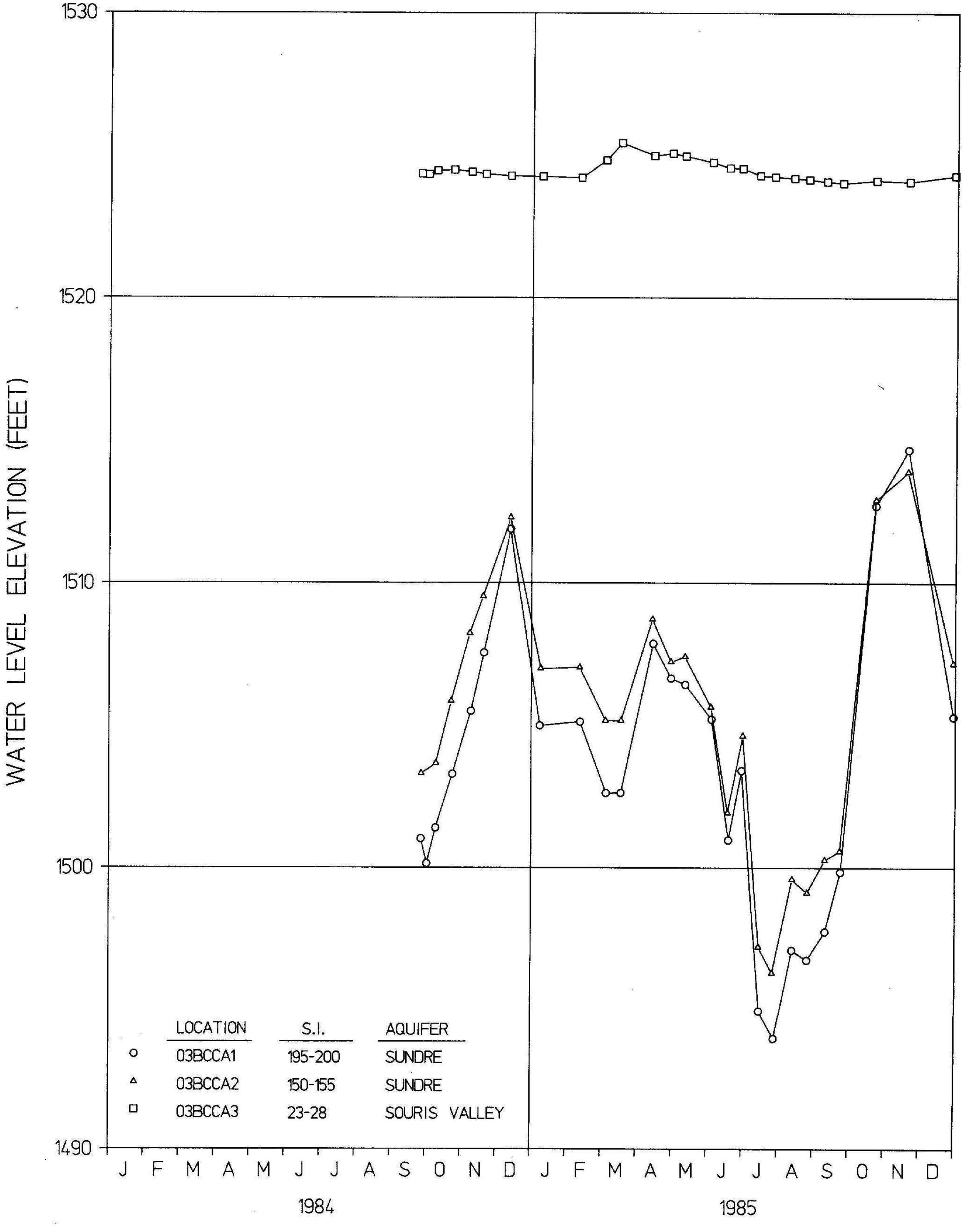


FIGURE 21. Hydrographs of water levels from piezometer nest 154-082-03BCCA showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

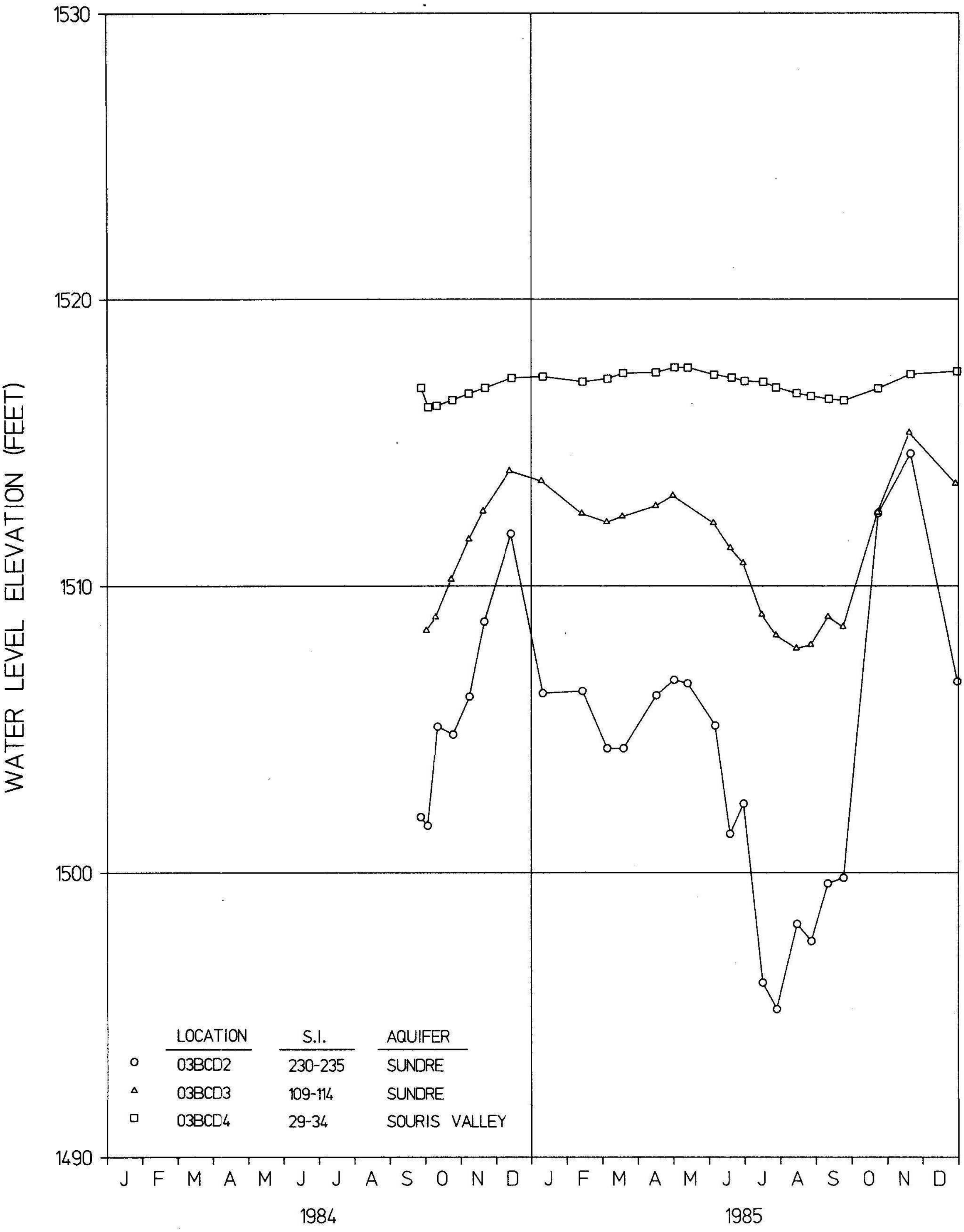


FIGURE 22. Hydrographs of water levels from piezometer nest 154-082-03BCD showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

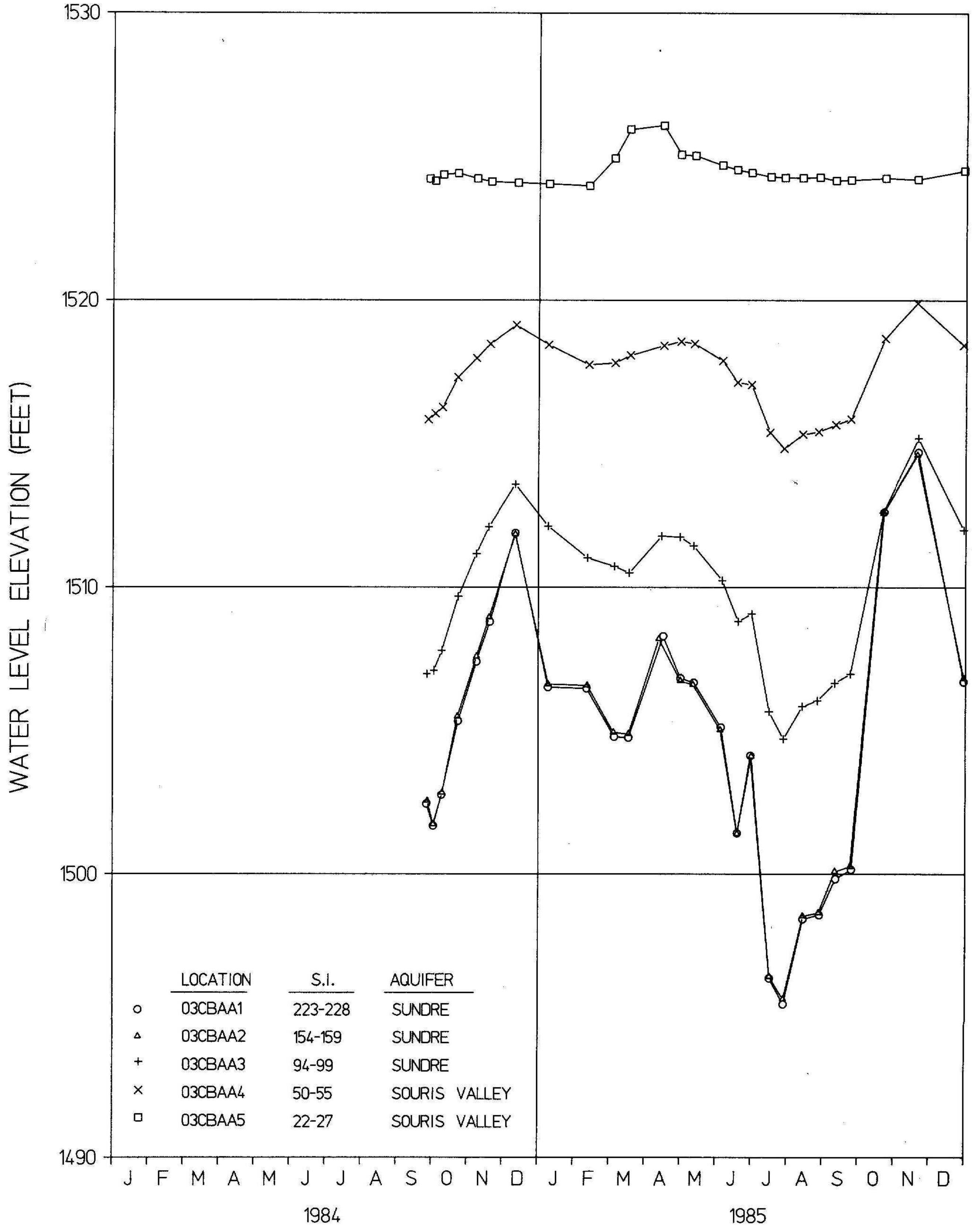


FIGURE 23. Hydrographs of water levels from piezometer nest 154-082-03CBAA showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

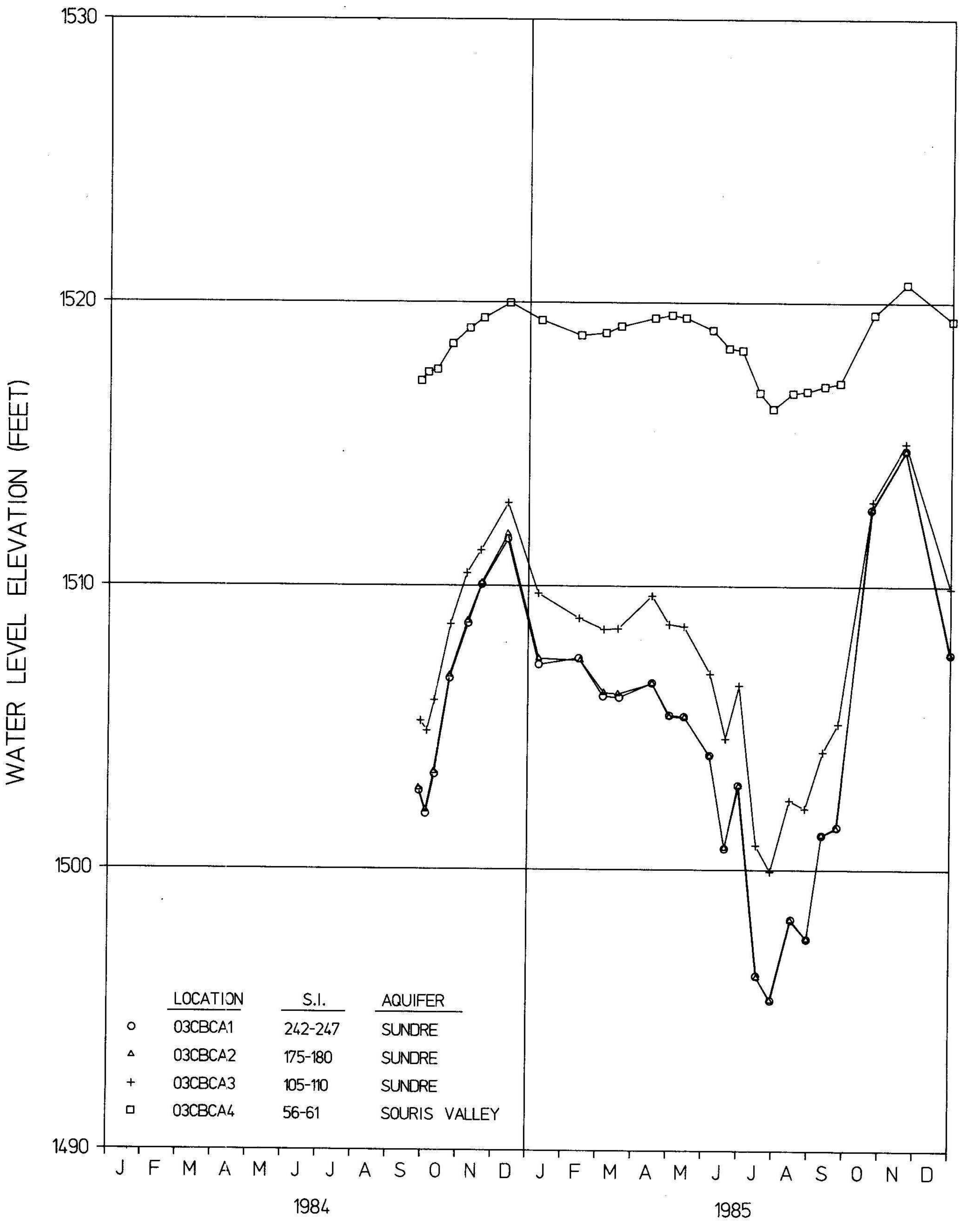


FIGURE 24. Hydrographs of water levels from piezometer nest 154-082-03CBCA showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

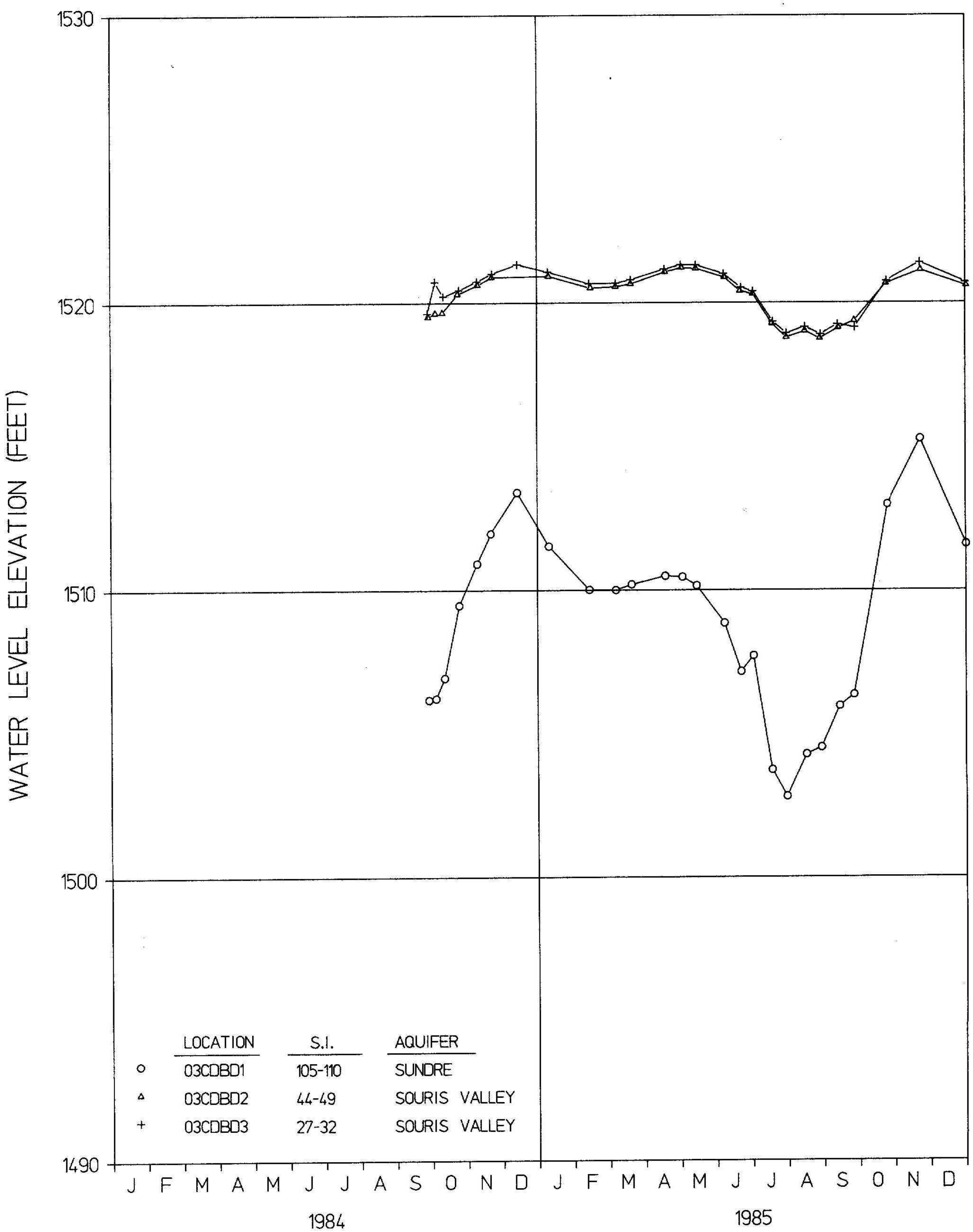


FIGURE 25. Hydrographs of water levels from piezometer nest 154-082-03CDBD showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

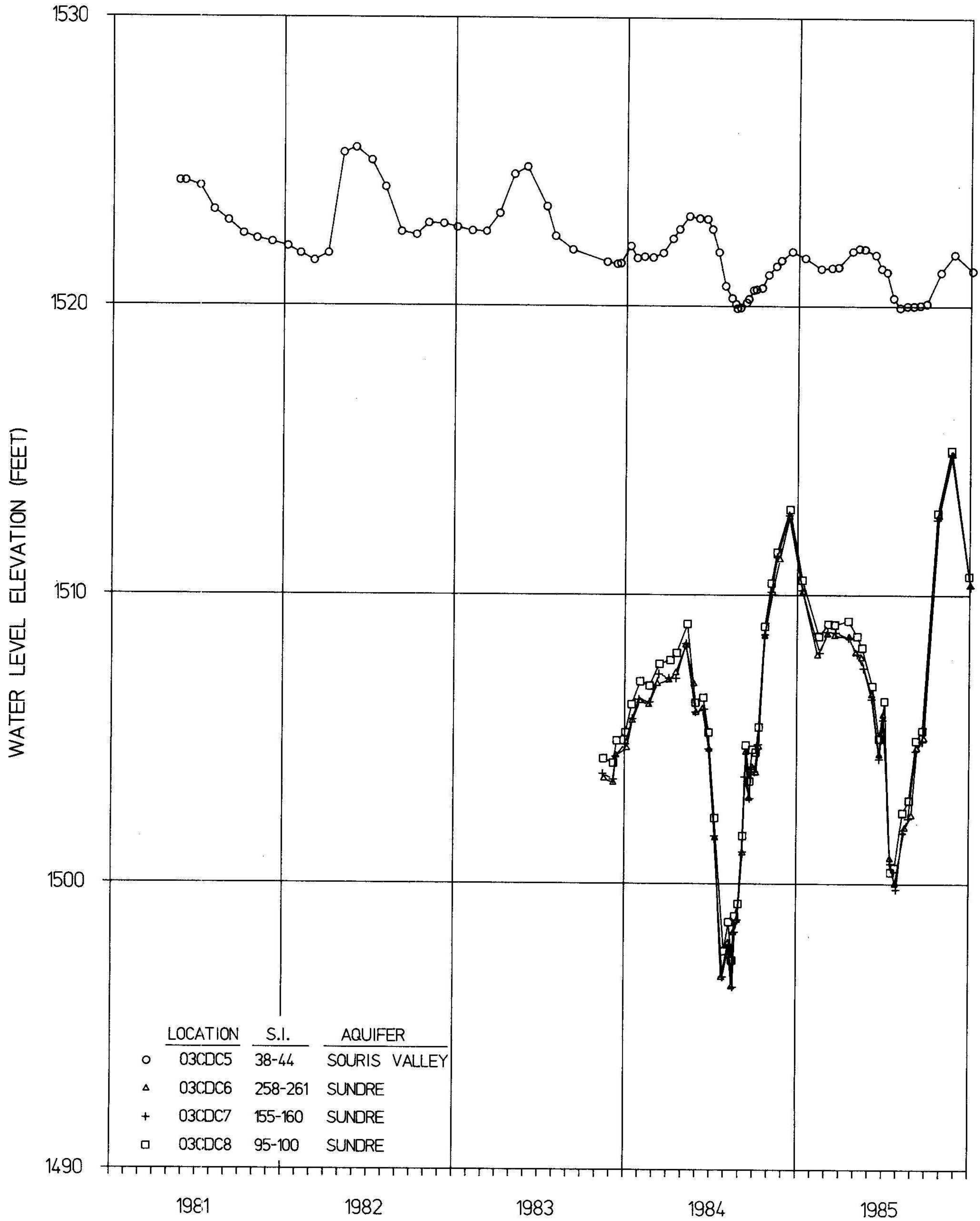


FIGURE 26. Hydrographs of water levels from piezometer nest 154-082-03CDC showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

level elevation with increasing depth relationship (fig. 21 through 26). Piezometer nest data indicates that pumping effects in the Sundre aquifer propagate up into portions of the Souris Valley aquifer (figs. 23, 24, and 25). Note, however, that water levels in two very shallow wells ($3BCCA_1$ and $3CBAA_1$) appear to respond more to climatic variations than to pumping (Figures 21, 22).

Based on the well nest data, ground water in the Souris River Valley moves downward from the surface through the Souris Valley aquifer, into the Sundre aquifer and finally is discharged from wells. Thus, long term pumping by the city of Minot has changed the dynamic equilibrium of the river valley-aquifer relationship. Due to pumping, the Souris River and Souris Valley aquifer are continual sources of water to the Sundre aquifer system instead of being sources during recharge events (high river stage, high precipitation) and sinks during discharge events (low river stage, evapotranspiration; this excludes bank storage).

Presented in Figures 27 and 28 are hydrographs of water levels obtained from two piezometer nests located in the eastern channel of the Sundre aquifer system (see fig. 7, hydrogeologic section D-D'). Note that for piezometers screened in the main body of the Sundre aquifer, water level elevations decrease slightly or are the same with depth. Water levels in the overlying till are generally 100 feet higher than water levels in the Sundre aquifer. This suggests that precipitation on the surface may move very slowly downward through the tills and eventually into the Sundre aquifer system. Flow within the eastern channel of the Sundre is slightly downward but principally lateral towards the pumping wells in the Souris River valley. Thus, the direction of vertical ground-water movement has remained the same with time, however, pumping of the Sundre well field has probably increased the downward gradient. If pumping has increased

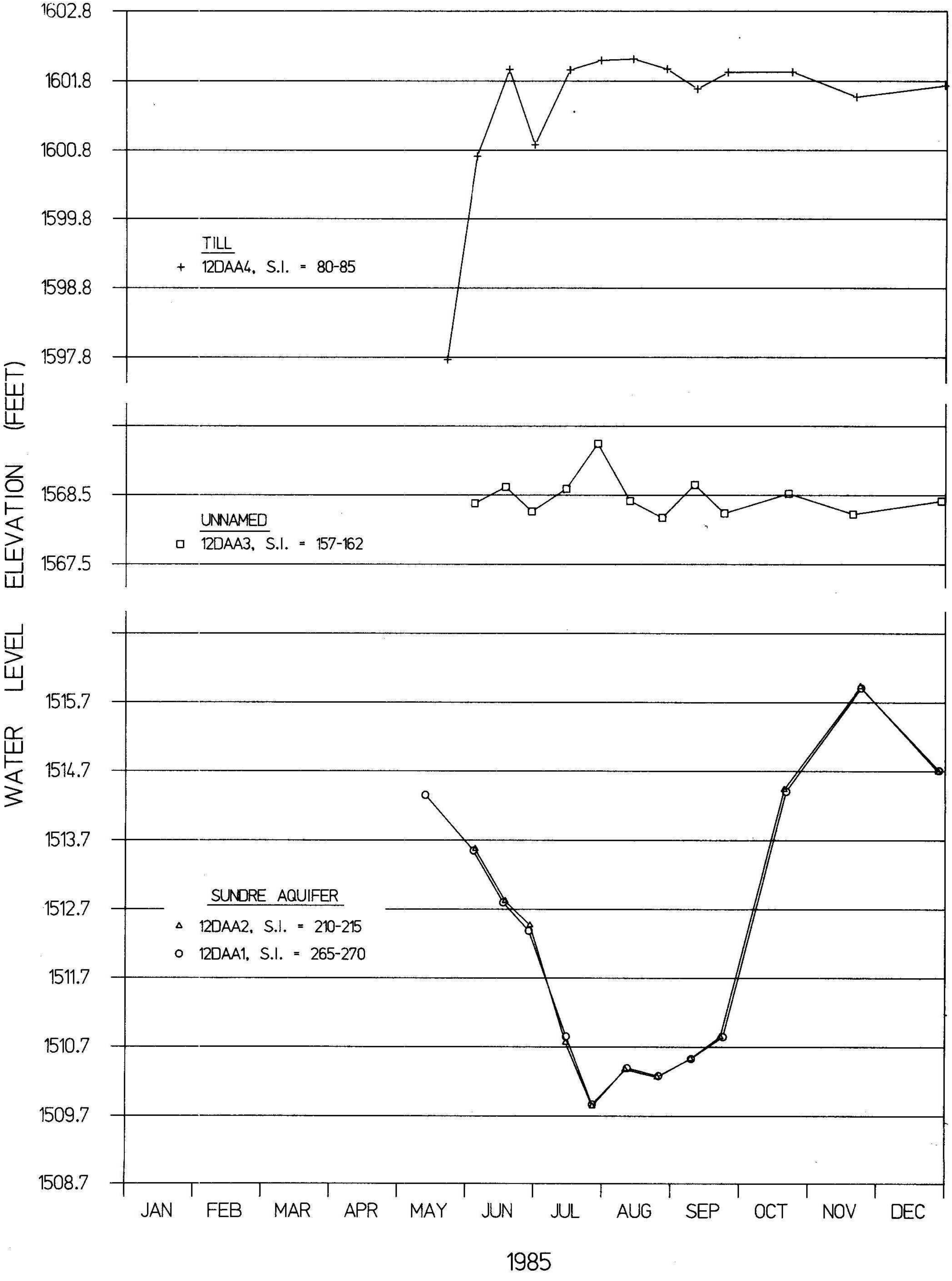


FIGURE 27. Hydrographs of water levels from piezometer nest 154-82-12DAA showing the vertical distribution of water levels in the Souris Valley and Sundre Aquifer systems.

