HYDROGEOLOGY OF THE MINOT AQUIFER, WARD COUNTY, NORTH DAKOTA

by

Steve W. Pusc

North Dakota Ground-Water Studies
Number 102 - Part II
North Dakota State Water Commission
David Sprynczynatyk, State Engineer

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

ND State Water Commission

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TABLE OF CONTENTS

ILLUSTRATIONS

Plate

Figure **page**

Figure **page**

TABLES

INTRODUCTION

General statement

Prior to 1916, the city of Minot relied solely on water from the Souris River for its needs. Highly irregular seasonal flows, poor water quality and increased water demands made this source of supply inadequate and undesirable (Akin, 1947). From 1916 to 1961, 18 large-capacity production wells were completed into the Minot aquifer to supply the ever increasing water demands of the city. By 1963, heavy long-term pumping of the Minot aquifer had resulted in over 70 feet of water level decline (Pettyjohn, 1967). This serious reduction of ground water in storage prompted ground-water investigations to define the sustained yield of the Minot aquifer and to identify means of enhancing Minot's water supply (Pettyjohn, 1967 and 1968). Test drilling done for Pettyjohn (1967) and (1968) led to the discovery of the high-yielding Sundre aquifer system. In 1974 and 1975, the city of Minot constructed five large-capacity production wells into the Sundre aquifer system. From 1977 through 1987, the city of Minot obtained about 1/3 of its water from the Minot aquifer, 1/3 of its water from the Sundre aquifer system, and 1/3 of its water from the Souris River. During the drought of 1988, however, the city was not able to obtain its 1/3 supply from the Souris River. To make up for the diminished surface water supply, the city of Minot increased demand from the Minot aquifer from 2.5 million gallons per day (mg/d) to as much as 6.5 mg/d. This increased withdrawal from the Minot aquifer resulted in a water level decline of 18.5 feet. To mitigate a further dewatering of the Minot aquifer, the city of Minot then increased pumping from the Sundre aquifer system.

The drought of 1988 highlighted the need for the city of Minot to develop an integrated water management plan (City of Minot, 1991). The basis for the management plan is a comprehensive analysis of the surface and ground-water resources in the Minot area. According to the City of Minot (1991),

> "A study of the Minot aquifer by the North Dakota State Water Commission to identify methods of making maximum use to the aquifer should be authorized, and the study recommendation should be implemented as soon as possible"

Purpose and objectives

In September of 1991, the city of Minot entered into an agreement with the North Dakota State Water Commission to conduct a comprehensive hydrogeologic investigation of the Minot aquifer in the vicinity of Minot, North Dakota. The purpose of this investigation was to increase the understanding of the geometry, occurrence, movement, response to pumping and quality of ground water in the Minot aquifer. Specific objectives of the Minot aquifer study were to:

1. Compile, review and analyze all existing data and literature concerning the Minot aquifer.
2. Collect additional stratigraphic and water level data to refine previous interpretations of the configuration and hydrology of the Minot aquifer.
3. Collect and analyze water samples from new and existing wells and from the Souris River.
4. Assess the relationship between the Souris River and the Minot aquifer.
5. Revise existing conceptual model of ground-water flow.
6. Determine the feasibility and need for developing a computer model of the Minot aquifer.
7. Prepare a report consisting of a compilation of the data collected and an interpretative report discussing the Minot aquifer.

Description of study area

Location

The Minot aquifer study area is located in the southwestern corner of the Souris River Basin in North Dakota(fig. 1). Specifically, the area investigated underlies and immediately surrounds the City of Minot as designated on figures 1 and 2 and Plate 1. (Township 155 North, Ranges 82 and 83 West, Ward County).

Land surface topography

The Minot aquifer study area is characterized by a broad, relatively flat Souris River floodplain with adjoining steep valley walls (fig. 2). Narrow, deep coulees, occupied by intermittent streams cut into the steep valley walls. Elevations range from 1550 feet along the Souris River floodplain to 1800 feet on the hills north and south of the Souris River Valley. Local relief is about 100 feet with maximum relief about 250 feet.

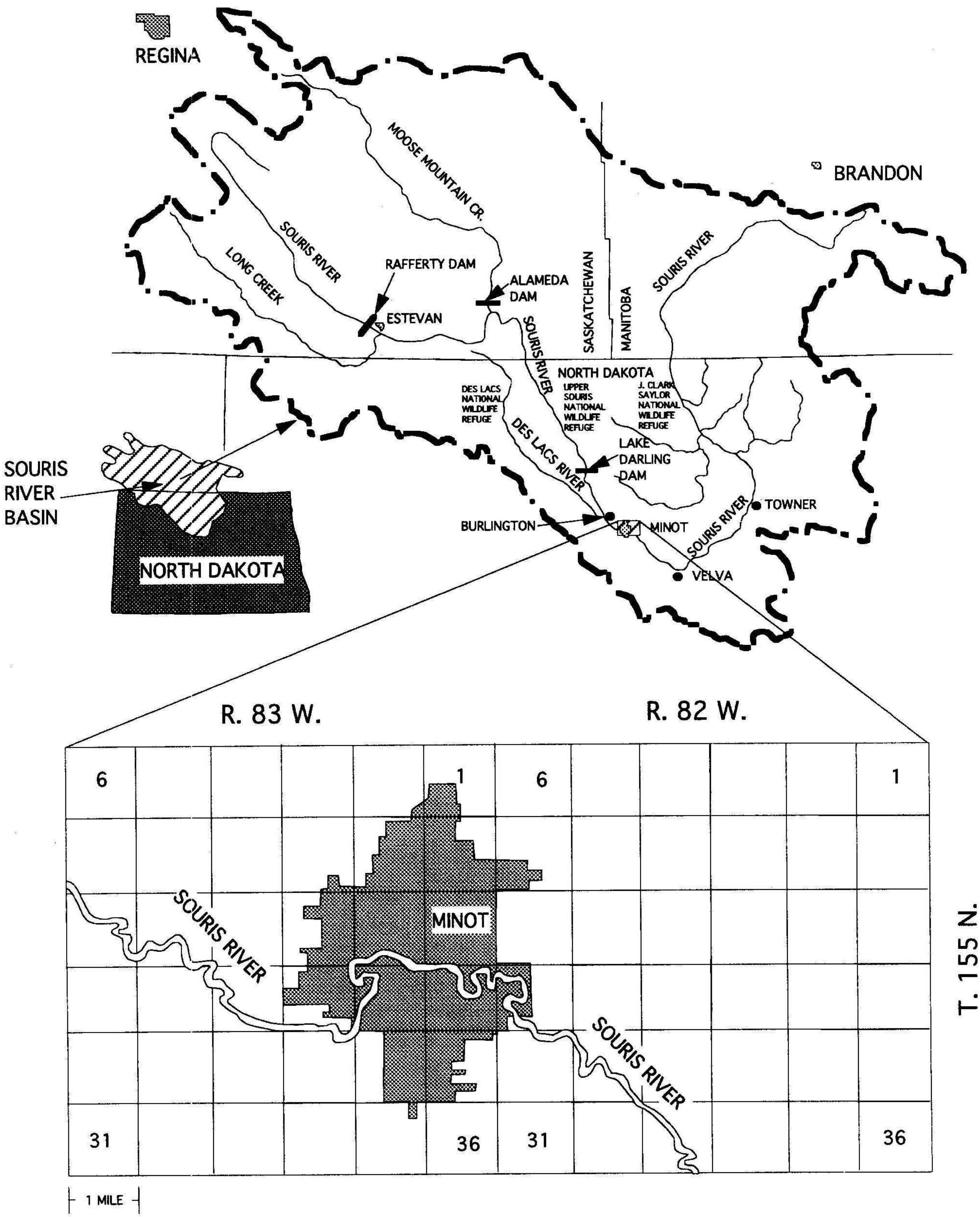
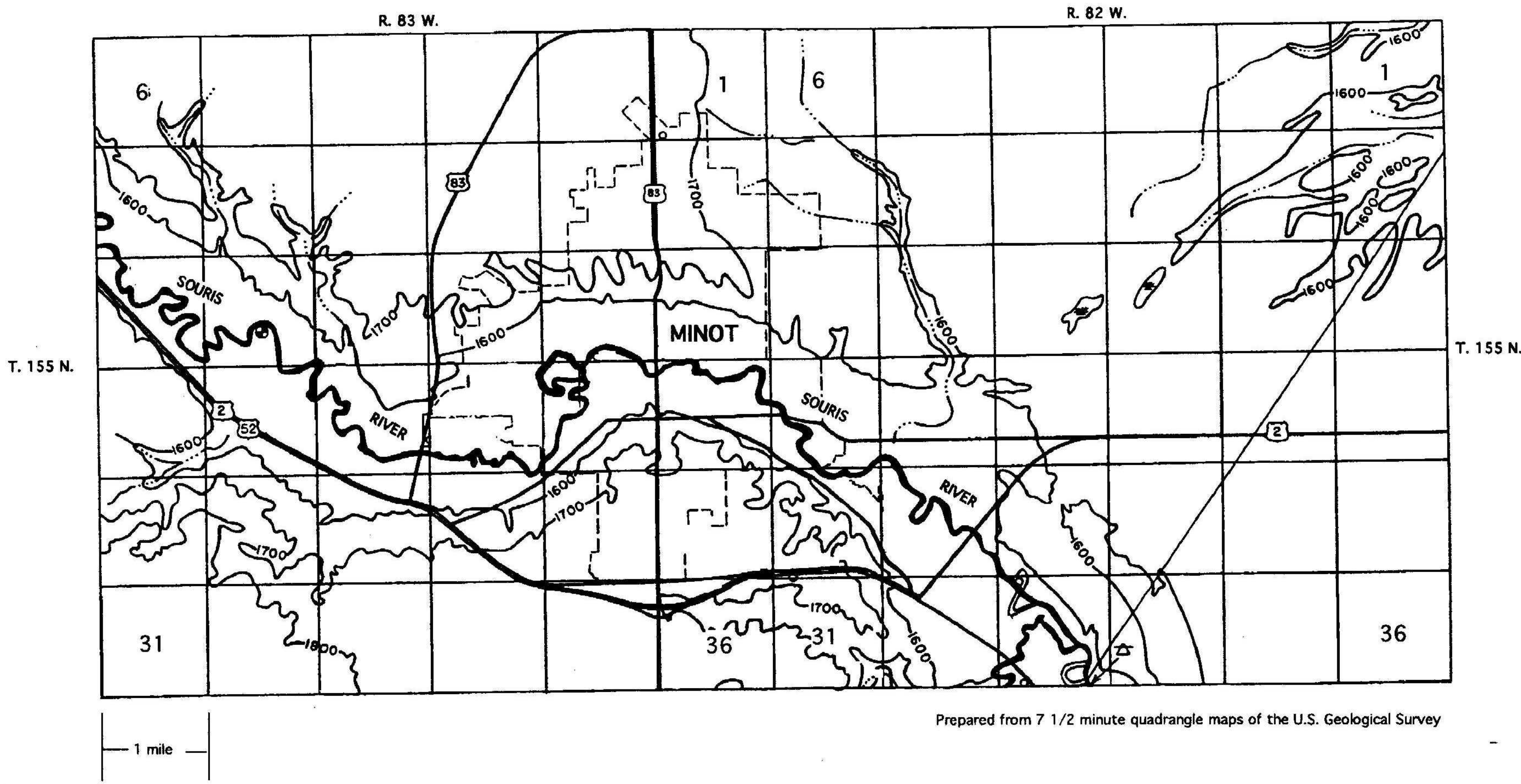


Figure 1. Location of the Souris River Basin, North Dakota and Canada and the Minot aquifer study area, Ward County, North Dakota



1600 Land surface elevation (in feet above NGVD)

Figure 2. Land surface topographic map of the Minot aquifer study area

Climate

The climate in the Minot area is classified as northern continental. Average annual precipitation at the Minot International Airport, for the period 1906-1991 was 16.4 inches (fig. 3, U.S. Weather Bureau, 1906-1991). Annual precipitation has ranged from 7.13 inches in 1934 to 26.99 inches in 1975 (fig. 3). Since 1961, average annual precipitation has been 17.99 inches or 1.59 inches above the long term average. Generally, about half of the precipitation occurs from May through July as summer convective thunderstorms.

Yearly extremes in temperature are common with summers typically in the 80 to 100 ^{0} F range and winters in the 0 to -20 ^{0} F range. Hot-dry periods in June, July and August generally result in the heaviest water use by the city of Minot (lawn watering etc.).

Souris River

The Souris River, an international stream that drains portions of the United States and Canada, is the major drainage system in the Minot aquifer study area (figs. 1 and 2). About 9,320 mi.^{2} of the total drainage area of 24,800 mi.^{2} is located in the United States (Wesolowski and Nelson, 1987). The Souris River originates in Canada, flows in a southeasterly direction and enters the United States near Sherwood, North Dakota (fig. 1). Des Lacs River is the major tributary of the Souris River in North Dakota (fig. 1).

Major impoundments on the Souris and Des Lacs Rivers above Minot include, Upper, Middle and Lower Des Lacs Lakes (Des Lacs National Wildlife Refuge) and Lake Darling (Upper Souris Wildlife Refuge). There are also several lowhead dams on the Souris River in the city of Minot that are used for water supply, irrigation and recreation purposes.

The U.S. Geological Survey has measured the discharge of the Souris River above Minot since 1903 (Township 155 North, Range 83 West, 17DBB, Plate 1). Maximum discharge recorded was 12,000 cubic feet per second (cfs) on April 20, 1904 (fig. 4, U.S. Geological Survey, 1992). In several years there has been no flow in the Souris River. Average discharge over the period 1903-1992 is 156 cfs (U.S. Geological Survey, 1992). Major flood events have occurred in 1882, 1904,

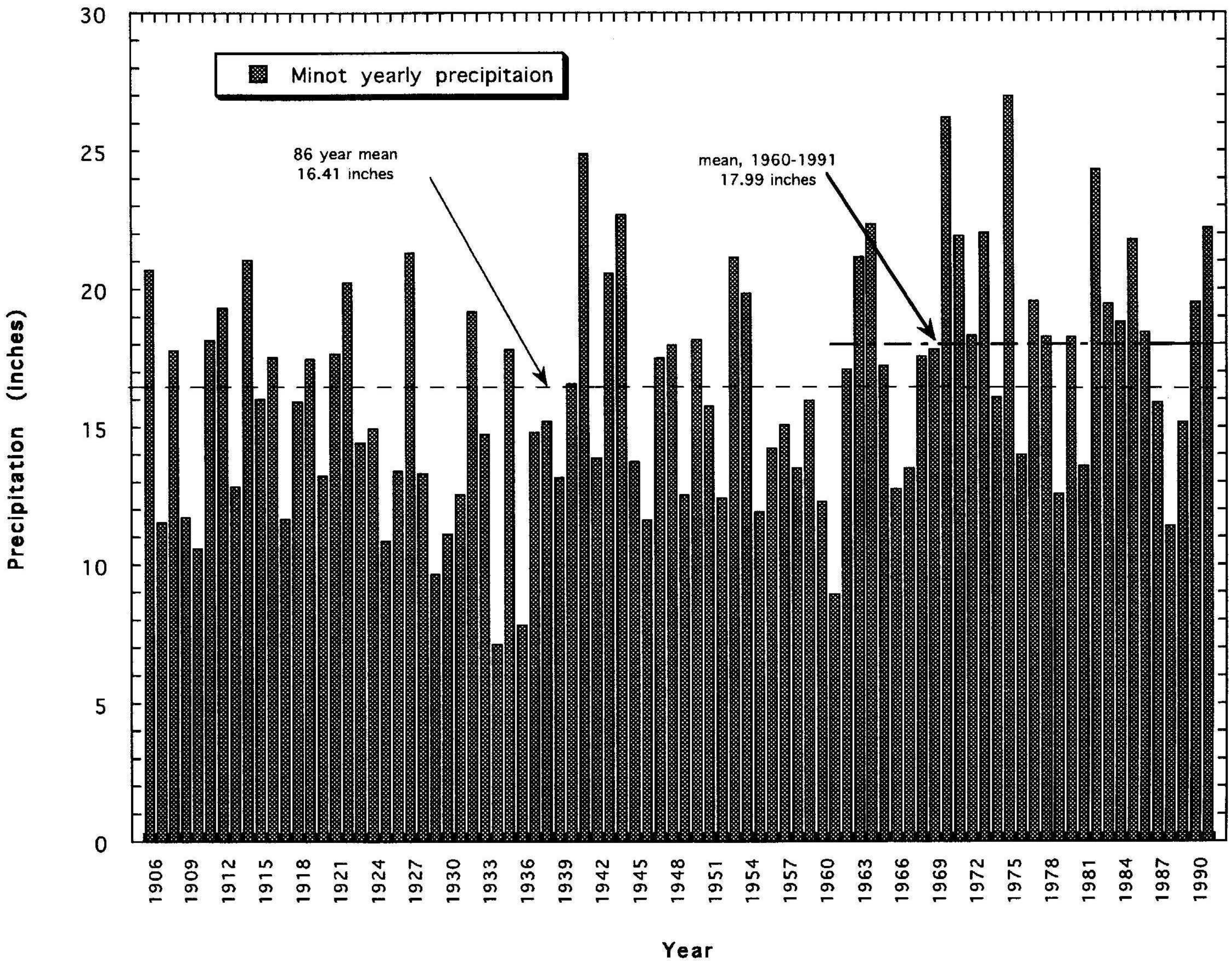


Figure 3. Yearly precipitation at the Minot International Airport (U.S Weather Bureau, 1906-1991)

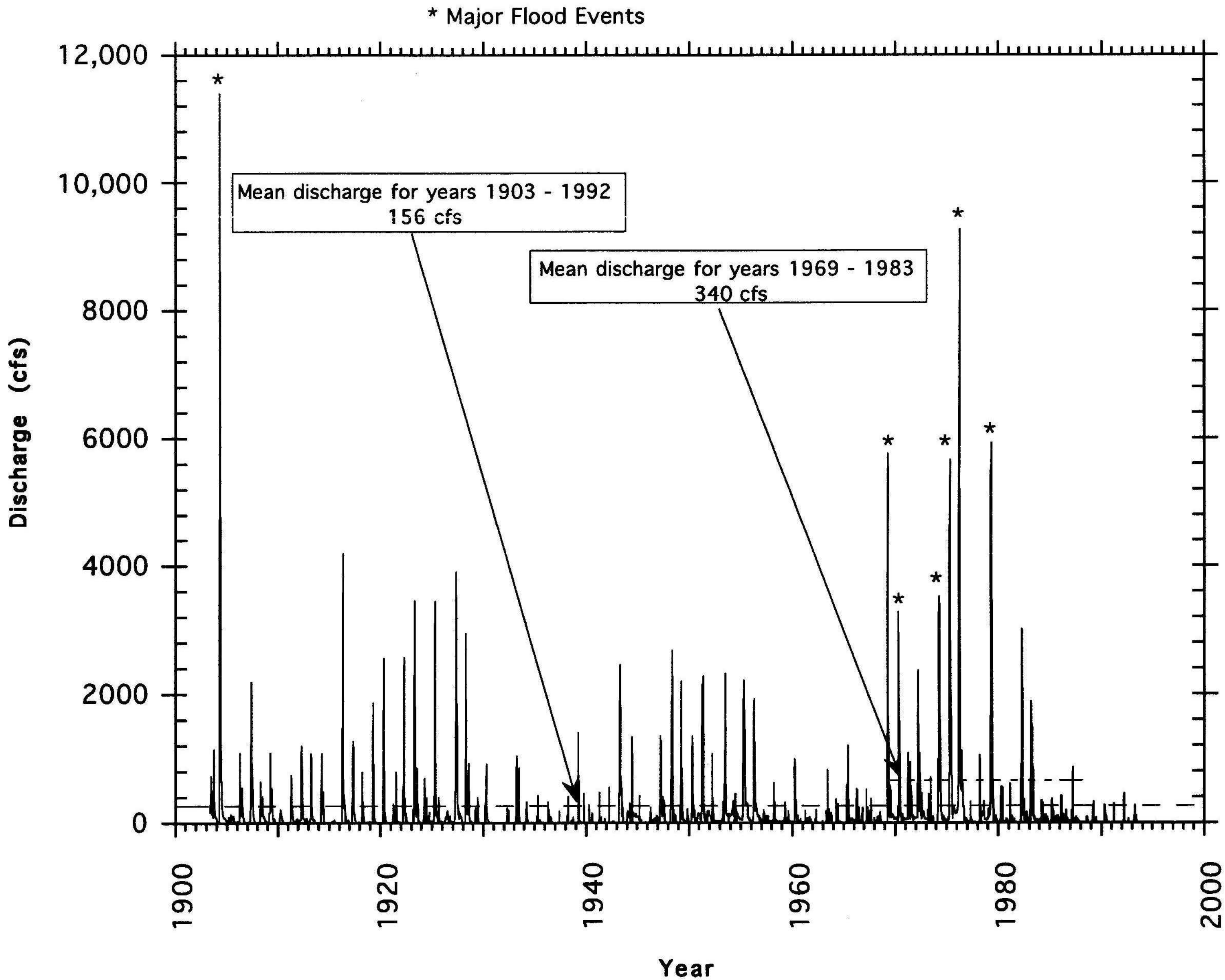


Figure 4. Mean Daily Discharge of the Souris River above Minot (Data from U.S. Geological Survey, 1903-1992)

1969, 1970, 1974, 1975, 1976, and 1979 (Federal Emergency Management Agency, 1982). Note also that from 1969 through 1983, average flow of the Souris river above Minot was 340 cfs or about double the long term average flow rate (fig. 4)

The Souris River is a source of water for a number of uses. Current major water users on the Souris River include the City of Minot, U.S. Fish and Wildlife Service and the Eaton Irrigation District. In addition, their are several individuals who have irrigation water rights from the Souris River.

Since 1936, discharge of the Souris River above Minot has been controlled mainly 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).

Operation of Lake Darling Dam involves releasing enough water from the dam to accommodate spring runoff while retaining sufficient water to fill the Lake Darling conservation pool. Under normal operating conditions. maximum releases from the reservoir and thus maximum discharge of the Souris River above Minot occurs anytime from February through May (fig. 4). 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 (fig. 4). Variations in releases from Lake Darling during the summer, fall and winter months depend on four factors: (1) needs at the J. Clark Salyer National Wildlife Refuge downstream from Lake Darling; (2) safety considerations (3) consideration of special requests from North Dakota or Manitoba and (4) compliance to interim measures between Canada and the United States for minimum flow of 20 cfs in the Souris River back into Canada (International Souris River Board of Control, 1983). As stated by the International Board of Control (1983),

> "Once Lake Darling is drawn down to the required level, releases will be set to match inflow until flows at the Minot gage reach the target level shown in the table."

Operation of the Lake Darling Dam will be modified to account for the operation of the two new dams in Canada (U.S. Corps of Engineers, 1988).

Historic flooding along the Souris River, especially at Minot, North Dakota, has provided the impetuous for numerous flood control measures along the river. According to the Corps. of Engineers (1988) flood control measures on the Souris River have included, 1) channel modification in Minot (completed in 1979), 2) Velva levee project (completed in 1987), 3) modification of the gated outlet of Lake Darling Dam (in progress) and 4) the purchase of approximately 400,000 acre-feet of flood storage operation and maintenance in Saskatchewan. The Souris River Basin Project has resulted in the construction of Alameda and Rafferty reservoirs in Canada. According to the Corps of Engineer (1988):

> "The project will provide water supply and flood control benefits to the Province of Saskatchewan, provide 100-year flood control benefits for the city of Minot, North Dakota, and significantly reduce flood damages along the main stem of the Souris River in North Dakota."

The Corps of Engineers (1988) in their summary remarks state,

> "With the construction of two dams in Saskatchewan, the Canadians will be able to retain their legally apportioned fifty percent share of the natural flow originating in the Saskatchewan portion of the Souris River Basin. Prior to this development, North Dakota received an annual average of eighty-five percent of these natural flows. With the dams in place and the water supply reduced, existing water uses in the State will have to be reduced. Development based on the historical flows will be difficult to maintain."

With the new dams in Canada, flow characteristics of the Souris River will change. These changes in flow patterns need to be investigated in light of water needs in the entire basin (including the city of Minot).

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 municipal, private and industrial wells in the area. Limited ground-water 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 ground water in 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 (1947) report presented an excellent historical account of Minot's surface 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, 1970 and 1971) and Pettyjohn, and Hutchinson (1971) greatly refined the understanding of ground-water conditions in the Souris River Valley near Minot and briefly discussed the newly discovered Sundre aquifer system. Ground-water data used for Pettyjohn (1967, 1970 and 1971) and Pettyjohn and Hutchinson (1971) were presented in Pettyjohn and Hills (1965). Pettyjohn (1966, unpublished) discussed the construction and results of an electric analog model of the Minot aquifer. Pettyjohn (1968B) and Pettyjohn and Fahy (1968) discussed the design and construction of artificial recharge facilities in the Minot area.

A ground-water survey of Renville and Ward Counties was conducted on a cooperative basis by the NDSWC, North Dakota Geological Survey and the U.S. Geological Survey. Part I, *Geology*, was a comprehensive investigation of the surficial geology and general discussion of the subsurface geology (Bluemle, 1989). Part II, *Basic Data*, included an inventory of test holes, well logs, water level measurements and chemical analyses (Pettyjohn, 1968A). Part III, *Ground-water Resources*, presented 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 detailed discussion of the location, areal extent, thickness, hydrologic properties and water quality of the Minot aquifer was included.

Kehew (1982) discussed the role that catastrophic flooding may have had in the formation of the Souris spillway in Saskatchewan and North Dakota. According to Kehew (1982) the large point bar deposits (gravel pits west of the city of Minot) were formed at the inside of a spillway meander.

In 1983, Kehew completed a report entitled "*Geology and Geotechnical Conditions of the Minot Area, North Dakota*". The report describes the geologic and hydrogeologic conditions affecting construction and waste disposal in the Minot area.

A well head protection program for the Minot aquifer has been completed (North Dakota State Department of Health and Consolidated Laboratories, 1993) The report delineates a well head protection area within which a contaminant source inventory and contaminant management should be addressed. The well head protection area protects ground-water quality by performing the following three functions: 1) Identifies a zone around public water supply wells needing increased protection activities, 2) Identifies a management zone for all or part of a well's potential recharge or contribution area and 3) Provides a buffer zone that allows time to respond to a contamination event before the contaminant reaches the well (North Dakota State Department of Health and Consolidated Laboratories, 1993).

Methods of Study

Hydrogeologic investigation of the Minot aquifer study area was accomplished by test drilling at 25 sites, installing 35 monitoring wells and measuring and recording depth to water in the 35 new monitoring wells and in 4 existing monitoring wells. Additional work included: (1) a complete review and assembly of all existing data and literature 2) measuring the level of the Souris River at selected sites, and (3) collecting surface water and ground-water samples for chemical analyses.

Test holes were drilled with a Failing model 1250 forward hydraulic mud rotary drill rig owned by the NDSWC. Monitoring wells were constructed using either $1^1/_4$ inch or 2 inch diameter polyvinyl chloride (PVC) casing with 5 or 10 foot long PVC screens. One deep monitoring well at the North Hill soccer complex was constructed with 2 inch diameter steel casing.

Nests of monitoring wells were constructed specifically for this investigation to determine the vertical distribution of water levels and water quality in the area. Construction of the monitoring well nests involved the drilling of an initial deep test hole to determine the stratigraphy at the site. Once the stratigraphy at the site was known, the number and depth of monitoring wells required could be determined. The initial deep test hole also served as a hole for the deep monitoring well. After drilling was completed, 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. High solids bentonite 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 used to fill the annular space to land surface. The grout was allowed to "set" and then the monitoring wells were back washed with a small quantity of fresh water and pumped with compressed air for development. Subsequent monitoring wells were completed at each nest site by moving the drilling rig ahead 15 to 20 feet and drilling the next hole.

Samples of drill cuttings were collected and visually analyzed on a continuous basis throughout the drilling process. Resistivity and spontaneous potential logs were run in most of the NDSWC test holes. Copies of the geophysical logs are available for inspection in the office of the NDSWC. Locations of all test holes and monitoring wells are presented on plate 1. Pertinent data at each test hole site are published in Part I of this report (Pusc, 1994).

The mean sea level elevation (NGVD of 1929) for all monitoring wells, city production wells and river stage sites was established by differential leveling (Pusc, 1994). The surveying was conducted by the Public Works Department of the City of Minot. Land surface elevations for test hole sites where no monitoring wells were installed were estimated using 7 $^{1}/_{2}$ minute topographic quadrangle maps published by the USGS.

Depth to water measurements were recorded on a monthly basis in the 39 monitoring wells and 5 river stage sites throughout the study area (Pusc, 1994). Water levels were measured with steel tapes, electronic well sounders, and one continuous recorder. In addition, the USGS monitors the flow of the Souris River just west of the city of Minot, North Dakota (Plate 1).

A continuous float type water level recorder is installed in city production well 8 of the Minot well field (plate 1). Water level data from the well are transmitted directly to the water treatment plant via phone lines.

Water level data collected for this study were coupled with the existing data to evaluate: (1) the horizontal and vertical direction of ground-water movement, (2) ground-water level response to natural recharge and discharge events, and (3) ground-water level response to ground-water withdrawals due to pumping.

Water samples for chemical analysis were collected from all of the monitoring and production wells in the study area. The water sampling procedure involved the collection of 500 milliliters (ml) of raw water, 500 ml of filtered water and 500 ml of filtered and acidified (nitric acid) water. Samples from selected wells were also sampled for selected trace metals. 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 laboratory.

State Water Commission monitoring wells were sampled using two methods; pumping with a gas squeeze bladder pump or by bailing with a PVC point source bailer. Water samples were obtained from the city supply wells by using the existing turbine pumps.

Prior to sampling with a bailer or gas squeeze pump, at least three casing volumes of water were removed to introduce formation water into the well. After evacuating at least three casing volumes of water, either the well was pumped further with the gas squeeze pump or a variable capacity PVC point source bailer was lowered to just above the bottom of the well screen. Bailing and/or pumping continued until enough water was secured for the sample. Water chemistry data are presented in Part I of this report (Pusc, 1994).

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. 5). 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 155-83-04ADD is located in the SE1/4 SE1/4 NE1/4 of Section 4, Township 155 North, Range 83 West (fig. 5). Consecutive terminal numerals are added if more than one well is located in a 10-acre tract.

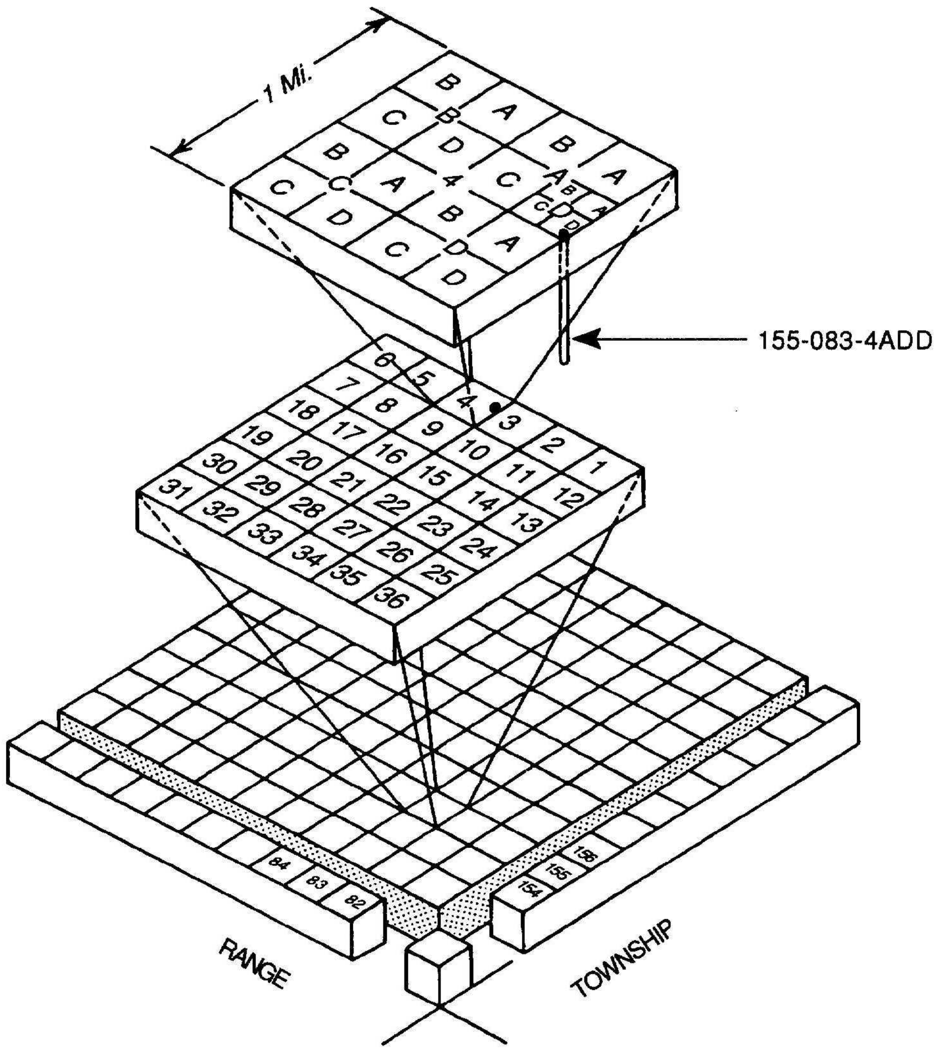


Figure 5. Location-numbering system.

