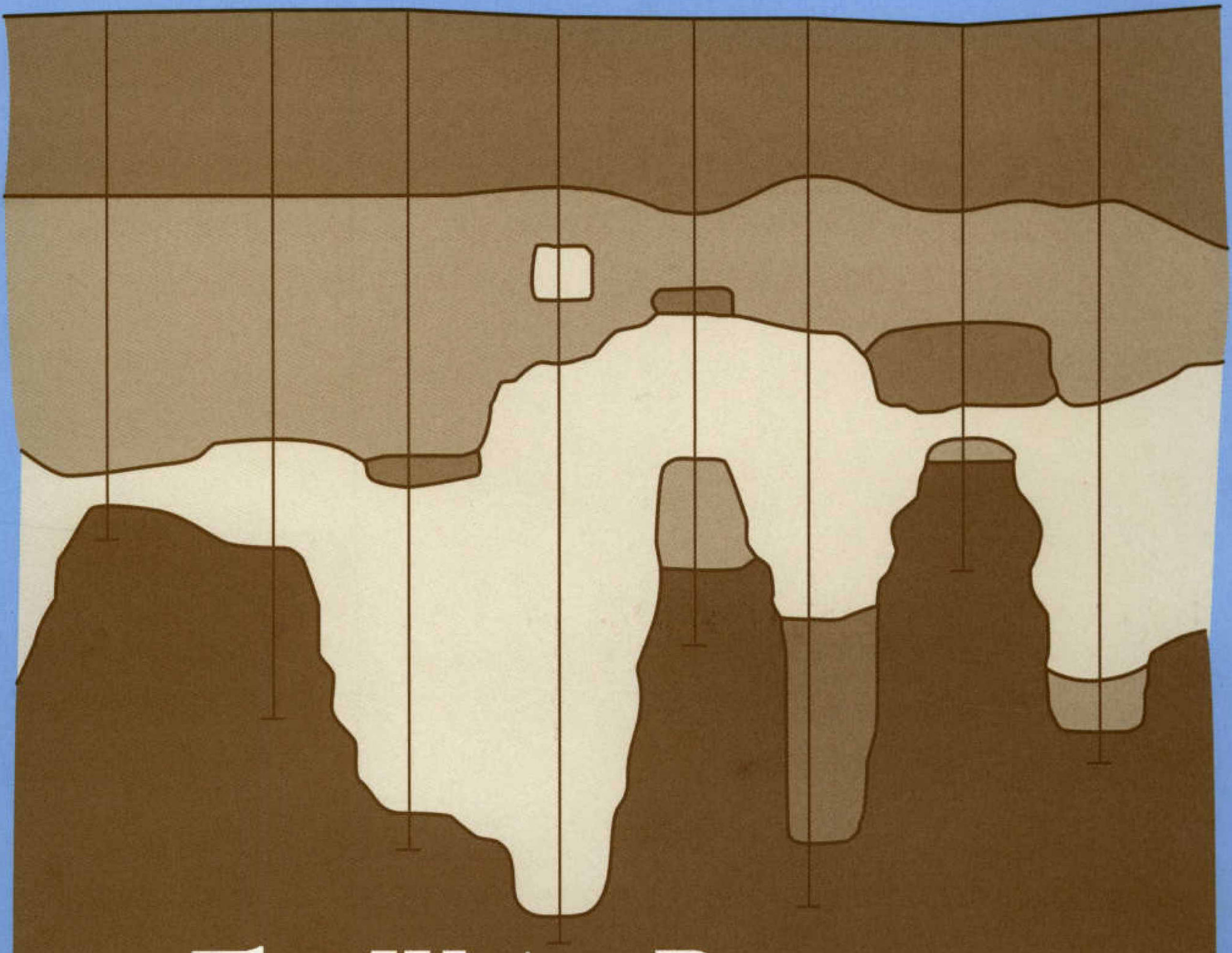

The Water Resource Characteristics of the West Fargo Aquifer System

By David P. Ripley
North Dakota State Water Commission

North Dakota Ground-Water Studies Number 106 - Part II
2000

THE WATER RESOURCE CHARACTERISTICS OF THE WEST FARGO AQUIFER SYSTEM, CASS and RICHLAND COUNTIES, NORTH DAKOTA

By

David P. Ripley

North Dakota State Water Commission

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INTRODUCTION

STATEMENT OF THE PROBLEM

Ground water in the Fargo/Moorhead area of the Red River Valley has been used to a significant degree as a source of water since the late 1800s. Since that time, the level of water in the aquifers in this area has continuously declined. Utilization of the West Fargo aquifer system (WFAS) has steadily increased through time as the area has grown, and the growth continues. North Dakota water users of the WFAS are concerned about the long-term viability of this water supply. As a result, the Southeast Cass Water Resource District (SCWRD) entered into an agreement with the North Dakota State Water Commission (SWC) to study the WFAS.

PURPOSE AND SCOPE

The purpose of this study was to:

1) determine how much ground water is available from the West Fargo Aquifer System; and
2) predict aquifer system response to future ground-water withdrawals.

Specific objectives of this report were to develop a conceptual model of the WFAS and a computer model of the WFAS. Aspects of the conceptual model include definition of aquifer geometry, hydraulic properties, water chemistry, water use and associated water-level response, ground-water movement, and aquitard hydraulic properties. An inventory and evaluation of existing data was made.

The evaluation of existing data provided the basis for collection of additional hydrologic data in the study area. Test holes were completed at various sites using a Failing 1250 forward mud rotary drilling rig. Lithologic logs of the test holes were made by describing drill cuttings. Piezometers were constructed at selected sites to measure water levels and collect water samples for chemical analysis.

The limits of the study area were based on one known (the WFAS general location), and one unknown (the degree of connection with Minnesota aquifers). The north, west, and south boundaries of the West Fargo aquifer system seemed to be relatively well defined as a result of earlier studies. The east boundary was less well defined. The east boundary appeared to approximately coincide with the North Dakota/Minnesota border. Additionally there seemed to be significant ground-water resources in Minnesota, and it was not clear whether there was a hydrologic connection between those resources in Minnesota and the WFAS. The study area was expanded toward the east to include the Buffalo aquifer. The study area is shown in figure 1.

During the early part of the study, the conceptual model of the WFAS evolved significantly from the initial starting conceptual model. As the study continued, the evolving conceptual model departed further and further from the vision that was the basis of the initial study design. Parts of the three major aquifer units were not entirely separate. New sub aquifers were found that connected other parts of the three major sub aquifers. More sub aquifers were found. Areas within the major aquifers were found to be poorly or indirectly connected. The result was a highly complex WFAS.

Due to the complexity of the WFAS, it was not considered practical to develop a computer model of the WFAS within the time and financial constraints of the original study. As a result, the study was scaled down to develop a conceptual hydrologic model of the WFAS and provide an estimate of existing ground-water storage and long-term yield capability of the WFAS.

LOCATION NUMBERING SYSTEM

Wells and test holes presented in this report are numbered according to a system based on the location in the public land classification of the United States Bureau of Land Management (figure 2). The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. Letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 139-049-04ADD is located in the SE 1/4 of the SE 1/4 of the NE 1/4 of Section 4, Township 139 North, Range 49 West (figure 2). Consecutive terminal numerals are added if more than one well is located in a 10-acre tract.

The wells in some areas are more accurately located. In this study each 10-acre area was further divided into 2.5-, or 0.625-, or 0.15625-acre areas (particularly in Minnesota) in the same manner described above. Thus, well 139-049-06DBADC is located in the SW 1/4 of the SE 1/4 of the NE 1/4 of the NW 1/4 of the SE 1/4 of Section 6, Township 139 North, Range 49 West.

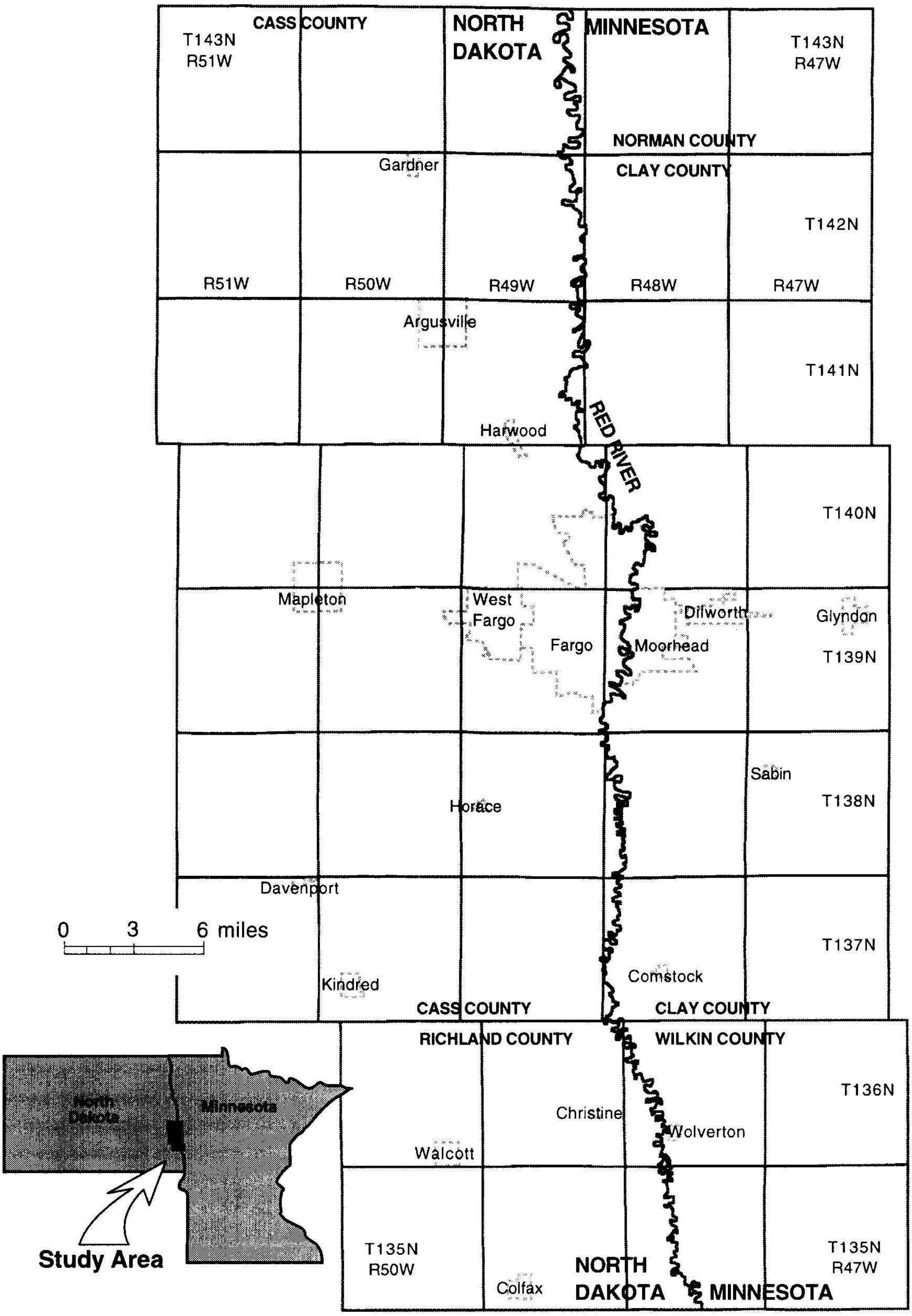


FIGURE 1. **Location of the West Fargo aquifer system study area.**

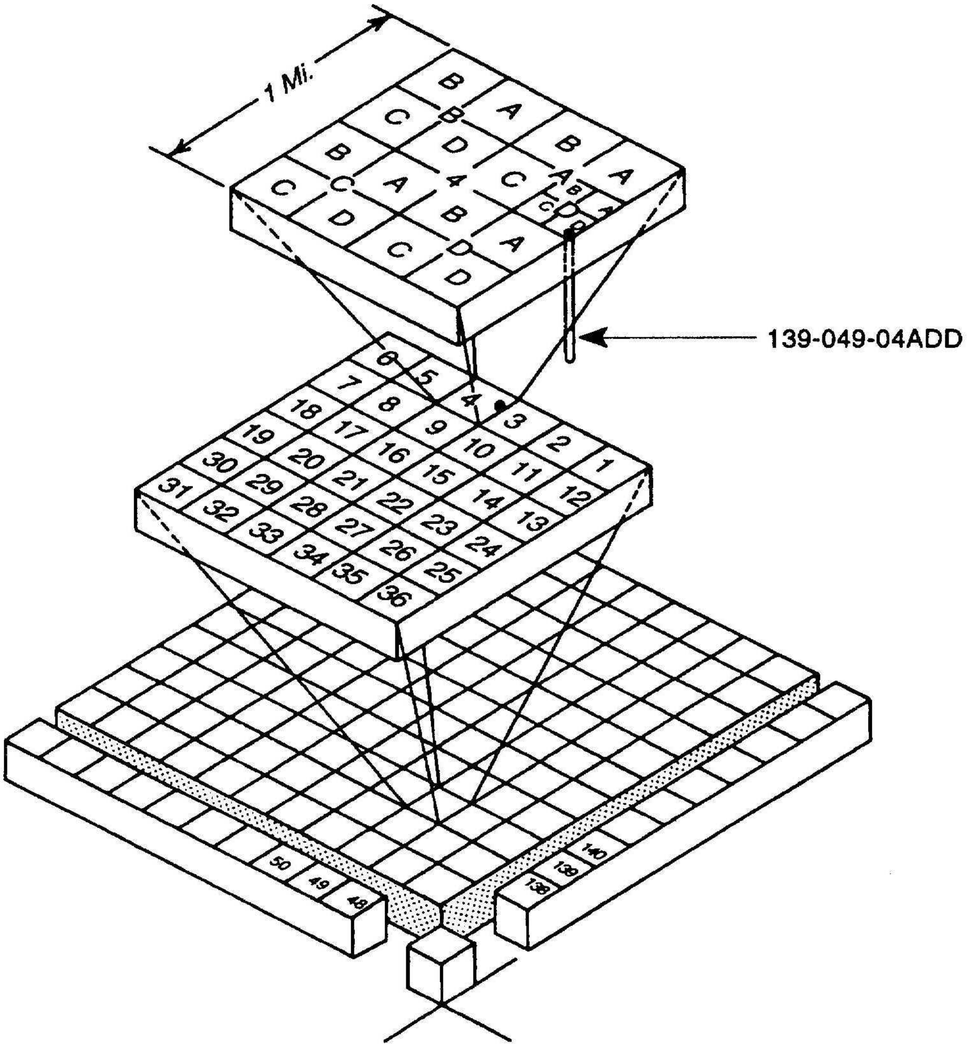


FIGURE 2. Location-numbering system.

ACKNOWLEDGEMENTS

A study of this size results from the work of many people. The base of this study is built upon the solid work of earlier investigators. The work that was accomplished with respect to this study began with the data acquisition phase of the study. Field work consisted of test drilling and the installation of observation wells and piezometers. Gary Calheim and Albert Lachenmeier were instrumental in the completion of the test-drilling program under conditions that were often quite difficult. Water-level measurements and chemical sampling were accomplished by Kelvin Kunz, Merlyn Skaley, and James MacArthur. Laboratory analyses of water samples were done by Garvin Muri and MaryBeth Osborn.

The data that was collected for this study, and the data that predates this study were managed in the SWC North Dakota Water Resource Database. The database was designed by Chris Bader, and he was a tremendous help throughout the long study time period. Mike Hove was instrumental in handling the overwhelming reams of data that have been assembled over the years and entered in the SWC database. Brenda Hove provided many of the figures in this report. Her production and editing of the figures help to make the report more presentable.

The size of this study and the size of the report made editing difficult. I appreciate the efforts of Milton Lindvig and Robert White in editing various portions of the study. Robert Shaver's efforts in editing the entire report are greatly appreciated. His critical review distinctly improved this report. His work with stable isotopes has inspired the isotope work in this study that has helped lead to critical insights regarding recharge.

This report has been a long time in coming, and has been awaited by many. I deeply appreciate the overtaxed patience of Florenz Bjornson and Jim McLaughlin. Wanting this study to be done for them has helped me push through many interruptions over the years. This study could not have been completed in the time that it has, without the patience and leadership of Milton Lindvig.

I would like to dedicate this study to my wife, Sarah, and my children, Becca and Will.

DESCRIPTION OF THE STUDY AREA

LOCATION

Most of the WFAS is located in the eastern 40 percent of Cass County (figure 1). Cass County is located along the eastern edge of North Dakota, south of the middle of the eastern margin of the state. The study area includes the eastern 40 percent of Cass County, as well as the western third of Clay County in Minnesota. The western third of Clay County was incorporated into the WFAS study area, because the WFAS was known to occur very close to the Minnesota state line, and there were known aquifers in Minnesota that might interact with the WFAS. Additionally, the study area includes small portions of Norman and Wilkin counties in Minnesota, and Richland County in North Dakota.

The study area is located in the Red River valley. Glacial Lake Agassiz once occupied the area, and as a result, the landscape is flat and nearly featureless with a very gentle slope towards the north. Only the occasional streams and drainage that dissect the former lake bottom break the extreme flatness. The one slightly significant topographic feature is the riverbed of the Red River.

POPULATION AND GROWTH

The major communities in the area are the cities of Fargo, North Dakota, and Moorhead, Minnesota. These two cities lie along the banks of the Red River, which separates the two states. Significant settlement of the area began in the late 1800s, about the time that the railroad arrived in the area in 1871 (Moorhead) and 1872 (Fargo). The area has continued to grow through the years, and in 1997 the population of Cass and Clay counties combined is estimated to be about 167,000. The area is growing at an estimated rate of about 1 percent annually. The growth is not only occurring in Fargo and Moorhead, but in other smaller cities in the area like West Fargo, and Dilworth as well. Additionally, many small communities are growing or have recently been developed, and much semi-rural development is occurring in areas that were formerly farmland.

Water supplies for the population in the area historically have been provided from both surface water and ground water. Going back to the 1870s, wells were installed in the area to provide water for individual homes and farmsteads. Later some small city supplies and some small industries began to use ground water as a water supply. Water companies also provided ground water as a drinking water supply. As the farming community developed, ground water was the source of water supply for farmsteads and farming operations. With the advent of suburban housing developments in the Fargo/Moorhead area, ground water has been the main source of water supply in the form of either rural water connections, or individual wells.

The two big cities (Moorhead and Fargo) in the study area have used significant amounts of surface water for their supplies. Moorhead has used the Red River as a source of their water supply at least since 1878. However, there have been times when the river was only part or none of the city's water supply. Up to 1909 the Moorhead supply came predominantly from the Red River. From 1910 to 1918 Moorhead's water supply was a combination of surface and ground water. From 1919 to 1960 Moorhead used only ground water as a source for their municipal supply. Moorhead has used a combination of ground water and surface water since 1961. The Red River also has been a source of water for Fargo since at least 1890. For 11 of the 15 years during the time period from 1938 to 1952, Fargo augmented their surface water supply from the Red River with ground water.

WATER RESOURCE CHARACTERISTICS OF AQUIFER UNITS IN THE WEST FARGO AQUIFER SYSTEM

GENERAL HISTORY

GEOLOGIC

Beneath the Fargo-Moorhead area at the base of the bedrock and glacial debris that has been deposited in the area over millions of years are the Precambrian crystalline or granitic rocks. They have been encountered in the study area through drilling at depths ranging from 132 to 512 feet. One test hole drilled in 1888 and/or 1889 in Clay County encountered the Precambrian material from 365 feet to 1901 feet. When the Precambrian surface (weathered or not) is encountered, there is little chance for significant quantities of water.

In some areas the sediments lying immediately above the Precambrian crystalline or granitic rocks are Cretaceous shale and sandstone formations. The Cretaceous rocks are generally of two types. The most common Cretaceous formation is the Graneros Shale. The Graneros Shale is not a source of water. Another less commonly occurring Cretaceous formation is the Dakota Sandstone. When present, the Dakota Sandstone is usually thin, and is seldom a source of ground water in the study area.

These Cretaceous sediments were deposited by seas that invaded the weathered Precambrian surface. Because the land surface had previously been exposed to erosion and weathering, the surface was irregular, and the subsequent Cretaceous sediment was irregularly deposited on top of the Precambrian rocks. The Cretaceous seas eventually receded, and the land surface was again weathered and eroded. This process continued from the end of the Cretaceous time period until the onset of the earliest glaciation.

Once glaciation started to occur in this area, surface features and shallow sediments have been repeatedly rearranged. There have been at least four periods of major glacial activity in the area, and each of those major periods have had repetitive advances of the front of the glaciers associated with them. With each advance came a partial destruction of what was deposited earlier. Additionally, with each subsequent retreat of the glacier front there occurred yet another rearrangement of earlier glacial deposits, and an additional depositional phase of more glacial sediment as the glaciers melted.

The main point of this brief geologic history is that the spatial distribution of the glacial sediments (approximately 200 to 400+ feet thick) is extremely complex. It is within these sediments that the West Fargo Aquifer System is found. There is a tremendous amount of subsurface information available in some parts of this study area, and as a result some aspects of the system are well documented. In spite of this density of data, however, and because of the incredible degree of variability of the glacial sediments, some of the interpretations presented are based on estimates and conjecture.

WATER USE

The aboriginal people in the area had surely been using surface water for thousands of years, and may have been using very minor amounts of shallow ground water as well. The use was minimal in comparison to the relative size of the resource, because there were no significant settlements of people and the per capita use was small. Late in the 1800s, the area began to experience settlements that were of a sufficient size, such that public water supplies were developed.

The earliest record involving municipal water for Fargo is the test drilling that was done in 1872 in Island Park. The test drilling resulted in the installation of a city well in Island Park. This well was not adequately productive for the city's use. Several privately drilled wells at the southwest edge of the settlement (an area between 2nd and 8th Av. S, and 15th and 21st St W), were able to produce water for the community that was delivered door-to-door by tank wagons. Around 1890 a system of distribution mains were put in for fire protection and sanitary purposes. In 1912 a rapid-sand filtration plant was built, and surface water from the Red River has been the primary water source for the city of Fargo since then. The only exception is during the drought years that occurred in the 1930s, 1940s, and the early 1950s, when the Fargo aquifer was used to augment the city surface-water supply.

Early records for Moorhead show that their supply was obtained solely from the Red River from 1878 to 1910. In 1910 the first Moorhead municipal well was installed in what is now known as the West Moorhead aquifer. Two additional wells were drilled in that same aquifer in 1913 and 1916. From 1910 until 1918, Moorhead used both surface water and ground water. From 1919 until 1927 the total water supply for

Moorhead was derived from the West Moorhead aquifer. In 1927 the Moorhead water supply was augmented with water supplied from the East Moorhead aquifer. From 1927 until 1948 these two aquifers provided all of Moorhead's water supply. In 1948 the city began to use the Buffalo aquifer, and soon after that, stopped using the West Moorhead aquifer. In 1960 a new water treatment plant was installed. This plant could utilize Red River water as well as ground water. Since 1961 Moorhead has used a combination of surface water from the Red River with ground water from the East Moorhead and Buffalo aquifers.

Other communities in the area began changing from individual supply wells and house-by-house water delivery, to central supply systems during the time from the early 1900s (Dilworth, 1907) through the 1930s (West Fargo, 1937). Dilworth's supply came from what is now known as the West Dilworth aquifer, and West Fargo's supply from what is now known as the West Fargo North (WFN) aquifer.

Industrial ground-water use increased through this same time period (Moorhead Laundry, 1906; Fairmont Creamery, 1923; Union Stockyards, 1936). The Moorhead Laundry water supply may have been derived from the West Moorhead aquifer, or it might have been an isolated unit that lies between the Fargo and West Moorhead aquifers. The Fairmont Creamery water supply was derived from the West Moorhead aquifer, and the Union Stockyard supply came from the WFN aquifer.

Additional industrial use after the 1930s derived water primarily from existing municipal water supplies, with the exception of a few industries in the West Fargo area, and Cass Clay Creamery in Fargo. The beef processing plant in West Fargo that has had several names in the last 35 years has used ground water from the WFN aquifer since the early 1960s. The Cargill sunflower processing plant has also used the WFN aquifer since 1979. The Cass Clay Creamery plant has used the Fargo aquifer since 1956, although city water was used additionally until about 1983, when the primary water source for the plant became the Fargo aquifer.

In the 1970s and 1980s significant changes in municipal water use patterns occurred as a result of the increase in the area's urban population and as a result of the shift of that population. Particularly on the North Dakota side, and to a lesser degree on the Minnesota side of the study area, there has been the development of clusters of small communities, and numerous large-acre-tracts of single dwelling properties out a small distance from the Fargo/Moorhead hub. On both sides of the Red River this has resulted in many individual domestic wells being installed into various distinct and indistinct lenses of sand and gravel. Some of these are part of an identifiable aquifer unit, and some are not.

Of more interest volumetrically is the increase in both the number and the annual use of the municipal water supplies that occur to a much greater degree in

North Dakota, and the rural water supply provided by Cass Rural Water Users, Inc. (CWRU) in North Dakota. There is no counterpart to CWRU in Minnesota.

Most of the small municipal supplies in the area have originated within the last 20 years, and several of the municipal supplies that do predate the 1970s, have grown significantly in the last 20 years. Most of the wells associated with these community ground-water supplies are wells that have been installed into some of the same various distinct and indistinct lenses of sand and gravel referred to earlier. Some of these sand and gravel units are part of an identifiable aquifer unit, and some are not.

Those communities in the North Dakota portion of the study area that are not self-supplied rely on CRWU for their water. Additionally, numerous individual homes and farmsteads are supplied by CRWU. CRWU utilizes three water sources for its ground-water supply; namely the Page, the Sheyenne Delta, and the West Fargo South (WFS) aquifers. Their distribution area is larger than the study area, and for all intents and purposes, most of the water that they supply to users within the study area is provided from the WFS aquifer. The utilization of the WFS well field began in 1976.

Another significant change in the water use pattern began in 1983 when the city of West Fargo derived a part of its ground water from the WFS aquifer. In 1982 and before, 100 percent of its water use was derived from the WFN aquifer. Since 1984 the city of West Fargo has derived between 30 and 55 percent of its water from the WFN aquifer, and the remainder from the WFS aquifer.

DISCUSSION OF AQUIFER UNITS

OVERVIEW

The locations of the WFAS aquifer units are shown in figure 3. For the purposes of this report, the aquifer units comprising the WFAS that will be discussed are the West Fargo North, the Fargo, the Nodak, the Prosper, the 94/10, the Horace, the Ponderosa, the West Pleasant, and the West Fargo South. Some of these aquifer units underlie tens of square miles, and have been used extensively as a source of ground water. Other aquifer units are quite small, and are minimally used as a source of water, if at all. Some times the differentiation between units is distinct and clear, and some times the differentiation between units is not distinct. The main reason for inclusion of the small aquifer units in this discussion is that they appear to be connected to the larger units to some degree.

There are additional bodies of sand and gravel in the area that will not be considered in the discussion because they appeared to be small, and/or were not significantly related to the WFAS. Figure 4 shows the location of about 25 possible aquifer units that will not be described in detail. Some of these aquifer units are only a

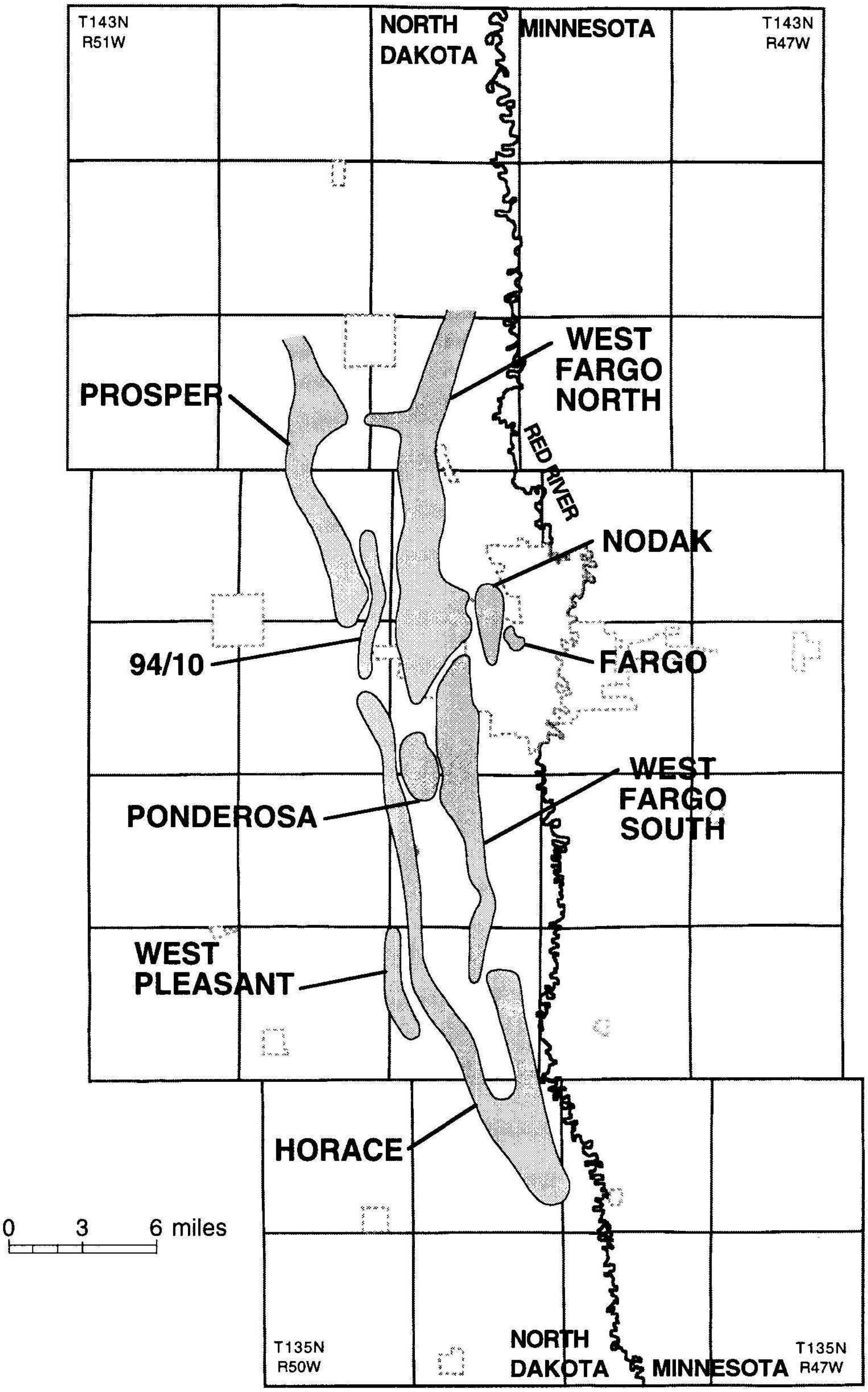


FIGURE 3. Location of West Fargo aquifer units.

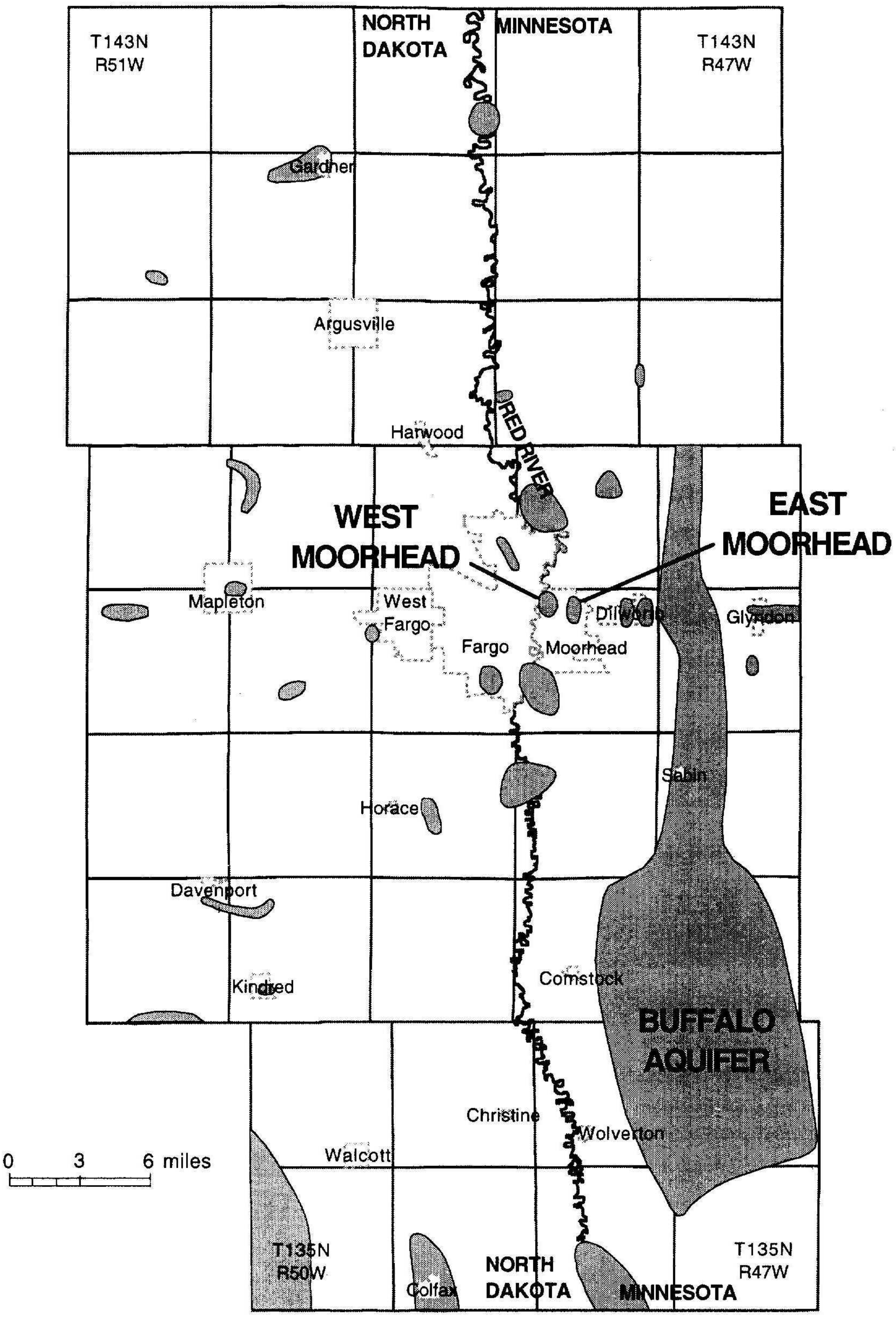


FIGURE 4. Location of aquifers in the study area which are not discussed in detail.

square mile or less in area. The most significant aquifer unit in the area that is not related to the West Fargo aquifer system is the Buffalo aquifer. It stretches over 30 miles in a north-south direction, and the western margin of the aquifer is usually found 3 to 7 miles east of the Red River. Of the sand and gravel bodies depicted in figure 4, only the East and West Moorhead aquifers (seen in the north part of Moorhead) will be discussed in relation to the WFAS.

As each aquifer unit is discussed, the data associated with that area will be evaluated. A variety of different kinds of data will be evaluated to help describe the size, areal extent, aquifer properties, chemical characteristics, historical utilization, water-level response, and interconnectivity of the unit within the aquifer system. In the different areas the amount and nature of the available data varies widely. This can make some interpretations difficult. An example would be a situation where the analysis of the only available set of parameters (water levels, for instance) would show a possible relationship between sub aquifers, but no other data is available to additionally support such an interpretation.

Besides the large variations in the amount and nature of the available data, the interpretations of the available ground-water data within an area can vary. The evidence interpreted from existing data can be vague or unclear. In some instances, different parts of the data can even lead to contradictory interpretations. For example, an analysis of the water quality of samples taken from of a set of wells in one area might show striking similarity, whereas an analysis of the water levels of wells from the same area would show very little similarity, or vice versa.

The discussion will start with the West Fargo North aquifer unit, which has been the most extensively utilized aquifer of any of the aquifer units in the area. This will be followed by a discussion of the Fargo aquifer unit that has been used for the longest time period. The discussion will proceed generally from north to south. The alphabetic order of the geologic sections shown on figure 5 shows the order in which the aquifer units will be discussed in the following descriptions.

Each aquifer unit discussed in the West Fargo aquifer system will be referred to as an aquifer. In reality each of these aquifers is a relatively discreet aquifer response unit (i. e. an aquifer area with similar water-level fluctuations).

WEST FARGO NORTH AQUIFER

Aquifer size and location

The West Fargo North (WFN) aquifer is one of the larger units of the WFAS as shown in figure 6. The aquifer boundary at the north end of WFN aquifer is unknown, and may extend further to the north than indicated by the aquifer boundary line. The

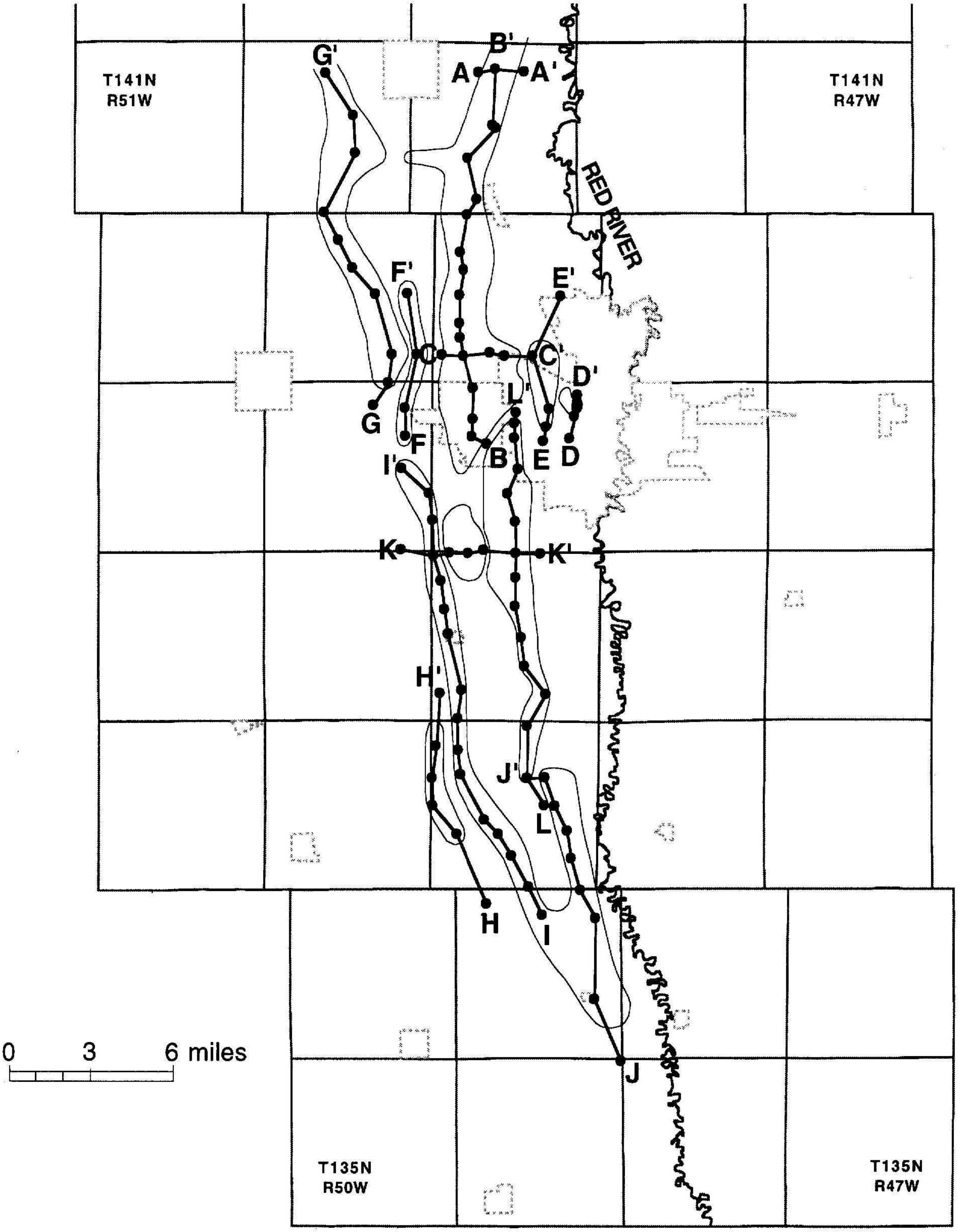


FIGURE 5. Location of geologic sections.

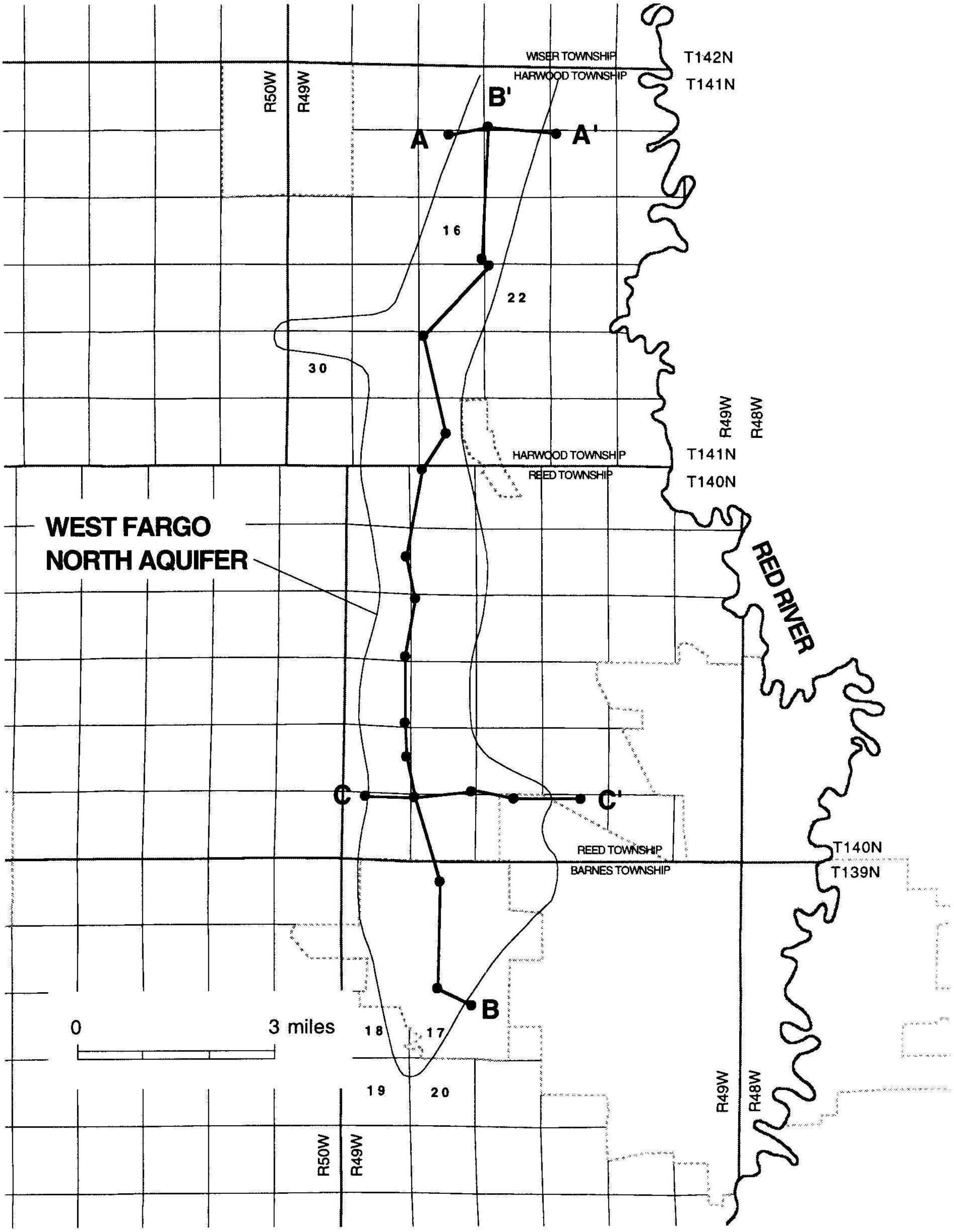


FIGURE 6. **Location of the West Fargo North aquifer and geologic sections A-A', B-B', and C-C'.**

remainder of the boundaries on the east, south, and west are based on a combination of water-chemistry, water-level, and lithologic-description data.