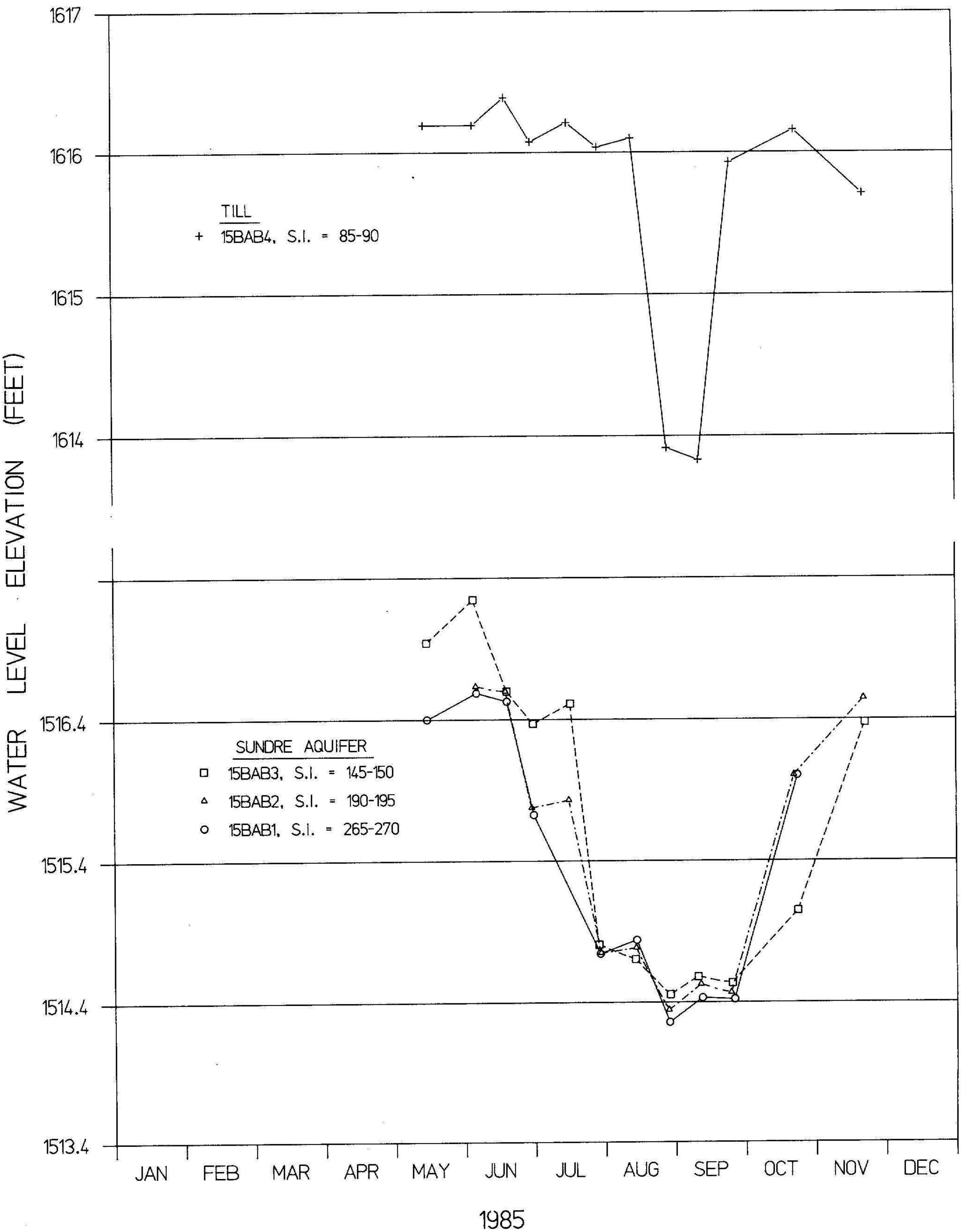


FIGURE 28. Hydrographs of water levels from piezometer nest 154-81-15BAB showing the vertical distribution of water levels in the eastern channel of the Sundre Aquifer system.

the downward gradient, then a larger quantity of water may now be moving from the overlying tills into the Sundre aquifer.

Water levels in neither the till well or an overlying sand body at nest site 154-82-12DAA appear to respond to pumping of the Sundre aquifer (fig. 26). The decline in water levels in till well 154-81-15BAB$_4$ is actually a result of sampling the observation well and not as a result of pumping the Sundre aquifer. It may be, however, that water level data from the till wells has not been collected long enough to determine the long-term effects of pumping.

Water level response to pumping

Souris Valley aquifer

Long term hydrographs from four wells screened in sand and gravel of the Souris Valley aquifer are presented on Plate 2. A good correlation to pumping of the underlying Sundre aquifer is reflected in all the hydrographs. At three of the sites, the Souris Valley and Sundre aquifers are believed to be one continuous aquifer (3CDB$_3$, 3DCD, 11BCB). In these areas the water level in the Souris Valley aquifer has declined 28 to 32 feet as a result of pumping the Sundre aquifer.

Observation well 155-82-33CCD is screened in a portion of the Souris Valley aquifer which does not immediately overlie the Sundre aquifer (figs. 3 and 5). Water levels in this well did not respond during the 1969 aquifer test, however, long term pumping, since 1976, of the Sundre aquifer has caused water level declines of 15 to 20 feet (pl. 2). This indicates that pumping of the Sundre aquifer induces leakage from both overlying and nearby Souris Valley aquifer deposits.

Sundre aquifer

Presented on Plate 2 are hydrographs from representative wells completed in: (1) the eastern channel of the Sundre aquifer, (2) the Sundre aquifer in the vicinity of the Minot well field, and (3) the western channel of the Sundre aquifer. Development in 1976 is reflected by an immediate water level response in all the wells. Note that during periods of heavy use water levels declined and with less use water levels rose. Drawdown response to pumping from 1976 to 1985 has been recorded 13 miles east of the well field (pl. 3). Stabilizing water levels appear to be due to both the system approaching equilibrium conditions and to a gradual decline in total water pumped per year from 1983 to 1985 (pl. 2).

Presented in Figure 29 are hydrographs comparing water level elevations in the eastern channel of the Sundre aquifer system versus water level elevations in the adjoining New Rockford aquifer. Both wells are screened in sand and gravel which was deposited in the bedrock valley described in Chapter 2 (fig. 4). Water levels in 154-80-20BBB responded to pumping of the Minot well field, while water levels in 154-79-16CCC did not (fig. 29). Also, water levels in 16CCC are 30 to 35 feet lower in elevation than water levels in 20BBB (fig. 29). Differences in water level response and elevation support the concept of a low transmissivity barrier between 154-80-20BBB and 154-79-16CCC (pl. 3).

Presented in Figure 30 are hydrographs from representative wells screened in the western channel of the Sundre aquifer system. Water levels in 154-82-7AAA and 154-82-6ADB$_1$ responded to pumping of Minot's Sundre well field while water levels in wells to the north did not show a strong correlation to pumping (fig. 30). These water level responses indicate that a low transmissivity barrier probably truncates the buried channel somewhere between 155-82-6ADB$_1$ and 155-83-36ABB (pl. 3).

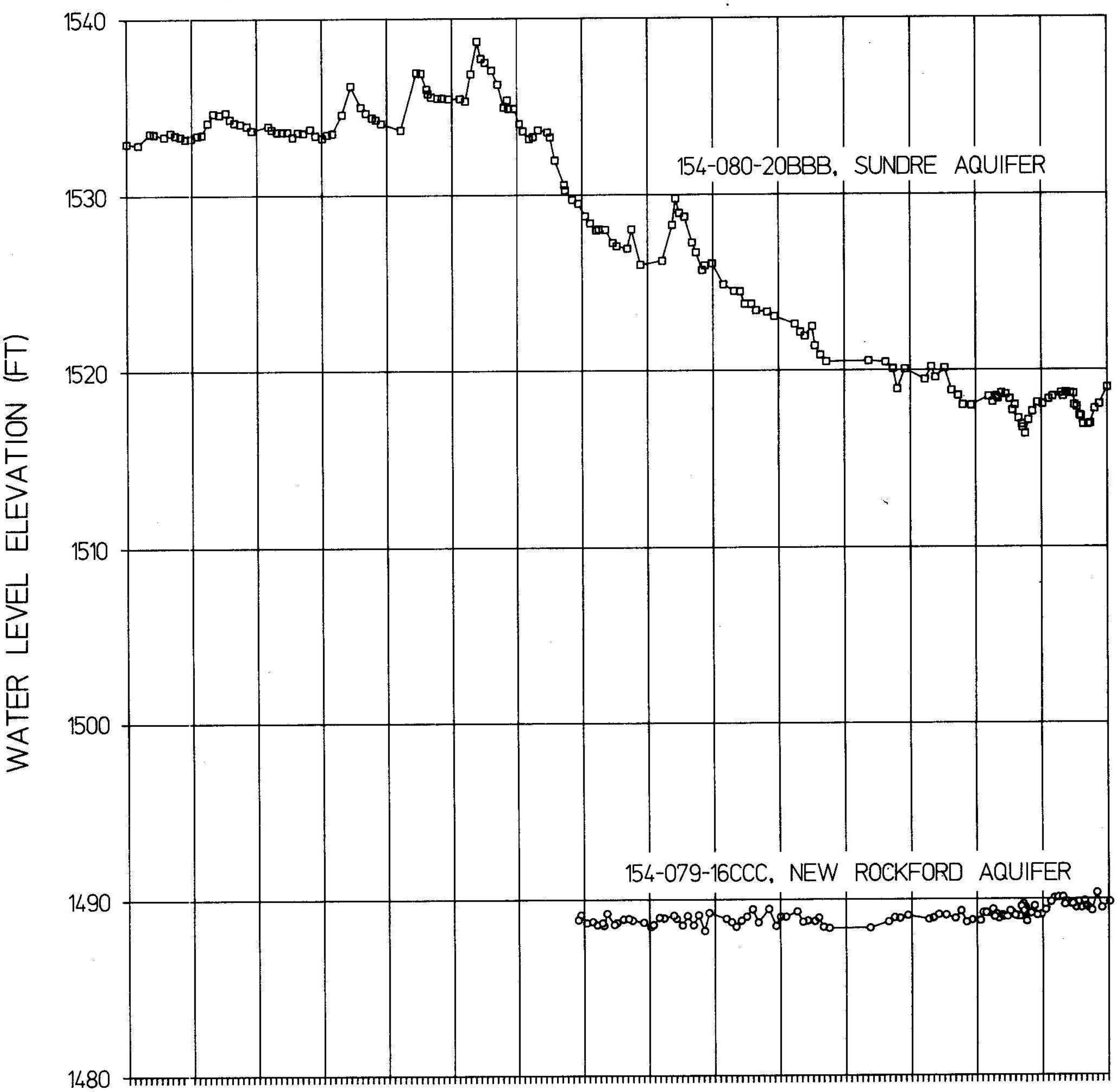


FIGURE 29. Hydrographs comparing water level elevations in the eastern channel of the Sundre Aquifer versus water level elevations in the adjoining New Rockford Aquifer.

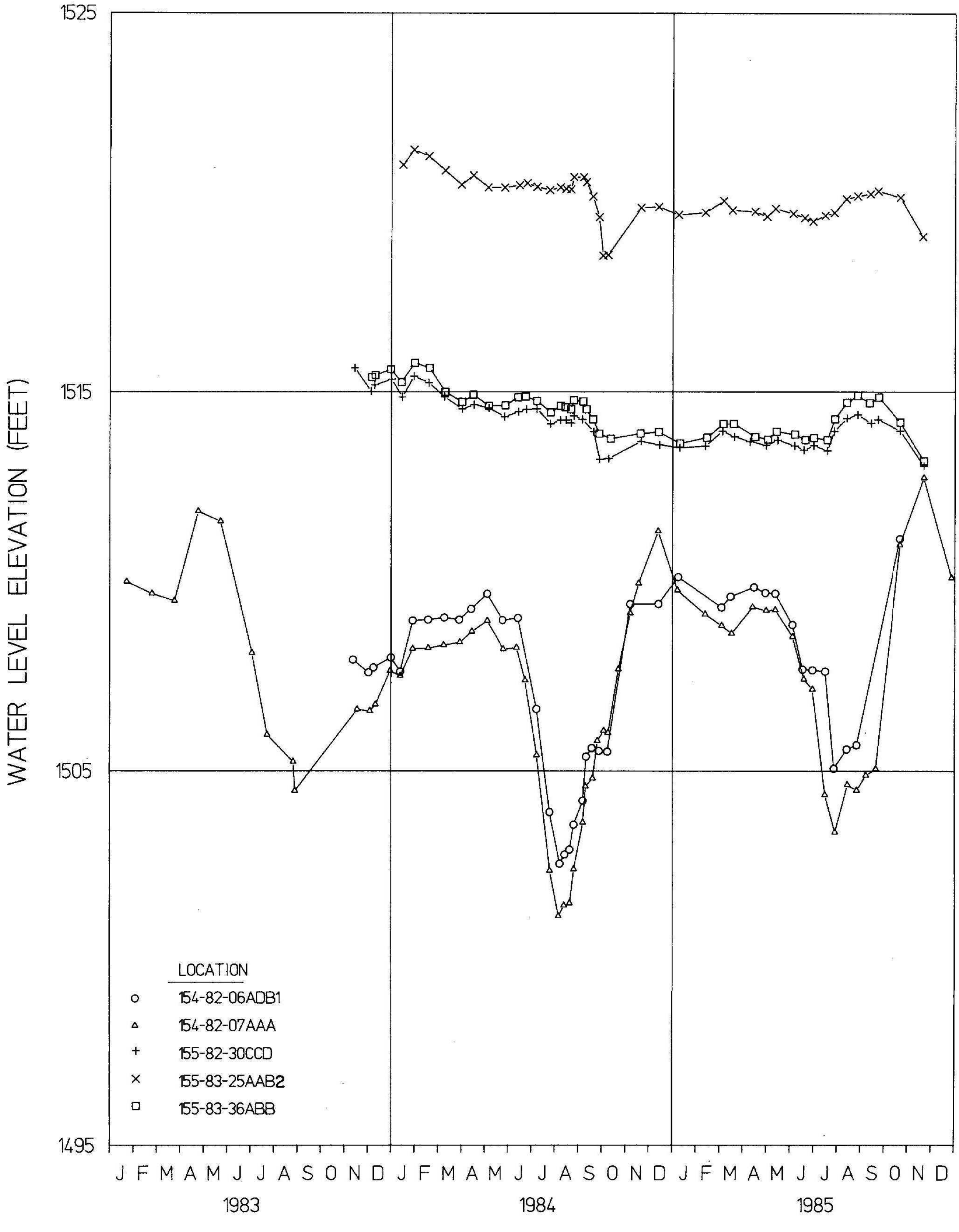


FIGURE 30. Hydrographs comparing water levels from observation wells screened in the western channel of the Sundre Aquifer system.

Water level response to stage height of the Souris River

Since development (1976), fluctuations in ground-water levels have been dominated by pumping patterns of the Sundre well field. As such, it is very difficult to determine the effects of a rising or falling Souris River stage on ground-water levels. Also, a rising river stage in the spring of the year meant that the city of Minot used less water from the Sundre aquifer and more from the Souris River. Thus, it is difficult to determine how much water level recovery during a high river stage event, such as 1979, was due to a rising river or how much recovery was due to less well pumpage. To further complicate the matter, there has been only one major flood event (1979) with which to correlate water levels since well pumpage began (1976).

Channelization of the Souris River below Minot, to accommodate flood flows, was completed in 1976. Because of these efforts, inundation of the Souris River floodplain should not occur with the same frequency as it once did. Consequently, flood control efforts would reduce the amount of natural recharge to the Sundre aquifer by preventing major overbank recharge events. Data to conclusively substantiate this hypothesis is presently insufficient.

Ground-water movement

Ground-water movement in the Sundre aquifer just before development (1975) and after 10 years of pumping is presented on plate 3. Water levels presented on Plate 3-A were obtained during low river stage, before development (August 13 and 14, 1975). The 1985 water levels presented on Plate 3-B were obtained during low river stage, and heavy July water use by the city of Minot (July 29, 1985). Plate 3-C shows the near maximum drawdowns generated by taking the difference of Plate 3-A and 3-B.

Ground-water movement during low river flow conditions of August, 1975 was generally towards the Souris River. Elevations range from 1536 feet in the far eastern channel of the Sundre to 1529 feet near the river (Plate 3-A). Gradients varied from .09 feet/mile in the eastern channel of the Sundre aquifer to 7 feet /mile near the river.

Ground-water movement during heavy water use of July 1985 was toward Minot's Sundre well field from all directions (Plate 3-B). Elevations in the eastern channel ranged from 1521 feet near 154-80-24DAA to 1492 feet near well A of the Minot Sundre well field. Gradients varied from .75 feet/mile out in the eastern channel to over 10 feet/mile near the well field. Water level elevations in the western channel ranged from 1514 to 1500 feet. Note also that the gradient changed several times along the aquifer, probably reflecting changes in aquifer transmissivity.

Because there are five wells pumping at varying rates at different times of the year, it is difficult to depict the potentiometric surface near the pumping wells. Therefore, no attempt was made to accurately represent the multiple overlapping cones of depression created by the pumping wells.

Water level change, 1975-1985

The water level change (residual drawdown) as a result of pumping has been approximately 17 to 25 feet in the far eastern channel of the Sundre aquifer (pl. 3-C). Near the well field the decline is between 31-40 feet. In the western channel of the Sundre aquifer, water level declines of about 28 feet have occurred. Note that the water level change in the western channel is far greater than the eastern channel. This, again, is a result of the decrease in transmissivity across this part of the channel coupled with the river recharge boundary to the north and east. A perspective of how much water level decline has occurred over the past 10 years, is presented on hydrogeologic sections in Figures 6 and 7.

WATER QUALITY

Introduction

Several factors contribute to the quality of ground water: the type of soil in the recharge area, the soil and rock types the ground water encounters along its flow path, regional topography, length of flow path, velocity of ground-water flow, temperature and pressure. The temporal and spatial distribution of chemical constituents may be used to identify time and place of recharge, place of discharge and residence time within the aquifer (Back and Hanshaw, 1971).

The chemical analyses of ground water in the study area were separated into types with each type having a similar ionic distribution. Each type represents a distinct hydrochemical facies. To differentiate the hydrochemical facies, the major ionic distribution of each chemical analysis was plotted on Piper and Schoeller diagrams. The distribution of the hydrochemical facies was analyzed in relation to location within the flow system, transmissivity, and topography. The overall objective was to utilize water chemistry data to substantiate and/or further define the conceptual model of the ground-water flow system.

Ground-water quality under natural conditions

Analyses of water samples collected in 1968 and 1969 were plotted on a Piper trilinear diagram (fig. 31). Generally, ground water obtained from the study area prior to development can be divided into four major hydrochemical facies. The first hydrochemical facies includes ground water collected from shallow sand and gravel deposits of the Souris Valley aquifer. Total dissolved solids (TDS) ranged from 473 to 1130 milligrams per liter (mg/l). Sulfate (SO_4)

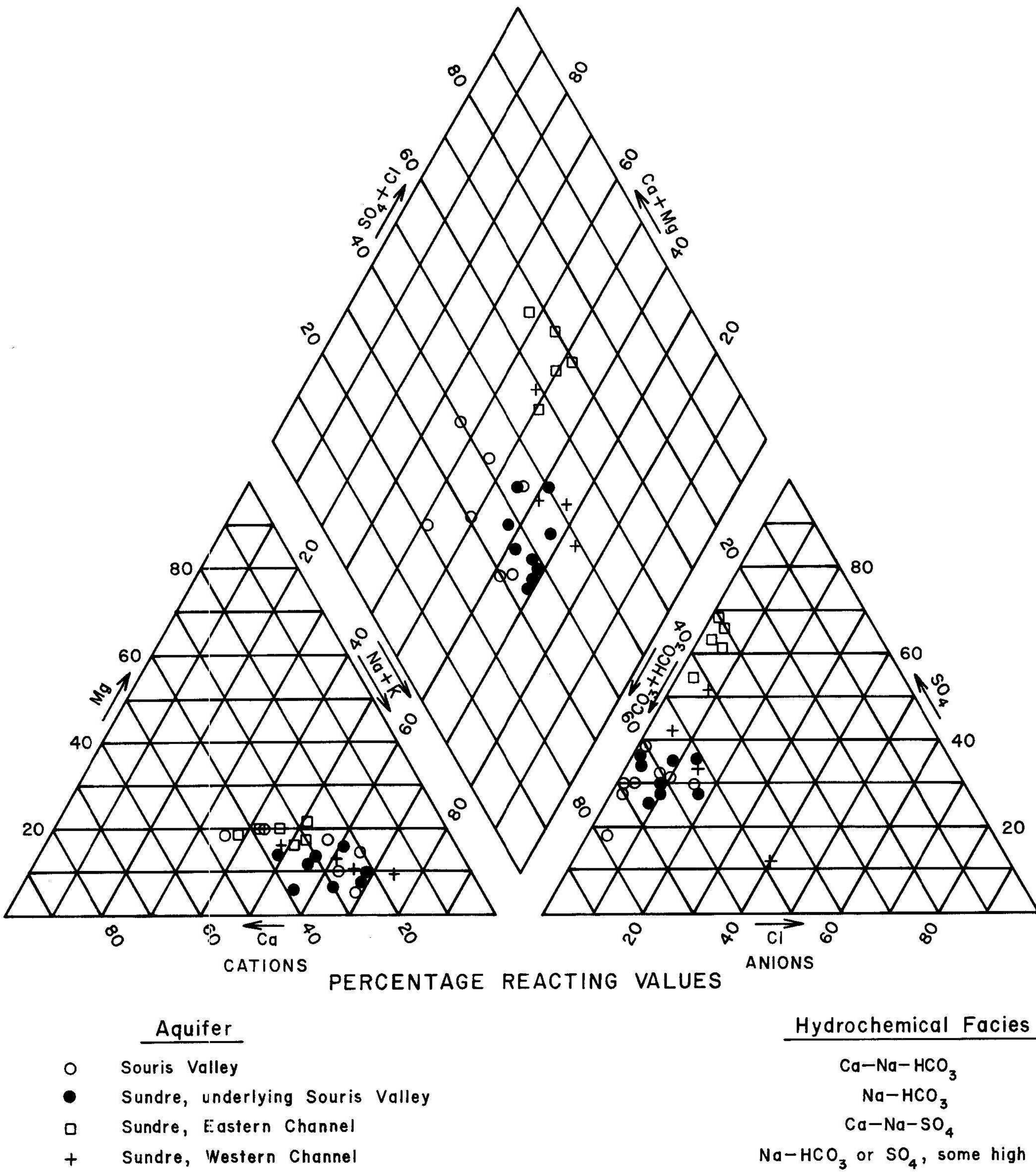


FIGURE 31. Piper diagram showing the chemical distribution of water quality in the Sundre aquifer system study area (samped,1968 & 1969).

levels were generally low to medium, ranging from 136 to 303 mg/l while sodium (Na) ranged from 38 to 246 mg/l. Locally, ground water from the Souris Valley aquifer contained high concentrations of iron. Hardness varied from soft to hard (100 to 481 mg/l). Generally, ground water from the Souris Valley aquifer, under natural conditions, could be classified as a calcium or sodium bicarbonate type with low to moderate TDS (Ca or Na-HCO_3, fig. 31).

The second hydrochemical facies included ground-water samples collected from wells screened in that part of the Sundre aquifer which underlies the Souris Valley aquifer. These waters were chemically very similar to ground water in the overlying Souris Valley aquifer, except that the sodium bicarbonate (Na-HCO_3) type dominates over the calcium type (fig. 31). The simularity in hydrochemical facies between the Souris Valley and Sundre aquifers in this area suggests rather rapid downward movement of recharge water in the absence of clay.

The third hydrochemical facies included ground-water samples collected from the eastern channel of the Sundre aquifer system. These waters were high in total dissolved solids (1790-2140 mg/l). Sulfate (SO_4) levels ranged from 762-1100 mg/l while sodium (Na) levels ranged from 286 to 403 mg/l. High levels of sulfate (SO_4) were probably a result of dissolution of gypsum in the glacial drift and/or oxidation of organics (lignites) and pyrite (Hendry, 1984). The slow movement of ground water out in the eastern channel resulted in a long-residence-time environment, which would tend to increase the dissolved solids. Generally, ground water in the eastern channel of the Sundre aquifer, under natural conditions (1969), could be classified as a calcium - sodium - sulfate (Ca-Na-SO_4) type with high to very high total dissolved solids (fig. 31).