Acknowledgments

The collection of data for this report was made possible by the cooperation of residents and officials of the city of Minot, North Dakota 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. Robert Schempp, City Manager of Minot; Alan Walter, Director of Public Works; Mike Korman, Assistant Director of Public Works; Byron Thronson, Supervisor of Minot's Water Treatment Plant; Mike Nielsen, City Park Director and Mike Brunner, Assistant City Park Director deserve special mention for their cooperation. Particular recognition is due to North Dakota State Water Commission personnel: G. J. Calheim and A. L. Lachenmeier for drilling and logging test holes and constructing monitoring wells in some of the most difficult drilling conditions in North Dakota; G. O. Muri and M. E. Osborn for chemical analyses of water samples and M. H. Hove, K. K. Kunz, M. Skaley and M. E. Osborn for compiling the water level and quality files. Special thanks to C. D. Bader for developing the data base programs used for this report. Appreciation is also expressed to M. O. Lindvig and R. B. Shaver, of the NDSWC for their critical review of the report. Special 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.

GEOLOGIC SETTING

General Geology

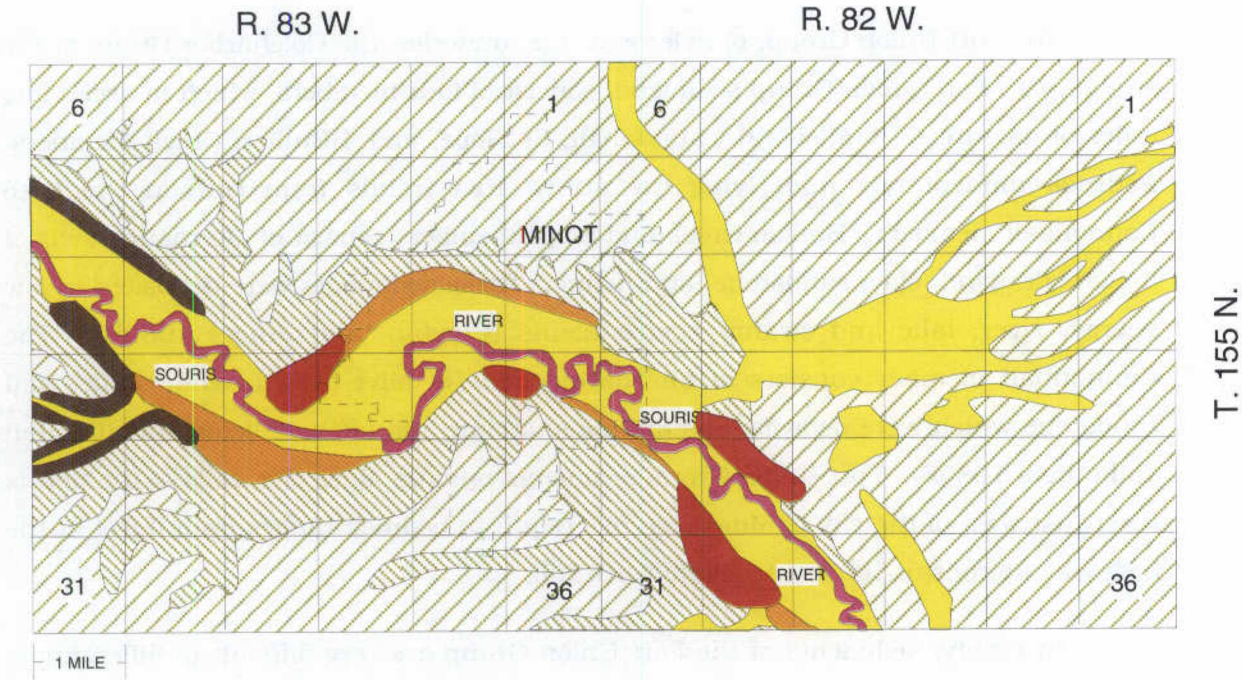
Unconsolidated geologic materials occurring in the study area are the result of alluvial and glaciofluvial geologic processes (fig. 6). River sediment and glacial drift covers most of the study area with the drift being the older and more dominant of the sediments. Unconsolidated sediments in the area have been divided into two main groups: the Oahe Formation and 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 deposits include (fig. 6):

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
4). glacial collapse topography comprised of fine grained organic materials

The depositional history of Oahe Formation sediments occurring in the Souris River Valley is complex. Abandoned oxbows detected from air photos, land surface topographic maps, and ground surveys indicate that the Souris River has changed course several times throughout its history. Meandering of the Souris River across the floodplain has resulted in fine grained backwater and overbank deposits in some areas, and coarser grained channel lag, point bar, and terrace deposits in others (fig. 6). As the river changed course, these sediments were reworked and redeposited across the floodplain.

Unconsolidated sediments deposited during Pleistocene glaciation in North Dakota are assigned to the Coleharbor Group (Clayton and others, 1980B). These glacial sediments are composed of poorly sorted, silty, sandy, pebbly clay (till), glaciofluvial sand and gravel, lacustrine silt and clay and detrital lignite fragments. All of the study area, with the exception of the Souris River Valley and its tributaries is mantled by glacial till (fig. 6).



EXPLANATION

FORMATION	SYMBOL	DESCRIPTION	ORIGIN
OAHE		DARK, OBSCURELY BEDDED, ORGANIC CLAY AND SILT GENERALLY OVERLAYING CROSS BEDDED SAND	RIVER SEDIMENT, OVERBANK OR CHANNEL DEPOSITS OCCURRING ON FLAT PLAINS OF MODERN STREAMS
OAHE		DARK, OBSCURELY BEDDED SANDY TO SILTY, SOME VERY FINE	RIVER SEDIMENT DEPOSITED BY EPHEMERAL STREAMS ON SLOPING SURFACES (ALLUVIAL FANS) NEAR THE MOUTHS OF COULEES
OAHE/COLEHARBOR		BEDDED SAND AND GRAVEL, MOSTLY POORLY SORTED GRAVEL CONTAINING GRAVEL WITH COBBLES AND BOULDERS	RIVER SEDIMENT DEPOSITED IN LARGE BARS AND TERRACES IN THE SOURIS RIVER VALLEY
COLEHARBOR		POORLY SORTED SAND, SILT, CLAY, AND SAND AND GRAVEL	GLACIAL SEDIMENT ERODED BY SLOPE WASH
COLEHARBOR		NON BEDDED, POORLY SORTED SAND, SLIT, CLAY, PEBBLES, COBBLES, BOULDERS (TILL)	GLACIAL DRIFT SEDIMENT DEPOSITED BY COLLAPSE OF STAGNANT ICE
FORT UNION		ALTERNATING BEDS OF SAND, SILT, CLAY AND LIGNITE	RIVER, LAKE AND SWAMP SEDIMENT

FIGURE 6 . Generalized surfical geologic map of the Minot area, Ward County, North Dakota (modified from Lemke, 1960, Pettyjohn, 1967, Bluemle, 1982, Kehew, 1983, Pusc, 1987B and Bluemle, 1989)

Bedrock Geology

The Fort Union Group, of Paleocene Age, underlies the Coleharbor Group in the study area. Fort Union Group sediments consist of four members, which in ascending order of age are: 1) Ludlow, 2) Cannonball, 3) Slope, and 4)Bullion Creek Members. Bedrock immediately underlying the study area trends 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, and others 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 and others 1980B). Fort Union Group sediments outcrop along the walls of the Souris River just west of the city of Minot (fig. 6). Depth to bedrock ranges from 0 feet at the bedrock outcrops to 500 feet beneath North Hill.

In reality, sediments of the Fort Union Group are very difficult to differentiate accurately by visual inspection of mud rotary drill hole cuttings (Pusc, 1987B). Thus, for this report, bedrock sediments immediately underlying the study area were classified as Fort Union, undifferentiated.

A structure contour map of the top of the Fort Union Formation is presented in figure 7. The most striking feature is a deep bedrock valley which trends from northwest to southeast and crosses beneath the Souris River Valley in the vicinity of the city of Minot. The bedrock valley varies in width from 1 to 2 miles. It is within portions of this bedrock valley that sand and gravel of the Northwest buried-channel and South Hill aquifers were deposited. Further to the southeast, the Sundre aquifer system occupies portions of the same bedrock valley as the Northwest buried-channel and South Hill aquifers (Pusc, 1987B). The other noticeable bedrock valley occurs beneath the entire length of the Souris River Valley (fig. 7). Portions of this bedrock valley contain sand and gravel of the Souris Valley aquifer system (Minot aquifer in the vicinity of Minot).

Sandstone and lignite beds of the Fort Union Formation yield small to moderate quantities of ground water to domestic wells in the area. Flowing wells completed in the Fort Union (located in the Souris River Valley) are common. Many springs along the Souris River valley wall flow from the contact of a bed of Fort Union lignite with an underlying clay (Pettyjohn and Hutchinson, 1971).

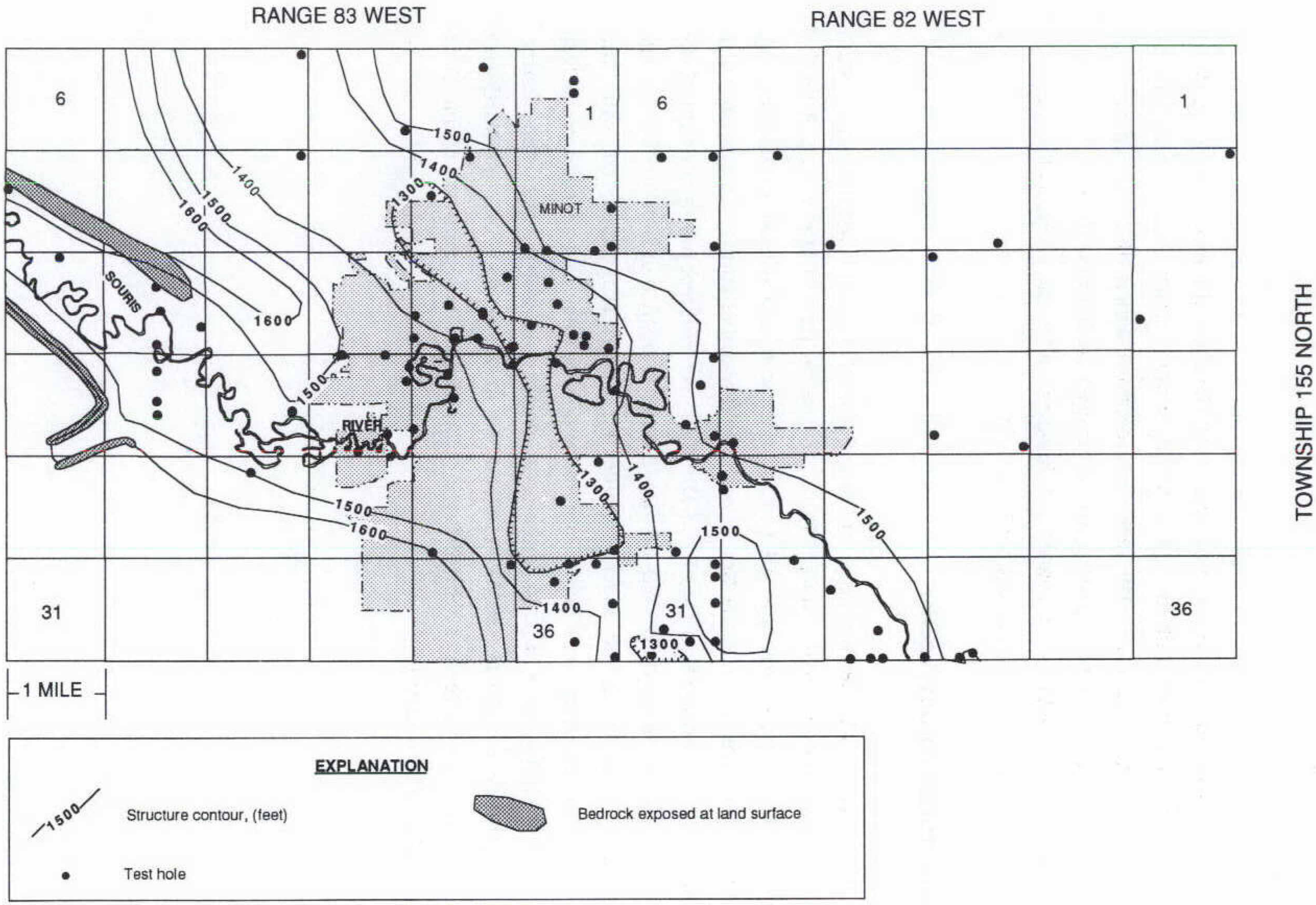


Figure 7. Stucture contours of the top of the Fort Union Formation (undifferentiated, modified from Bluemle, 1986 and Pusc, 1987B)

Aquifers

Introduction

Unconsolidated sand and gravel aquifers in the general area of the city of Minot include the Northwest buried-channel, South Hill, Sundre, Souris Valley, North Hill and Minot aquifers (figs. 8 and 9). Hydrogeologic sections which illustrate the vertical relationships of the various aquifers are presented in figures 10 and 11. Maps illustrating the total thickness and saturated thickness of the more permeable sand and gravel sediments are presented in figures 12 and 13.

Northwest buried-channel aquifer

The Northwest buried-channel aquifer consists of deeply buried deposits of sand and gravel that extend northwestward from the central part of Minot (figs. 8 and 9) (Pettyjohn, 1971). The aquifer is about 1 to 1.5 miles wide and at least 4 miles long (fig. 8). Test drilling revealed that the Northwest buried-channel aquifer ranges from less than 50 feet thick northwest of the city of Minot to over 100 feet just southwest of the Minot International Airport(155-083-12, figs. 10 and 12). A test hole drilled for this investigation at the North Hill Soccer Complex (155-083-11) revealed that sand and gravel of the Northwest buried-channel aquifer is 65 feet thick and occurs from 268 to 333 feet below land surface (figs. 12 and 13). In general, the Northwest buried-channel aquifer is overlain by 250 to 350 feet of glacial till and clay (fig. 10). The Northwest buried-channel aquifer merges with the Minot aquifer in the vicinity of Minot State University (figs. 8, 9 and 10).

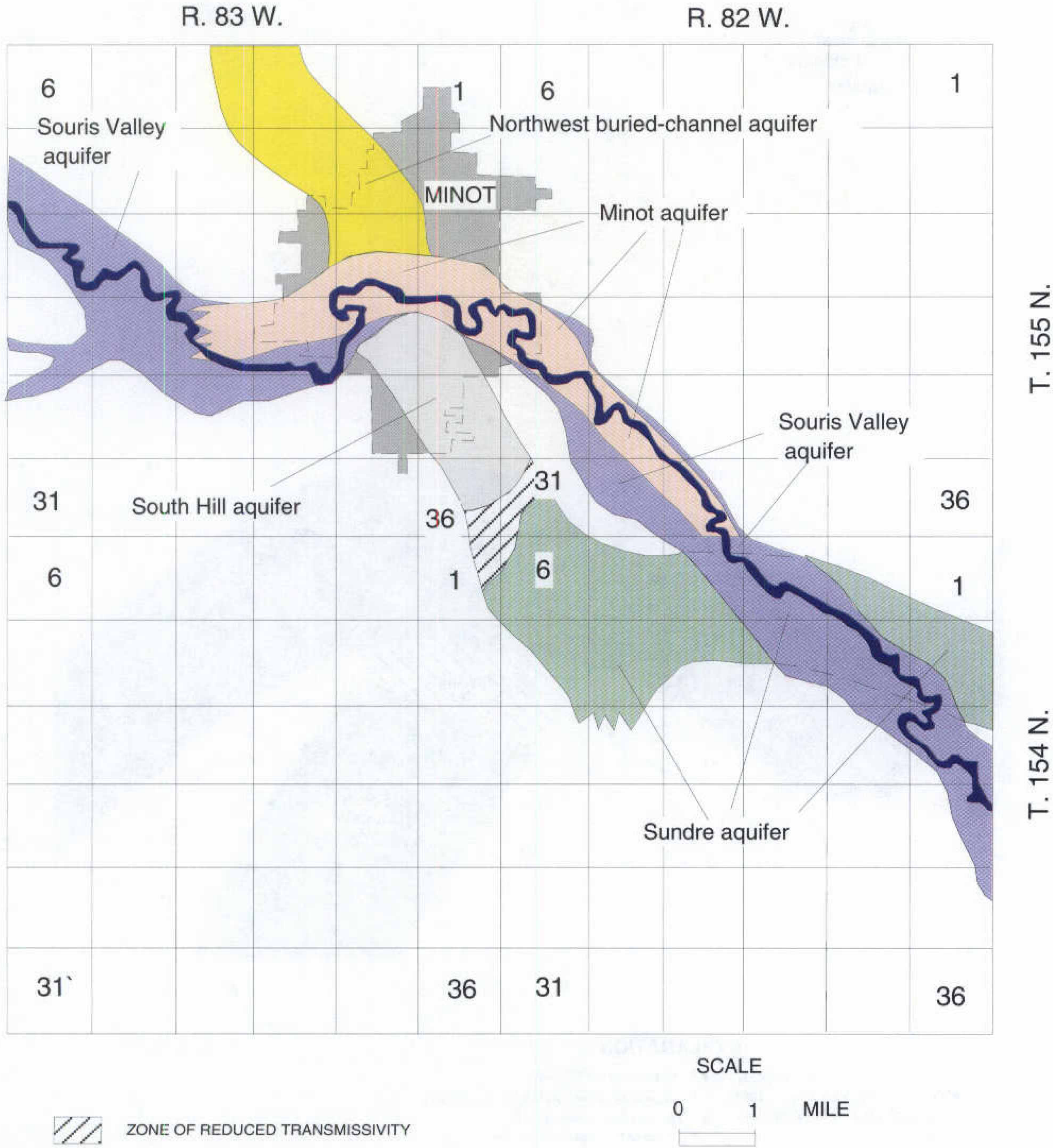


FIGURE 8 . MAJOR AQUIFERS IN THE MINOT AREA, WARD COUNTY, NORTH DAKOTA (MODIFIED FROM PETTYJOHN AND HUTCHINSON, 1971 AND PUSC, 1987B)

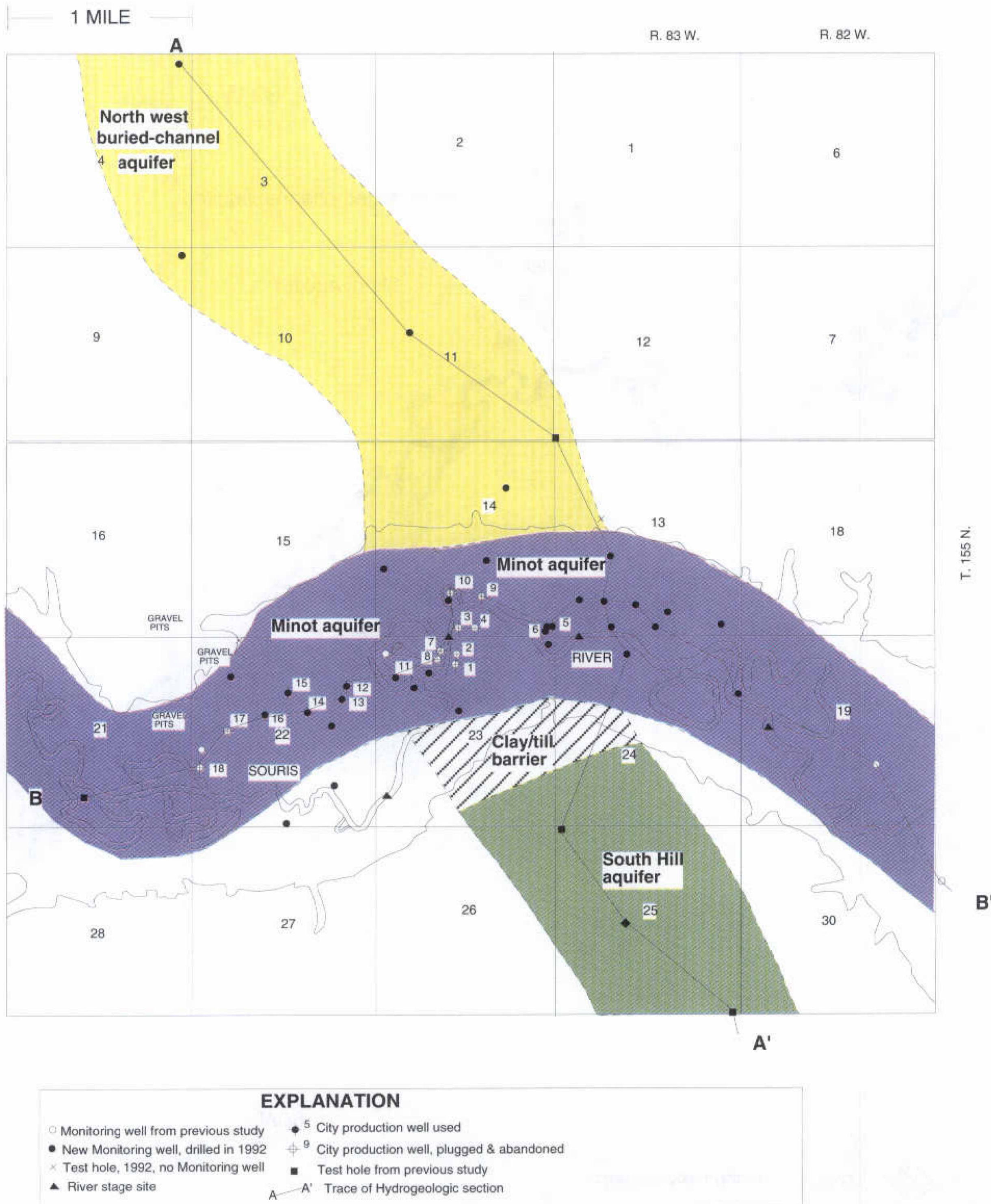


FIGURE 9. LOCATION OF THE MINOT, NORTHWEST BURIED-CHANNEL AND SOUTH HILL AQUIFERS NEAR MINOT, NORTH DAKOTA

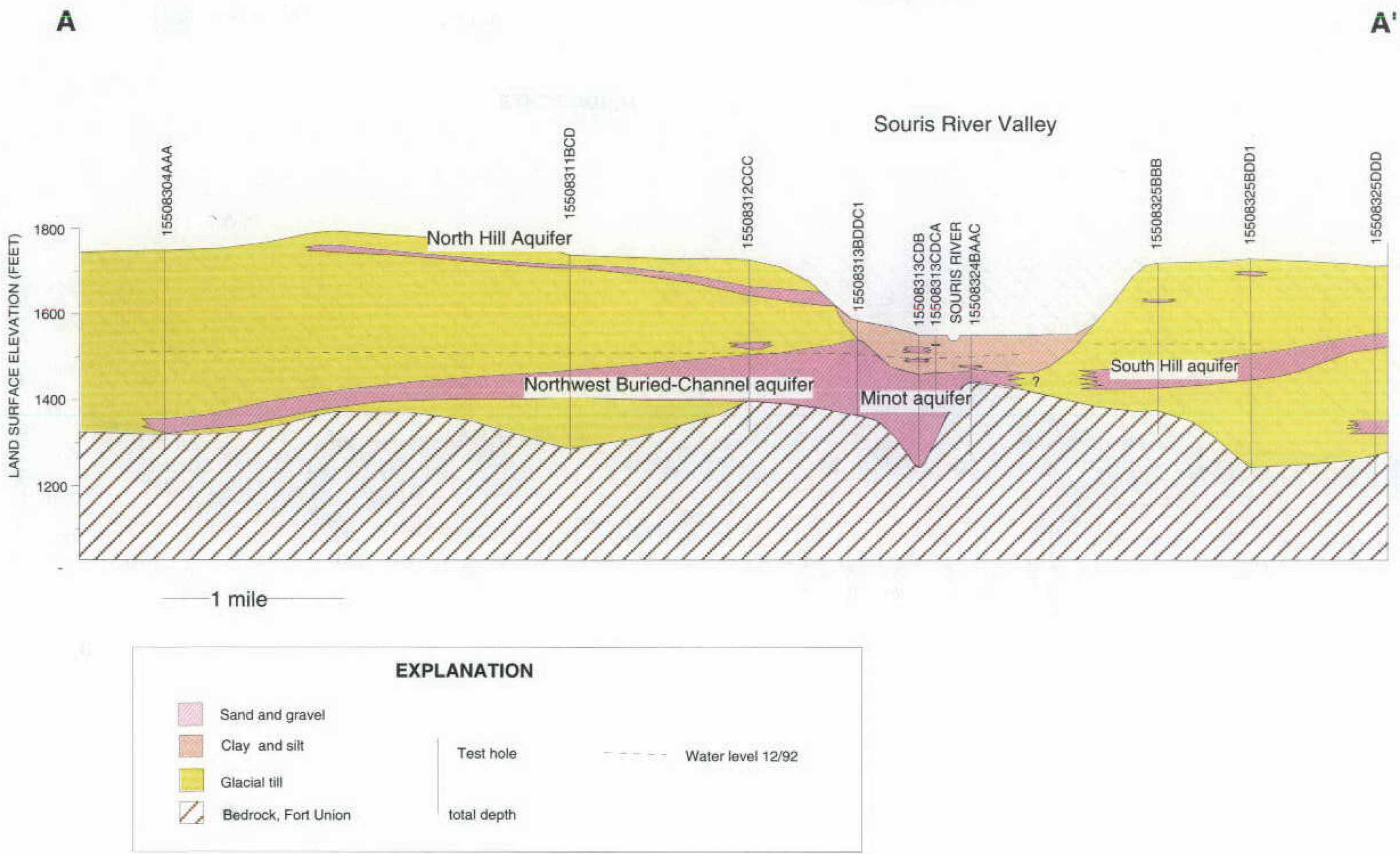


FIGURE 10 . HYDROGEOLOGIC SECTION A - A' SHOWING THE MAJOR AQUIFERS IN THE MINOT AREA, WARD COUNTY, NORTH DAKOTA

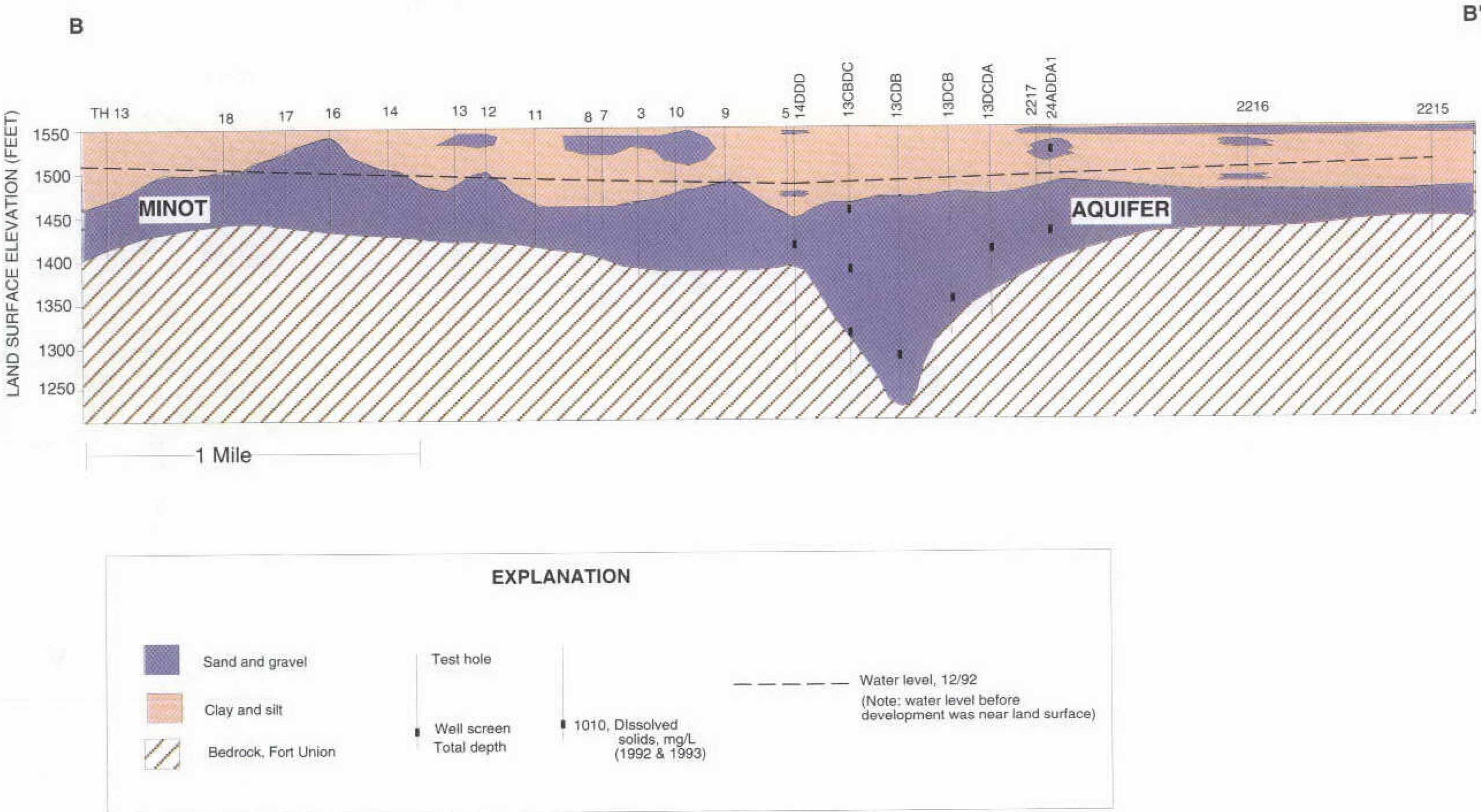


FIGURE 11. HYDROGEOLOGIC SECTION B - B' THROUGH THE MINOT AQUIFER , SOURIS RIVER VALLEY IN MINOT, NORTH DAKOTA

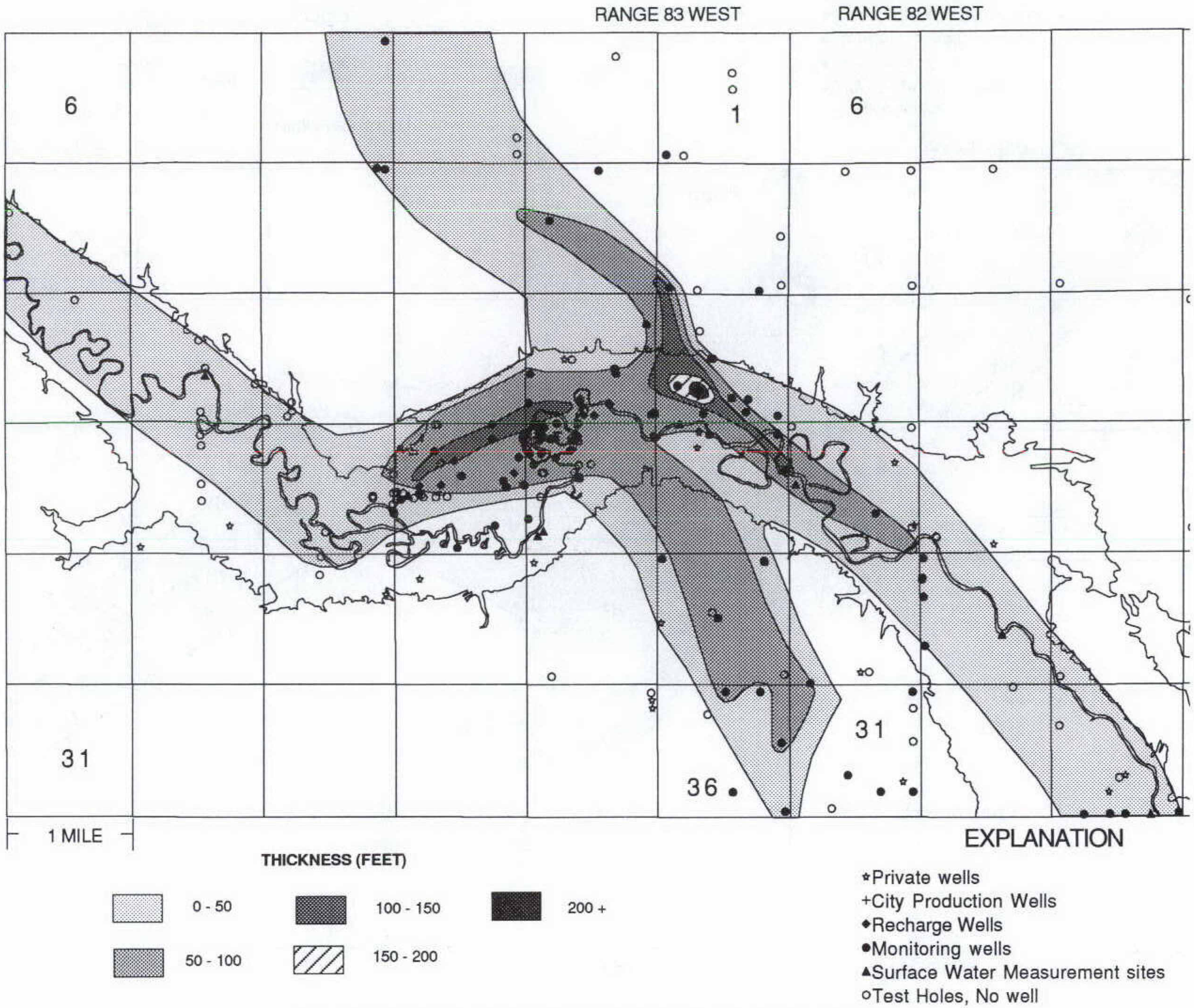


Figure 12. Thickness of sand and gravel in the Minot area.