Along the southeast boundary of the WFN aquifer there are a series of significant differences between water levels (especially historically) in the wells located in the WFN aquifer and the water levels in the wells of the Nodak and West Fargo South (WFS) aquifers. Water chemistry differences also help support the evidence that points to a fairly well defined boundary on the southeast side of the WFN aquifer.

The southern boundary of the WFN aquifer is not well defined. Limited water-level and water-quality information exists in sections 17, 18, 19, and 20 of Barnes Township (T139N, R49W). The boundary in that area is drawn on the basis of the limited number of lithologic descriptions with very little other supporting information.

The southern part of the west boundary of the WFN is fairly well defined because of the water-level differences between wells in the WFN aquifer, and those wells whose well screens are located in isolated sand and gravel units or in other aquifers like the 94/10 aquifer unit. The water levels are lower in the WFN aquifer. In addition the 94/10 aquifer generally has water with higher chloride and lower sulfate concentrations than does the water of the WFN aquifer.

From this area on the west side of West Fargo, to the area west of Harwood (all along the west side of Reed Township), the limits of the WFN aquifer are primarily determined by analysis of the lithologic logs available. Some wells that occur near, but outside of, the west edge of the WFN aquifer have water levels that are higher than the water levels observed in the wells with screens located in the WFN aquifer. This indicates that those wells are not part of the WFN aquifer.

North of Harwood, in T141N, R49W (Harwood Township), there is one area that shows a deviation from the general northward trend of the western margin of the WFN aquifer. Along the north edge of section 30 of Harwood Township there are two wells for which water chemistry, and lithologic logs are similar to those of the WFN aquifer. The water levels are a little higher than expected, but they are close enough that the hydraulic gradient is about 7.5 feet per mile. This indicates a connection that is less than normal (2 to 5 feet per mile is the expected range of hydraulic gradient values), but the connection is good enough to still be considered a part of the WFN aquifer. The boundaries of this resulting irregular bulge to the west are not well documented, but this area will be considered part of the WFN aquifer in this study.

In the northern part of Harwood Township and in the southern part of Wiser Township (T142N, R49W) there are a few test holes with lithologic descriptions that indicate that there are no sand and gravel intervals at those locations. The delineation of the northern portion of the western margin of the WFN aquifer is based on those lithologic descriptions.

Eighty-eight test holes and wells located in the WFN aquifer were investigated. Of these, 12 did not have a lithologic log. The descriptions of the remainder showed that the material in this aquifer is comprised predominantly of sand and gravel. The texture of the sand ranges from fine to coarse, and is more commonly medium to coarse, often grading into gravel, particularly with depth. The degree of sorting of the sand is usually described as being fairly well sorted, although the sand is sometimes described as being poorly sorted and not as permeable.

Based on lithologic logs for 66 test holes and wells, the average thickness of the WFN aquifer is estimated at 72 feet. Sand lenses above and below some parts of the main channel of the WFN aquifer are described in about 20 percent of the logs. These lenses that are probably connected to the aquifer add an average of about 7 feet of aquifer thickness, resulting in an average thickness of about 79 feet for the WFN aquifer.

The top of the aquifer is usually encountered at an average depth of about 120 feet, with the highest and lowest values being 77 and 180 feet below land surface. The bottom of the aquifer is encountered at an average depth of 192 feet below land surface, with the minimum and maximum values ranging from 131 to 281 feet below land surface.

Figure 7 shows a geologic section (A-A') located at the north end of the WFN aquifer. Figure 7 shows two presentations of the same geologic section. The bottom, wider geologic section has no vertical exaggeration. The vertical and horizontal scales are the same. The top, thinner geologic section has a vertical exaggeration of 105.6 times. The vertical scale is enlarged by 10.56 times, and the horizontal scale is smaller by 10 times. This results in a vertical exaggeration of 105.6 times. With one exception, all of the remaining geologic sections in this report will be on the same scale as the geologic section on the top of figure 7.

Using the same vertical exaggeration of the top geologic section in figure 7, figure 8 shows a generally north-south cross section of the WFN aquifer along B-B'. This geologic section shows the highly irregular nature of the aquifer top, bottom, and thickness. This geologic section also shows the highly variable nature of the aquifer within a small distance in sections 16 and 22 (T141N, R49W).

Geologic section C-C' also shows the irregularity of the aquifer top, bottom, and thickness (figure 9). Notice that on the right side of the geologic section two test holes (140-049-34BBB and 140-049-34ABB2) show similar sand and gravel thickness and elevation. While the two easternmost observation wells in this geologic section show a similar aquifer interval, the water-level difference between these two sites has historically been 8 to 10 feet. This is a hydraulic gradient of about 16 to 20 feet per

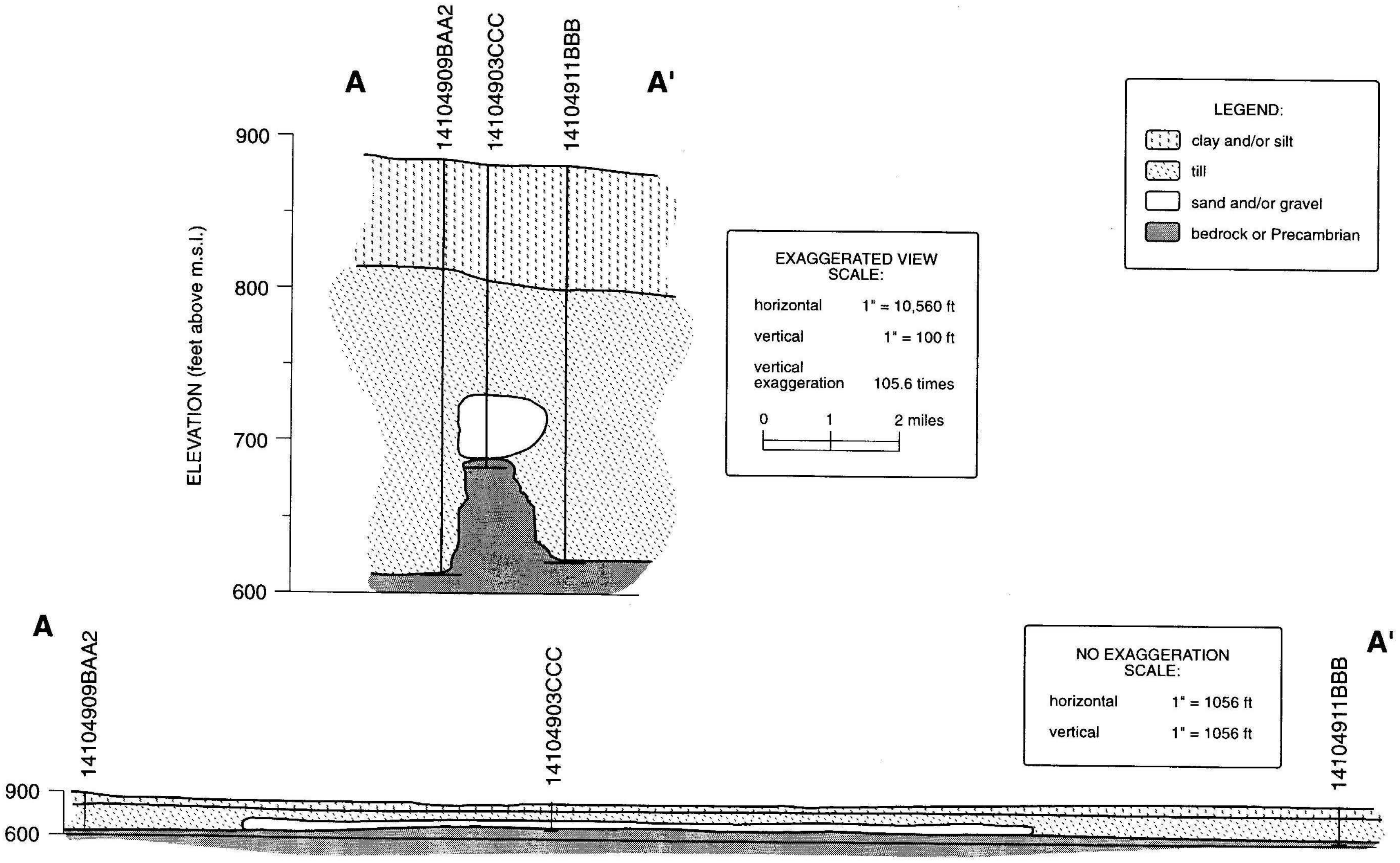


FIGURE 7. **Geologic section A-A' of the West Fargo North aquifer showing the difference between vertical exaggeration and no exaggeration.**

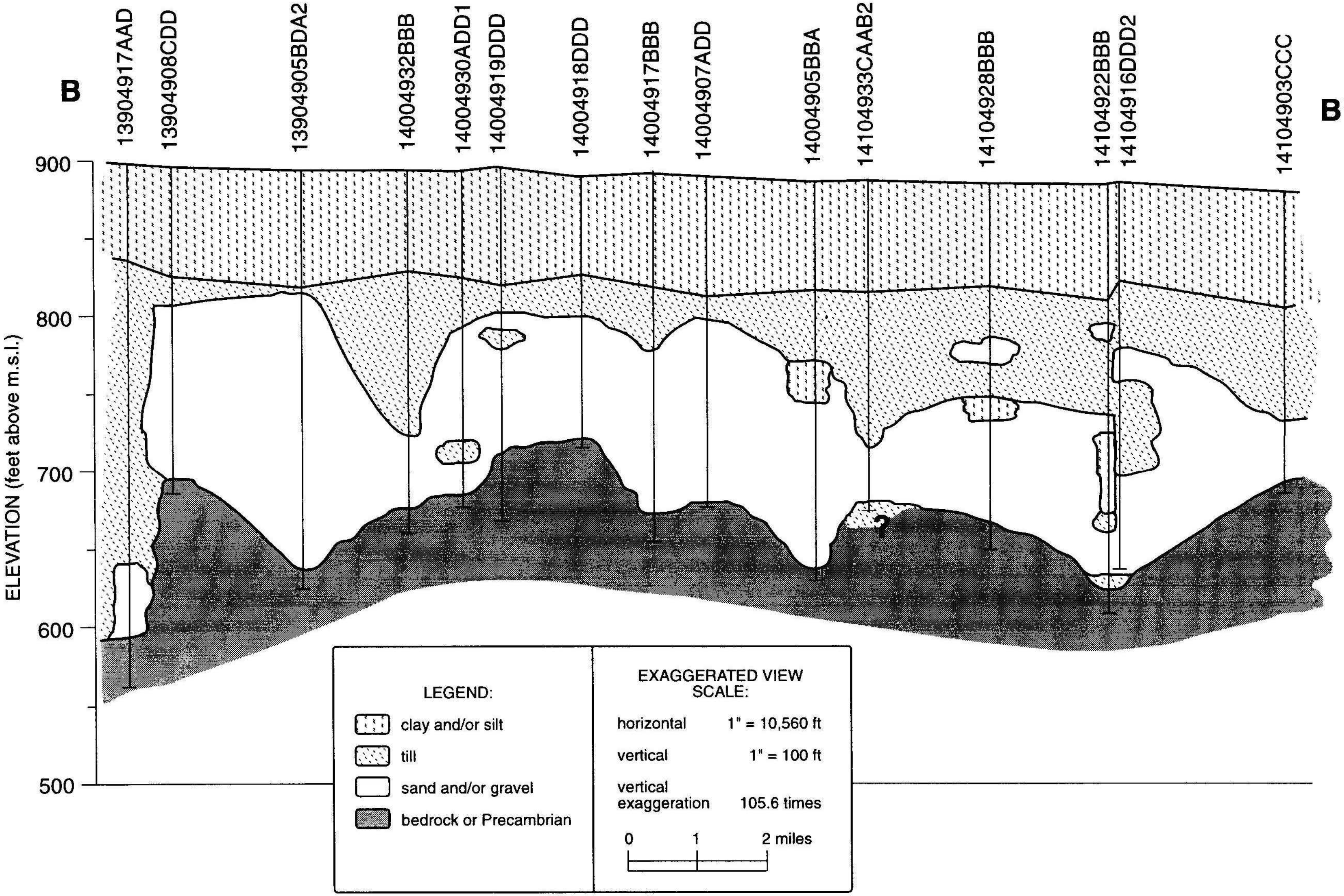


FIGURE 8. Geologic section B-B' showing a longitudinal profile in the West Fargo North aquifer.

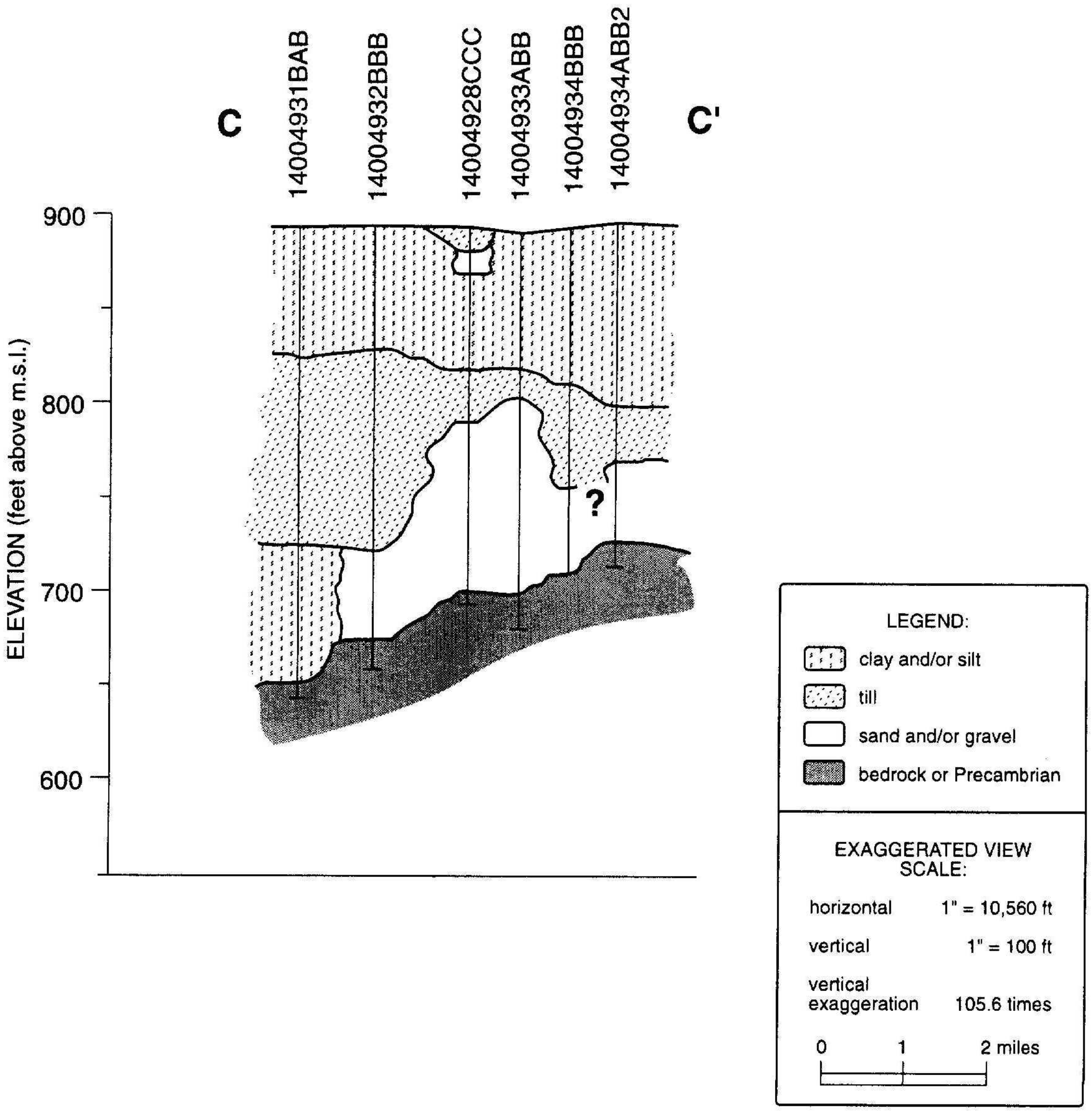


FIGURE 9. **Geologic section C-C' showing a transverse profile in the southern part of the West Fargo North aquifer.**

mile, and indicates that the two observation wells are not completed in the same aquifer.

Based upon the boundaries shown in figure 6, the areal extent of the aquifer is approximately 27 square miles. There are portions of the aquifer that have little data, or conflicting data which means that the aquifer could be considered to be larger or smaller, depending on which way an interpretation might change. The interpretation in places shows a well-defined aquifer boundary. In other places, the boundary between the WFN aquifer and an adjacent aquifer is indistinct and poorly defined.

The approximate volume of the water-bearing sands and gravels of the WFN aquifer is computed by multiplying the average thickness of the aquifer by the areal extent of the aquifer, which amounts to about 59 billion cubic feet. A discussion later in the report will talk about the relationship between the volume of the aquifer, and the amount of water stored in this aquifer volume.

Two aquifer or pumping tests have been conducted using two large-capacity wells completed in the WFN aquifer. The first test was conducted in November of 1963, using the Riverside production well that was located at 139-049-06DCD1. This well is currently described as West Fargo city well #8, and was installed in October, 1963. The production well was pumped continuously for 36 hours at a rate of 500 gallons per minute. Calculated transmissivity values derived from the pumping test data ranged from 7,500 to 43,000 feet squared per day. Lindvig (1964) indicates a transmissivity of 10,000 feet squared per day and a storage coefficient of 0.0007 are conservative estimates of these aquifer parameters in the test area.

The second test was run in June of 1972 on a new West Fargo municipal well located at 139-049-09BBA (city well #5). The municipal well was pumped continuously for 100 hours at a rate of 500 gallons per minute. Calculated transmissivities ranged from 5,900 to 16,000 feet squared per day with the residual drawdown analysis giving the lowest transmissivity values and the distance-drawdown analysis giving the largest values. Schmid (1972) indicates a transmissivity of 10,000 feet squared per day, and a storage coefficient of 0.07 are reasonable estimates of these aquifer parameters in the test area. Using the closest observation well (#1) he estimated the storage coefficient to be about 0.20.

These variations in the above calculated aquifer parameters are to be expected when the physical setting of the aquifer is so complex. Many of the assumptions inherent in the equations used to solve for the aquifer parameters are not met. Due to the irregular top of the aquifer, part of the drawdown cones developed during the two tests may have dropped below the top of the aquifer, and parts of the drawdown cones may have remained above the top of the aquifer causing spatial variability in storativity. In addition, no evaluation was made on the nearby barrier boundaries to the south and east. Varying boundary conditions can also impact the results of a pump or aquifer test. As a result, the above calculated aquifer parameters should be used with caution.

Aquifer water use and water-level history

It is likely that water was first used from the West Fargo North aquifer when the first well was installed into that aquifer sometime in the 1800s. Quite likely it was drilled for a farmstead overlying the WFN aquifer. Indications are that the water levels in the early wells were above land surface. As additional wells were drilled into the aquifer, the amount of water being removed increased, and the water levels began to decline and approximate land surface. Dennis et al (1949) reported that by 1885, "....many of the wells did not flow, although the water levels were, for the most part, at or very near the land surface."

Besides WFN aquifer water use from farmstead wells, it is possible that the WFN aquifer was utilized as a source of drinking water for households in nearby communities. Byers et al (1946) reported that the population of Fargo rose from 2,693 to 5,664, and that the water was taken directly from the Red River during the time period from 1880 to 1890. They also reported that during this time period water was still sold door-to-door for human consumption. Most of the water that was sold door-to-door was derived from wells. It is possible that some of the wells that supplied this 'door-to-door' water may have been located in the WFN aquifer.

Just after the turn of the century, Hall (1905) reported that "....all water, save only that caught upon the roofs of buildings, and stored in cisterns (an amount barely sufficient for strictly household purposes), must be obtained from wells." The water levels at that time that are tabulated in his 1905 report show that at the north end of the WFN aquifer a few wells still flowed, but that at the south end of the WFN aquifer, water levels were 5 to 8 feet below land surface. These 'lowered' (presumably) water levels in the WFN aquifer are very likely due to withdrawals from individual wells.

However, the lowered water levels in the WFN aquifer could also be partially due to the heavier utilization of wells to the east. These would be wells that were not completed in the WFN aquifer. Hall reports one well in the northeast of section 2 (139-49) with a water level that is 68 feet below land surface. These lower water levels that are found in the partially connected aquifers to the east could have caused leakage of water from the WFN aquifer (with higher water levels) to the more heavily used aquifers to the east (with lower water levels). This would result in declining water levels in the WFN aquifer, without any water being diverted directly from wells in the WFN aquifer.

Dennis et al (1949) refers to the time period of 1885 to 1910 as a time period where, "there was no great lowering of water levels in the area". The earliest recorded significant water use derived from wells in the study area is the diversion made from the

Moorhead West aquifer by the city of Moorhead beginning in 1910. This diversion lowered the water level significantly in the Moorhead West aquifer, and appears to have lowered the water levels in the Fargo, and the Moorhead East aquifers through indirect connections.

It is conceivable that this lowering of the water levels in the Fargo aquifer could have resulted in some lowering of the water levels in the WFN aquifer (through slow leakage over many years). The 1937 water levels measured in section 6 (T139N-R49W) were 10 to 25 feet below land surface, showing that it is likely that water levels in the WFN had declined significantly from 1905 to 1937, even though there was not significant water use from the WFN aquifer until 1936.

In 1936, the stockyards in West Fargo began to use the WFN aquifer as their water supply. The following year the city of West Fargo (then known as the city of Southwest Fargo) also began using the WFN aquifer. Mr. C. J. Ferch drilled two wells in 1937 and by 1938 his distribution system provided water for 74 establishments in West Fargo. Estimates of water use made by Dennis and others (1949) show that West Fargo's annual diversion grew from about 500,000 gallons in 1937 to about 2,600,000 gallons in 1947. Starting in 1936, the Union Stockyards Co. use of water from the WFN aquifer increased from 26 million gallons (Mg) to 220.3 Mg in 1947. These water use figures were determined by using the electric power consumed to estimate total water use.

No WFN aquifer water-use records have been found for the time period 1948 to 1965. This is unfortunate, because in the time period between 1948 and 1965 there are some significant variations in the water levels that were measured in observation well 139-049-06ADB (see figure 10). Early in the 1948-65 time period water levels declined at a significant rate in the vicinity of observation well 139-049-06ADB (about 8 ft/yr). Later, during a four-year time period from 1958 through 1961, the water level declined at a rate of about 6 ft/yr. However, during this same 1948-65 time period there were two shorter time periods in which the water level was rising (1949-52 and 1956-57). If there were reasonably reliable water-use data available for this time period, that data would provide additional insight as to how big the WFN aquifer is, and how it responds to different stresses.

A summary of the available WFN water-use data is presented in Table 5I on pages C230-1 in Volume C of the data report for this study. Since the publication of the data report, an error of omission has been noted. At one time, water permit #1103 had been issued for the City of Riverside. Subsequently, this permit has been assigned to the City of West Fargo. Because the Riverside permit had been enveloped by West Fargo, water use associated with the Riverside well was not listed in Table C, "Municipal ground-water use in the ND portion of the study area, not including Fargo & West

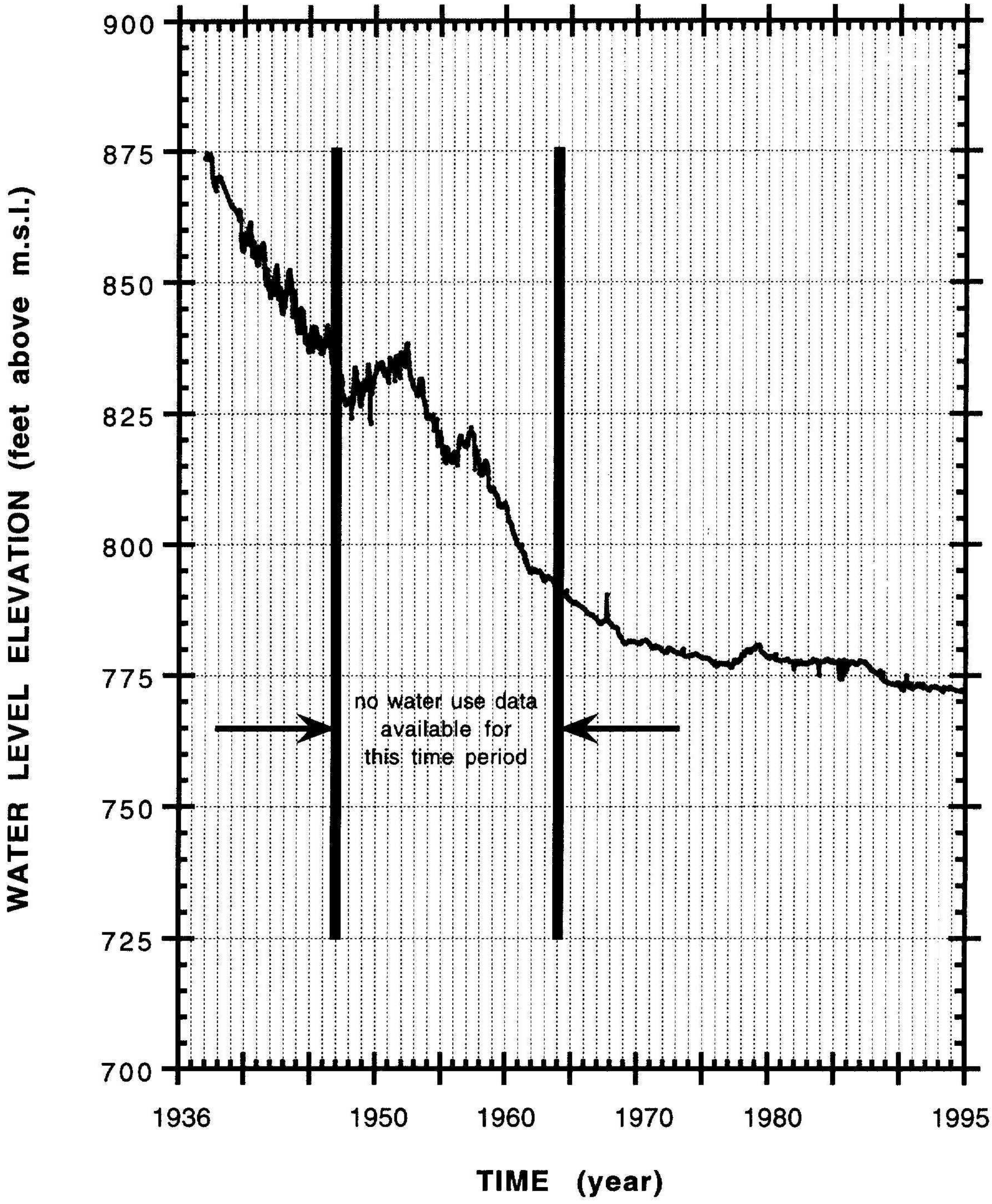


FIGURE 10. Hydrograph of observation well 139-049-06ADB showing period of no available water use data in the WFN aquifer.

Fargo". However, the use associated with the Riverside well also was not included in West Fargo's use listed neither in Table 5F, nor in summation for the WFN aquifer found in Table 5I. This is not a significant omission in most years (use generally varied from 0 to 23 Mg). However, from 1990 to 1992 the quantity of water pumped from the Riverside well ranged from 54 to 99 million gallons per year (Mg/y). The data missing from the water use tables is included in figure 11.

Figure 11 shows a bar chart of annual water use from the WFN aquifer. Water use generally increased from 1936 until 1974. A generally decreasing trend follows from 1975 until 1987. After a large increase in 1988 (from about 350 Mg the year before to over 600 Mg), annual water use from the WFN aquifer has settled into a fairly stable range of annual volume of water consumption of about 450 to 550 Mg.

The two figures (10 and 11) show a fair degree of similarity between water use and water levels for the time periods 1936 to 1947 and 1965 to about 1982. However, a divergence began in 1983. For four straight years from 1984 to and including 1987, the average annual water consumption was less than the average annual use for the three-year time period from 1977 to 1979. And yet the rise in water levels observed in the hydrograph in figure 10 for the 1977-79 time period does not appear in the 1984-87 time period. In the same way, the steady decline in water consumption observed in figure 11 from 1988-93 is not noticeable in the water levels in figure 10. One possible explanation for this lessening relationship between water use, and water levels as observed in 139-049-06ADB is that significant water-level changes occurred in an adjacent aquifer that is hydraulically connected to the WFN aquifer.

It was in 1983 that the city of West Fargo began to obtain a part of their water supply from the West Fargo South (WFS) aquifer. That is, in fact, why WFN water consumption was lower beginning in 1983. Before this utilization of the WFS aquifer, water levels in the WFS aquifer were about 60 to 70 feet higher than the water levels in the WFN aquifer. By 1987 the water levels at the north end of the WFS aquifer were only about 10 to 15 feet higher than the water levels at the south end of the WFN aquifer. This significant change in the water level of the WFS aquifer very likely has significantly reduced the movement of ground water from the WFS aquifer to the WFN aquifer, and consequently has lessened the water-level increase that had been previously observed after a time of prolonged lesser water consumption.

Figure 12 shows the locations of the high yield wells that have produced significant quantities of water from the WFN aquifer, and the locations of observation wells whose water levels have been measured. Most of the production wells are located in the southernmost portion of the WFN aquifer, and only the Harwood wells are outside of that southern area. The city of Harwood generally uses only 3 to 6 percent of

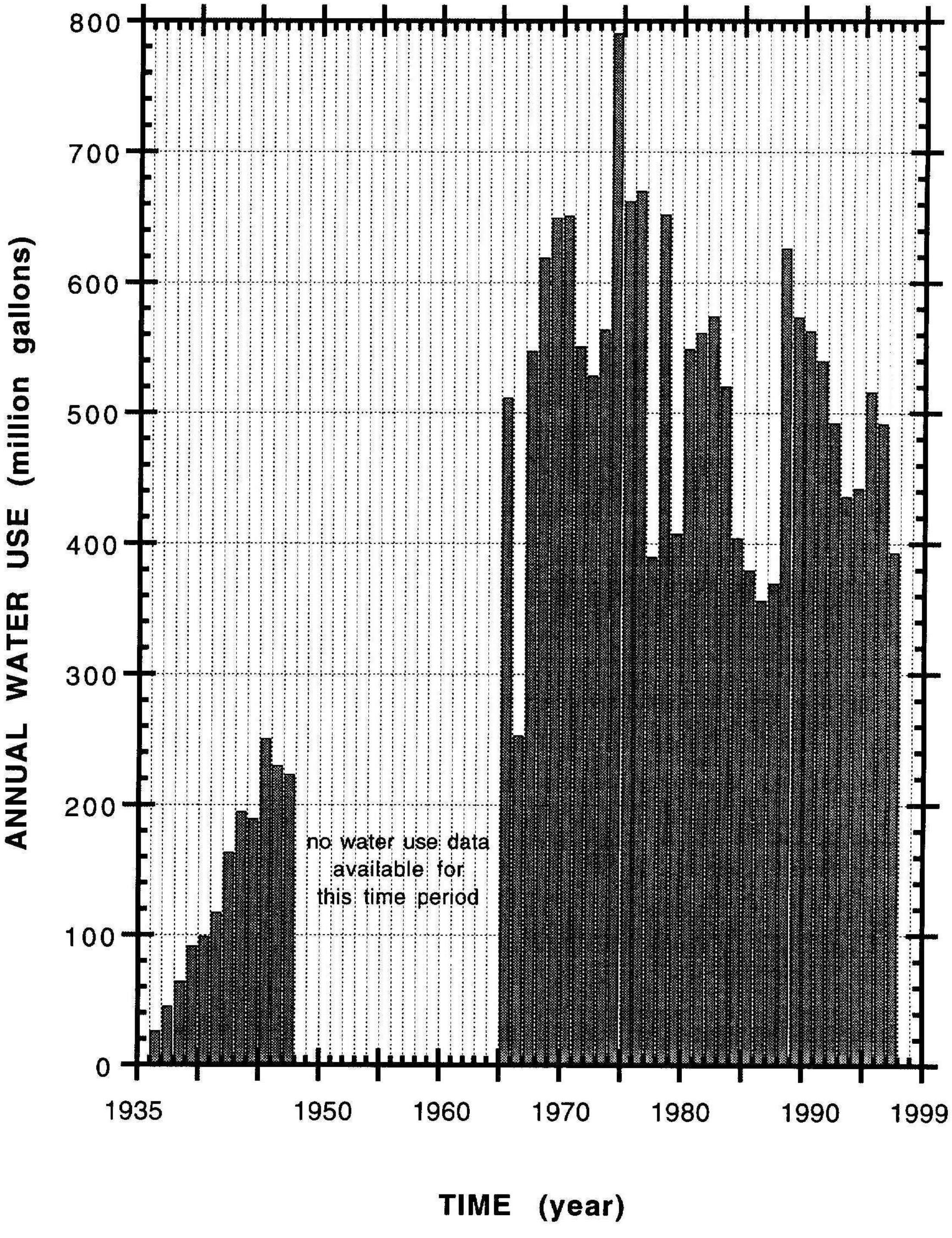


FIGURE 11. Annual water use from the West Fargo North aquifer.

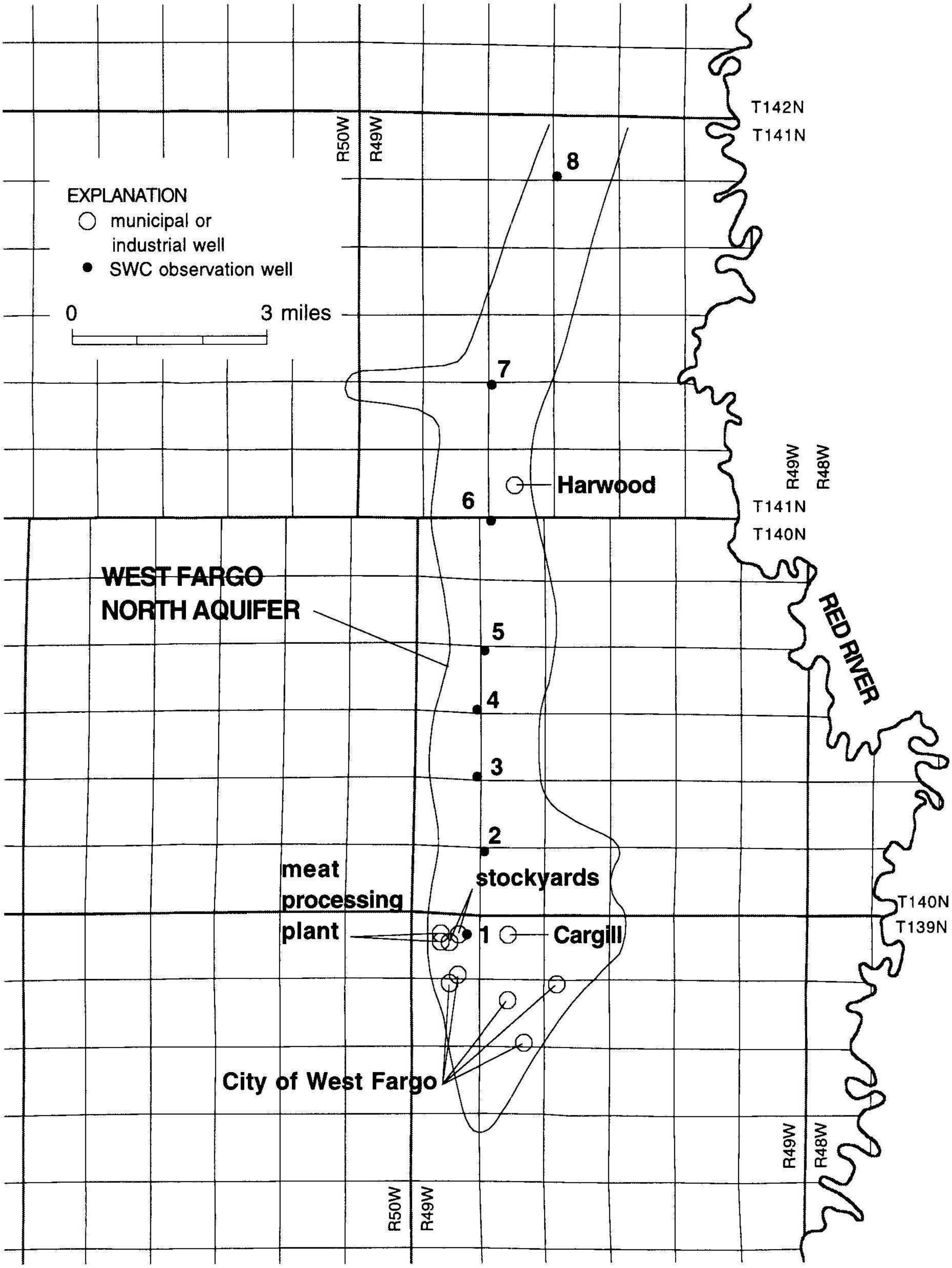


FIGURE 12. Locations of production wells and selected observation wells in the West Fargo North aquifer.

the total amount of water withdrawn from the WFN aquifer, so 94 to 97 percent comes from the southern area.

Figure 13 displays at least one hydrograph for each of the eight sites depicted in figure 12. One site, 140-049-19DDD, has had three different observation wells (3a, 3b, and 3c) measured for water levels, hence there are three lines all representing the same site. The southernmost site shown in figure 12 is the observation well 139-049-06ADB (#1). This well produced the water levels for the hydrograph shown in figure 10, and the later years (1961-1995) of that hydrograph produce the lowest curve shown in figure 13. Each succeeding upward curve on figure 13, is represented by the next site north indicated on figure 12 with the one exception mentioned for site #3, which has three curves representing the one site. The vertical scale is also different for figure 13 than it is for figure 10.

Figure 13 shows a fairly similar pattern for all of the hydrographs. There are, however, a couple of significance differences. The first is that the lengths of record for the wells are different. Only three sites have water-level records measured in the 1960s. Five sites have records that start in 1981 or 82, and the water-level measurements for one site begin in 1991.

The second significant difference is that beginning with the southernmost observation well (#1), each well to the north has a hydrograph characterized by more subdued water-level fluctuations. The water-level elevation in well #1, for instance, dropped 3.8 feet in the two-year span from early 1988 to the end of 1989. During this same time period water-level changes for #2 through #8 (skipping #4 which didn't exist at that time) were 2.1, 1.7, 1.5, 1.4, 1.3, and 1.2 feet, respectively.

Notice that under the lesser water usage during the time period 1977 up through 1987 (averaging about 470 Mg/y) the water level for #2 remained at an elevation of about 781 to 782, and that #1 remained near 777 for that same period. Notice, additionally however, that the other wells in figure 13 all showed declines for the same time period. Closer to the center of the cone of depression created by the production wells (shown in figure 12), the water levels were stabilizing, but further out the cone was still subsiding. Before enough time had passed to reach a broader stability, the aquifer use was increased. Thus it is not known if an equilibrium would have been reached at that pumping volume. It is not known that an equilibrium would have been reached, but it is probably unlikely.

An additional perspective can be gained from figure 13 by comparing an additional variable, namely distance. Figure 14 shows only 15 years of the water-level record. However, figure 14 also shows the map distance between the wells, and the computed hydraulic gradient between each two consecutive wells. The hydraulic

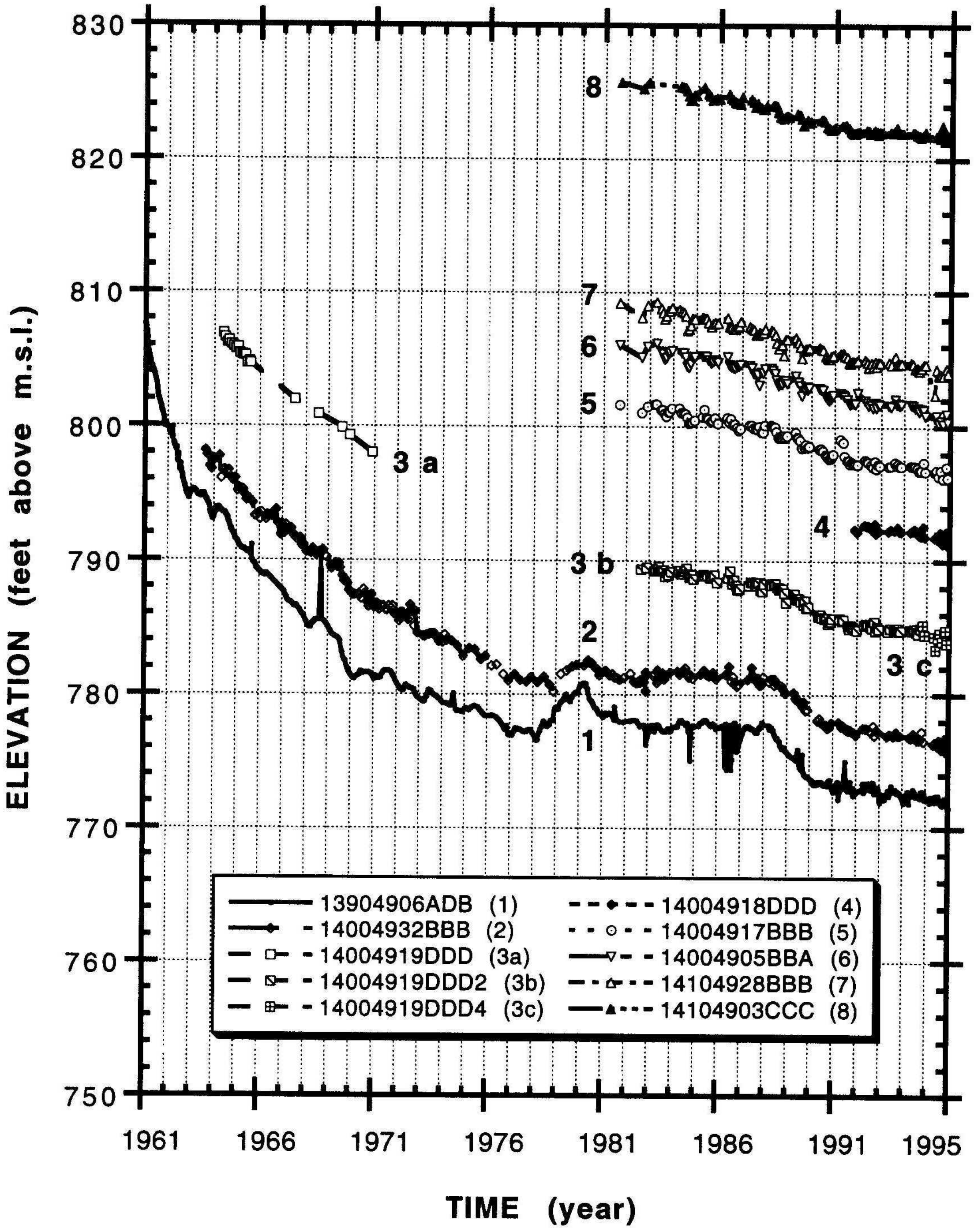


FIGURE 13. Hydrograph of selected observation wells located in the West Fargo North aquifer.