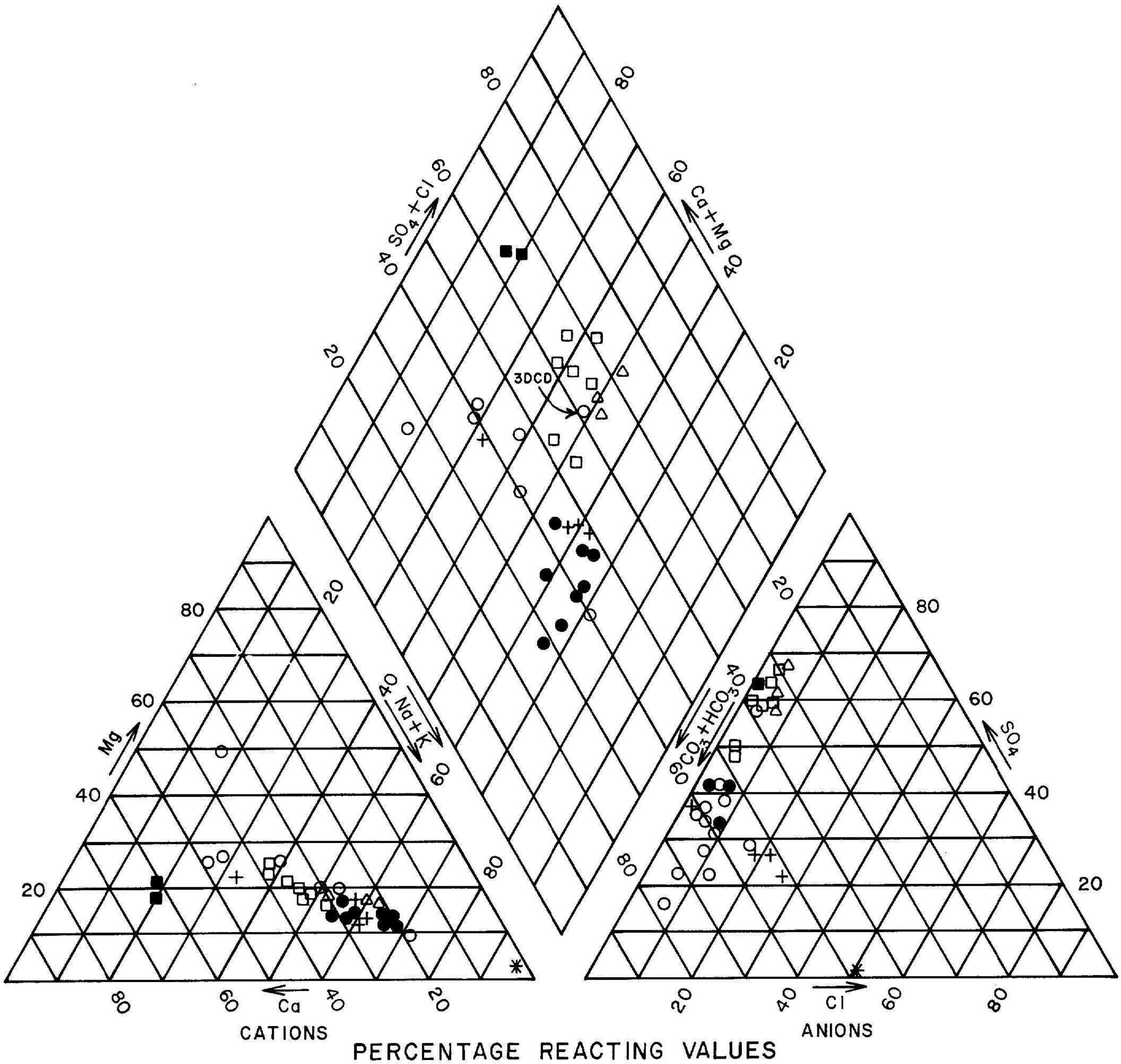
The fourth hydrochemical facies included ground-water samples collected from the western channel of the Sundre aquifer system. These waters could be classified as sodium-bicarbonate ($Na-HCO_3$) types, with an occasional high chloride level (33 to 304 ppm, fig. 31). Total dissolved solids were rather high, ranging from 1010 to 1910 mg/l. Sulfate (SO_4) levels ranged from 142-334 ppm while sodium (Na) varied from 230-537 mg/l.

Ground-water quality after development

A Piper trilinear diagram for the June 27, 1985 ground-water samples is presented in Figure 32. Generally, ground water obtained from the study area following development can be divided into seven major hydrochemical facies. The increase in hydrochemical facies in 1985 as compared to 1969 results from: (1) physically sampling more types of ground-water environments (i.e. bedrock and till) and, (2) pumping induced changes in water quality. Figure 33 shows a geographic and vertical distribution of the facies type or types.

The first hydrochemical facies includes ground-water samples collected from shallow sand and gravel deposits of the Souris Valley aquifer (figs. 32 and 33). Total dissolved solids are moderate (715 mg/l to 1040 mg/l) while sulfate (SO_4) levels are low to medium (38 to 260 mg/l, figs 32 and 33). The water is soft to hard and locally can contain excessive amounts of iron. Basically, ground water from the Souris Valley aquifer (June, 1985) can be classified as a calcium or sodium bicarbonate type ($Ca-Na-HCO_3$, figs. 32 and 33).

The second hydrochemical facies includes ground-water samples collected from that part of the Sundre aquifer underlying the Souris Valley aquifer north of the Souris River in Section 3 and in the vicinity of Minot city wells A, B, and C (figs. 32 and 33). Piezometer nest information indicates that ground water in this area ranges from a calcium-sodium-bicarbonate ($Ca-Na-HCO_3$) type water



Aquifer

- ○ Souris Valley
- ● Sundre, underlying Souris Valley near wells A, B+C
- △ Sundre, underlying Souris Valley near well D+E
- □ Sundre, Eastern Channel
- \+ Sundre, Western Channel
- ■ Glacial till water
- ✱ Bedrock

Hydrochemical Facies

- $Ca-Na-HCO_3$
- Ca or $Na-HCO_3$
- $Na-SO_4$
- $Ca-Na-SO_4$
- $Na-HCO_3$
- $Ca-SO_4$
- $Na-Cl$

FIGURE 32. Piper diagram showing the chemical distribution of water quality in the Sundre aquifer system study area (sampled, June 27,1985).

be classified as sodium-bicarbonate (Na-HCO_3) types, with an occasional high chloride level (33 to 304 ppm, fig. 31). Total dissolved solids were rather high, ranging from 1010 to 1910 mg/l. Sulfate (SO_4) levels ranged from 142-334 ppm while sodium (Na) varied from 230-537 mg/l.

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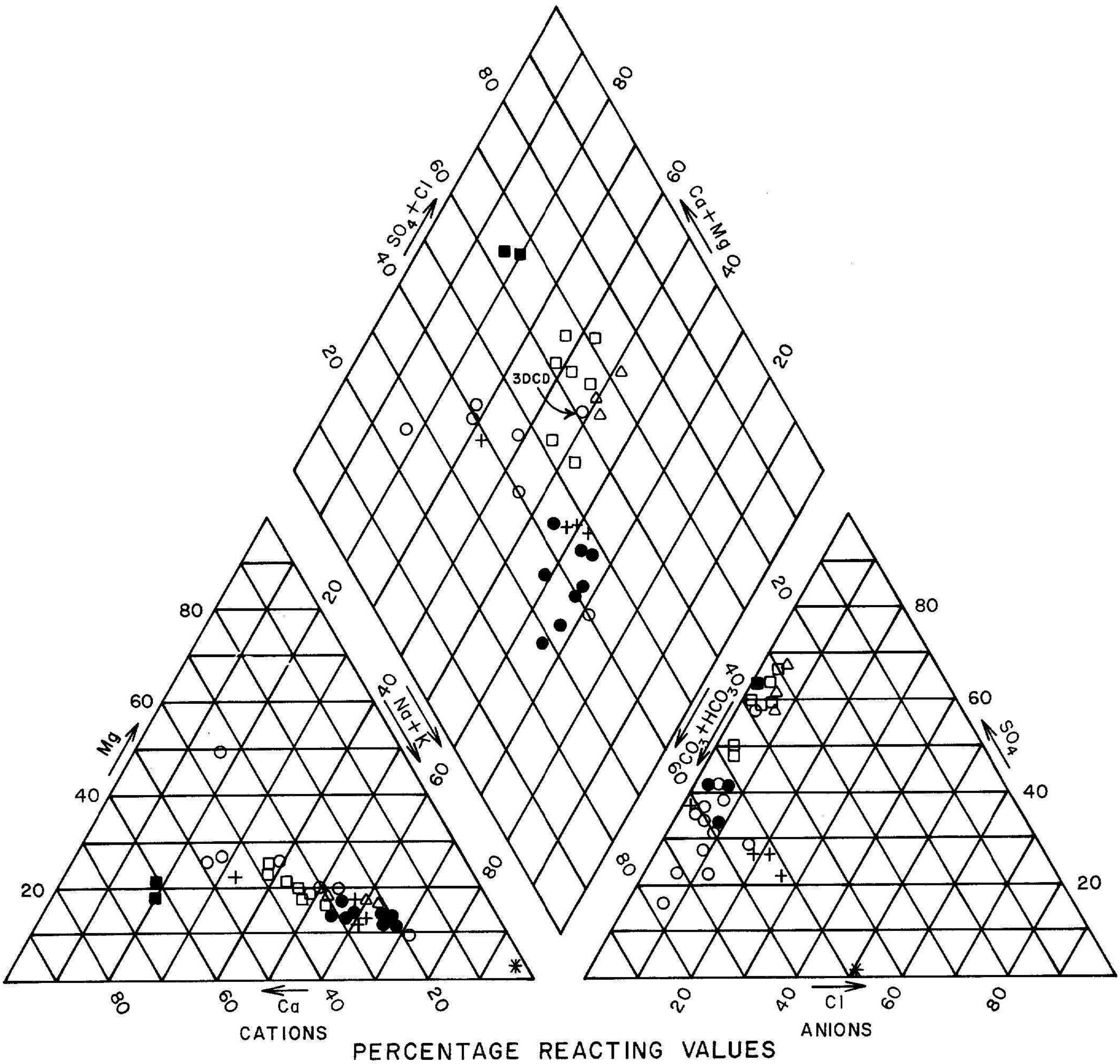
The second hydrochemical facies includes ground-water samples collected from that part of the Sundre aquifer underlying the Souris Valley aquifer north of the Souris River in Section 3 and in the vicinity of Minot city wells A, B, and C (figs. 32 and 33). Piezometer nest information indicates that ground water in this area ranges from a calcium-sodium-bicarbonate (Ca-Na-HCO_3) type water



Aquifer

- ○ Souris Valley
- ● Sundre, underlying Souris Valley near wells A, B+C
- △ Sundre, underlying Souris Valley near well D+E
- □ Sundre, Eastern Channel
- + Sundre, Western Channel
- ■ Glacial till water
- ✱ Bedrock

Hydrochemical Facies

- $Ca-Na-HCO_3$
- Ca or $Na-HCO_3$
- $Na-SO_4$
- $Ca-Na-SO_4$
- $Na-HCO_3$
- $Ca-SO_4$
- $Na-Cl$

FIGURE 32. Piper diagram showing the chemical distribution of water quality in the Sundre aquifer system study area (sampled, June 27,1985).

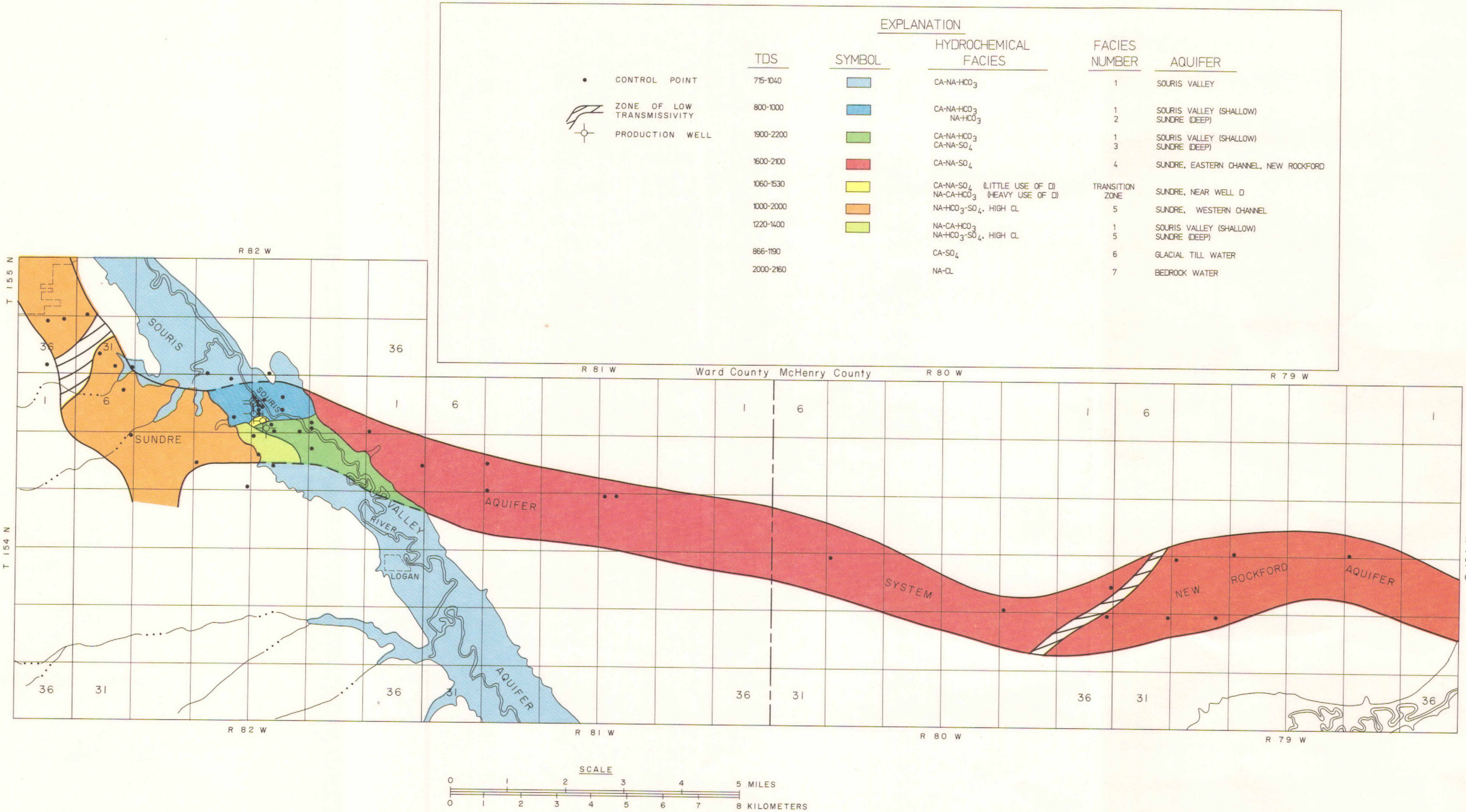


FIGURE 33. Generalized distribution of Major Chemical Facies, Souris Valley and Sundre Aquifers (June 27, 1985).

in the overlying Souris Valley aquifer to a sodium-bicarbonate ($Na-HCO_3$) type water in the underlying Sundre aquifer (fig. 34). Inspection of Schoeller diagrams in Figure 34 indicates that while the calcium (Ca) and magnesium (Mg) concentrations decrease, the sodium (Na) concentration increases, suggesting cation exchange within the clays. Total dissolved solids (TDS) range from 600 mg/l near the top of the Sundre aquifer to almost 1000 mg/l near the base (Figure 35). Sulfate (SO_4) levels vary from 100 mg/l near the top of the Sundre to 350 mg/l at the base (fig. 36).

The third hydrochemical facies includes ground-water samples collected from wells screened in that part of the Sundre aquifer underlying the Souris Valley aquifer in the vicinity of Minot city wells D and E (figs. 32 and 33). Limited piezometer nest data from this area indicates that the ground-water quality trends from a calcium-sodium-bicarbonate ($Ca-Na-HCO_3$) type water in the overlying Souris Valley aquifer to sodium-sulfate ($Na-SO_4$) type water in the underlying Sundre aquifer (fig. 37). Total dissolved solids (TDS) range from 800 mg/l at the top of the Sundre aquifer to over 2000 mg/l at the base of the Sundre aquifer (fig. 35). Inspection of Figure 37, indicates that while the calcium concentration (Ca) generally decreases with depth, the sodium (Na) concentration increases, again reflecting that cation exchange is an important geochemical control. Sulfate (SO_4) levels range from 360 mg/l at the top of the Sundre aquifer system to over 1000 mg/l at the base (fig. 36).

The fourth hydrochemical facies includes ground-water samples collected from the eastern channel of the Sundre aquifer system (fig. 32 and 33). Inspection of Figure 38 indicates that all of the major ion concentrations increase with

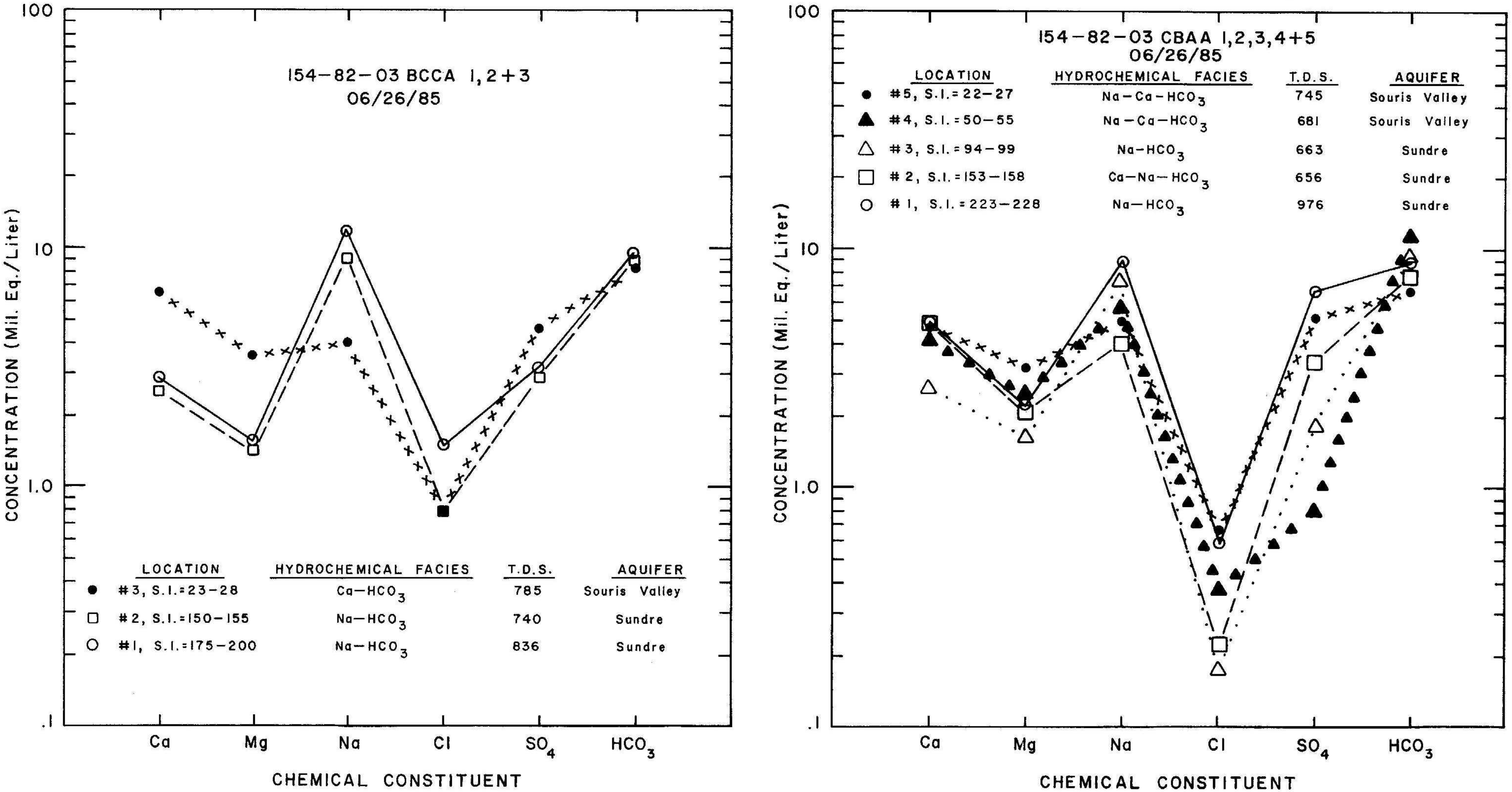


FIGURE 34. Schoeller diagrams showing the vertical distribution of selected cations and anions in the Souris Valley and Sundre aquifers near Minot production wells A & B.

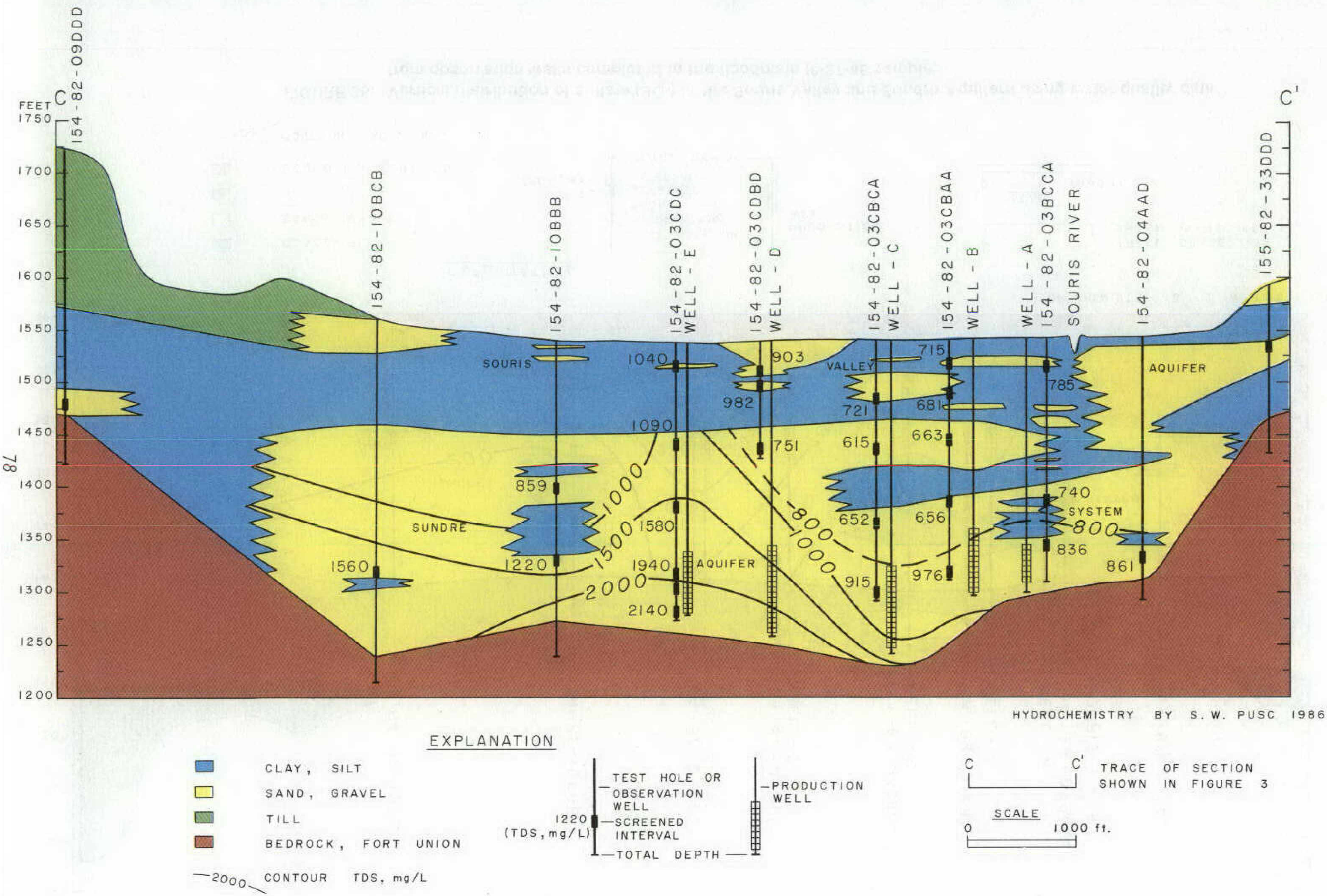


FIGURE 35. Vertical distribution of total dissolved solids (TDS) in the Souris Valley and Sundre Aquifers using water quality data from observation wells completed in the floodplain (6-27-85 sample).