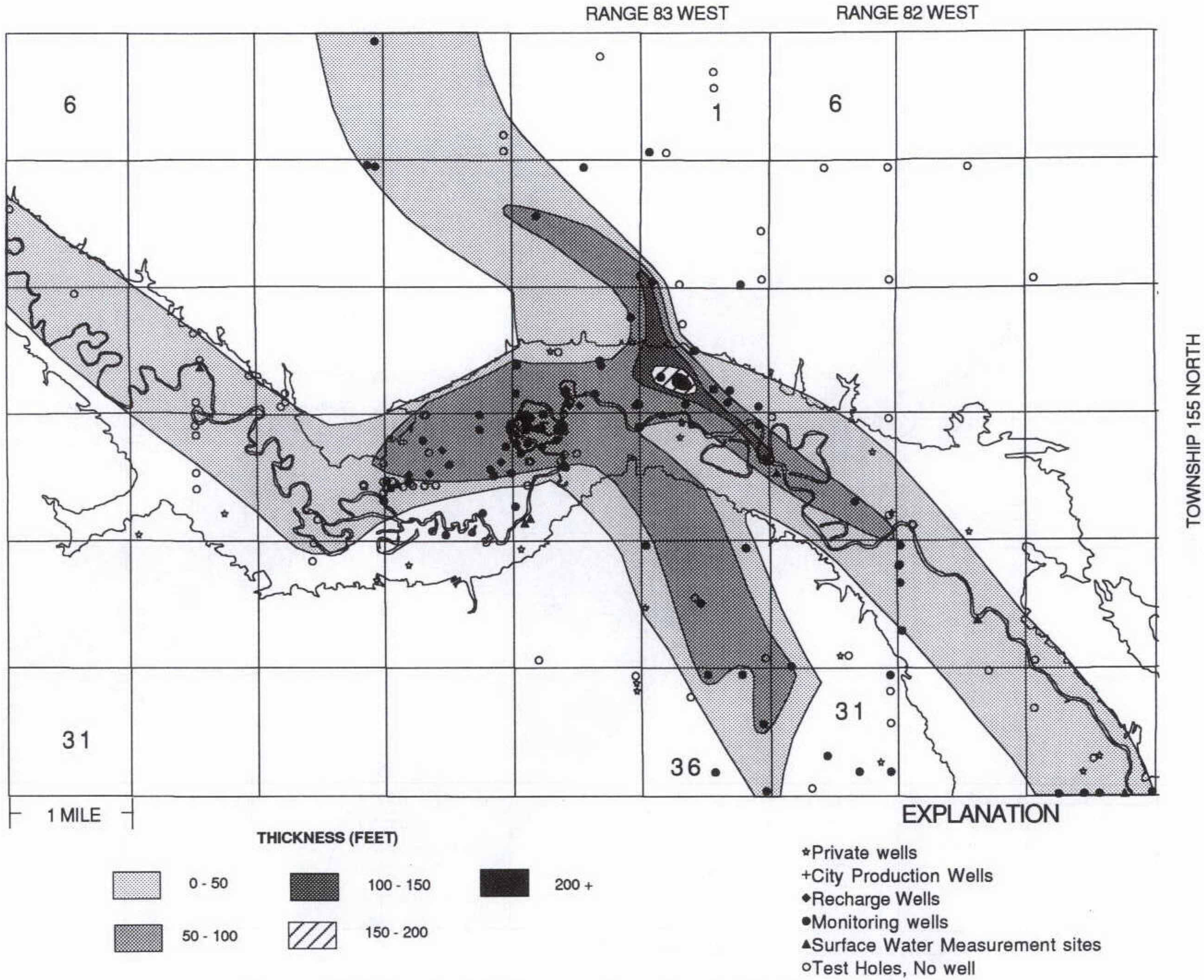


Figure 13. Saturated thickness of sand and gravel in the Minot area.

South Hill aquifer

The South Hill aquifer consists of deeply buried, discontinuous deposits of sand and gravel that occur southeast of the city of Minot (figs. 8 and 9). Individual deposits of the South Hill aquifer occur in a band that totals at least 1 mile wide and 2 to 2.5 miles long. Thickness of the South Hill aquifer ranges from 18 feet to 75 feet (figs. 10, 12 and 13). In general, the aquifer is overlain by 220 to 350 feet of glacial till and clay (fig. 10).

Sundre aquifer system

The Sundre aquifer system is a deeply buried deposit of sand and gravel that occupies portions of the same bedrock channel as the Northwest buried-channel aquifer and the South Hill aquifer (figs. 7 and 8). The Sundre aquifer system is separated from the South Hill aquifer by a clay/till barrier in the area just north of First Larson Coulee (fig. 8) (Pusc, 1987B). This barrier isolates the Sundre aquifer system from the other aquifers in the Minot area. Because of this distinct separation, the Sundre aquifer system will not be considered in the discussion of hydrogeology of the Minot aquifer. If more detail is needed on the Sundre aquifer system, the reader is referred to Pettyjohn and Hutchinson (1971) and Pusc (1987B).

Souris Valley aquifer system

The Souris Valley aquifer system consists of alluvial and terrace deposits that occupy portions of the Souris River Valley(figs. 8 and 9). The aquifer occurs, in places, along the entire length of the Souris River Valley in Ward and McHenry Counties (Pettyjohn and Hutchinson, 1971, Randich, 1981, Kehew, 1983 and Pusc, 1987B). In the Minot area, the Souris Valley aquifer system has been named the Minot aquifer in the vicinity of Minot, the Burlington aquifer at the confluence of the Souris and Des Lacs Rivers and Lower Souris Valley aquifer downstream of Minot (Pettyjohn, 1967 and Pettyjohn and Hutchinson, 1971).

North Hill aquifer

The North Hill aquifer is a shallow glaciofluvial deposit of sand and gravel located within glacial till in the uplands at the north end of Minot (figs. 10 and 14) (Pettyjohn, 1967 and 1971 and Pettyjohn and Hutchinson, 1971). The aquifer covers an area of about 5 square miles. Thickness of the North Hill aquifer varies from 2 to 30 feet and the top of the aquifer occurs from 26 to 66 feet below land surface (fig. 10) (Pettyjohn and Hutchinson, 1971). In general, 26 to 66 feet of glacial till and clay overlies and confines the North Hill aquifer (fig. 10).

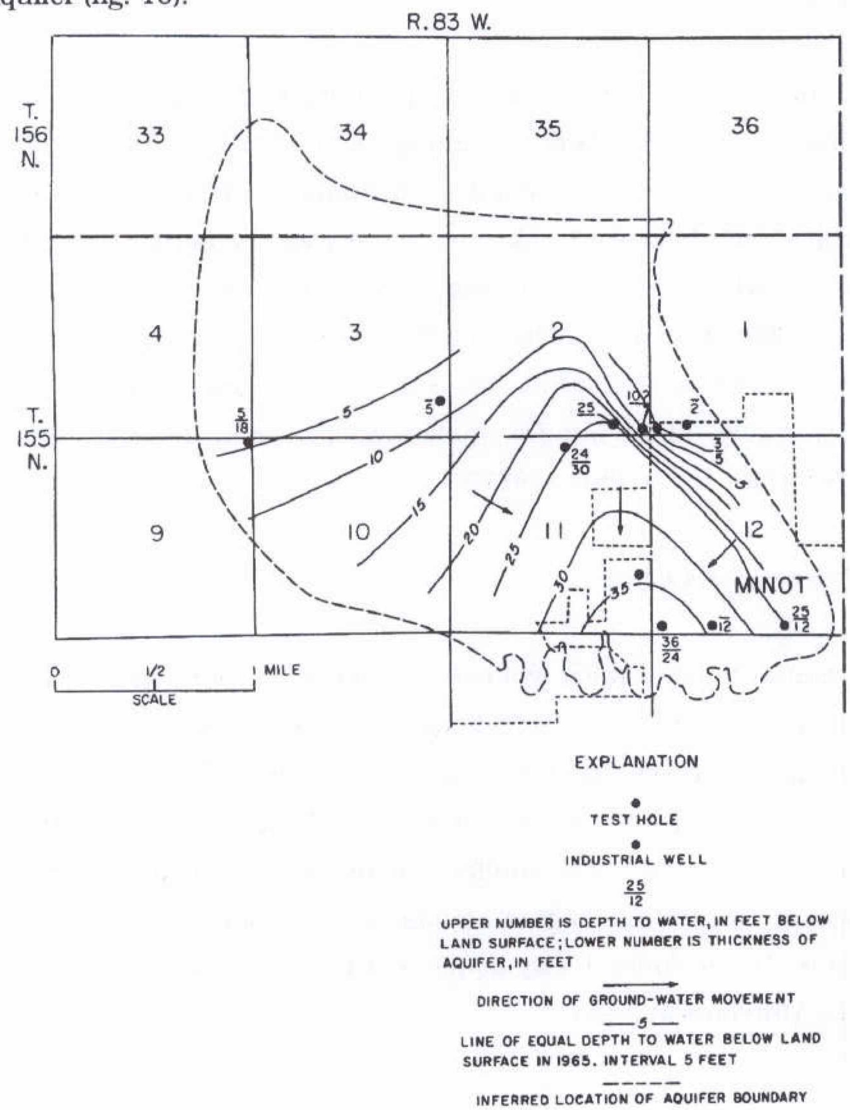


FIGURE 14. Location of the North Hill aquifer (Modified from Pettyjohn and Hutchinson, 1971)

Minot aquifer

The Minot aquifer consists of saturated sand and gravel deposits of the Souris Valley aquifer system that occur in the Souris River Valley in the vicinity of Minot, North Dakota (figs. 8 and 9) (Akin, 1947, Pettyjohn, 1967 and Pettyjohn, 1971 and Pettyjohn and Hutchinson, 1971). Before development the Minot aquifer was fully saturated (fig. 12). Pumping by the city of Minot has reduced the saturated thickness of the western unconfined portion of the Minot aquifer by approximately 50 to 60 feet (fig. 13).

The Minot aquifer primarily consists of very coarse sandy gravel containing an abundance of boulders. At most drilling sites, layers of boulders and coarse gravel were encountered preventing penetration of the entire thickness of the Minot aquifer. In fact, the drilling was so difficult that as many as 5 tri-cone bits and over 100, 50 pound bags of high yield bentonite drilling gel were needed to keep circulation and penetrate a few feet into the aquifer (Pusc, 1994).

The Minot aquifer in the vicinity of Minot is 0.5 to 1 mile wide, 6 to 7 miles long and occupies an area of approximately 6 to 7 square miles (fig. 9). In general, the Minot aquifer is overlain and confined by 50 to 100 feet of alluvial clay and silt (figs. 10 and 11). Pettyjohn (1967) determined that sand and gravel occurs from near land surface down to a depth of 100 feet in the area from the large sand and gravel pits at the west end of Minot to Oak Park (figs. 12 and 13).

Previous investigations determined that the Minot aquifer was commonly 30 to 50 feet thick, however in some locations the aquifer was thought to be at least 85 feet thick (Pettyjohn, 1967 and Pettyjohn and Hutchinson, 1971). Depth to the bottom of the Minot aquifer was thought to be approximately 100 to 150 feet below land surface. Test drilling done as part of the current investigation revealed, however, an area where the Minot aquifer is thicker and deeper than previously thought. In Hammond Park, NDSWC test hole 13DCB penetrated the Minot aquifer from 100 to 306 + feet below land surface (figs. 11 and 12). This establishes the thickness of the Minot aquifer in this area to be over 200 feet. Additional test drilling revealed, however, that this thicker sequence of sand and gravel is very narrow; less than 1/4 mile wide (figs. 11 and 12). Based on the available data, the saturated thickness of the Minot aquifer varies from 50 feet in the area of city wells 17 and 18, 50 to 100 feet in Oak Park, 40 feet near city wells 5 and 6, 200 + feet in Hammond Park, 100 feet in Roosevelt Park and 35 feet thick near the State Fair Grounds (figs. 10, 11 and 13).

Pettyjohn (1967) estimated that the amount of water in storage (65 - 150 foot interval) in the Minot aquifer is about 56,000 acre-feet.

Akin (1947) using the results of testing city well 3 estimated that the transmissivity of the Minot aquifer ranges from 163,000 to 259,000 gallons per day per foot (gpd/ft.). Pettyjohn (1967) using production well drawdown data stated that,

> "The transmissibility in much of the Minot aquifer probably exceeds 250,000 gpd per ft, which is higher than in any other areas in North Dakota known at this time."

Specific capacities (which is a measure of the pumping rate per foot of drawdown) for selected production wells are presented in table 1.

TABLE 1. Specific capacities for city of Minot production wells(modified from Pettyjohn, 1967)

	SPECIFIC CAPACITY(GPM PER FOOT OF DRAWDOWN)		
WELL	ESTIMATED 1964 (1)	PRODUCTION TESTS (2)	AKIN(1947)
4	--	13	21
5	**156**	**177**	**150**
6	**175**	**135**	--
7	--	71	--
8	**156**	**47**	--
9	14	62	--
10	25	38	--
11	**57**	**40**	--
12	**120**	**89**	--
13	**57**	**25**	--
14	**400**	**533**	--
15	**200**	**200**	--
16	**150**	**100**	--
17	--	114	--
	--	--	--

*** wells in bold print are in service(1992) others are plugged and abandoned**
(1) Data for Minot city wells estimated from airline gage under static conditions and after 13 hours of pumping.
(2) Calculation from routine 24 hour production pumping tests.

Specific capacity ranged from 14 gallons per minute per foot of drawdown (well 9) to 533 gpm per foot of drawdown (well 14, see Pettyjohn, 1967 p.42).

The high yielding nature of the Minot aquifer has been know for years. Simpson (1929) when discussing the 1916 testing of city production well 1 states,

> " ... and the well on pumping yielded 890 gallons per minute, or about 1,500,000 gallons a day, one of the largest yields ever obtained from any well in North Dakota."

Reported pumping rates for production wells in the Minot aquifer are presented in table 2 .

TABLE 2. Pumping rates for city of Minot production wells

City production well	Reported pumping rate (gpm)
1	500
2	800
3	?
4	?
5	**750**
6	**750**
7	700
8	**800**
9	?
10	?
11	**600**
12	**600**
13	**600**
14	**950**
15	**800**
16	**650**
17	**700**
18	?

*** wells in bold print are in service(1992) others are plugged and abandoned**

The coefficient of storage has been estimated to range from 7×10^{-5} in the confined portion of the Minot aquifer to 0.10 in the unconfined portion of the Minot aquifer(Pettyjohn, 1967).

GROUND-WATER FLOW SYSTEMS

Introduction

Ground-water levels rise and fall in response to recharge to and discharge from the ground-water flow systems. Factors affecting ground-water levels in the area are: (1) stage (discharge) of the Souris River, (2) precipitation, (3) evapotranspiration, (4) leakage from overlying and surrounding alluvial and or glacial drift material, (5) leakage from bedrock sediments, (6) large scale ground-water withdrawals by the city of Minot (7) small scale ground-water withdrawals by local residents and (8) the 1965 through 1975 artificial recharge efforts by the city of Minot. Other factors such as earth tides, earthquakes, loading or a change in barometric pressure also can cause water levels to fluctuate, however these water level changes do not result from recharge to or discharge from the ground-water flow systems.

North Hill aquifer

Ground water in the North Hill aquifer occurs under confined conditions (figs. 10 and 14). In general, depth to water ranges from 2 to 47 feet below land surface (Pettyjohn and Hutchinson, 1971). Ground-water movement in the North Hill aquifer is to the south and the aquifer discharges in a zone of springs and seeps along the north wall of the Souris River Valley (fig. 14) (Pettyjohn, 1967). According to Pettyjohn (1967)

> " A spring issuing from the North Hill aquifer in 155-083-14BCA has formed a lake, and an overflow stream from the lake has a discharge of more than 14 gallons per minute...The high concentration of sulfate in the water, the abrupt changes in thickness, and the apparent lack of natural recharge areas suggest that this aquifer does not have good potential for development."

Northwest buried-channel aquifer

Ground water in the Northwest buried-channel aquifer occurs under confined conditions (fig. 10). Depth to water in this deeply buried channel aquifer varies with land surface elevation and date measured. Pettyjohn (1968A) reported a depth to water of 217 to 219 feet below land surface in the monitoring well located at 155-083-04AAA. From 1984 through 1992, depth to water in 04AAA ranged from 232 to 242 feet below land surface. The gradual decline in water levels in the Northwest buried-channel aquifer is in response to pumping of the Minot aquifer (fig. 15). In 1992 and 1993, depth to water in the State Water Commission monitoring well located at 155-083-11BCD (North Hill Soccer Complex) was in the 230 foot range while just north of the Minot State University Dome, depth to water in the Northwest buried-channel aquifer was more than 150 feet below land surface.

The water level gradient of the Northwest buried-channel aquifer slopes at about 4 feet per mile towards the Souris River Valley (fig. 16). Ground-water movement in the aquifer is towards the southeast with discharge into the Minot aquifer (fig. 16). Using the Darcy relationship with a water level gradient of 4 feet per mile, an aquifer width of 1 mile, thickness of 75 feet and a hydraulic conductivity of 100 ft/day, results in an estimated flow of 250 acre-feet per year (200,000 gallons per day) moving from the Northwest buried-channel aquifer into the Minot aquifer.

South Hill aquifer

Ground water in the South Hill aquifer occurs under confined conditions (fig. 10). Depth to water in this deeply buried aquifer ranges from 195 to 240 feet below land surface (Pusc, 1994). Water levels in the South Hill aquifer appear to respond more to pumping in the Sundre aquifer system than to pumping in the Minot aquifer (fig. 17). Although the South Hill aquifer occupies the same bedrock valley as the Sundre aquifer system, a zone of reduced transmissivity prevents any significant quantities of water from moving from the South Hill aquifer into the Sundre aquifer system. The lack of response to pumping in the Minot aquifer further suggests that the South Hill aquifer is separated from the Minot aquifer by clay/till barriers (figs. 8, 9 and 10).

Souris Valley aquifer system

In the study area, the Minot aquifer is the major segment of the Souris Valley aquifer system being investigated. Sediments of the Souris Valley aquifer system both upstream and downstream of the Minot aquifer are hydraulically connected to the Minot aquifer. Pumpage from the Minot aquifer portion of the Souris Valley aquifer system causes ground water both upstream and downstream of the Minot aquifer to move toward the pumping centers to replace a portion of the water being pumped from the Minot aquifer (fig. 16).

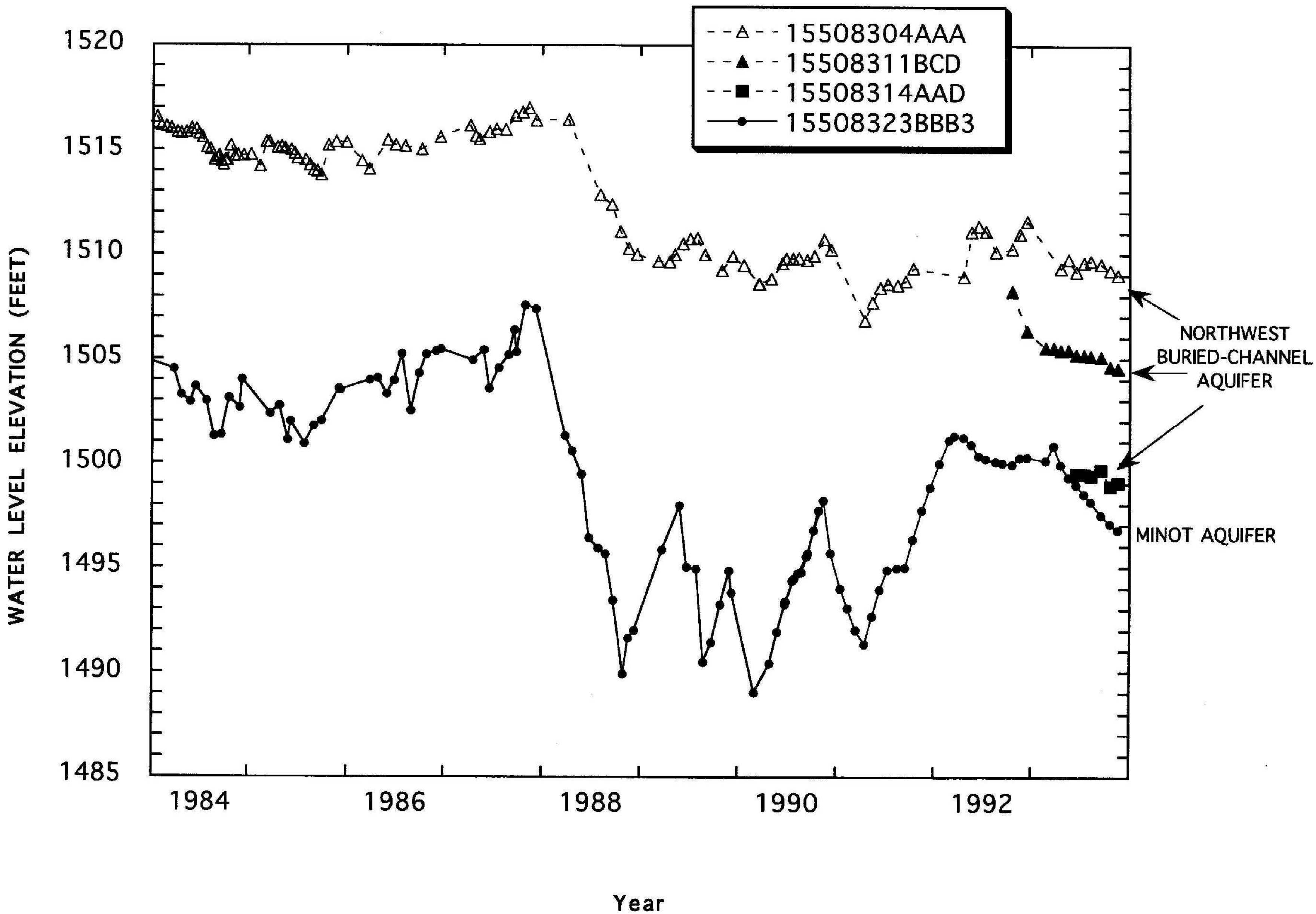
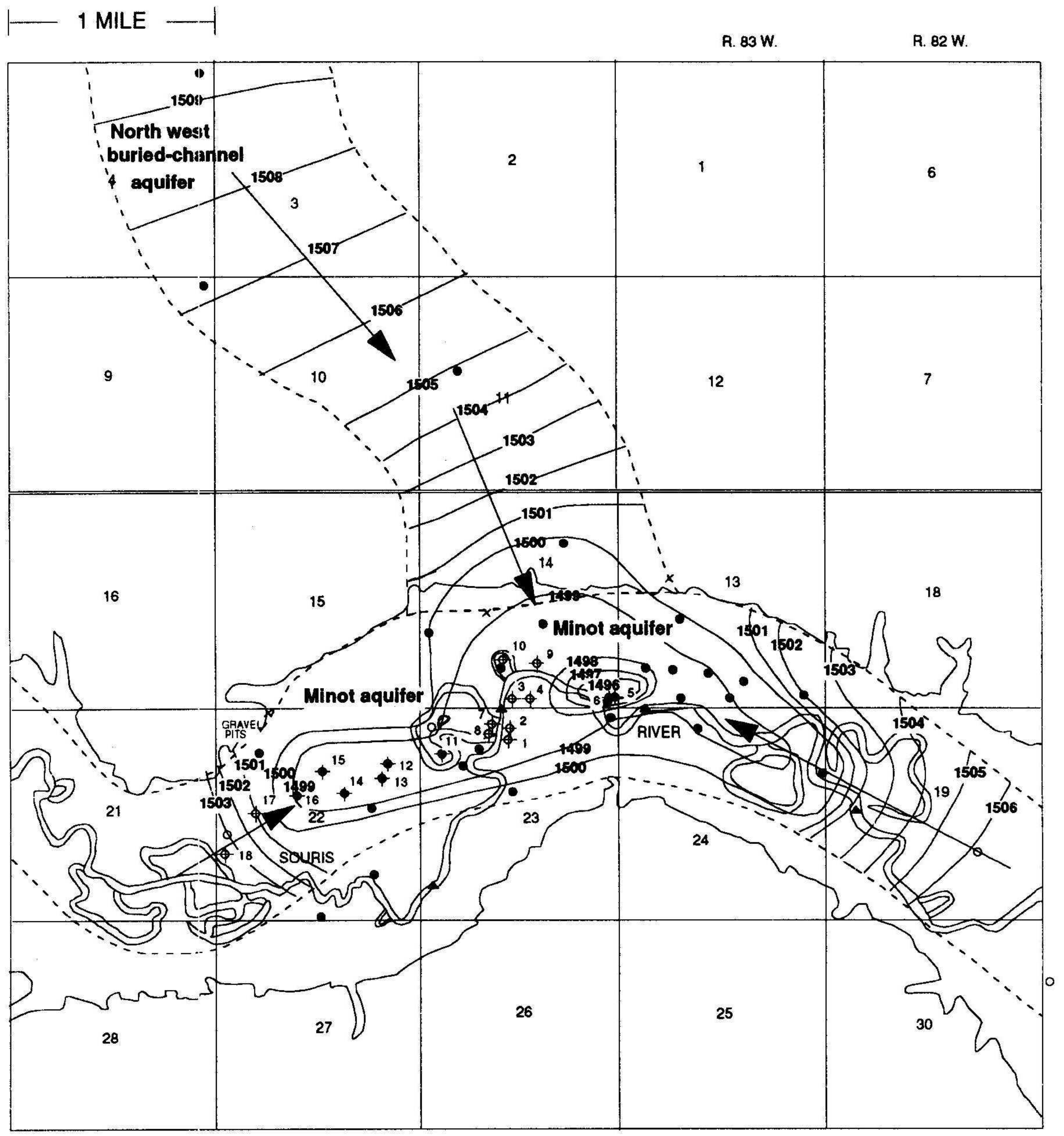


FIGURE 15. COMPARISON OF WATER LEVELS IN THE MINOT AQUIFER AND WATER LEVELS IN THE NORTHWEST BURIED-CHANNEL AQUIFER



EXPLANATION

- o Monitoring well from previous study
- • New Monitoring well, drilled in 1992
- × Test hole, 1992, no Monitoring well
- ▲ River stage site
- City production well used
- City production well, plugged & abandoned
- ■ Test hole from previous study
- 1500 Water level contour, feet
- Direction of ground-water flow

FIGURE 16. MAP SHOWING THE CONFIGURATION OF THE WATER LEVEL SURFACE OF THE MINOT AND NORTHWEST BURIED-CHANNEL AQUIFERS, DECEMBER, 1992

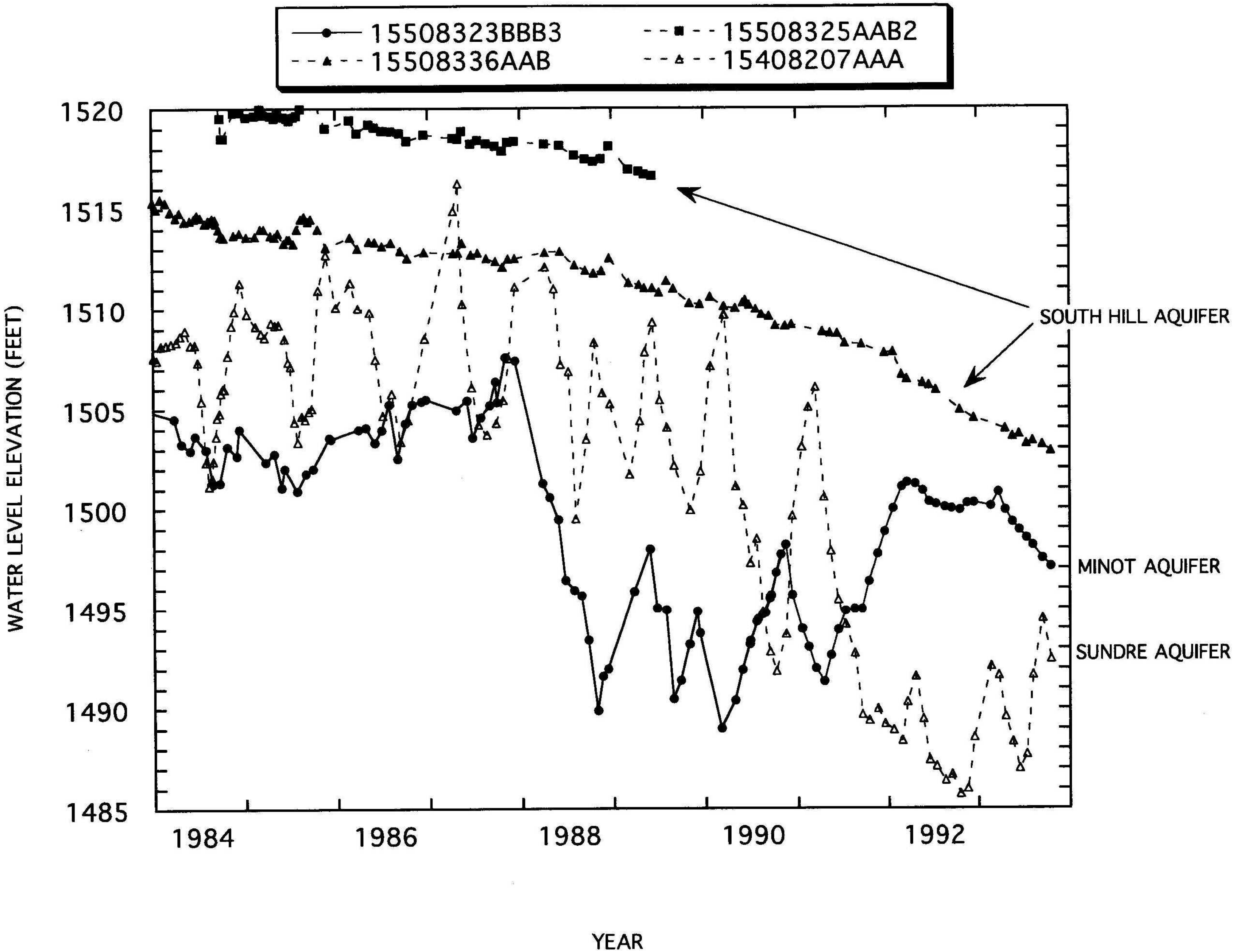


FIGURE 17. COMPARISON OF WATER LEVELS IN THE MINOT, SUNDRE AND SOUTH HILL AQUIFERS.