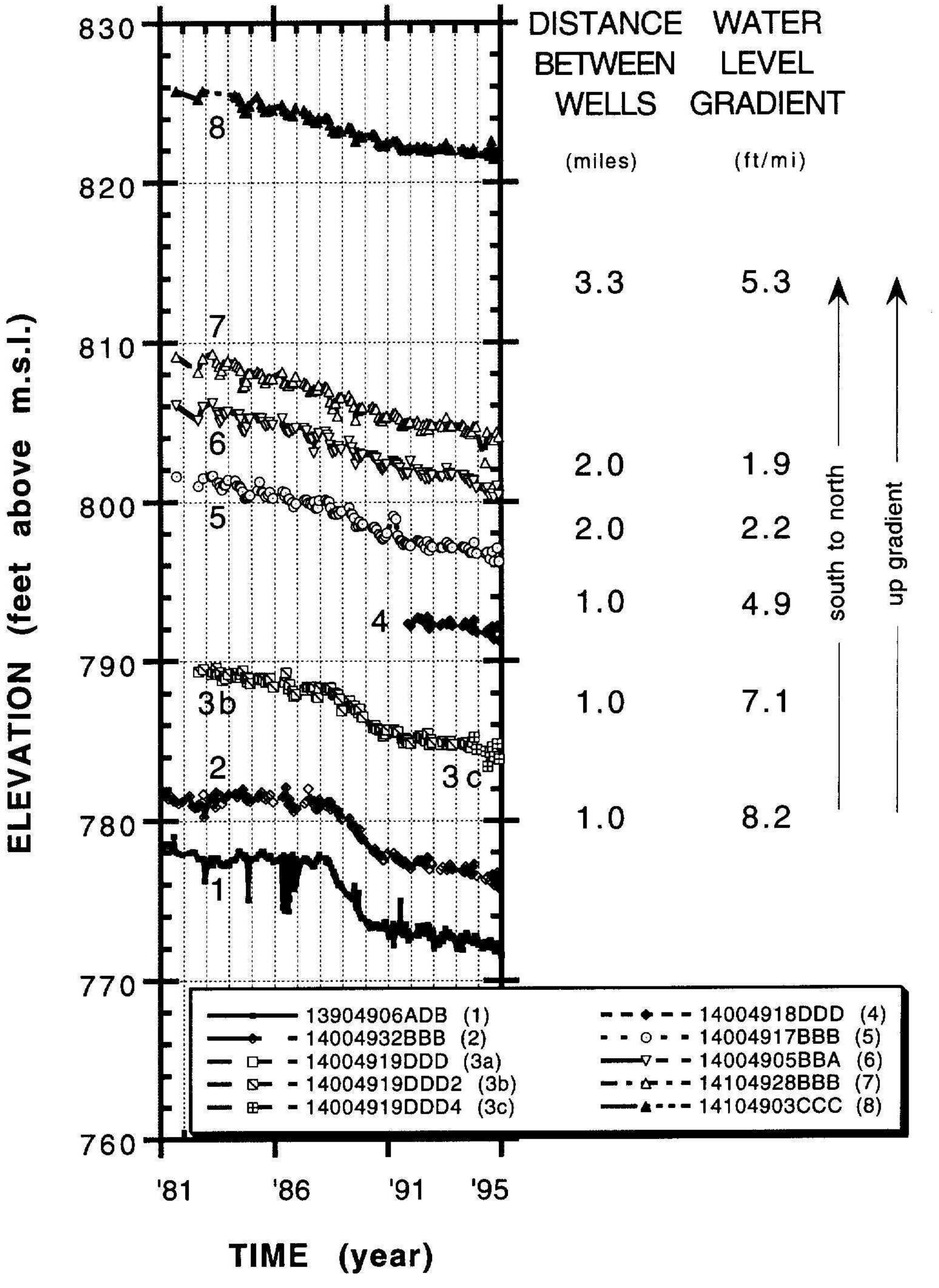


FIGURE 14. Hydrograph of selected observation wells in the West Fargo North aquifer showing the hydraulic gradient between the observation wells.

gradient is the water-level difference in feet between two wells expressed as a gradient in feet per mile.

If the properties of the WFN aquifer are the same throughout the different parts of the aquifer, the hydraulic gradient should stay reasonably consistent. The hydraulic gradient of 5.3 feet/mile between curves 7 and 8 (see figure 14) is misleading, because there is a minor pumping center between the two wells represented by the curves. The pumping center is the city of Harwood's well field, that results in a small cone of depression that is between 140-049-05BBA and 139-049-28BBB. This small cone of depression distorts the larger cone of depression caused by the 10 production wells at the south end of the West Fargo North aquifer.

With this exception, the remaining segments of the WFN aquifer represented on figure 14 should have fairly consistent hydraulic gradients. This is not so. There is over a four-fold difference in the hydraulic gradients. The most likely reason for this is that there is an approximately four-fold variation in the values of transmissivity for the WFN aquifer. If other variables are relatively uniform, the ability of the aquifer to transmit water is about four times better in some reaches of the aquifer than in others. The variation in transmissivity may be due to differences in aquifer texture (grain size and particle sorting) and/or aquifer cross-sectional area.

Over the last 35 years observation well 139-049-06ADB has shown about 1.1 feet per year of water-level decline. Over the last 15 years the decline has averaged about 0.5 feet per year and over the last seven years it has also averaged about 0.5 feet per year, although most of that occurred in 1989 and 1990. From 1991 to 1995 the average annual water-level decline has been about 0.2 feet per year. At the north end of the WFN aquifer, observation well 141-049-03CCC has shown about 0.3 feet per year of water-level decline. For the last seven years the site has averaged about 0.2 feet per year of water-level decline.

Aquifer water chemistry

The water chemistry of the different aquifers in the WFAS varies greatly from one aquifer to another. Within some of the individual aquifers in the WFAS there is also, significant variability. As a general rule, however, each aquifer does have fairly characteristic water chemistry. In some of the aquifers there are not enough different sites or sample analyses to be able to say that the aquifer has consistent water chemistry characteristics throughout the aquifer, but several of the aquifers in the WFAS show fairly consistent water chemistry characteristics.

Figures 15 through 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The seventh aquifer shown in each figure is the West Fargo North aquifer, listed as WFN. These figures compare the concentration determined from the analyses of samples collected in wells completed in each of the aquifers. The box shows the range of values in which the middle 50 percent of the analyses occur, and the vertical lines show the variation of the middle 80 percent. The circles depict extreme values, or outliers. The horizontal line is the median value. The median is the center of the distribution, that is, 50 percent of the values are greater than the median value and 50 percent of the values are less than the median value.

Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The WFN, however, is well depicted with 39 different sites represented by one or more chemical analyses of samples collected from those sites.

Figure 15 shows that the WFN aquifer is relatively low in calcium concentration in comparison to other aquifers in the area. Only the WFS aquifer shows lower concentrations. There are a few sites in the WFN aquifer with higher calcium concentrations, as seen by the three small circles on figure 15. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the WFN aquifer is about in the middle of the group of nine aquifers with respect to chloride concentration. While there was a three-to-four-fold variation in the calcium concentration from one site to another, there is over a ten-fold variation in the chloride concentration from one site to another. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride. There is no regulation of this SMCL, and numerous public water supplies exceed this level. The 250 SMCL for chloride is very close to the median for the WFN aquifer. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. Only a few sites have chloride concentrations higher than 400 mg/liter.

Figure 17 shows that the WFN aquifer is in the low range of the group of nine aquifers with respect to hardness. Even though WFN hardness is in the low range

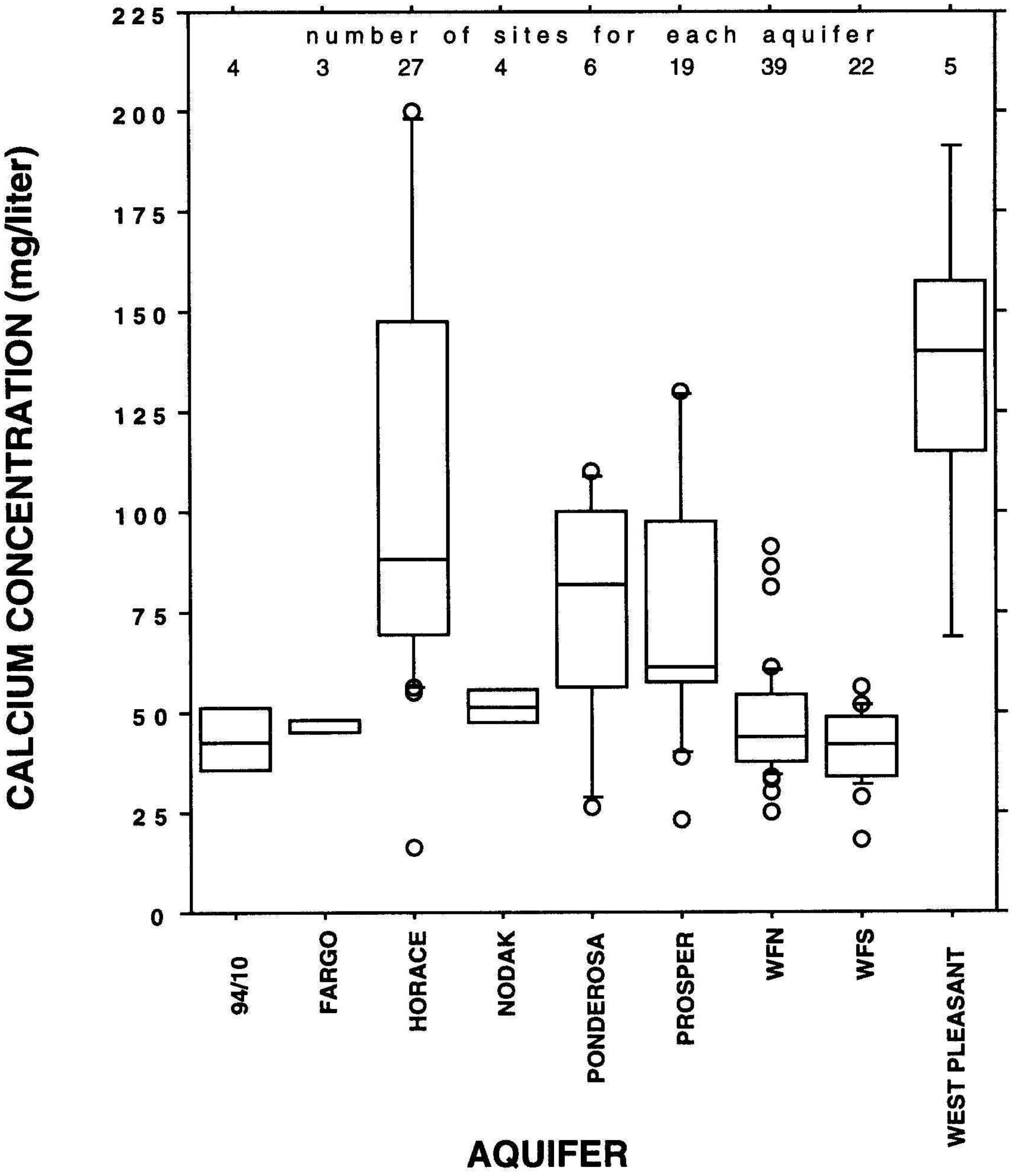


FIGURE 15. Plot showing the concentration of calcium in the different aquifers of the West Fargo Aquifer System.

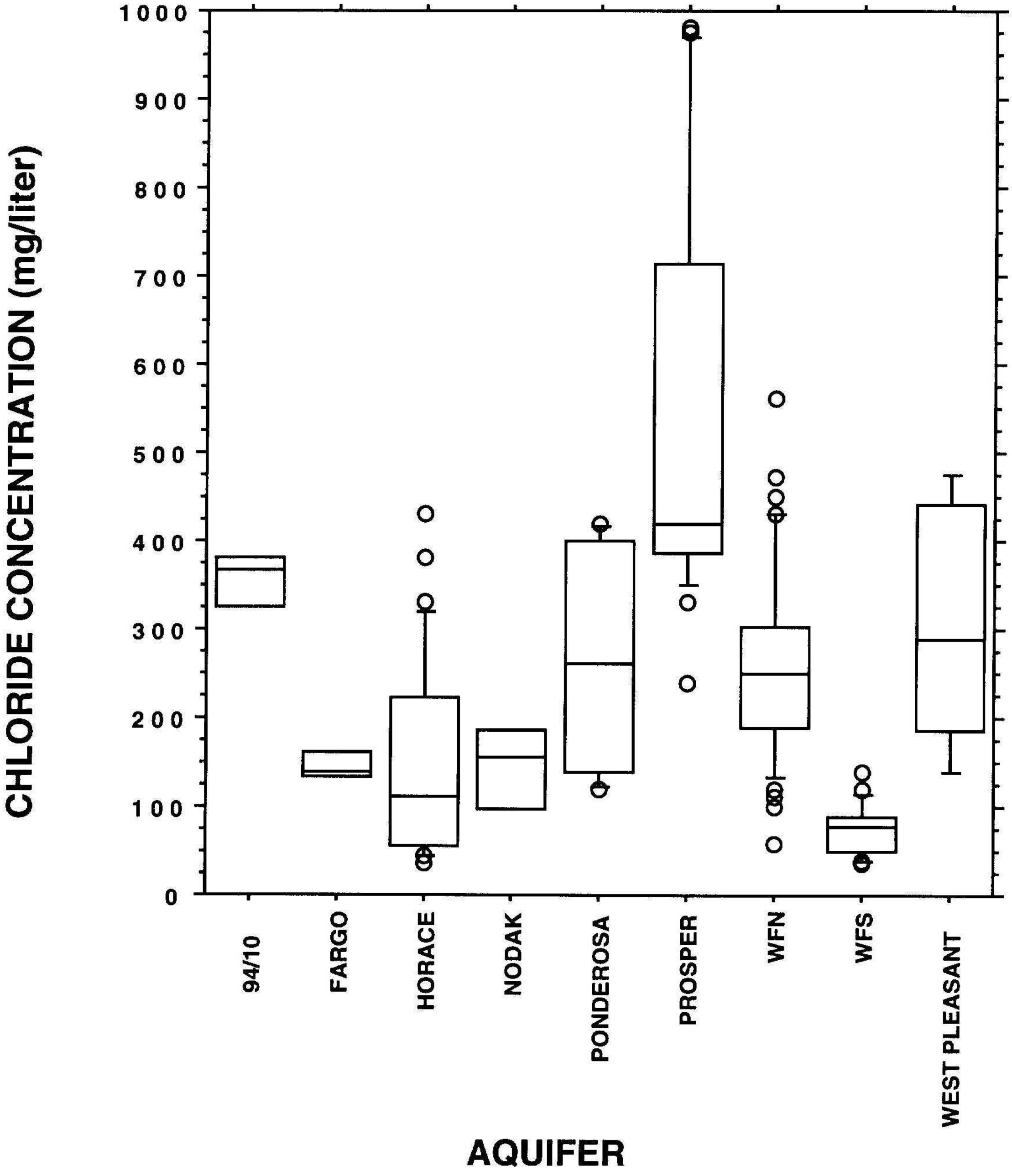


FIGURE 16. Plot showing the concentration of chloride in the different aquifers of the West Fargo Aquifer System.

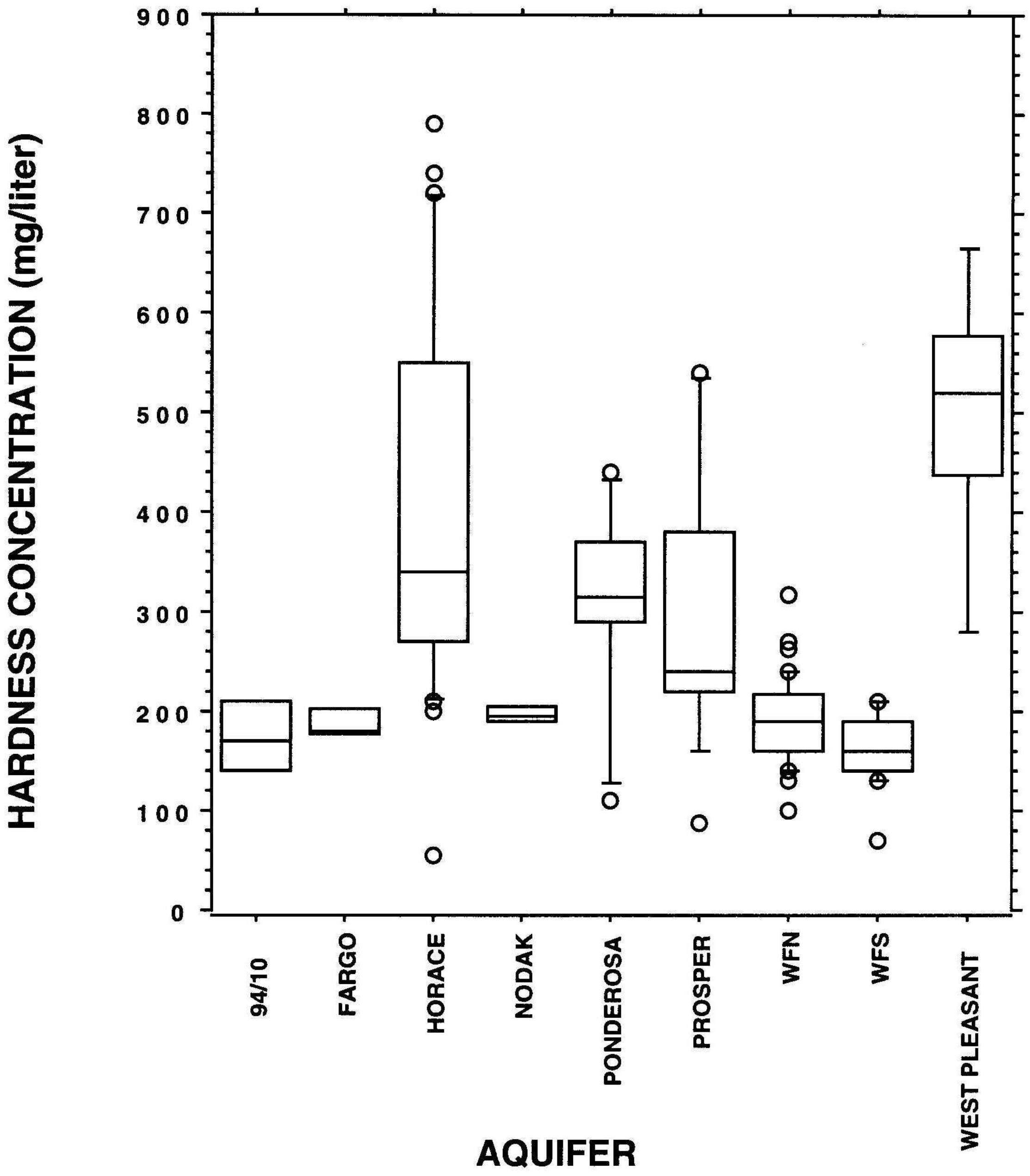


FIGURE 17. Plot showing the concentration of hardness in the different aquifers of the West Fargo Aquifer System.

among the WFAS aquifers, the median value of the WFN hardness (about 190 mg/liter) falls into the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce a lather as the hardness increases.

Figure 18 shows that the WFN aquifer is in the middle to high range of the group of nine aquifers with respect to the sodium concentration. Only the two northwesterly-most aquifers (94/10 and Prosper) are clearly higher in sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below every one of the sodium concentrations for every one of the 545 analyses that were performed on all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the WFN aquifer is relatively low in sulfate concentration in comparison to other aquifers in the area. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. All sites and all samples from all sites in the WFN aquifer had sulfate concentrations below the lower SMCL sulfate value of 250 mg/liter. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the WFN aquifer is about in the middle of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites of the WFN and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants.

The water in the WFN aquifer is a sodium-chloride to sodium-bicarbonate type. The total dissolved solids generally range from between 800 to 1100 mg/liter, and the water is generally hard to most often very hard. It is suitable for most purposes, but some sites with high TDS are marginal for irrigation purposes.

The general trend of water quality in the WFN aquifer is for lower TDS in the eastern and southern portions of the aquifer. Lower chloride and sodium concentrations seem to relate most closely to this south and east trend of better quality

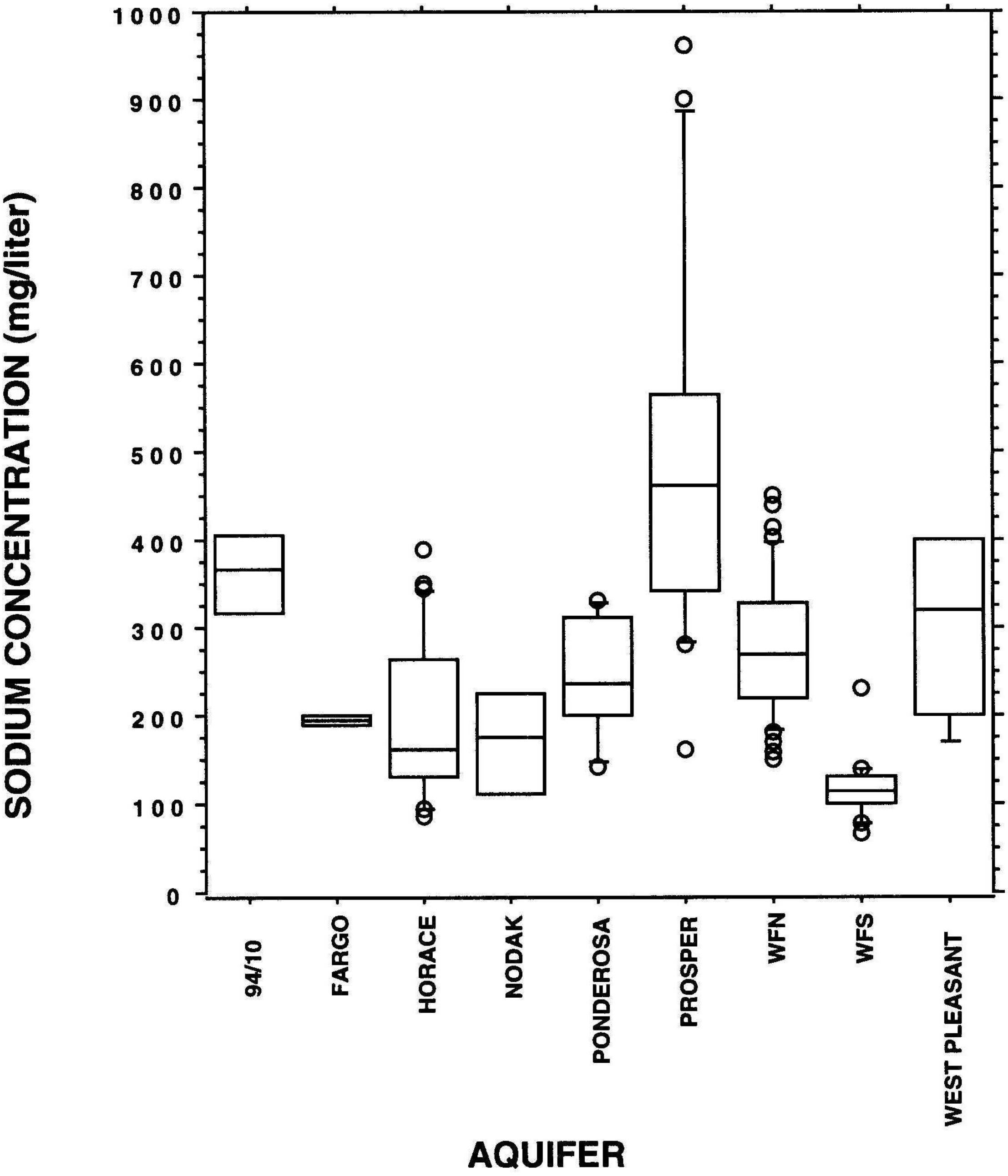


FIGURE 18. Plot showing the concentration of sodium in the different aquifers of the West Fargo Aquifer System.

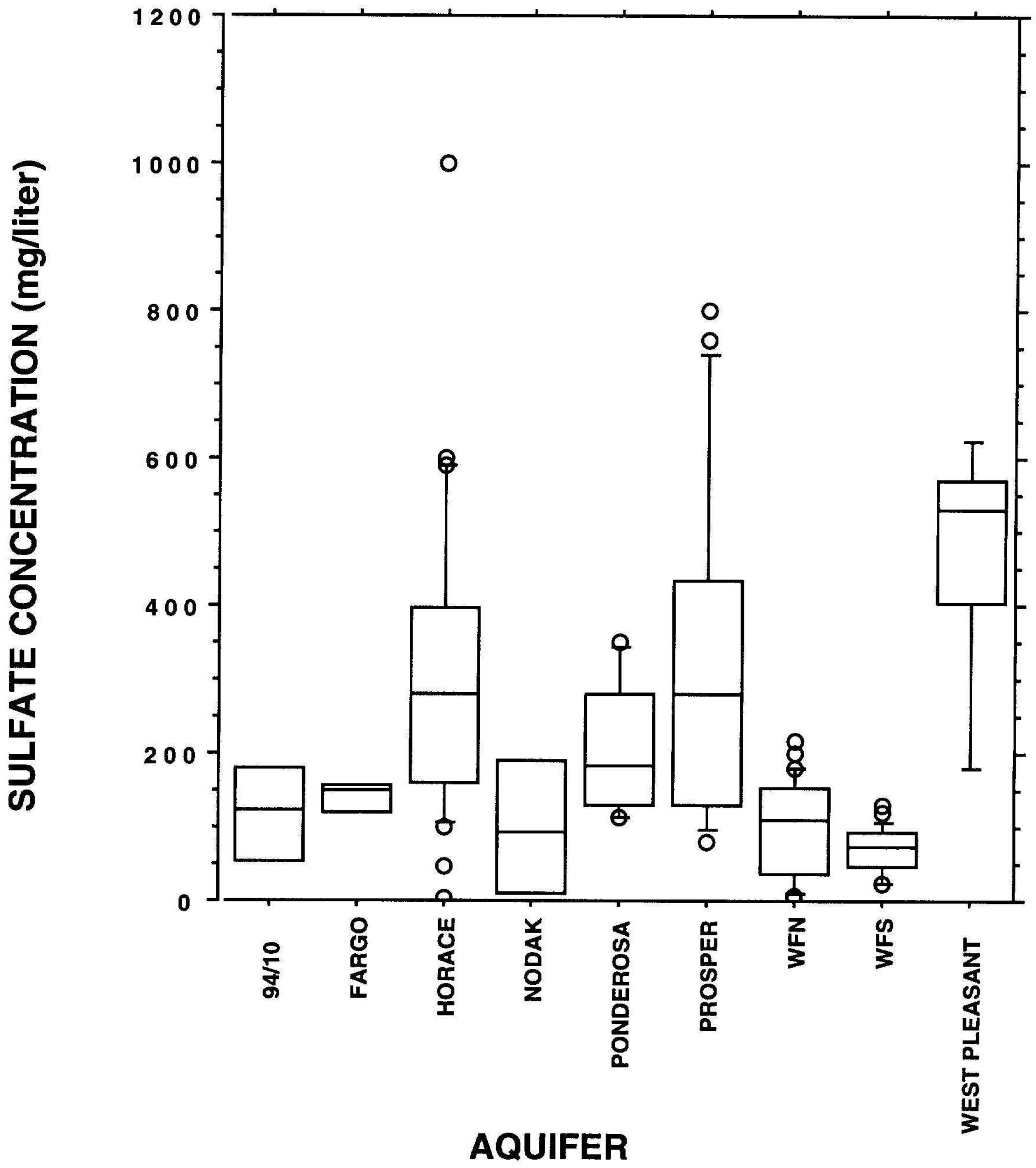


FIGURE 19. Plot showing the concentration of sulfate in the different aquifers of the West Fargo Aquifer System.

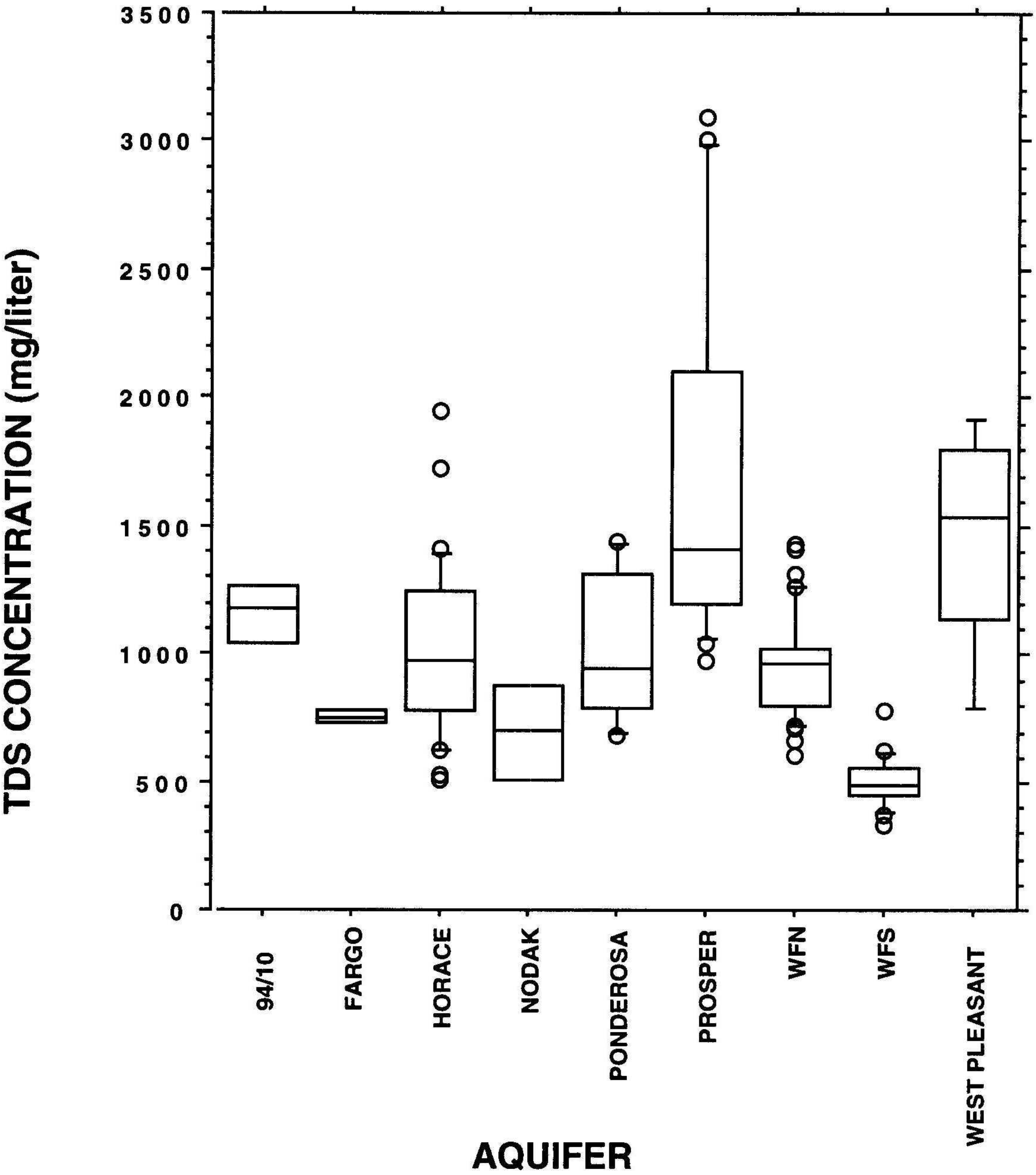


FIGURE 20. Plot showing the concentration of TDS in the different aquifers of the West Fargo Aquifer System.

water. Calcium, magnesium, sodium, bicarbonate and chloride concentrations all show the highest values on the west side of the WFN aquifer. For calcium, magnesium, and bicarbonate the area of highest concentration is the northwest part of Reed Township (140-049), and for sodium and chloride that area is the northwest part of Barnes Township (139-049).

Earlier in the discussion on aquifer size and location, the area north and west of Harwood that lies on an east-west trend was discussed as being anomalous. The water quality of one of the two observation wells in that area shows relatively good agreement with the general water quality of the WFN aquifer in that area, with the exception of sulfate concentrations. Observation well 141-049-30AAB has the highest sulfate values of any well sampled in the WFN aquifer. Additionally, the general chemical character of 141-049-30BBB is significantly different than the character of 30AAB. It seems that even though the water levels of these two wells show good historic agreement, the origin of the waters in these two parts of the aquifer may be different.

The isotopic data for hydrogen and oxygen also shows anomalous results in this same area. There are seven samples in the WFN aquifer that have been analyzed for heavy oxygen (oxygen-18) and heavy hydrogen (hydrogen-2), including the site at 30AAB. Heavy hydrogen is also called deuterium.

The stable heavy isotopes of hydrogen (deuterium) and oxygen (oxygen-18) have been investigated because the concentration of these isotopes provides information about the history of the water, and can indicate the climate (particularly temperature) when recharge to the aquifer occurred. Shaver (1995) collected rainfall and snowfall samples in 1989 and 1990. Figure 21 shows the results of the isotopic analyses of hydrogen and oxygen that were done on the samples collected for that study. The plot shows a very consistent linear relationship between deuterium and oxygen-18, in which the larger the negative number, the more depleted the sample is in the heavy isotopes with respect to the standard reference value.

The notation for expressing stable isotope ratio variations is to use the delta symbol (δ) to designate the relative difference in the ratio of the heavy isotope with respect to a reference. Because the differences between samples and the reference are small, δ-values are expressed in per mil differences (multiplied by 1000), and symbolized with (o/oo) to indicate that δ has been multiplied by 1000. The essence of this form of presentation is that there will be positive numbers if the sample has more heavy isotope than the reference, and negative numbers if the sample is depleted with respect to the reference.

Figure 21 shows that the snowfall samples lie on the graph in the lower left portion, indicating higher negative numbers for both $\delta^{2}H$ (deuterium) and $\delta^{18}O$ (oxygen-18), and indicating water that is highly depleted in the heavy isotopes. The

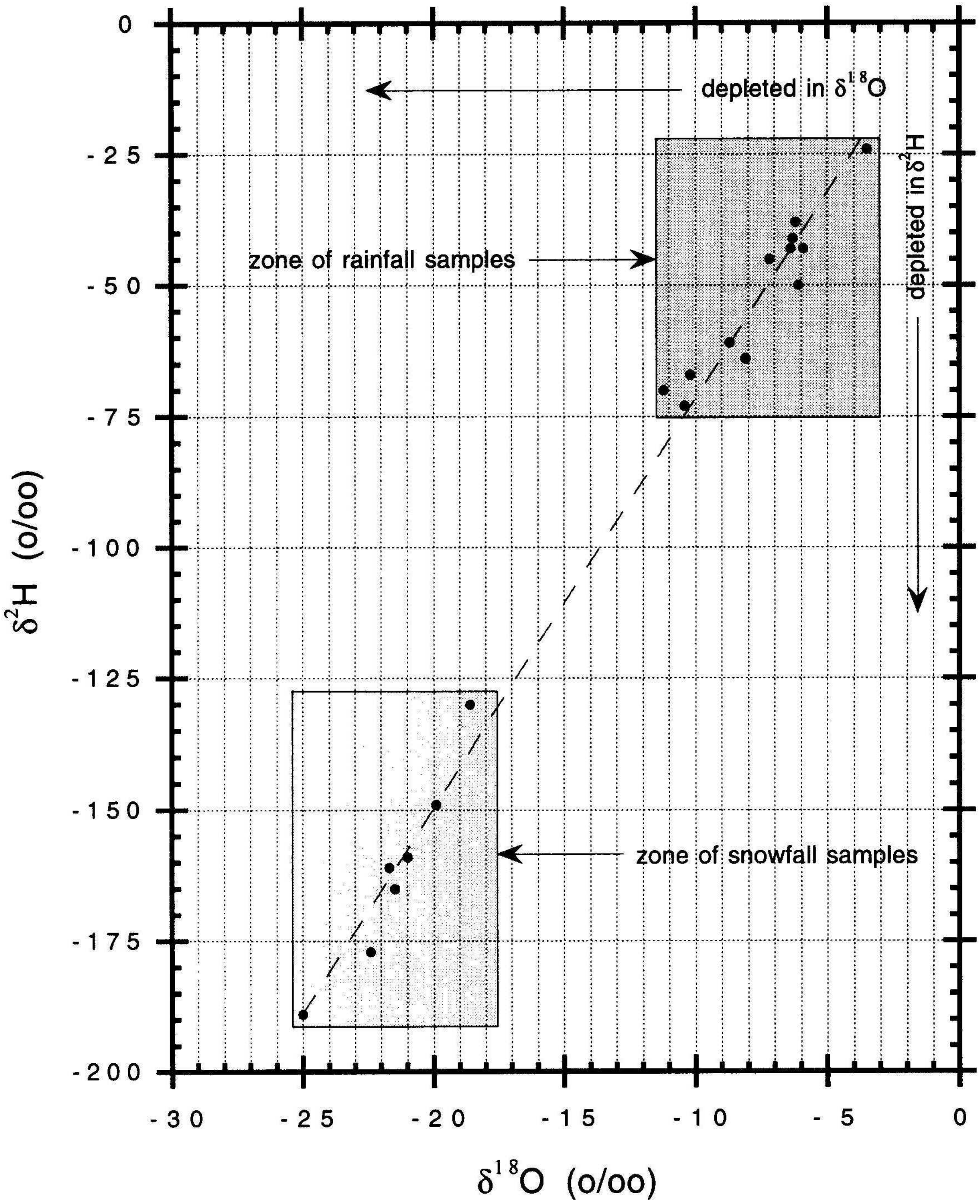


FIGURE 21. **Distribution of stable isotopes (deuterium and oxygen-18) in rainfall and snow samples in the Oakes area (from Shaver, 1995).**

upper right portion of the graph shows the zone of rainfall samples, indicating much less depletion of the heavy isotopes. When Shaver plotted the 29 Oakes ground-water samples on this same scale, 26 of the samples plotted between the two zones, and the other three samples plotted in the more depleted portion of the 'rainfall zone'.

Figure 22 shows the isotope data for the six samples taken from WFN aquifer. Five of the sites had samples that ranged in $\delta^{18}O$ values from -16.2 to -20.9, whereas 30AAB had a $\delta^{18}O$ of -9.1. These values show that 30AAB is significantly higher in $\delta^{18}O$ (less depleted) than the values that are found in the rest of the aquifer. The deuterium analyses show the same anomaly. The well at site 30AAB showed $\delta^{2}H$ value of only -67, whereas the other five WFN analyses showed values ranging from -122 to -157.

The isotope analysis at site 30AAB was done on a sample that was collected in September of 1994. Three earlier samples had all shown the water in this well to be a sodium-chloride type. The 1994 sample analysis showed the water to be a calcium-sulfate type, which was significantly harder. This could be indicative of an observation well that was overtopped by floodwater, and had surface water introduced into the well and the aquifer.

The remaining six samples of the WFN aquifer appear to be natural aquifer water, and these six samples are significantly depleted in heavy isotopes. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snow in North Dakota have shown values of approximately -18 to -25. Except for 141-049-30AAB, all of the WFN sample analyses showed $\delta^{18}O$ values near or in the range of snowfall samples.

A shallow unconfined aquifer generally receives both snowmelt and rainfall as recharge. These two entities mix, and the mixture varies, depending on the recharge dynamics of the aquifer system. If an aquifer is recharged by more rainfall than snowmelt, the isotopic signature of the water in the aquifer will resemble more closely the range of rainfall isotopes. For $\delta^{18}O$ this would be closer to the low range of -10 of rainfall, than to the high range of -18 of snowfall. As mentioned earlier, ground water from a shallow aquifer like the Oakes aquifer generally ranges from -11 to -14 in $\delta^{18}O$ values. Some deeper aquifers, like the Wahpeton Buried Valley aquifer, have most of the samples showing $\delta^{18}O$ values between -11 and -13. An aquifer with one of the colder documented $\delta^{18}O$ signatures is the New Rockford aquifer, which has a range of values of -13 to -18.