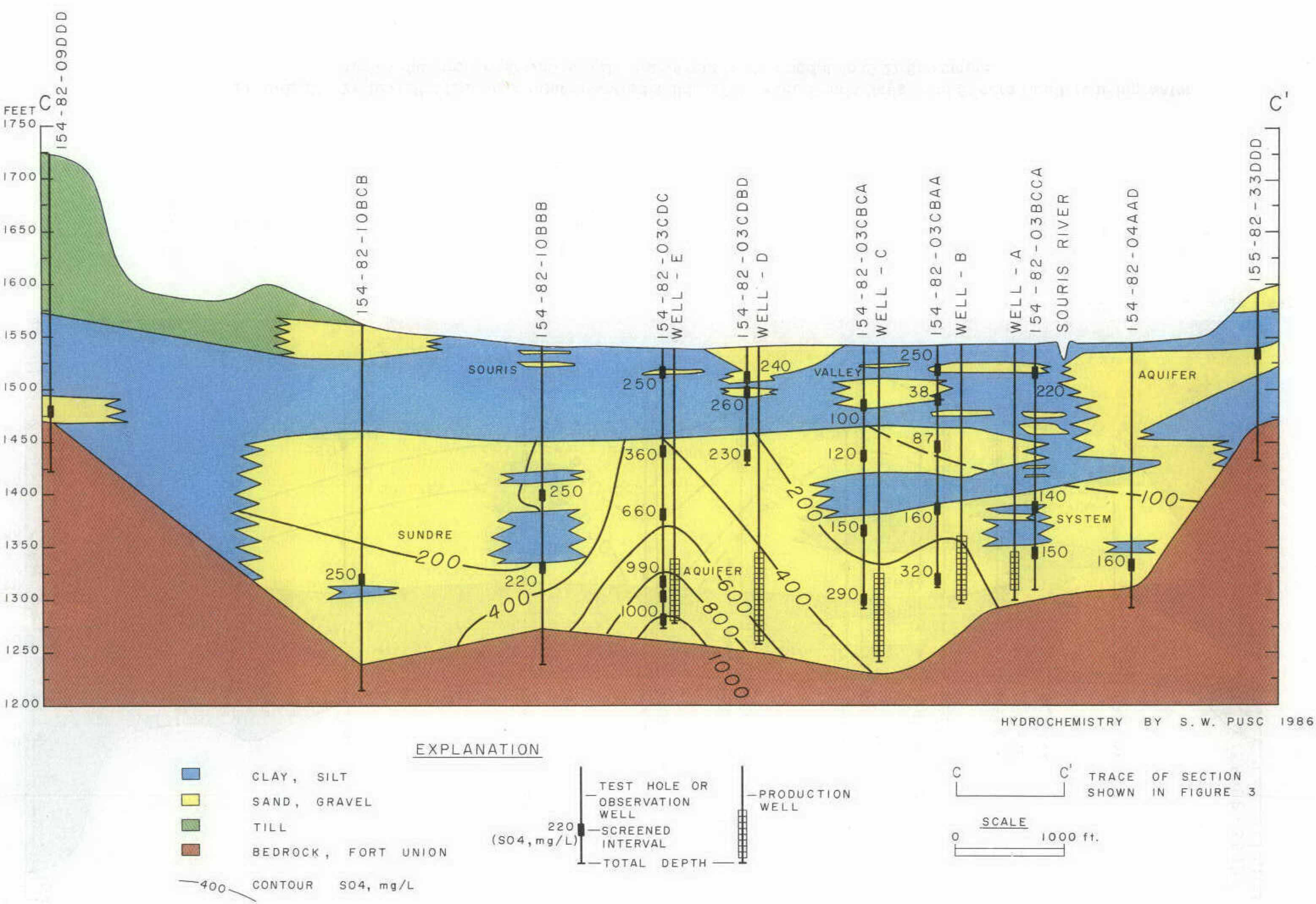


FIGURE 36. Vertical distribution of sulfate (SO_4) in the Souris Valley and Sundre Aquifers using water quality data from observation wells completed in the floodplain (6-27-85 sample).

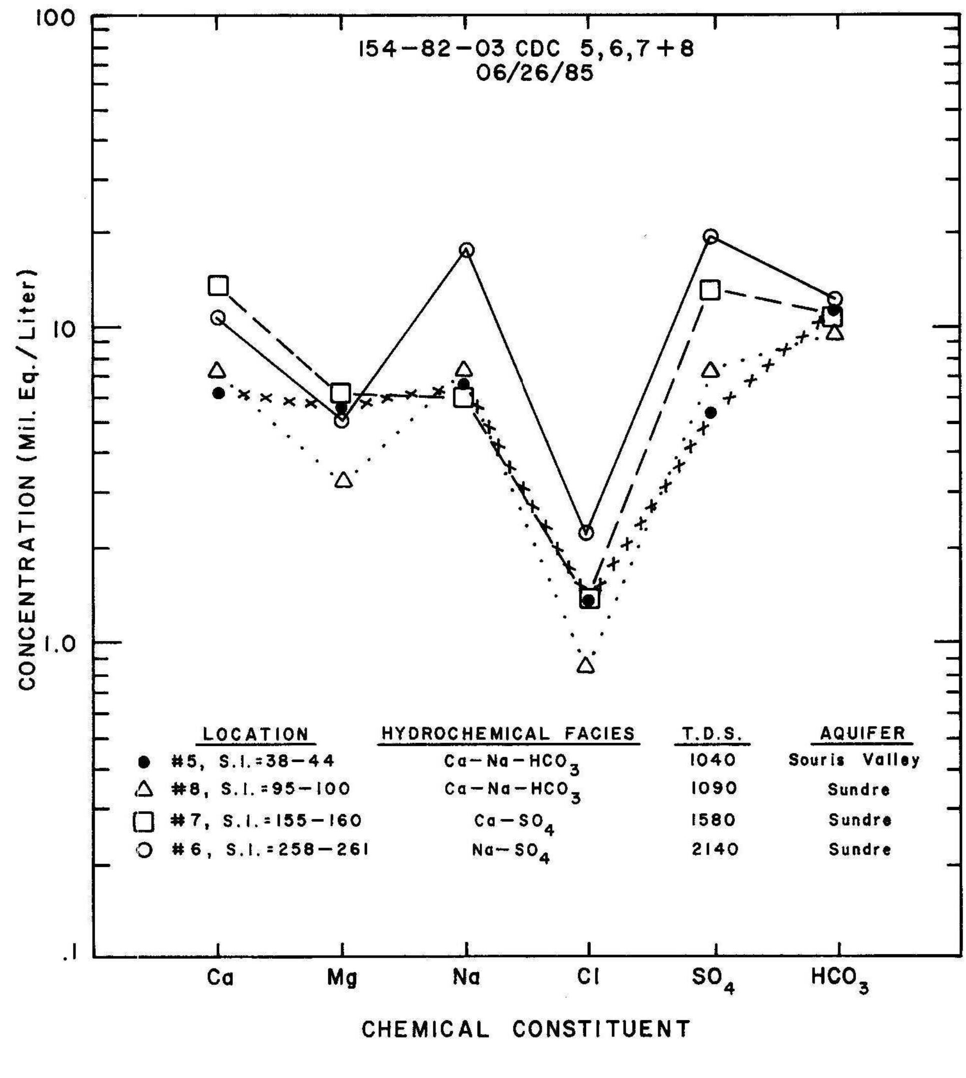


FIGURE 37. Schoeller diagrams showing the vertical distribution of selected cations and anions in the Souris Valley and Sundre aquifers near Minot production wells D & E.

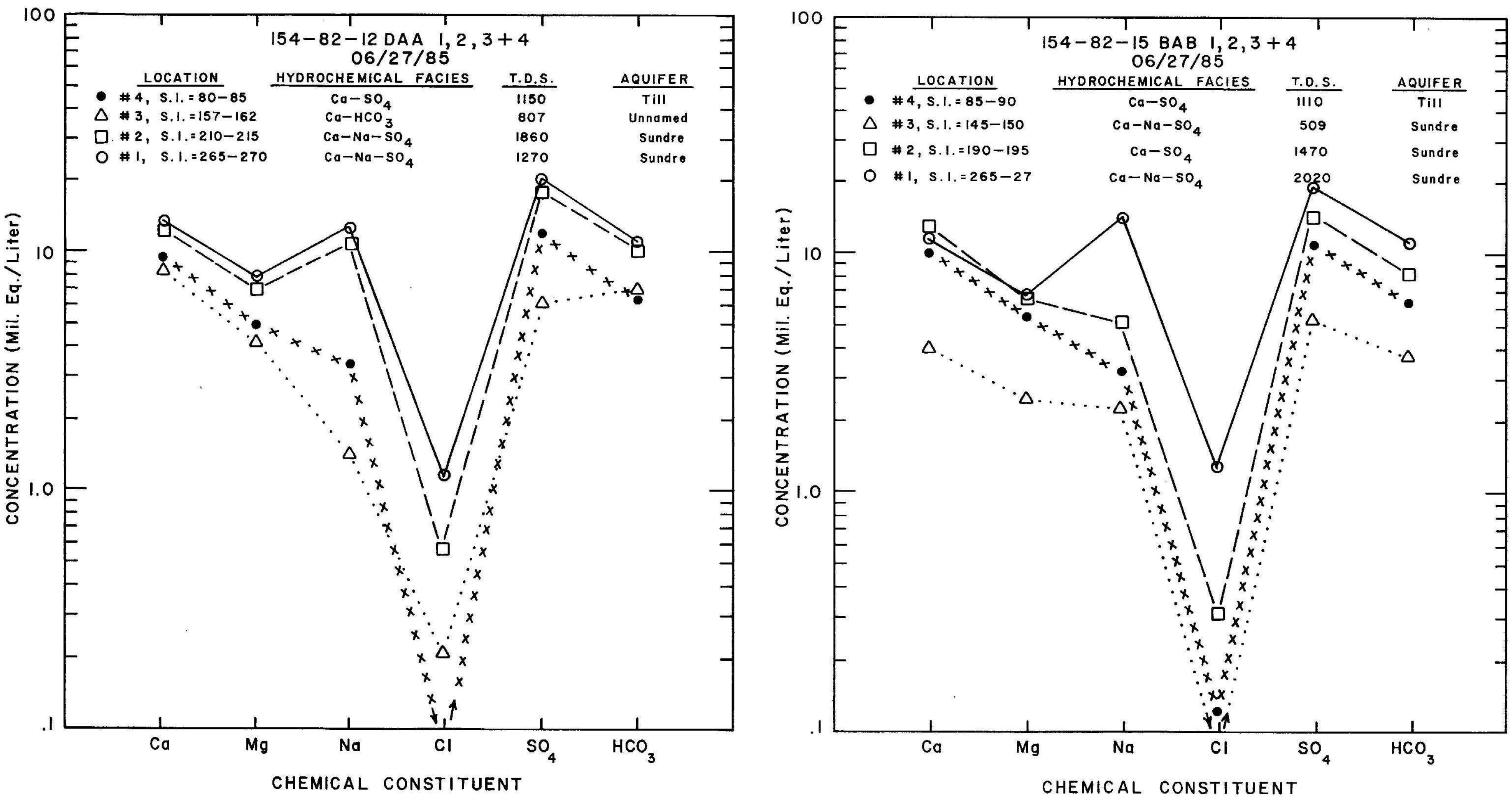


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FIGURE 38. Schoeller diagrams showing the vertical distribution of selected cations and anions in the eastern channel of the Sundre aquifer.

increasing depth. Total dissolved solids (TDS) in the eastern channel range from 500 mg/l at the top of the Sundre to over 2000 mg/l at depth (fig. 39). Sulfate (SO_4) levels range from 260 mg/l at the top of the Sundre aquifer to over 1000 mg/l at the base (fig. 40).

Despite these variations in water quality with depth, all ground water from the eastern channel of the Sundre aquifer system can be classified as a calcium or sodium-sulfate (Ca-Na-SO_4) type water with TDS ranging from 509 to 2100 mg/l (figs. 32 and 33). This means that regardless of TDS, the percentages of the major ions remain fairly constant.

The fifth hydrochemical facies includes ground-water samples collected from the western channel of the Sundre aquifer system. These waters can be classified as sodium-bicarbonate-sulfate (Na-HCO_3-SO_4) types (figs. 32 and 33). Chloride (Cl) levels in this part of the aquifer are high, ranging from 170 to 390 mg/l. Total dissolved solids (TDS) are very high, ranging from 1000 to 2000 mg/l (fig. 39). Sulfate (SO_4) levels, however, are only 300 to 400 mg/l, considerably less than SO_4 concentrations in the eastern channel of the Sundre aquifer (fig. 40).

The sixth hydrochemical facies includes ground-water samples collected from the glacial till. Limited data (two wells) indicate that the till water is a calcium-sulfate (Ca-SO_4) type (fig. 38). Total dissolved solids (TDS) are approximately 1100 mg/l (fig. 39). Sulfate (SO_4) levels are about 500 mg/l (fig. 40). Note that the overlying till water has a higher dissolved solids concentration than ground water sampled from the top of the Sundre aquifer (Figure 38). This suggests that the till water sampled is interstitial. Better quality water may be moving through fractures or more highly transmissive fluvial units in the till,

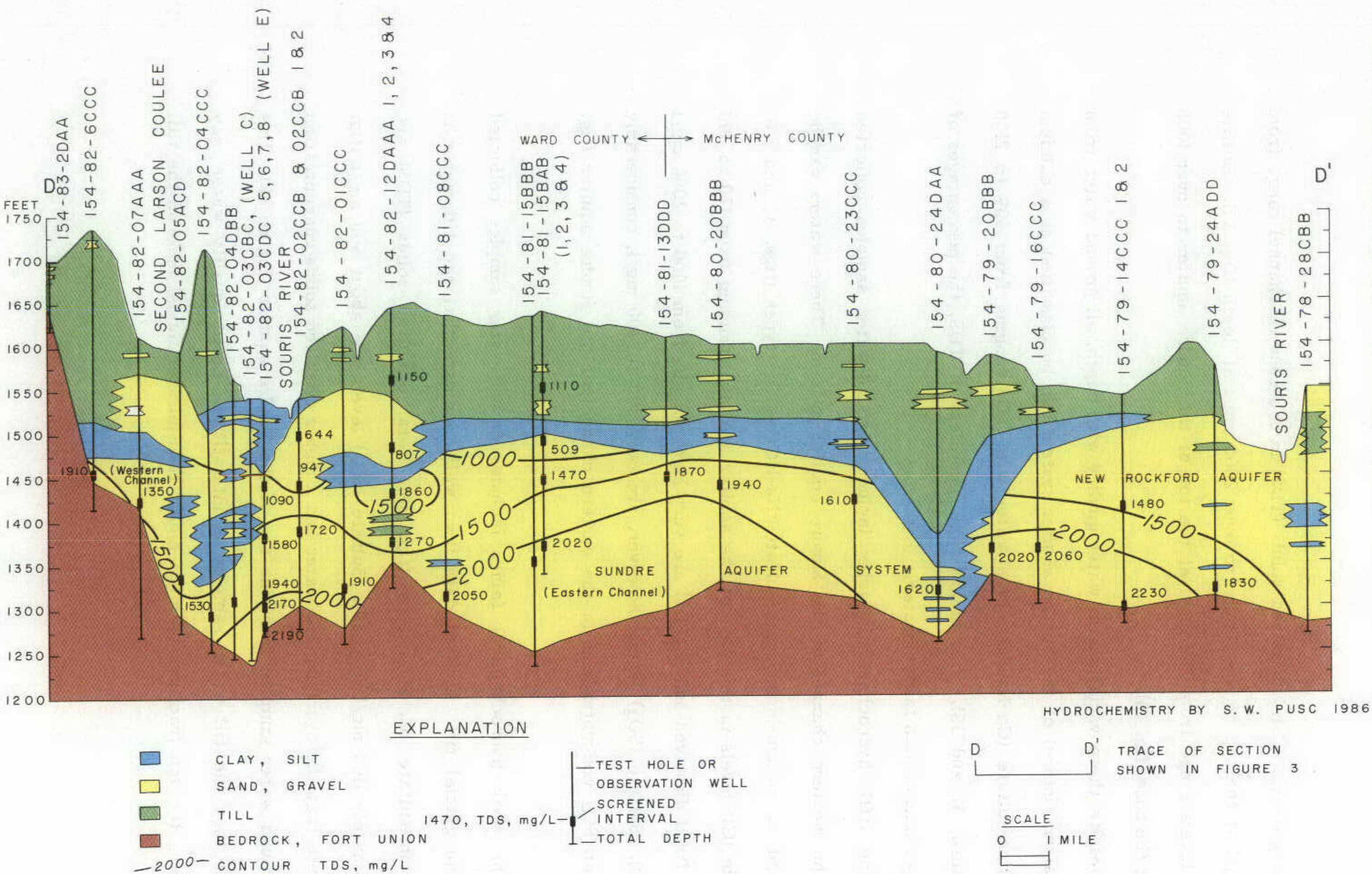


FIGURE 39. Vertical distribution of total dissolved solids (TDS) in the Sundre Aquifer using water quality data from observation wells completed along the axis of the channel (6-27-85 sample).

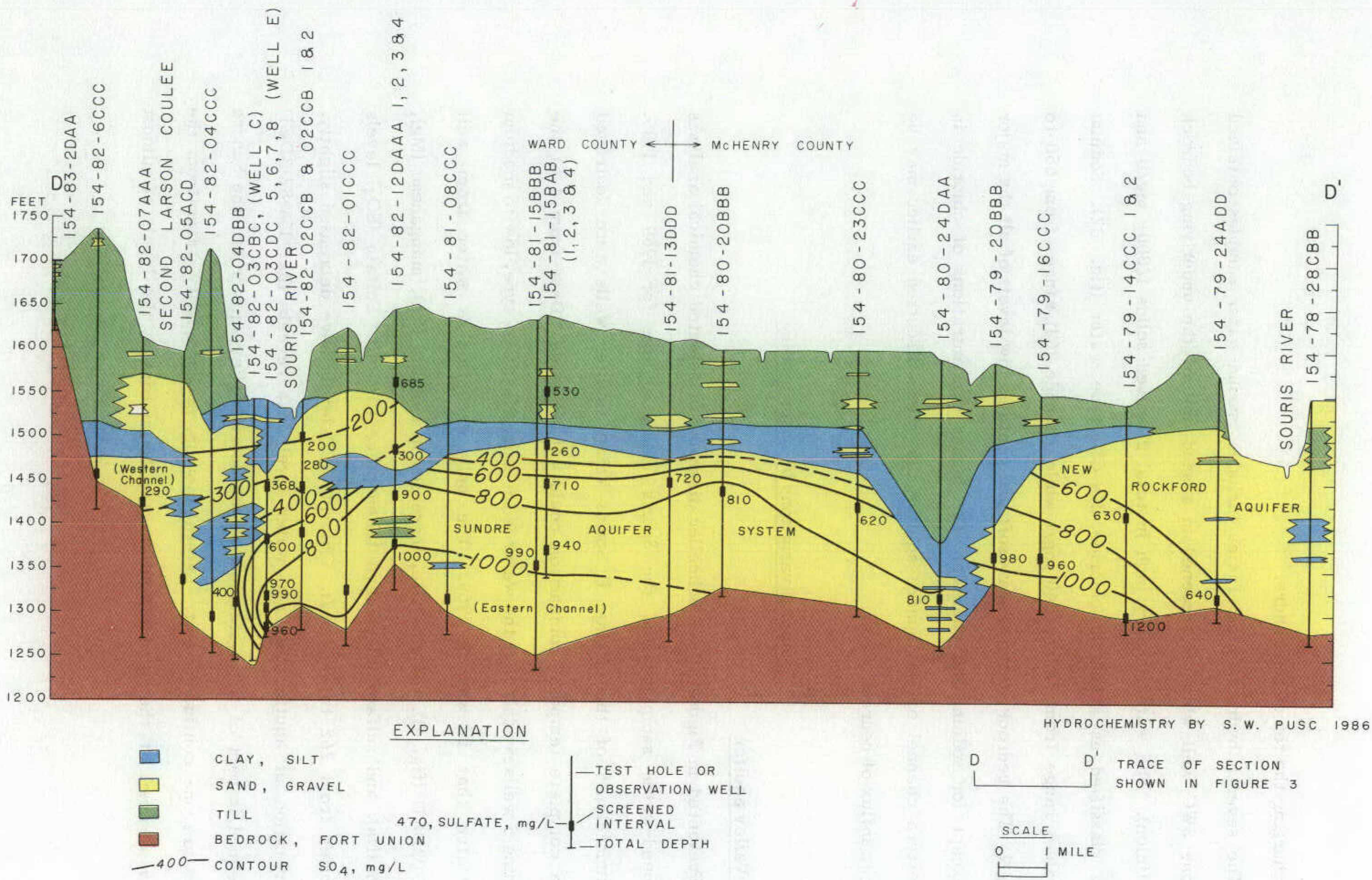


FIGURE 40. Vertical distribution of sulfate (SO_4) in the Sundre Aquifer using water quality data from observation wells completed along the axis of the channel (6-27-85 sample).

and recharging the top of the Sundre.

The seventh hydrochemical facies includes ground-water samples obtained from one SWC well which is screened in a sand unit of the underlying bedrock (Fort Union). The water is very high in total dissolved solids (2000+ mg/l) and can be classified as a sodium chloride (Na-Cl) type water (fig. 32). Sodium (Na) values range from 780 to 840 mg/l while chloride (Cl) ranges from 650 to 740 mg/l. The bedrock water is very soft and contains low levels of all the major ions except for sodium and chloride. The higher concentrations of chloride in the western channel of the Sundre aquifer that were discussed earlier may be due to an influx of bedrock water.

Temporal variations in water quality

Souris Valley aquifer

Presented in Figure 41 are Schoeller diagrams of selected chemical analyses of ground-water samples from the Souris Valley aquifer for 1969 and 1985. Unfortunately, 6 of the original 11 Souris Valley aquifer wells were destroyed thus, a complete temporal comparison could not be made. Data from 4 of the remaining 5 wells reveals that the water is the same Na-HCO_3 type, low to medium TDS water that it was in 1969. The only exception is water from well 154-82-03DCD (fig. 41). At this site, increases in calcium (Ca), manganese (Mg), sodium (Na), and sulfate (SO_4) have taken place (fig. 41). Sulfate (SO_4) levels have risen from 262 to 800 mg/l. Chloride (Cl) levels have decreased slightly. Interpretation of aquifer test and water level data reveals that 154-82-3DCD is screened in part of the system where the Souris Valley aquifer and the Sundre aquifer are one continuous unit. Lateral moving, poorer quality water from the eastern channel of the Sundre aquifer may be increasing the levels of almost

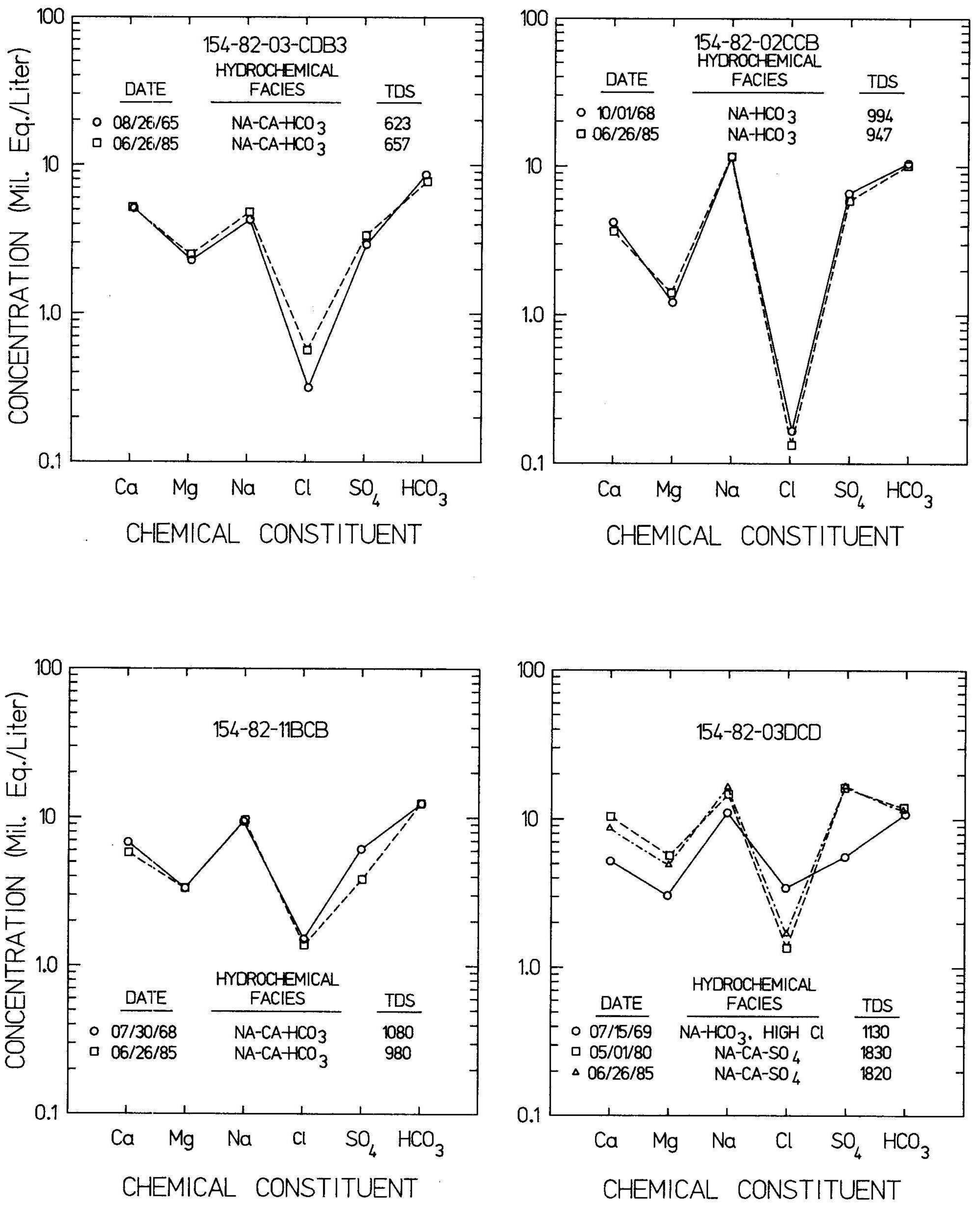


FIGURE 41. Schoeller diagrams showing temporal variations in selected cations and anions in the Souris Valley Aquifer.

all major ion concentrations in this part of the Souris Valley aquifer.

Sundre aquifer, eastern channel

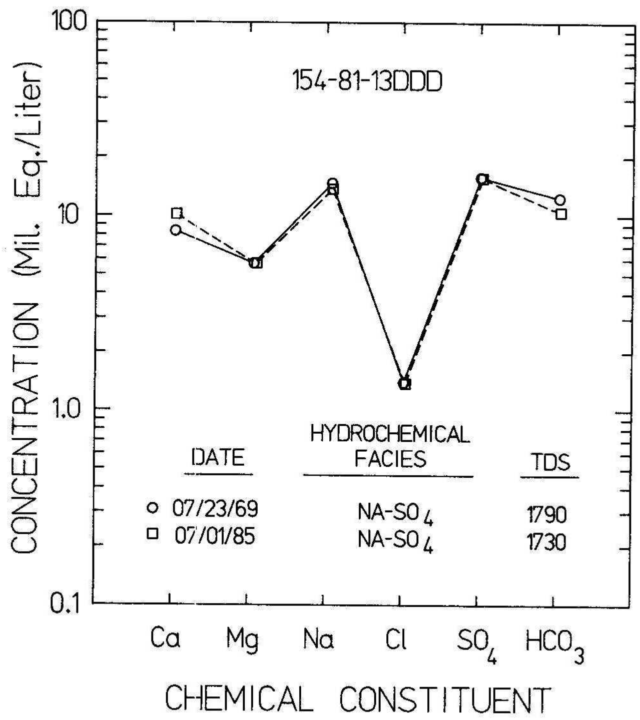
Presented in Figure 42 are Schoeller diagrams comparing the 1969 and 1985 analyses of samples from three wells screened in the eastern channel of the Sundre aquifer. Note that virtually no change in ground water quality has occurred in the past 16 years. The ground water is still a Na-SO_4 to Ca-Na-SO_4 type water (fig. 42).