Minot aquifer

Natural Recharge

Natural recharge to the Minot aquifer occurs by: 1) direct or indirect infiltration of precipitation, 2) inflow from adjacent bedrock and glacial drift deposits, and 3) seepage from the Souris River (Akin, 1947, Pettyjohn, 1967 and Pettyjohn and Hutchinson, 1971). Pettyjohn (1967) estimated that:

> "Natural recharge to the Minot aquifer is apparently about 3 million gallons per day."

Average annual precipitation at Minot is approximately 16 inches per year. Even under the most ideal conditions, only a small percentage of this total will infiltrate downward through the soil horizon and reach the Minot aquifer. Assuming that 10 percent of the 16 inches reaches the water table in areas favorable for recharge (estimated to be about 10 percent of the valley floor), the amount of recharge due to direct infiltration of precipitation would only be 64 acre-feet per year. Average long term water use from the Minot aquifer is about 1,600 acre-feet per year (1916-1992). Thus recharge to the Minot aquifer from direct precipitation is small when relative to the amount of water pumped from the system.

An estimation of the amount of recharge from the inflow of bedrock water is, as was the case with Pettyjohn (1967), difficult to determine. The fact that only a portion of the water in the Minot aquifer has taken on the sodium chloride characteristics of the bedrock water suggests that only a small amount of water moves from the bedrock into the Minot aquifer.

According to Pettyjohn (1967),

> "The Northwest buried-channel and lower Souris aquifers (Souris Valley aquifer system) probably supply the largest amount of recharge to the Minot aquifer. Estimates based on water-level gradients and drill-hole data suggest that recharge from these sources may be more than 2 mg/d."

Data collected since Pettyjohn (1967) and Pettyjohn and Hutchinson (1971) supports the conclusion of the movement of ground water from the Northwest buried-channel and Souris Valley aquifer systems into the Minot aquifer. A more detailed discussion of these recharge sources occurs later in this report.

Seepage from the Souris River into the Minot aquifer has been investigated as part of a number of studies. Akin (1947), determined that,

> "...the river appears to be the most important contributor to the water supply in the aquifer."

Pettyjohn (1967), comparing ground-water level and river discharge data concluded,

> "The data, which are from a 19-year period of record, indicate a direct relation between the discharge of the Souris River and the water level in the aquifer. In periods of drought, when the Souris River discharge is low, the water level declines; in periods of wet weather, when the river discharge is high, the water level rises."

In reality, this relationship is slightly more complex than Pettyjohn (1967) describes because during dry conditions and low river discharge, pumping from the Souris River by the city of Minot declines and water use from the Minot aquifer increases resulting in declining ground-water levels. During wet conditions and high river discharge, water use from the Souris River increases and water use from the Minot aquifer decreases. The resulting combination of high river flow and reduced aquifer pumpage results in rising ground-water levels.

Bradley (1963) using flow data collected along the Souris River in September of 1959 determined that there may have been as much as 8.4 cfs (5.4 mg/d) loss of stream flow between the Minot Country Club and the east Minot gaging station. Bradley (1963) attributed this loss to heavy pumping in the Minot well field. Pettyjohn (1967) states that some of the loss may have been due to leakage into broken sewer lines and into a shallow perched aquifer. Consequently, Pettyjohn (1967) thought that the estimated 5.4 mg/d of recharge from the Souris River water to the Minot aquifer was too large. Pettyjohn (1967) with little physical basis, lowered the estimated loss of the Souris River to the Minot aquifer from 5.4 to .5 mg/d.

An additional discussion of the response of water levels in the Minot aquifer to discharge of the Souris River is included in the section titled "Water level fluctuations."

Artificial Recharge

The first discussion of the feasibility of artificial recharge of the Minot aquifer was included in Akin (1947). Akin (1947), stated,

> " It is also possible that artificial recharge by water spreading would be feasible in areas such as that in the vicinity of U.S.G.S. tests A-2 and B-1, where sandy sediments exist from near the surface to depths of 90 to more than 120 feet and where water levels are approximately 40 feet below the land surface." (Unconfined portion of Minot aquifer in Northwest Minot)

Pettyjohn (1967), in his discussion of the feasibility of artificial recharge of the Minot aquifer delineated 4 potential artificial recharge sites in western Minot. Site 1 is the exposure of sand and gravel in the Minot Sand and Gravel Company pit at the west end of the city (fig. 18). Site 2 includes an area in the northern 1/2 of section 22 where test drilling revealed that sand and gravel occurs from the surface down to as much as 100 feet below land surface (fig. 18). Site 2 as outlined by Pettyjohn (1967) is now heavily developed by residential and commercial construction thus restricting the potential for water spreading projects. Site 3, in the area of city well 14, 16. 17 and 18 is the location where, in 1965, the city of Minot constructed an artificial recharge facility (fig. 18). According to Pettyjohn (1971):

> "The facility consists of a settling basin connected to a y-shaped canal system. Along the centerline of the canals are gravel-filled bored holes, called hydraulic connectors, that perforate the poorly permeable material that overlies the Minot aquifer. The hydraulic connectors range in diameter from 30 to 72 inches and from 28 to 34 feet in depth. The lower part of the hydraulic connectors taps sand and gravel in the dewatered upper part of the Minot aquifer."

Water was pumped from the Souris River into a settling basin. When the settling basin filled to a specified level, water flowed into the recharge basin and downward in the hydraulic connectors. During the period 1965 to 1975, it was estimated that as much as 2.6 billion gallons of water were recharged into the Minot aquifer (City of Minot, 1991). The recharge facility was destroyed during flooding events in the mid 1970's and no attempts to artificially recharge the Minot aquifer have been made since. Additional information on the artificial recharge facility constructed by the city of Minot is found in Pettyjohn (1967), Pettyjohn and Hutchinson (1971), Pettyjohn (1968B), and Pettyjohn and Fahy (1968).

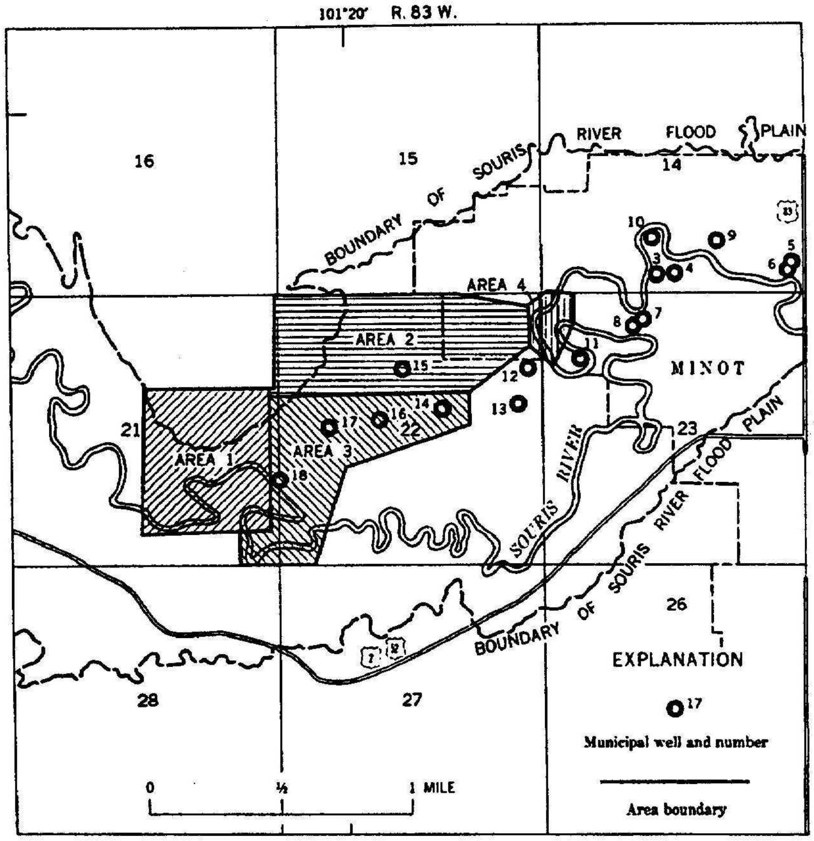


FIGURE 18. POTENTIAL RECHARGE SITES IN WESTERN MINOT (FROM PETTYJOHN, 1967)

Potential recharge site 4, is located in the western part of Oak Park (Pettyjohn, 1967, fig. 18). In this area, sand and gravel occurs from land surface down to over 100 feet. This site has additional potential because the Souris River flows through the area. Recharge could be enhanced by a combination of dredging the river bottom through the Oak Park loop of the river and by the construction a dam on this part of the river. A dam would increase the head of water to be recharged, increase the wetted area and increase residence time thus providing the potential for additional recharge to the Minot aquifer.

Natural Discharge

Under prepumping conditions, discharge from the Minot aquifer was through evapotranspiration, underflow out of the area, upward flow to the overlying Souris Valley aquifer system and seepage to the Souris River. Pumpage by the city of Minot now represents the largest discharge from the Minot aquifer. Because of the drawdown due to pumping, discharge from the Minot aquifer through evapotranspiration, upward flow to the Souris Valley aquifer system, seepage to the Souris River and underflow out of the area have all but been eliminated. Thus a large percentage of water being derived from the pumping of wells is coming from the capture of water that was previously discharging from the Minot aquifer.

Water use

The amount of water pumped annually from the Minot aquifer, the Souris River and the Sundre aquifer system by the city of Minot is presented on figures 19 and 20. Over the 77 year record, the city of Minot has used about of 232,000 acre-feet of water with 53% being derived from the Minot aquifer, 26% from the Souris River and 21% from the Sundre aquifer system (fig. 19). Long term water use by the city of Minot from all three sources has averaged approximately 2.7 mg/d (fig. 20).

Water use from the Minot aquifer, estimated by Akin (1947) was 440,000 gallons per day in 1916 (figs. 20 and 21). By 1936, water use from the Minot aquifer had increased to 1.4 mg/d. From 1937 to 1955 the city pumped between 1.1 to 1.4 mg/d from the Minot aquifer. In 1956, the city resumed pumping water from the Souris River, resulting in only 116,000 gallons per day being pumped from the Minot aquifer

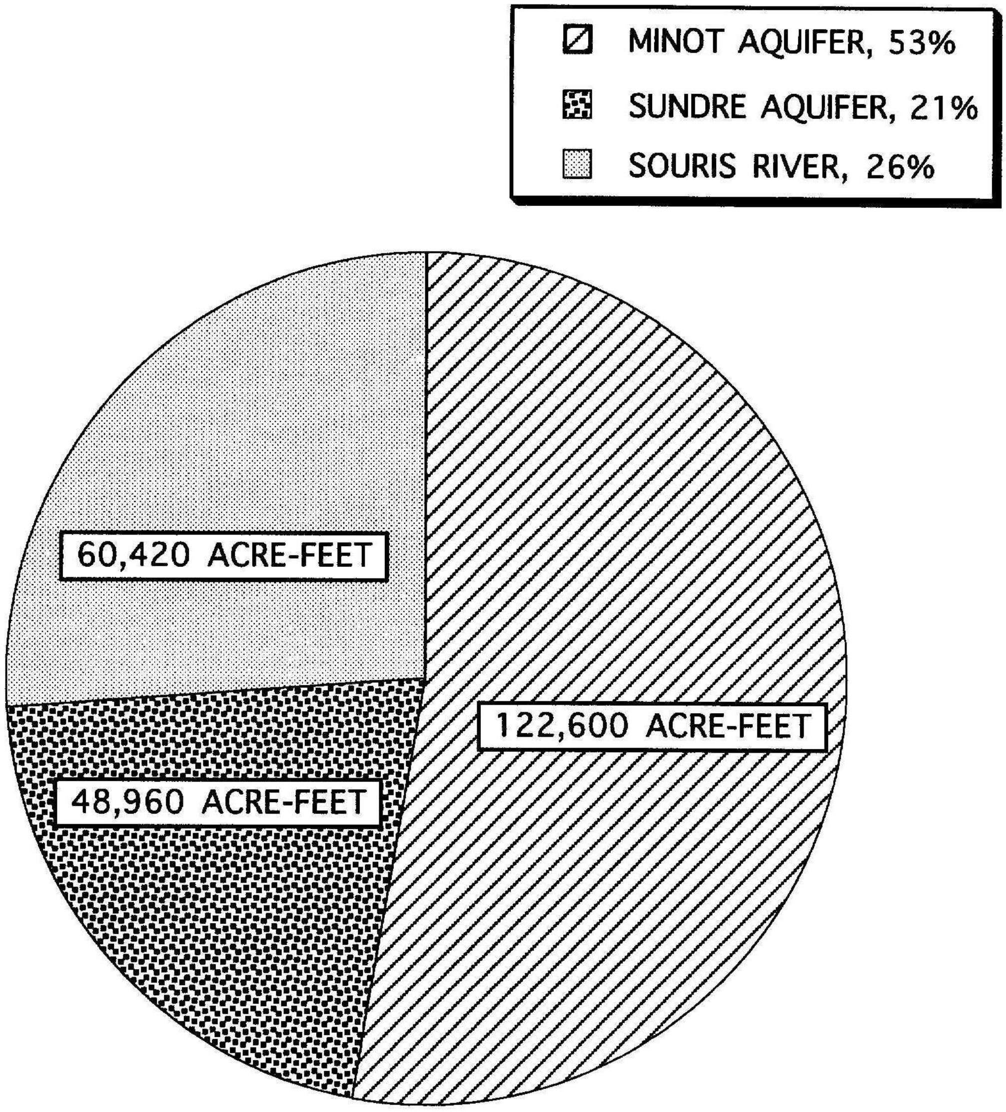


FIGURE 19. PIE CHART SHOWING TOTAL WATER USE BY SOURCE FOR THE CITY OF MINOT, NORTH DAKOTA (1916 - 1992)

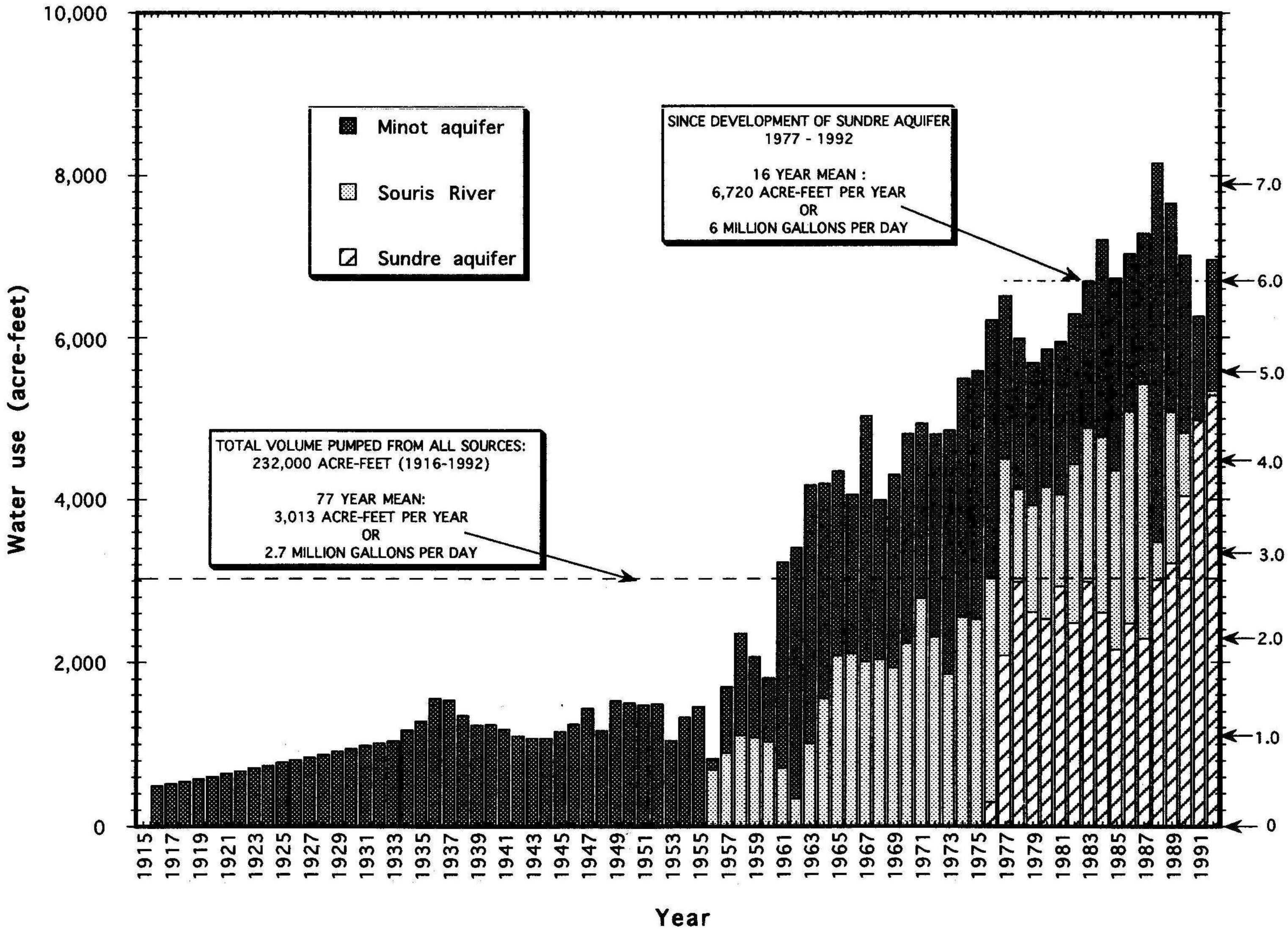


FIGURE 20. YEARLY WATER USE BY SOURCE, CITY OF MINOT, NORTH DAKOTA (1916-1992)

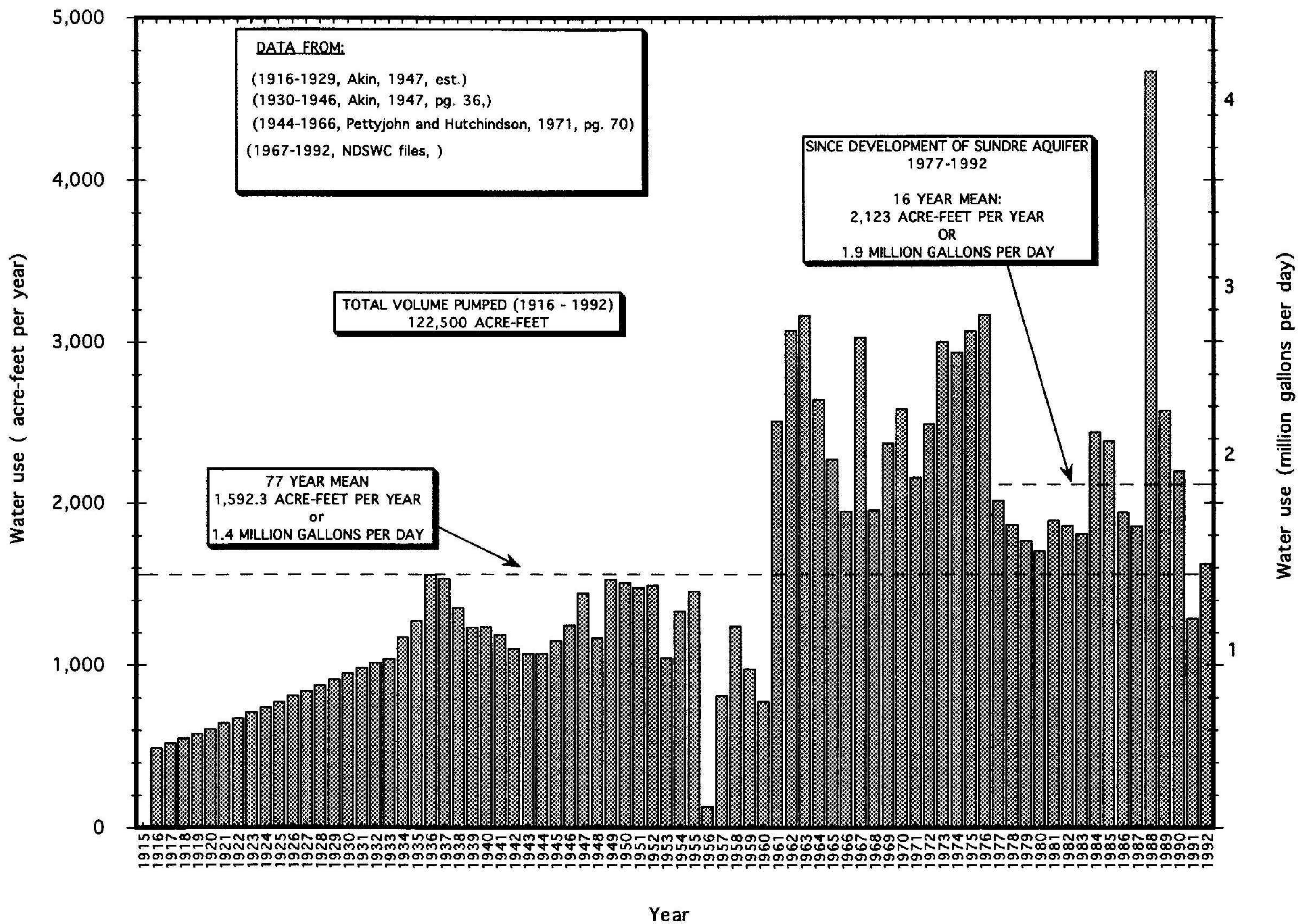


Figure 21. YEARLY WATER USE FROM THE MINOT AQUIFER (1916-1992)

(figs. 20 and 21). Between 1957 and 1960, the city pumped between 724,000 to 1.1 mg/d from the Minot aquifer. In 1961, demand from the Minot aquifer rose to 2.2 mg/d. Increased demand from the Minot aquifer was a combined result of (1) drought, (2) decrease of pumping directly from the Souris River, (3) increased population, and (4) water supply needs of the Minot Air Force Base (Pettyjohn, 1967). Pumpage from 1961 to 1976 ranged from 2.8 mg/d in 1963 to 1.7 mg/d in 1966. In 1976, pumpage from the Sundre aquifer system began with full operation reached in 1977 (fig. 20). From 1977 to 1987, pumping from the Minot aquifer stabilized in the 1.5 to 2.2 mg/d range. Through the period, 1961 through 1987 total annual water use by the city of Minot (from all sources) increased at a rate of about 0.3 mg/d (fig. 20).

In 1988, 8150 acre-feet (7.3 mg/d) of water was pumped from the three sources but, because of the severe drought (1988), only 6 percent of Minot's total water needs could be met from the Souris River (fig. 20). To make up for the diminished surface water supply, Minot increased pumping from the Minot aquifer to 4670 acre-feet or 4.2 mg/d (figs. 20 and 21). Maximum monthly water use was in June of 1988 when 6.5 mg/d was pumped from the Minot aquifer. Declining water levels in the Minot aquifer as a result of increased water use prompted the city to increase pumping from the Sundre aquifer system. From 1989-1992, water use from the Minot aquifer ranged from 1.4 to 2.3 mg/d (fig. 21).

Since development of the Sundre aquifer system in 1976, total water use from all three sources has averaged 6.0 mg/d (fig. 20). Of this 6.0 mg/d, 1.9 mg/d was pumped from the Minot aquifer, 1.4 mg/d from the Souris River and 2.7 mg/d from the Sundre aquifer system (fig. 20).

The amount of water pumped annually from each production well in the Minot aquifer for the period 1981 through 1992 is presented in figure 22. Average water use from the Minot aquifer for this period (1981-1992) was 1.97 mg/d. Highest average water use for the 12 year period was from wells 5 and 6 at 0.31 mg/d each (fig. 23). Next highest use was from well 14 at 0.30 mg/d (fig. 23). The lowest water use was from well 8 at 0.1 mg/d. In fact well 8 has not been used since 1989.

Individual well(Minot aquifer) water use for 1988 (highest use on record) ranged from 0.79 mg/d from well 14 to 0.02 mg/d from well 8 at (fig. 23).

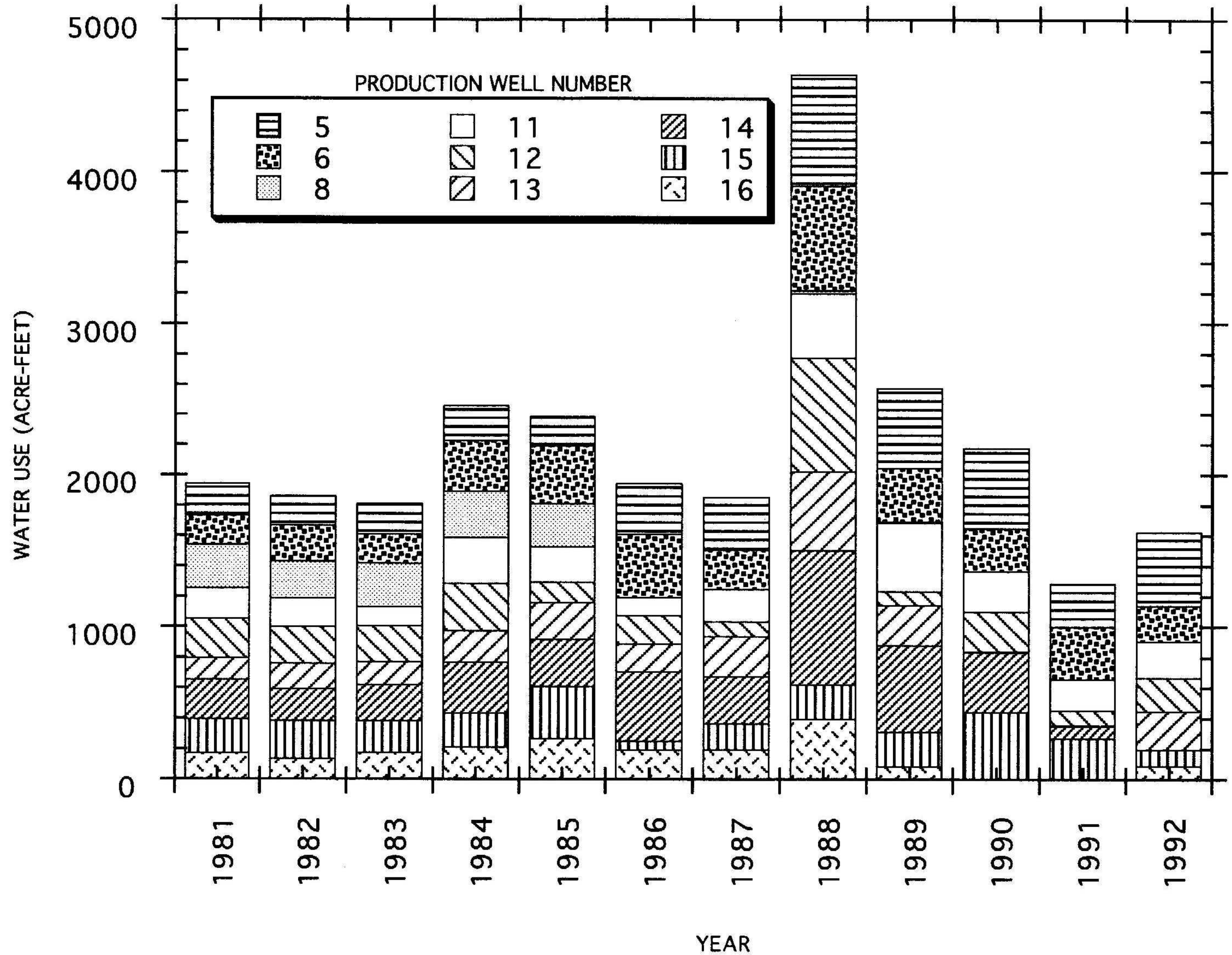


FIGURE 22 . PRODUCTION WELL WATER USE FOR THE CITY OF MINOT, NORTH DAKOTA (1981-1992)

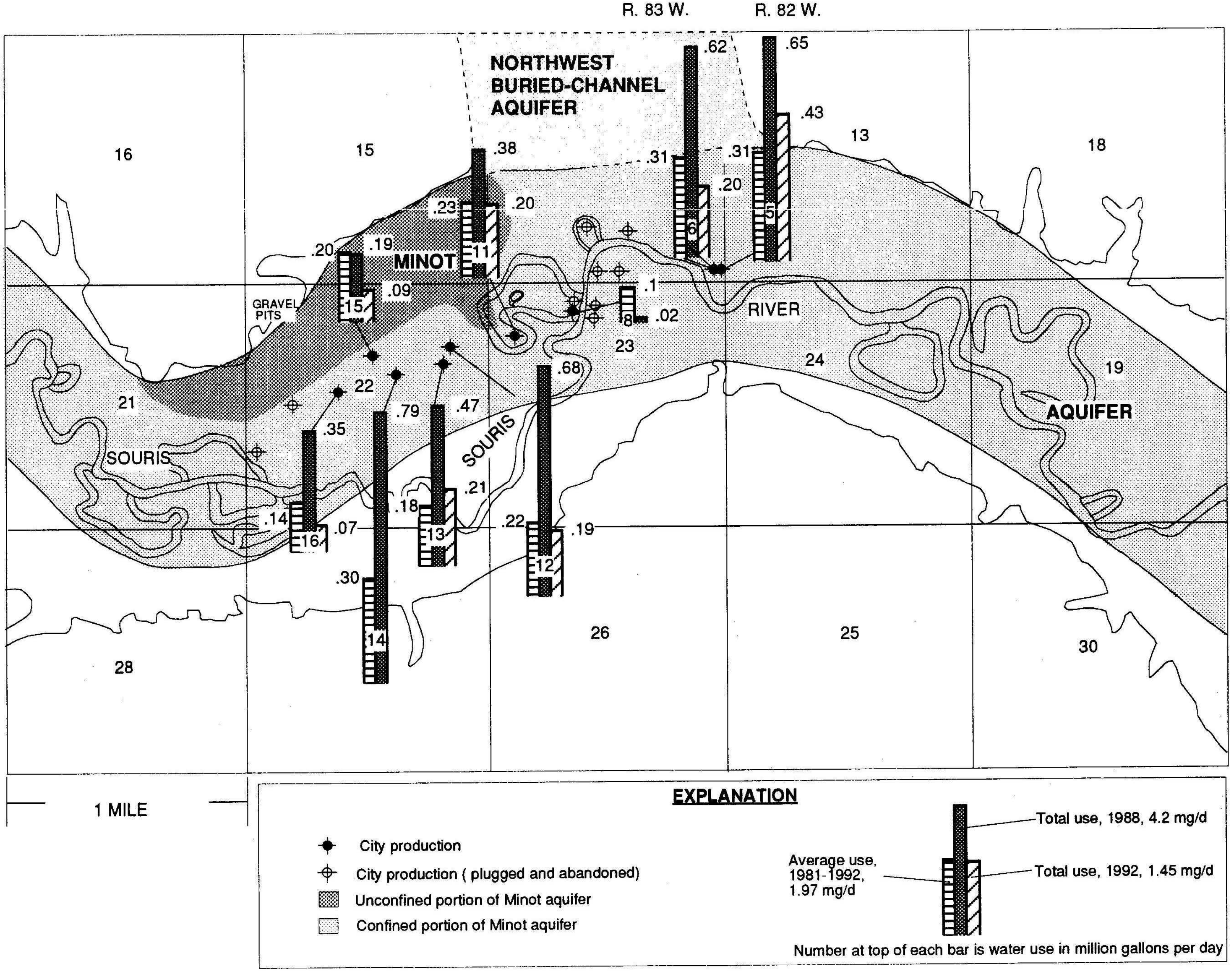


FIGURE 23. MAP SHOWING THE AREAL DISTRIBUTION OF WATER USE FOR THE MINOT AQUIFER (1981 - 1992)

In 1992, water use from the Minot aquifer was 1.45 mg/d (fig. 23). Highest use was from well 5 at 0.43 mg/d. Note that wells 8 and 14 were not pumped in 1992 (fig. 23).

Water level fluctuations

Intermittent water level records for the Minot aquifer date back to the early 1900's. From 1915 to 1917, the city of Minot obtained a few water level measurements at the time of test drilling and production well construction (Akin, 1947). No reliable water level data are available for the period 1917 to 1932. From 1933 to 1936, water levels were measured periodically in the Northern States Power Company production wells (155-083-24BAB, Akin, 1947). Some of these water levels appear to have been obtained in the production wells while they were pumping and thus do not represent the water level in the aquifer just beyond the pumping well. No water level measurements are available for the period 1937 to 1942. From 1942 to 1944, the city of Minot obtained frequent water level measurements in the Davis well (155-083-SW1/4 SE1/4 of section 14, Akin, 1947). Water level measurements were obtained periodically in a number of wells during the 1944 through 1946 investigation conducted by Akin (1947). The city of Minot obtained periodic water level measurements in city well 2 from 1944 through 1959 (Pettyjohn, 1967). Water level records were not recorded from 1960 through 1962. Water levels were measured from 1963 through 1966 in a number of wells during the ground-water investigations conducted by Pettyjohn (1967) and Pettyjohn and Hutchinson (1971). Since 1964, the NDSWC in cooperation with the U.S. Geological Survey has measured monthly water levels in 4 monitoring wells in the Minot aquifer (Pusc, 1994). Monthly water level data were also recorded in the new monitoring wells constructed as part of this investigation (Pusc, 1994). In addition, the city of Minot has kept a record of water levels in a number of city production wells.