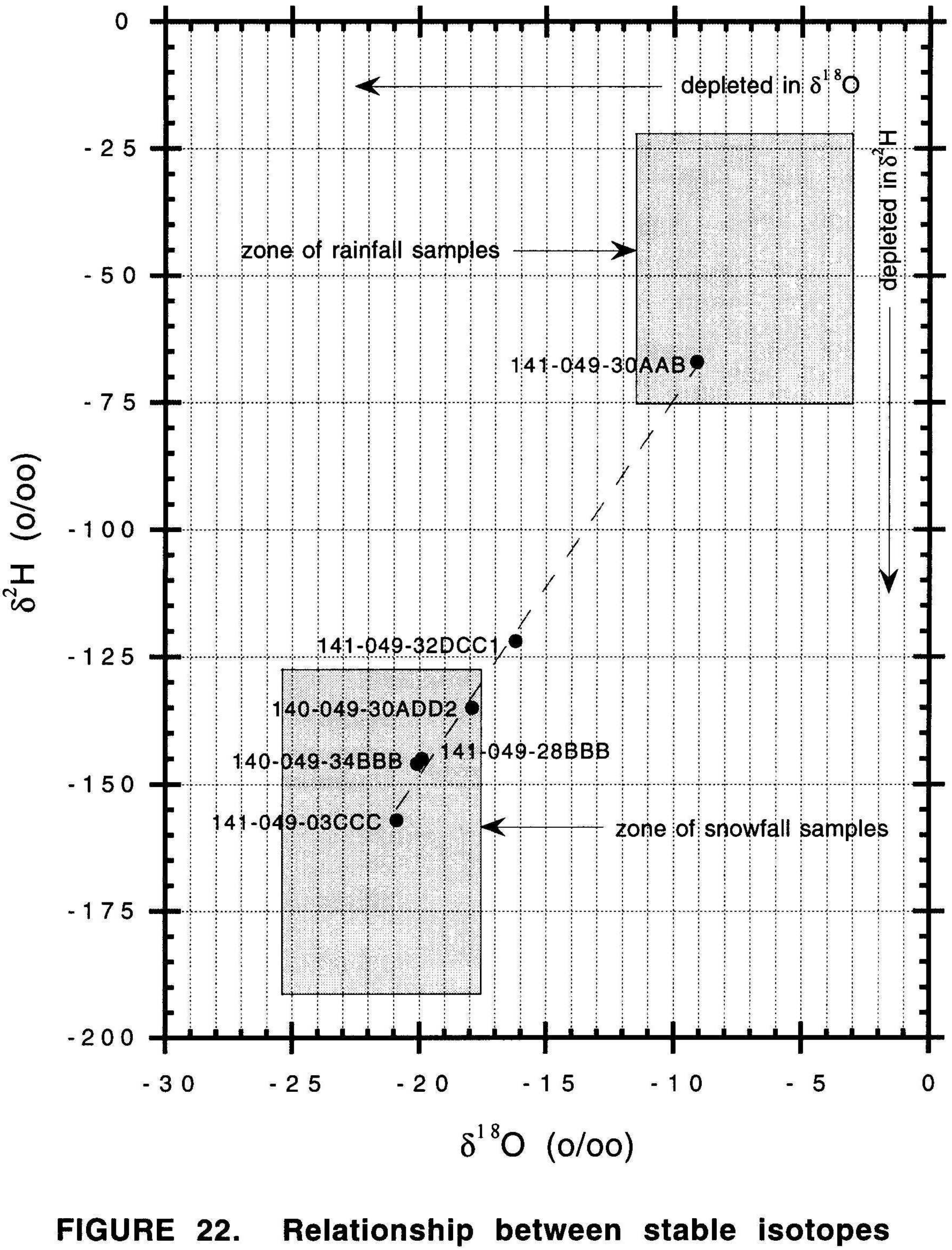


FIGURE 22. **Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the West Fargo North aquifer and precipitation at Oakes, N.D.**

The range of values for $\delta^{18}O$ in the WFN aquifer, as stated earlier, is -16.2 to -20.9. This range of $\delta^{18}O$ values is strikingly cold in its signature. This range does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely that the aquifer is receiving any significant amount of meteoric water as recharge. It is possible that there is slight recharge in the vicinity of 30AAB, however, a more likely explanation for this anomalous value is that the well was overtopped, and the water in the well was adulterated. Currently the isotopic values of water samples collected from WFN wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the WFN aquifer.

Ground-water movement

It is not possible to reconstruct the predevelopment system of ground-water movement for the West Fargo North aquifer. Very little data exists to determine the nature of the ground-water movement before any use was made of the West Fargo aquifer system. Knowing that water moves under the force of gravity from higher to lower locations, a couple of possibilities exist.

The first possibility is that upon the burial of the WFN aquifer by the activities of the glacier(s) and the subsequent development of Lake Agassiz, the water in the aquifer was trapped, and could not escape very easily through the overlying clays (deposited at the bottom of Lake Agassiz) and overlying tills (deposited by the receding glaciers). The water trapped in the aquifer in this process is referred to as 'trapped Pleistocene water'. When Lake Agassiz was fairly deep or when the ice sheet was thick, the water in the underlying aquifers would have been pressurized, due to the heavy overlying weight.

After Lake Agassiz drained, the movement of ground water would have been upward through the till and lake clay. The ground water moved very slowly, but eventually this trapped water might have reached the land surface. At the land surface this slow seepage would most likely have been removed by evapotranspiration, however some small accumulations could have occurred in the low-lying areas at the land surface, especially in the winter and early-spring time periods when evapotranspiration processes would be at a minimum.

Because water levels in the aquifer would be indirectly controlled by the overlying topographic surface, features like the Sheyenne and Red rivers, and the Red River valley would influence the ground-water movement. Not only would there be a vertical aspect to the flow system, but there would also be an east component of movement (towards the Red River), and a north component of movement (towards the lower part of the Red River valley).

The second possibility is that there were enough distributed sand and gravel bodies dispersed in the low-permeability tills and lake clays, such that lateral recharge could occur. In this scenario, recharge could occur on higher ground laterally away from the ground overlying the WFN aquifer. This recharge might occur where sands and gravels are located at or near the surface, and through a somewhat circuitous route of sand and gravel layers, the water could drain down and laterally into the WFN aquifer.

The most likely direction for this would be from the west where the higher ground is closest. Since the lowest place in the study area is the Red River, it follows that similar circuitous paths could exist for the water under pressure in the WFN aquifer to eventually seep out of the aquifer laterally towards the river bed of the Red River. Current data does not indicate that this process happened to any meaningful degree.

Water-level data clearly shows that the water in the WFN aquifer was under pressure in the 1870s, and that when wells were first completed into this aquifer the water flowed at land surface. Through the late 1800s it is likely that the number of wells continually increased, and it is also likely that some of these wells were initially allowed to flow unrestricted. This would have meant an increase of the movement of water out of the WFN aquifer. The increase in the flow of water out of the aquifer would have resulted in lower water levels.

Eventually, as more and more wells had water levels that approximated land surface, this rate of use could, presumably, have decreased. The rate of use would have decreased because the lowered water levels would have resulted in lower flows, and also because eventually the flows would stop, pumps would be installed, and the water would come out of the well in the aquifer only when the well was pumped. As mentioned earlier, Dennis et al (1949) made note that the period of 1885 to 1910 was a time period where there was no great lowering of the water levels in the area.

After 1910, some of the aquifers in the area began to be used to a more significant extent. Municipalities and industries were beginning to construct high yield wells. Those aquifers that were being used more extensively (like the Moorhead West and the Fargo) experienced significant water-level declines. This in turn could have caused water to drain from some of the aquifers that had higher water levels. The WFN may have been affected in this way.

During the time period from the 1910s until 1936, the ground-water movement in the aquifer may have gone from the WFN to other sand and gravel units that were connected to aquifers with lower water levels. Part of the movement of ground water out of the WFN aquifer also would have come from the numerous individual wells drilled into the WFN aquifer that were supplying water to individual homes, farmsteads, and businesses.

Whether there was recharge coming into the WFN over this time period is unclear. With all of the test drilling that has been done in the area of the WFN aquifer, there has been no indication of a shallow, surficial aquifer that could act as a conduit between the land surface, and the buried WFN aquifer. Any significant, vertical, downward, recharge into the aquifer is extremely improbable.

If there was any recharge to the system, lateral recharge is the more probable (though not necessarily probable) possibility. Water-level records that post-date this 1910 to 1930s time period show that the adjacent aquifers have experienced declining water levels during time periods when the use of water from that adjacent aquifer was minimal. The process of having lateral recharge coming into the WFN aquifer was most likely occurring during this time period. It is also probable that some ground water flowed out of the WFN aquifer into other aquifers with lower water levels, as well as some ground water flowing into the WFN aquifer from other aquifers that had higher water levels.

A key question that is, as yet, unanswered, is whether this lateral movement of ground water from an adjacent aquifer into the WFN aquifer represents true recharge. 'True recharge' in a traditional sense meaning precipitation infiltrating at land surface and flowing downward into the WFAS via whatever route or routes possible. In the setting of the WFAS, it is quite possible that this inflow does not represent snowmelt and/or rainfall moving or migrating into the flow system from the land surface. Instead this 'apparent recharge' (inflow) represents trapped Pleistocene water simply being transferred from one aquifer (including bedrock aquifers) to another.

The mechanism for transfer would be the difference in water levels from one aquifer to another. Once one aquifer in the WFAS was utilized as a significant source of water, the water levels in that particular aquifer would lower at a quicker rate than the water levels of adjacent, lesser-used, aquifers. Once the water-level differential (hydraulic gradient) between the two aquifers was large enough, the movement of ground water could occur from the aquifer with the higher water levels to the aquifer with the lower water levels. There is very little data to demonstrate this process before 1936, but after 1936, and especially after 1964, water-level data strongly supports the idea that this aquifer-transfer process is occurring in the WFAS.

In 1936 high yield wells were installed into the WFN aquifer, and municipal and industrial entities started to withdraw significant quantities of water from the WFN aquifer. As seen in figure 10, water levels started to decline at rates of 4 to 5 feet per year for about 10 years. Water use increased from about 25 million to over 200 Mg per year over this time period. Since 1936 the primary discharge from the WFN has been through wells, and the lowering water levels since that time show that the inflow into the aquifer has been less than what has been removed. The limited recharge that has occurred has come from one or more of several possible sources.

One possible source is the lateral movement of ground water from other aquifers with higher water levels that were discussed earlier. The lowering of water levels in relatively unused aquifers, and the somewhat similar and parallel hydrographs of two or more adjacent aquifers indicate that the lateral movement of ground water is a most likely possibility. A second possibility is direct recharge from the land surface that was also discussed earlier. No data currently supports this possibility.

A third possible source of additional water coming into the WFN aquifer is leakage from some of the less-permeable materials (lithologies) that surrounds the WFN aquifer. The main lithologies that surround the WFN aquifer are: a) the lake clay that generally overlies the aquifer; b) the till that is found above, beside, and beneath the aquifer; c) the Cretaceous clay, silt, shale, and the very occasional sandstone that lie beside and below the aquifer, and d) the Precambrian igneous and weathered igneous rock that also lie beside and predominantly below the aquifer. With the exception of the occasional Cretaceous sandstone, all of these lithologies have relatively small hydraulic conductivity values.

These lithologies (with the exception of the Cretaceous sandstone) cannot transmit ground water as fast as the aquifer sand and gravel lithologies. However, over a relatively large time period these lithologies can transmit significant amounts of ground water. As a result, these lithologies are classified as aquitards. Ground water stored in aquitards can, under some circumstances, leak out of these aquitards into the adjacent aquifers.

The relatively small hydraulic conductivity means that water does not move through the aquitard very easily. However, the water does in fact move through the material, even though that movement might be quite slow. Over a long time period, pseudo equilibrium is reached, where the water levels in the aquitards are almost as high as they are in the more permeable aquifers. Again, this is with the assumption that the primary reason for the WFN aquifer water levels being above land surface is that the overlying lake clay and till traps the water in the aquifer.

Once aquifers in the WFAS were utilized as water sources, and the water levels were lowered in aquifers like the WFN aquifer, the aquitards would have higher water levels than the aquifer. The small-hydraulic-conductivity lithologies would give up water much less easily than the aquifers. However, the surrounding aquitards would eventually give up some water to the aquifer, and this is an additional source of ground-water movement into an adjacent aquifer like the WFN.

The net result, in summary, is that only the discharge out of the WFN aquifer is known very well. This discharge is basically the sum of the water pumped from all the wells completed in the WFN aquifer. The only nearby aquifer with water levels lower than the water levels in the WFN aquifer is the Fargo aquifer. Two aquifers (the Nodak and the WFS aquifers) lie between the Fargo and the WFN and they both have water levels higher than either the WFN or the Fargo aquifers. Thus, it is quite unlikely that any ground water is currently moving from the WFN to the Fargo aquifer.

The inflow into the WFN aquifer is very poorly known. Any nearby aquifers with higher water levels (most) could be contributing water to the WFN aquifer, as well as the aquitards that surround the WFN aquifer. The only thing known for sure is that the recharge to the WFN is significantly less than the discharge from it, because the water levels continue to decline.

FARGO AQUIFER

Aquifer size and location

The map in figure 23 shows the area that is underlain the Fargo aquifer. This is the smallest aquifer that will be discussed in detail among the aquifers in the WFAS. The Fargo aquifer is only about one-half square mile in areal extent. The Fargo aquifer is smaller than some aquifers that will not be discussed. The reasons the Fargo aquifer will be discussed in detail despite the small size are the uses (past and present) that have been made of the water from the Fargo aquifer, and the impacts of that use. The impacts on water levels in this area resulting from utilization of different wells give insights on the complexity of some of the different nearby aquifers.

The north aquifer boundary of the Fargo aquifer appears to be in the vicinity of 11th Av. North, between 25th St. and 32nd St, in the northeast quarter of section 2 (T139N, R49W). Measurements of water levels in 1940 from a well located near 10th Av. N. and 27th St. show a good connection to the area near the Fargo city well (139-049-01CBD2) that was being pumped at that time. The city well is located near 1st Av. N. and 22nd St. in the southeast quarter of section 1. The aquifer may occur a little further to the north, but there is no data available to show that it definitely does.

To the east, test holes located near the intersections of 7th Av. N. & 25th St, 7th Av. N. & 22nd St., and 11th Av. N. & 19th St., all show little or no aquifer material. These test holes are all located in the northwest quarter of section 1. Additionally, further south and east, test holes near the intersections of 7th Av. N. & 19th St. and 7th Av. N. & 17th St. showed little or no aquifer material. There are no indications of the Fargo aquifer in the northwest quarter of section 1.

The south part of the Fargo aquifer does not appear to extend much beyond Main Street. There is one lithologic log of a well located near Main St. and 25th St. that

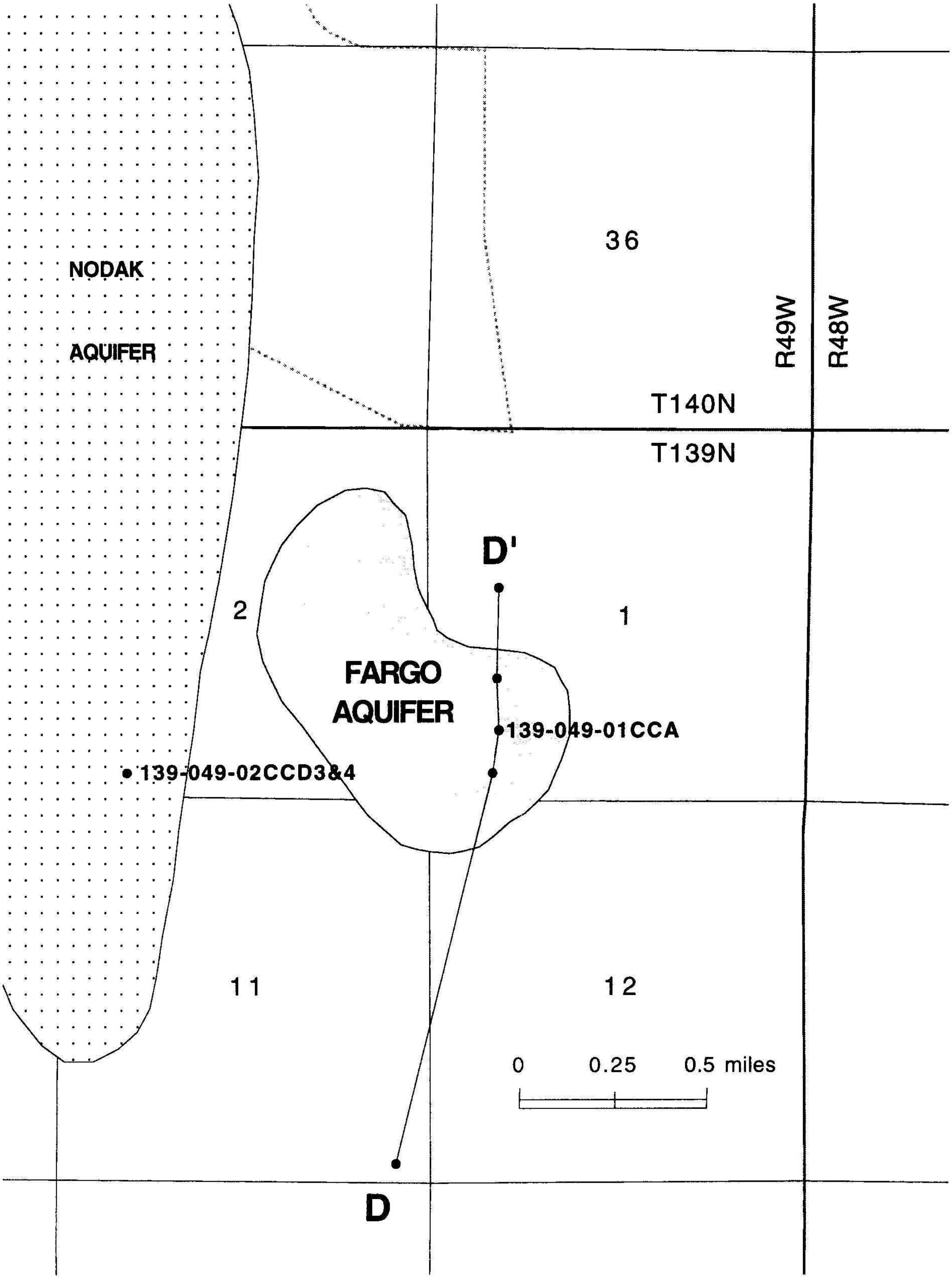


FIGURE 23. Location of the Fargo aquifer and geologic section D-D'.

shows sand from 140 to 170 feet. This site is located in the northeast corner of section 11, and is the only evidence that the Fargo aquifer occurs south of Main Street. Otherwise, two other test holes located south of Main Street show no aquifer. These test holes are near the intersections of Main St. and 27th St and 1st Av. S. and 21st St.

There is little available lithologic data on the west side of the Fargo aquifer to clearly delineate the western boundary. There is, however, a significant difference between the water-level elevation in the Fargo aquifer, and the water-level elevation in the Nodak aquifer since 1982. The observation well 139-049-01CCA (Fargo aquifer) has had water-level elevations ranging from about 25 to 35 feet lower than the water-level elevations in observation wells 139-049-02CCD3 and 4 (Nodak aquifer). Figure 23 depicts the location of the two sites, and shows that there is about 1-mile distance between these sites. The hydraulic gradient between these two wells averages about 30 feet per mile, which is a hydraulic gradient that indicates a poor hydraulic connection. For this reason the western margin of the Fargo aquifer is believed to be around the middle of section 2.

Eleven test holes and wells located in the Fargo aquifer were investigated. Of these, four did not have a lithologic log. The descriptions of the remainder showed that the material in this aquifer is comprised predominantly of sand and gravel. The sand is at times fine to medium, but more often the sand is medium to coarse, often grading into gravel (particularly with additional depth). The sand described in the logs is usually described as being fairly well sorted, although the sand is sometimes described as being poorly sorted and not as permeable.

Based upon lithologic logs for seven test holes and wells the average thickness of the Fargo aquifer is estimated at about 39 feet. There are sand lenses described above some parts of the Fargo aquifer in about six of the seven logs. Most of these lenses are probably not connected to the aquifer. This results in an average thickness of about 40 feet for the WFN aquifer.

The top of the aquifer is usually encountered at an average depth of about 141 feet, with the highest and lowest values being 125 and 155 feet below land surface. The bottom of the aquifer is encountered at an average depth of 180 feet below land surface, with the minimum and maximum values ranging from 135 to 204 feet below land surface.

Figure 24 shows a geologic section (D-D') of the Fargo aquifer. The geologic section and the map view show the aquifer to be quite small. With a thickness of about 40 feet across an area of about one-half square mile, the approximate volume of the Fargo aquifer is 0.5 billion cubic feet. A discussion later in the report will discuss the relationship between the volume of the aquifer, and the amount of water contained in this aquifer volume.

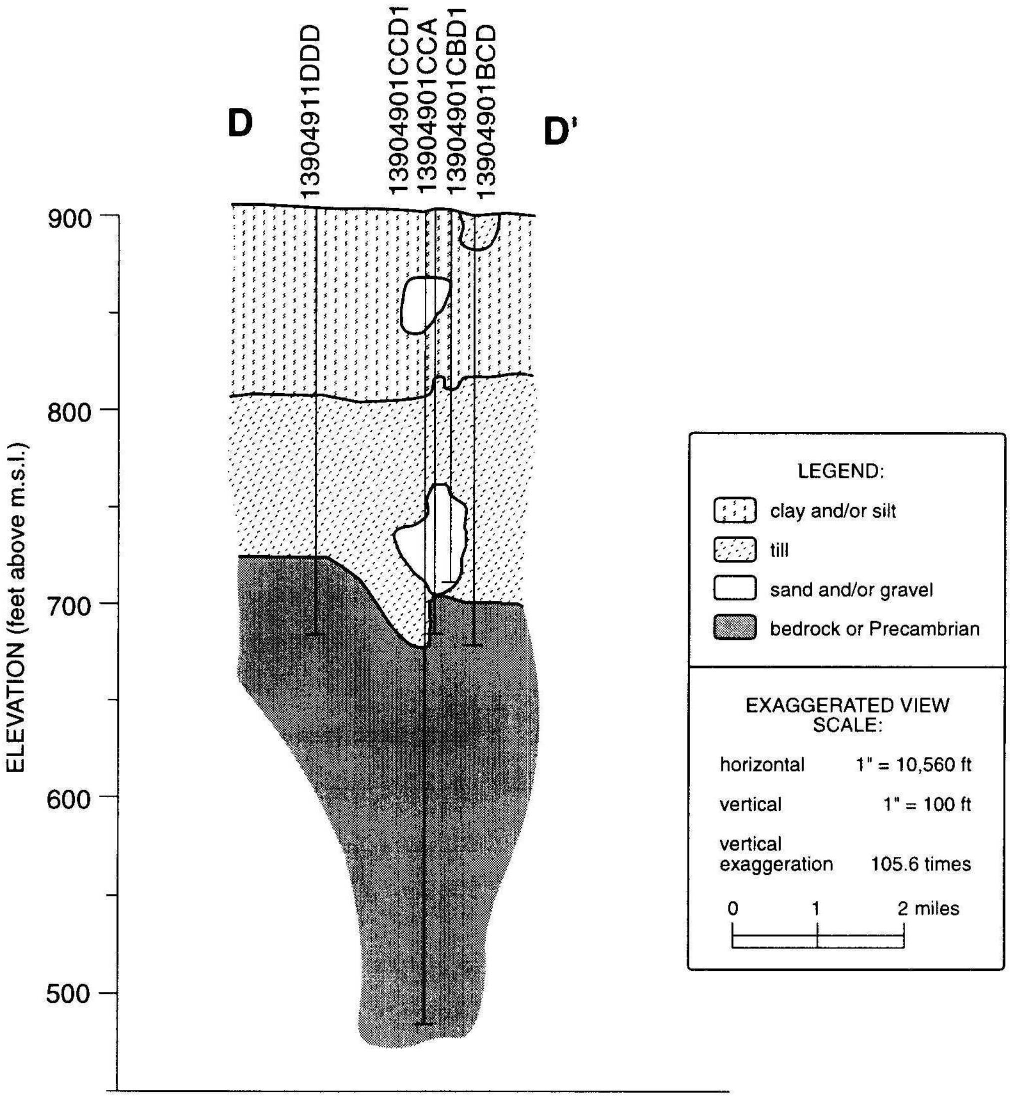


FIGURE 24. **South-north geologic section D-D' showing the Fargo aquifer.**

Aquifer water use and water-level history

The first documented well in the city of Fargo (but not located in the Fargo aquifer) was noted as having been installed in the summer of 1872. This well was in a location near 4th and Front streets (an intersection near Island Park that no longer exists). This 248-foot well was unproductive and was abandoned.

Byers et al (1946) report that several wells were later installed in an area bounded by 2nd Av. N. on the north, 9th Av. N. on the south, 16th St. on the east, and 21st St. on the west. These wells were located about one-half to three-fourths of a mile southeast of the Fargo aquifer. This early development is described as having occurred in the late 1800s and the early 1900s. The water derived "from these wells was hauled through the city in tank wagons and was sold door-to-door for drinking". It is quite likely that the use of these wells caused some indirect water-level declines in the Fargo aquifer. There are no water use figures for these wells.

Additional development of ground water in the area was occurring across the Red River in Moorhead during this same time period. The first well field developed in Moorhead was in the West Moorhead aquifer, near the old Fairmont Creamery Company. The volume of water pumped annually from the West Moorhead aquifer increased almost every year from 20 Mg in 1910, to about 120 Mg in 1927, when the city of Moorhead developed a second well field in the East Moorhead aquifer about a mile to the east. Water levels as low as 190 feet below land surface have been reported in the West Moorhead aquifer. It is likely that the low water levels in the West Moorhead aquifer affected the water levels in sand and gravel units between the Fargo and the West Moorhead aquifers, and ultimately lowered the water levels in the Fargo aquifer slightly.

Development of the Fargo aquifer to any significant degree started in 1938, when the only city of Fargo production well was completed. Figure 25 shows the annual use of the Fargo city well, 139-049-01CBD2, for the years from 1938 to 1952. Figure 25 also shows the annual water use of the Cass Clay Creamery well, 139-049-01CCA2, from 1983 to 1995. Most of Fargo's water use is included in the graph, but some of the use of the Fargo aquifer on the part of Cass Clay Creamery before 1983 is not available.

The water-level records for two Fargo aquifer observation wells (and one WFN aquifer observation well) are shown in figure 26. Water-level records from 1937 to 1956 are available for observation well 139-049-01CCD2, and water-level records from 1981 to 1995 are available for observation well 139-049-01CCA. Also shown on figure 26 is a hydrograph of observation well 139-039-06ADB, which had also been shown in figures 10, 13, and 14 in the discussion on the WFN aquifer. The water-level record for 6ADB will be used later for comparison.

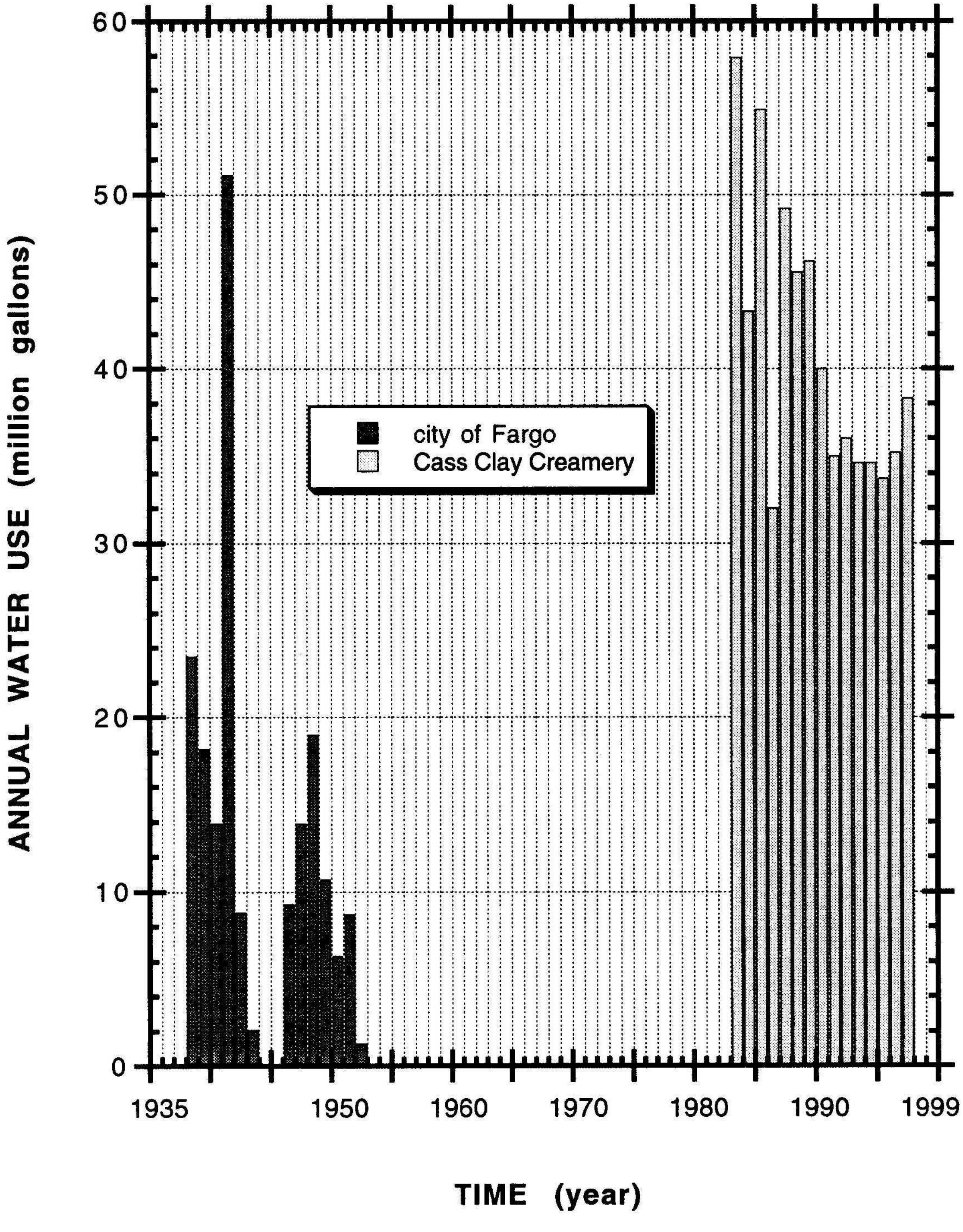


FIGURE 25. Annual water use from the Fargo aquifer.

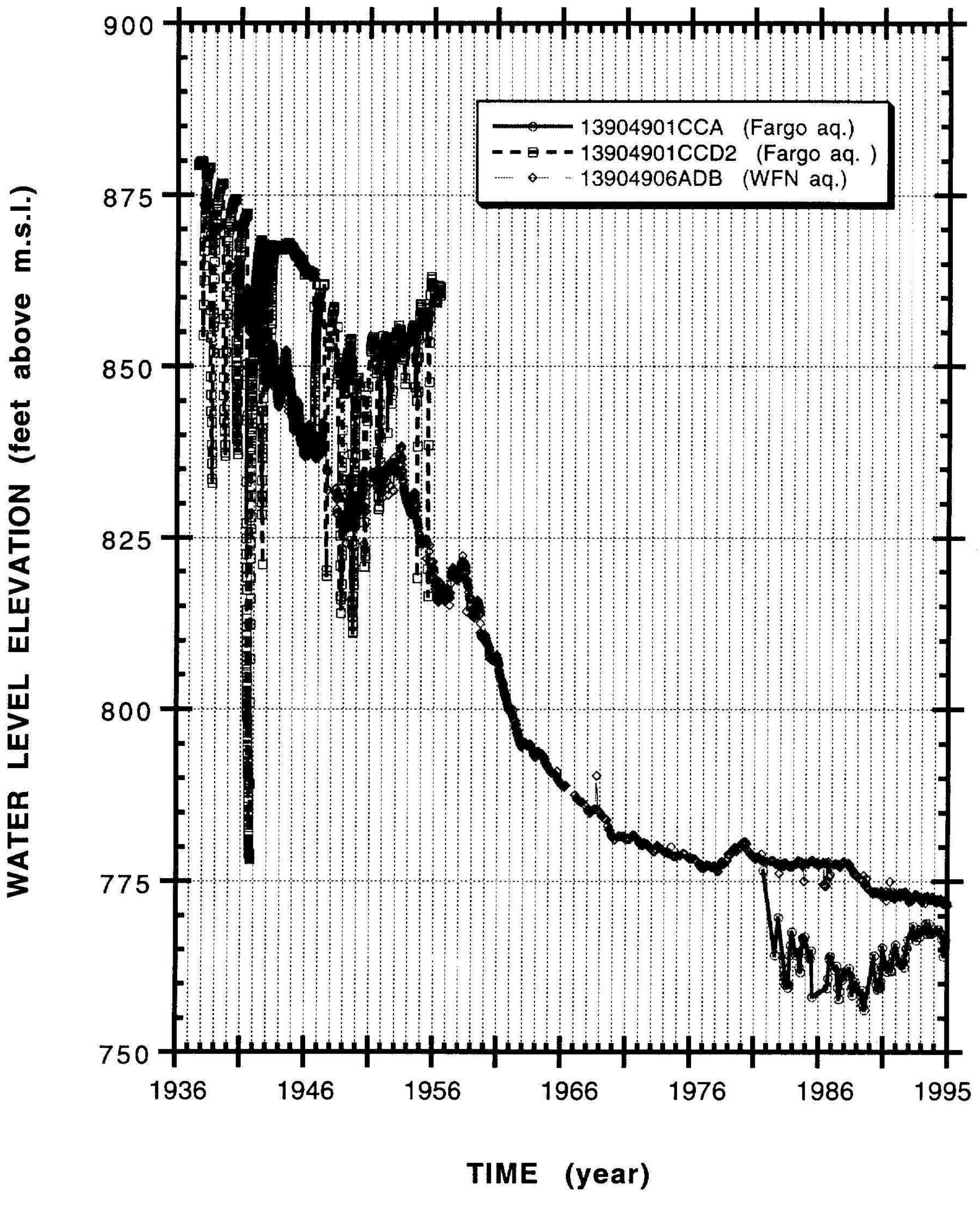


FIGURE 26. Hydrograph of selected observation wells from Fargo and West Fargo North aquifers.

When the city of Fargo began to use the Fargo aquifer in 1938, the water level was about 25 feet below land surface. Because only small amounts of water had been withdrawn by individual wells in the Fargo aquifer, it is thought that a significant portion of this approximately 25-foot decline was caused by the pumping of the wells that were described a few paragraphs earlier, that lie to the southeast and east. From 1938 until about 1948 there appears to be a fairly clear relationship between Fargo's ground-water use from the Fargo aquifer, and the water levels in well 139-049-01CCD2. In 1941 Fargo's annual use was the largest of any year from 1938 to 1952. The lowest water levels for that time period are also seen in 1941 (see figure 26).

After 1948 figures 25 and 26 do not show a clear relationship between water use and water levels. Other factors may be changing the previous pattern of more water use causing lower water levels. Water use in 1949 was about 55 percent of water use in 1948, and yet water levels went down about 5 feet in the Fargo aquifer. There are several possible explanations for this change. It is possible that the water-use records are erroneous. It is also possible that other unknown wells within the Fargo aquifer are producing significant amounts of water at this time. A third possibility is that increased pumping from wells located in other nearby aquifers results in lower water levels in those nearby aquifers that indirectly causes an additional decline in water levels in the Fargo aquifer.

Until 1953 it appears as if the lowering of water levels in the WFN (as indicated by the water-level records of 139-049-06ABD) could be causing the decline in the water levels of 139-049-01CCD2 in the Fargo aquifer (see figure 26). However, the time period from 1953 to 1956 does not show the same possible relationship. The similar water-level pattern for the period 1938-53 appears that it might be a coincidence. Additionally, figure 26 shows that the WFN aquifer has displayed higher water levels than the Fargo aquifer from 1981 to 1995. The reversal of which water level is higher and the dissimilar pattern of water levels indicate a limited hydraulic connection between these two aquifers. It is not clear why Fargo aquifer water levels do not correspond well to Fargo aquifer water use since 1949.

There is some missing water use data from the time period of 1952 to 1982. Klausing (1968) reports that the Cass-Clay Creamery began using the Fargo aquifer June 1, 1956. In the time period from 1956 to 1965 Klausing estimates that about 19.9 million gallons per year were used based upon the volume of wastewater discharged into the Fargo sewer system. This is the only estimate of water use for the Fargo aquifer during this time period.

By using two observation wells, 139-049-01CCA and 139-049-01CCD2, the average water-level decline for the Fargo aquifer for the 60 years from 1936 to 1995 is about 1.9 feet per year. Over the last 15 years the average decline has been about 0.7

feet per year. Over the last seven years the water level has actually risen about 0.5 feet per year. This is due to the recovery of the aquifer from a time period of heavier pumping in the 1980s (see figure 25).

Aquifer water chemistry

Figures 15 to 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The second aquifer shown in each figure is the Fargo aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The Fargo is one of these aquifers, with only three sites being represented.

Figure 15 shows that the Fargo aquifer is relatively low in calcium concentration in comparison to other aquifers in the area. The WFS, the 94/10, and the WFN aquifers show lower concentrations. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the Fargo aquifer is relatively low in chloride concentration in comparison to other aquifers in the area. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. No sites had chloride values near 250 mg/liter.

Figure 17 shows that the Fargo aquifer is in the low range of the group of nine aquifers with respect to hardness. Even though Fargo aquifer hardness is in the low range among the WFAS aquifers, the median value of the Fargo aquifer hardness (about 180 mg/liter) just falls into the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the Fargo aquifer is in the middle of the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the Fargo aquifer is about average in comparison to other aquifers in the area with respect to sulfate concentration. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. All sites and all samples from all sites in the Fargo aquifer had sulfate concentrations below the lower SMCL sulfate value of 250 mg/liter. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the Fargo aquifer is relatively low among the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Sometimes referred to as salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites of the Fargo and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants.

The water in the Fargo aquifer is a sodium type, with no dominant anion, although anion concentrations in the water samples tend more towards bicarbonate than sulfate. The total dissolved solids generally range from 700 to 800 mg/liter, and the water is generally hard to very hard. The water is suitable for most purposes. No samples were drawn from the Fargo aquifer for the stable isotope analysis of oxygen and hydrogen.

Ground-water movement

There are no specific records (as there were with the WFN aquifer) to show that the Fargo aquifer once had water levels that were above the land surface. All indications, however, show that the likely scenario is that at the time that the WFAS was first utilized as a source of water, the water levels in all of the WFAS aquifers were above land surface. The flow system at that time would be very similar to what was described earlier for the WFN aquifer, except that because this aquifer is so small, the north and east components of ground-water movement would likely be minimal, because there was little topographic variation in the overlying land surface. A few domestic wells would lower the water level slightly, and as more wells were installed and utilized, the water level would eventually approach land surface, and then drop below the land surface.

There are no records showing that any large yield wells were producing water from the Fargo aquifer before 1938. Even though only small amounts of water were being withdrawn from the Fargo aquifer, water levels in the Fargo aquifer were over 25 feet below land surface in 1937. It is likely that indirect connections to wells in an undefined aquifer to the southeast, and wells completed in the West Moorhead aquifer to the east, led to leakage from the Fargo aquifer to these two areas. Both areas were being utilized as a source of community water, and that utilization would have led to larger drawdowns in those aquifers. The anticipated low water levels were documented in the West Moorhead aquifer. With water levels higher in the Fargo aquifer, this led to leakage out of the Fargo aquifer into adjoining areas of greater water use.

After 1938, and the utilization of the Fargo aquifer as a water supply for the city of Fargo, the water levels in the Fargo aquifer indicate that most of the water moving out of the Fargo aquifer was being pumped out of the aquifer by the production well 139-049-01CBD2. Instead of most or all of the water moving out of the Fargo aquifer into areas to the east and southeast, it is likely that a lesser amount of ground water flowed towards the east from the Fargo aquifer. Additionally, some ground water flowed into the Fargo aquifer from the southeast and the Nodak aquifer (see figure 23).

Low water levels in the West Moorhead aquifer would have maintained the hydraulic gradient from the Fargo aquifer to the West Moorhead. Static water levels in the East Moorhead aquifer ranged from 115 to 135 feet in 1934 and 1935. It is likely that since the East Moorhead aquifer wells came on line from 1927 to 1932, that water levels in the West Moorhead aquifer were at or below the depths measured in the East Moorhead. Thus, a significant hydraulic gradient between the West Moorhead and the Fargo aquifers still existed, such that there would have been some ground-water movement from the Fargo aquifer to the West Moorhead aquifer through the 1930s.

Because there are virtually no water level and water use records for the time period from 1956 to 1980, little can be stated definitively about the ground-water movement during this time. Based on the significant water-level change during that time period (about an 80-foot drop), and available records in other areas, a few things can be postulated. The significantly lower water level could have been caused by significant water use from the Fargo aquifer. Such a large use would most likely have been noticed and documented by one of the later studies. There is no known documentation of significant water use at this time. There are likely three main mechanisms by which ground water moved out of the Fargo aquifer in the time period up to 1981, which resulted in lower water levels.

The most dominant component of ground-water movement out of the Fargo aquifer was probably caused by the very low water levels in the West Moorhead aquifer. Water levels in the West Moorhead aquifer that were about 135 feet below land surface in the mid 1930s dropped to 190 feet by 1947 as reported by McLain (1977). After the city of Moorhead developed an additional ground-water supply from the Buffalo aquifer in 1948, use of both the East and West Moorhead aquifers was reduced, and static water levels rose to about 170 feet below land surface in the 1950s. At this level, water would still move from the Fargo aquifer to the West Moorhead aquifer.

The city of Moorhead began to incorporate surface water into their total water supply in 1961. This further reduced the use of the East Moorhead aquifer (use of the West Moorhead was discontinued in the early 1950s), and water levels were as high as about 160 feet below land surface through the 1960s. Use of the East Moorhead aquifer increased in the early 1970s, and water levels have generally been between 185 and 195 feet through the 1980s and the early 1990s. The water levels in the West and East Moorhead aquifers may have been the largest influence on water levels in the Fargo aquifer up to the 1980s, and possibly beyond.

The second main component of outflow from the Fargo aquifer up to 1981, might have been an indirect effect from the WFN aquifer through the Nodak aquifer. There are no water-level records for the Nodak aquifer during this time. The WFN hydrograph in figure 26, however, shows a water-level decline of about 50 feet in the time period up to 1981. The Nodak aquifer lies between the WFN and Fargo aquifers, and while there are no water-level records for this time period, subsequent water-level records do show that water levels in the Nodak aquifer are likely influenced by water levels in the WFN aquifer. Similarly, recent data shows that Nodak aquifer water levels in another part of the Nodak aquifer appear to be influenced by low water levels in the Fargo aquifer.

The pattern of movement of ground water through this time period (approximately pre-1950 to pre-1980) would have most likely been from the Fargo aquifer to the Nodak aquifer. This movement would have continued from the Nodak aquifer into the WFN aquifer, where it would have been drawn into one of the several WFN production wells in service through the 1950s, '60s, and '70s. There is no direct evidence during this time period that this was occurring, however, data before and after this time period suggests that it was likely.

The third factor that may have had a significant influence on the water levels such that they lowered to about 125 feet below land surface, would be utilization of the Fargo aquifer itself. Earlier it was stated that it was unlikely that the lowered water levels were due entirely to the ground-water withdrawals from the Fargo aquifer. It is possible, however, that the combination of several undocumented small uses of the aquifer, and some unrecorded utilization by the city and/or Cass Clay Creamery could have produced some of the 80 feet of water-level decline observed by 1981.

After 1981 the water levels in the Fargo aquifer have been lower than the water levels in the pumping center of the WFN aquifer. This means that ground water flows from the Nodak aquifer west to the WFN aquifer, but also from the Nodak aquifer east to the Fargo aquifer. It is probable that some ground-water flow also still occurs towards the West Moorhead aquifer, and ultimately to Moorhead's East Moorhead well field. The remainder of the ground water flow out of the Fargo aquifer is comprised predominantly of the withdrawals that are made from the Cass Clay Creamery Company well (139-049-01CCA2).