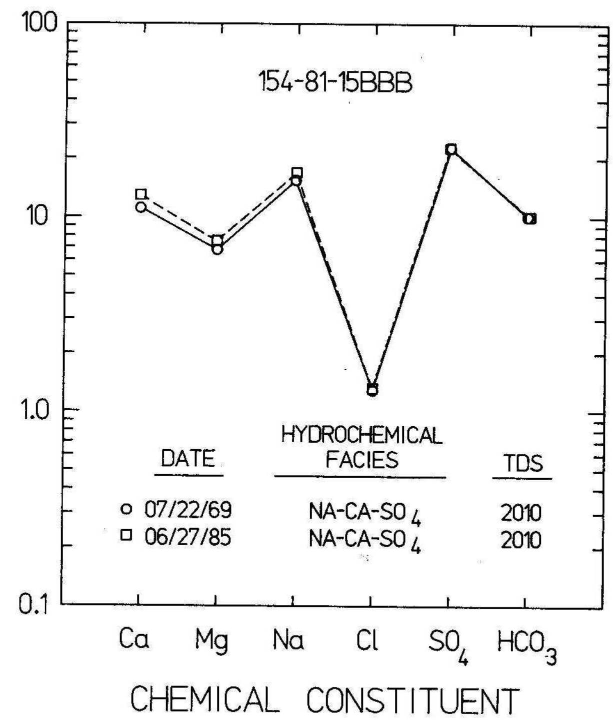
Sundre aquifer, underlying the Souris Valley aquifer

Comparison of samples collected and analyzed in 1969 and 1985 from wells screened in that part of the Sundre aquifer underlying the Souris Valley aquifer reveals that ground water in portions of the aquifer has undergone changes in water quality, while ground water in other portions of the aquifer remains unchanged.

North of the Souris River (in Section 3) and near wells A and B, only minor increases in calcium (Ca), sodium (Na) and chloride (Cl) concentrations have been observed in ground water from the Sundre aquifer (fig. 43). The only noticeable change in water quality from 1975 to 1985 in either production well A or B has been a slight increase in Cl (fig. 44). Basically, ground water from this part of the Sundre aquifer is the same Ca-Na-HCO_3 type that it was 10 to 16 years ago. It appears that the proximity of better quality recharge water from the Souris River and overlying Souris Valley aquifer is keeping the water quality in this part of the Sundre aquifer stable.

Ground water collected from one well screened in the Sundre aquifer east of well C indicates that ground water from this portion of the Sundre aquifer has undergone subtle changes in quality. Since 1968, all major ion concentrations





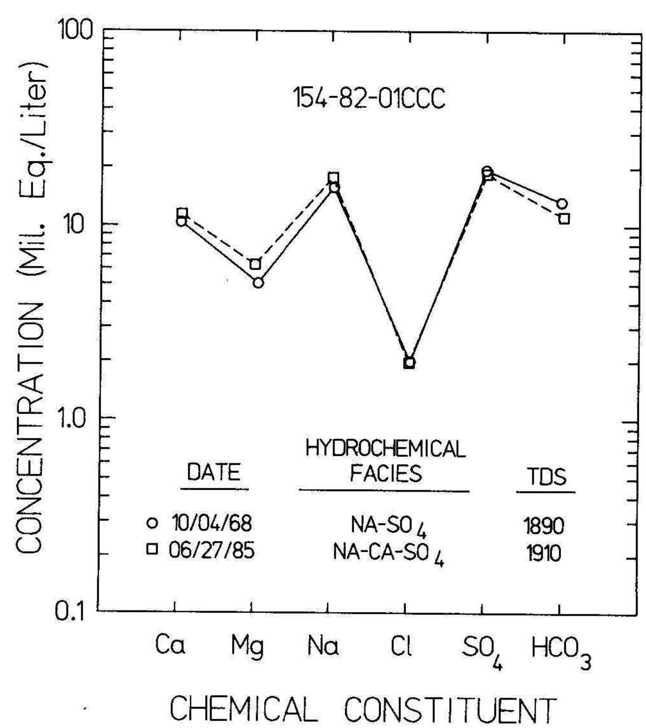


FIGURE 42. Schoeller diagrams showing temporal variations in selected cations and anions in the eastern channel of the Sundre Aquifer.

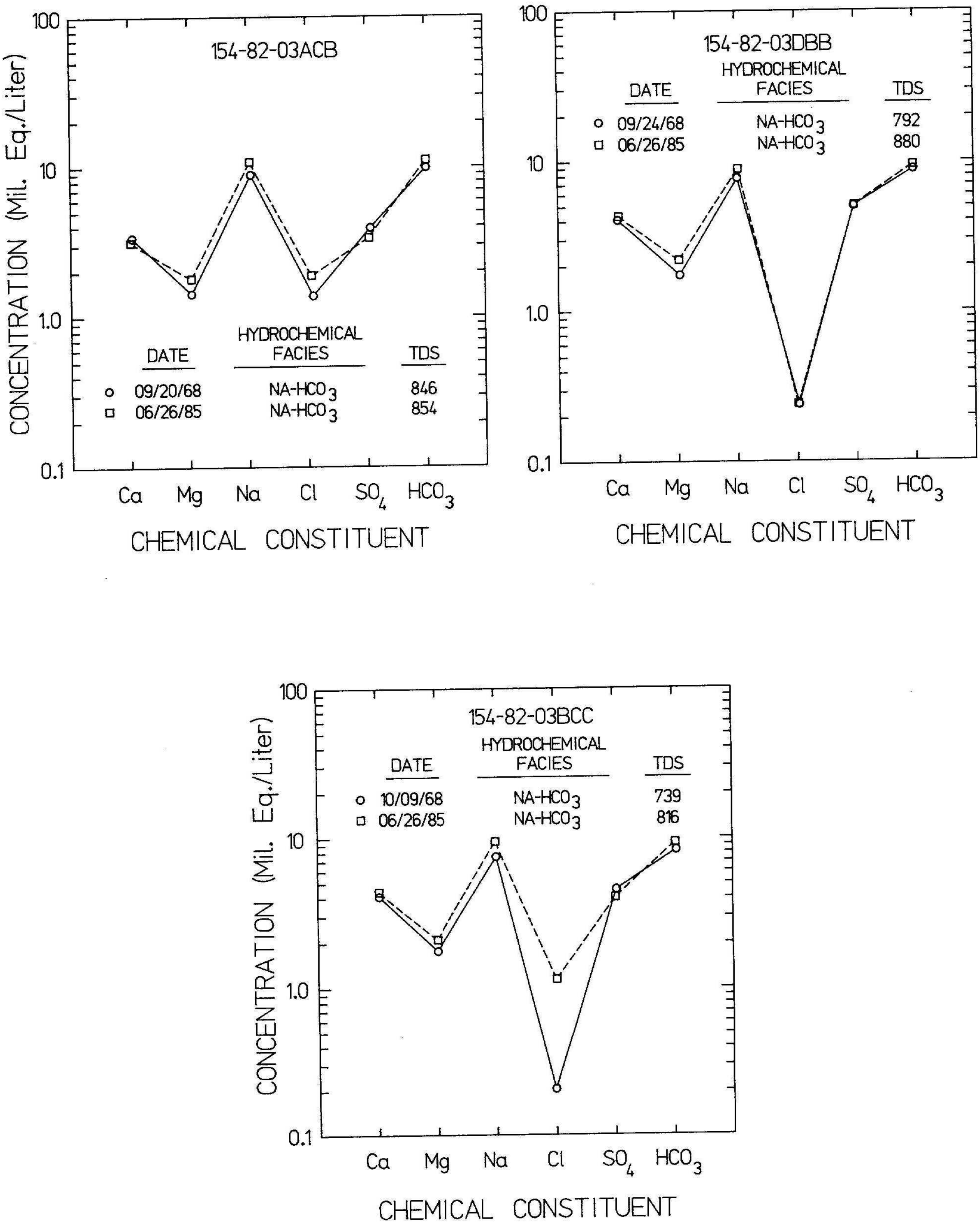


FIGURE 43. Schoeller diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer, north of the Souris River in Section 3 and near Minot production wells A & B.

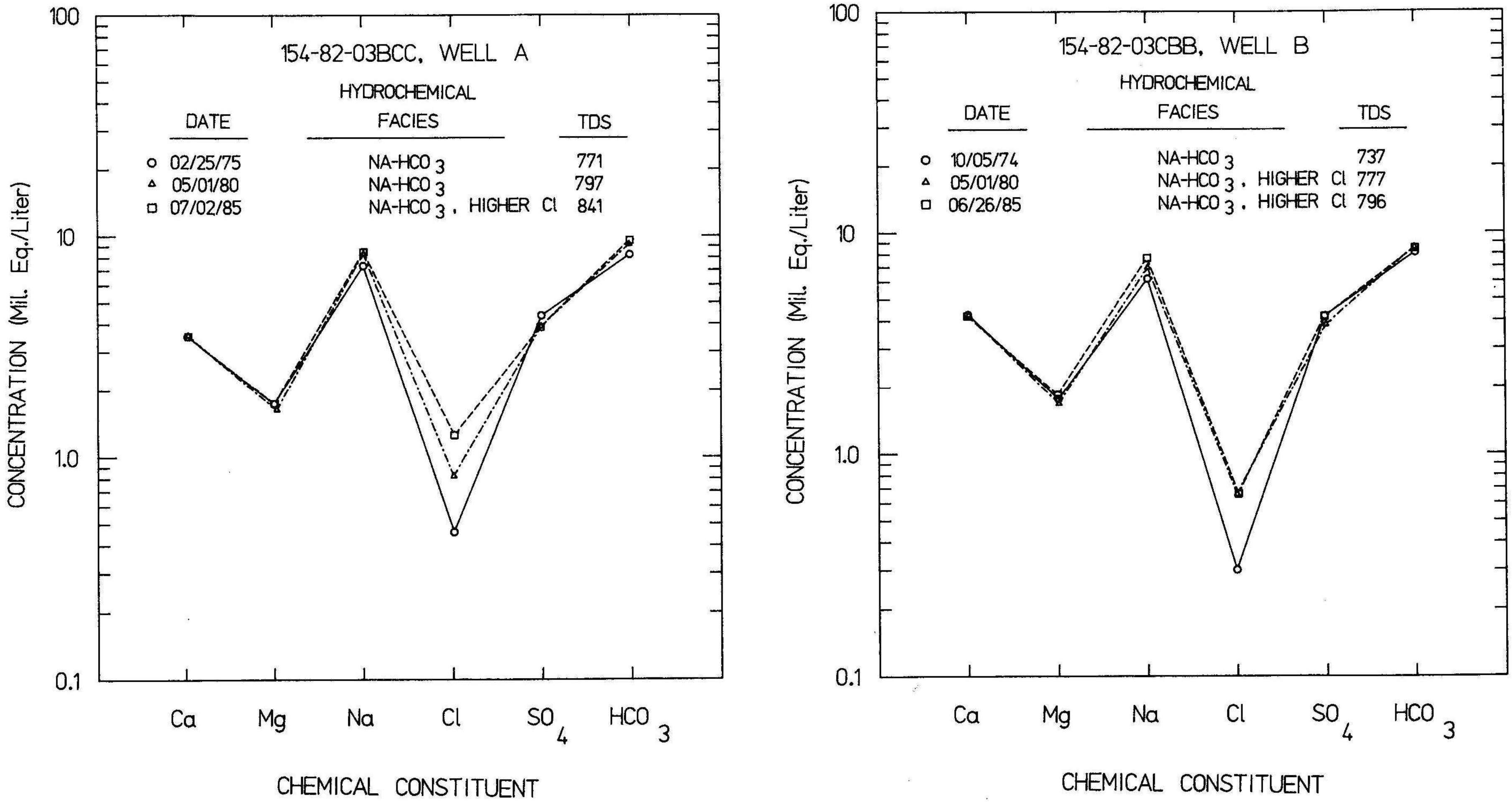


FIGURE 44. Schoeller diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer, Minot production wells A & B.

have increased slightly with time, except for chloride and bicarbonate (fig. 45). Sulfate (SO_4) levels have risen from 238 to 360 mg/l (fig. 45). In 1975, (at the start of development) ground water pumped from Well C was a low to medium TDS, Na-HCO_3 type water (fig. 46). Ground water pumped from well C in 1985 appears to vary in quality depending on the pumping pattern of the 5 Sundre aquifer wells. Prolonged periods of pumping only wells A, B, and C (10/84 to 3/85) seem to result in an increase in the SO_4 and TDS levels in ground water from well C (fig. 47). Sulfate levels in ground water from Well C decrease when well D to the south is pumped more (fig. 47).

The vertical distribution of major cations and anions just southeast of Well C is illustrated in Figure 45. Generally, levels of most chemical constituents increase with depth. Sulfate levels range from 100 mg/l in the overlying Souris Valley aquifer to 320 mg/l at the base of the Sundre aquifer (fig. 45). Ground water from this part of the study area remains, however, a Ca-Na-HCO_3 type water; both temporally and vertically. The increase in SO_4 concentration in water pumped from Well C does not appear to be derived from the overlying Souris Valley aquifer.

Ground water collected from two observation wells screened in that part of the Sundre aquifer near wells D and E have undergone substantial changes in water quality (fig. 48). Basically, all major ion concentrations have increased with time (except Cl). The largest increase has been in sulfate (SO_4) which has risen from a 1968 predevelopment level of 150-240 mg/l, to 900-1000 mg/l in 1985 (fig. 48). Ground water in the area has changed from a sodium-bicarbonate (Na-HCO_3) type water prior to development to a sodium-sulfate (Na-SO_4) type water in 1985 (fig. 48).

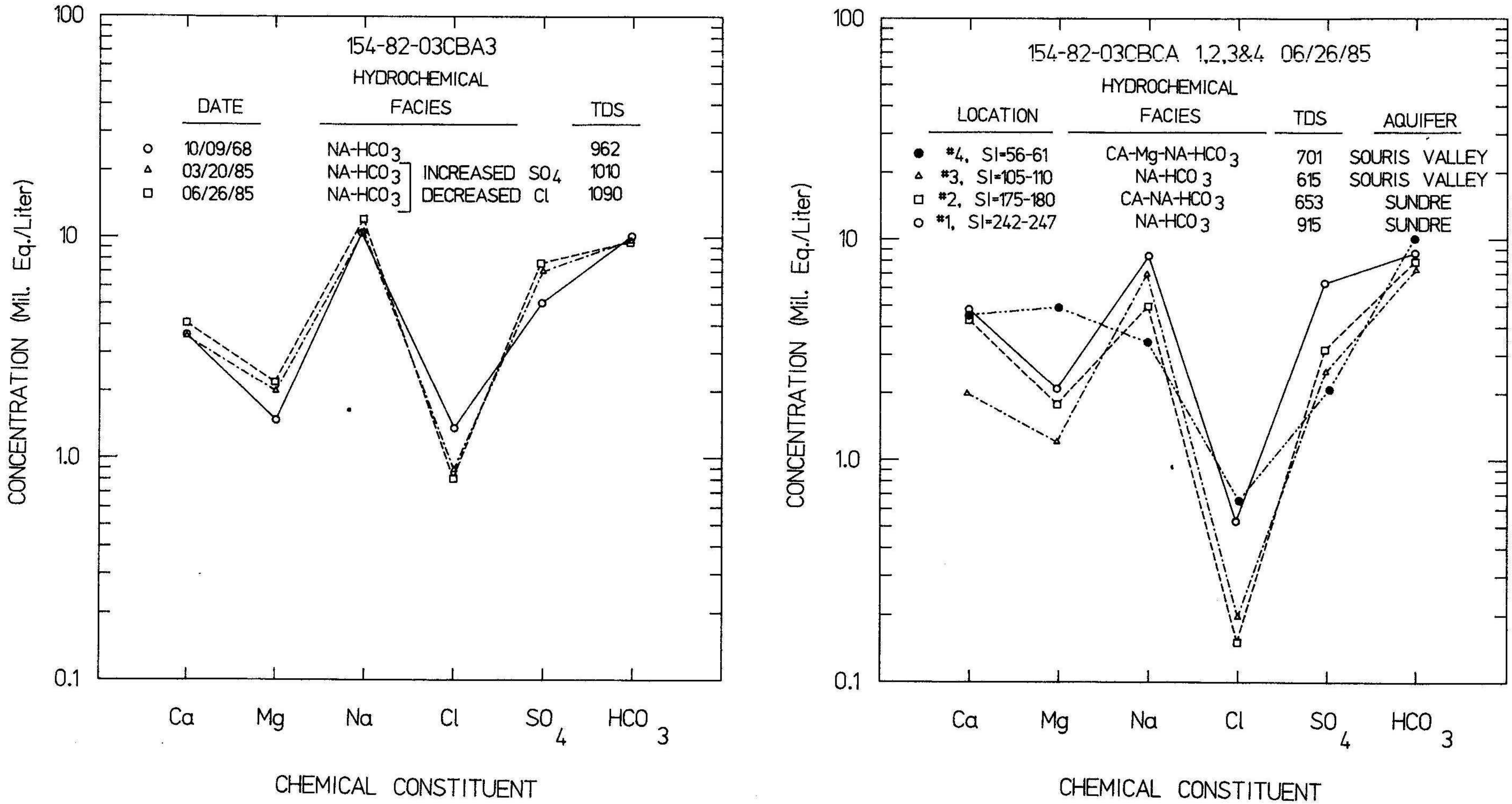
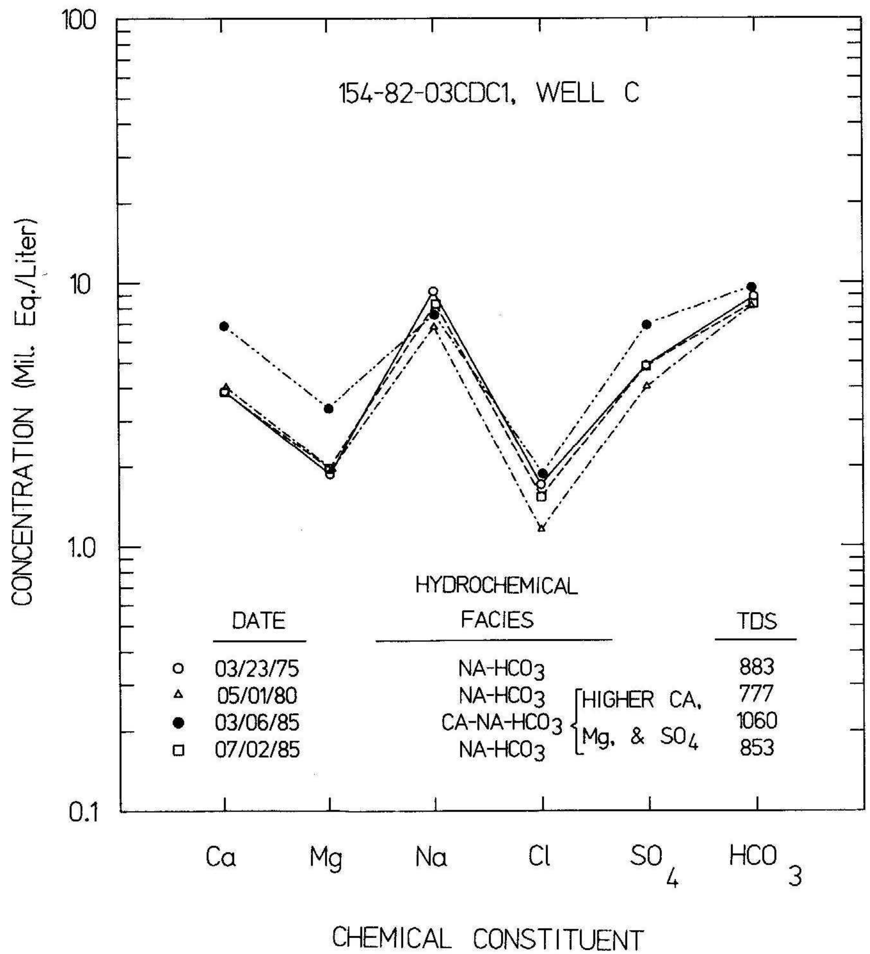


FIGURE 45. Schoeller diagrams showing temporal variations and vertical distribution in selected cations and anions in the Sundre Aquifer east and southeast of Minot production well C.



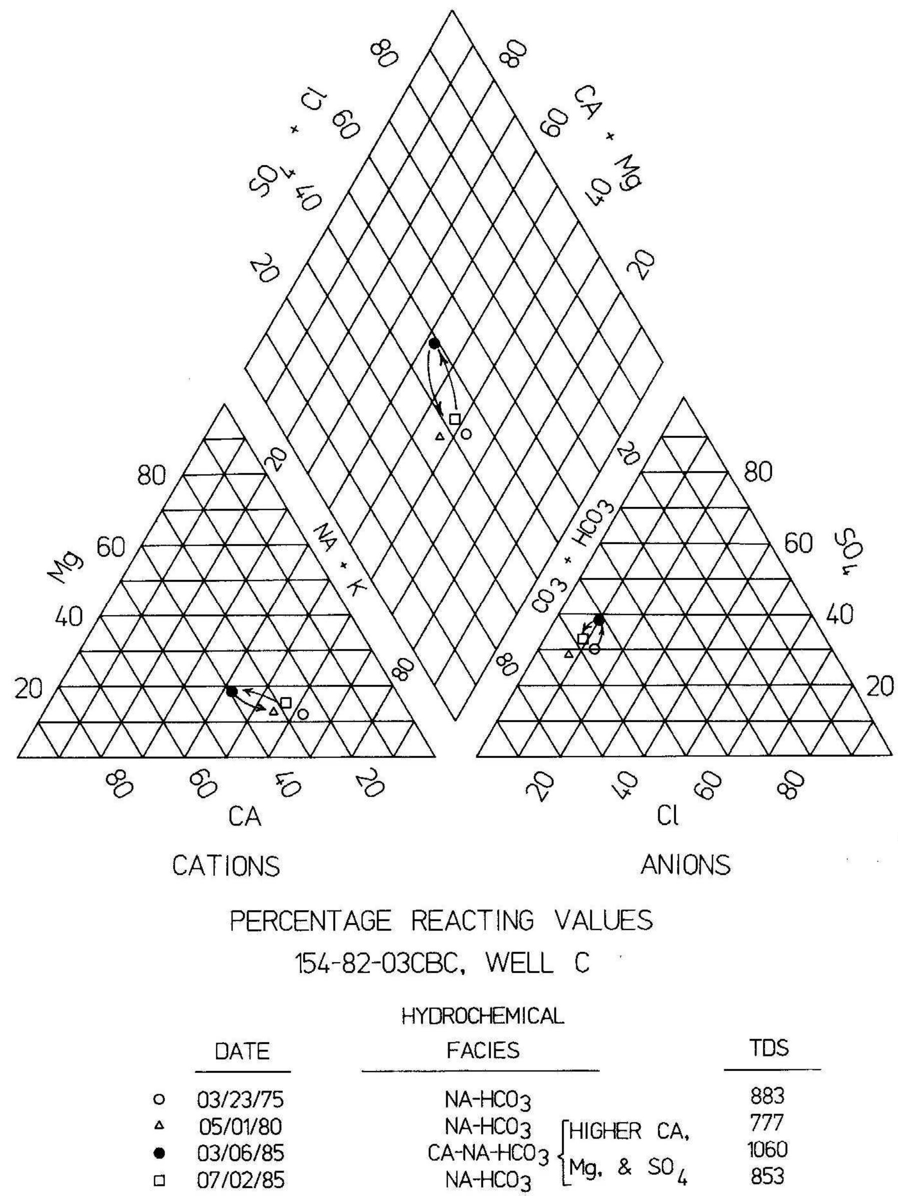


FIGURE 46. Schoeller and Piper diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer, Minot production well C.

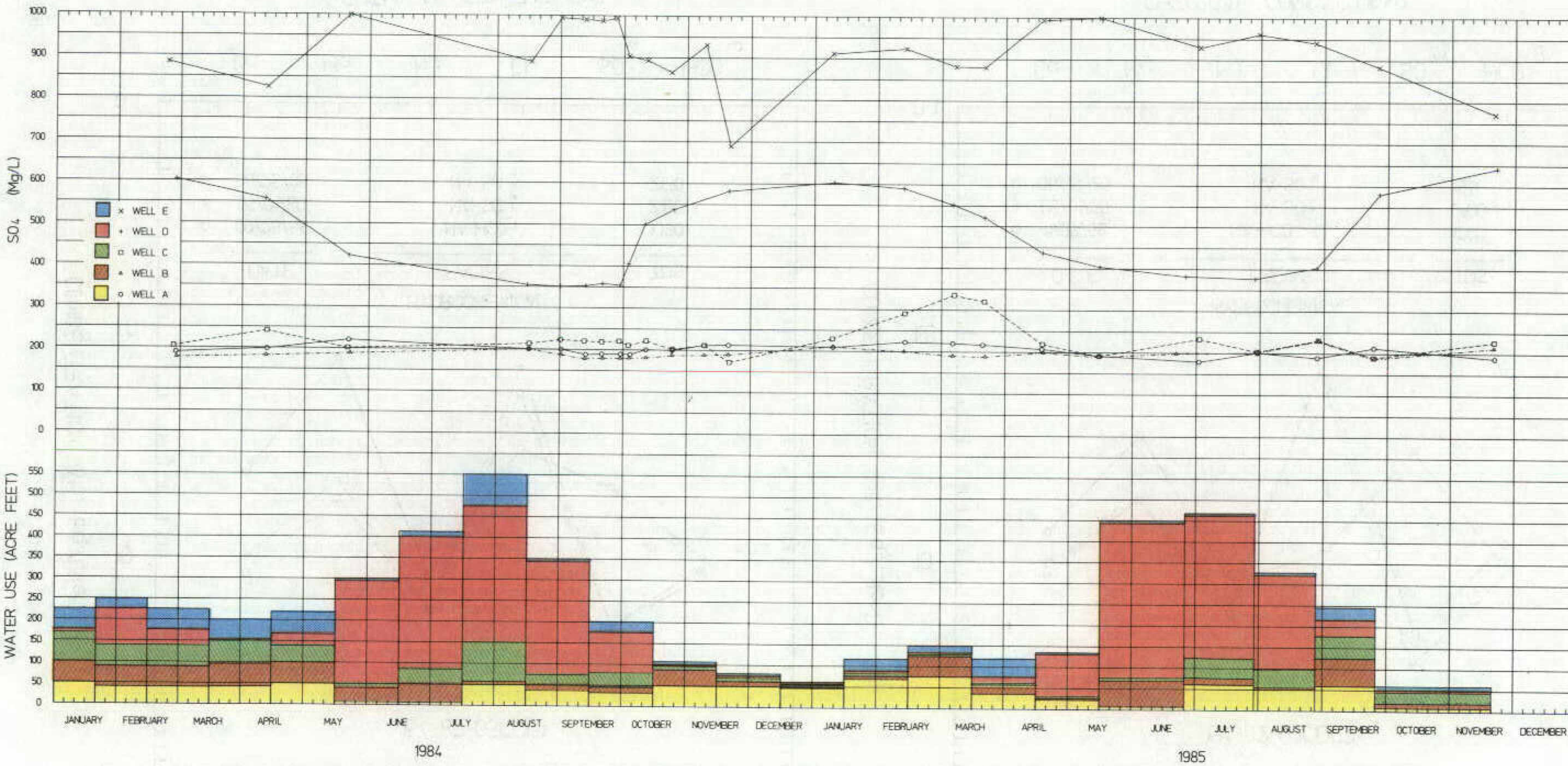


FIGURE 47. Comparison of water use and sulfate (SO_4) levels in ground water from Minot production wells A, B, C, D, and E.