The water level in the Minot aquifer fluctuates in response to recharge to and discharge from the aquifer system. During the spring, water levels in the Minot aquifer rise in response to recharge from precipitation, leakage from the Souris River and a reduction in city pumping (figs. 24, 25 and 26). During the summer months, water levels decline in response to reduced recharge coupled with increased pumping of the city production wells. During the fall and winter, water levels generally rise or remain stable due to a reduction in pumping.

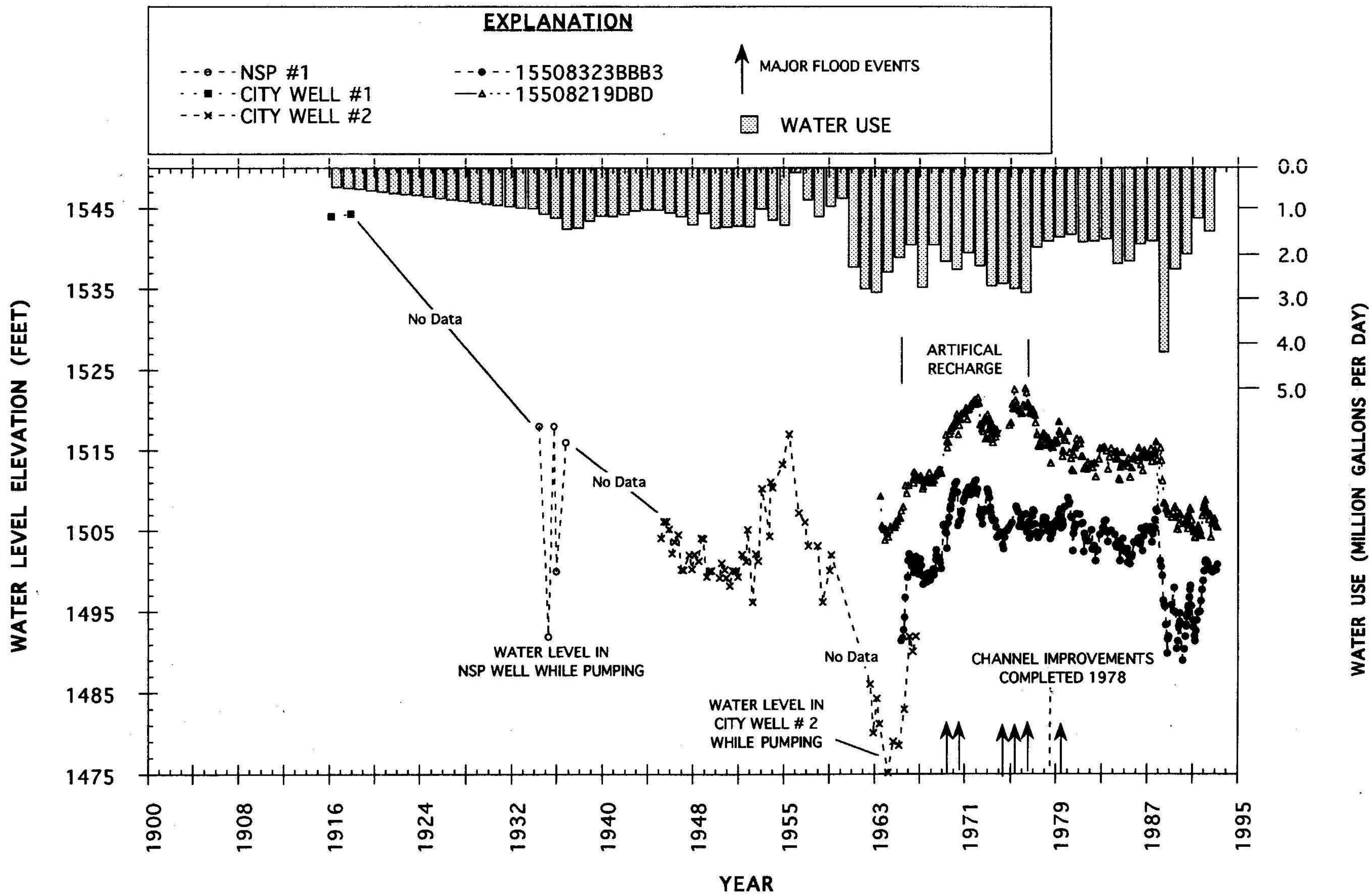


FIGURE 24. COMPARISON OF WATER LEVELS IN THE MINOT AQUIFER WITH WATER USE FROM THE MINOT AQUIFER (1916 - 1992)

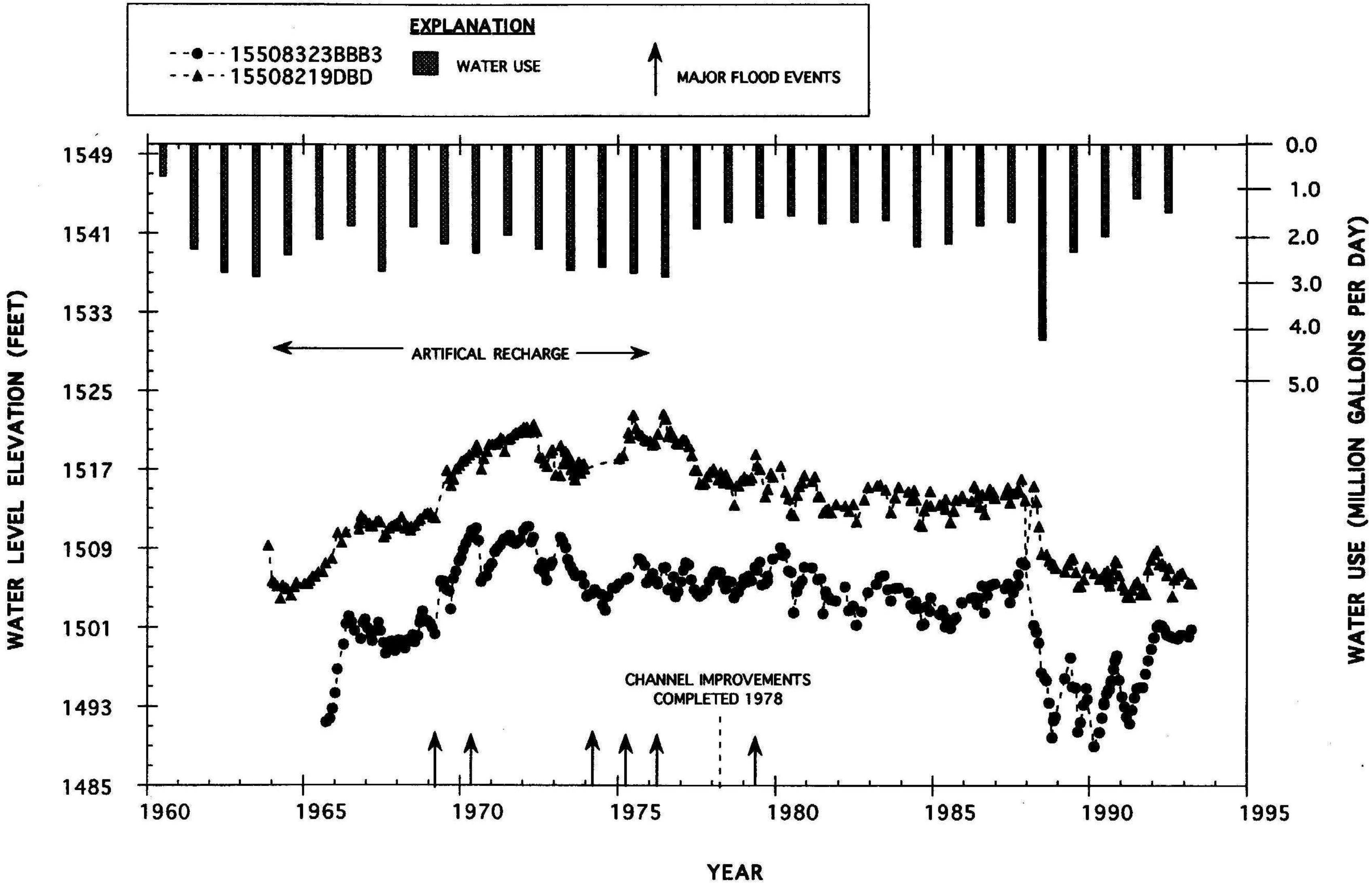


FIGURE 25. COMPARISON OF WATER LEVELS IN THE MINOT AQUIFER WITH WATER USE FROM THE MINOT AQUIFER (1964 - 1992)

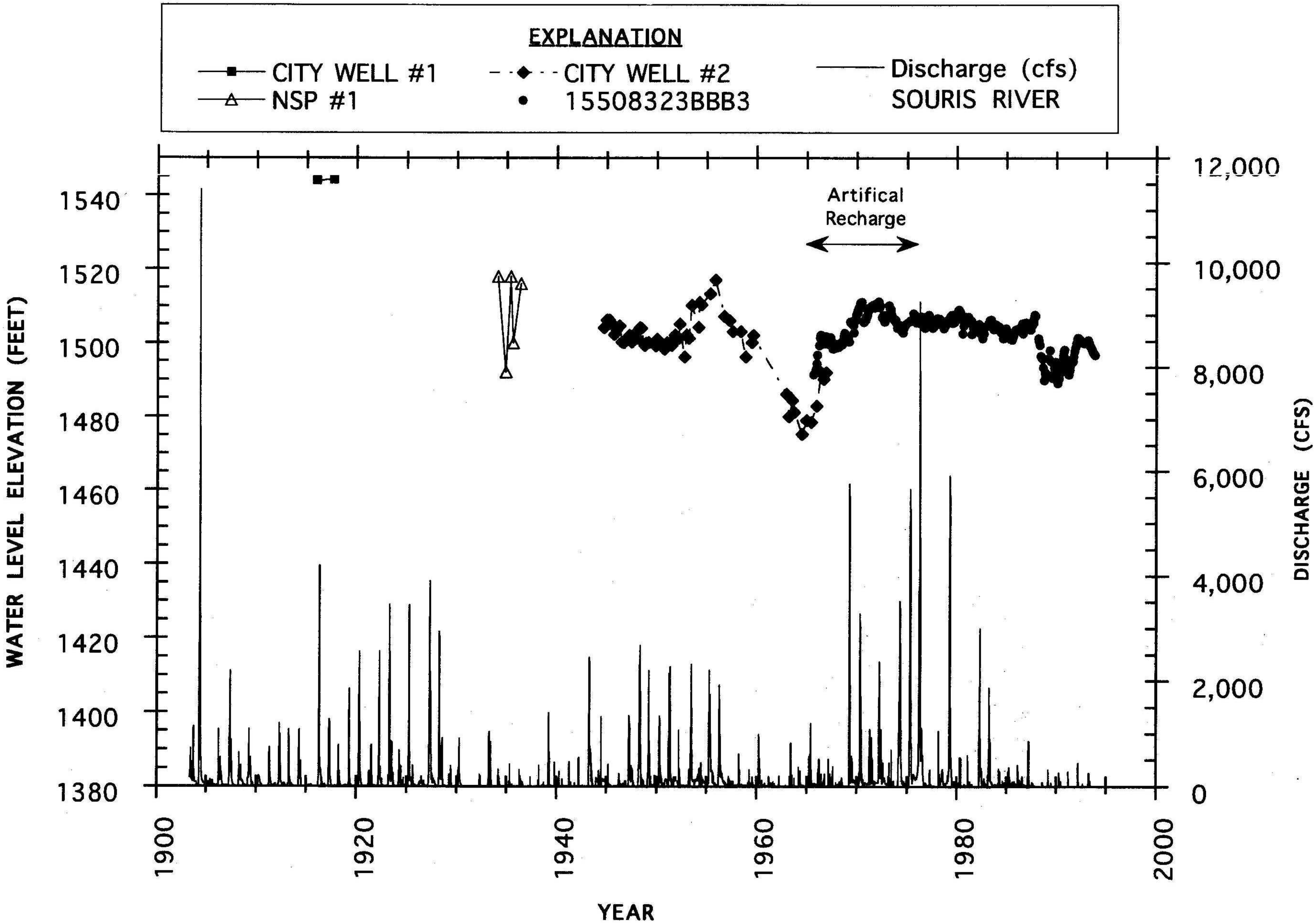


FIGURE 26. COMPARISON OF WATER LEVELS IN THE MINOT AQUIFER WITH DISCHARGE OF THE SOURIS RIVER ABOVE MINOT (1903 - 1992)

Simpson (1929) during his discussion of the construction of production well 1 (1916), states,

> "The water in the well (1) rose within 10 feet of the top, 12 feet higher than the water level in the river."

According to Akin (1947), the water level record indicates that,

> "...the original undisturbed water level in the Minot aquifer in the vicinity of Minot was about 1544 to 1545 feet above mean sea level or from 2 to 3 feet above river elevation." (fig. 24)

From 1916 (start of Minot's pumping) to 1936 the water level in the Minot aquifer declined approximately 27 feet as a result of pumping an average of 750,000 gallons per day (fig. 24).

From 1944 through 1952 water levels in the Minot aquifer declined at a rate of about 1 foot per year as a result of the pumping between 1.0 to 1.4 mg/d (fig. 24). Water levels rose about 5 feet per year from 1955 to 1956 from the combined effects of decreased aquifer pumping (0.1 mg/d in 1956) and increased Souris River stage (figs. 24 and 26). Water levels declined rapidly (5 feet per year) at the close of 1961 after the completion of and subsequent heavy pumping from city wells 11, 12, 13, 14, 15, 16, 17 and 18 (Pettyjohn, 1967). By 1964, depth to water in city well 8 (pumping well) was about 75 feet below land surface. Water levels rose about 10 to 12 feet from 1965 to 1966 due to artificial recharge efforts by the city of Minot (Pettyjohn, 1971). Major flood events in 1969 and 1970 resulted in approximately 12 feet of water level rise (figs. 25 and 26). Water levels declined about 8 feet from 1971 through 1975 due to increased use by the city of Minot (fig. 25). Major flood events in 1974, 1975 and 1976 caused water levels in the Minot aquifer to rise slightly despite heavy use by the City of Minot (fig. 26).

In 1977, use from the Sundre aquifer system began to replace part of the use from the Minot aquifer. The reduction in pumping of the Minot aquifer caused water levels in the Minot aquifer to remain relatively constant (fig. 25). Again, a flood event in 1979 caused water levels in the Minot aquifer to rise almost 6 feet. From 1980 through 1985 water levels in the Minot aquifer declined about 8 feet or about 1.6 feet per year. This modest 6 year decline was due to the pumping of about 1.8 mg/d of water over these years. With less water use in 1986 and 1987, water levels in the Minot aquifer rose slightly (fig. 25). Heavy water use in 1988 of 4.2 mg/d resulted in a water level decline of about 18.5 feet. Note that this increased pumping resulted in the lowest water level in the Minot aquifer since 1965 (water level in a non-pumping monitoring well).

The relatively low water level in the Minot aquifer combined with very low flow in the Souris River prompted the city to rely heavily on water from the Sundre aquifer system. Decreasing water use from the Minot aquifer from 1989 to 1992, has resulted in a overall recovery of water levels from the 1988 low (fig. 25). Depth to water in the Minot aquifer from 1988 through 1992 ranged from 55 to 65 feet below land surface. The largest seasonal decline was about 6 feet just south of city wells 5 & 6 (fig. 16). More drawdown occurred in this area because, in 1992, city wells 5 and 6 accounted for approximately 50% of the total pumping from the Minot aquifer (fig. 23).

One well nest was constructed to determine the vertical water level relationships within the thickest known section of the Minot aquifer. The three wells are screened at the top, middle and bottom of the Minot aquifer (fig. 27). At this site (Hammond Park) water levels at the bottom of the Minot aquifer were the lowest. Water levels in the middle of the Minot aquifer were slightly higher than water levels at the bottom of the Minot aquifer. Water levels at the top of the Minot aquifer were consistently higher than water levels at the middle or bottom of the Minot aquifer (fig. 27). These data indicate that because of pumping, ground water in the Minot aquifer moves downward and lateral towards the cone of depression created by the pumping wells.

Well nests were also constructed at sites where a shallow interval of sand and gravel (Souris Valley aquifer system) was encountered in the sediments which overlie the confined portion of the Minot aquifer. At all these sites, water levels in the overlying Souris Valley aquifer system were higher than water levels in the Minot aquifer(figs. 28 through 33). In addition, pumping of the Minot aquifer had little if any apparent affect on water levels in the overlying Souris Valley aquifer system. The lack of response in the shallow Souris Valley aquifer to pumping in the Minot aquifer suggest that the intervening clay and silt deposits prevent significant amounts of water from recharging the confined portion of the Minot aquifer.

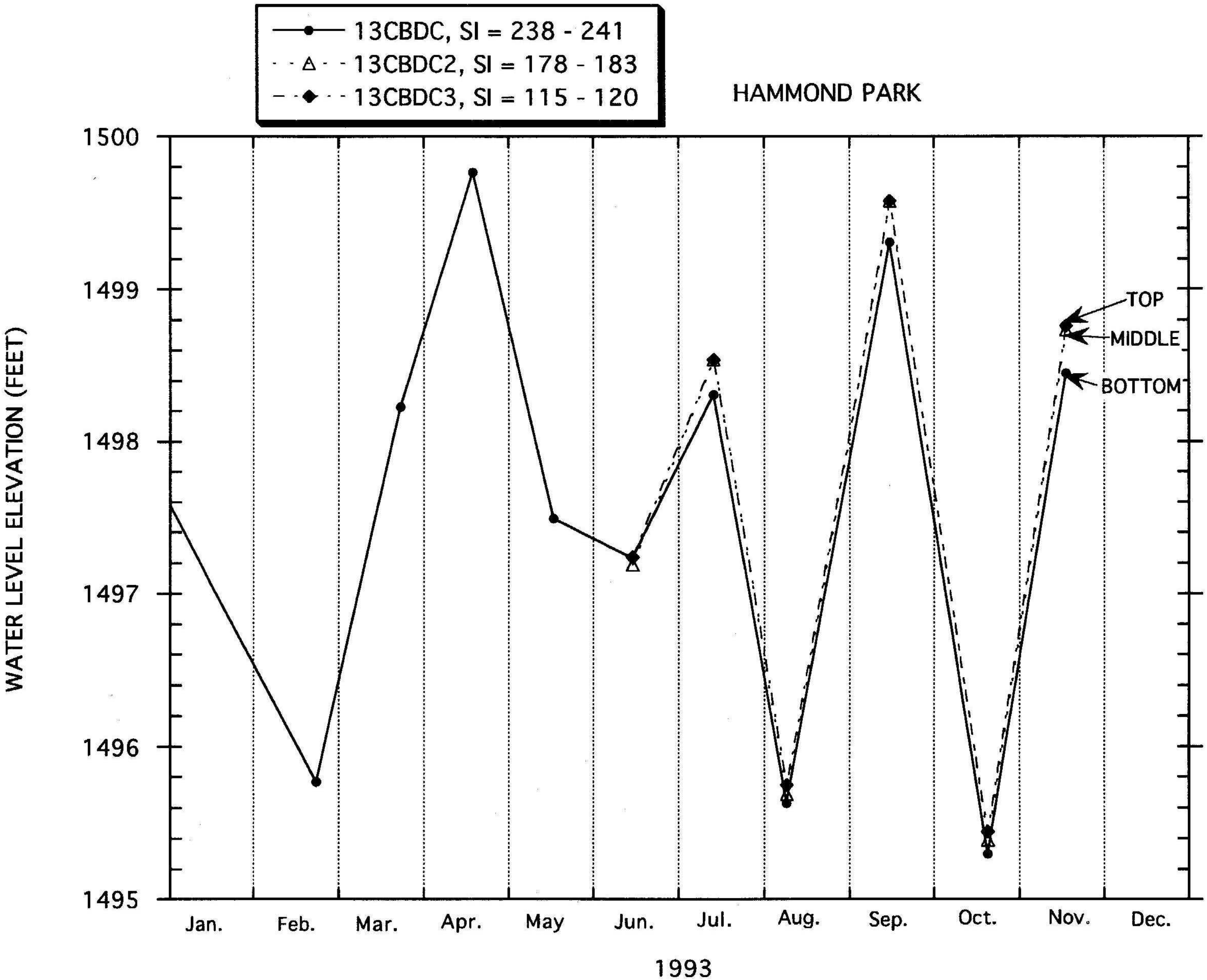


FIGURE 27. HYDROGRAPHS OF WATER LEVELS FROM PIEZOMETER NEST 155-083-13CBDC SHOWING THE VERTICAL DISTRIBUTION OF WATER LEVELS IN THE MINOT AQUIFER.

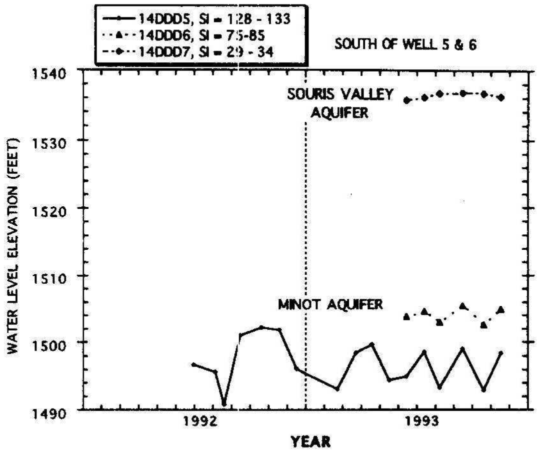


FIGURE 28. Hydrographs of water levels from piezometer nest 155-083-14DDD showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

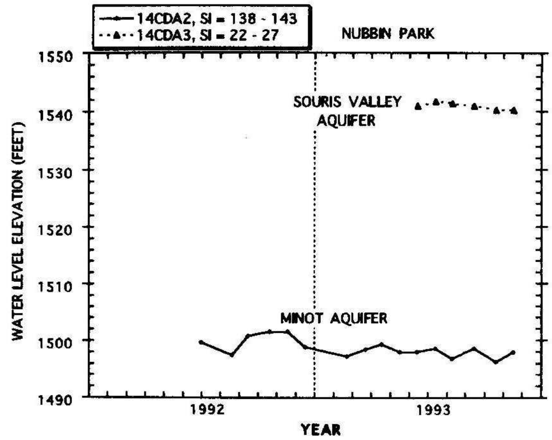


FIGURE 29. Hydrographs of water levels from piezometer nest 155-083-14CDA showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

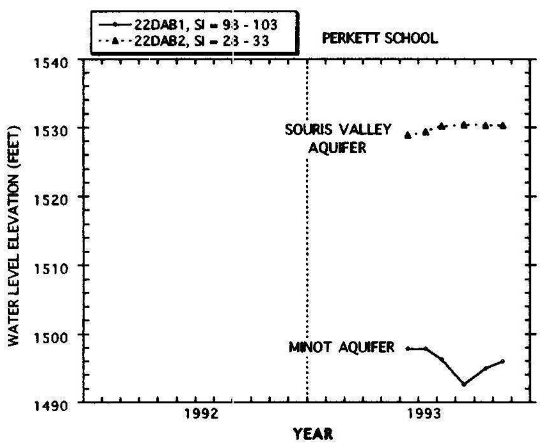


FIGURE 30. Hydrographs of water levels from piezometer nest 155-083-22DAB showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

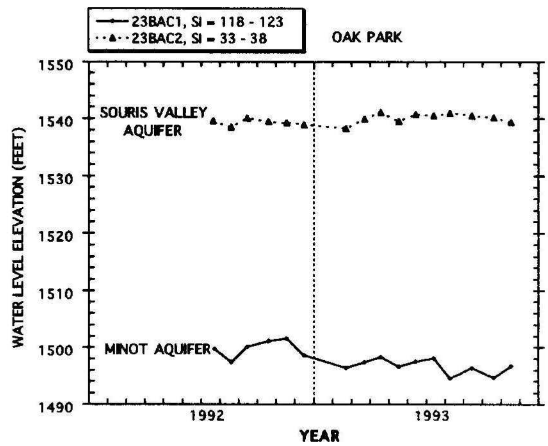


FIGURE 31. Hydrographs of water levels from piezometer nest 155-083-23BAC showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

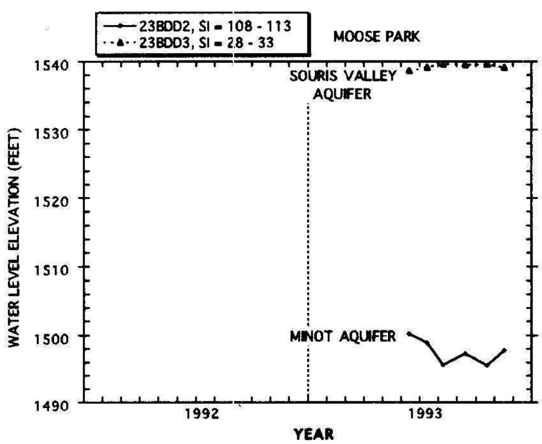


FIGURE 32. Hydrographs of water levels from piezometer nest 155-083-23BDD showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

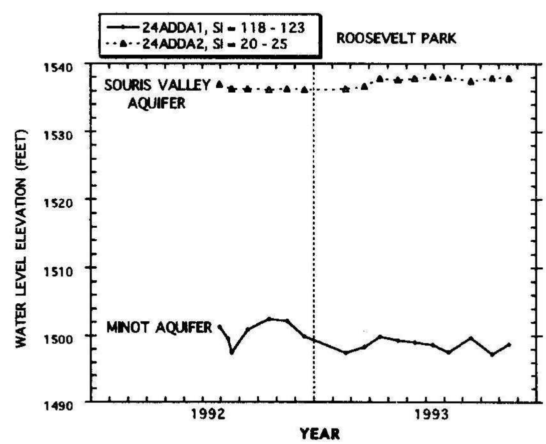


FIGURE 33. Hydrographs of water levels from piezometer nest 155-083-24ADDA showing the vertical distribution of water levels in the Souris Valley and Minot aquifers.

Ground-water movement

Ground water moves under the influence of gravity from areas of recharge to areas of discharge. The fact that water levels in the Minot aquifer before development were higher than the height of the Souris River indicate that ground-water flow was towards the river. Before development, ground-water discharge from the Minot aquifer occurred as base flow to the Souris River or by evapotranspiration. Pumping by the city of Minot has altered the natural ground-water flow system. Ground water in the Minot aquifer now moves from all directions into the cone of depression created by the city of Minot pumping wells (fig. 16). The cone of depression created by pumping has elongated both up and down the valley floor (fig. 16). Generally, ground-water movement from the north and south is restricted by the relatively impermeable glacial till which forms the north and south walls of the valley. Ground water also moves from the Northwest buried-channel aquifer into the cone of depression in the Minot aquifer (fig. 16). Interestingly, the water level contour map show on figure 16 is very similar to the water level contour map presented by Pettyjohn (1967). It appears that long term recharge has been sufficient to maintain water levels in the Minot aquifer if the average annual appropriation is maintained in the 1 to 3 mg/d range. In fact, the long term record indicates that a use of about 2 mg/d balanced rather well with the amount of recharge that was able to move into the Minot aquifer.

WATER QUALITY

Souris River

The chemical quality of water sampled from the Souris River above Minot varies within a wide range. In general, water from the Souris River above Minot can be classified as a calcium-sodium bicarbonate type with dissolved solids concentrations ranging from less than 200 milligrams per liter (mg/L) to as much as 1300 mg/L (fig. 34). Pettyjohn and Hutchinson (1971), using water quality data for the Souris River at Verendrye, determined that there is a relationship between the quality and quantity of water in the Souris River (fig. 35). According to Pettyjohn and Hutchinson (1971),

> "From late fall to early spring, when most of the low flow may be attributed to ground-water discharge, the water is more mineralized than during other times of the year. The water generally has the highest concentration of dissolved solids in November and December; whereas, the lowest concentrations generally are in April during the spring runoff."

In general, water quality data for the Souris River above Minot supports the quality/quantity relationship outlined by Pettyjohn and Hutchinson (1971) (fig. 36). During low flow conditions(from late fall to early spring), water in the Souris River above Minot generally contained increased dissolved solids concentrations (fig. 36). The river water during low flow trended towards a sodium-sulfate type water reflecting the contribution of ground water as base flow to the river.

The lowest dissolved solids concentrations generally occurred during high flows in the river (fig. 36). Notable exceptions occurred during the late spring when local precipitation and snow melt resulted in water which contained low concentrations of total dissolved solids despite very low flow (fig. 36). In addition, during releases from Lake Darling following an extended low flow period in the river, the river water can remain highly mineralized despite flows of over 200 cfs (fig. 36). The poorer water quality during relatively high flows appears to be due to mixing of water from Lake Darling with stagnant base flow water from the river channel.