In summary, the current flow system for the Fargo aquifer consists of two significant outflows, and two significant inflows. Figure 25 shows the water use from the Cass Clay Creamery Company production well, 139-049-01CCA2 (1983-1995). This is one of the significant outflows. There may be a few other wells that currently produce water from the aquifer, but it is unlikely that they produce significant volumes of water. The only other significant outflow that may be occurring would be the leakage of water from the Fargo aquifer to the West Moorhead aquifer. Water levels in the West Moorhead aquifer are currently about 40 to 50 feet lower than the water levels in the Fargo aquifer.

The two inflows coming into the Fargo aquifer are leakage from the nearby Nodak aquifer, and leakage from the aquitards surrounding the Fargo aquifer. The same process of leakage from aquitards that was discussed in detail in the "Ground-water movement" section on the WFN aquifer occurs in the Fargo aquifer. Additionally, there are relatively permeable areas to the southeast from which water for municipal use was derived in the late 1800s and the early 1900s. These areas likely provide some recharge in the form of leakage to the Fargo aquifer.

As water levels in the area subside, this contribution of water from the surrounding aquitards to the recharge of the Fargo aquifer could lessen. Currently, however, the water levels in the Fargo aquifer are among the most stable in the area. There appears to be a relative balance between water coming into the Fargo aquifer, and water moving out of the Fargo aquifer.

NODAK AQUIFER

Aquifer size and location

The map in figure 27 shows the area that is underlain by the Nodak aquifer. This aquifer is one of the small aquifer units in the WFAS system. However, the

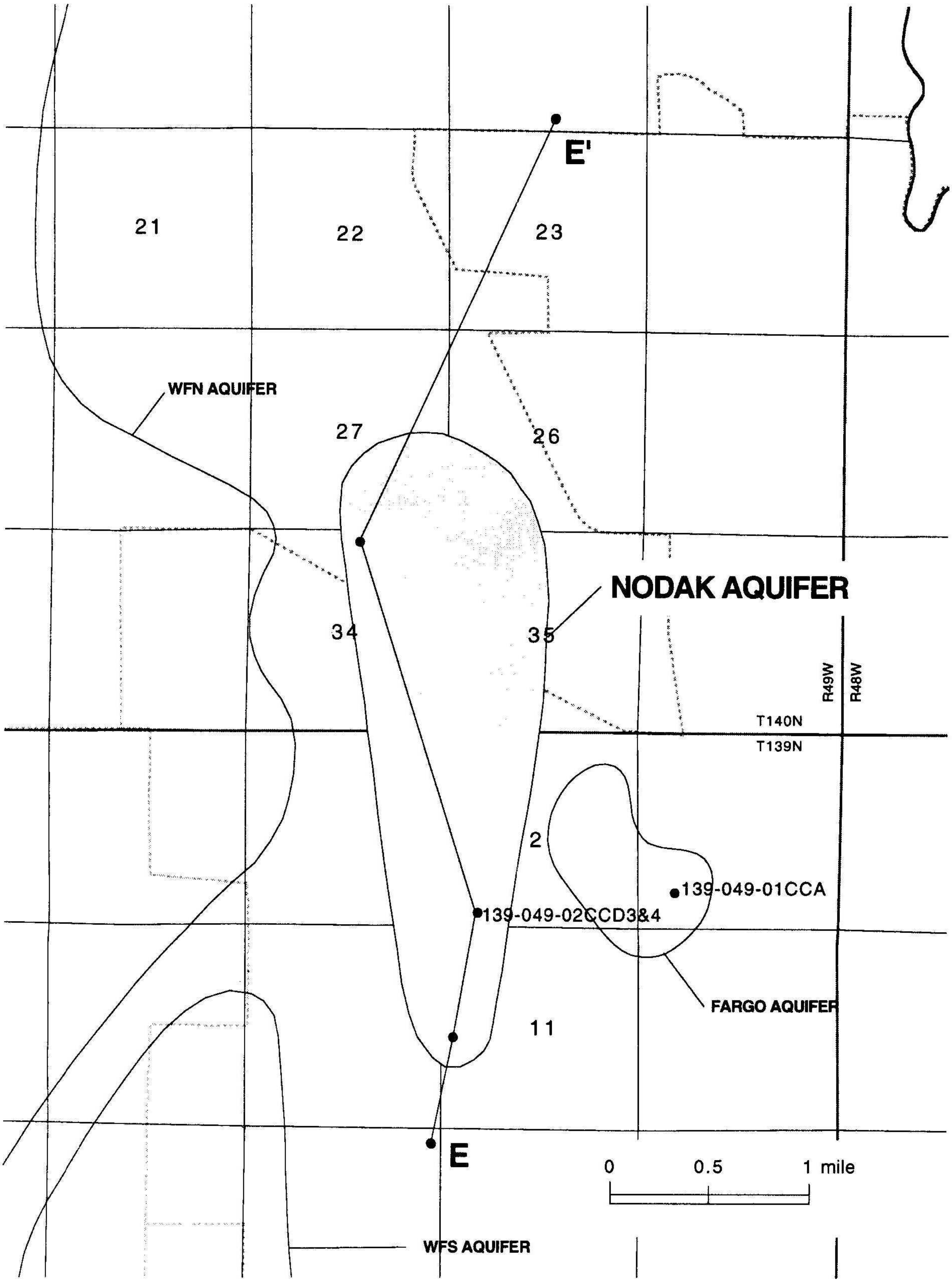


FIGURE 27. Location of the Nodak aquifer and geologic section E-E'.

relationship to two of the large aquifers (the WFS, and the WFN) and one of the most significant small aquifers (the Fargo) increases the importance of the Nodak aquifer.

The limits of the Nodak aquifer at the north end are not well defined. The limits of the Nodak aquifer are drawn as they are mostly on the basis of water-level patterns. Water levels from observation wells in the north end of sections 34 and 35 (T140N, R49W) show patterns that relate closely with water levels of observation wells in sections 2 and 11 (T139N, R49W). Thus the north end of the aquifer is drawn through sections 26 and 27 (T140N, R49W). It is possible that the Nodak aquifer could extend further to the north. There is a domestic well in the middle of the southern part of section 23 that has sand in the same interval as the northern part of the Nodak aquifer, however, the water level in that well in late 1996 was about 8 to 12 feet higher than the water levels in the northern part (about one mile south of the domestic well) of the Nodak aquifer.

The Nodak aquifer could also extend further to the north-northwest into the southwest quarter of section 22, which would place the aquifer just to the east of Reile's Acres. The Nodak aquifer could also be hydraulically connected to the small aquifer (Reile's Acres aquifer) that provides water for the subdivision in the southeast of section 21.

The eastern margin of the Nodak aquifer is based primarily upon lithologic records of several test holes that show little or no sand or gravel intervals. Additionally, there is the 25 to 35 foot difference in water levels between 139-049-02CCD3 and 4 (Nodak aquifer) and 139-049-01CCA (Fargo aquifer) that was discussed in the Fargo aquifer section. This difference indicates a poor hydraulic connection between the sand and gravel intervals of the two areas, thus indicating two different aquifers.

The south end of the Nodak is delimited with lithologic logs indicating an absence of permeable sands and gravels. Several lithologic logs also indicate an absence of sand and gravel units on the west side of the aquifer, except towards the north side of the western margin of the Nodak aquifer. Observation wells 140-049-34ABB2 and 3 (Nodak aquifer) and 140-049-34BBB (WFN aquifer) are about a half mile apart. There are no test holes between them with a lithologic log showing that the aquifer sections in the two sites are not continuous. However, the difference in the water levels between the two sites shows there is a hydraulic discontinuity between them.

Twelve test holes and wells located in the Nodak aquifer were investigated. Of these 12 test holes or wells, nine wells or test holes had a lithologic log. The deeper aquifer intervals found in sections 2 and 11 in T139N, R49W (Barnes Township) consist predominantly of sand with a little gravel described in some of the logs. The shallower aquifer intervals found in sections 34 and 35 in T140N, R49W (Reed Township) consist predominantly of gravel with sand described in some of the logs.

Figure 28 shows a geologic section (E-E') of the Nodak aquifer from south to north. This geologic section indicates hydraulic continuity between the shallow sand in the north and the deeper sand in the south. Hydraulic continuity is inferred because water levels and patterns of water-level fluctuations are similar in both areas. The actual deposition of the aquifer probably occurred at different times (at least two), and the shallow gravels were probably deposited on top of the earlier deposited sands of the lower part of the aquifer.

The average thickness of the Nodak aquifer estimated from the available logs is about 68 feet. The top of the aquifer is usually encountered at a depth of about 231 feet in Barnes Township, and at about 145 feet in depth in Reed Township. The highest top of aquifer occurs at 192 feet in Barnes Township, and at 126 feet in Reed Township. The bottom of the aquifer is usually encountered at an average depth of about 361 feet in Barnes Township, and at about 182 feet in depth in Reed Township. The lowest bottom of aquifer occurs at 426 feet in Barnes Township, and at 169 feet in Reed Township.

Based on an estimated average thickness of 68 feet and an areal extent of 2.6 square miles, the volume of the Nodak aquifer is about 5 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water in storage in this aquifer.

Aquifer water use and water-level history

No documented water use data for the Nodak aquifer is available. All documented wells in place before the 1950s in this area were shallow wells. In the 1950s and 1960s some wells were installed into the Nodak aquifer, however no water use figures are available for these wells. It is probable that these wells did not produce significant amounts of water. Production from the few non domestic wells in the Nodak aquifer may have caused small localized cones of depression, however large, aquifer-wide drawdowns were most likely not caused by pumping from the Nodak aquifer.

Water-level records for the Nodak aquifer begin in the 1960s with the publication of the Klausing report (1966). A few water levels in this area are available from Byers et al (1946) and Dennis et al (1949), however these water levels are all associated with unconnected shallow sand and gravel lenses that are above the Nodak aquifer. From the available records it appears that early wells installed in this area were predominantly shallow (20 to 90 feet), and that starting in the mid-late 1950s new wells in this area were installed into the Nodak aquifer (about 300 to 400 feet).

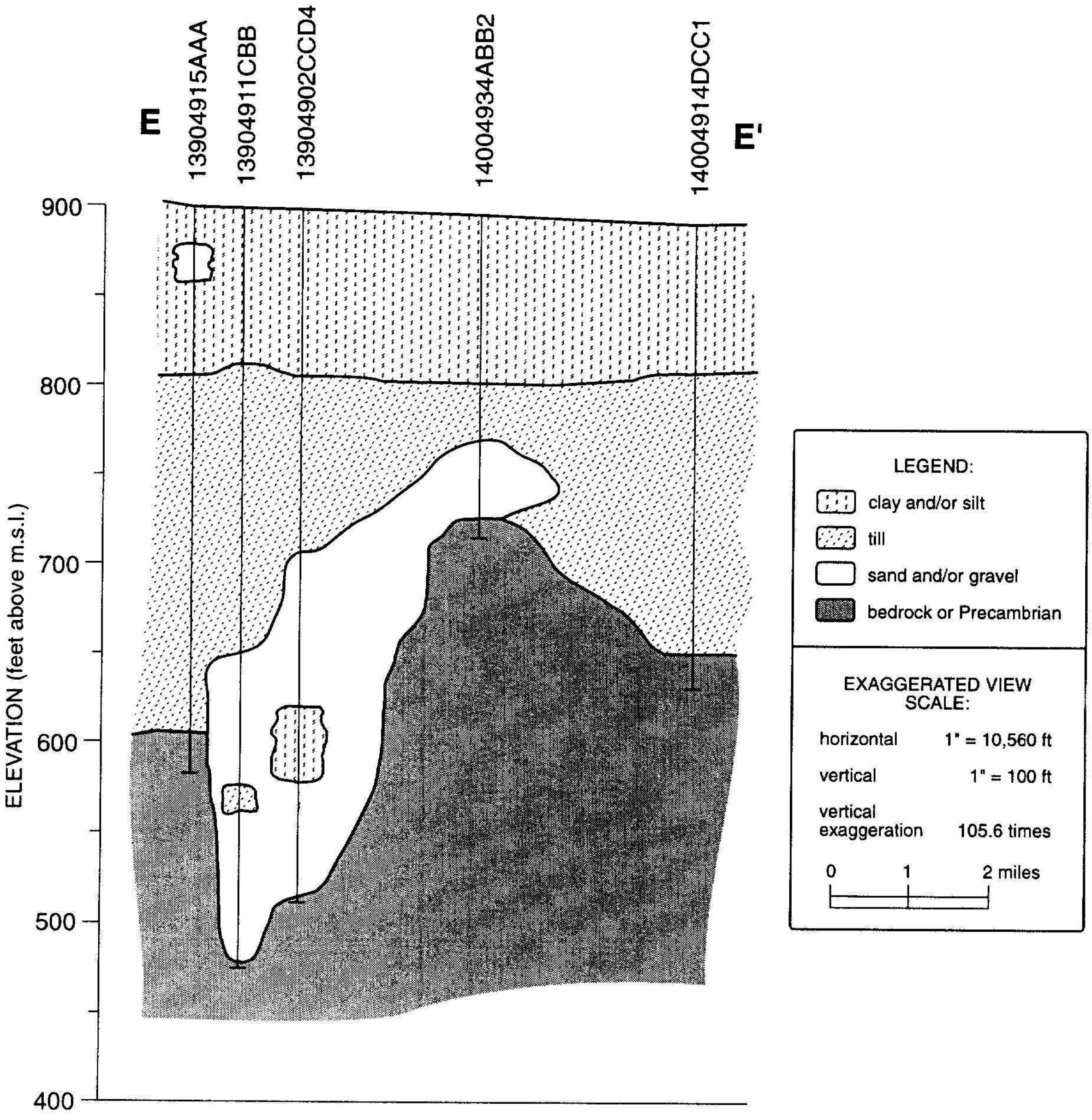


FIGURE 28. **South-north geologic section E-E' showing the Nodak aquifer.**

Regularly scheduled water-level measurements that are continuous to the present did not start until 1982. Figure 29 shows a hydrograph of four observation wells, and one production well that are located in three sites. The production well (139-049-02CCD3) is the well with the large annual fluctuations in water-level elevations. In 1990 an observation well (139-049-2CCD4) was installed near the production well to facilitate easier measurements. Observation well 140-049-34ABB2 was replaced by 140-049-34ABB3 in 1994. These two sites, along with the third site represented by observation well 140-049-35BAA are the three sites where water-level measurements have been made on a regular basis since 1982.

The hydrograph shows a declining water-level elevation for all three sites, and there is little indication that this decline is caused by utilization of water from the Nodak aquifer. The highest water levels among the three Nodak sites appear to be found at the 2CCD site in the early '80s, the 35BAA site in the mid-late '80s, and either the 2CCD or 35BAA site in the '90s. The lowest water levels are almost always found at the 34ABB site. This indicates that near the 34ABB site there is likely to be found an area into which the ground water of the Nodak aquifer is moving.

About a half mile to the west from observation wells 34ABB2 and 34ABB3 is observation well 139-049-34BBB completed in the WFN aquifer. Figure 30 is a hydrograph showing the water-level elevations for 34BBB as well as for the two wells at site 34ABB. Because observation well 34BBB was not installed until 1991, the water-level elevations of an additional, nearby WFN observation well (139-049-03BBB) are also included in figure 30. The water levels show that water could move from site 34ABB to 34BBB because the water levels are lower at 34BBB, however, the difference in the water-level patterns indicate that either they are not connected, or that there are other factors that complicate the flow system. Also, the water-level pattern for the 34ABB site show annual fluctuations that are larger than the annual fluctuations of the WFN aquifer in this area as indicated by the water-level patterns of 34BBB and 03BBB. This would not be the case, if leakage from 34ABB to 34BBB were the only reason water levels were declining in the vicinity of 34ABB.

Figure 31 shows a hydrograph of two Nodak wells at one site (2CCD) and an observation well in the Fargo aquifer (139-049-01CCA). The two sites are about a mile apart, however the Nodak site may be near a portion of the Nodak aquifer that is about a quarter of a mile away from a portion of the Fargo aquifer. Again, the water-level elevation of the Fargo aquifer observation well indicates that water could move from the Nodak aquifer to the Fargo aquifer. The hydrograph comparison in figure 31 also shows that the water-level patterns are not the same, and that if there is a hydrologic connection between these sites, it is complicated by other water-level influences.

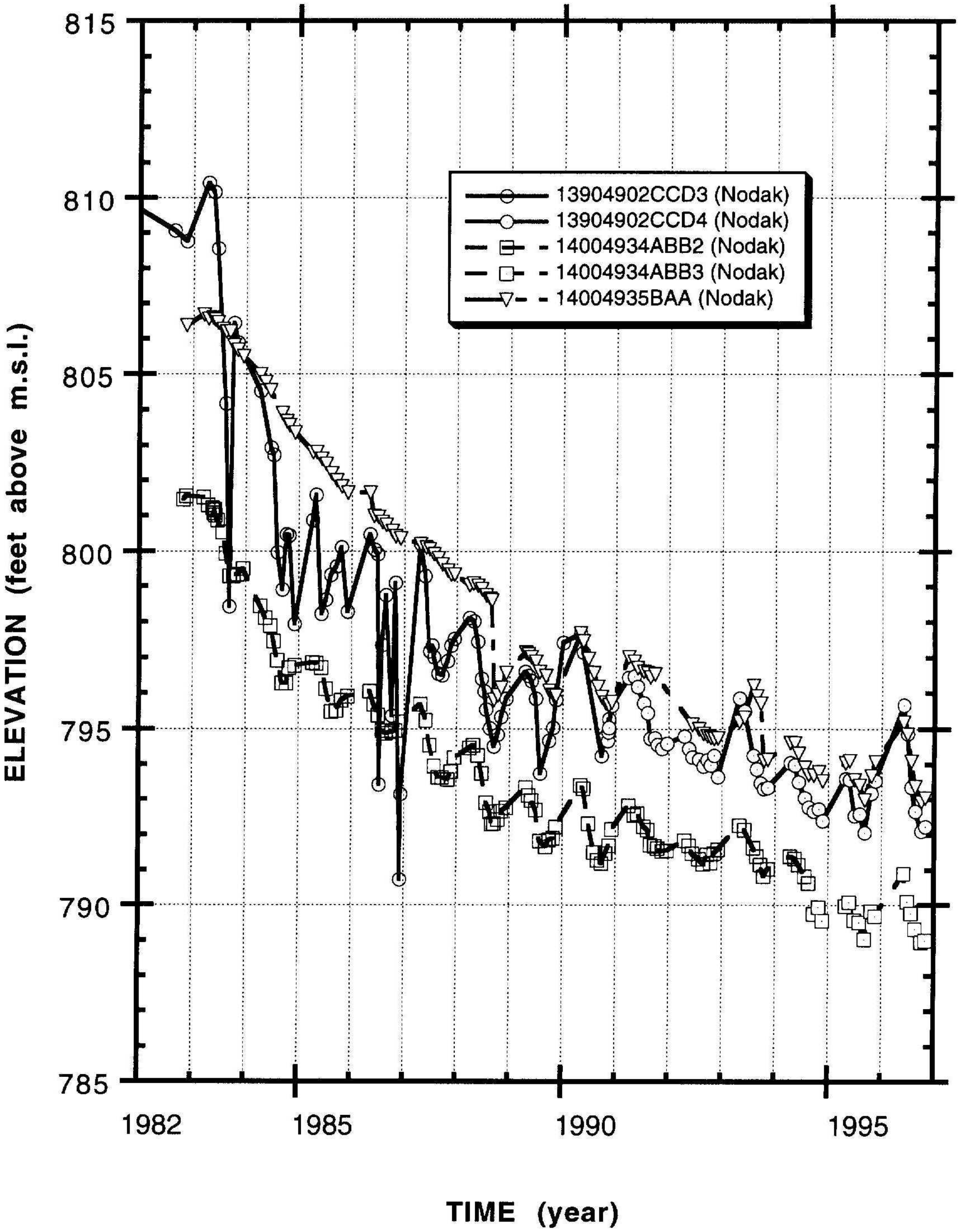


FIGURE 29. Hydrograph of observation wells located in the Nodak aquifer.

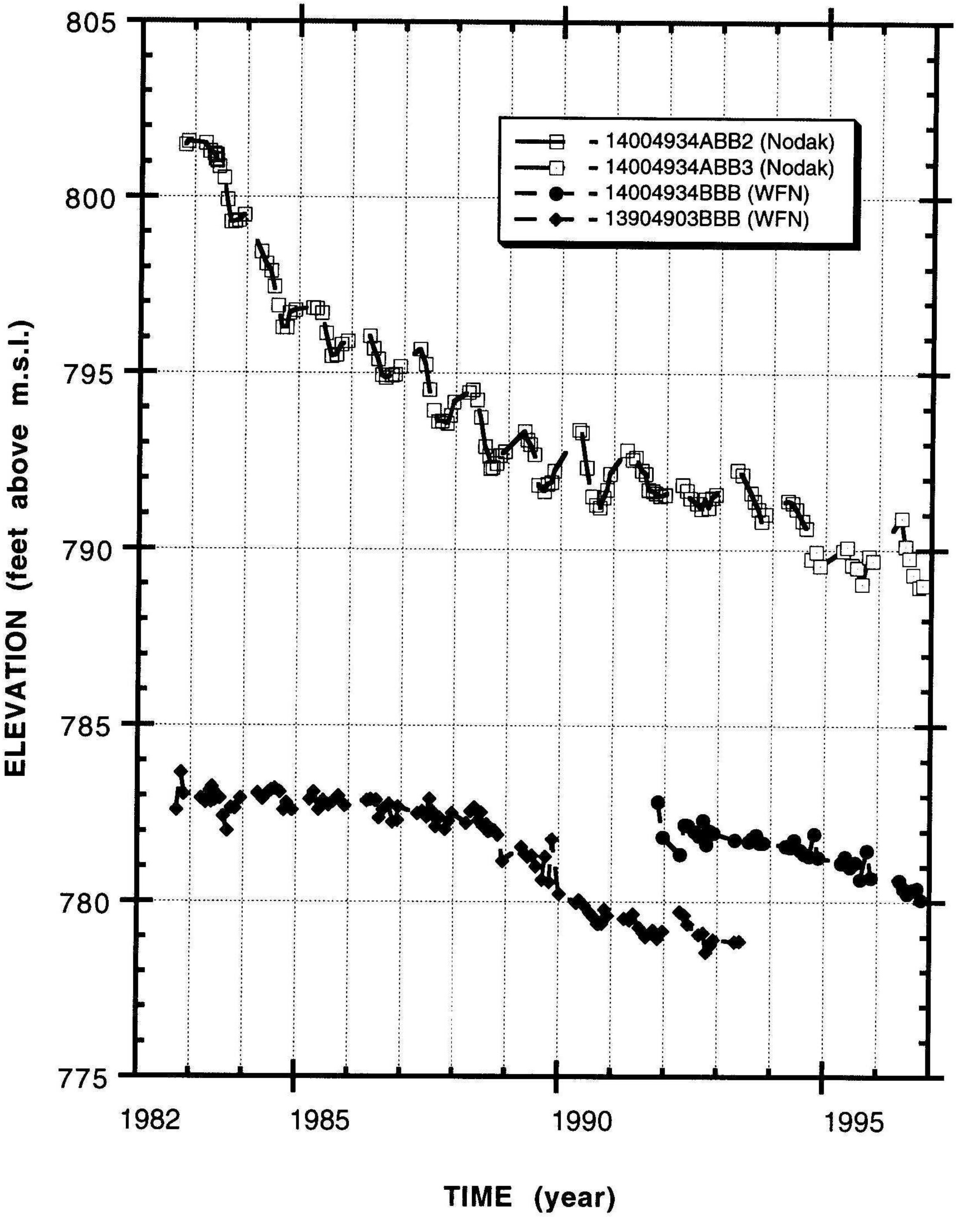


FIGURE 30. Hydrograph of observation wells located in the Nodak and West Fargo North aquifers.

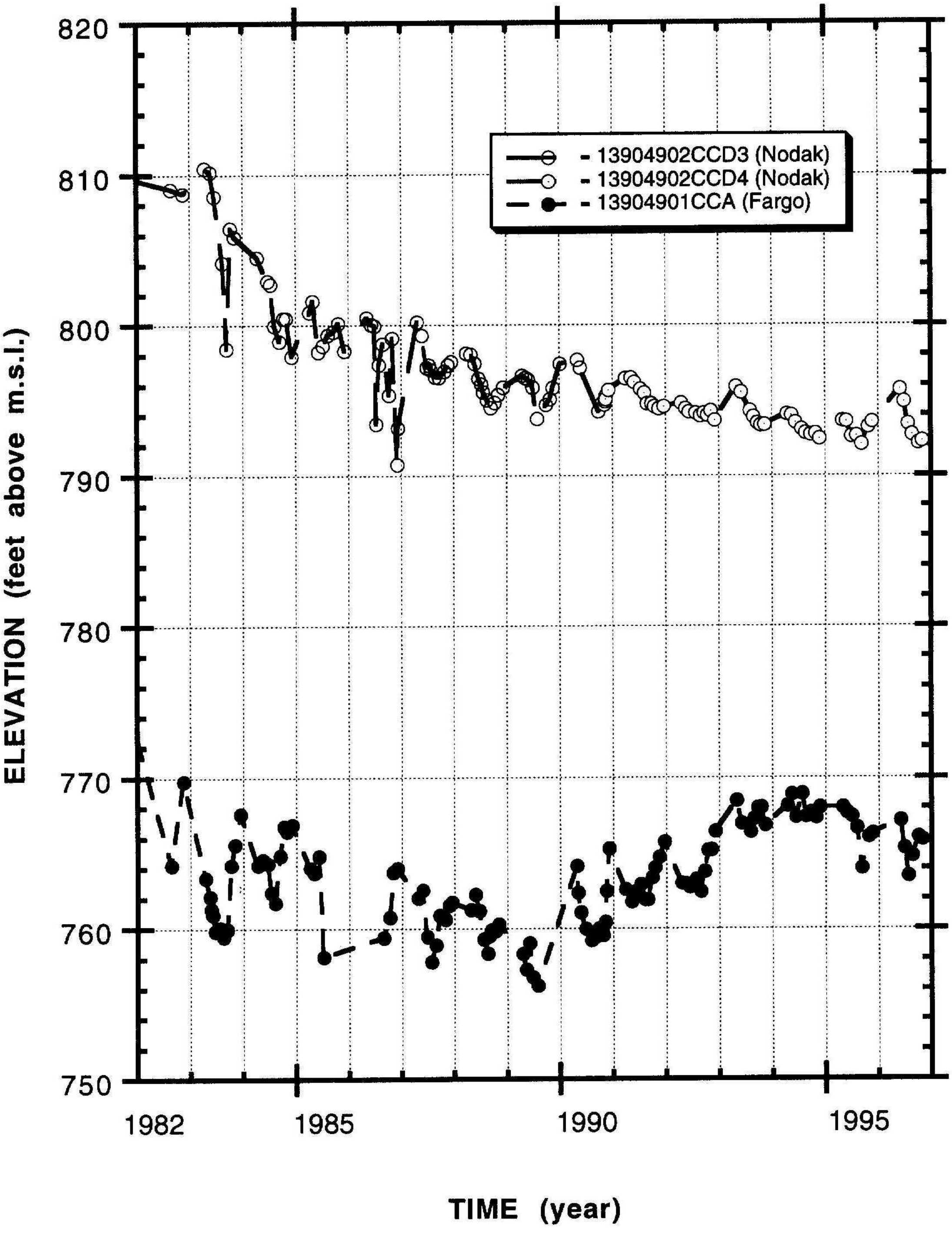


FIGURE 31. Hydrograph of observation wells located in the Nodak and Fargo aquifers.

Finally, figure 32 shows a hydrograph of the same two Nodak wells at one site (2CCD) along with an observation well in the West Fargo South aquifer (139-049-09ADD). In this instance the water-level elevations at the Nodak site are about 25 feet lower than the water-level elevations of the WFS aquifer observation well in the early 1980s. Once utilization of the new WFS aquifer well field began in 1983, the water levels declined almost 40 feet the first two years. During these same two years the water level in the Nodak aquifer went down about 12 feet in elevation. For several years the water-level elevations at both sites were quite similar, but since 1991 the water levels in the WFS aquifer have been lower.

For the 15 years from 1982 to 1996 the water levels in the southeast part of the Nodak aquifer (139-049-02CCD3 and 4) have declined at an average annual rate of about 1.2 feet per year. In the northwest part of the aquifer (140-049-34ABB2 and 3) the average annual decline for, these 15 years has been about 0.9 feet per year. For the seven years from 1990 to 1996 these sites, respectively, have averaged about 0.6 and 0.5 feet per year.

Aquifer water chemistry

Figures 15 to 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The fourth aquifer shown in each figure is the Nodak aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

Because there are less than sites, depiction of the chemical character of some aquifers is limited. The Nodak is one of these aquifers, with only four sites being represented.

Figure 15 shows that the Nodak aquifer is relatively low in calcium concentration in comparison to some of the other aquifers in the area. The 94/10, the Fargo, the WFN, and the WFS aquifers show slightly lower concentrations, while the others show significantly greater concentrations. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

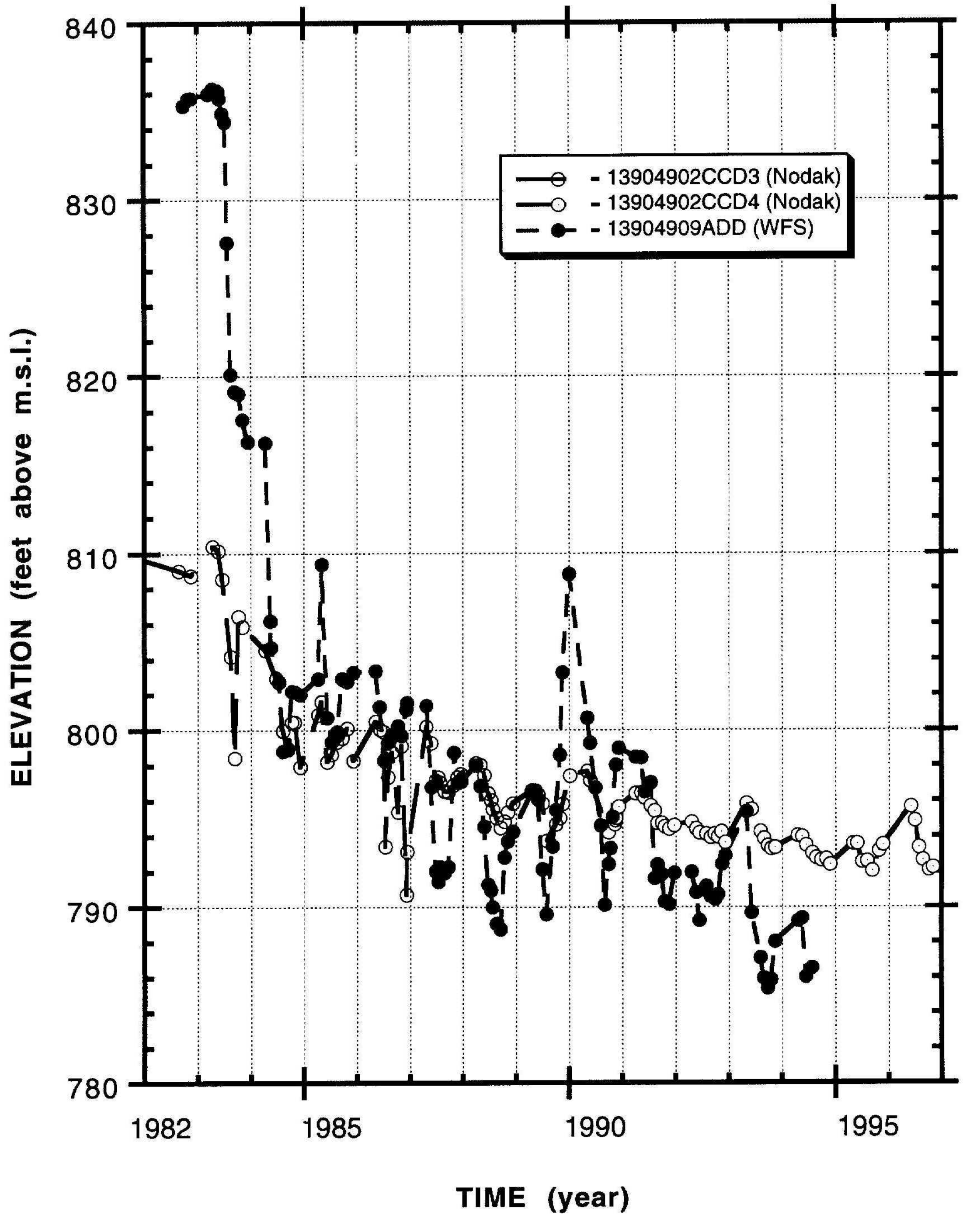


FIGURE 32. Hydrograph of observation wells located in the Nodak and West Fargo South aquifers.

Figure 16 shows that the Nodak aquifer is relatively low in chloride concentration in comparison to other aquifers in the area. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. No sites had chloride values near 250 mg/liter.

Figure 17 shows that the Nodak aquifer is in the low range of the group of nine aquifers with respect to hardness. Even though Nodak aquifer hardness is in the low range among the WFAS aquifers, all of the samples from the Nodak aquifer that were analyzed had hardness values that fell into the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the Nodak aquifer is relatively low among the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the Nodak aquifer is among the lowest in comparison to other aquifers in the area with respect to sulfate concentration. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. All sites and all samples from all sites in the Nodak aquifer had sulfate concentrations below the lower SMCL sulfate value of 250 mg/liter. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the Nodak aquifer is among the lowest of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Only the WFS aquifer is clearly lower in TDS. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites of the Nodak and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants.

The water in the Nodak aquifer is predominantly a sodium type, with no dominant anion although a few samples show the dominant anion to be bicarbonate. The total dissolved solids generally range from between 500 to 900 mg/liter, and the water is very hard. The water is suitable for most purposes.

Figure 33 shows the isotope data for the two samples taken from Nodak aquifer. The two sites had samples that ranged in $\delta^{18}O$ values from -20.1 to -20.5, and in $\delta^{2}H$ values from -149 to -153. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in ND have shown values of approximately -18 to -25.

The two Nodak aquifer samples are in the "snowfall" range. This range of $\delta^{18}O$ values is strikingly cold in its signature. This range does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values of water samples collected from Nodak wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the Nodak aquifer.

Ground-water movement

There are a few water-level measurements in the early mid 1960s for the Nodak aquifer, and the remainder of the Nodak water-level data has been gathered since 1982. A higher degree of uncertainty should be applied to the pre-1980s discussion, because of this lack of water-level data.

There is reason to believe that the Nodak aquifer is like the WFN and Fargo aquifers, in that water levels in the aquifer were likely above land surface up to the 1870s. Thus the ground-water movement would have been from the aquifer to the surface via some circuitous route through the overlying aquitards. Because the aquifer is relatively small, the land surface above the aquifer has little topographic variation and the regional topographically driven north and east ground-water movement components were likely quite small. After a few wells were installed, the water levels would have been lowered. However, because the land overlying the Nodak aquifer was settled later than some of the other areas, and because early on there appear to have

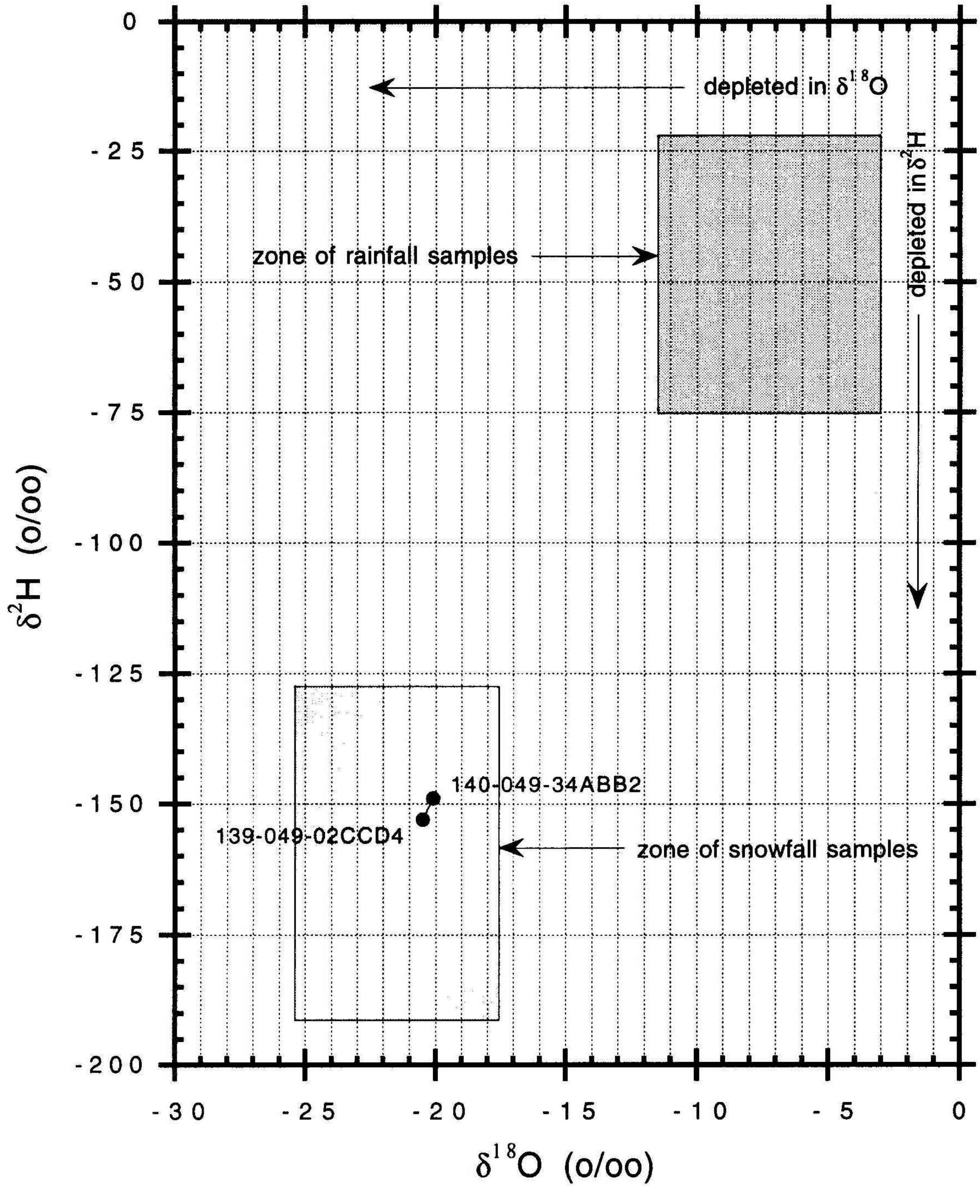


FIGURE 33. **Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the Nodak aquifer and precipitation at Oakes, N.D.**

been numerous shallow wells that were installed in sand and gravel lenses that lie above the Nodak aquifer, utilization of the Nodak aquifer itself may not have been a significant contributor to the early lowering of the water levels in the Nodak aquifer.

The Nodak aquifer may have had water-level declines that occurred because of the utilization of the Fargo aquifer, and the area southeast of the Fargo aquifer in section 12, that caused water-level declines in those areas. Those water-level declines then led to leakage out of the Nodak aquifer, and into the Fargo aquifer and the area in section 12 where some of the first wells in the Fargo area provided water for the door-to-door sales of water.

Once significant utilization of the West Fargo North aquifer began in 1936, it is likely that the Nodak aquifer also contributed water to the WFN aquifer. Sometime around 1950 it is also possible that the water level in the Nodak aquifer was lowered sufficiently (primarily because of leakage into WFN aquifer), so that the leakage from the Nodak to the Fargo aquifer was reversed, and leakage went from the Fargo aquifer into the Nodak aquifer. There is no direct data to support or not support these conjectures, but given the history that is known about the WFN and Fargo aquifers, it does seem probable.

Sometime after the early-mid 1960s (possibly in the late 1970s or very early 1980s), the Fargo aquifer was pumped enough to have the water levels in the Fargo aquifer once again become lower than the water levels in the Nodak aquifer. At this point in time, the ground-water flow between the aquifers would have reversed again, and water would have flowed from the Nodak aquifer to the Fargo aquifer.

Activities in another aquifer (the West Fargo South aquifer) significantly impacted the movement of ground water in the Nodak aquifer beginning in 1983. Before 1975 there were no high yield wells producing water from the WFS aquifer. In 1975 Cass Rural Water Users installed three wells and began withdrawing at a rate of 50 to 70 million gallons per year (Mg/y). That well field was about 11 to 12 miles from the Nodak aquifer, and did not have a large impact on water levels in the area of the Nodak aquifer. However, in 1983 the city of West Fargo began utilizing up to about 275 Mg/y from a part of the WFS aquifer that was about 2 miles from the Nodak aquifer. Figure 32 shows the large water-level decline that occurred in the WFS aquifer observation well (139-049-09ADD) when the city of West Fargo began to utilize the WFS aquifer for part of their water supply.