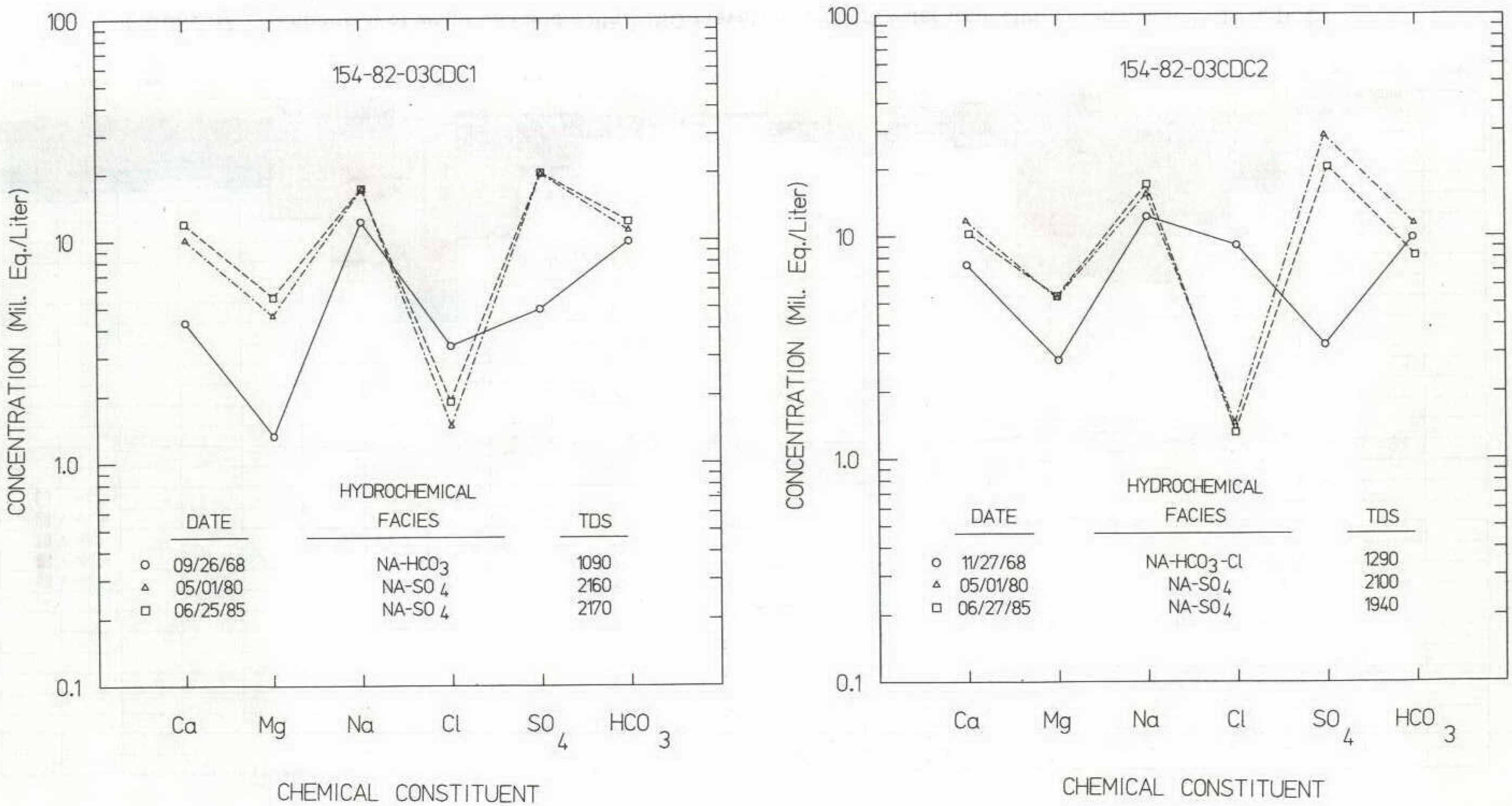


FIGURE 48. Schoeller diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer near Minot production wells D & E.

Temporal variations in water quality of ground water pumped from Well D is shown in Figure 49. Prior to development, water from Well D was a Na-Ca-HCO_3 type (fig. 49). In 1985, the water was still a Na-Ca-HCO_3 type, however, most all the chemical constituent levels have increased (figs. 48 and 49).

The pumping pattern of the 5 Sundre aquifer wells appears to also affect the quality of ground water pumped from Well D. During heavy utilization of well D, both the TDS and sulfate concentrations in the ground water decrease (figs. 47 and 49). When well D is shut down and most of the city supply is pumped from wells A, B, and C, both the sulfate and TDS levels in water from Well D increase. When the largest use is from wells A, B, or C, the water from well D converts to a poorer quality Na-Ca-SO_4 type water. When the largest use is from well D the water reverts back to a better quality Na-Ca-HCO_3 type (figs. 47 and 49). It appears that well D (2800 gpm) induces better quality water from the north to move towards the well and mix with poorer quality water being diverted from the south and east, resulting in an overall improvement in water quality from well D.

Ground water pumped from well E has undergone the most change in quality since development. Before development (1974), water from well E was a Ca-HCO_3 type, (fig. 50). Since development, the water has converted to a Na-Ca-SO_4 type, (fig. 50). Total dissolved solids have increased from 932 mg/l in 1974 to almost 2000 mg/l in 1985. Sulfate levels have risen from 200 to 1000 mg/l. Sulfate levels appear to increase with increased use of well D (fig. 47). Generally, water from this part of the Sundre aquifer is now very similar to water in the eastern channel of the Sundre aquifer (fig. 32). It appears that pumping of the Sundre

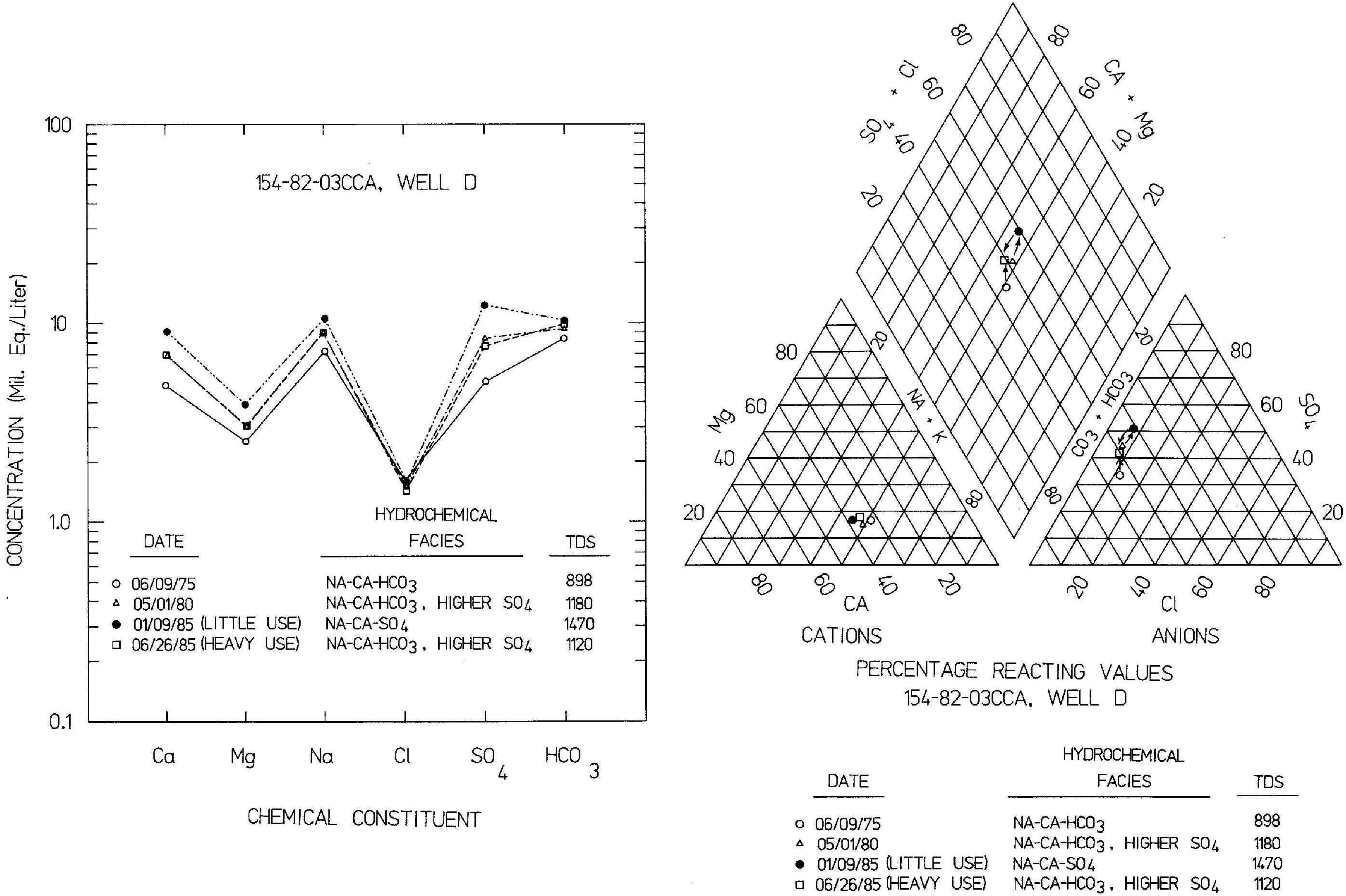


FIGURE 49. Schoeller and Piper diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer, Minot production well D.

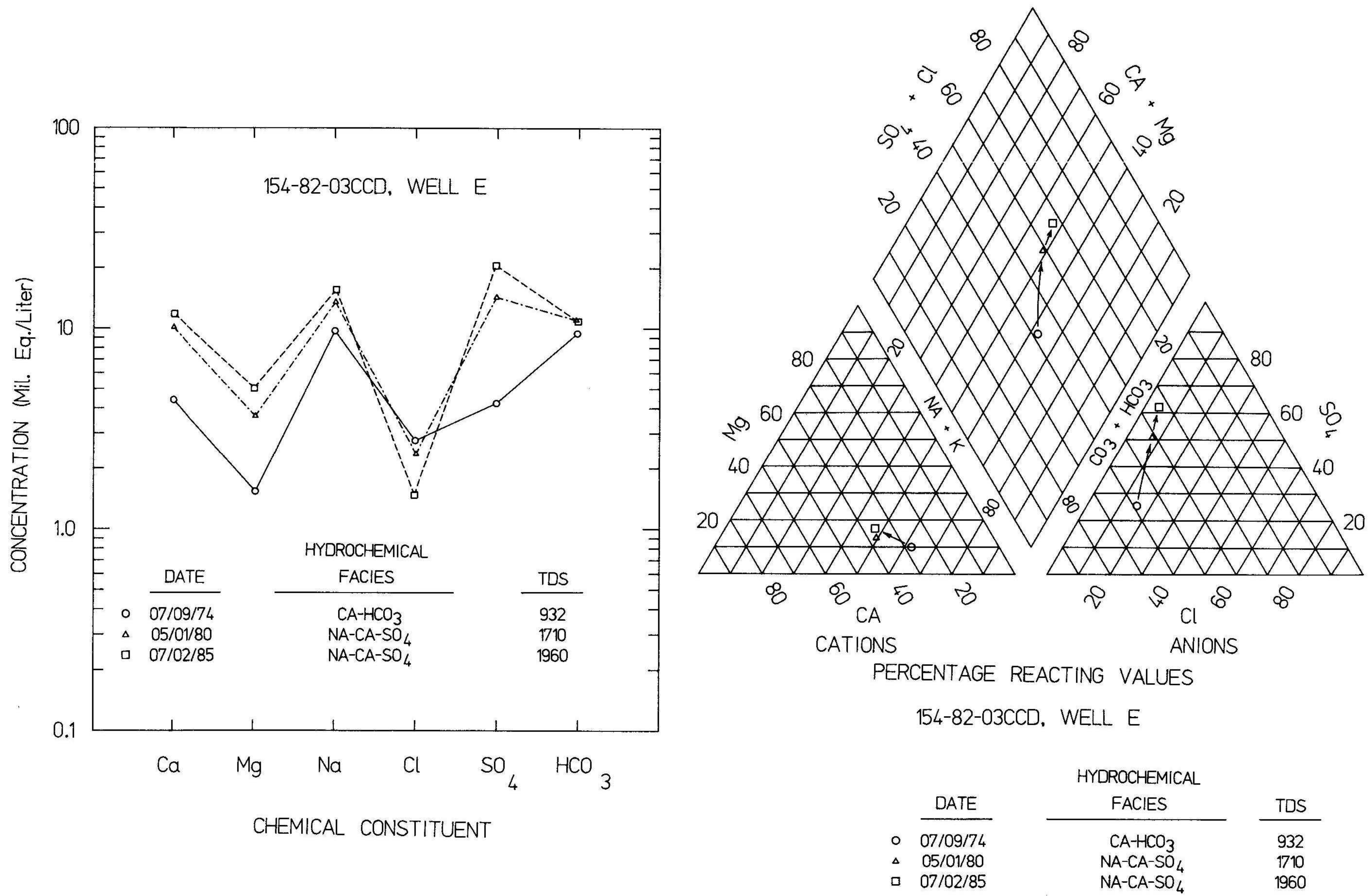


FIGURE 50. Schoeller and Piper diagrams showing temporal variations in selected cations and anions in the Sundre Aquifer, Minot production well E.

wells has induced poorer quality water from out in the eastern channel of the Sundre aquifer to flow towards the southern end of the well field. Ground water pumped from Well E is of the poorest quality because: (1) well E is the first well to intercept ground-water flow from the eastern channel and (2) wells A, B, C, and D intercept better quality water from the north before it can move to well E.

Sundre aquifer, western channel

Very limited data (one well) indicates that the concentrations of both calcium (Ca) and Magnesium (Mg) have increased in the water from the western channel of the Sundre aquifer (fig. 51). Chloride (Cl) has decreased by almost half (fig. 51, 304 to 170 mg/l). Sulfate levels have only risen from 142 to 190 mg/l. Generally, water from this part of the Sundre aquifer is the same calcium-bicarbonate ($Ca-HCO_3$) water as it was 16 years ago (fig. 51). It appears that elevated sulfate levels observed in wells E and D are not coming from the western channel of the Sundre aquifer system.

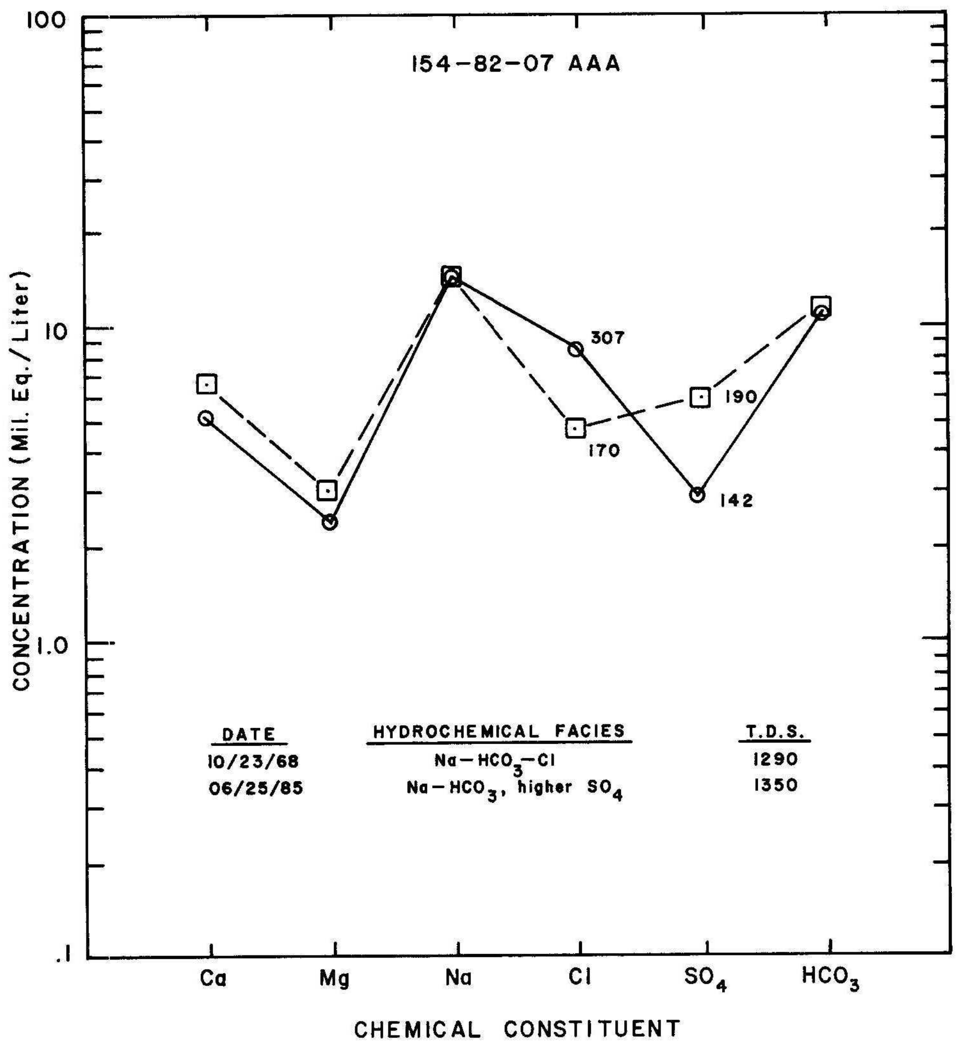


FIGURE 51. Schoeller diagram showing temporal variations in selected cations and anions in the western channel of the Sundre aquifer.

COMPUTER SIMULATION OF THE SUNDRE AQUIFER SYSTEM

Introduction

Computer simulation of the Sundre aquifer system was accomplished with a model developed by McDonald and Harbaugh (1984) entitled, "A Modular Three-Dimensional Finite Difference Ground-Water Flow Model". The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial differential equation:

$$(1)\quad \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t}$$

where:

x, y and z are cartesian coordinates aligned along the major axes of hydraulic conductivity, Kxx, Kyy, Kzz.

h is the potentiometric head (L)

W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1})

S_s is the specific storage of the porous material (L^{-1})

t is time (t)

The iterative numerical technique used to solve equation 1 is the strongly implicit procedure. Ground-water flow within the aquifer using the McDonald and Harbaugh model is simulated using a block-centered, finite-difference approach. Details on the mathematics of the model are presented in McDonald and Harbaugh (1984).

Description of the model

To model the Sundre aquifer system, the study area was divided into variable sized squares or rectangular blocks, called cells. The finite-difference grid used in modelling the Sundre aquifer system consisted of 9 rows, 62 columns and 2 layers (pl. 4). Cell width along columns was held constant at 800 feet. Cell length along rows varied from 3200 feet in the eastern channel of the Sundre aquifer to 800 feet in the Souris River valley (pl. 4). A finer mesh was used in the river valley because of the need to simulate the effects of evapotranspiration, river leakage, areal recharge, interaquifer-leakage and pumpage, which all take place in the river valley. The Sundre computer model represents an area 19.01 miles long and 1.36 miles wide (pl.4). Values of land surface elevation, starting head, storage coefficient and/or specific yield, hydraulic conductivity and/or transmissivity, recharge rate, and evapotranspiration rate were assigned to each cell. Values of river stage, riverbed conductance and elevation of the bottom of the riverbed were assigned to those cells representing the Souris River (pl. 4). Cells representing pumping wells were assigned well discharge values (pl. 4). The model assumes that values assigned to each cell are uniform over the entire cell.

Two layers were used in the model to represent three different hydrogeologic units. Layer one (top layer) represents the Souris Valley aquifer from elevation 1450 feet to land surface, and the adjoining glacial drift material from 1450 to land surface. Layer two (bottom layer) represents the Sundre aquifer from elevation 1300 to 1450 feet. Vertical hydraulic conductivity was specified between layers representing the Souris Valley aquifer and Sundre aquifers to simulate the effects of vertical leakage.

The physical boundaries of the Sundre aquifer system are of three types (with the exception of the overlying Souris Valley aquifer): (1) a semi-permeable boundary of till which overlies and surrounds the Sundre aquifer both east and west of the Souris River valley, (2) low transmissivity (clay/till) barriers which truncate the Sundre aquifer both on the east and west ends of the channel, and (3) the underlying low transmissivity bedrock material. Because all these physical boundaries are of such a low hydraulic conductivity as compared to the Sundre aquifer, they were assumed to be no flow boundaries in the model. Cells representing aquifer material were specified as active or variable head cells.

Aquifer properties

Hydraulic conductivity

Initial estimates of hydraulic conductivity of the Souris Valley aquifer were based on an aquifer test conducted by Pettyjohn (1970) using the old Bison power plant well located in 154-82-3CAC. Pettyjohn 1970, presented a range in transmissivity values of 17,000 ft^2/day to 24,000 ft^2/day for the Souris Valley aquifer (formerly the lower Souris aquifer). Using a mean thickness of 100 feet, the range in hydraulic conductivity of coarser portions of the Souris Valley aquifer would be 170 to 240 ft/day. Values within this range, however, appeared too large in initial model simulations. Test hole data from the area indicate that, in reality, the Souris Valley aquifer is an interbedded sequence of clay, silt, sand and gravel. Therefore, the variation in hydraulic conductivity is probably .1 to 250 ft/day. A uniform value of 100 ft/day was finally selected, which appears to result in the best replication of the actual flow system. Transmissivity (T) of the Souris Valley aquifer was calculated by the model by multiplying the saturated thickness (b) times the assigned hydraulic conductivity (K), i.e. T=Kb. Thus, the transmissivity of the Souris Valley aquifer changed whenever the water level changed. For the steady state simulation, land surface elevations, estimated from USGS 7½ minute quadrangle maps, were used as starting heads for both the Souris Valley aquifer and Sundre aquifer.

An initial estimate of 200 ft/day for the hydraulic conductivity of the Sundre aquifer was based on data from the 1969 aquifer test and from estimates based on grain size. Inferred changes in thickness of the Sundre aquifer were accounted for by specifying the appropriate transmissivity (T=Kb) values. Transmissivity of the Sundre aquifer model varied from 5,000 ft^2/day (25 feet thick) on the channel flanks to 30,000 ft^2/day (150 feet thick) along the channel axis.

Storage

Initially, a specific yield of .2 (unconfined) was assigned to cells representing the Souris Valley aquifer. Simulations utilizing specific yields within this range, however, produced water levels which were too low as compared to measured water levels. Based on the interbedded and unconfined to semi-confined nature of the Souris Valley aquifer, a specific yield of .02 was assigned. This lower value of specific yield resulted in model generated values of water level elevations more in agreement with measured values.

Data from the 1969 aquifer test were used to estimate storage coefficient for the Sundre aquifer. Aquifer test data analyses yielded a range of values for storage coefficient of 1.0×10^{-3} to 2.0×10^{-3}. Values within this range, however, caused the east and west channels of the Sundre to be not responsive enough to recharge and discharge events in the valley. A storage value of 3×10^{-4} was finally selected in order to get the model to respond to the imposed stresses in a manner which is in closer agreement with actual measured values.

Leakage

Test drilling, aquifer tests, and water level measurements have demonstrated that a hydraulic connection exists between the Souris Valley aquifer (Layer 1) and Sundre aquifer (Layer 2). Very little information is, however, available to quantify the rate or volume of leakage between aquifers. To simulate the effects of vertical leakage, an estimated value of vertical hydraulic conductivity of a one foot thick silty clay layer (.35 ft/day) between cells representing the Souris Valley aquifer and Sundre aquifer was input into the model. Vertical hydraulic conductivity in the model is defined as the confining bed hydraulic conductivity divided by the confining bed thickness. The model assumes no storage in the confining bed and flow through the confining bed is vertical. In reality, water derived from storage in the confining beds is probably a major component of the ground-water flow system. The inability to account for water derived from storage in the confining beds is one of the model's major weaknesses.

Steady state model

Introduction

Prior to 1975, the Souris Valley aquifer and Sundre aquifer were in equilibrium or steady state conditions; meaning that the amount of water entering the system was equal to the amount of water leaving the system. The steady state model was formulated first to serve as a base for the more detailed transient model.

Areal recharge

Recharge via precipitation was simulated by assigning infiltration rates to individual cells within the steady state model. The model then calculates a volumetric rate of recharge into a cell by multiplying the area of the cell times the infiltration rate. Recharge to the Sundre computer model is applied only to the highest active node.

Varying amounts of recharge were applied to different areas of the steady state model depending on surficial geology. Recharge rates of between 4 to 6 inches per year were applied to cells in the Souris River valley while only .1 inch/year was applied to the Sundre aquifer east and west of the Souris River valley. Recharge rates in this range were sufficient to allow for a reasonable match between the steady state model generated water levels and measured water levels.

Evapotranspiration

Before ground-water development, evapotranspiration (ET) was believed to be a major process which discharged water from ground-water flow systems in the area. Unfortunately, hydrologic data needed to estimate the rate of ET in the Souris River valley were never collected. Maximum ET rates for both the steady state and transient models were estimated by a trial and error procedure of adjusting ET rates within reasonable limits.

The ET rate used by the computer model depends on the position of the water level relative to the ET surface, the ET extinction depth and the maximum ET rate selected. The ET rate is a linear function which decreases from the maximum ET rate selected, to zero as the water level declines to the extinction depth. The ET rate is set to zero when the water level falls below the ET extinction depth. A maximum ET rate of 14 to 17 inches/year with an extinction depth of 6 to 8 feet resulted in steady state and transient model generated water levels which were in agreement with measured values.