Fort Union Formation

Ground water sampled and analyzed from the Fort Union Formation in the Minot area was predominantly a sodium chloride type water with dissolved solids

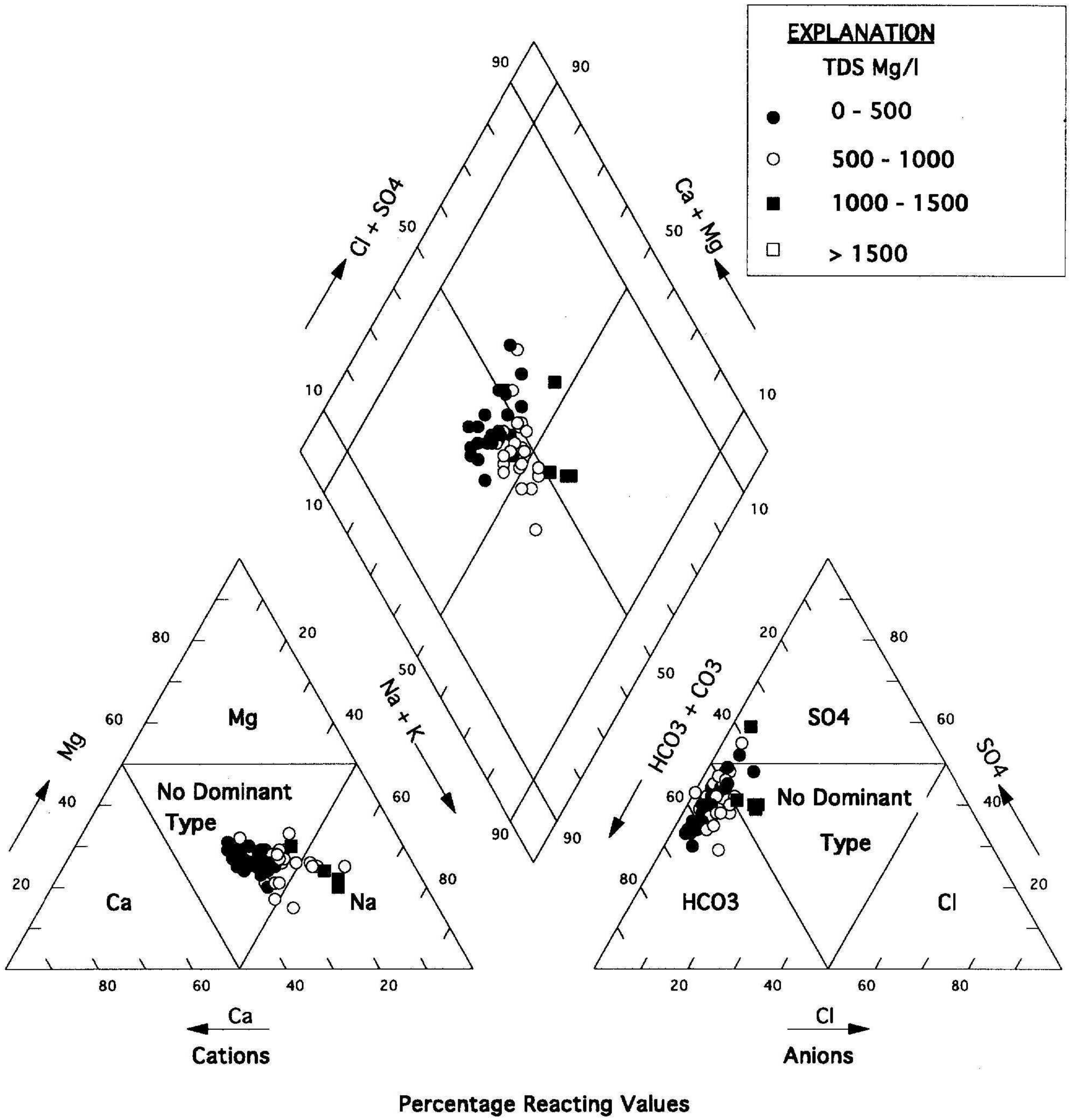


FIGURE 34. PIPER DIAGRAM SHOWING THE CHEMICAL QUALITY OF WATER FROM THE SOURIS RIVER ABOVE MINOT (1969 - 1992)

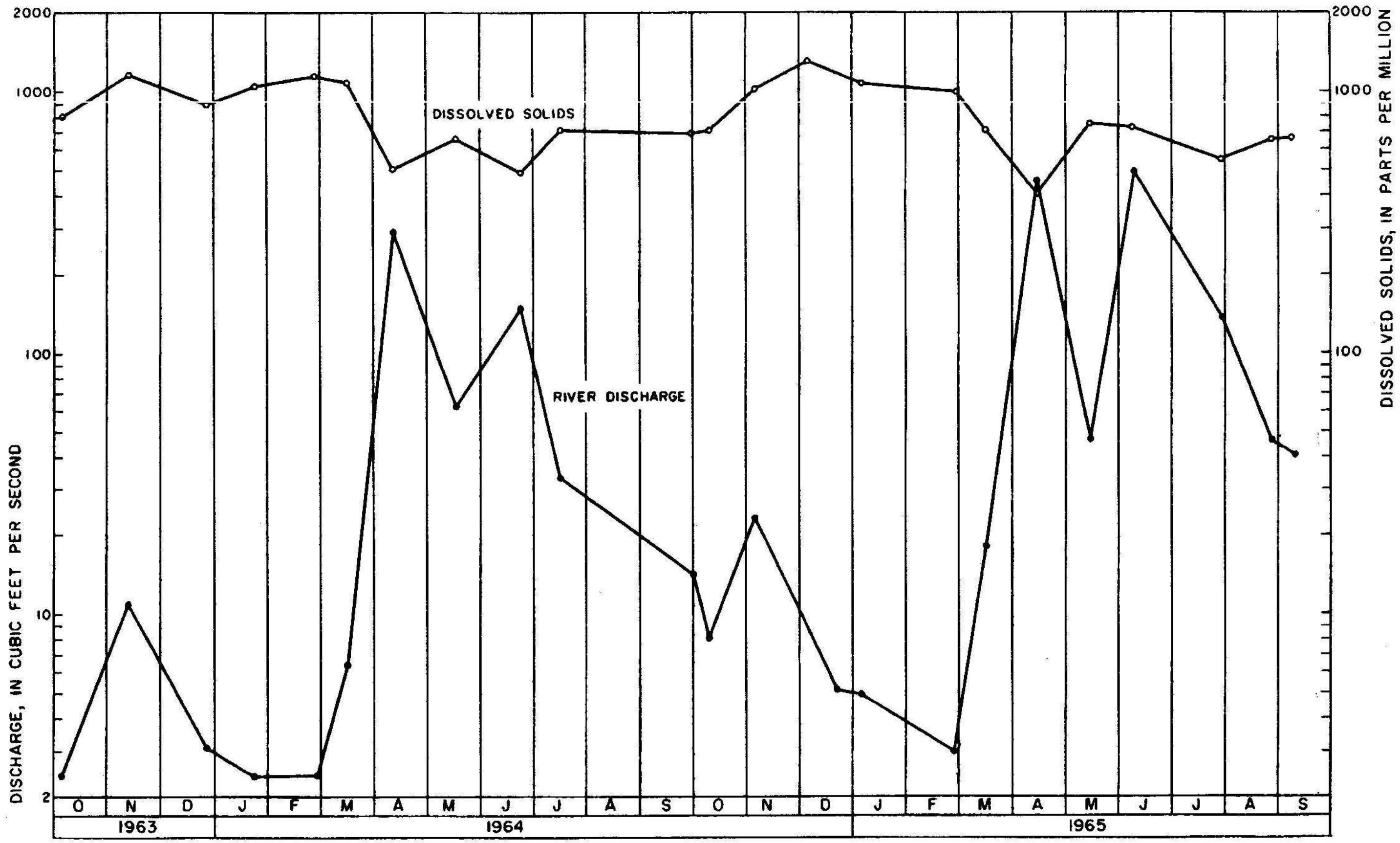


FIGURE 35. COMPARISON OF DISCHARGE AND TOTAL DISSOLVED SOLIDS OF THE SOURIS RIVER AT VERENDRYE, OCTOBER 1963 AND SEPTEMBER 1965(FROM, PETTYJOHN AND HUTCHINSON, 1971)

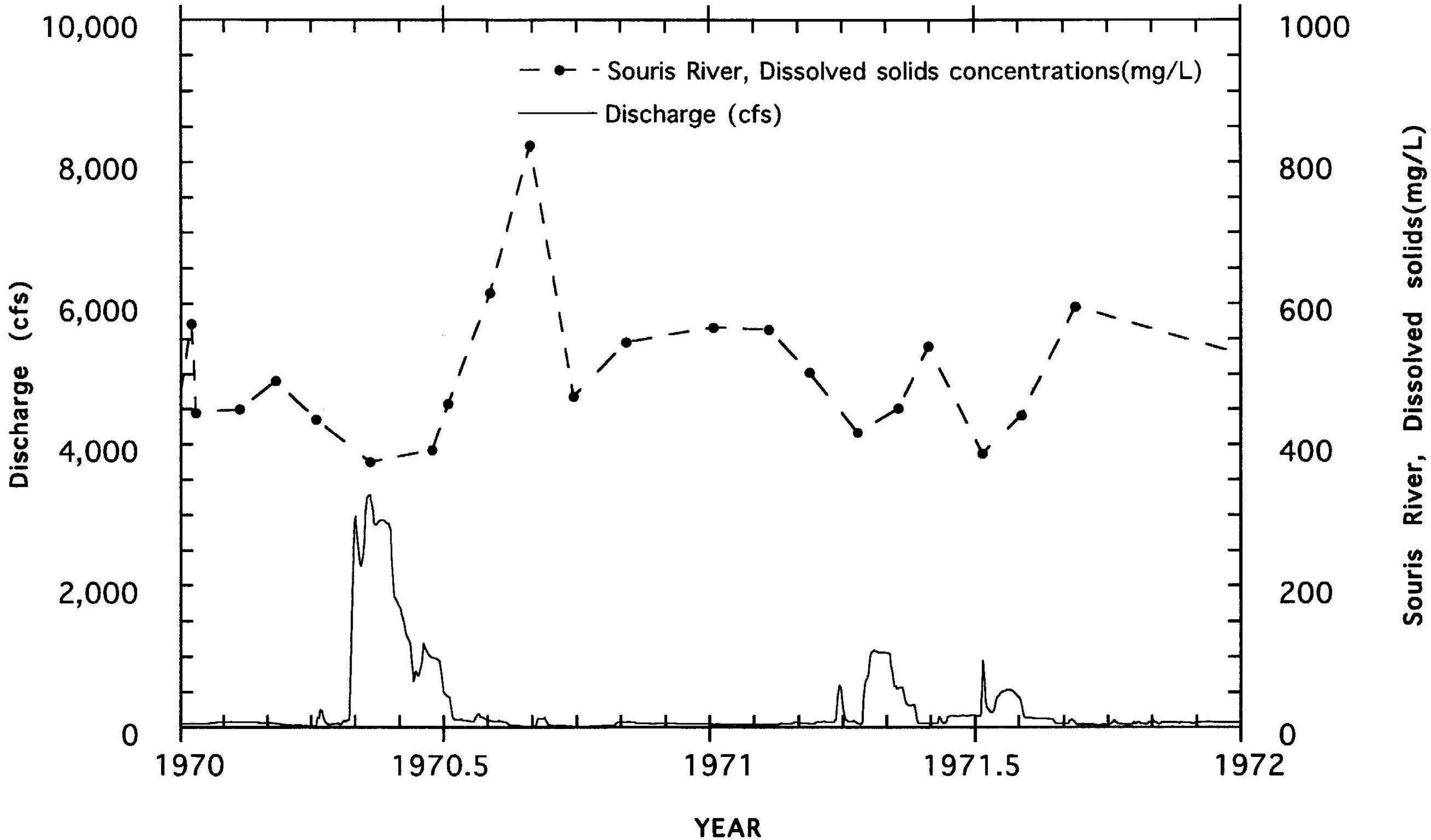


FIGURE 36. COMPARISON OF DISCHARGE AND DISSOLVED SOLIDS CONCENTRATIONS OF THE SOURIS RIVER ABOVE MINOT (1970 AND 1971)

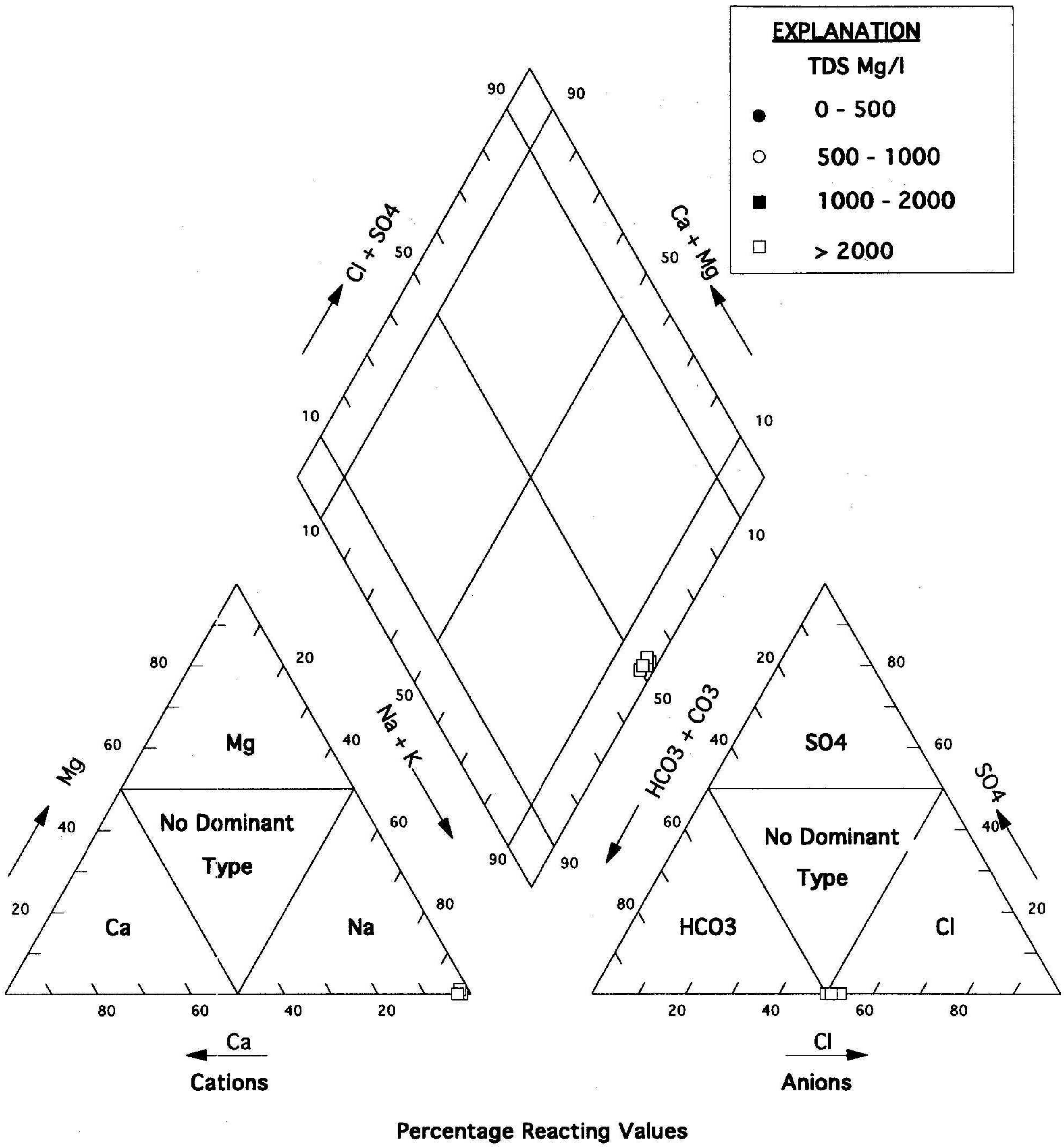


FIGURE 37. PIPER DIAGRAM SHOWING THE CHEMICAL QUALITY OF WATER FROM THE FORT UNION FORMATION

concentrations exceeding 2,000 mg/L (fig. 37) (Pettyjohn and Hutchinson, 1971 and Pusc, 1987B). Sodium concentrations ranged from 780 to 840 mg/L while chloride concentrations ranged from 650 to 740 mg/L. Water from the Fort Union Formation was very soft and contained low levels of all the major ions except for sodium and chloride.

Northwest buried-channel aquifer

Ground water in the Northwest buried-channel aquifer was predominantly a sodium bicarbonate water with dissolved solids concentrations ranging from 1360 to 1570 mg/L (fig. 38). The water was hard with elevated concentrations of chloride (350 mg/L), sodium (400 mg/L), sulfate (530 mg/L) and iron (.38 mg/L).

Souris Valley aquifer system

During the course of this investigation, several wells were completed into shallow sand units of the Souris Valley aquifer system which overlie the Minot aquifer. In general, shallow ground water of the Souris Valley aquifer system was a sodium-calcium bicarbonate type water with low dissolved solids concentrations (600 to 700 mg/, fig. 39). It appears that infiltration of precipitation and Souris River water is keeping water in the shallow sand and gravel units of the Souris Valley aquifer system rather fresh. The existence of good quality water in the Souris Valley aquifer system also means that there is a supply of replenishable fresh water in storage above the Minot aquifer. In places, this fresh water may move downward into the Minot aquifer to replace a portion of the water being pumped from the Minot aquifer by the city of Minot.

Minot aquifer

Introduction

Water quality data for the Minot aquifer dates back to the early 1900's. Simpson (1929) presented water quality data for city well 2 and for the well supplying the State Normal School (Minot State University). Akin (1947) published water quality data for wells 1, 2 and 3 (1932 data) and wells 1,2,3 and 4 (1940 data). Wells 1, 2, 3, and 4 were plugged and abandoned several years ago. Production well 5(still in use) was

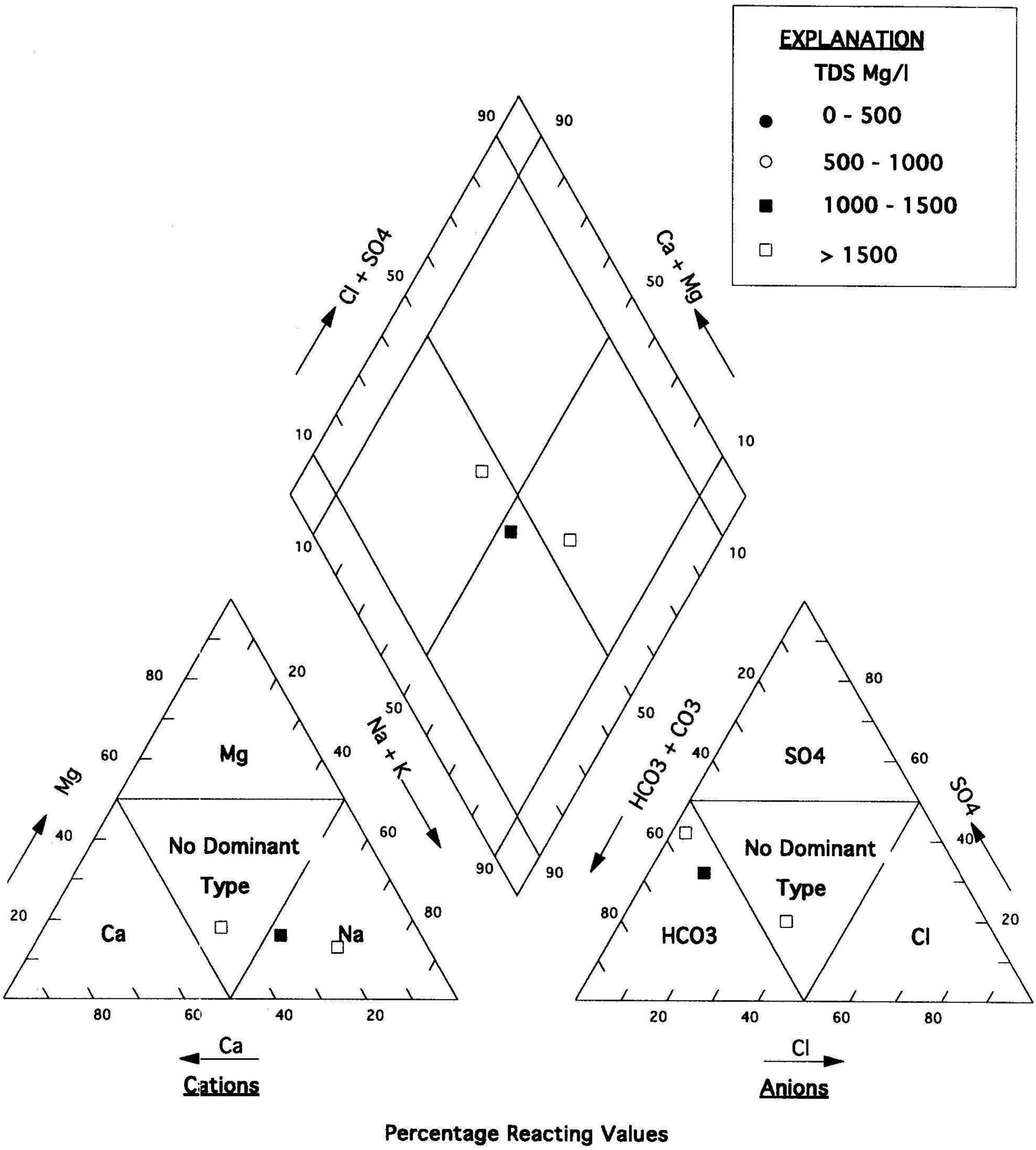


FIGURE 38. PIPER DIAGRAM SHOWING THE CHEMICAL QUALITY OF WATER FROM THE NORTHWEST BURIED-CHANNEL AQUIFER

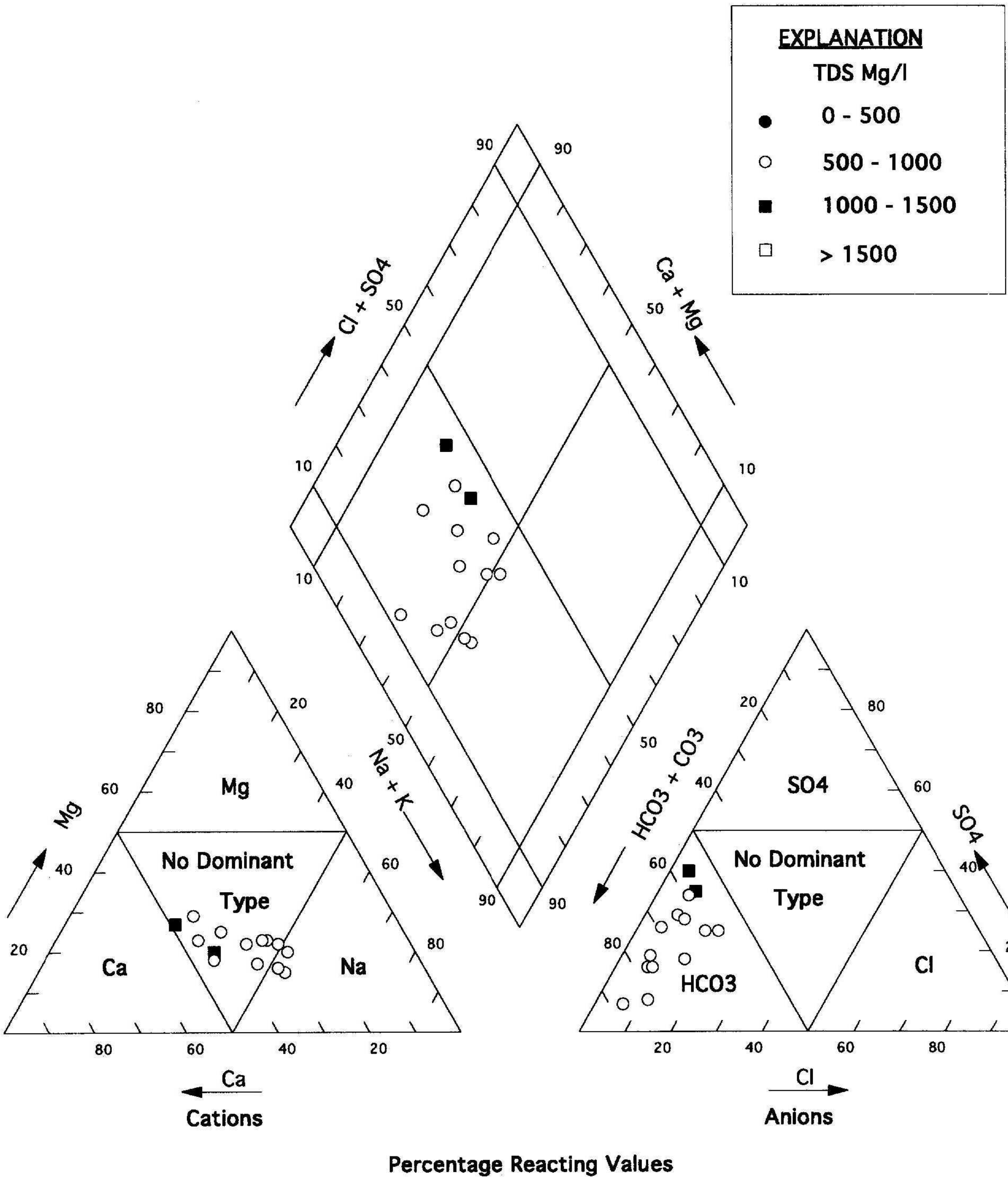


FIGURE 39. PIPER DIAGRAM SHOWING THE CHEMICAL QUALITY OF WATER FROM THE SOURIS VALLEY AQUIFER SYSTEM

sampled in 1946, shortly after construction. Periodic water quality analyses for the city of Minot production wells 5, 6, 7, 8, 11, 12, 13, 14, 15 and 16 are available for the period 1963 through 1993. Water quality data for 1992 and 1993 are available for all the monitoring wells installed during this investigation.

1921

Simpson, 1929 reports a total dissolved solids concentration of 1135 mg/L in water sampled from city production well 2 (confined portion of the Minot aquifer, just east of Oak Park). As stated by Simpson (1929),

> "The water is very soft and has a slight color from organic stain, but this color has decreased somewhat since the initial pumping."

Water from well 2, in 1921, had a rather high chloride concentration (200 mg/L) probably due to the natural discharge of chloride rich bedrock water moving upward into the Minot aquifer.

Water sampled from the Minot State University well in the Minot aquifer (confined portion of aquifer) had a dissolved solids concentration of 1454 mg/L. The chloride concentration was 232 mg/L or very similar to the chloride concentration of water from city well 2.

1932

By 1932 the city had pumped over 4 billion gallons of water from the Minot aquifer. Dissolved solids concentrations in 1932 varied from 657 mg/L from well 1, 924 mg/L from well 2 and 1555 mg/L from well 3 (just south of Nubbin Park). The water from wells 1 and 2 was a sodium bicarbonate water. The reduction in dissolved solids concentration from the years 1921 to 1932 is probably due to the capture of better quality water from the western unconfined portion of the Minot aquifer. Water from well 3, with a chloride concentration of 300 mg/L, was trending towards a sodium-chloride type water.

1940

Water from wells 1 and 2 was still a sodium bicarbonate type with dissolved solids concentrations of 742 and 648 mg/L, respectively. Wells 3 and 4 had total dissolved concentrations of 1220 and 1262 mg/L, respectively.

1963 - 1993

The quality of water from the Minot aquifer, in 1963, was discussed in some detail by Pettyjohn (1967) and Pettyjohn and Hutchinson (1971). Based on water quality data from a number of city production wells, Pettyjohn (1967) and Pettyjohn and Hutchinson (1971) subdivided water in the Minot aquifer into 4 groups(fig. 40). It must be kept in mind that by 1963 the city Minot had pumped almost 18 billion gallons (an average of 1 mg/d) of water from the Minot aquifer. Area A included water from city well 18 which was a sodium-potassium bicarbonate water (fig. 40). According to Pettyjohn (1971),

> "The water is brown from leaching of the abundant detrital lignite in the aquifer and of the beds of lignite in the Fort Union Formation. "

In Area B, (city wells 13, 14, 16 and 17) ground water had higher sodium-potassium, bicarbonate and chloride concentrations than most of the other city wells(fig. 40). Pettyjohn and Hutchinson (1971) speculate that the wells in area B are deriving water predominately from the south and southwest and from the underlying Fort Union Formation explaining the higher concentrations of sodium-potassium, bicarbonate and chloride.

Area C includes sand and gravel of the northwestern unconfined portion of the Minot aquifer (fig. 40, City wells 7, 8, 11, 12 and 15). The water was generally low in dissolved solids concentrations suggesting recharge from the surface (leakage from the Souris River and infiltration of precipitation).

Area D is in the area of city wells 5, 6, 9, and 10 (fig. 40). Water in this portion of the aquifer was higher in dissolved solids, chloride, magnesium and sulfate than water from area C. Water quality in this portion of the Minot aquifer is being influenced by poorer quality water moving from the Northwest buried-channel aquifer into the Minot aquifer (fig. 16).

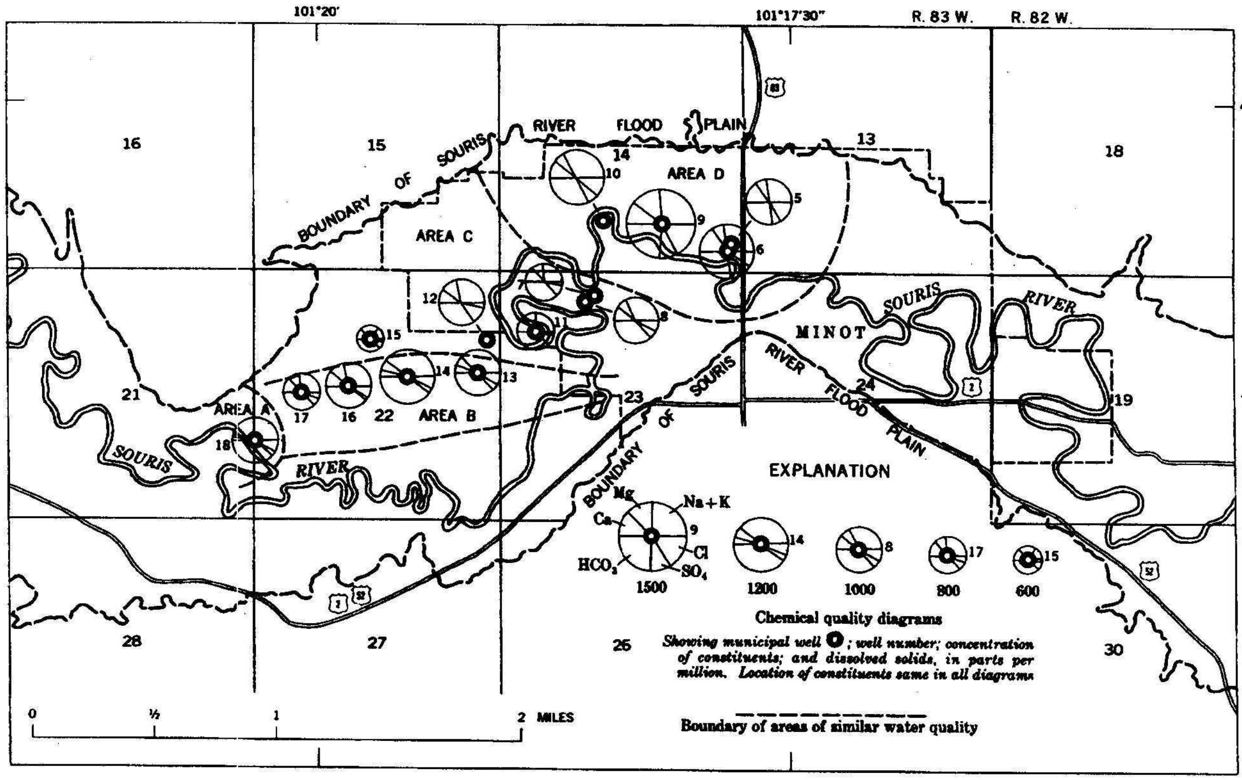


FIGURE 40. MAP SHOWING THE CHEMICAL QUALITY OF WATER AND DISSOLVED SOLIDS CONCENTRATIONS IN THE MINOT AQUIFER, 1963 (FROM PETTYJOHN, 1967)

Through the period, 1963 to 1993, the city almost doubled yearly use from the Minot aquifer (fig. 21). The spatial and temporal distribution of water chemistry in the Minot aquifer has been affected by this increased pumpage. Changes in water chemistry are described from west (well 16) to east (well 5) in the Minot aquifer.

Well 16

Water from production well 16, in 1963, was a sodium bicarbonate type water with a dissolved solids concentration of 883 mg/L (figs. 41 and 42). From 1968 through 1970, water from well 16 improved slightly in quality with total dissolved solids decreasing to 772 mg/L (fig. 42). The improvement in quality through this time period is probably due to the high river stages providing good quality water to the aquifer in this area. Beginning in 1986, water from well 16 has progressively increased in dissolved solids concentration (fig. 42, 990 mg/L). Since the 1960's, water from well 16 has experienced an overall increase in sodium (205 to 290 mg/L) and sulfate (26 to 100 mg/L) concentrations (fig. 41). The slight increase in mineralization appears to be caused by heavy water use coupled with several years of minimal recharge.

Well 15

Water from well 15 had (1963) and remains to have (1993) the lowest dissolved solids concentrations as compared with all the other productions wells in the Minot aquifer (figs. 42 and 43). The low dissolved solids concentrations in this area are due to relatively direct and rapid infiltration of Souris River water and precipitation in the unconfined portion of the aquifer (fig. 16). In 1963, water from well 15 was a calcium-sodium-magnesium bicarbonate type with a dissolved solids concentration of 558 mg/L (fig. 42). From 1963 to 1970, the dissolved solids concentration increased to 758 mg/L (fig. 42). Since 1986, dissolved solids concentrations have varied from 1071 mg/L in 1989 and to 950 mg/L in 1993. The major constituent concentrations to increase have been sodium (67 to 170 mg/L) and sulfate (96 to 170 mg/L). The slight increase in mineralization appears to be caused by heavy use coupled with several years of reduced recharge.