Figure 34 shows a representative water-level record for four sites in the vicinity of the Nodak aquifer. Each site is in a different, but hydraulically connected, aquifer. The four aquifers are the Fargo, the Nodak, the WFN, and the WFS aquifers. Figure 27 shows a map of how the aquifers are spatially distributed. Two of the sites are depicted in figure 27. The third site, located in the WFS aquifer, is just over a mile south and

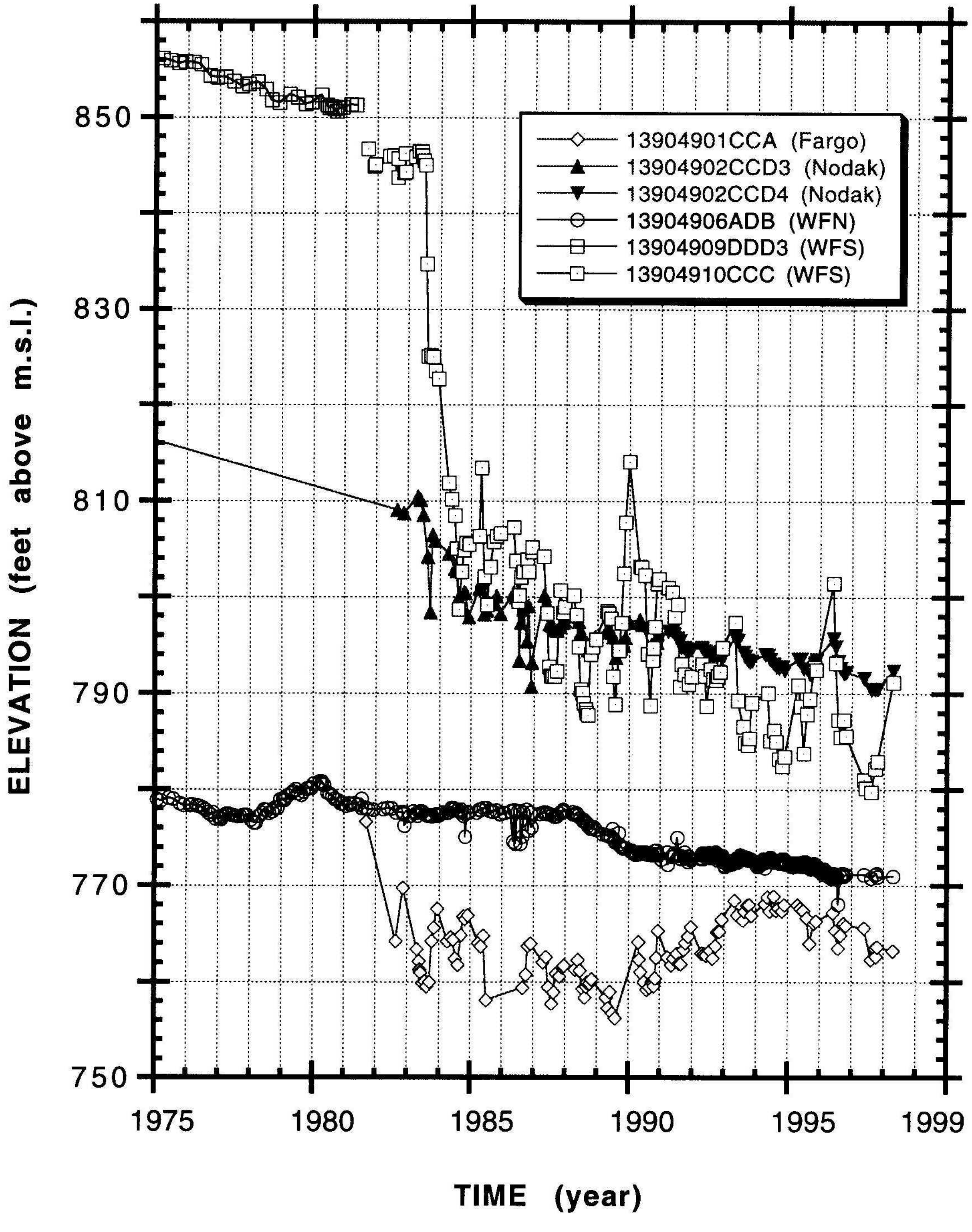


FIGURE 34. Hydrograph of wells located in the Fargo, Nodak, WFN, and WFS aquifers.

west of 139-049-02CCD3 and 4. This site is represented by observation wells 139-049-09DDD3 and 139-049-10CCC. The fourth site is located about a half-mile north and 3 1/2 miles west of 139-049-02CCD3 and 4. This site is about one-half mile west of the west margin of the map in figure 27. The observation well at this site is 139-049-06ADB, the recorder well with a continuous water-level record dating back to 1937.

The main point of figure 34 at this stage of the discussion is to show the influence of water levels in the WFS aquifer on water levels in the Nodak aquifer. Before the significant 1983 to 1985 water-level decline in the WFS aquifer, the water level in the WFS aquifer was about 40 feet higher than the water level in the Nodak aquifer. The water level in the WFS aquifer was also about 70 feet higher than the water level in the WFN aquifer. Before 1983, water was likely leaking from the WFS to both the WFN and Nodak aquifers. From 1985 to about 1990 water levels were fairly similar in the Nodak and WFS aquifers. Since 1990 the water-level elevations in the WFS have been predominantly lower than the water-level elevations in the Nodak aquifer.

An interpretation could be placed on this water-level data, whereby the conclusion could be drawn that the two aquifers are unrelated, because the water-level patterns are different. However, a careful look at the Nodak water levels in the time period from 1983 to 1985 shows that the water levels in that two-year time period declined about 10 feet, or 5 ft/yr. While there are no actual water-level measurements from the 1960s to 1982, the measurements in 1963 and 1964 indicate that the Nodak water levels were declining at an average rate of less than 1 ft/yr. Figure 34 shows that the average water-level decline for the last 12 years has also been less than 1 ft/yr.

Prior to 1983 ground water appears to have been moving from the WFS aquifer to the Nodak aquifer. After 1985, the inflow to the Nodak aquifer has likely been minimal, and after 1990 ground water is likely flowing from the Nodak aquifer to the WFS aquifer. Currently the water-level records indicate that ground water in the Nodak aquifer is flowing into the Fargo, the WFN, and the WFS aquifers. The rate of this discharge is extremely difficult to quantify.

Historically, inflow into the Nodak aquifer has occurred at different times from the Fargo, WFN, WFS, and other small, unidentified aquifers in the area. These forms of inflow no longer occur. The only likely contributions of inflow may be leakage from the aquitards surrounding the Nodak aquifer, and from small, unidentified, unused aquifers in the area. The rate of inflow from these sources is difficult to quantify.

94/10 AQUIFER

Aquifer size and location

The map in figure 35 shows the area that is underlain by the 94/10 aquifer. The aquifer is a relatively small, relatively unused aquifer. The north end of the aquifer

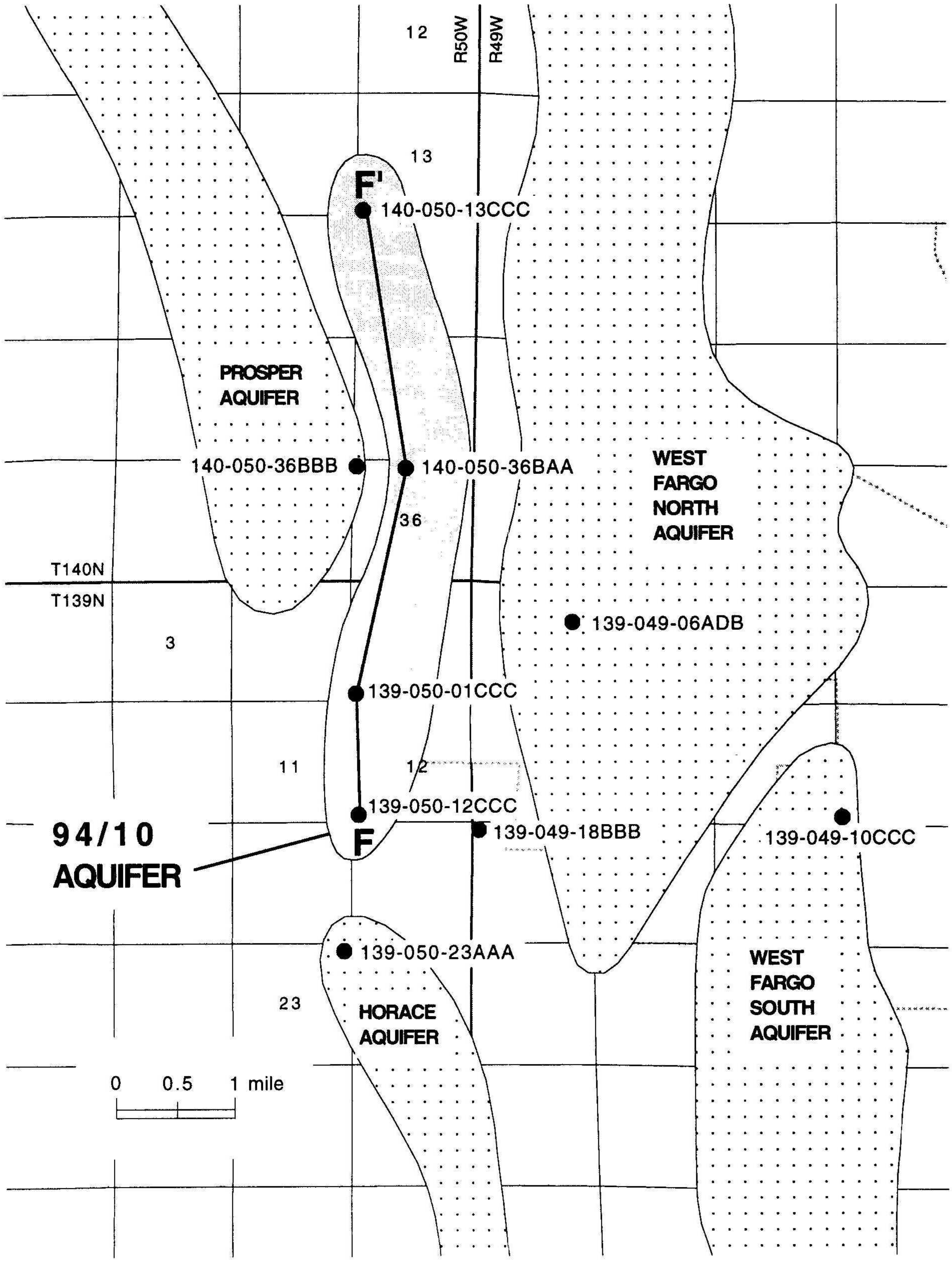


FIGURE 35. Location of the 94/10 aquifer and geologic section F-F'.

is not well defined. Wells have been installed for the Maple Sheyenne Association and for Maple Sheyenne Meadows in the northwest part of section 12, T140N R50W. The Maple Sheyenne Assoc. well was installed in 1980, and the water level at that time was 15 to 20 feet higher than the elevation of the water in observation well 140-050-13CCC (94/10 aquifer) would be predicted to have been. The Maple Sheyenne Meadows well was installed in 1994, and while the water level was more similar to water levels in the 94/10 aquifer, the depth of this well was over 100 feet deeper than the wells in the area that were completed in the 94/10 aquifer, and also over 100 feet deeper than the Maple Sheyenne Assoc. well.

Numerous test holes between the 94/10 aquifer and the WFN aquifer show no sand or gravel sections of consequence. Water-level comparisons between the WFN and the 94/10 aquifers also show 45 to 50 feet of elevation difference, indicating a very significant hydraulic conductivity barrier between the two aquifers.

At the south end of the aquifer a significant water-level difference exists between 139-050-12CCC (94/10 aquifer) and 139-050-23AAA (Horace aquifer). Before 1983 the difference was about 25 feet, and in 1997 the difference was about 15 feet. There is clearly a hydraulic discontinuity between the 94/10 and the Horace aquifers.

Test holes in sections 3 and 11 of T139N R50W and section 36 of T140N R50W show no significant sand and gravel sections west of the 94/10 aquifer. The aquifer boundary between the 94/10 and the Prosper aquifers is clear from an analysis of the water levels of 140-050-36BBB (Prosper aquifer) and 140-050-36BAA (94/10 aquifer). Water levels in 36BAA are always between 8 and 9 feet lower than water levels measured at the same time is well 36BBB. The hydraulic gradient between the two wells is about 16 to 18 feet per mile, a gradient indicating a poor hydraulic connection between the 94/10 and the Prosper aquifers.

There are nine test holes and wells located in the 94/10 aquifer that were investigated. Of these nine, eight have lithologic logs. The descriptions of the permeable material in the logs consist predominantly of gravel in the southern part of the aquifer, and predominantly of sand in the northern portion.

The permeable zones are found at higher elevations in the northern part of the 94/10 aquifer, and at lower elevations in the southern part of the aquifer. In the northern part of the 94/10 aquifer found in Raymond Township (140-050) the average depth to the top of the aquifer is 133 feet, and the average depth to the bottom of the aquifer is 167 feet. Because the permeable zones are layered, the average thickness of the 94/10 aquifer in Raymond Township is only 16 feet. The southern portion in Mapleton Township (139-050) has an average depth to the top of the aquifer of 167 feet, and an average depth to the bottom of the aquifer of about 250 feet. The average thickness in Mapleton Township is about 80 feet.

Figure 36 shows a south-to-north geologic section (F-F') of the 94/10 aquifer. The coarser sands and gravels are found in the thicker portion of the aquifer in the south, and the thin portion of the aquifer to the north is comprised of sand. Because of the difference in the material in the aquifer, and because of the difference in the elevation in which the aquifer material is found, it is likely that the aquifer was deposited at different times under different conditions. The water level and the water quality records of both parts of the aquifer show very similar patterns, and it is for this reason the two different segments are considered as one aquifer.

Figure 36 also shows the large difference in thickness in the two parts of the 94/10 aquifer. Because the two parts each represent about half of the mapped area of the aquifer, and because each part has half of the test holes or wells that have a lithologic description, the average thickness figures for the aquifer probably reasonably depict the overall aquifer thickness in spite of the wide variation in aquifer thickness. With an average thickness of about 48 feet, and an area of about 3.2 square miles, the approximate volume of the 94/10 aquifer is 4.3 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

Aquifer water use and water-level history

No documented water use has been found for the 94/10 aquifer. There have only been about a half dozen farmsteads that have been located above the aquifer, as well as a few businesses along Highway 10. The most significant water use from the aquifer probably resulted from the Hi-Ten Motel. The majority of the decline of water levels that has been observed in the 94/10 aquifer has probably resulted from leakage into the West Fargo North aquifer.

Figure 37 shows a hydrograph using all of the available water-level data for the 94/10 aquifer. In 1981 and 1983 several observation wells were installed into the 94/10 aquifer, and water-level measurements for the aquifer began at that time. The 'spike' observed in the curve for observation well 140-050-13CCC in 1990 is not indicative of the water level in the aquifer. The observation well was run over, clipped off at land surface, became plugged, and water ran into the well. The water slowly drained out of the 'plug', as the water level in the plugged well began to become closer to the water level in the aquifer. The well was repaired and pumped clean, and the water levels in this well again became indicative of water levels in the aquifer.

In 1983 the water levels for 139-050-01CCC, 139-050-12CCC, and 140-050-36BAA were within about one foot of each other. In 1983 and 1984 a nearby aquifer experienced a significant water-level decline, and this impacted the two southern observation wells more than 140-050-36BAA. This point will be covered more fully in

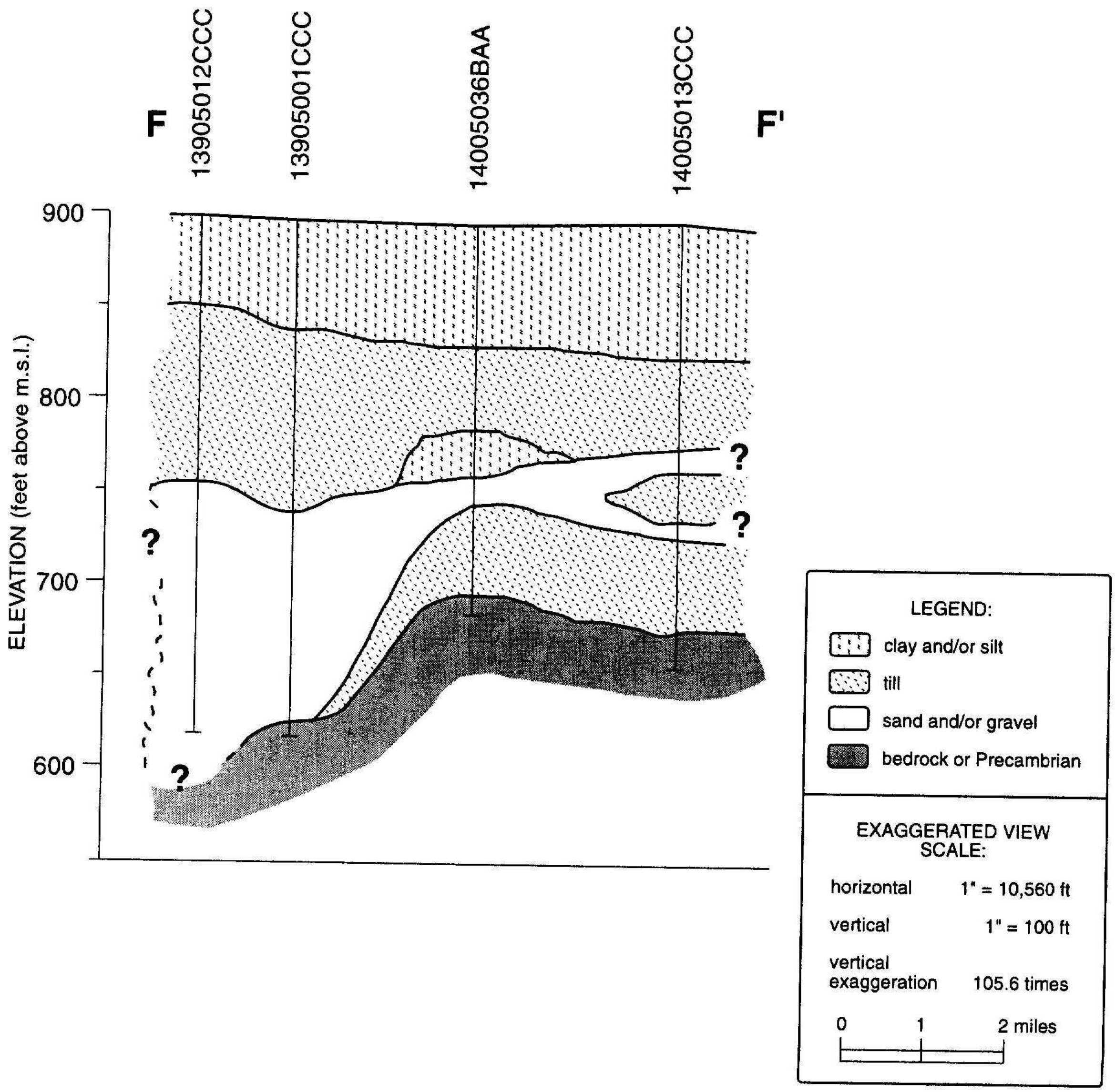


FIGURE 36. South-north geologic section F-F' showing the 94/10 aquifer.

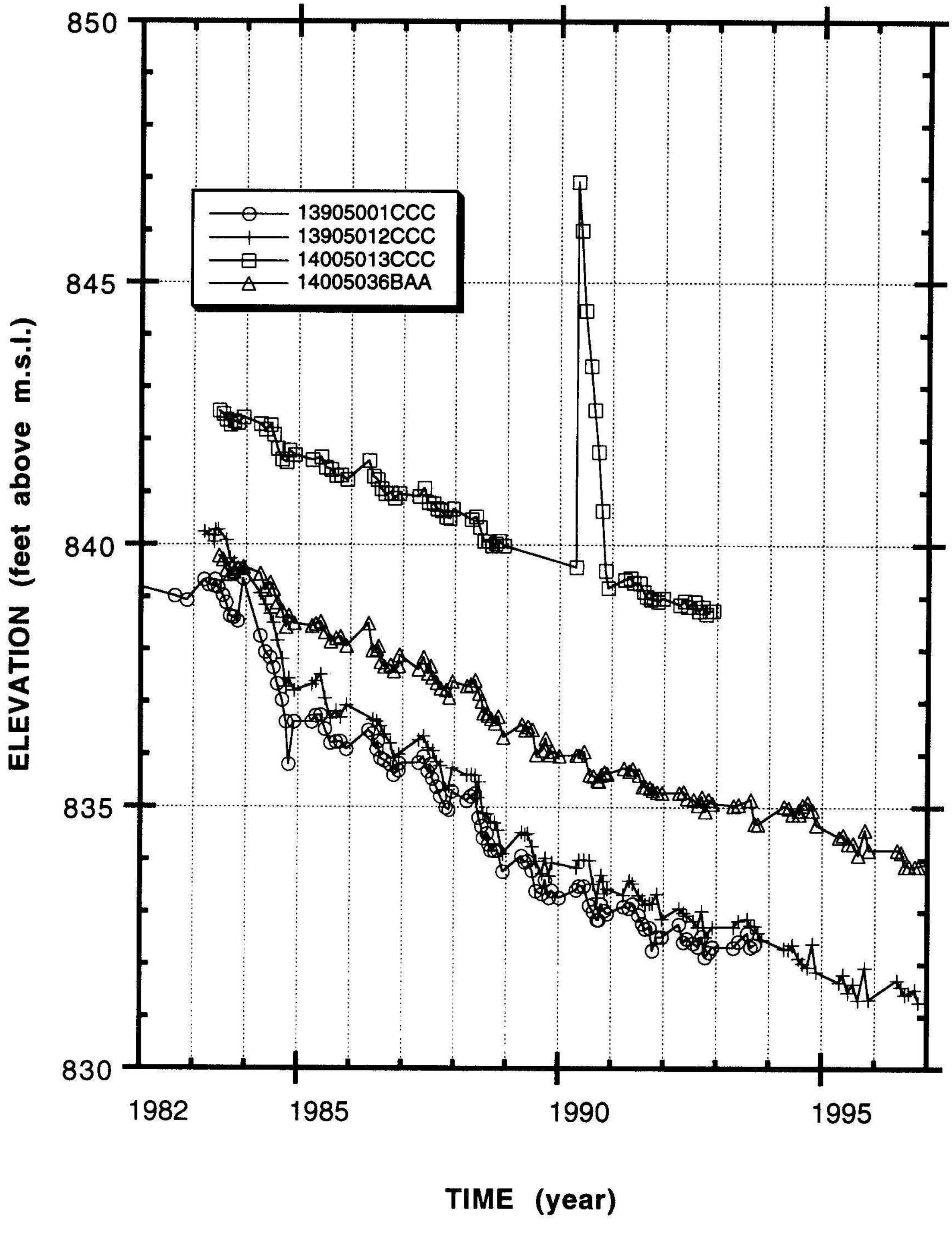


FIGURE 37. Hydrograph of observation wells located in the 94/10 aquifer.

the section on the ground-water movement of the 94/10 aquifer. It is pointed out now to show that even though the curves of the water-level patterns are a little different for that time period, these observation wells appear to be very well connected, and this indicates that they are screened in the same 94/10 aquifer unit.

The water-level patterns show a declining water level for all of the wells. From 1983 through 1996 the water level in 36BAA declined about 6 feet, and the water level in 12CCC declined about 9 feet. This is about 0.4 and 0.6 feet per year, respectively. For the last seven years this has been about 0.3 and 0.4 ft/yr, respectively. Most, if not virtually all, of this decline is due to leakage into other nearby aquifers.

Aquifer water chemistry

Figures 15 through 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The first aquifer shown in each figure is the 94/10 aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The 94/10 aquifer is one of these aquifers, with only four sites being represented.

Figure 15 shows that the 94/10 aquifer is relatively low in calcium concentration in comparison to some of the other aquifers in the area. The WFN and the WFS aquifers show similar low concentrations, while the others show higher or significantly higher concentrations. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the 94/10 aquifer is relatively high in chloride concentration in comparison to other aquifers in the area. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride, and all samples from the 94/10 aquifer exceed this value. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. The highest values for chloride concentration in the 94/10 aquifer approximate 400 mg/liter.

Figure 17 shows that the 94/10 aquifer is among the lowest in concentration of the group of nine aquifers with respect to hardness. Only the WFS aquifer has a lower median value for hardness. Even though 94/10 aquifer hardness is in the low range among the WFAS aquifers, the median value of the 94/10 aquifer hardness falls just below the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the 94/10 aquifer is fairly high among the group of nine aquifers with respect to the sodium concentration. Only the Prosper aquifer has a higher median value. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the 94/10 aquifer is among the lowest in comparison to other aquifers in the area with respect to sulfate concentration. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. All sites and all samples from all sites in the 94/10 aquifer had sulfate concentrations below the lower SMCL sulfate value of 250 mg/liter. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the 94/10 aquifer is among the highest of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Only the Prosper and West Pleasant aquifers are higher in TDS. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites of the 94/10 aquifer and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants.

The water in the 94/10 aquifer is a sodium-chloride type. The total dissolved solids generally range from between 1050 to 1250 mg/liter, and the water is hard to very hard. The water is suitable for many purposes, but marginal for several purposes.

Figure 38 shows the relationship between stable isotopes of ground water in the 94/10 aquifer and precipitation at Oakes, ND. The one sample had a $\delta^{18}O$ value of -19.4, and a $\delta^{2}H$ value of -144. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in North Dakota have shown values of approximately -18 to -25.

The 94/10 aquifer sample is in the "snowfall" range. This value of $\delta^{18}O$ is strikingly cold in its signature. A value like this does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values of a water sample collected from a 94/10 aquifer well indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the 94/10 aquifer.

Ground-water movement

The main tool used to determine flow paths within a complex aquifer system is water levels. In the case of the 94/10 aquifer, regular water-level measurements began in 1983, except for a few measurements in observation well 139-050-01CCC, which begin in 1981. Klausing (1966) lists one 1959 water level for 139-050-02AAA. That one 1959 measurement is in agreement with the post-1983 data that shows that the water levels in the 94/10 aquifer are higher than those measured in the WFN aquifer, and lower than those measured in either the Prosper or Horace aquifers (see figure 35 for spatial relationships). A high degree of uncertainty should be applied to the pre-1980s discussion, because there is so little water-level data before 1983.

There is reason to believe that the 94/10 aquifer is like the WFN and Fargo aquifers, in that water levels in the 94/10 aquifer were likely above land surface prior to the 1870s. Thus, ground-water movement would have been from the aquifer to the surface through the overlying aquitard. Because the aquifer is relatively narrow in an east-west direction, the topographically driven east flow component was likely quite small. There may have been a northward flow component due to the north part of the aquifer being overlain by a land surface that was a little topographically lower than the

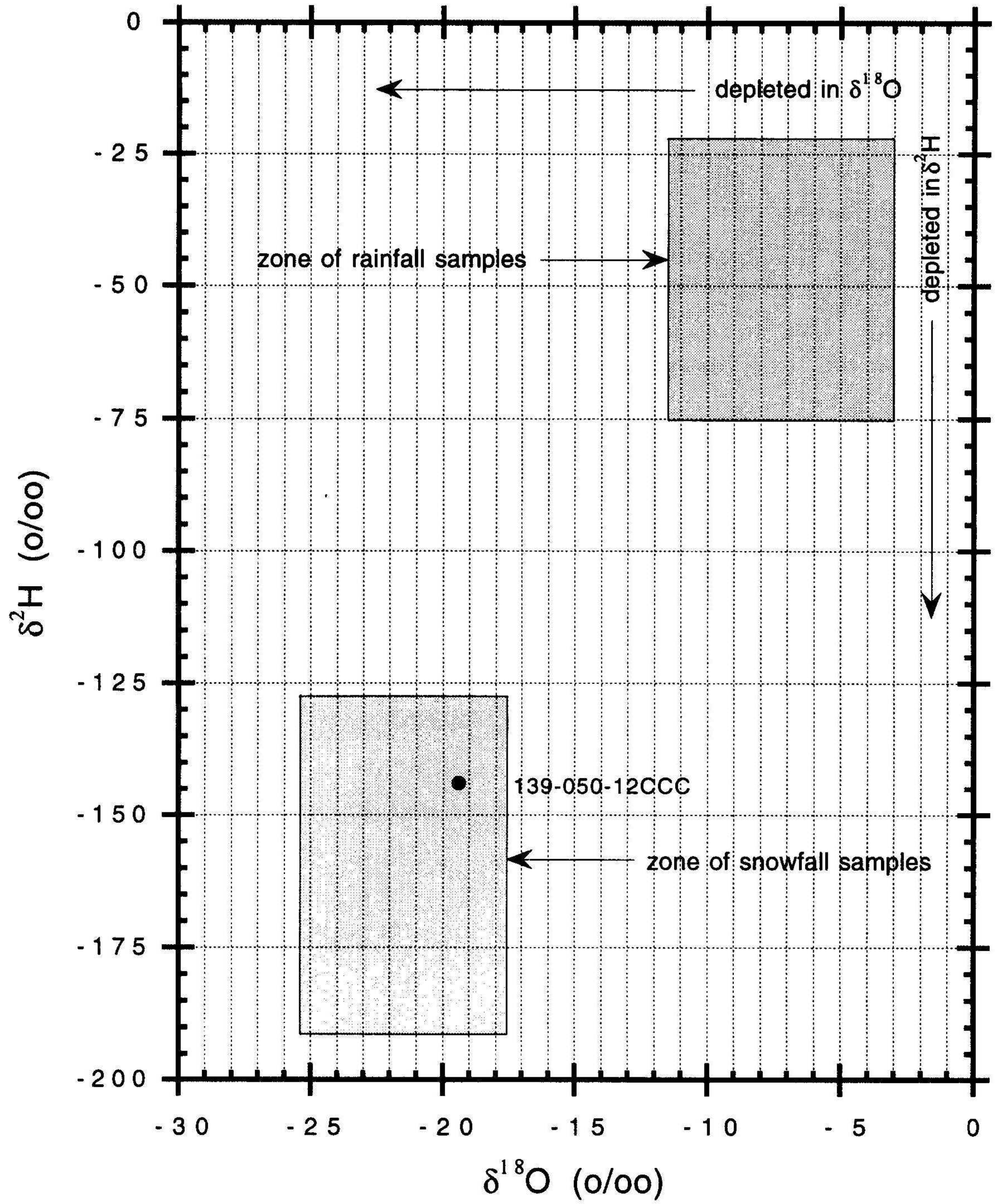


FIGURE 38. **Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the 94/10 aquifer and precipitation at Oakes, N.D.**

land surface overlying the south end of the aquifer. Once a few wells were installed, the water levels would have been lowered in the vicinity of those wells.

Figure 39 is a hydrograph showing the water levels measured in selected wells from the three aquifers that lie adjacent to the 94/10 aquifer. Also included are water levels measured for a well in the WFS aquifer, and for a well in an undefined unit lying between the 94/10, the WFN, and the Horace aquifers. Figure 35 shows the locations of the wells represented in figure 39.

Figure 39 shows a large difference between the water levels in the 94/10 aquifer and the WFN aquifer (about 60 feet in 1996). During the 14 years of water-level data collection for the 94/10 aquifer, that differential has remained pretty much the same. Observation wells in the 94/10 aquifer are approximately 1 1/2 miles west of observation wells in the WFN aquifer, and this results in a very high hydraulic gradient of about 40 feet per mile. This means that it takes a large differential to move water from the 94/10 aquifer to the WFN aquifer. Because little use was made of water from the 94/10 aquifer in the late 1800s and the early 1900s, and because the WFN wasn't significantly used until the 1930s, it is likely that the water levels in the 94/10 aquifer were not very much below land surface until after the late 1930s.

After the late 1930s, the water levels in the WFN aquifer began to subside at a rate greater than 4 feet per year. Where previously the ground-water flow in the 94/10 aquifer had been upwards towards the land surface, the combination of the poor hydraulic connections to the WFN aquifer, along with the lower water levels in the WFN aquifer, allowed for ground water flow from the 94/10 aquifer to the WFN aquifer. The 35-foot-deep, water-level measurement in 1959 for well 139-050-02AAA (Klausing, 1966) supports the concept that a significant hydraulic gradient existed in 1959. The data also supports the likelihood that the water level in the 94/10 aquifer started to decline appreciably below land surface in the 1940s, when there was an adequate water-level differential to allow for ground-water flow from the 94/10 aquifer to the WFN aquifer. This ground-water flow pattern is currently in place as well, and is the major discharge from the 94/10 aquifer.

Inflow into the 94/10 aquifer is occurring from several sources. The two major inflows are leakage from the Prosper aquifer and possibly the Horace aquifer. The fact that leakage from the Prosper aquifer is occurring is clear. The water-level curves have similar patterns, only the Prosper aquifer water levels are higher. As mentioned earlier in the discussion, the hydraulic gradient between 140-050-36BBB and 140-050-36BAA is about 16 to 18 feet per mile. This large gradient indicates a hydraulic discontinuity occurs between these sites.

An analysis of all of the Prosper aquifer water levels also shows that the lowest water levels in the aquifer are found at the extreme southern end of the aquifer. This

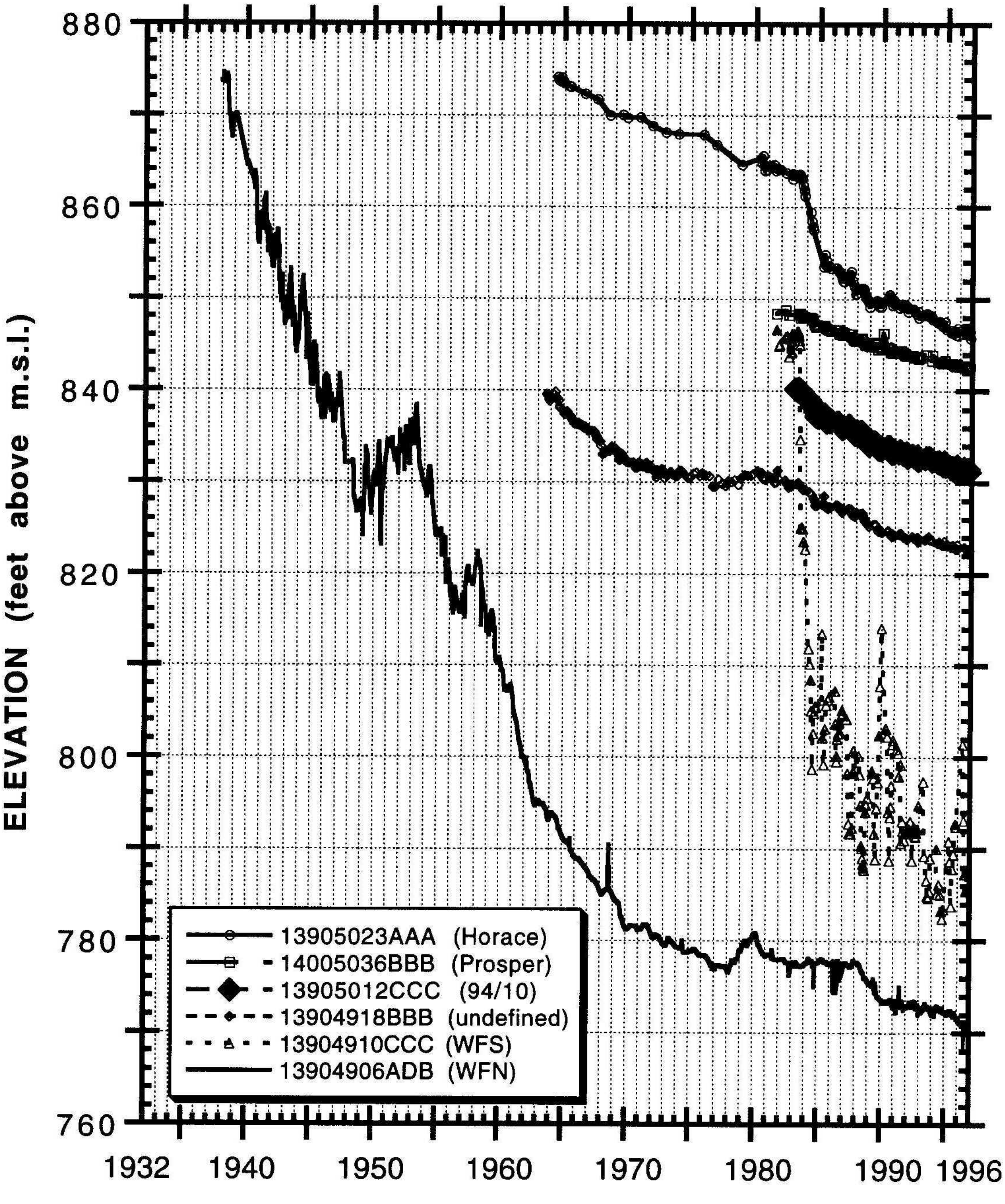


FIGURE 39. Hydrograph of selected wells from several aquifers in the vicinity of the 94/10 aquifer.

means that a significant amount of the water in the Prosper aquifer is draining out of the south end of the aquifer. Because there is no high yield well field at the south end of the Prosper aquifer, one logical place for that water to be going is into the 94/10 aquifer.

The relationship with the Horace aquifer is not as clear. Even though figure 39 shows that (in 1983) observation well 139-050-23AAA (Horace aquifer) had water levels that were about 24 feet higher than the water-level elevations in observation well 139-050-12CCC (94/10 aquifer), this does not necessarily mean that water flowed from the Horace to the 94/10 aquifer. It could be that both aquifers had ground water flowing into the WFN aquifer which had much lower water levels than either of these two aquifers. However, in 1983 there was a significant change in the WFAS flow system that impacted both the Horace and the 94/10 aquifers, and gave an additional insight as to what the flow pattern might be.

As mentioned earlier, in 1983 the city of West Fargo began to pump up to 275 million gallons per year from the WFS aquifer. Because of a connection between the Horace and the WFS aquifer (this connection will be discussed later in the Horace aquifer section of the report), the rate of water-level decline observed for 139-050-23AAA increased significantly during the 1983 to 1985 time period. Because there are no continuous water-level records for any wells in the 94/10 aquifer, it is not as clear as it might be; however, there is a larger rate of water-level decline for 139-050-12CCC for the 1983 to 1985 time period. It appears that the rate of ground-water flow from the Horace to the 94/10 aquifer may have been reduced, and that this may have caused the increased rate of the lowering of the water level in the 94/10 aquifer.

There is one other observation well represented in figure 39 that has not yet been discussed. Observation well 139-049-18BBB does not appear to be in any of the three aquifers that are within one mile of the well. The well is likely screened in a lens, or a small sub aquifer that is related to at least the Horace and the WFN, and possibly the 94/10. It is likely indicative of so many small lenses or sub aquifers in the area that help transmit ground-water movement from one aquifer to another.

In summary, the current flow systems for the 94/10 aquifer consists of one major outflow, and two significant inflows. The major outflow from the 94/10 aquifer is into the WFN aquifer through the one-half to one mile of fine-grained materials that lie between the two aquifers along a 6-mile stretch. These fine-grained materials have sufficient sand and gravel layers to transmit some water.

The inflow is derived predominantly as leakage from the Prosper aquifer. The one-half to one mile of fine-grained material that lie between the Prosper and the 94/10 aquifers along a 4-mile stretch, similarly conduct water from the Prosper to the 94/10 aquifer. A lesser, but possibly significant amount of water also leaks from the Horace aquifer to the 94/10 aquifer.

The only likely contributions of additional inflow may be leakage from the till and clay aquitards surrounding the 94/10 aquifer, and from other small, unidentified, unused aquifers in the area. The rate of inflow and outflow from all of these sources is difficult to quantify.

PROSPER AQUIFER

Aquifer size and location

The map in figure 40 shows the area that is underlain by the Prosper aquifer. The aquifer is the fourth largest aquifer in the WFAS. The north part of the aquifer is poorly defined. The Prosper aquifer may extend further to the north-northwest than figure 40 shows. In this area there are no wells with water-level measurements that show significant water-level elevation differences, or test holes with lithologic descriptions that show no significant sand or gravel units. Without such evidence to indicate that there is a clear aquifer boundary at the north end of the aquifer the Prosper aquifer is truncated just north of the northernmost observation well (141-050-09AAA2) that has water-level measurements that relate well with water-level measurements of other wells in the Prosper aquifer.

The aquifer boundary in virtually all of Berlin Township (T141N, R50W) is poorly defined for the reasons stated in the paragraph above. The only portion of the aquifer boundary that is fairly well defined in Berlin Township is the easternmost portion of the Prosper aquifer where a part of the WFN aquifer lies within about a mile of the Prosper aquifer. Observation well 141-050-23DDD (Prosper aquifer) has had water levels that consistently have been about 40 feet higher than the water levels that have been measured in observation well 141-049-30BBB (WFN aquifer). The 40-foot-water-level differential occurs over a distance of about one mile. This shows clearly that the two areas are in different aquifers, and is the only clear aquifer boundary indication for the Prosper aquifer in Berlin Township.

In Raymond Township (T140N, R50W) there are several aquifer boundary indications on the east and south sides, but limited evidence for the location of the aquifer boundary exists for the west side. The lithologic log of a test hole in the south center portion of section 3 shows no significant sand or gravel units. Further south on the east side of the Prosper aquifer in Raymond Township, the 94/10 aquifer has water levels that indicate a hydraulic discontinuity occurs between the two aquifers. Water levels in observation wells 140-050-15DDDC1 and 2 (Prosper aquifer) are consistently about 10 feet higher than those in observation well 140-050-13CCC (94/10 aquifer). Well 13CCC is about one mile east of 15DDDC1 and 2.

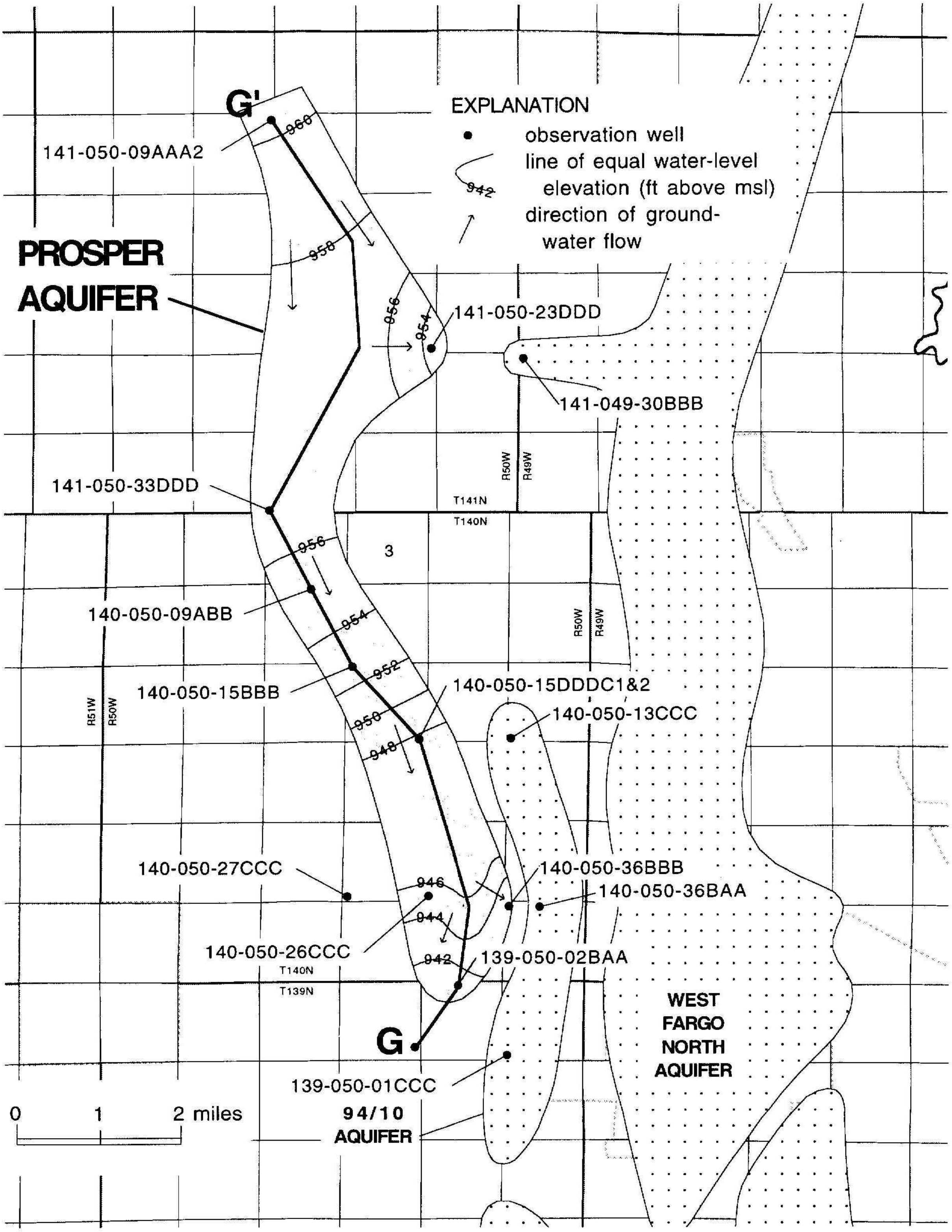


FIGURE 40. Location of the Prosper aquifer, altitude of potentiometric surface, direction of ground-water flow, and geologic section G-G'.