Evapotranspiration was not used to directly extract water from cells representing the east and west channels of the Sundre aquifer because water levels in these areas are too deep to be affected by phreatophytes and evaporation from the surface.

<u>Souris River</u>

Water level and water quality data indicate that prior to development, the Souris River was a source of water to the Souris Valley aquifer and the Sundre aquifer during high river stage events and a drain to each aquifer during low river stage events. To simulate the effect of river/aquifer interaction, the Souris River was divided into reaches. Cells through which a river reach passed were specified as river cells (pl. 4). Conductance through the bottom of the river bed was calculated using the equation (McDonald and Harbaugh, 1984):

$$CRIV = \frac{KWL}{m} \qquad (2)$$

Where:

CRIV = conductance, river bed

K = the hydraulic conductivity of the river bed

W = the width of river reach

L = the length of the reach

m = the river bed thickness

A uniform river bed conductance of 1000 ft^2/day was assigned each river cell by using equation 2 and estimated values of K = .35 ft/day (silty clay) and m = 20 feet. Values of W and L were obtained from air photos and topographic maps. Values of model river stage were estimated using river stage data from the USGS gage above Minot and correlating them with observed stage readings at the Saugstad Bridge. Elevation of the bottom of the riverbed was estimated by using land surface elevation from USGS 7½ minute quadrangle maps and subtracting the assumed thickness of 20 feet for the riverbed.

For the steady state model, river stages of between 1525 to 1527 feet were used to simulate the effect of the ground-water flow system to low river flow. The model assumes that the river stage assigned to a cell remains constant during the steady state run.

Calibration

The Sundre computer model was calibrated for both steady-state (equilibrium) and transient conditions. The steady state model was calibrated by comparing model generated water levels with water levels measured during August of 1969. This time period was chosen because of the near equilibrium conditions existing during a low river stage, low recharge period. Ending water levels from the steady-state model were used as starting heads for the transient model.

Before any model can be used to predict the effects of ground-water development, it must be able to reproduce measured water levels within the aquifer with a reasonable degree of accuracy. During calibration of the steady state model, several adjustments were made to hydraulic conductivity/transmissivity, river conductance, interaquifer leakage, river stage, areal recharge and evapotranspiration until model generated water levels were close to the measured values. The lack of data on all the above parameters necessitated a trial and error procedure until water levels and direction of flow within the aquifer were accurately reproduced. During the calibration process, it became evident that various combinations of the above parameters generated similar water levels. For example, increasing areal recharge could be adjusted for by increasing the ET rate, thereby resulting in the same solution as when a lower areal recharge, lower ET rate were used. Thus, all the solutions were non-unique.

Presented in Figure 52-B are steady state model generated water levels in the Sundre aquifer for August of 1969. Figure 52-A, shows the measured water levels for that date. In general, the model generated water level contour map is in close agreement with the water level contour map drawn from the measured data. In the river valley, model generated water levels are about 1 foot too low. In the east and west channels of the Sundre aquifer, model generated water levels range from 0 to 1 foot too low to 1 foot too high (fig. 52). Because land surface elevation in the model is based on topographic maps (5 foot contour intervals), it was concluded that attempts at a closer match of steady state model generated water levels versus measured water levels were unjustified. Slight errors also result from not accounting for pumpage of Minot's old well field.

Ground-water flow patterns generated by the model were similar to ground-water flow patterns in the real system. Ground-water movement simulated by the steady state model was, lateral along the east and west channels of the Sundre aquifer towards the Souris River valley, and upward from the Sundre aquifer into the Souris Valley aquifer (fig. 52-B). Discharge from the steady state model occurred as outflow to the Souris River and evapotranspiration.

Listed in Table 4 is the volumetric water budget calculated by the steady state version of the model. As is evident, the only input to the system during the steady state run is areal recharge. Discharge from the system was through ET and river leakage. Ground-water leakage into the river was 1.08 acre-feet/day or approximately 1 ft^3/sec over the one day simulation period. This correlates rather well with the low river flow measurements in 1969.

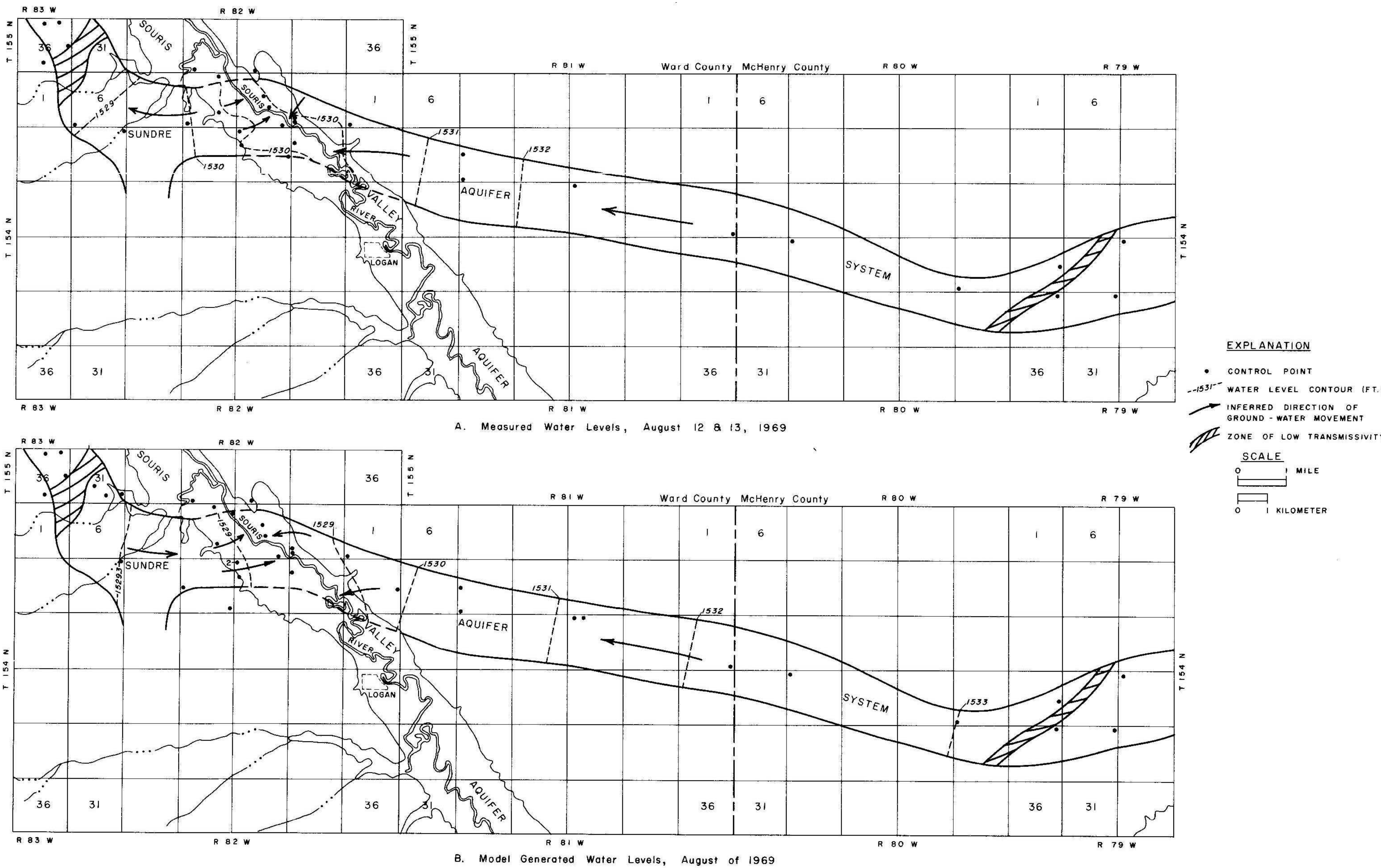


FIGURE 52. Comparison of measured water level contour map for August of 1969 versus steady state model generated water level contour map for that time of the year.

Table 4. Volumetric water budget for steady-state model

	Volume in (acre-feet)	Volume out (acre-feet)
Storage	0	0
Constant head	0	0
Recharge	1.98	0
ET	0	.83
River leakage	0	1.08
Total	1.98	1.91

% discrepancy .3%

Transient model

Discretization of time

Simulation time within the transient model is divided into stress periods, which are time intervals during which all external stresses are constant. Each stress period is, in turn, divided into time steps (McDonald and Harbaugh, 1984). Stress periods of three different types were used in the transient version of the Sundre model. Each stress period represents a unique hydrologic season of the year: (1) a river stress period, generally 30 to 90 days long, to simulate the effects of the spring of the year with high river stage and high areal recharge event. (2) an evapotranspiration (ET) stress period, 90 days long, to simulate the effects of high ET rates, low river stage, and moderate areal recharge and, (3) a baseflow stress period, anywhere from 185 to 245 days long, to simulate the effects of no ET, low areal recharge and low river stage. The transient version of the Sundre model simulates hydrologic conditions for the time period 1970-1985 using 49 stress periods. Pumping withdrawals were added to the appropriate stress periods from 1976-1985.

Areal recharge

Areal recharge rates to the transient model, as with the steady state model, were spatially varied depending on the nature and thickness of the surficial geologic materials. Recharge rates used included a low recharge rate into the east and west channels of the Sundre aquifer and higher recharge rates to cells representing the Souris Valley aquifer. A constant rate of .1 to .2 inches per year input into the east and west channels of the Sundre proved to result in the best match of observed versus model generated water levels. This rate was not varied from stress period to stress period.

Recharge rates in the Souris River Valley were, however, varied according to stress period. During the ET stress period (June, July, and August) low to moderate amounts of recharge were applied (.3 to .5 inches/month). Although about 37% of the average annual precipitation (19.42 inches, U. S. Weather Bureau, 1968-1985) falls during June, July and August, probably most of it is transpired by plants and evaporated so that only a small amount actually recharges the aquifer during the ET stress period.

During the base flow stress period (September of the year to the next river stress period in the spring), very low to moderate recharge was applied to cells representing the Souris Valley aquifer (0-.3 inches/month). The amount of recharge input into a particular base flow stress period depended on the amount of rain occurring that particular year. If heavy summer (ET period) and fall (base flow period) rains occurred back to back, a higher base flow stress period recharge rate was applied. If a very dry ET stress period was followed by a dry baseflow stress period, very little recharge was needed to generate water levels similar to measured water levels. No additional recharge was assumed to enter the system once the frost zone was established in the winter.

During the river stress period, low to very high recharge rates were applied to the Souris Valley aquifer based on both the amount of precipitation that occurred over that river stress period and over the preceding base flow stress period (0 to 1 inch/month). Heavy rains in the fall (base flow period) would tend to build up the soil moisture, thereby increasing the potential for recharge in the spring or vice versa.

Areal recharge over the river stress period was also increased to account for the effects of the river overflowing its bank and inundating the floodplain during a very high river stage event. In fact, between 1 to 2 inches/month of areal recharge were needed during some very high river flow periods in order for the model to generate water levels similar to those measured during a flood event. This further substantiates that flooding of the river over its banks was a major source of recharge to ground water flow systems in the area.

Evapotranspiration (ET)

The ET rate (14 to 17 inches/year) and ET extinction depth (6 to 8 feet) used by the transient model were the same as those values used in the steady state model. The only time period in which ET was extracted in the transient model was during June, July, and August (ET stress period). ET was assumed to be negligible during the rest of the year, therefore, ET was not used to extract ground water from the transient model from September to May.

Souris River

Fluctuations in river stage were simulated in the transient model by raising or lowering the water level in a river cell depending on the height of the gage readings on the Souris River above Minot. Length of a river stress period was correlated to observed stage events at the gage above Minot. River stress periods in the model ranged from 30 to 90 days long. Physical parameters for the river (river bed conductance and elevation of bottom of river bed) were the same as those used for the steady state simulation. River stage input into the transient model varied from a 15 foot rise for some years (1970, 1975, 1976) to no rise during others (1981, pl. 2).

Pumping stresses

The five large capacity wells tapping the Sundre aquifer were represented in the model by specifying a constant negative flux (well discharges) over a given stress period at the corresponding cell. The fluxes were calculated using monthly power use data supplied by Northern States Power. Wells A and B were lumped together at one cell, while wells C, D, and E occupied separate cells. The total volume of water pumped from a given cell for a given time period was averaged to a constant discharge rate over the given time period. Location of the pumping cells is shown on Plate 4. Well discharge data are presented in Pusc, 1987.

Calibration

The ultimate goals of a modelling study would be to, accurately predict future hydrologic conditions and/or to assess hypothetical changes to the flow system. Before the Sundre model can be used as a predictive tool, it is necessary to demonstrate that the model can simulate measured water level responses to historic hydrologic conditions. The transient simulation required considerable adjustment of recharge, evapotranspiration, and streamflow values, within reasonable limits, in an attempt to reproduce measured water levels. Values of river bed conductance, hydraulic conductivity and/or transmissivity, vertical leakage, and storage coefficient were also adjusted within estimated limits until a reasonable agreement between simulated and actual water levels was attained.

Two observation wells were selected to compare water levels generated by the model versus measured water levels. Each well was selected for its unique hydrogeologic setting. The first well, 154-82-03CDC$_1$, represents the long term water level fluctuations in the Sundre aquifer underlying the Souris Valley aquifer (fig. 53). The second well, 154-80-20BBB, represents the long term water level fluctuations in the eastern channel of the Sundre aquifer (fig. 54).

Generally, computer simulated water levels follow the same general trends as the measured water levels. Note, however, that under natural conditions (1970-1975), the model generates water levels which are too high during a high river stage event and generates water levels which are too low during a low river stage event. This is believed to be partly due to the sparcity of measured water levels. If measurements would have been taken more frequently, the measured water levels may have been closer to the water levels that the model predicted. Also, because of topographic map constraints, land surface elevations in the transient model are to the nearest 5 feet. It was concluded that attempts at a near perfect match of transient model generated versus measured water levels were unjustified. The slight time lag or lead response to imposed stresses is due to the inability to exactly duplicate the timing of recharge and discharge events.

Model generated water levels following development (1976-1985) range

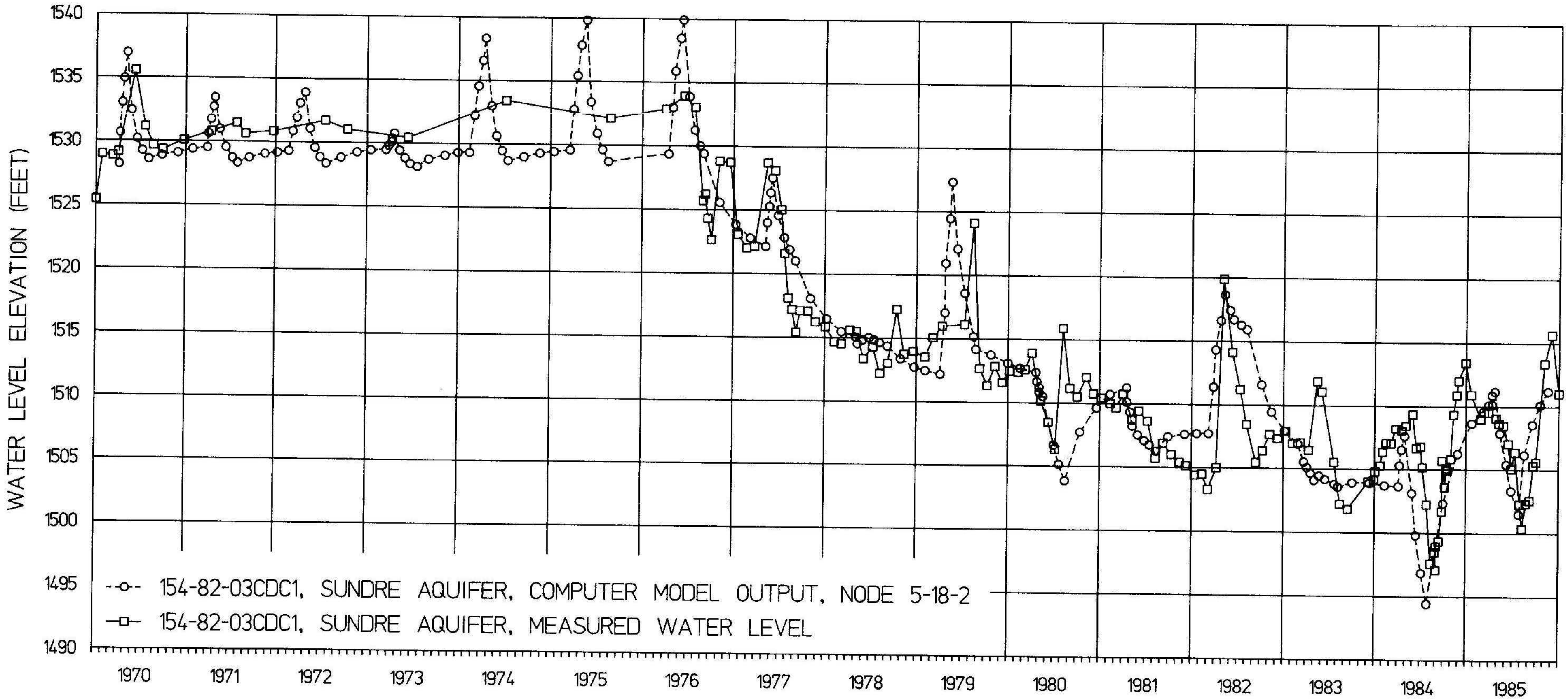


FIGURE 53. Hydrographs comparing measured water levels versus transient computer generated water levels for 154-82-03CDC1, Sundre Aquifer in Souris River Valley.

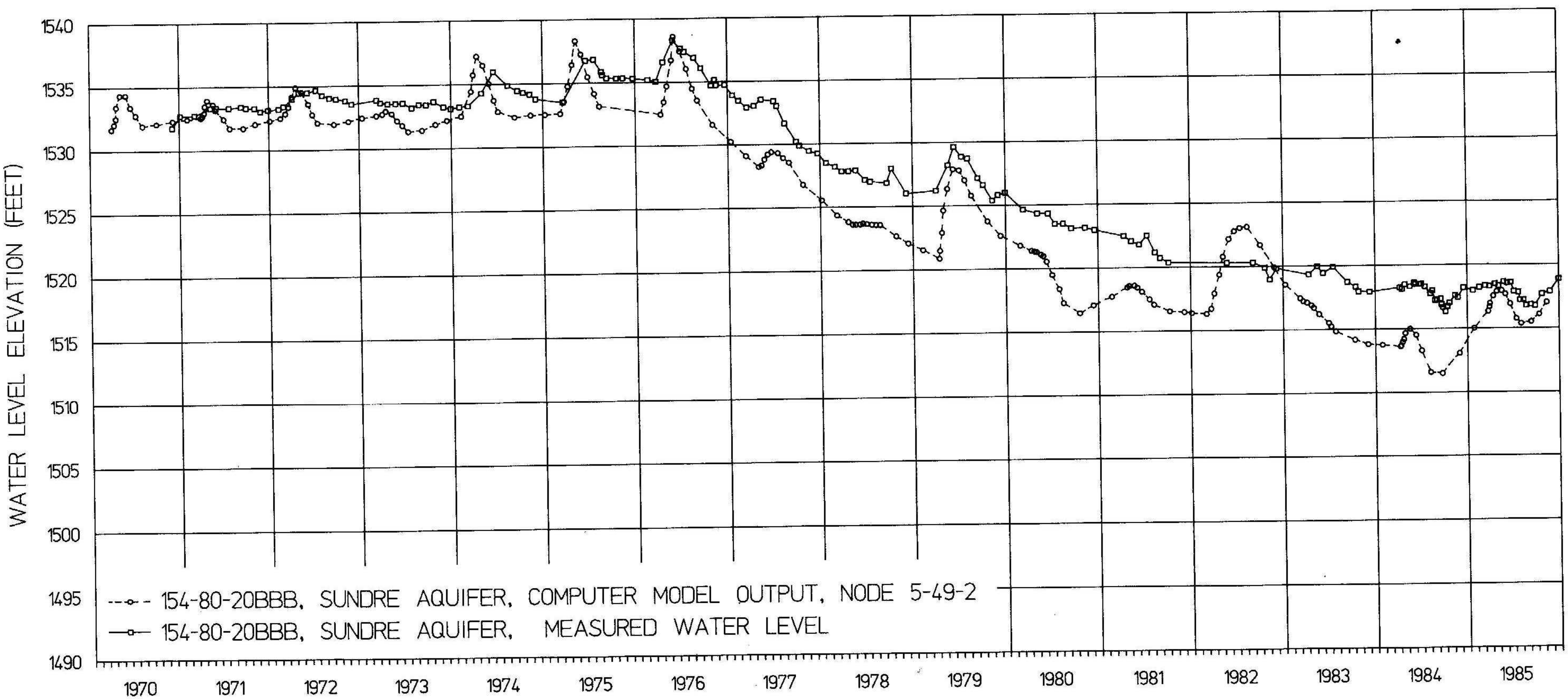


FIGURE 54. **Hydrographs comparing measured water levels versus transient computer generated water levels for 154-80-20BBB, Sundre Aquifer, eastern channel.**

from a fairly good match in the Souris River valley to too low (1-3 feet) in the eastern channel of the Sundre (figs. 53 and 54).

Water level contour maps generated by the model were compared to water level contour maps constructed from measured water levels. Three separate events were compared: 1) a low river stage, high ET, low recharge, no pumping period (fig. 55-A); 2) a high river stage, no ET, high areal recharge, no pumping period (fig. 55-B), and 3) a heavy pumping (1985), high ET, low recharge, low river period (fig. 56).

In general, the model confirms the conceptual flow systems discussed in Chapter 3. During natural low river flow conditions (prior to 1976), ground-water flow simulated by the model consisted of the same flow components as the real system: 1) lateral movement in the east and west channels of the Sundre aquifer towards the Souris River valley, 2) upward movement from the Sundre aquifer to the Souris Valley aquifer, and finally 3) discharge occurring as Souris River flow and evapotranspiration (fig. 55-A).

During high river stage, ground-water movement simulated by the transient model consisted of the same flow components as the real system: 1) downward flow from the Souris River and Souris Valley aquifer into the Sundre aquifer and 2) lateral movement toward the east and west in the Sundre aquifer (fig. 55-B).

Flow patterns generated by the transient model for a heavy pumping scenario (1985) are very similar to the flow patterns inferred from measured water levels. Note that in both cases, ground-water flow is directed towards the pumping wells located in Section 3 (fig. 56). Variations in water level elevation and gradient

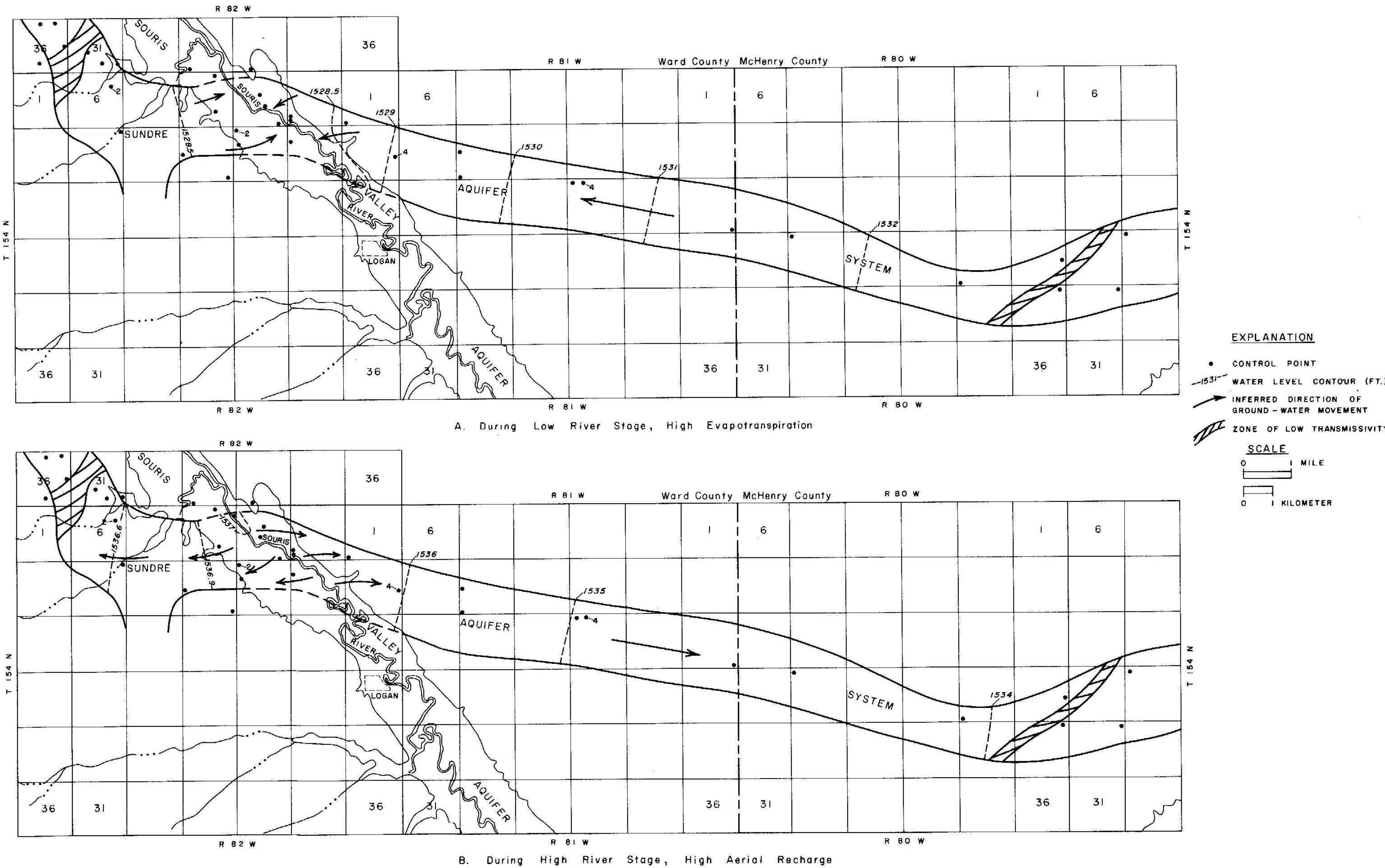


FIGURE 55. Transient model generated water level contour maps during a low river stage event (A) and a high river stage event (B). Prior to development.