Well 16

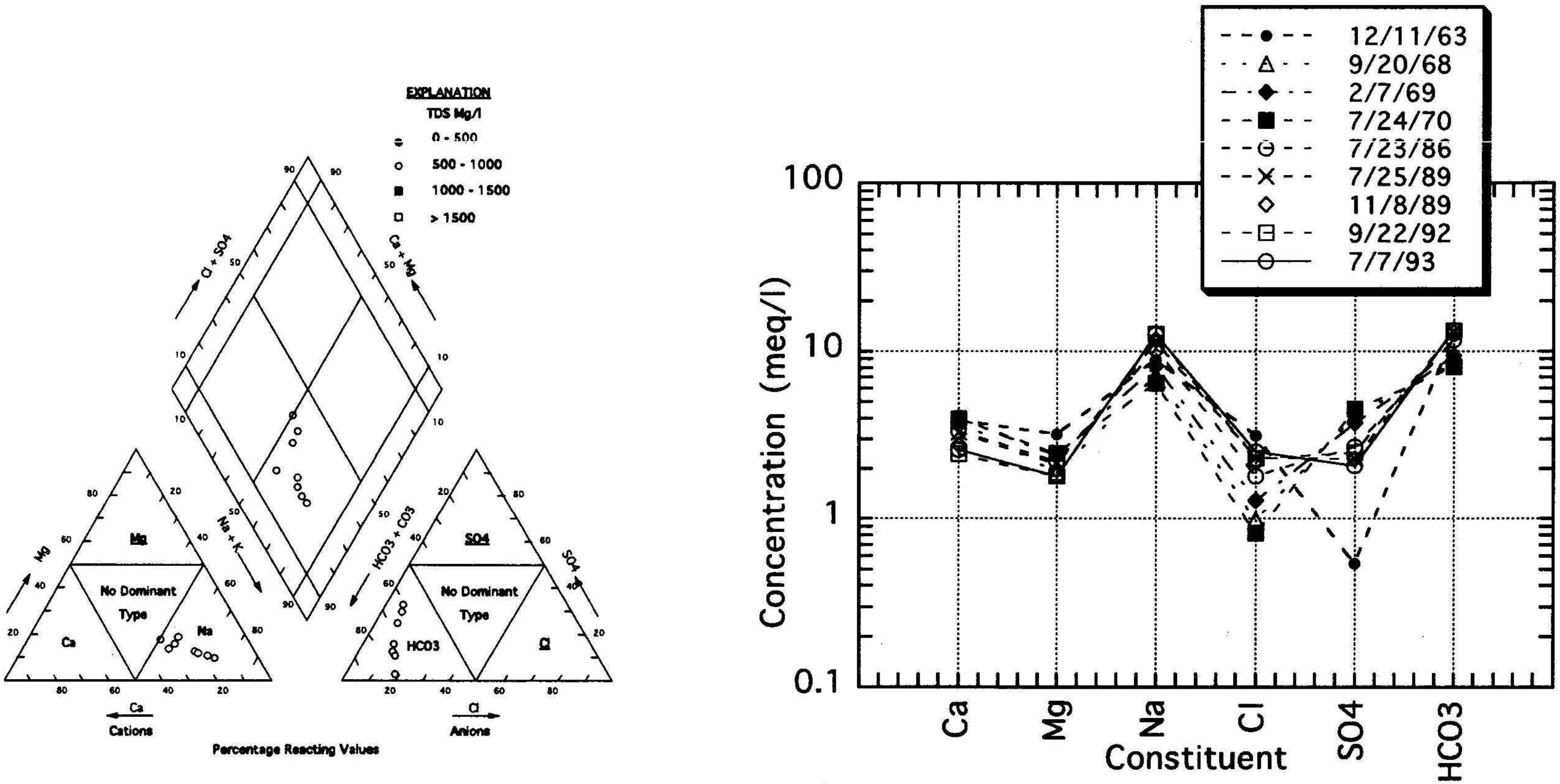


FIGURE 41. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 16

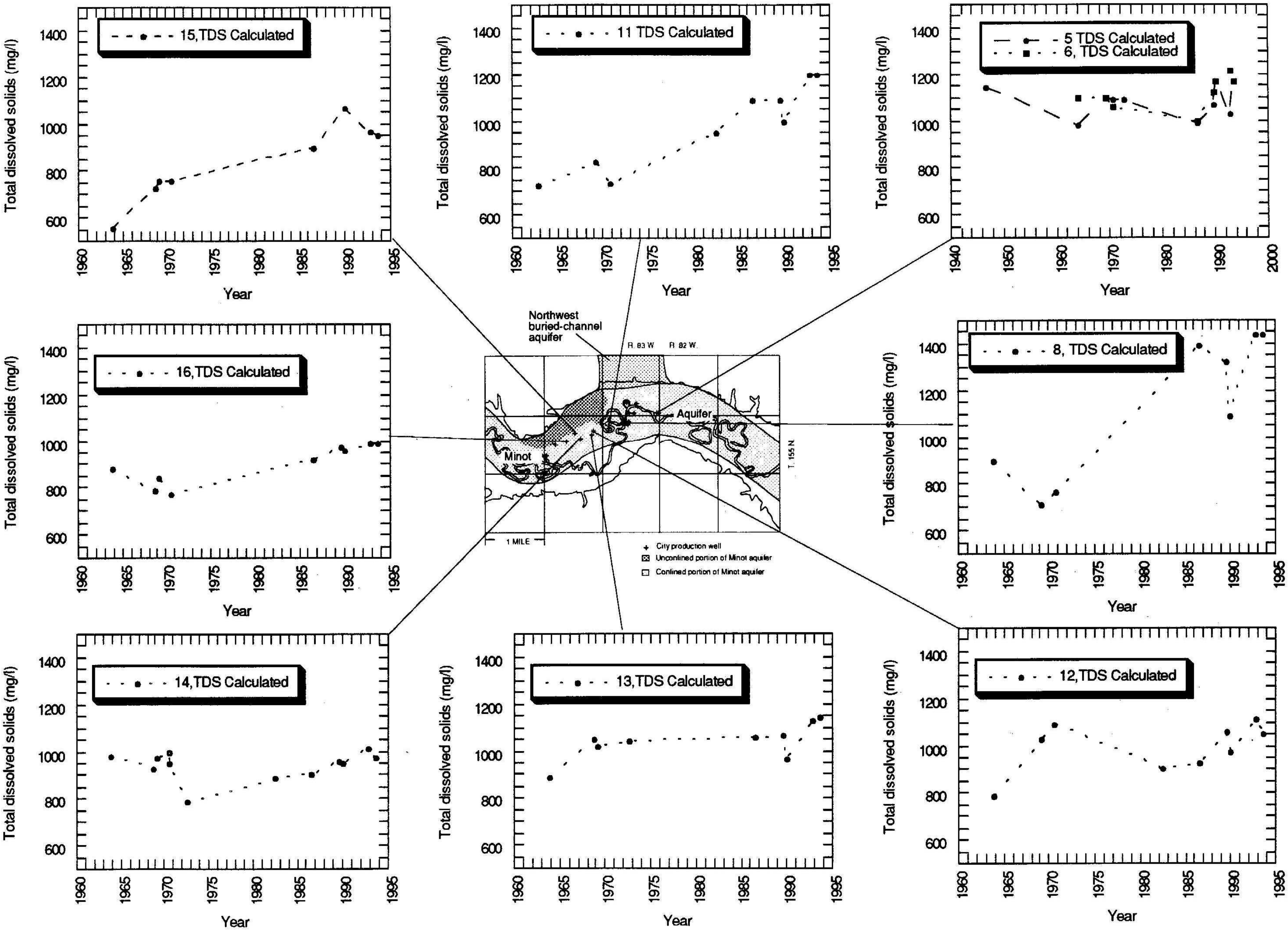
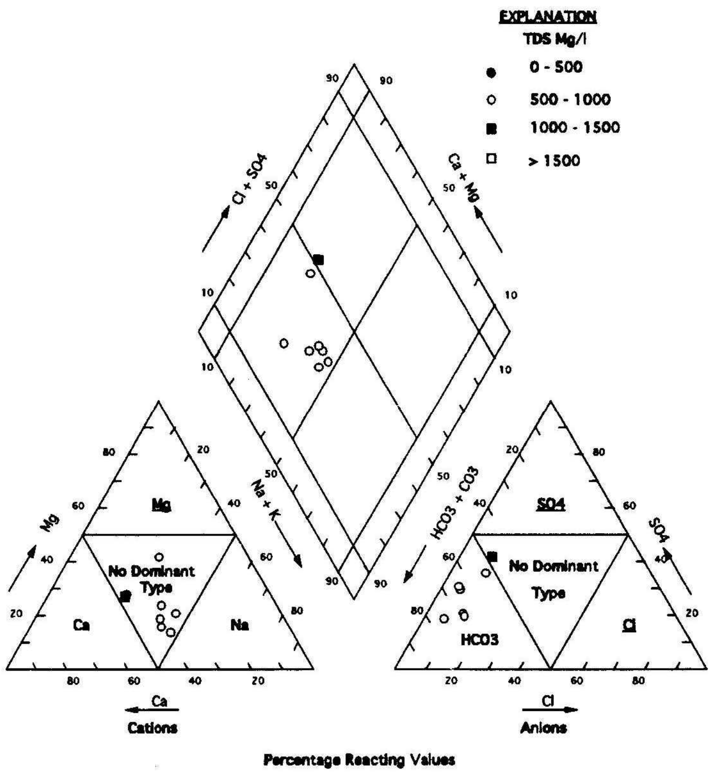


FIGURE 42 . VARIATIONS IN DISSOLVED SOLIDS CONCENTRATIONS OF WATER PUMPED FROM PRODUCTION WELLS IN THE MINOT AQUIFER

WELL 15



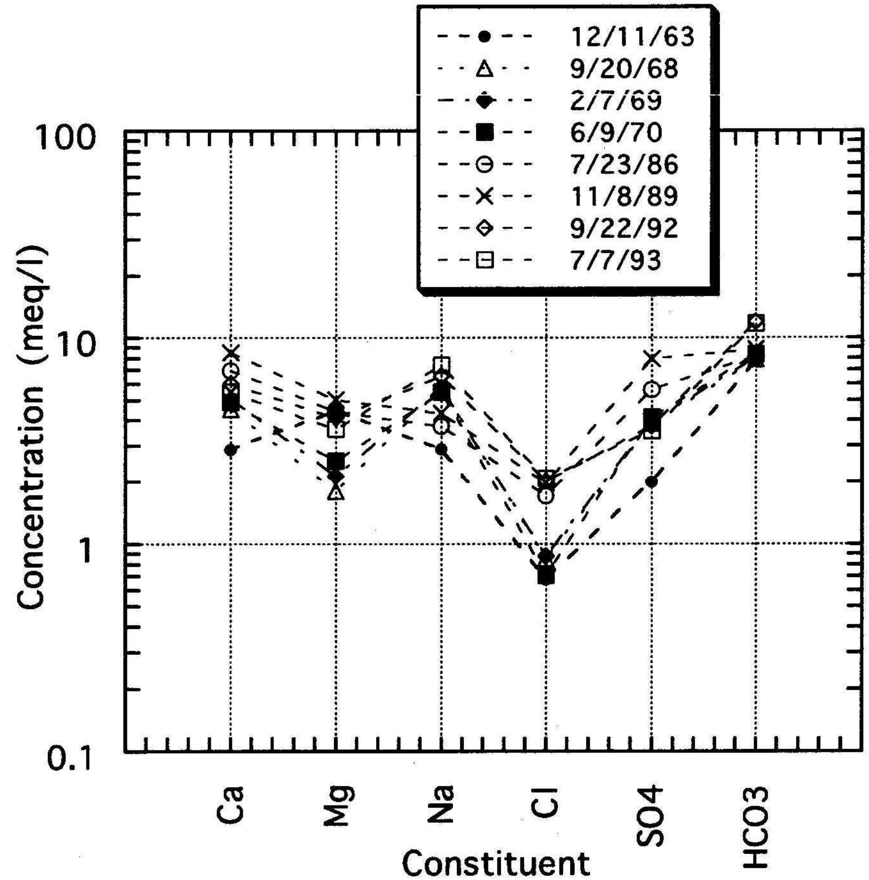


FIGURE 43. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 15

Well 14

The quality of water from production well 14 has remained relatively stable over the past 30 years of pumping(figs. 42 and 44). In 1963, the water was a sodium-bicarbonate type water with a dissolved solids concentration of 982 mg/L (fig. 42). Total dissolved solids concentrations have fluctuated from a low of 787 mg/L in 1982 to a high of 1010 mg/L in 1992 (fig. 42). It appears that well 14 is located such that a mix of good quality from the west and north balances with poorer water from the east resulting in a rather stable type (fig. 16). In fact, production wells 12 and 13 (east of well 14) may be intercepting the poorer water from the east, preventing a large increase in dissolved solids concentration in water pumped from well 14.

Well 13

Water from well 13, in 1963, was a sodium-bicarbonate type water with a total dissolved solids concentration of 885 mg/L (figs. 42 and 45). In 1993, the water was still a sodium-bicarbonate type water, however, many of the chemical constituents have increased in concentration (fig. 45). Over the past 30 years, sodium concentrations have risen from 265 mg/L in 1963 to 360 mg/L in 1993. Chloride concentrations have decreased slightly (102 to 87 mg/L). In 1993, the dissolved solids concentration was 1140 mg/L for an increase of 255 mg/L over the 1963 value (fig. 42). The increased mineralization is probably due to poorer quality water moving to well 13 from the east and south (fig. 16).

Well 12

Water from well 12 has fluctuated between a distinct sodium-bicarbonate type water to a calcium-sodium bicarbonate type water (fig. 46). Dissolved solids concentration in 1963 was 788 mg/L with a variation between 900 and 1100 mg/L since 1969 (fig. 42). Since 1988, increased pumping and minimal recharge have resulted in a steady increase in the mineralization of water pumped from well 12. The increased mineralization is probably due to poorer quality moving to well 12 from the east and south (fig. 16).

Well 14

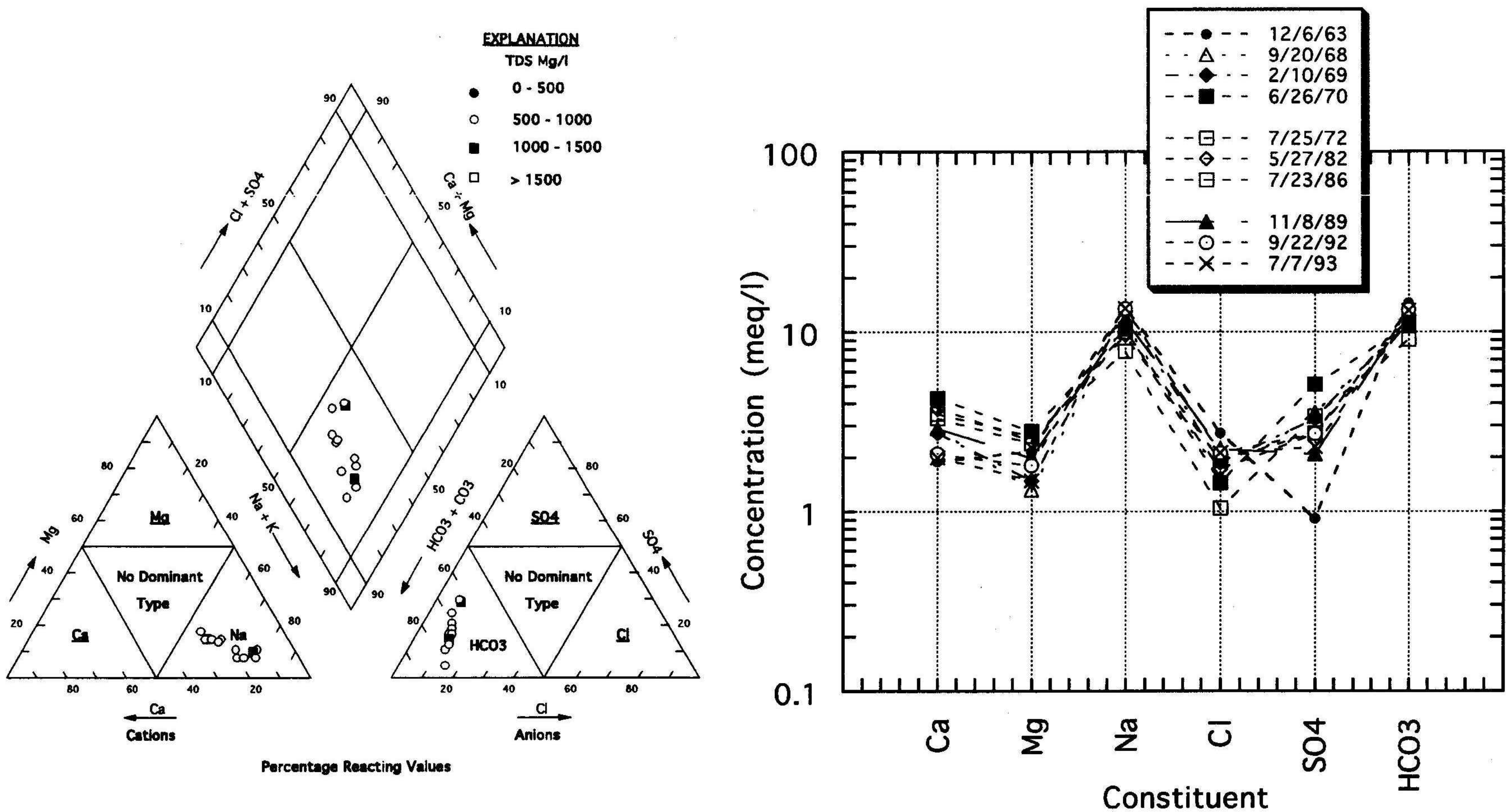


FIGURE 44. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 14

WELL 13

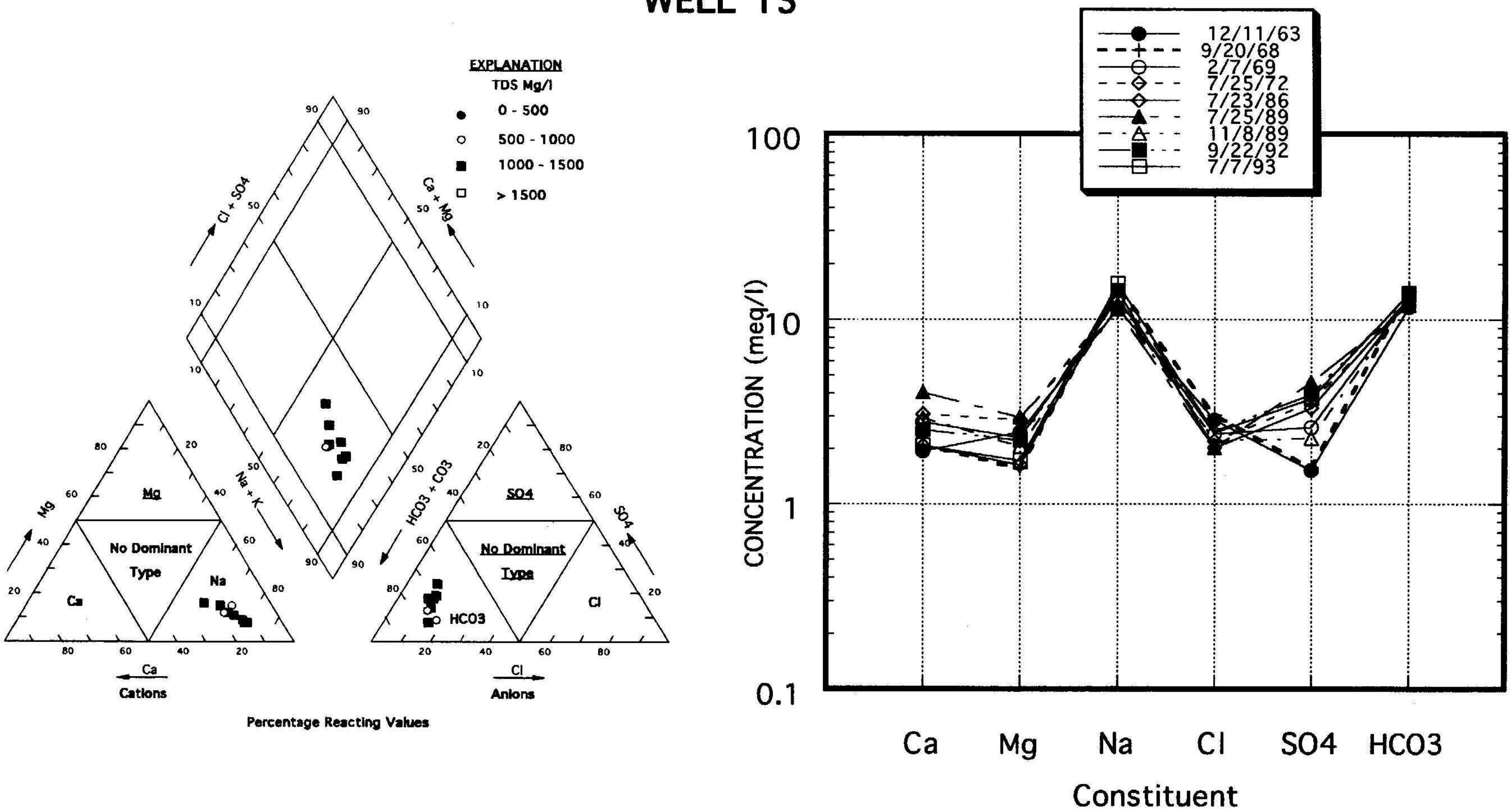


FIGURE 45. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 13

WELL 12

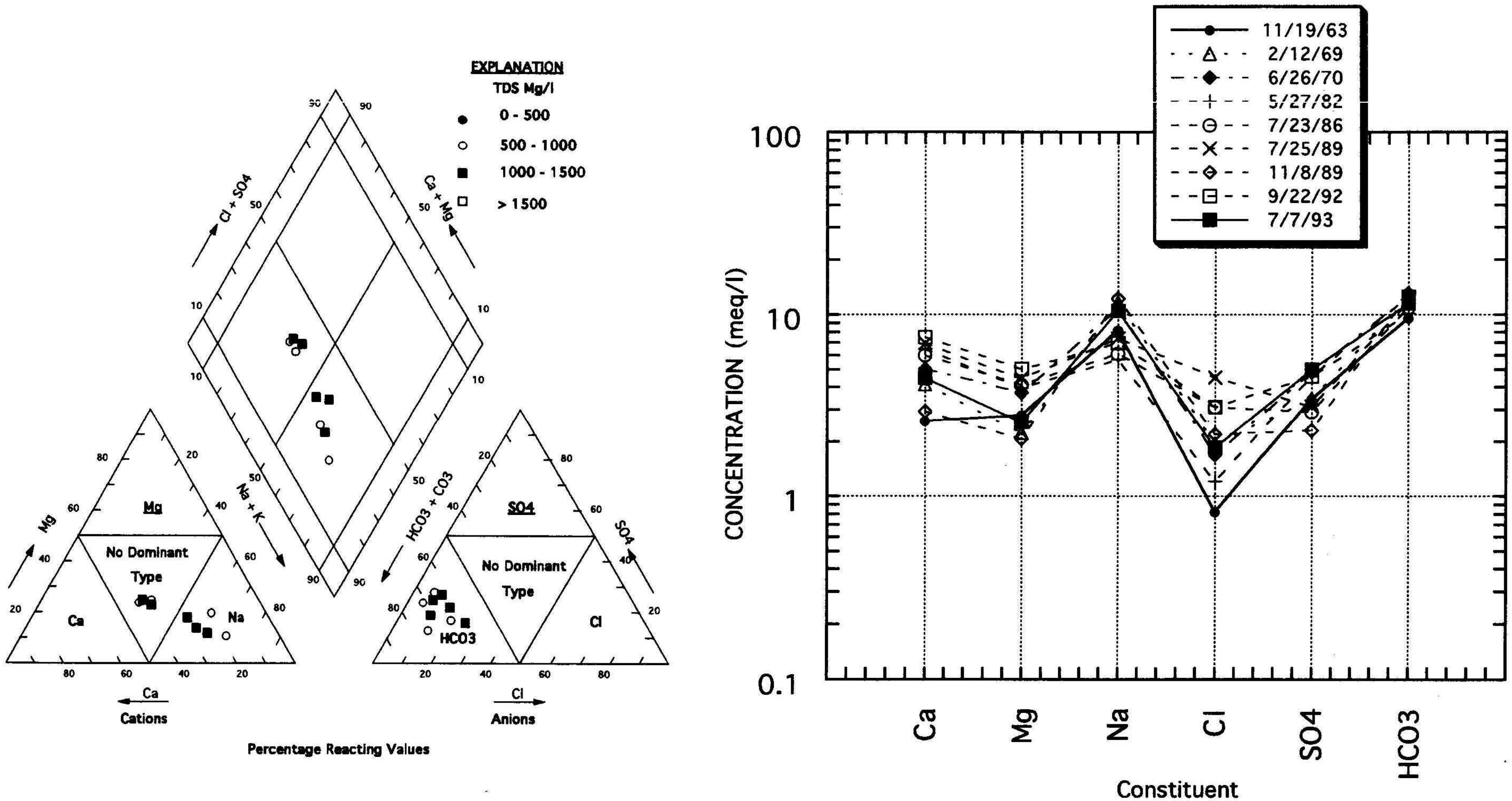


FIGURE 46. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 12

Well 11

Water from well 11 has experienced the largest overall change in water quality of any of the water from the active production wells (figs. 42 and 47). The water has evolved from a calcium-sodium bicarbonate type water in 1963 to a sodium bicarbonate water in 1993 (fig. 47). Dissolved solids concentrations have increased from 722 mg/L in 1963 to 1200 mg/L in 1993 (428 mg/L, fig. 42). Increased concentrations of calcium (66 to 120 mg/L), magnesium (26 to 42 mg/L), sodium (235 to 370 mg/L), chloride (81 to 340 mg/L), sulfate (96 to 120 mg/L) and bicarbonate (717 to 842 mg/L) concentrations have been detected. Increased mineralization is again due to increased pumping coupled with the lack of recharge in the area. In addition, well 11 is flanked by large capacity wells to the east and west. This means that a large portion of the good quality water that would have moved from the west is now being intercepted by wells 12, 13, 14, 15 and 16. Ground water from the Northwest buried-channel aquifer and the eastern confined portion of Minot aquifer appears to be moving towards well 11 and causing increased mineralization (fig. 16). The large increase in chloride concentrations (29 to 190 mg/L) suggests that a portion of the water is being derived from the chloride rich Fort Union Formation (which underlies the area) or from the Northwest buried-channel aquifer.

Wells 5 and 6

Wells 5 and 6 are only 300 feet apart and thus both reflect similar changes in water quality with time. Both wells are completed in the confined portion of the Minot aquifer. Water sampled and analyzed from well 5 in 1946 (well completed, 1946) was a sodium bicarbonate type water with a dissolved solids concentration of 1147 mg/L (fig. 42).

Since 1946, water from well 5 has remained a sodium bicarbonate type (fig. 48). Since 1963, water being pumped from wells 5 and 6 has, however, experienced minor increases in dissolved solids concentrations (well 5, 980 to 1170 mg/L; well 6, 1100 to 1170 mg/L, figs. 42, 48 and 49). It appears that more saline water from the Northwest buried-channel aquifer is moving into this portion of the Minot aquifer and causing an overall increase in dissolved solids concentration (fig. 16). Water from the Minot aquifer east of wells 5 and 6 is however keeping the water pumped from wells 5 and 6 below the 1500 mg/L dissolved solids concentrations detected in the Northwest buried-channel aquifer.

WELL 11

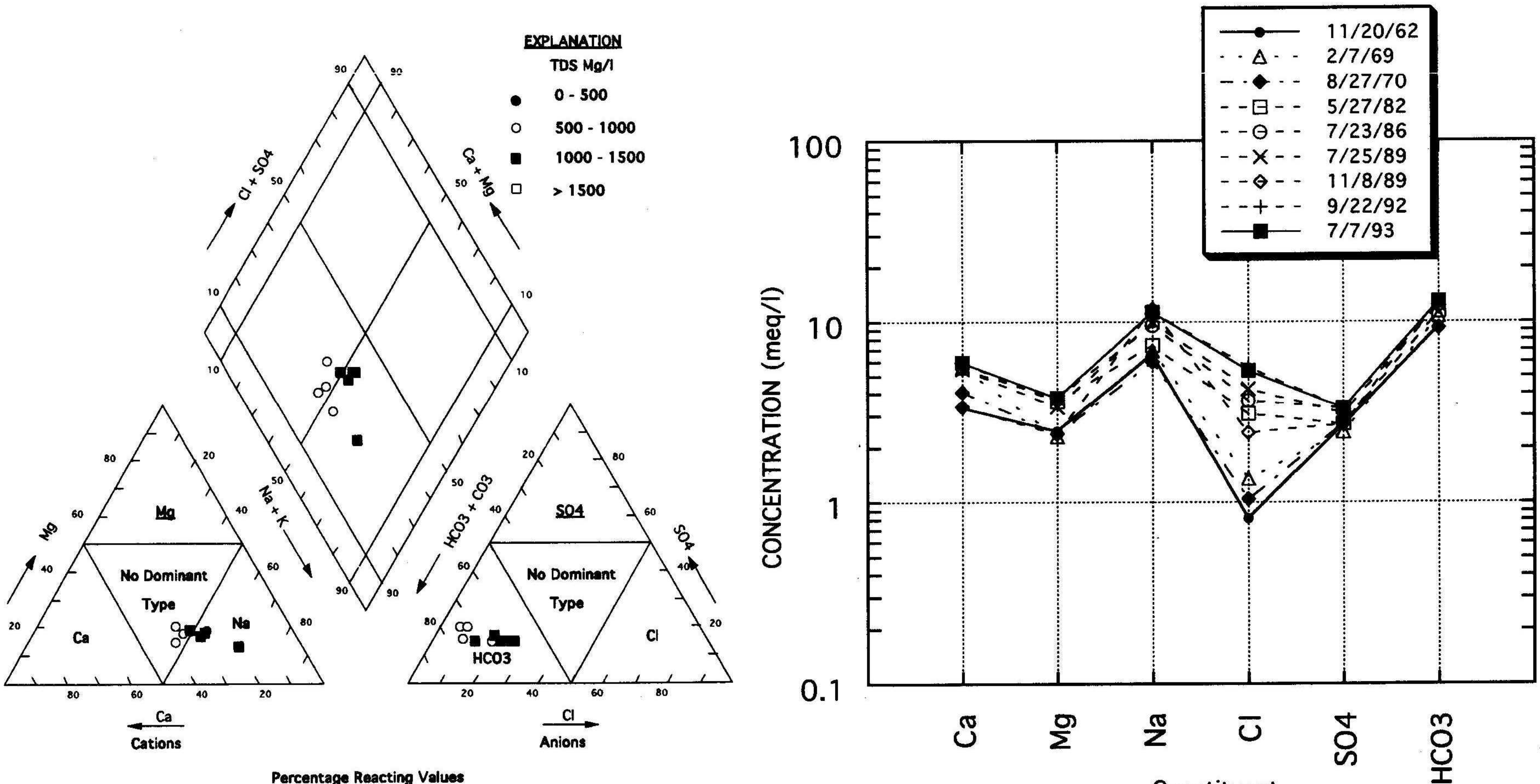
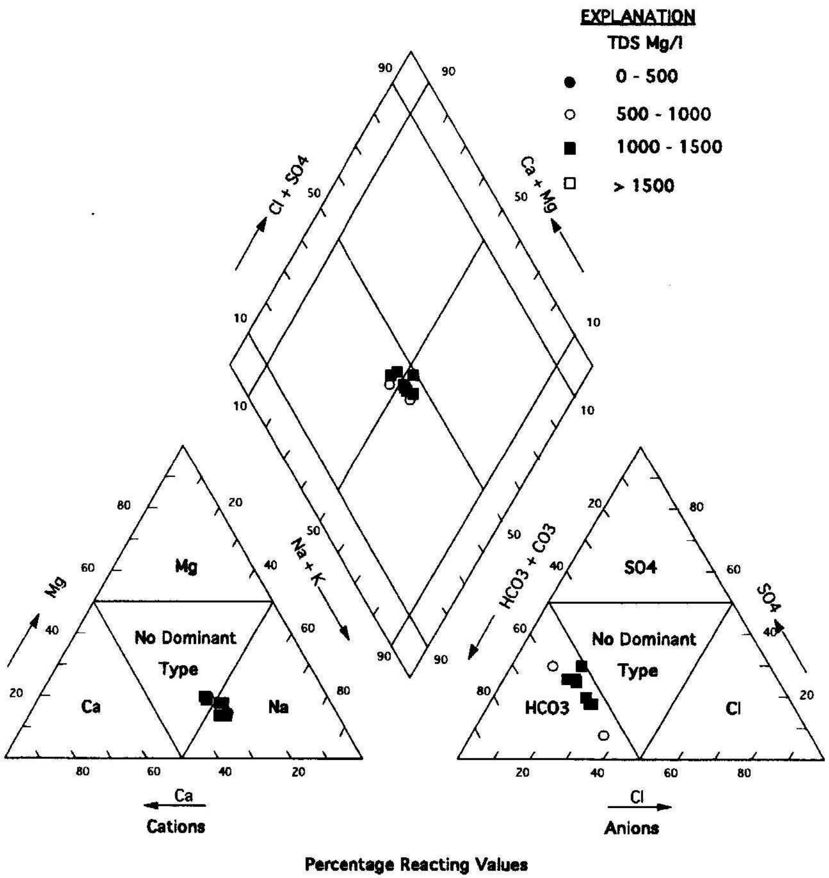