Further evidence of the boundary between the Prosper and 94/10 aquifers is found two miles to the south, where observation wells 140-050-36BBB (Prosper aquifer) and 140-050-36BAA (94/10) are less than one-half mile apart. The difference in the water level between the two wells is generally about 8 to 9 feet, which results in a hydraulic gradient between the two sites of about 18 feet per mile. This clearly shows a hydraulic discontinuity lies between the two sites, and separates the two aquifers.

On the west side of the south end of the Prosper aquifer there is another significant water-level elevation difference that indicates an aquifer boundary. The water levels for observation well 140-050-27CCC (no identified aquifer) have consistently been 16 to 18 feet higher those for 140-050-26CCC (Prosper aquifer). These two wells are about one mile apart, and the hydraulic gradient between them is about 17 feet per mile, a gradient indicative of a poor hydrologic connection.

From this area near 27CCC, north to the area near observation well 141-050-09AAA2 at the north end of the Prosper aquifer there is little clear evidence available to determine a western boundary for the aquifer. The main criteria used are the presence of deep sands and gravels, and the basic pattern that most of the aquifers in the WFAS are between three-fourths and one and one-half mile wide. These two guiding principles lead to the configuration of the western boundary of the Prosper aquifer, as depicted in figure 40.

In the northwest 20 percent of Raymond Township there is a very persistent (five lithologic descriptions describe the unit in this area) shallow sand and gravel layer that overlies the Prosper aquifer. In fact one of the five sites, observation well 141-050-33DDD, is screened in this shallow aquifer, and the water-level measurements in 33DDD display the same pattern of fluctuations as do the measurements of the 200-to-300-foot-deep wells of the Prosper aquifer. There is a fairly good chance that this shallow lens extending to the west is a well-connected portion of the Prosper aquifer. The lens appears to be 30 to 37 feet thick, and found between the depths of 64 to 132 feet. Because there are no corroborating water-level measurements to support this concept, this shallow lens will not be considered part of the Prosper aquifer in the following discussion. The estimated areal extent of the Prosper aquifer is about 14.6 square miles.

There are 19 test holes and wells located in the Prosper aquifer that were investigated. Of these 19, 15 had lithologic descriptions for a significant portion of the aquifer interval. A few of the logs described only sand, however most of the logs described combinations of sand and gravel. Several of the logs described primarily only gravel. Overall the material described in the logs consists of some fine to medium to coarse sand, with extensive gravel-sized material incorporating a significant portion of the permeable material in the Prosper aquifer. The shallow aquifer material consisted of predominantly gravels with one exception.

The aquifer interval in the southern tip of the Prosper aquifer was generally found from 200 to 250 feet below land surface, and in the rest of the aquifer the interval was generally found below 200 feet up to 325 foot below land surface. The exception is the overlying sand found in the central and northern portion of the aquifer as shown in figure 41. Figure 41 is a geologic section of the Prosper aquifer (G-G') that extends from south to north. The location of the geologic section G-G' is shown on figure 40.

The average depth to the top of the aquifer is about 210 feet below land surface, and the average depth to the bottom of the aquifer is about 270 feet below land surface. Overlying sand units that appear to be connected average about 124 and 167 feet, respectively, to the top and bottom of the overlying unit. The main body of the Prosper aquifer averages about 58 feet in thickness. The overlying gravel and sand units average about 17 feet in thickness. Though the top and bottom average 43 feet for the overlying aquifer units, the smaller average thickness results because overlying units are not found at all sites. The combination of the overlying connected aquifer units and the main Prosper aquifer results in an estimated average thickness of 75 feet for the Prosper aquifer.

With an average thickness of about 75 feet, and an area of 14.6 square miles, the approximate volume of the Prosper aquifer is 30.5 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

Aquifer water use and water-level history

No significant water use from the aquifer (probably less than a million gallons per year on the average) has been noted. There appears to have been only domestic and farmstead wells installed into the Prosper aquifer. Probably about 20 to 25 farmsteads have been located above the aquifer. The majority of the decline of water levels that has been observed in the Prosper aquifer has probably resulted from leakage into the 94/10 and West Fargo North aquifers.

Figure 42 shows a hydrograph of selected sites in the northern two-thirds of the Prosper aquifer. Figure 43 shows a hydrograph of selected sites in the southern one-third of the Prosper aquifer. The scales for the two figures are different because of the difference in the data in each figure. Only one observation well, 141-050-09AAA2 (figure 42), has any water-level measurements that predate 1981, and some of the wells in both figures were not installed until the 1990s.

The clear pattern for all of the observation wells is one of declining water levels. From 1982 to 1984 observation well 141-050-23DDD shows a rising water level,

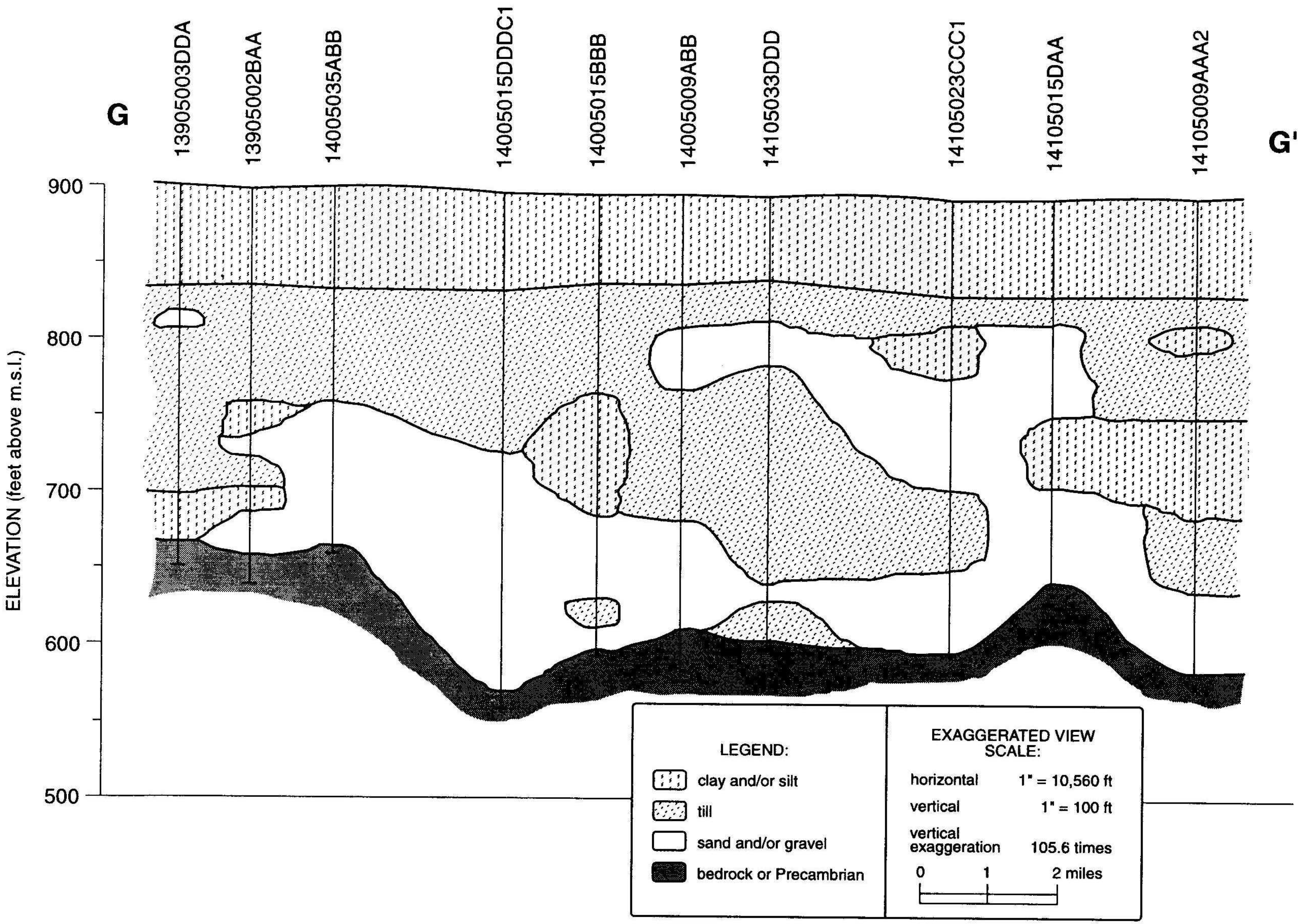


FIGURE 41. South-north geologic section G-G' showing the Prosper aquifer.

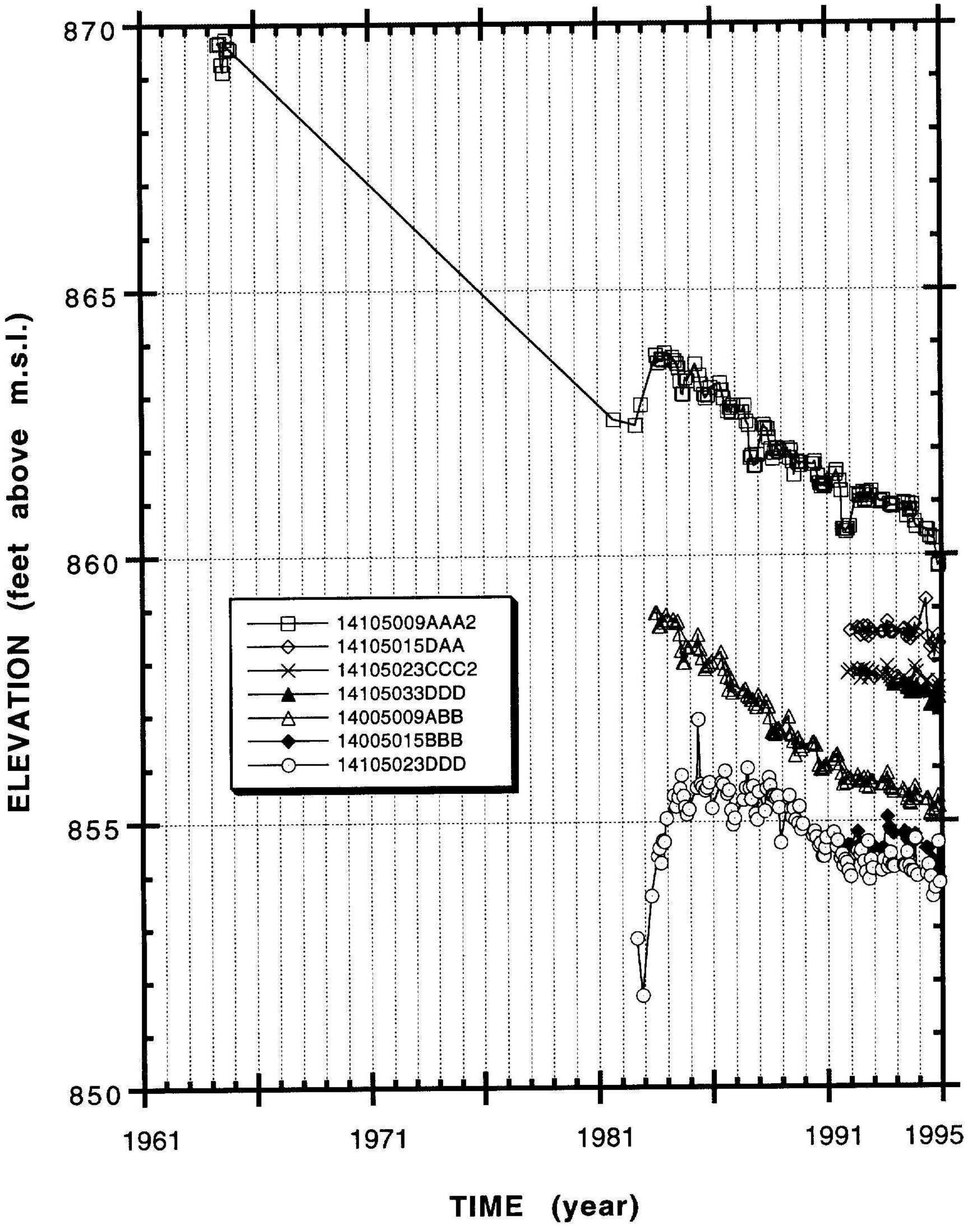


FIGURE 42. Hydrograph of observation wells located in the northern part of the Prosper aquifer.

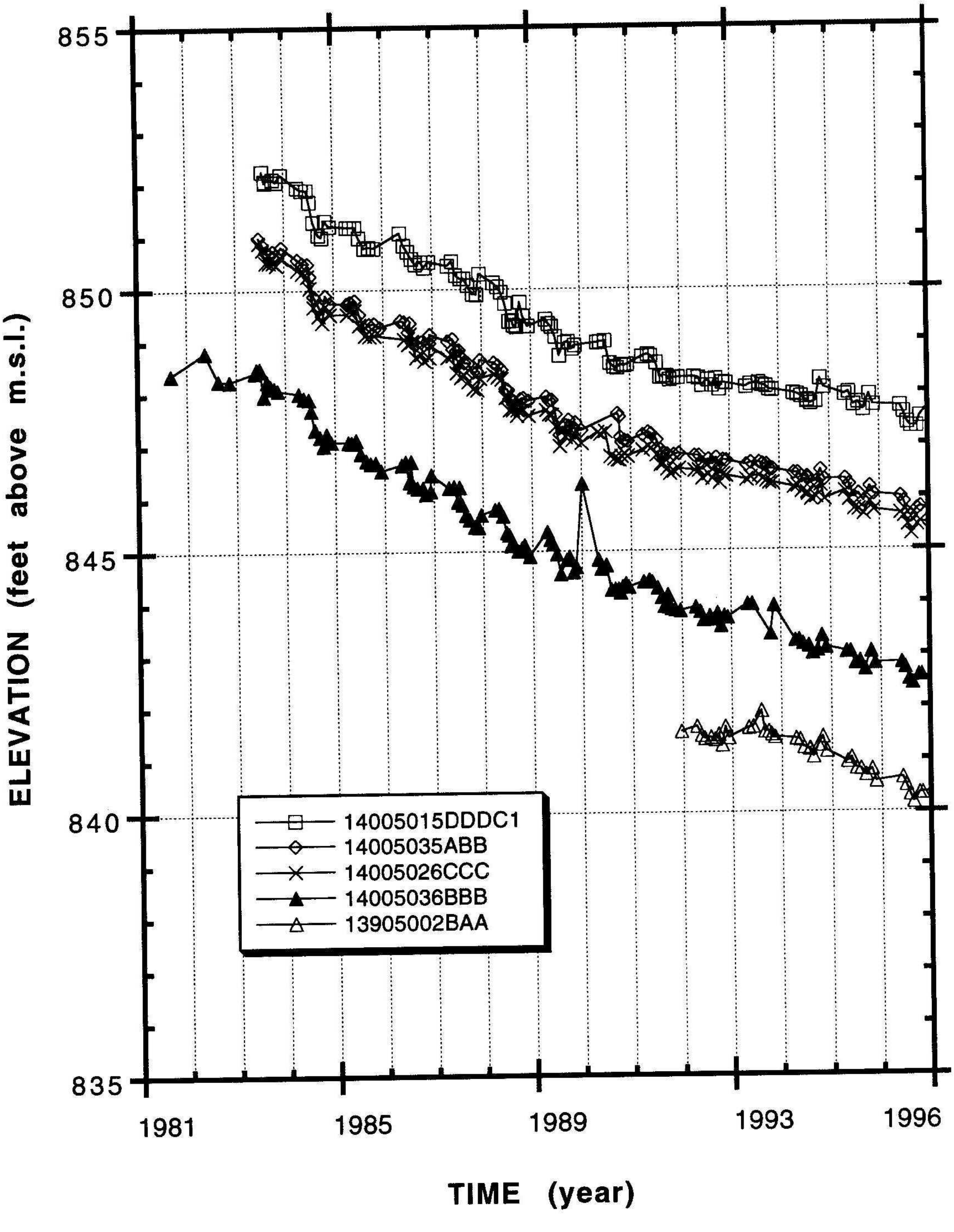


FIGURE 43. Hydrograph of observation wells located in the southern part of the Prosper aquifer.

however it is possible that the well was partially plugged, and that it took several years before the water levels in the observation well accurately indicated what the water levels in the surrounding aquifer were. Subsequent sampling that has been done in the 1980s and in the 1990s would seem to indicate that the observation well is no longer partially plugged.

The highest water-level elevations measured in the Prosper aquifer are in the observation well furthest to the north, and the lowest levels in the aquifer are in the observation well furthest to the south. This indicates that the most significant leakage from the aquifer is out the south end of the aquifer. Figure 40 shows the lines of equal water levels (potentiometric lines) that were drawn on the basis of water-level measurements taken on November 2, 1996. The potentiometric lines in figure 40 show a second area where there are low water levels that indicate an area of discharge from the Prosper aquifer. The second area is around observation well 141-050-23DDD on the east side of the Prosper aquifer where the aquifer is furthest to the east in Raymond Township.

The hydraulic gradient from the north part of the aquifer to the south end of the Prosper aquifer is not uniform (just as there is not a uniform hydraulic gradient with the WFN aquifer). This lack of uniformity can indicate variations in the aquifer transmissivity, among other things. Aquifer transmissivity is the ease with which the aquifer allows ground-water movement through the aquifer matrix. Figure 44 shows the map distance between the wells, and the hydraulic gradient between each two consecutive wells going from north to south. The hydraulic gradient is the water-level difference in feet between two wells expressed as a gradient in feet per mile.

Figure 44 shows that the hydraulic gradient from the north end of the Prosper aquifer to the south end averages about 2 feet per mile. However, some portions are 1 foot per mile or less, while other portions are 5 feet per mile or greater. At the north end the hydraulic gradient is smaller because there is leakage out of the aquifer in the vicinity of 141-050-23DDD, and so there is less flow to the south along the axis of the aquifer into Raymond Township. In close to this area that leaks ground water from the Prosper aquifer to the WFN aquifer, the hydraulic gradient is larger as the ground water flows into and through a more narrow, constricted area.

However, out away from the "steep" water-level slope coming into the cone that develops, there is at the edge of the cone a flatter configuration of the water level. The result is that to the south, west, and north there are water levels that are all the same elevation. This effect further flattens the water-level surface, and makes the hydraulic gradient smaller, because measuring the gradient from north to south in this area means measuring the gradient sort of parallel and not at right angles to the potentiometric lines. Thus, the small hydraulic gradient in the vicinity of observation

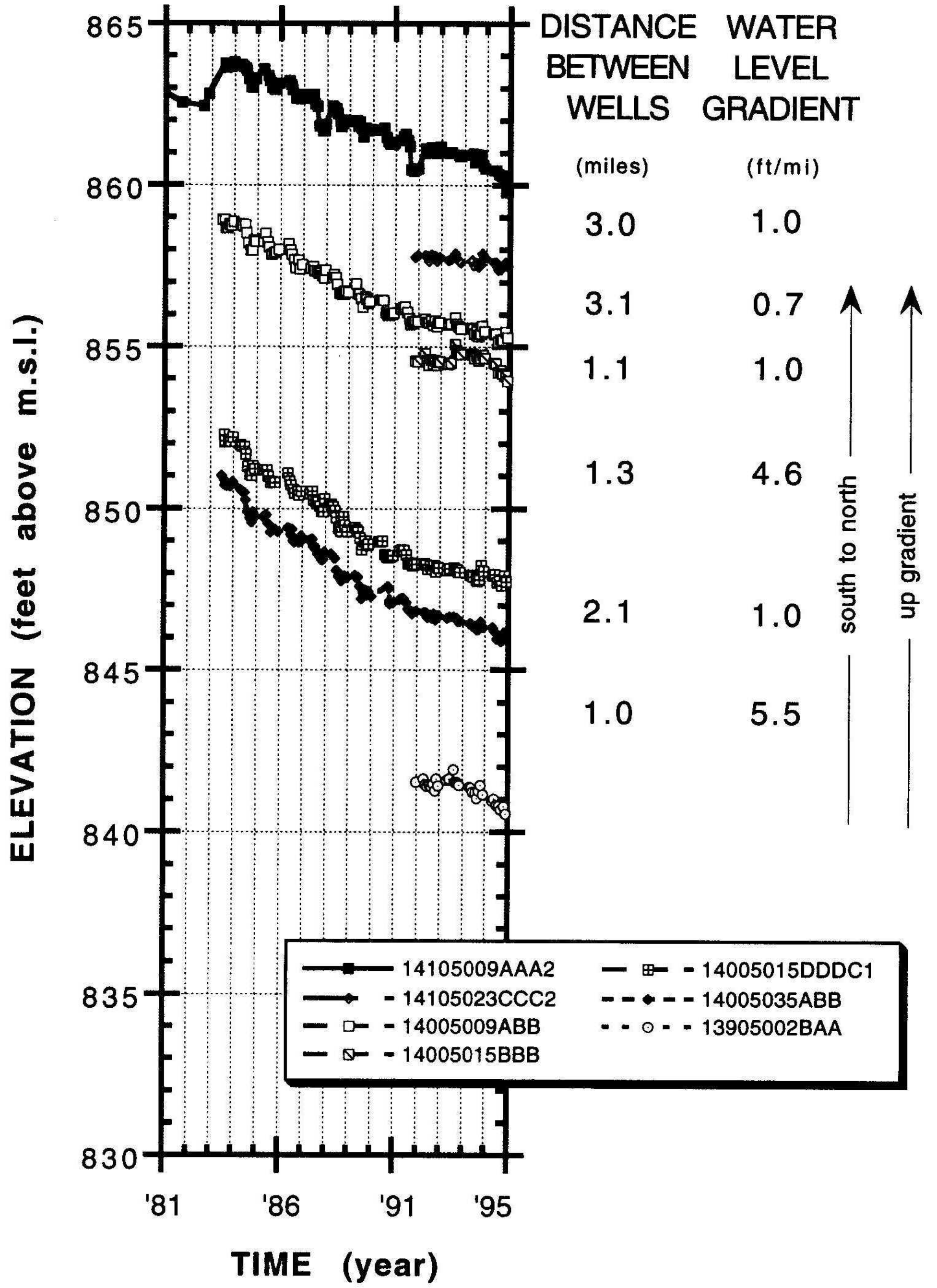


FIGURE 44. Hydrograph of selected observation wells in the Prosper aquifer showing the hydraulic gradient between the observation wells.

wells 141-050-09AAA2, 141-050-23CCC2, and 140-050-09ABB may be partially due to this 'lip of the cone' effect.

Conversely, the larger hydraulic gradient in the vicinity of 139-050-02BAA may be partially due to being closer to the center of the cone of depression. Even though there may be mitigating effects in certain parts of the Prosper aquifer, there are still portions of the aquifer where the changes in the hydraulic gradient most likely do indicate changes in aquifer transmissivity. One such area is the reach between 140-050-15BBB and 140-050-15DDDC1 and 2, where there is a hydraulic gradient of almost 5 feet per mile. In this reach it is likely that the aquifer material is not as permeable, or the aquifer cross-sectional area is not as large.

The water levels in the observation wells in the northern two-thirds of the Prosper aquifer have declined about 0.3 feet per year (see Figures 42 and 43) over the last 15 years. The water levels in the observation wells on the south end of the Prosper aquifer have declined about 0.4 feet per year over the last 15 years. For the last seven years, this rate has lessened to 0.2 feet per year for the northern portion of the aquifer, and 0.25 feet per year for the southern wells in the Prosper aquifer. Virtually all of this decline appears to be due to leakage to the 94/10 and the WFN aquifers.

Aquifer water chemistry

Figures 15 through 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The sixth aquifer shown in each figure is the Prosper aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. Because 19 sites have chemical data available, there is a good representation of the general character of the water quality for the Prosper aquifer.

Figure 15 shows that the Prosper aquifer is in the middle range of calcium concentration in comparison to the other aquifers in the area. The range of values is similar to the Ponderosa aquifer. However, the median value is significantly lower. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the Prosper aquifer is very high in chloride concentration in comparison to other aquifers in the area. Both the median and extreme values for the Prosper aquifer are higher in chloride concentration than for any other of the aquifers of the WFAS. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride, and all but one of the samples from the Prosper aquifer exceed this value. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. The highest values for chloride concentration in the Prosper aquifer are well over the 400 mg/liter level. Even the median value exceeds 400 mg/liter.

Figure 17 shows that the Prosper aquifer is in the middle range of the group of nine aquifers with respect to hardness. About 90 percent of the Prosper aquifer hardness values are in the USGS category of "very hard" water, which is generally above 180 mg/liter. The remaining values fall into the "hard" category. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the Prosper aquifer is the highest among the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the Prosper aquifer is among the highest in comparison to other aquifers in the area with respect to sulfate concentration. Only the West Pleasant aquifer has a higher median value than the Prosper aquifer. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. The median value for the Prosper aquifer is about the equivalent of the SMCL, and only two outliers have values that exceed the EPA Drinking Water Standard. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present. The same two outliers exceed 600 mg/liter.

Figure 20 shows that the Prosper aquifer is among the highest of the group of nine aquifers with respect to the TDS concentration. Only the West Pleasant aquifer has a higher median value for TDS, however, the Prosper aquifer has higher outlier values for TDS than does the West Pleasant aquifer. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites that were sampled from the Prosper aquifer and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants. Most of the water from the Prosper aquifer is not suitable for plants.

The water in the Prosper aquifer is a sodium-chloride type. The total dissolved solids range from between 1,000 to over 3,000 mg/liter, and the water is mostly very hard. The water is marginal for most purposes.

Figure 45 shows the relationship between stable isotopes of ground water in the Prosper aquifer and precipitation at Oakes, ND. The eight sites had a $\delta^{18}O$ value that ranged from -16.1 to -20.0, and a $\delta^{2}H$ value that ranged from -122 to -147. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in North Dakota have shown values of approximately -18 to -25.

The Prosper aquifer samples are in the "snowfall" range, except for two sites that show significant depletion in the two stable isotopes, but do fall slightly outside of the "snowfall" zone between the "snowfall" and "rainfall" zones. This range of $\delta^{18}O$ values is strikingly cold in its signature. This range does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values of water samples collected from Prosper aquifer wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the Prosper aquifer.

Ground-water movement

Virtually all of the available water-level data for the Prosper aquifer has been acquired since 1983. Only one observation well (141-050-09AAA2) has any measurements that predate 1981. Klausing (1966) lists four domestic wells screened in

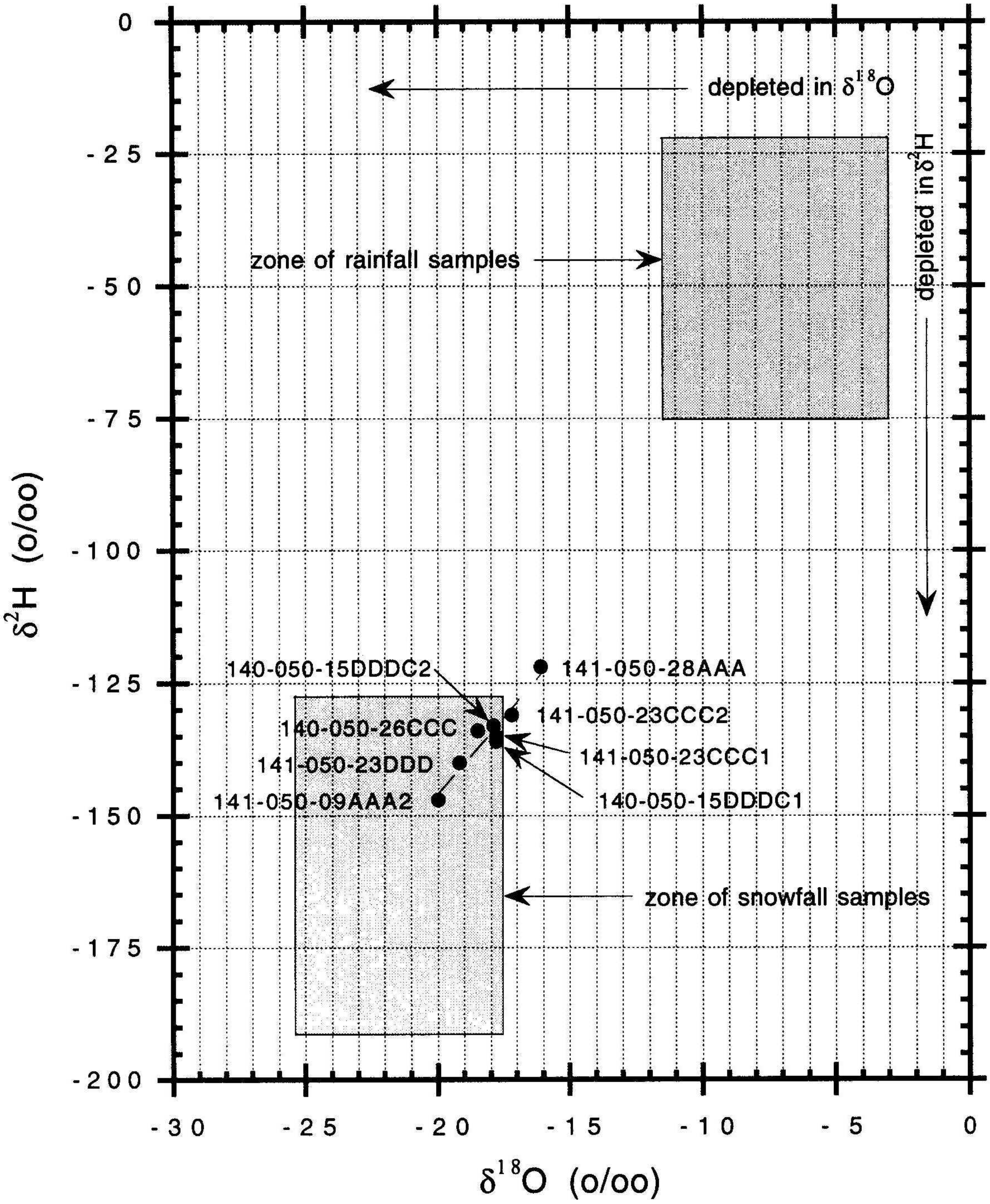


FIGURE 45. Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the Prosper aquifer and precipitation at Oakes, N.D.

the Prosper aquifer that have one water-level measurement in the 1960s. As mentioned earlier, there is no water use data available, and there are no indications that there has been any use made of the Prosper aquifer other than water that was used for farmsteads and individual homes.

Before any development occurred anywhere in the Fargo/Moorhead area, it is likely that the water level in the Prosper aquifer was at or above land surface. While there is no direct evidence of this, the fact that several other nearby aquifers did have water levels above land surface, indicates that the Prosper aquifer water levels were probably at or above land surface at the time the first wells were being installed in the study area. Thus ground-water movement would have been from the aquifer to the surface via the overlying aquitard consisting of till and lake clay. The aquifer is narrow in an east-west direction, and the topographically-driven eastern flow component was likely quite small. There may have been a northward flow component due to the north part of the aquifer being overlain by a topographically lower land surface. Once a few wells were installed, the water levels would have been lowered in the vicinity of those wells.

Because the areas closer to the Red River (towards the east) were settled earlier, and because those settlements were more densely populated, and required more water, the use of more water resulted in lower water levels to the east (see the earlier discussions on the WFN, Fargo, and Nodak aquifers). As mentioned earlier, when the water levels in the WFN aquifer began to decline significantly, ground water in the 94/10 aquifer began to leak significantly into the WFN aquifer, and ground water from the Prosper aquifer began to leak into both the WFN and 94/10 aquifers. This leakage most likely occurred in the vicinity of observation wells 141-050-33DDD, 140-050-36BBB, and 139-050-02BAA.

The earliest direct evidence of the Prosper aquifer ground-water flow pattern is found in the 1960s. The four domestic wells that have water-level measurements in the 1960s show that the well furthest to the north had the highest water-level elevation. The next lower water level was in the well that was the next furthest south, and so on until the southernmost well had the lowest water-level elevation.

Figures 42 and 43 show this same relationship of the highest water-level elevations in the north, and the lowest water-level elevations in the south for the time period since 1983. Besides showing the north-to-south ground-water movement, the potentiometric surface shown in figure 40 also indicates that the leakage is occurring in the vicinity of observation wells 141-050-23DDD, 140-050-36BBB, and 139-050-02BAA. While the general locations of the outflow from the Prosper aquifer is fairly clear, the magnitude of that ground-water movement is not. Neither hydraulic properties of the material connecting the two aquifers, nor the cross-sectional area through which the ground water is moving is known to any reasonable degree.

Figure 46 shows a five-year time period that was selected to compare the hydraulic gradient between observation wells with screens completed in the Prosper aquifer, and observation wells that are located near those Prosper wells, but are completed in a different aquifer. Wells 140-050-13CCC, 140-050-36BAA, and 139-050-01CCC have well screens completed in the 94/10 aquifer, and observation well 141-049-30BBB is completed in the WFN aquifer (see figure 40 for locations).

Figure 46 shows each pair of locations as having the same symbol, the first of which is a filled symbol indicating the Prosper well, and the second as an open symbol indicating the nearby observation well to the east. The legend shows every second location (2nd, 4th, 6th, and 8th) with the distance it is from the location listed above it. The numbers seen on the right side of the figure indicate the water-level difference between each two nearby wells that are completed in the two different aquifers.

The purpose of this figure is to show the relative difference in the leakage from the Prosper aquifer going into the 94/10 aquifer, in comparison to the leakage going into the WFN aquifer. While the cross-sectional area through which the ground-water movement is occurring is not known, the three pairs of sites relating the Prosper and the 94/10 are stretched across a 3- to 4-mile reach on the east side of the south end of the Prosper aquifer. The hydraulic gradient between the related pairs of observation wells range from about 8 to 18 feet per mile. A hydraulic gradient of 8 feet per mile indicates a fairly good connection between the two aquifers. Two sites could almost be considered as being within one aquifer when the hydraulic gradient is less than 6 to 9 feet per mile in these circumstances.

Figure 46 shows that the connection between the Prosper and the WFN aquifers exists over a much smaller reach (possibly as small as only several hundred feet), and that the hydraulic gradient is about 36 feet per mile. This is 2 to 4.5 times the hydraulic gradient observed at the south end of the Prosper aquifer. A larger hydraulic gradient will drive more ground-water movement through a comparable cross-sectional area of material. However, the material between the Prosper aquifer and the WFN aquifer, even if the thickness is equal, is possibly 50 times less permeable than the material between the Prosper aquifer and the 94/10. It is an unfounded guess to say that the thickness is comparable, but if it were, there might be 10 to 20 times as much movement of water going from the Prosper aquifer to the 94/10 than there is from the Prosper to the WFN.

Inflow into the Prosper aquifer likely occurs as a result of the leakage of other small, unidentified aquifers in the area, and from the aquitards surrounding the Prosper aquifer. One possibly significant source of leakage is an unnamed, shallow

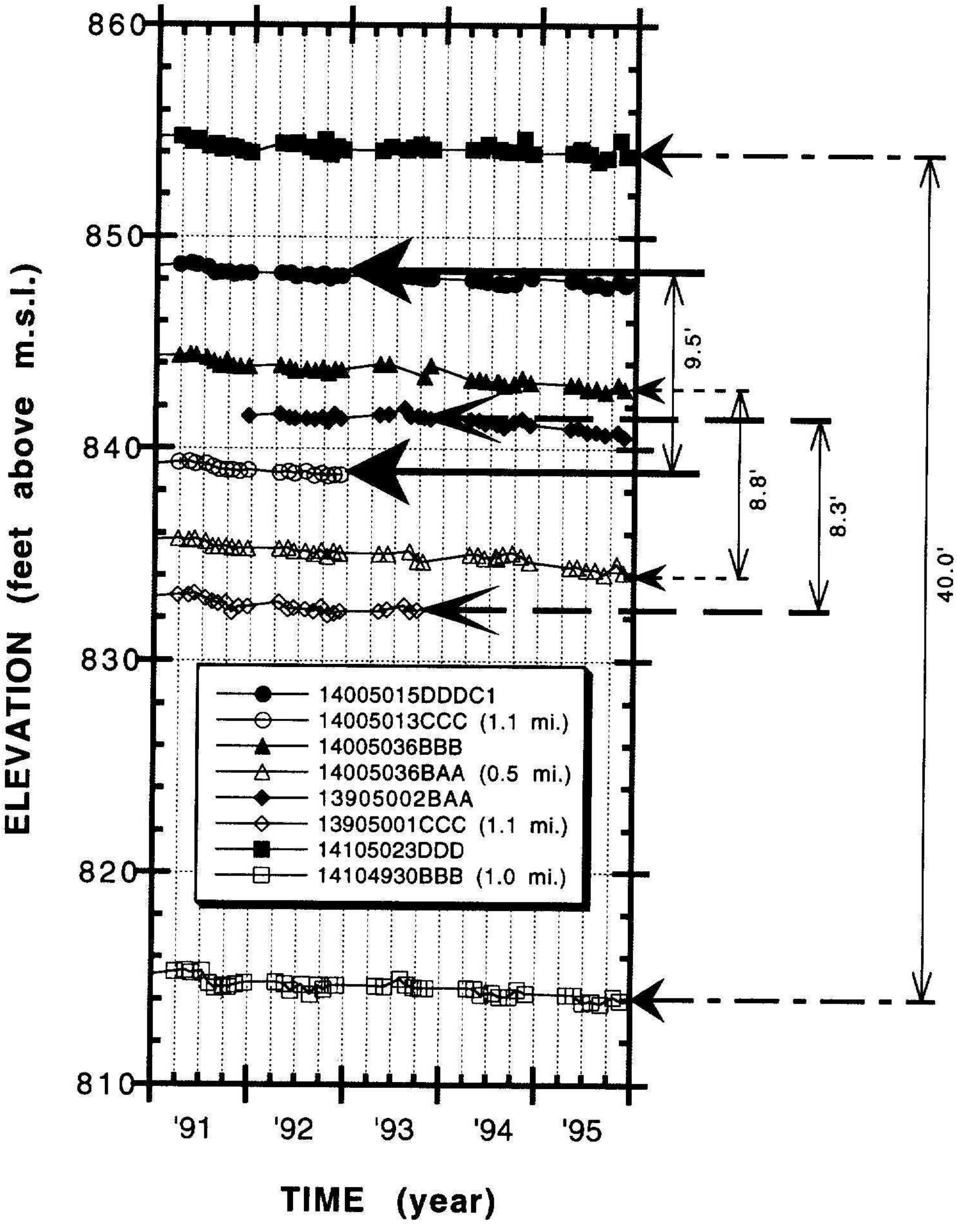


FIGURE 46. Hydrograph of selected observation wells located in or near the Prosper aquifer.

aquifer found in the northwest corner of Raymond Township. This aquifer appears to occur fairly consistently in about a 6 to 8 square mile area at depths of about 65 to 130 feet. One of the sites that appears to be in this small unnamed aquifer has water levels that relate well to the Prosper aquifer. Significant leakage into the Prosper aquifer could be from this aquifer.

Otherwise, the bulk of the water entering the Prosper aquifer is very likely drainage from aquitards surrounding the aquifer. These aquitards give up water very slowly to the Prosper aquifer. Also it is likely that some small sand and gravel units contribute water to the Prosper aquifer on a very small scale.

WEST PLEASANT AQUIFER

Aquifer size and location

The map in figure 47 shows the area that is underlain by the West Pleasant aquifer. The aquifer is a small, relatively shallow aquifer that parallels the west side of the Horace aquifer for about 5 to 6 miles. Figure 48 shows a geologic section of the aquifer (geologic section H-H'). The south end of the West Pleasant aquifer appears to be the deepest, especially on the east side. The separation between the West Pleasant aquifer and the Horace aquifer is quite narrow, possibly less than 2,000 feet in places. The aquifer is closely related, hydrologically, to the Horace aquifer.

The limits of the east side of the West Pleasant aquifer are not clear lithologically, however there are water-level differences that clearly indicate a hydraulic discontinuity between the observation wells in the West Pleasant aquifer and the observation wells in the Horace aquifer. In the report by Ulteig Engineers, Inc. (1979b) water-level measurements showed a 10-foot difference between observation wells 137-049-06CCD (West Pleasant aquifer) and 137-049-07AAA (Horace aquifer) in 1977. The distance between these wells is less than one mile. The same report also showed a 12-foot difference between 137-049-29ADD (West Pleasant aquifer) and 137-049-28BAA (Horace aquifer). The distance between these wells is about 0.7 miles.

Beyond the north and south ends of the West Pleasant aquifer there are test holes that show an absence of any significant sand or gravel layers. There is little test-hole information to delineate the western boundary of the West Pleasant aquifer. There is also inadequate water-level information to note any aquifer boundaries. The boundaries are drawn as they are on the west side, because the general nature observed for most of the aquifers in the WFAS is that they are between three-fourths and one and one-half miles wide. Additionally, the aquifer appears to thin toward the west. The estimated areal extent of the West Pleasant aquifer is about 3.2 square miles.