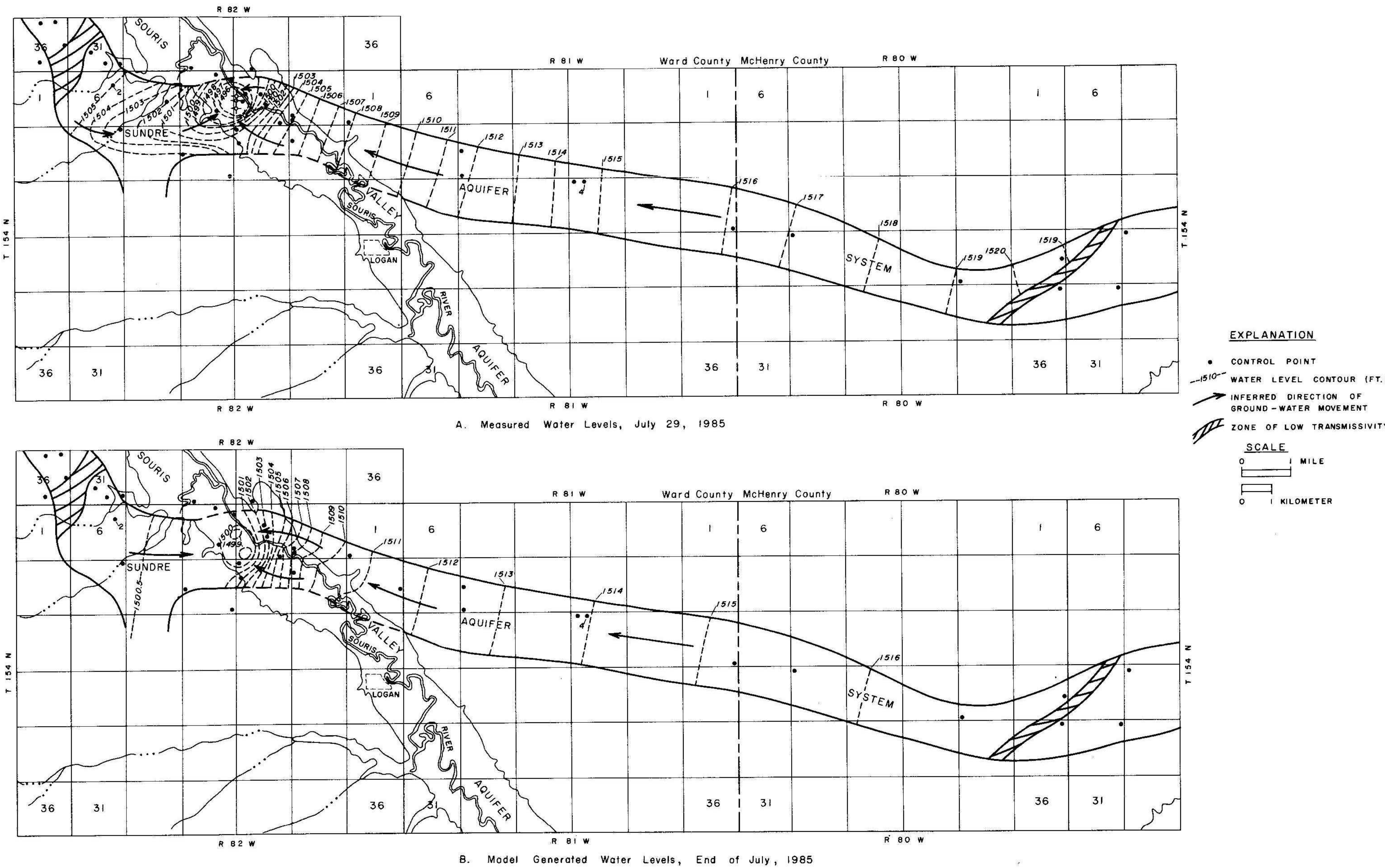


FIGURE 56. Comparison of measured water level contour map, July 1985, during heavy pumping versus transient model generated water level map for the same time period.

are mostly due to five factors: 1) in reality, there are directional differences in hydraulic conductivity (K) of the Sundre aquifer which cause breaks in slope of the piezometric surface. The model does not account for all the subtle variations in K, and therefore the model does not reproduce the same water level gradient variations. 2) The timing of the monthly measured water levels may not coincide with the model generated water levels. 3) A drop in water level as a result of pumping would tend to induce a greater volume of leakage from the surrounding geologic materials. The computer model does not account for this induced recharge. 4) The water level in each cell is uniform over the entire cell resulting in a steplike function that cannot fully simulate the continuum of nature. 5) The averaged pumping rate over a given time period in the model cannot fully simulate true variations in pumping rate.

Water budget

Listed in Table 5 is the volumetric water budget calculated by the Sundre transient computer model. Recharge to the predevelopment portion (1970-1976) of the transient model was comprised mainly of areal recharge (67%). Thirty percent (30%) of the recharge came from storage while only 3% was derived from the river (table 5). Ground water discharging out of the pre-development portion of the transient model included water released from storage (31%), evapotranspiration (35%) and river flow (33%, table 5).

Inspection of the post development time period of the water budget (1976-1985) reveals that pumping greatly affected the flow system. Pumping over the last 10 years has accounted for 88% of the ground water discharging from the system. To make up for the water pumped from the system, the model results show a reduction in the amount of ground water naturally discharging into the river from 33% to 1% (table 5). Evapotranspiration was reduced from 35% of the discharge leaving the system to 2% leaving the system. Water derived from storage accounted for 10% of the water. Most of the ground water was derived, however, by increasing the amount of water naturally moving from the river into the aquifer (from 3% to 63%, table 5). Although the areal recharge per year stayed essentially the same between non-development and development portions of the model, the percentage of the budget for areal recharge dropped from 67 to 25%.

The model suggests that 63% of the water presently recharging the system is derived from the river. When water use is compared to the average flow of the Souris River, however, the volumes pumped represent a small portion of the average river flow. Over the past 10 years the city of Minot has pumped an average of 2.1 million gallons per day (mg/d) from the Sundre well field. The model indicates that the river has been contributing 1.5 mg/d. These volumes, however, represent a very small percentage of the average yearly flow of 109 mg/d in the Souris River (USGS, 1903-1985).

Table 5. Volumetric water budget for the predevelopment portion of the Sundre transient model (A), compared to the development portion (B)

	A Prior to Development 1970-1975				B During development 1976-1985			
	Recharge		Discharge		Recharge		Discharge	
	(A-F/yr)*	(%)	(A-F/yr)*	(%)	(A-F/yr)*	(%)	(A-F/yr)*	(%)
Storage	280 (.025)	30	280 (.025)	31	319 (.028)	12	261 (.023)	10
Areal Recharge	629 (.056)	67	0 (0)	0	667 (.061)	25	0 (0)	0
Wells	0 (0)	0	0 (0)	0	0 (0)	0	2364 (2.11)	88
ET	0 (0)	0	312 (.032)	35	0 (0)	0	51 (.005)	2
River	30 (.003)	3	297 (.027)	33	1704 (1.52)	63	25 (.002)	1
Totals	939		889		2690		2701	

*Figures in parenthesis are in units of million gallons/day

Sensitivity analysis

Before the Sundre computer model can be used as a predictive tool, it must be tested for its sensitivity to changes in assigned parameters. The following discussion outlines the effects of varying model input parameters, up or down, from the assigned value. Hydrographs generated during the sensitivity analyses were too numerous to present. Copies of the figures are available for inspection at the offices of the North Dakota State Water Commission.

Transmissivity (T), hydraulic conductivity (K)

The model is slightly sensitive to changes in the value of transmissivity (T) assigned to the Sundre aquifer. One effect is to steepen (lower T) or flatten (higher T) the gradient out in the east and west channels. Also with a smaller transmissivity value, less water is conducted toward the area of withdrawal and greater declines in hydraulic head occur in the immediate vicinity of the pumping wells. With a higher T, the opposite occurs and not enough drawdown is calculated by the model.

Decreasing the hydraulic conductivity (K) of the overlying Souris Valley aquifer has the effect of raising water levels slightly in both the Souris Valley aquifer and Sundre aquifer. Along with this water level rise is an accompanying increase in the amount of water taken up by evapotranspiration. On the other hand, increasing the hydraulic conductivity of the Souris Valley aquifer has the effect of dampening the water level response in both the Souris Valley aquifer and Sundre aquifer.

Storage coefficient (S)

The sensitivity of the model to adjustment in storage coefficient (S) of the Sundre aquifer was varied. A smaller S (3.0×10^{-6}) caused water levels in the east and west channels of the Sundre to be too responsive to recharge and discharge in the valley. On the other hand, a larger S (3.0×10^{-3}) caused the water levels in these portions of the aquifer to be not responsive enough to recharge and discharge in the valley.

In the river valley, adjustments in the value of S of the Sundre aquifer had little or no effect on results. It appears that other factors control water level response in the river valley, while out in the channel, storage coefficient is one of the dominant factors.

Water level response in the Sundre transient model is very sensitive to the storage properties of the overlying Souris Valley aquifer. When storage is increased from .02 to .2, the Souris Valley aquifer has the ability to take more water into storage without having as large of a change in water level. The effect is to dampen water level response in both the Souris Valley aquifer and underlying Sundre aquifer. On the other hand, when S is decreased to .002, only a small amount of water is needed to cause a rather large water level change in the Souris Valley aquifer. This larger water level change in the Souris Valley aquifer is quickly transferred down into the Sundre aquifer causing model simulated water levels that are too high.

Vertical hydraulic conductivity

The model is also sensitive to changes in vertical hydraulic conductivity between layers (leakage). Reducing the vertical conductance slows the transfer of water between aquifers. During heavy pumping, the result is to not allow enough water to leak into the Sundre aquifer from the overlying Souris Valley aquifer. With less leakage, the model has to derive more water from the Sundre aquifer thereby drawing water levels down past measured values. The model appears to respond better if water is allowed to move rather easily between the two aquifers. The sensitivity of the model to vertical conductance suggests that a poor understanding of leakage could be one of the major drawbacks of the model.

River bed conductance

The sensitivity of the transient model to changes in river bed conductance is reflected in both the water levels generated and the water budget. In the pre-development portion of the model (1970-1975), a lower river bed conductance term (increased river bed thickness from 20 feet to 40 feet) caused less water to both enter and leave the system via the river. The effect was to not raise water levels high enough during a flood event and to hold water levels up too high during low river flow.

The lower river bed conductance term had a dramatic effect on both the water levels and the water budget of the pumping portion of the model (1976-1985). Because less water was able to move from the river to the aquifer, the model generated water levels in response to pumping that were too low. In fact, during heavy pumping of 1985, the model predicted water level elevations which were 60 to 70 feet lower than measured values. The sensitivity of the model to river bed conductance suggests that a poor understanding of the surface water/ground-water connection is another major weakness of the model.

Feasibility of the model as a predictive tool

Before it is feasible to use the Sundre computer model as a predictive tool, it is necessary to: 1) demonstrate that the model can simulate measured water level response to historic hydrologic conditions (calibration) and to 2) test the sensitivity of the model to changes in assigned values.

During calibration and sensitivity analysis, four areas of weakness in the model became apparent. A high level of uncertainty in these areas preclude the use of the Sundre model as a predictive tool. The primary areas of weakness are: 1) numerous combinations of input parameters generated similar water levels making all the solutions non-unique. Thus, there is a high level of uncertainty as to which set of parameters is the "correct set". 2) Under the observed range of stresses, the model appears reliable. Several head dependent terms, however, (interaquifer-leakage, ET, river leakage, etc.) may cause the model to be totally unreliable under a new set or magnitude of stresses. 3) The model does not account for water derived from storage in the confining beds. In reality, a considerable volume of water is probably obtained from storage in the confining beds when pumping. The inability to account for this unknown, but considerable, volume of water would be a major source of error in any predictive model. 4) The model is very sensitive to the assigned values of river bed conductance, interaquifer-leakage, and the physical properties of the Souris Valley aquifer. A poor understanding of these very important physical parameters causes a high degree of uncertainty in any predictive simulation.

Conclusions from the model

1) Flow and water level response within the Sundre aquifer system can be reproduced using computer simulation. The computer model suggests that the dominant factors controlling ground-water flow in the Sundre aquifer are: (A) the magnitude and timing of recharge (precipitation and river flow) and discharge (evapotranspiration, river flow, and pumping), (B) the hydraulic properties of the Souris Valley aquifer, and (C) the rate of leakage between the Souris Valley and Sundre aquifers.

2) Large scale ground-water withdrawals have changed the dynamic nature of the river-aquifer relationship in the model. With the lower water levels, the river always acts as a source of water to the ground-water flow systems. The only ground water the river now receives is probably from bank storage. The model suggests that 1.5 mg/d are now moving from the river into the ground-water flow systems.

3) Uncertainty in the following five areas preclude the use of the Sundre computer model as a predictive tool: (1) non-unique solution, (2) several head dependent terms may cause the model to be unreliable under a new set of conditions, (3) the model does not account for water derived from storage in the confining beds, (4) model is very sensitive to the highly uncertain parameters of river bed conductance, interaquifer leakage, and properties of Souris Valley aquifer, (5) long term predictive models are eventually dominated by climate (areal recharge, ET, river flow) and pumping. Uncertainties in weather prediction are well known. Prediction of future pumping can also be a major source of error (Konikow, L.F., 1986).

4) The model is not very sensitive to changes in the physical properties of the east and west channels of the Sundre aquifer. Thus, additional drilling is not needed to further define these segments of the system.

5) At one time it was believed that the Sundre and New Rockford aquifers were one continuous system (Randich, 1981A and Pettyjohn, 1970). Limited water level data suggested, however, that a low transmissivity barrier truncates the channel southeast of Simcoe, ND. In order to simulate the measured water levels, the model had to be terminated near Simcoe, thus confirming the existence of the barrier. The model also confirmed that a barrier exists just southeast of Minot.

SUMMARY

The Sundre aquifer system occupies portions of a buried, bedrock valley which extends from northwest of the city of Minot, North Dakota, beneath the Souris River at two locations, and continues east into McHenry County. Width of the Sundre aquifer ranges from 1 to 2 miles. Thickness varies from 30 feet in the western channel to 250 feet thick in the Souris River valley. In the Souris River valley, the Sundre aquifer generally occurs from 90 to 210 feet below land surface. Thickness of the eastern channel of the Sundre aquifer ranges from 100 to 250 feet thick.

The Sundre aquifer system consists of varying amounts of sand and gravel with occasional interbeds of silt and clay. Low transmissivity (T) barriers truncate the Sundre aquifer just southeast of Minot and about 6 miles east of the Ward-McHenry County line. The low transmissivity barrier in McHenry County represents the boundary between the Sundre and the New Rockford aquifers. Total length of the Sundre aquifer, between the low T barriers, is approximately 18 miles.

In the Souris River floodplain, the Sundre aquifer is overlain by sand and gravel deposits of the Souris Valley aquifer. The Souris Valley aquifer varies from an interbedded sequence of clay, silt, sand and gravel to one continuous section of sand and gravel. Thus, there are places where the Souris Valley aquifer and Sundre aquifer are one continuous hydrologic unit. In the upland areas adjacent to the Souris River valley, the Sundre aquifer is overlain by a considerable thickness of glacial till.

Data from one long term aquifer test of the Sundre aquifer yields transmissivity values of 32,000 ft^2/day to 36,000 ft^2/day, and storage coefficient ranging from 1×10^{-3} to 2×10^{-3}. Drawdown data from the test indicate that the Sundre aquifer is a leaky-confined aquifer with numerous barrier boundaries.

Well yields from the Sundre aquifer range from 2-5 gpm from small diameter domestic wells to 2800 gpm from well D of the Minot well field. Presently, the city of Minot has five large capacity wells which draw ground water from the Sundre aquifer system. Average water use since 1976 has been 2.1 mg/d. Water use in 1985 was 2.6 mg/d.

Bedrock underlying the area consists of consolidated silt, clay and sandstone units of the Fort Union Formation. These units exhibit a very low hydraulic conductivity in comparison to sand and gravel deposits of the overlying Sundre aquifer system.

Recharge to the Sundre aquifer before development occurred from three main sources: (1) from precipitation moving through the Souris Valley aquifer and downward into the Sundre aquifer, (2) from the Souris River during high river stage via the Souris Valley aquifer and, (3) precipitation moving slowly through glacial till which overlies the Sundre aquifer in the upland areas east and west of the Souris river valley. Natural discharge from the Sundre aquifer before development of the Sundre well field was by evapotranspiration and river flow in the Souris River valley.

Before development, fluctuations of ground-water levels in the Sundre aquifer system were primarily due to stage fluctuations of the Souris River, precipitation, and evapotranspiration. A rise in river stage resulted in a corresponding rise in ground-water levels, while a decrease in river stage resulted in a decline in water levels. The highest ground-water levels usually occurred during the months of March through June in response to maximum stage of the Souris River and local snowmelt and precipitation events. Lowest ground-water levels were in the late fall in response to evapotranspiration and low river stage.

Precipitation events during the summer and fall months had little effect on the water levels.

Depth to water in the Sundre aquifer before development was primarily a function of land surface elevation and season of the year. On the floodplain, depth to water ranged from 5 to 10 feet below land surface. In the upland areas adjacent to the souris River valley, depth to water in the Sundre varied from 100 to 110 feet.

Ground-water movement in the Sundre aquifer system prior to development was controlled by the stage of the Souris River, precipitation, and evapotranspiration. Under low river flow conditions, high evapotranspiration, low areal recharge events, the Souris River valley acted as a regional discharge area and all ground-water movement in the Sundre aquifer was directed toward the river valley. Under these conditions, ground water flow was, downward through the overlying tills into the east and west channels of the Sundre aquifer, lateral movement towards the Souris River valley, and finally upward from the Sundre aquifer to the Souris Valley aquifer. Discharge from the Souris Valley aquifer occurred as outflow to the Souris River and by evapotranspiration.

When the stage of the Souris River rose in the spring, all ground-water movement in the Sundre aquifer system was away from the river. Movement during high river stage was, downward from the Souris River and Souris Valley aquifer, into the Sundre aquifer, and lateral toward the east and west in the Sundre aquifer. Before development the Souris River valley was a recharge area for the Sundre aquifer during high river stage, high precipitation events and a discharge area during low river stage, high evapotranspiration events.

In 1985, fluctuations of water levels and ground-water movement in the Sundre aquifer system are dominated by pumping patterns of the Sundre well field. The cone of depression created by the wells directs ground water in the Sundre aquifer toward the well field from all directions. During periods of heavy use (summer) water levels decline, and during less use (winter) water levels recover. Ten years of pumping has resulted in 17 to 25 feet of decline in the eastern channel of the Sundre aquifer. In the well field, declines of 31 to 40 feet have occurred. The decline occurring as a result of pumping, however, represents a very small percentage of the total amount of water available in storage.

The Sundre aquifer system is highly productive. Under present rates of withdrawal the water levels have stabilized with a relatively small decline. Larger withdrawals will result in a short interval of additional water level decline and then stabilize at the lower level. The total yield potential cannot be determined, however the capacity of the aquifer is significantly larger than the amount currently being pumped. An increase in pumping, however, may result in some further change in water quality.

Piezometer nest data indicate that ground water in the Souris River valley now (1985) moves downward from the surface (precipitation and Souris River flow), through the Souris Valley aquifer, into the Sundre aquifer, and finally is discharged from wells. Because of pumping, the Souris River always acts as a source to the ground-water flow systems instead of the river being a source during high river flow and a sink during low river flow (except for bank storage), as was the case before development.

Before development, the quality of ground water in the area could be divided into four major hydrochemical facies: (1) a low to average TDS, Ca-Na-HCO_3 type water in the Souris Valley aquifer, (2) a low to average TDS, Na-HCO_3 type water in the Sundre aquifer underlying the Souris Valley aquifer, (3) an average to high TDS, Ca-Na-SO_4 type water in the eastern channel of the Sundre and (4) a high TDS, Na-HCO_3-SO_4 type water in the western channel of the Sundre. Before development, the proximity of the Souris River to the Souris Valley aquifer and underlying Sundre aquifer provided the recharge mechanism needed to keep the water in this part of the aquifer relatively low in dissolved solids. Recharge of poorer quality water from overlying drift deposits, slow movement, reversals in flow direction, and long flow paths appears to have resulted in a high TDS, poorer quality water in the east and west channels of the Sundre aquifer.

Generally, ground water from the study area following development can be divided into seven major hydrochemical facies. The increase in the number of hydrochemical facies from 1969 to 1985 was due to both physically sampling more types of ground-water environments and from pumping-induced changes in water quality. The seven hydrochemical facies types identified in the area in 1985 are: (1) A low to average TDS, Ca-Na-HCO_3 type in the Souris Valley aquifer, (2) a low to average TDS, Ca-Na-HCO_3 type water in that part of the Sundre aquifer which underlies the Souris Valley aquifer, north of the Souris River in Section 3 and near Minot city production wells A, B, and C, (3) an average to high TDS, Ca-Na-SO_4 type water in the Sundre aquifer near city production wells D and E, (4) an average to high TDS, Ca-Na-SO_4 type water in the eastern channel of the Sundre (5) an average to high TDS Na-HCO_3-SO_4 type water in the western channel of the Sundre (6) an average TDS, Ca-SO_4 type water in the glacial till and (7) a very high TDS, Na-Cl type from the bedrock.

The general area which has undergone the most noticeable change in water quality is the Sundre aquifer near Minot city production wells D and E. Near well E, ground water has changed from a Ca-Na-HCO_3 in 1969 to a Na-Ca-SO_4 type in 1985. Ground water in this part of the Sundre aquifer is now very similar to ground water in the eastern channel of the Sundre aquifer. It appears that heavy pumping of the Minot city wells is drawing poorer quality water from the eastern channel towards the southern end of the well field where wells D and E are located.

Pumping pattern also appears to affect the quality of the ground water pumped from wells completed in the Sundre aquifer system. During heavy use by well D, sulfate levels in ground water from well D decrease from 600 to 350 mg/l. It appears that well D (2800 gpm) induces fresher water from the north to move towards the well and mix with the poorer quality water being derived from the south and east; resulting in an overall improvement in water quality from well D. When well D is shut down, and most of the water is pumped from wells A, B, and C, sulfate levels in well D increase. With prolonged, heavy use of wells A, B, and C, and limited use of well D, the water from well D converts to a Na-Ca-SO_4 type water. It appears that wells A, B, and C are intercepting better quality water from the north and preventing it from migrating toward well D. Pumping of just wells A, B, and C also appears to draw poorer quality water from the south and east, past wells D and E, thereby increasing the levels of dissolved solids in D and E. Prolonged use of wells A, B, and C without pumping well D eventually causes a slight degradation in the quality of ground water pumped from well C.

An areal three-dimensional ground-water flow model was developed to simulate ground-water movement in the Sundre aquifer system. The model simulates hydrologic conditions prior to development (1970-1975) and following the introduction of pumping wells (1976-1985). The model was calibrated by comparing model generated water levels with measured water levels.

Generally, model-generated water level contour maps and hydrographs were in close agreement with maps and graphs prepared from the measured data. Numerous combinations of input parameters generated similar results making all of the solutions non-unique. The model's inability to account for water derived from storage in the confining beds, and the sensitivity of the model to changes in leakage between aquifers, river conductance, and the physical properties of the Souris Valley aquifer preclude the use of the model for predictive purposes.

Basically, computer modelling of the Sundre aquifer system confirmed the conceptual model of ground-water flow in the area. Primary benefits from the modelling effort have been to provide a disciplined format to improve the understanding of the ground-water flow system and to identify those processes which dominate ground-water flow under changing conditions. Future work can concentrate on quantifying the dominant processes instead of analyzing minor processes of the flow system.

The transient model simulation indicated that, before development (1970-1975), 67% of the annual recharge entered the system as areal recharge. Only about 3% was derived from the river, while 30% was derived from storage. Discharge from the model before development was evenly divided between evapotranspiration, leakage into the river and water out of storage.

Pumping of wells from 1976-1985 changed the dynamic equilibrium of the system. Now, about 88% of the water leaving the system is from pumping wells. Ten percent (10%) of the water was derived from storage within the aquifer. A portion of the water pumped was derived from reducing ground water discharging into the river (from 33 to 1%). Lowering of water levels also caused a large reduction in the amount of water leaving the system via evapotranspiration (35 to 2%). Most of the ground-water was derived, however, by increasing the amount of water leaking from the river into the aquifer (3 to 63%). No significant impacts to the river are expected, given that the present average annual well discharge (2.1 mg/d) only represents a very small percentage of the average annual river flow (109 mg/d).

Based on the modelling effort, the following processes presently dominate ground-water flow in the area: (1) well pumpage from the Sundre aquifer (2) leakage from the Souris River into the Souris Valley aquifer (3) leakage from the overlying Souris Valley aquifer into the Sundre aquifer (4) storage within the aquitards, and (5) areal recharge. A thorough knowledge of each one of the above processes will be needed before a reliable predictive model is possible.

RECOMMENDATIONS

1) Continue measuring water levels in the area on at least a monthly basis to assess the impact of future pumping.

2) Obtain water samples from the production wells on at least a quarterly basis to assess any changes in water quality with time. If more detail is desired on water quality versus pumping pattern, it would be recommended to do extensive sampling coordinated with controlled pumping cycles.

3) Future work should concentrate on delineation of the Souris Valley aquifer and its connection to both the Souris River and the underlying Sundre aquifer system. The heterogeneous nature of the Souris Valley aquifer creates spatial variations in the rate of recharge to the Sundre aquifer system. The hydraulic properties of the Souris Valley aquifer must be defined before a reasonably accurate quantification of some of the processes is possible.

4) Due to the hydraulic connection between the Souris Valley aquifer and Sundre aquifer, land use practices on the floodplain should be monitored. Additional study could then be geared to investigate the effects that a particular practice would have on the hydrologic system.

5) The city of Minot should keep an accurate record of the amount of water pumped from each well. One way to accomplish this would be to program the computer at the water treatment plant to keep track of how long each individual pump is used.

6) Presently, water levels cannot be measured in any of Minot's production wells due to their physical design. Stilling wells or reliable air lines should be installed in each well the next time a bowl assembly is pulled for servicing.

7) The inability to accurately and uniquely identify and quantify river leakage, inter-aquifer leakage, and storage in the aquitards precludes the use of the Sundre computer model as a predictive tool at this time. Nonetheless, predictive simulations should be attempted in order to compare the model's response to documented future stresses. This would be useful in proving and improving the validity of the model's predictive accuracy. The Sundre model should be periodically updated and tested as more data are collected.

8) Initiate studies of alternatives for the management of the Souris River-Sundre aquifer system to enhance the water supply potential of the system.

9) To further test the capacity of the Sundre aquifer system, the Sundre well field could be pumped at a higher rate for an extended period of time. During this controlled test, water levels and water quality should be carefully monitored to document the effects that the additional stress has on the system.

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