FIGURE 47. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 11

WELL 5



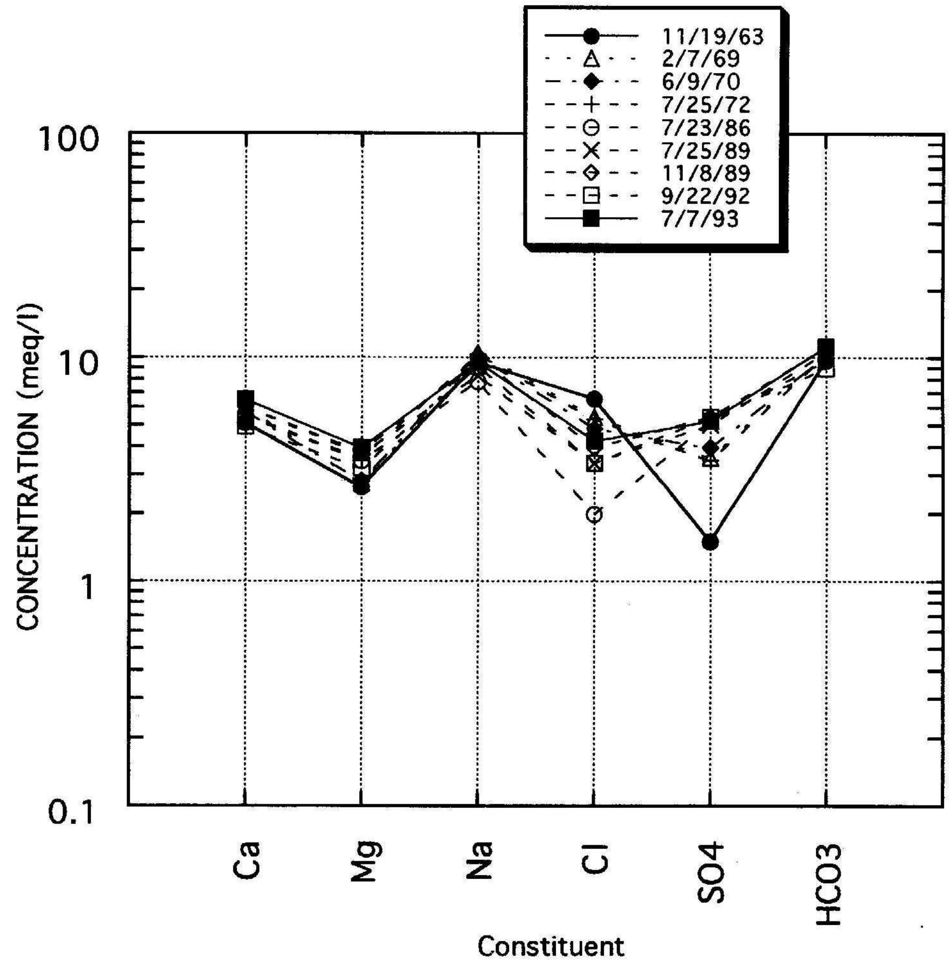


FIGURE 48. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 5

WELL 6

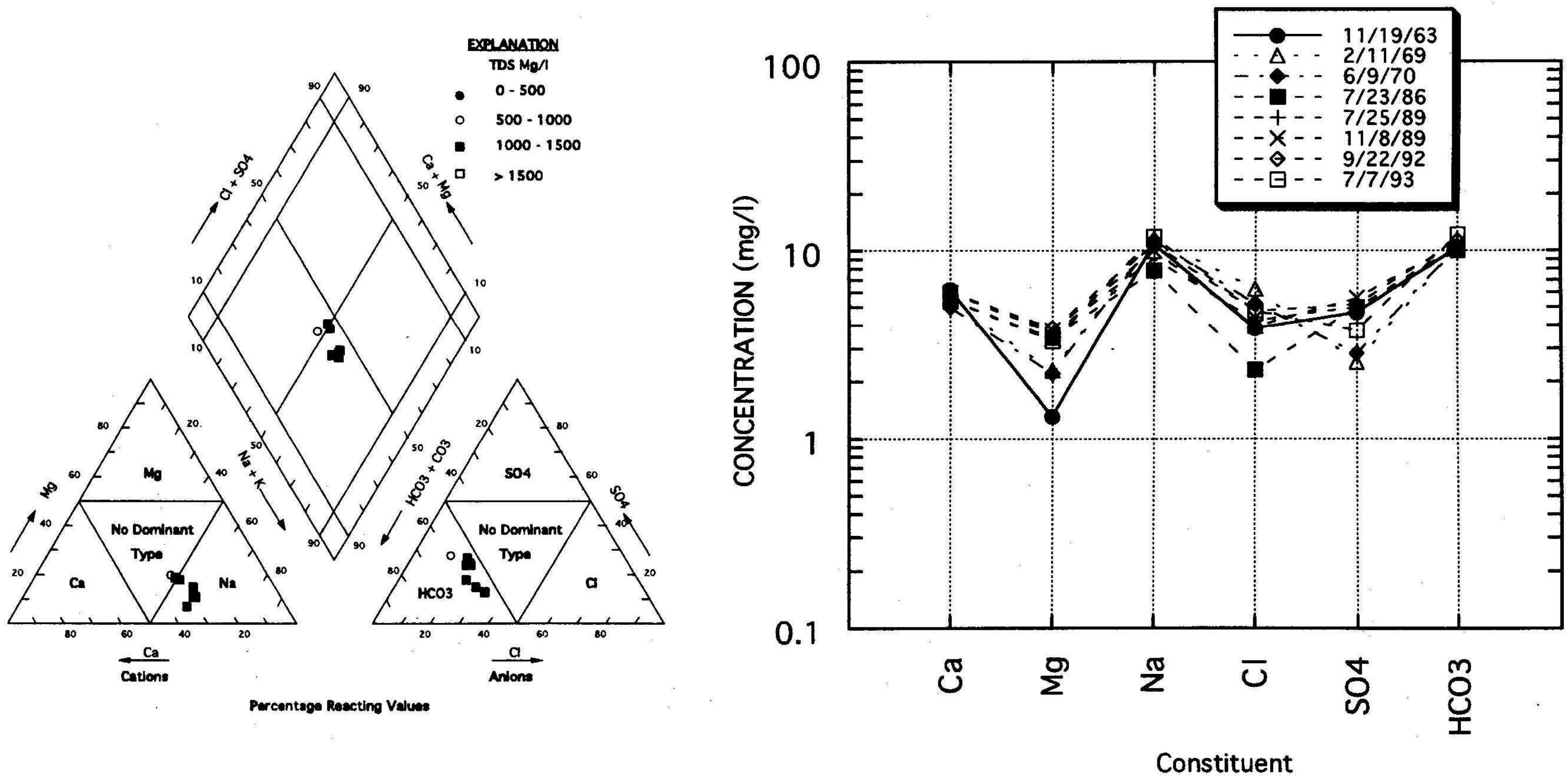


FIGURE 49. PIPER AND SCHOELLER DIAGRAMS SHOWING WATER QUALITY VARIATIONS WITH TIME, MINOT PRODUCTION WELL 6

In summary, the quality of water from the Minot aquifer (production well data) for the period 1963 to 1992 was highly variable with dissolved solids concentrations ranging from 558 to 1440 mg/L (Table 3). The 1963 through 1992 average dissolved solids concentration was about 1000 mg/L.

Table 3. Summary of Minot aquifer water quality, 1963-1992, mg/L

	Ca	Mg	Na	HCO3	SO4	Cl	Hardness (CaCO3)	Iron	TDS
Min.	38	16	67	473	26	24	170	0	558
Max.	170	61	370	882	380	340	680	5.1	1440
Average	90	34	230	693	166	104	366	2.1	1000

Production well water quality data for 1992 is summarized in table 4. In 1992, the average total dissolved solids concentration was 1121 mg/L. Overall, the 1992 average dissolved solids concentrations are higher than the 1963 through 1992 average dissolved solids concentrations. Interestingly, the quality of water in 1992 was very similar to the quality of water from the confined portion of the Minot aquifer in 1921. When viewed in the long term, the quality of water in the confined portion of the Minot aquifer has changed very little over the past 50 years.

Table 4. Summary of Minot aquifer water quality, 1992, mg/L

Well	Date sampled	Ca	Mg	Na	HCO3	SO4	Cl	Hardness (CaCO3)	Iron	TDS
5	7/7/93	110	40	270	745	180	170	440	2.3	1170
6	7/7/93	130	48	220	681	250	150	520	2.9	1170
8	7/7/93	120	42	370	842	120	340	470	3.2	1440
11	7/7/93	120	46	260	787	160	190	490	2.8	1200
12	7/7/93	90	31	240	701	240	66	350	2.4	1050
13	7/7/93	42	21	360	848	180	87	190	1.5	1140
14	7/7/93	40	18	310	801	110	75	170	1.9	976
15	7/7/93	110	44	170	718	170	74	460	0.6	953
16	7/7/93	52	22	290	818	100	90	220	4.0	990
Average		90	35	277	771	168	138	368	2.4	1121

Monitoring well water quality data from 1992 and 1993 indicate that ground water in the Minot aquifer was a sodium bicarbonate type with dissolved solids concentrations ranging from 835 mg/L at 23AAD (area of Via View Park) to 1670 mg/L at 14 CDA2 (area of old city production well 10, figs. 50 and 51).

Ground water sampled from the deep monitoring well in Hammond Park had a dissolved solids concentration of 1500 mg/L, with a sodium concentration of 520 mg/L (figs. 50 and 51). Ground water in the deeper and thicker sand and gravel of the Minot aquifer is not of as good of quality as water presently being pumped from the existing city production wells.

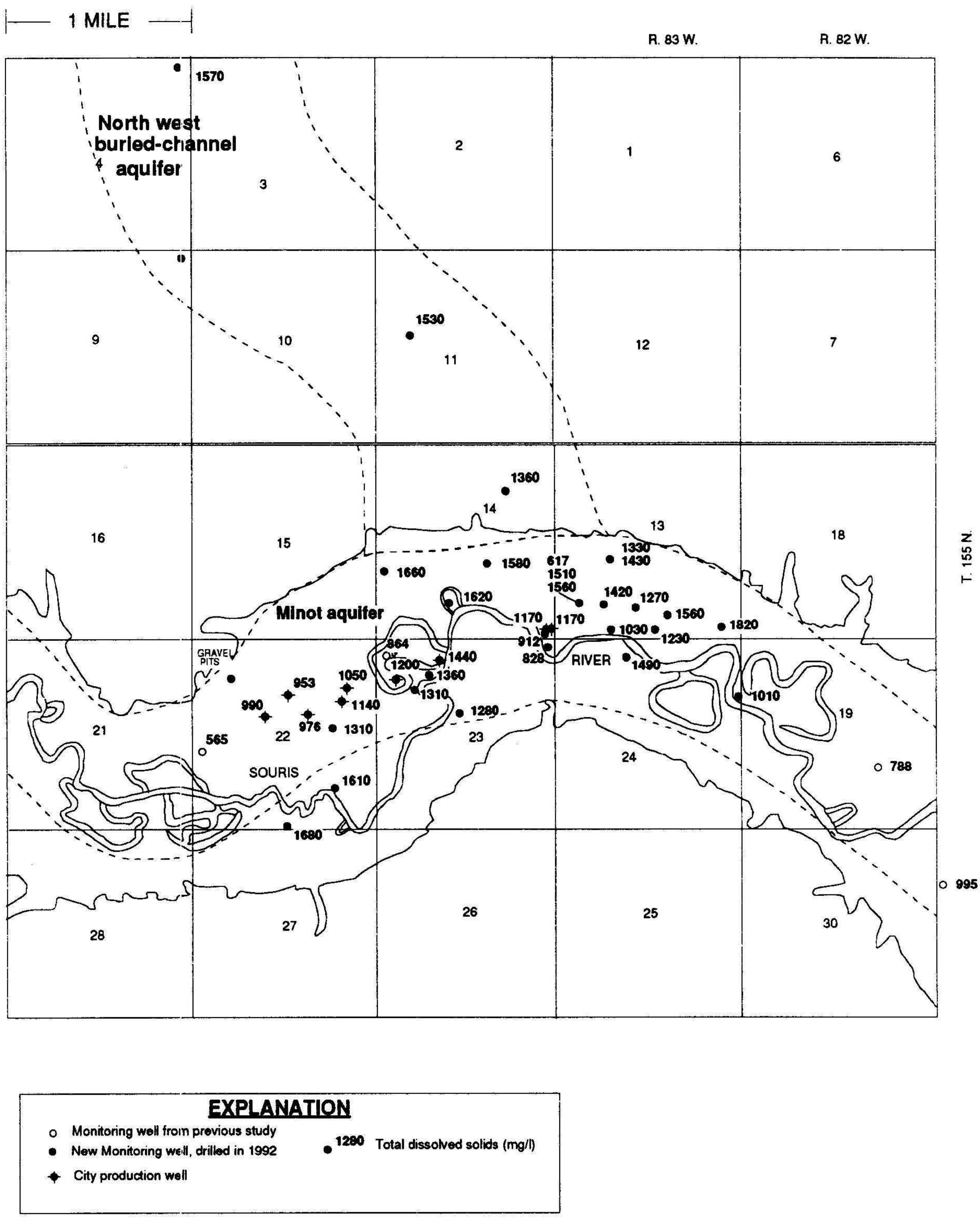
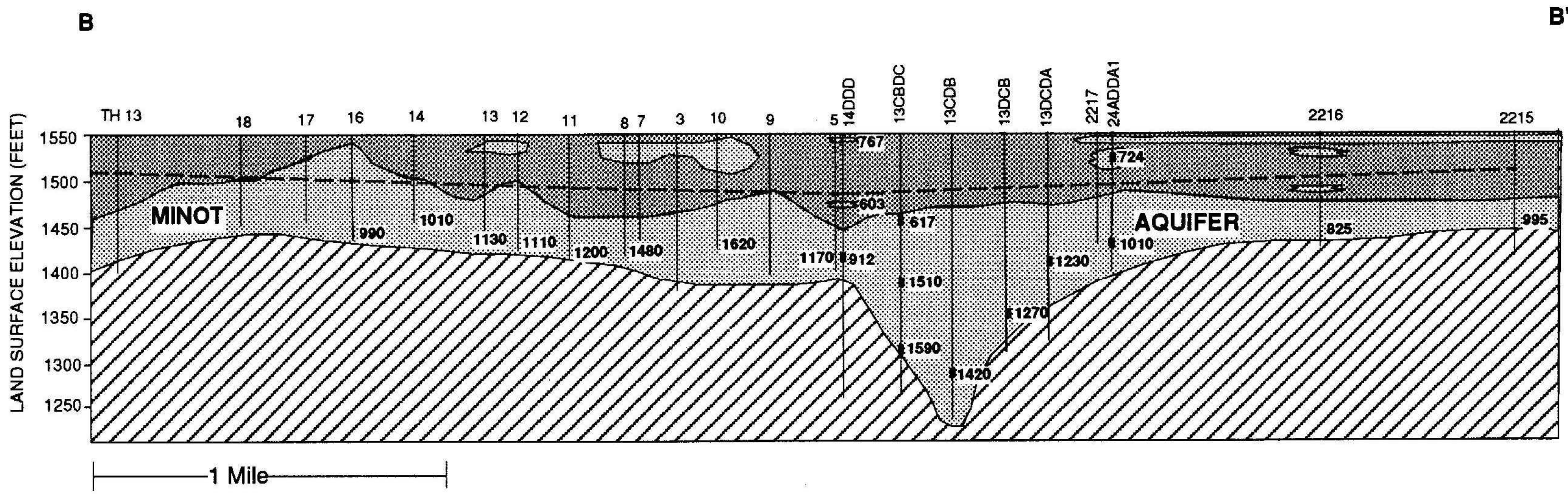


Figure 50. Map showing the areal distribution of dissolved solids concentrations in the Minot aquifer (1992 & 1993)



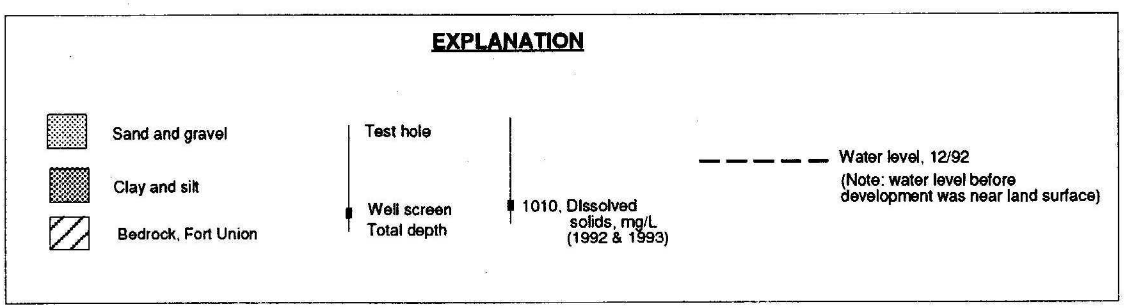


FIGURE 51. DISSOLVED SOLIDS CONCENTRATIONS AT SELECTED SITES IN THE MINOT AQUIFER ALONG HYDROGEOLOGIC SECTION B-B'

Ground-water quality from the nested piezometer constructed in the thickest section of the Minot aquifer (Hammond Park) revealed that the quality of water varies considerably with depth (fig. 51). Dissolved solids concentrations varied from 617 mg/L at the top, 1510 mg/L in the middle and 1560 mg/L near the base of the Minot aquifer (fig. 51). Ground water from the top of the Minot aquifer was similar to water in the overlying sediments of the Souris Valley aquifer system. Ground water near the base of the Minot aquifer was similar in quality to ground water in the underlying Fort Union Formation (fig. 37).

CONCEPTUAL MODEL OF GROUND-WATER FLOW

Prior to development, ground water in the Minot aquifer was in a state of dynamic equilibrium; that is, the amount of recharge to the ground-water flow system was equal to the amount of discharge from the ground-water flow system. Recharge to the natural ground-water flow system was by direct infiltration of precipitation, inflow of water from bedrock and glacial drift sediments and infiltration from the Souris River. Discharge from the natural ground-water flow system was by evapotranspiration, seepage to the Souris River, and as underflow to adjacent areas. Because the Souris River was the low point of the ground-water flow system, it represented the regional discharge area. During low river stage and dry conditions, ground water in the area before development moved towards the Souris River Valley and discharged as base flow to the river or as evapotranspiration. During high river stage, (esp. overbank flooding), the water level in the Souris River would be higher than the water level in the Minot aquifer and ground-water flow would be downward into the Minot aquifer.

Pumping by the city of Minot now represents the largest discharge of water from the Minot aquifer. Because the water level has declined significantly in the Minot aquifer, losses by evapotranspiration and seepage to the Souris River are negligible. In fact, the lowered ground-water level results in a condition where the Souris River always has a higher water level than the Minot aquifer creating the potential for continual downward movement from the river to the aquifer. Ground-water flow in the area is now towards the pumping wells to replace the water being discharged. Based on the available data it appears that a sustained yield of approximately 2 mg/d can be pumped from the Minot aquifer. Long term climate trends (either dry or wet) would, of course, alter the sustained yield potential of the Minot aquifer.

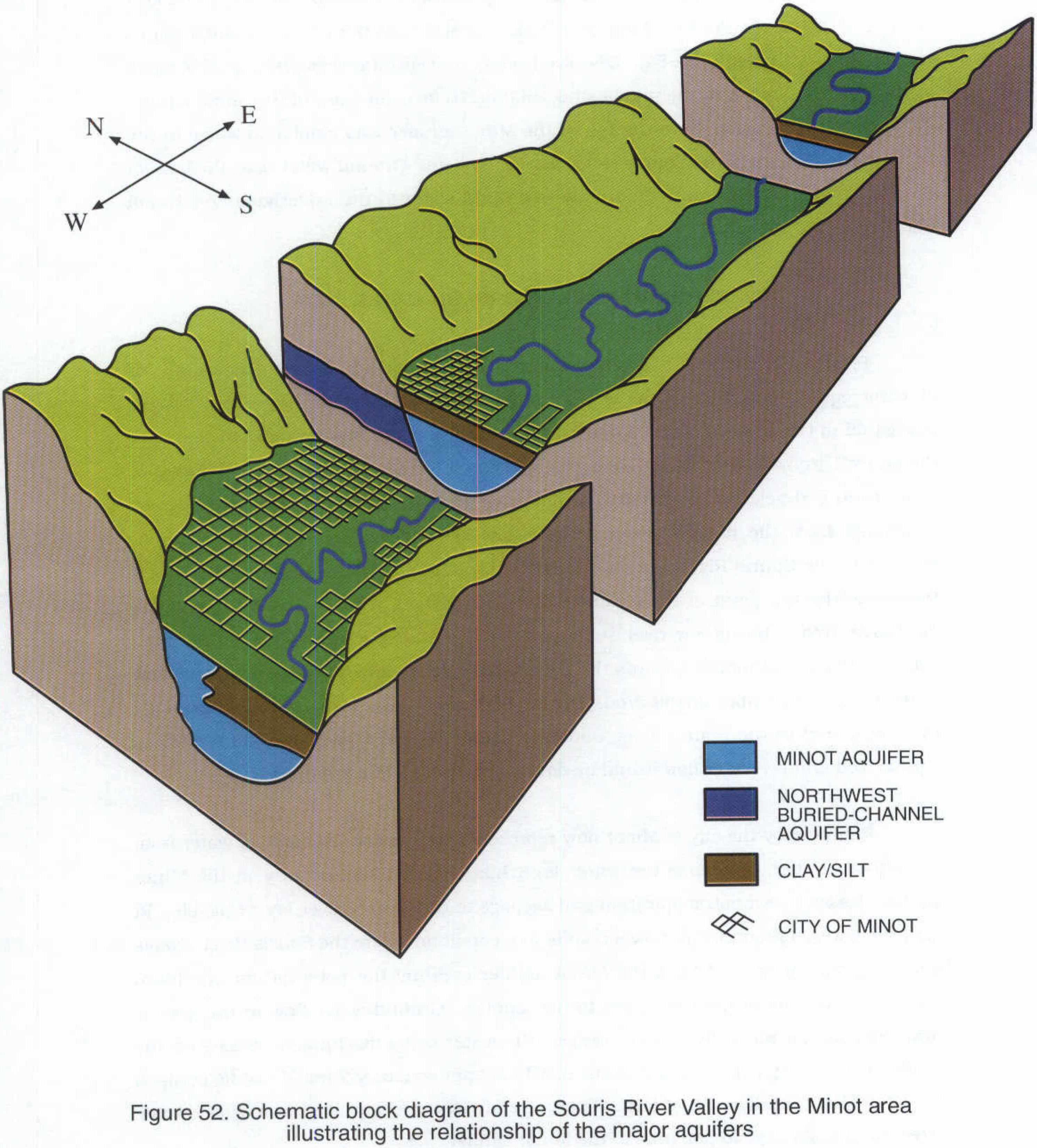


Figure 52. Schematic block diagram of the Souris River Valley in the Minot area illustrating the relationship of the major aquifers

SUMMARY AND CONCLUSIONS

The Minot aquifer consists of saturated sand and gravel deposits of the Souris Valley aquifer system that occur in the Souris River Valley in the vicinity of Minot, North Dakota. Saturated thickness of the Minot aquifer varies from 50 feet in the area of city wells 17 and 18, 50 to 100 feet in Oak Park, 40 feet near city wells 5 and 6, 200 + feet in Hammond Park, 100 feet in Roosevelt Park and 35 feet thick near the State Fair Grounds. The Minot aquifer in the vicinity of Minot is 0.5 to 1 mile wide, 6 to 7 miles long and covers approximately 6 to 7 square miles. In general, the Minot aquifer is overlain by 50 to 100 feet of alluvial clay and silt. The Minot aquifer is however, unconfined from Oak Park to the large gravel pits in western Minot. The transmissivity of the Minot aquifer ranges from 163,000 to 259,000 gpd/ft. The coefficient of storage has been estimated to range from 7×10^{-5} in the confined portion of the Minot aquifer to 0.10 in the unconfined portion of the Minot aquifer. Well yields from the Minot aquifer range from 2 to 5 gpm from small diameter domestic wells to 950 gpm from well 14 of the Minot well field. Presently the city of Minot has nine large capacity well which pump ground water from the Minot aquifer. Long term average use from the Minot aquifer has been 1.4 mg/d (1916-1992). During the drought of 1988, an average of 4.2 mg/d was pumped from the Minot aquifer. Maximum monthly use was in June of 1988, when 6.5 mg/d was pumped from the Minot aquifer. Average water use from the Minot aquifer since 1976 has been 1.9 mg/d. Average water use in 1992 was 1.45 mg/d.

The quality of water from the Minot aquifer in 1992 was highly variable with dissolved solids concentrations ranging from 835 to 1670 mg/L. Average dissolved solids concentration in the city production wells was 1121 mg/L (1992). In general, water in the Minot aquifer was lowest in total dissolved concentrations in the western unconfined portion of the aquifer. Dissolved solids concentrations increased in the eastern confined portion of the Minot aquifer.

In the Souris River floodplain, the Minot aquifer is overlain by sediments of the Souris Valley aquifer system. The Souris Valley aquifer system varies from an interbedded sequence of clay, silt, sand and gravel to one continuous section of sand and gravel. Thus there are areas where the Souris Valley aquifer system and the Minot aquifer are a continuous hydrologic unit. In addition, sediments of the Souris Valley aquifer system both upstream and downstream of the Minot aquifer are hydraulically connected to the Minot aquifer. Pumpage from the Minot aquifer portion of the Souris Valley aquifer system causes water both upstream and downstream of the Minot aquifer to move toward the pumping centers to replace a portion of the water being pumped from the Minot aquifer.

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 Minot aquifer. Water quality data however indicates that there is some movement of ground water from the Fort Union Formation up into the Minot aquifer.

In the Minot area, a deep bedrock valley trends from northwest to southeast and crosses beneath the Souris River Valley. The bedrock valley varies from 1 to 2 miles wide. It is within portions of this bedrock valley that sand and gravel of the Northwest buried-channel and South Hill aquifers were deposited. Further to the southeast, the Sundre aquifer system occupies portions of the same bedrock valley as the Northwest buried-channel and South Hill aquifers.

The Northwest buried-channel aquifer consists of buried outwash of sand and gravel that extends northwestward from the city of Minot. The aquifer is 1 to 1.5 miles wide and is at least 4 miles long. The Northwest buried-channel aquifer ranges from less than 50 feet thick northwest of the city of Minot to over 100 feet just southwest of the airport. In general, the Northwest buried-channel aquifer is overlain by 250 to 350 feet of glacial till and clay. The Northwest buried-channel aquifer merges with the Minot aquifer in the vicinity of Minot State University.

Ground water in the Northwest buried-channel aquifer occurs under confined conditions. Depth to water in this deeply buried channel aquifer is generally in excess of 200 feet. Water levels in the Northwest buried-channel aquifer respond to pumping in the Minot aquifer confirming the hydraulic connection between the two aquifers. Ground-water movement in the Northwest buried-channel aquifer is towards the southeast with discharge into the Minot aquifer. An estimated flow of 250 acre-feet per year (200,000 gallons per day) is moving from the Northwest buried-channel aquifer into the Minot aquifer.

Prior to development, ground water in the Minot aquifer was in a state of dynamic equilibrium; that is, the amount of recharge to the ground-water flow system was equal to the amount of discharge from the ground-water flow system. Recharge to the natural ground-water flow system was by direct infiltration of precipitation, inflow of water from bedrock and glacial drift sediments and infiltration from the Souris River. Discharge from the natural ground-water flow system was by evapotranspiration, seepage to the Souris River, and as underflow to adjacent areas. Because the Souris River was the low point of the ground-water flow system, it represented the regional discharge area. During low river stage and dry conditions, ground water in the area before development moved towards the Souris River Valley and discharged as base flow in the Souris River or as evapotranspiration. Water levels in the Minot aquifer before development were above the height to the river. During high river stage, (esp. overbank flooding), the water level in the Souris River would be higher than the water level in the Minot aquifer and ground-water flow would be downward into the Minot aquifer.

Pumping by the city of Minot now represents the largest discharge of water from the Minot aquifer. Depth to water as a result of pumping is currently 55 to 65 feet below land surface. Because of the water level decline in the Minot aquifer, losses by evapotranspiration and seepage to the Souris River are negligible. In fact, the lowered ground-water level results in a condition where the Souris River always has a higher water level than the Minot aquifer creating the potential for continual downward movement from the river to the aquifer. Ground-water flow in the area is now towards the pumping wells to replace the water being discharged. Based on the available data, it appears that a sustained yield of approximately 2 mg/d can be obtained from the Minot aquifer. Fluctuations in long term climate trends (either dry or wet) would, of course, alter the sustained yield potential of the Minot aquifer.

MANAGEMENT CONSIDERATIONS

The general objective of ground-water management is to ensure the optimization of the design, operation and control of ground-water development (IAHS, 1988). Optimization of the Minot aquifer means to withdraw water at a rate which balances with the long term recharge to the system while maintaining the quality of the water pumped. Based on the available data it appears that a sustained yield of approximately 2 mg/d can be pumped from the Minot aquifer. In addition, short term yields of 3 to 4 mg/d are possible from the Minot aquifer.

Several areas appear favorable for the construction of new wells in the Minot aquifer. Additional wells in the Minot aquifer would not mean however that additional water would be available for use. New wells in Hammond Park and Roosevelt Park would only increase the short term peaking capacity during heavy summer use. Poorer water quality with depth at Hammond Park may, however preclude this area from development.

The deepening of existing production wells in the Minot aquifer may make better use of the available drawdown in the area. The extremely rocky base of the Minot aquifer and poorer water quality with depth, however, suggests that this alternative may not be desirable.

The Northwest buried-channel aquifer is not a viable alternative for future development because of poor water quality, limited recharge, large pump lifts and the interception of water that is already moving into the Minot aquifer. No additional water resources would be realized from tapping the Northwest buried-channel aquifer.

The South Hill aquifer because of its limited recharge, small storage capacity, deep water levels and poor water quality excludes it from future additional development.

The available data indicates that the geologic setting of the Minot aquifer is favorable for artificial recharge. In addition, previous attempts have proven that rates of as high as 4 mg/d are possible. Artificial recharge will only be possible if surplus water is available (probably Souris River) on a fairly frequent basis. Additional work will have to be done however to assess the potential of artificial recharge.

Sufficient data exists to develop a computer model of the Minot aquifer. In reality, over the past 77 years, we have been observing a large physical model of a ground-water flow system (Minot aquifer) under a variety of stresses. This observation of the Minot aquifer has allowed the determination of a sustained yield which is more "real" than any computer simulation could provide. A computer model of the Minot aquifer would probably not increase our understanding of the sustained yield capabilities of the system. A model could be used however to evaluate the sources of recharge i.e. Souris River, bedrock, and Northwest buried-channel thereby increasing our understanding of the system. The model could also be used to evaluate the potential changing conditions of flow in the Souris River and its affect on water availability in the Minot area. A computer model could also be used to investigate the potential for artificial recharge to the system.

RECOMMENDATIONS

1) Continue to measure water levels in the area on at least a monthly basis to assess the impacts of pumping, river stage fluctuations and precipitation. In addition the city should continue to maintain the continuous water level recorder that is in well 8.

2) Continue to sample and analyze water from the Minot aquifer production wells and monitoring wells to monitor changes in water quality with time.

3) Recharge from the Souris River is very important to the long term water yielding capability of the Minot aquifer. Because of this importance, low flow measurements through Minot should be considered to determine if losses in stream flow can be detected.

4) Due to the hydraulic connection between the Souris River, Souris Valley aquifer system and Minot aquifer, land use practices on the floodplain should be closely monitored and appropriate wellhead protection ordinances and restrictions be adopted. For the Minot aquifer this takes on even more significance because the urban center overlies a major portion of the Minot aquifer.

5) Flow in the Souris River is also essential for the city of Minot because of direct use from the river and as a potential source of artificial recharge water. Thus, there is a need to evaluate what the flow potential is for the Souris River given the effects of dams in Canada.

6) The geology of the Minot aquifer is favorable for artificial recharge especially in the Oak Park area and at the gravel pits west of Minot. Additional investigation would be needed however to assess the artificial recharge potential. Several shallow holes would be needed in the Oak Park loop of the Souris River channel to determine thickness of steam bed. This work could be followed up with a pilot study of recharging the aquifer in the area. The potential for artificial recharge of the Minot aquifer should also take into consideration the urban setting in which artificial recharge (i.e. settling basins etc.) would need to be conducted. In addition, areas of known surface contamination would need to be considered before artificial recharge is done. A determination of the availability of surplus water also needs to be considered in evaluating artificial recharge.

7) The City of Minot production wells in the Minot aquifer range in age from 30 to almost 50 years old. Wells of this vintage are likely to become less efficient with time. Controlled specific capacity tests should be conducted on the wells to compare with earlier specific capacity tests. If the wells are shown to be less efficient than they were in the past, the wells screens should be cleaned and the wells redeveloped. In addition, down hole cameras could be run in the wells to determine the condition of the well screens.

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