There are ten test holes and wells located in the West Pleasant aquifer that were investigated. Of these ten, eight had lithologic descriptions for a significant portion of

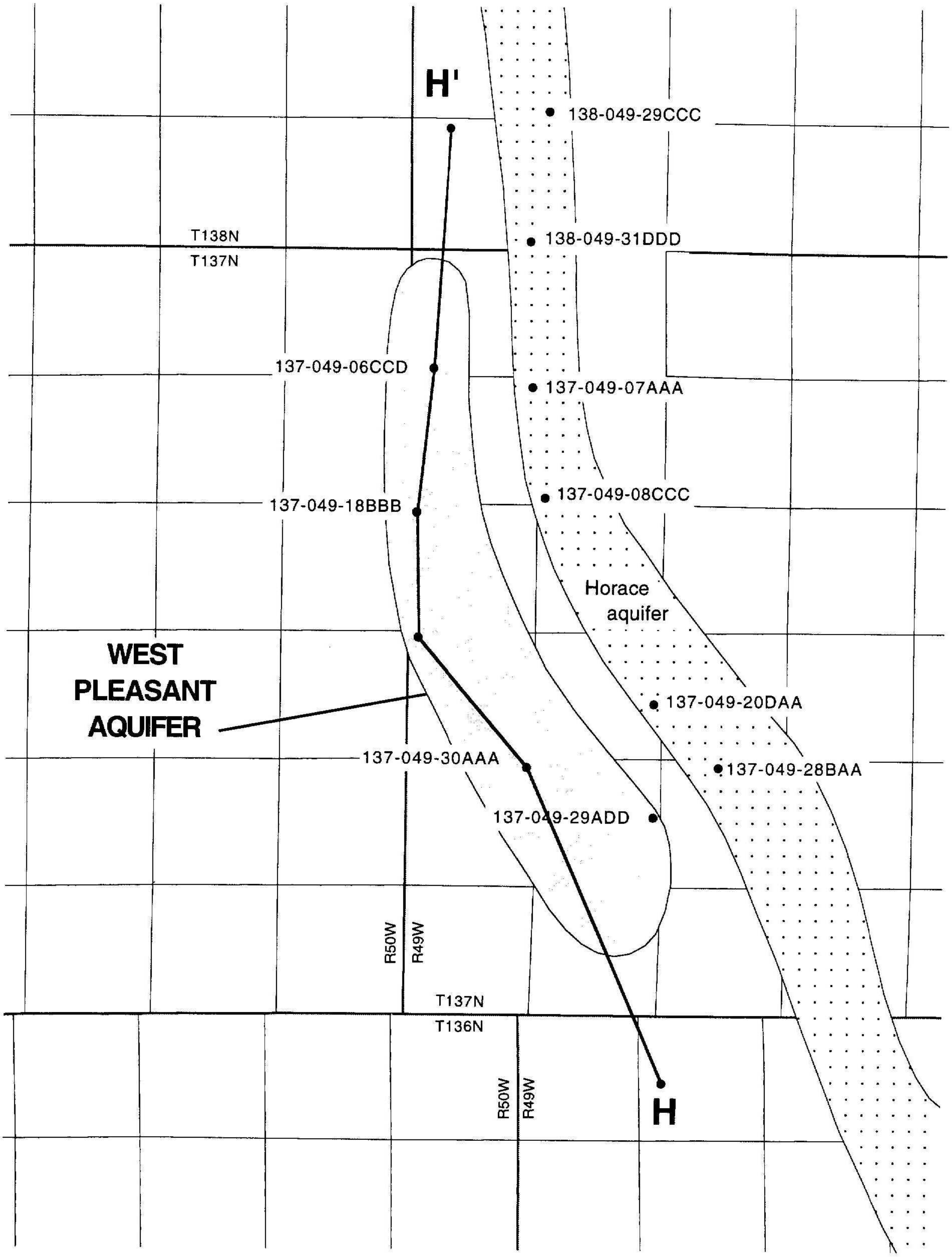


FIGURE 47. Location of the West Pleasant aquifer and geologic section H-H'.

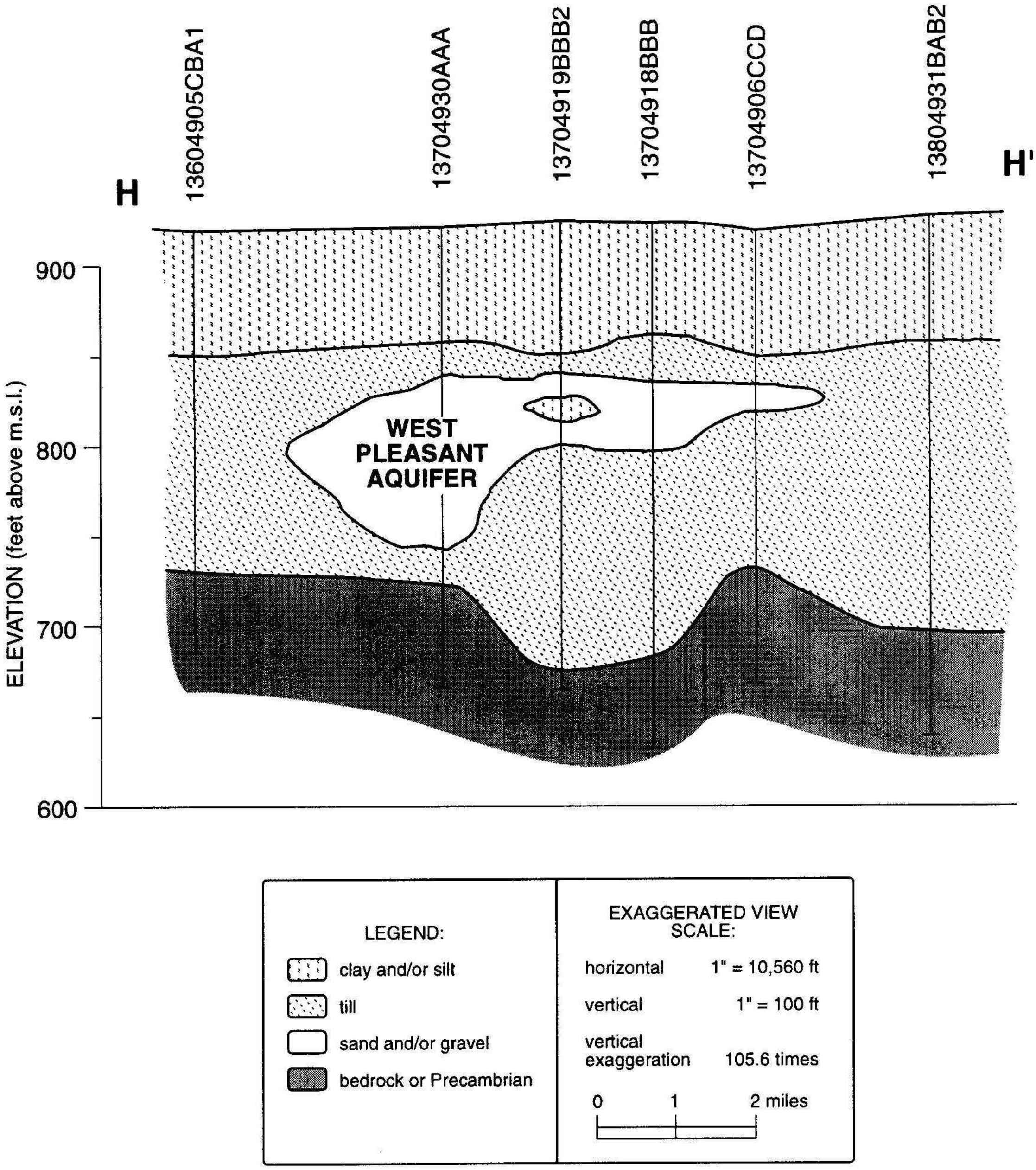


FIGURE 48. **South-north geologic section H-H' showing the West Pleasant aquifer.**

the aquifer interval. The West Pleasant aquifer is predominantly comprised of poorly-sorted to well-sorted sands and gravels. Every lithologic description had significant amounts of gravel in the description, except for the lithologic description for 137-049-29ADD, which was comprised entirely of a well-sorted, medium-to-coarse sand.

The average depth to the top of the West Pleasant aquifer is about 90 feet below land surface. The top of the aquifer ranges from 70 to 110 feet below land surface. The bottom of the aquifer is not as uniform and consistent. Most of the lithologic descriptions for holes drilled into the West Pleasant aquifer show the sand and gravel ending within about 100 feet (plus or minus 20 feet) below land surface. There are a few holes that show sand and gravel at depths of up to 150 to 180 feet, and one test hole, 29ADD, showed a depth of 275 feet below land surface. The average depth to the bottom of the aquifer is about 145 feet below land surface. The average thickness of the West Pleasant aquifer is about 57 feet.

With an average thickness of about 57 feet, and an area of about 3.2 square miles, the approximate volume of the West Pleasant aquifer is 5 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

Aquifer water use and water-level history

There is no documented water-use data for the West Pleasant aquifer. There have likely been five to ten farmsteads overlying the aquifer. Water use from the aquifer has been quite small. It is likely that virtually all of the water-level decline that has occurred in the West Pleasant aquifer is due to leakage into the Horace aquifer.

Figure 49 shows a hydrograph of the water-level measurements for three observation wells screened in the West Pleasant aquifer. All three wells display declining water levels. Figure 50 shows a hydrograph with the same three wells included, along with the water-level measurements for four observation wells located in the nearby Horace aquifer. The lowest curve is a plot of the measurements for observation well 138-049-29CCC. The curve shows several irregularities in the late 1980s and early 1990s that are a result of the well being plugged and the unsuccessful efforts to clean out the material plugging the well. It is believed that there was road construction in the mid-1980s that may have damaged the well. It is probable that the water-level record for this site is valid for the time period before 1984, and possibly 1987. Post-1987 measurements should be ignored.

Figure 51 shows a hydrograph of four of the seven observation wells that were shown on figure 50, however this shows better detail because the scale for figure 51 shows a smaller range of elevation and fewer years. The main intent of these hydrographs is to show the relationship between the Horace water levels and the West

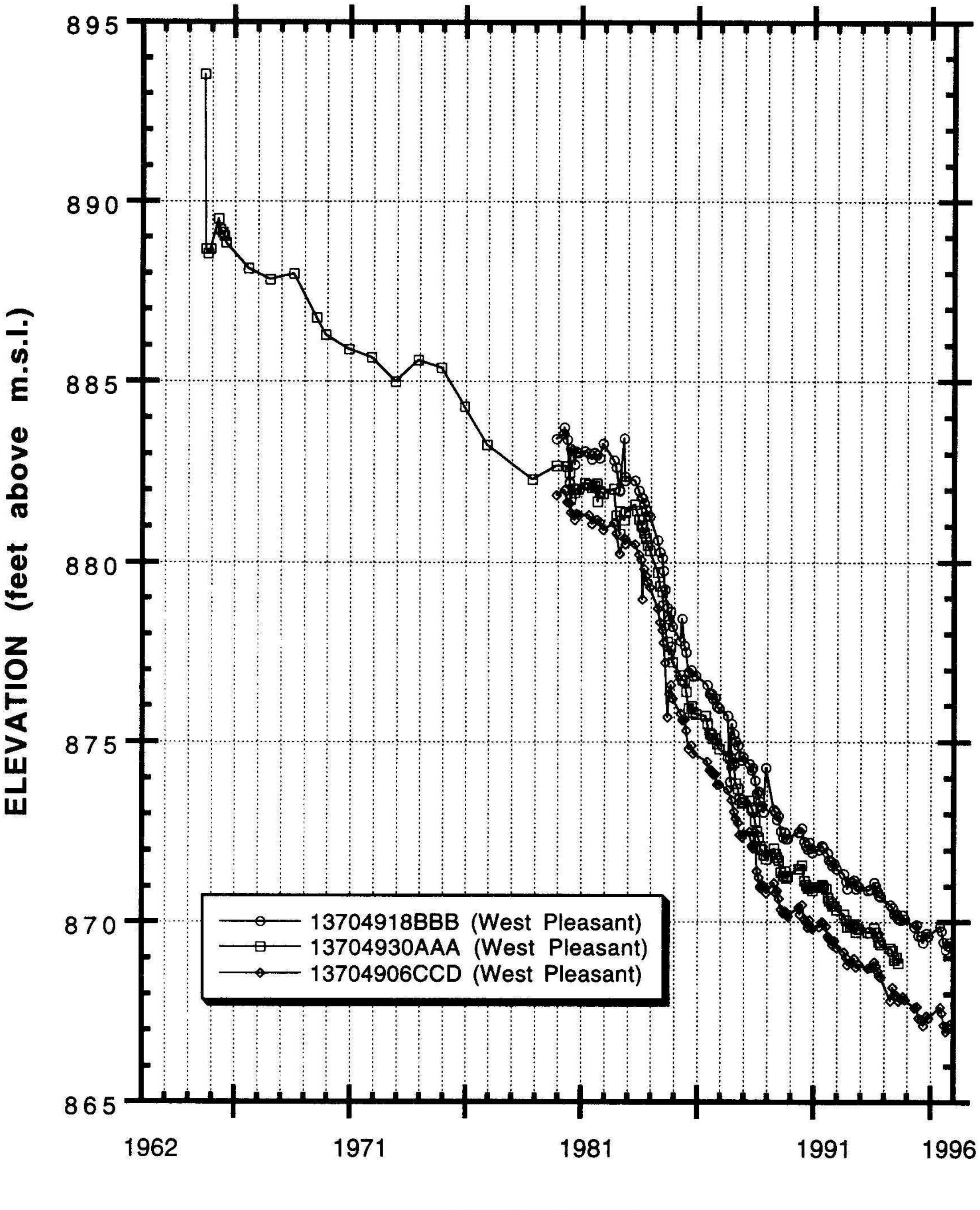


FIGURE 49. Hydrograph of observation wells located in the West Pleasant aquifer.

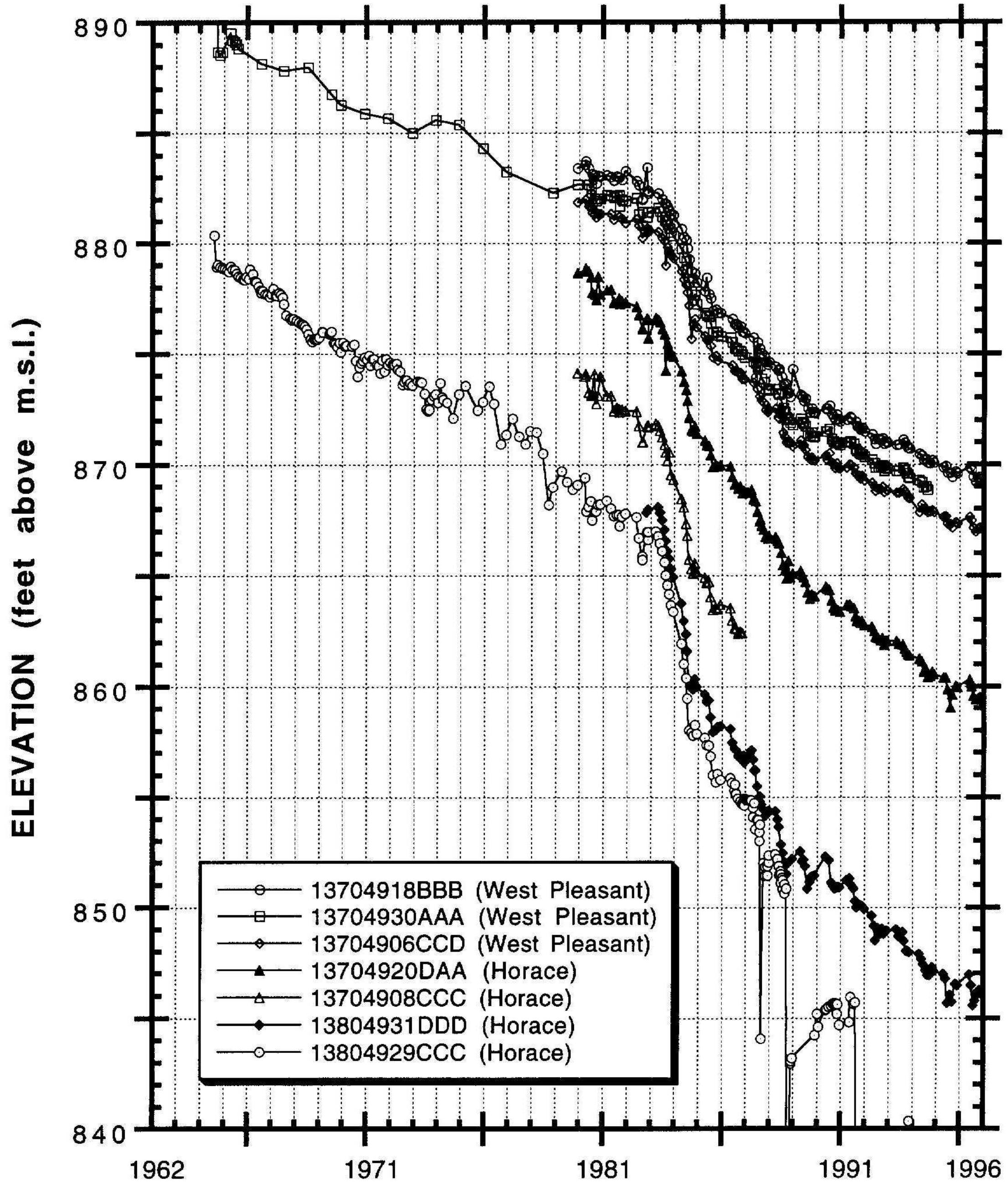


FIGURE 50. Hydrograph of selected observation wells located in the West Pleasant and Horace aquifers.

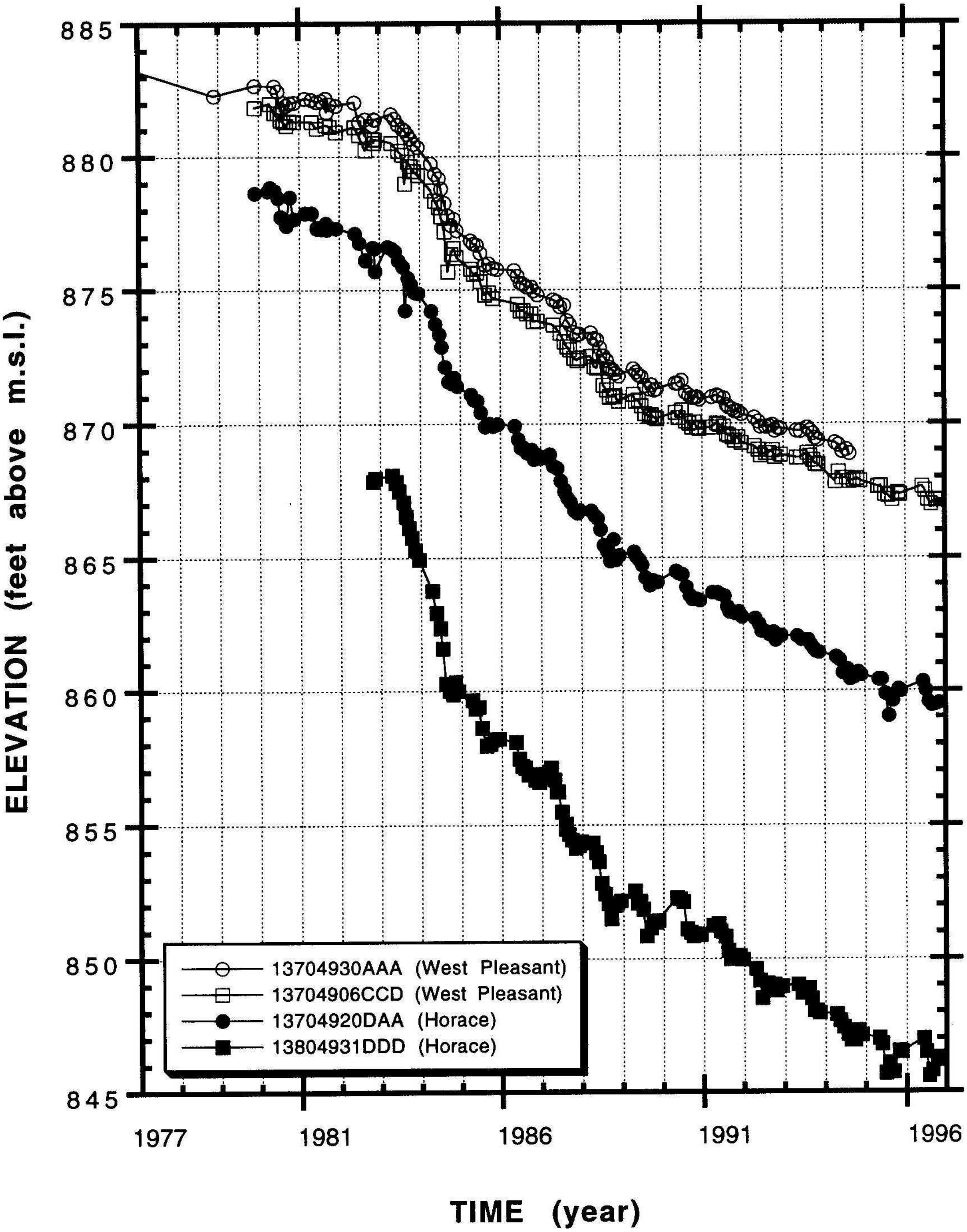


FIGURE 51. Hydrograph of selected observation wells located in the West Pleasant and Horace aquifers.

Pleasant water levels. In all instances the Horace water levels are lower, and the patterns of both aquifers are fairly similar. The conclusion is that even though there has been very little water withdrawn from the West Pleasant aquifer, the water use in the Horace aquifer, and aquifers that the Horace aquifer is connected to have caused most of the water-level decline observed in the West Pleasant aquifer.

Figures 49, 50, and 51 show that water levels were declining at a rate of about 0.5 feet per year from 1965 until 1983. In 1983 the city of West Fargo began utilizing up to about 275 Mg/y from a part of the WFS aquifer that is indirectly connected to the Horace aquifer. Figures 50 and 51 show the increase in the rate of water-level decline that occurred in the Horace observation wells when the city of West Fargo began to utilize the WFS aquifer for part of their water supply in 1983. This decline in the Horace water levels led to the decline in the West Pleasant aquifer water levels.

Figure 49 shows that the water levels have declined on the average about 0.9 feet per year from the start of 1982 until the end of 1996. The average decline from the start of 1991 to the end of 1996 has been about 0.5 feet per year. Virtually all of this decline in the West Pleasant aquifer water levels appears to be due to leakage to the Horace aquifer.

Aquifer water chemistry

Figures 15 through 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The ninth aquifer shown in each figure is the West Pleasant aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The West Pleasant aquifer is one of these aquifers, with only five sites being represented.

Figure 15 shows that the West Pleasant aquifer is the aquifer with one of the largest ranges of calcium concentration in comparison to the other aquifers in the area. The median value of calcium concentration for the West Pleasant aquifer is much higher than for any other aquifer. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the West Pleasant aquifer is high in chloride concentration in comparison to other aquifers in the area. Both the median and extreme values for the West Pleasant aquifer are the third highest in chloride concentration among the other aquifers of the WFAS. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride, and most of the samples from the West Pleasant aquifer exceed this value. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. Some of the highest values for chloride concentration in the West Pleasant aquifer are over the 400 mg/liter level.

Figure 17 shows that the West Pleasant aquifer has the largest median value with respect to hardness of the group of the nine aquifers. All of the West Pleasant aquifer hardness values significantly exceed the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the West Pleasant aquifer is among the highest among the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the West Pleasant aquifer is extremely high in comparison to other aquifers in the area with respect to sulfate concentration. The West Pleasant aquifer has a median value for sulfate that is almost twice as high as the next highest median value for any of the other aquifers in the area. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. The median value for the Prosper aquifer exceeds the EPA Drinking Water Standard. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present. Outliers exceed the 600 mg/liter value.

Figure 20 shows that the West Pleasant aquifer is among the highest of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. The West Pleasant aquifer has the largest median value for TDS. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. Otherwise, all sites that were sampled from the West Pleasant aquifer and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants. Most of the water from the West Pleasant aquifer is not suitable for plants.

Because so many constituents are high in the water sample analyses from the West Pleasant aquifer, there is no dominant anion, and calcium is very slightly the dominant cation. The total dissolved solids range from between 800 to over 1900 mg/liter, and the water is extremely hard. The water is marginal for most purposes.

Figure 52 shows the relationship between stable isotopes of ground water in the West Pleasant aquifer and precipitation at Oakes, ND. The one sample had a $\delta^{18}O$ value of -19.6, and a $\delta^{2}H$ value of -154. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". Samples of rainfall in North Dakota have shown (figure 21) values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in North Dakota have shown values of approximately -18 to -25.

The West Pleasant aquifer sample is in the middle of the "snowfall" range. This value of $\delta^{18}O$ is strikingly cold in its signature. A value like this does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values of a water sample collected from a West Pleasant aquifer well indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the West Pleasant aquifer.

Ground-water movement

One of the main tools used to determine flow paths within a complex flow system is the analysis of historic water-level measurements. The first such measurements for the West Pleasant aquifer were taken in 1964. The West Pleasant aquifer observation well (137-049-30AAA) is the only well that has measurements that go back that far in time. Water-level measurements for the other observation wells in the West Pleasant

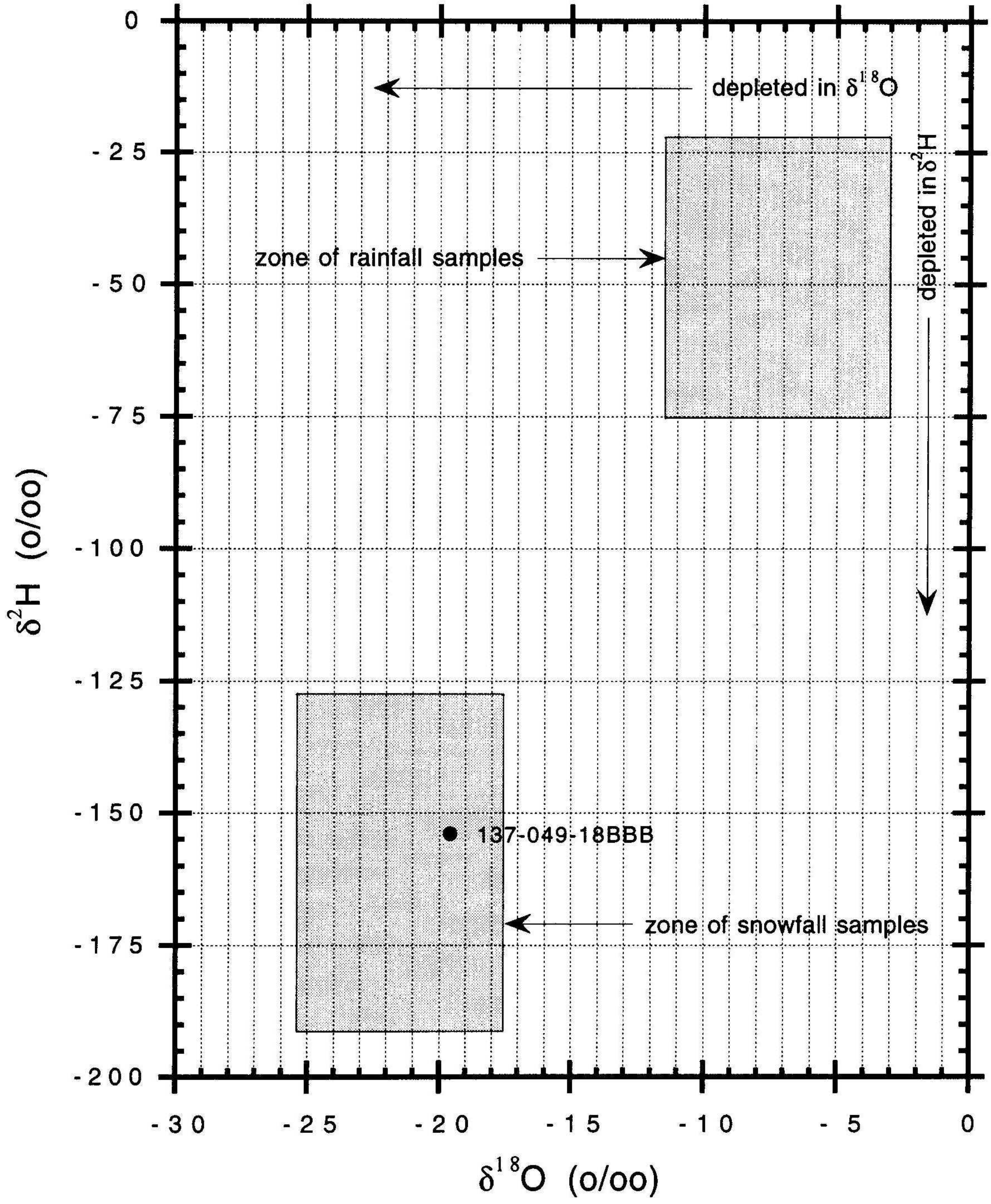


FIGURE 52. Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the West Pleasant aquifer and precipitation at Oakes, N.D.

aquifer begin in 1979. As a result, the discussion about the ground-water movement that predates 1979, and especially 1964, has a higher degree of uncertainty associated with it.

It is likely that the West Pleasant aquifer is similar to the WFN and the Fargo aquifers (aquifers that have a longer record of water levels), in that the water levels were probably at, or slightly above, land surface before the area was settled. As with those aquifers, it is likely that ground-water movement in the West Pleasant aquifer before the late 1800s went upward from the aquifer, toward land surface, where the water levels were lower. The ground-water levels at the surface were likely lower, because the evapotranspiration processes withdrew water at land surface, especially in low-lying areas.

Because the lake clays that lie between the West Pleasant aquifer and the land surface are so continuous, thick (generally about 60 to 70 feet), and characterized by a small hydraulic conductivity, upward ground-water movement was likely slow and minimal. Occasional till layers near the surface, and occasional small sand lenses within the lake clay change this scenario very little. Because no water had been withdrawn from any other aquifers in this area, the water levels in the different aquifers were likely fairly similar. There was probably very little lateral ground-water movement, except for the north and east flow resulting from topographic influences.

In the late 1800s certain aquifers did have water withdrawn from them, and there was a water-level decline that occurred in those aquifers that were utilized for a ground-water supply. These water-level declines, in turn, likely caused water to seep from other nearby, untapped aquifers into the first aquifers that were used. Depending on the degree of connection between the untapped aquifer with the higher water levels, and the aquifer used for a ground-water supply with the lower water levels, there would have been some flow into the utilized aquifer. Due to the lack of water-level measurements in this area, it is not possible to state when the water levels in the West Pleasant aquifer began to decline from this influence. It is likely that water-level declines began somewhere in the time period from the early 1900s to the 1930s.

Figure 10 shows the 85 feet of water-level decline that occurred in a WFN aquifer well from 1937 to 1964, and figure 26 shows the 100 feet of water-level decline that occurred in the Fargo aquifer from 1937 to 1981. It is likely that some water-level decline occurred in this time period within the West Pleasant aquifer. The first recorded data on actual water levels in the West Pleasant aquifer are shown in figure 49. The water levels were about 25 to 30 feet below land surface in 1964. Because farmsteads were so few in number and because there were no towns overlying the aquifer, it is most improbable that the 'assumed' water-level decline occurred only from direct use of the West Pleasant aquifer.

Figure 50 shows water levels for several wells in both the West Pleasant aquifer and in the Horace aquifer. Two wells on this graph have measurements that date back to 1964. They are observation well 137-049-30AAA (West Pleasant aquifer) and observation well 138-049-29CCC (Horace aquifer). Figure 47 shows that they are about 5 miles apart. Another Horace observation well, 137-049-20DAA, is about a mile away from 30AAA, and about 4 1/2 miles from 29CCC. From the 1979 to 1996 time period the water levels in 30AAA have been 10 to 13 feet lower than the water levels in 20DAA, resulting in a hydraulic gradient of 2 to 3 feet per mile. It is likely that a similar hydraulic gradient has been maintained for many years, ever since the Horace aquifer began to respond to ground-water withdrawals from other aquifers in the area. There are areas north of the city of Horace where leakage occurs from the Horace aquifer to both the WFN and the WFS aquifers.

The relationship between 20DAA and 29CCC is discussed, because it is likely the leakage that is currently occurring from the West Pleasant aquifer to the Horace aquifer across much of the eastern margin of the West Pleasant aquifer has occurred historically as long as water levels were lower in the Horace aquifer than they were in the West Pleasant aquifer. Thus, flow likely also occurred from the area around 30AAA toward the area around 20DAA. In this instance the water-level difference has been about 5 to 9 feet, and results in a gradient that represents a well connected, but different aquifer.

Figure 51 shows two pairs of nearby observation wells that indicate the water-level differences between the West Pleasant aquifer and the Horace aquifer for the time period 1979 to 1996. At the north end of the West Pleasant aquifer observation well 137-049-06CCD has water levels that are about 20 feet higher than the water levels for observation well 138-049-31DDD, which is about 1.4 miles away. This results in a hydraulic gradient of about 15 feet per mile. If the flow from the West Pleasant aquifer to the Horace aquifer were evenly distributed across the full reach of the east side of the West Pleasant aquifer, the hydraulic gradients would be fairly similar. The fact that the hydraulic gradient is lower at the southern end of the West Pleasant aquifer, indicates that the aquifers are probably better connected at the south end of the West Pleasant aquifer.

Figure 50 shows all three of the West Pleasant aquifer wells that have regularly measured water levels. While all three wells have very similar water-level elevations (within about 2 feet of each other), the central well consistently has the highest water levels. This means that within the aquifer there is some ground-water movement from the central portion of the West Pleasant aquifer toward the north and south ends. However, it is likely that most of the ground-water movement is toward the east, and the Horace aquifer.

Inflow into the West Pleasant aquifer likely occurs as a result of the leakage from the aquitards surrounding the West Pleasant aquifer. This fine-grained material gives up water very slowly to the West Pleasant aquifer. There may be small sand and gravel lenses that are slightly or moderately connected to the West Pleasant aquifer that contribute leakage as well.

HORACE AQUIFER

Aquifer size and location

The map in Figure 53 shows the area that is underlain by the Horace aquifer. The aquifer stretches out for about 22 miles in a north-northwest/south-southeast direction. It is generally relatively narrow (approximately one mile in width), and appears to be the result of two coalescing channels. The western channel-like feature is the longest part of the Horace aquifer (about 22 miles), and the eastern channel-like feature is about 9 1/2 miles in length. Where the two portions of the Horace aquifer coalesce, the aquifer width may be as much as 2 and 1/2 miles. Figure 53 also shows the location of geologic sections I-I' (western portion) and J-J' (eastern portion).

Starting at the north end of the Horace aquifer, the existence of a boundary between the Horace aquifer and the 94/10 aquifer is clear from the significant water-level difference between the two aquifers. Water-level elevations from two observation wells (one in each aquifer) that are located about one mile apart have shown water-level differences of between 15 and 24 feet.

Moving south along the west side of the Horace aquifer, before reaching the north end of the West Pleasant aquifer, there are a few test holes that show an absence of sand and gravel units. There are also, however, a few test holes or wells to the west of the Horace aquifer that have lithologic descriptions that depict significant sand or gravel units. Inadequate information exists to show whether these are connected (tributary-like) units, or if they are relatively unconnected isolated sand and gravel lenses. Because there are occasional lithologic logs showing no sand or gravel intervals that result in a fairly consistent width to the Horace aquifer of about 3/4 of a mile to 1 mile, these individual units are not shown as being part of the Horace aquifer. It could be that some of them are part of the Horace aquifer, and that there is a greater width to the Horace aquifer in some places on the west side.

The limit of the west side of the Horace aquifer in the vicinity of the West Pleasant aquifer is not clear lithologically. However, there are water-level differences that clearly indicate a zone of reduced hydraulic conductivity between the observation wells in the Horace aquifer and the observation wells in the West Pleasant aquifer. In the report by Ulteig Engineers, Inc. (1979b) water-level measurements showed a 10-foot difference between observation wells 137-049-06CCD (West Pleasant aquifer) and

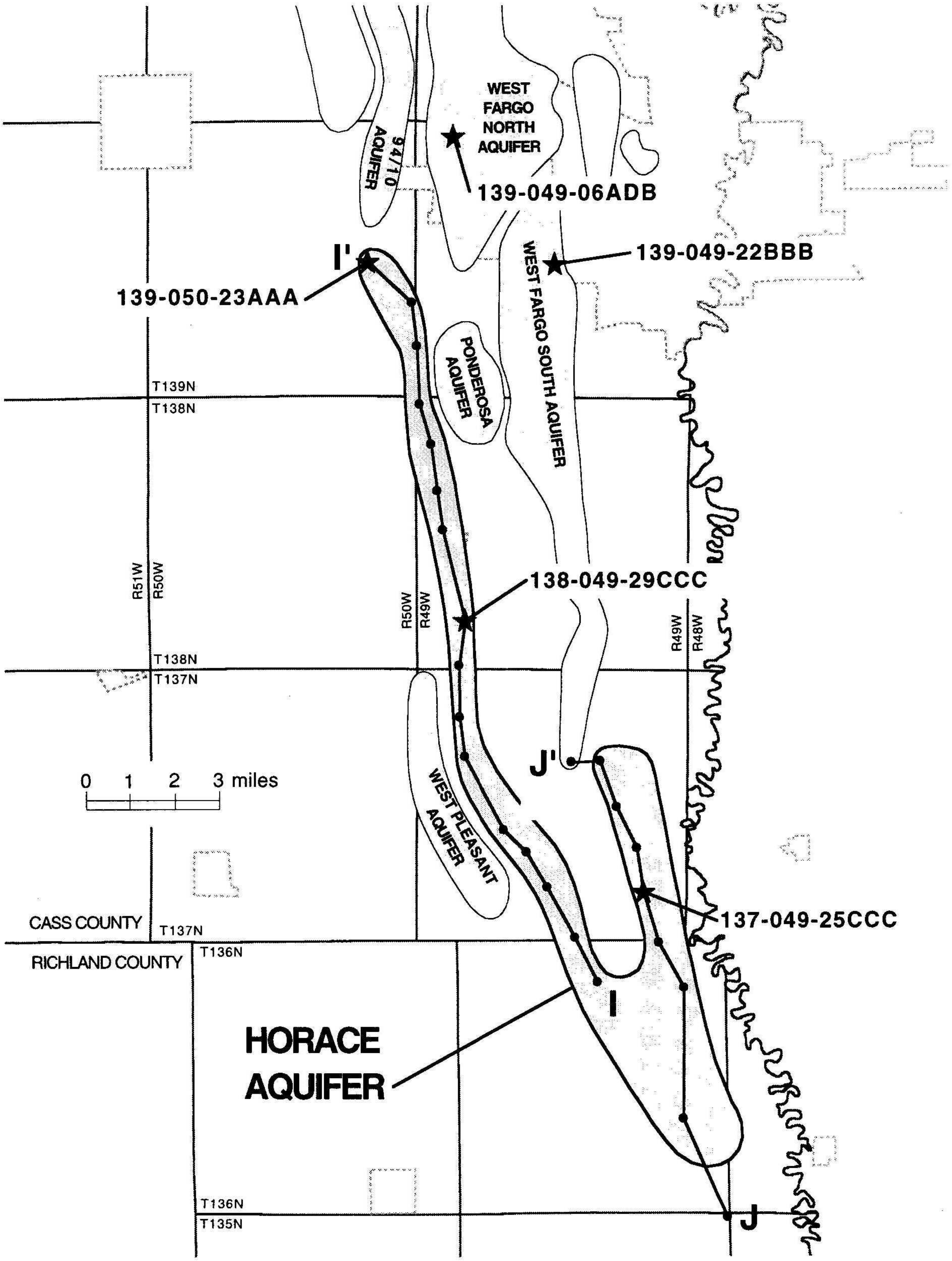


FIGURE 53. Location of the Horace aquifer and geologic sections I-I' and J-J'.

137-049-07AAA (Horace aquifer) in 1977. The distance between these wells is less than one mile. The same report also showed a 12-foot difference between 137-049-29ADD (West Pleasant aquifer) and 137-049-28BAA (Horace aquifer). The distance between these wells is about 0.7 miles. The hydraulic gradients that result from these water-level differences at these distances are 10 feet per mile or greater, and indicate that these two aquifers are possibly related, but not continuous.

The aquifer boundary on the southwest side of the Horace aquifer is estimated based upon the few lithologic logs that show little or no sand or gravel intervals. At the far south end of the Horace aquifer, water-level differences indicate that the aquifer appears to terminate just south and east of the city of Christine.

There is little data available to accurately depict the east margin of the east portion of the Horace aquifer. There is only one test hole at the south end of the Horace aquifer with a lithologic log, and one observation well with water-level measurements at the north end of the east portion of the Horace aquifer that can be used to infer aquifer boundaries. There may be tributary-like sand and gravel bodies located along the Red River that are connected to the Horace aquifer. Without direct evidence, however, the east margin of the east portion of the Horace aquifer is drawn solely on the basis of the lithologic log in the south showing no significant sand or gravel, and the 15-foot water-level difference between two observation wells that are about 1.3 miles apart.

Near the center of Pleasant Township (T137N, R49W) the Horace and the West Fargo South aquifers are less than one-half mile apart. There are two observation wells with water levels that are about 7 to 8 feet different in elevation. These two wells are about one-half mile apart, resulting in a hydraulic gradient between the two aquifers of at least 15 feet per mile. The two aquifers are clearly related (based upon water-level patterns), but there is a significant zone of small hydraulic conductivity that separates the two aquifers so that a hydraulic gradient as high as 15 feet per mile can be maintained.

Figure 53 shows an area between the east portion and the west portion of the Horace aquifer that is not aquifer material. The basis of this area is predicated on two factors. There is one test hole near the county line with a lithologic log that shows no significant sand or gravel. The aquifer discontinuity that is observed at the county line is projected northward based on the fact that the water-level patterns become more and more dissimilar with distance north from the county line. The aquifer discontinuity is also projected northward on the basis of extending the channel-like character that both segments of the Horace aquifer display.

The eastern margin of the western portion of the Horace aquifer along the reach from the southern end of the WFS aquifer north to the southern end of the Ponderosa aquifer is based on several test holes showing no aquifer section between the WFS and

Horace aquifers. Additionally, the water-level data shows distinctly different patterns. There are also significant water quality differences observed in the analyses of samples taken from the Horace and the WFS aquifers.

The interpretation of a boundary between the Ponderosa and Horace aquifers is based on differences in water-level elevations. The water-level elevation differences in two observation wells about one-half mile apart are consistently about 7 feet, resulting in a hydraulic gradient of about 15 feet per mile. This is indicative of a zone of small hydraulic conductivity between the two aquifers.

Finally, the non-aquifer area shown on figure 53 that lies between the Horace, Ponderosa, WFN, and 94/10 aquifer is based on lithologic log and water-level data. The lithologic log from one test hole in that area shows very limited aquifer material. Additionally, an observation well in this area shows that the water level has been 24 to 38 feet lower than the water level in a Horace observation well that is about 1.4 miles away.

The Horace aquifer, as depicted in figure 53, extends across an area of about 26.8 square miles. There are several areas where the aquifer may be larger, and a few areas where the aquifer may be smaller. Figures 54 and 55 show south-to-north geologic sections I-I' and J-J', which depict the west and east parts, respectively, of the Horace aquifer. Geologic section I-I' shows more complexities and irregularities in the west part of the Horace aquifer, than does geologic section J-J' in the east part of the Horace aquifer.

There are 58 test holes and wells located in the Horace aquifer that were investigated. Of these, 53 had lithologic descriptions for a significant portion of the aquifer interval. The range of lithologic descriptions for the different sand and gravel units is quite varied. Some sand units were fine grained, and some of the gravel units were very coarse, grading into boulders in some test holes. The lithologic descriptions usually showed the material becoming coarser with depth, with numerous sites transitioning from medium sands to gravels with increasing depth. The eastern portion of the Horace aquifer appeared to be more gravelly than the western portion.

The average depth to the top of the Horace aquifer is about 136 feet below land surface. The top of the aquifer ranges from 57 to 328 feet below land surface. As seen in the contrast between the two geologic sections in figures 54 and 55, the western portion of the Horace aquifer (figure 54) has the more irregular top of aquifer. The average top of the aquifer is about 146 feet below land surface in the western portion of the Horace aquifer, whereas it is only about 103 feet below land surface on the average to the top of the Horace aquifer in the eastern portion.

The average depth to the bottom of the Horace aquifer is about 233 feet below land surface. The bottom of the aquifer ranges from 101 to 375 feet below land surface.

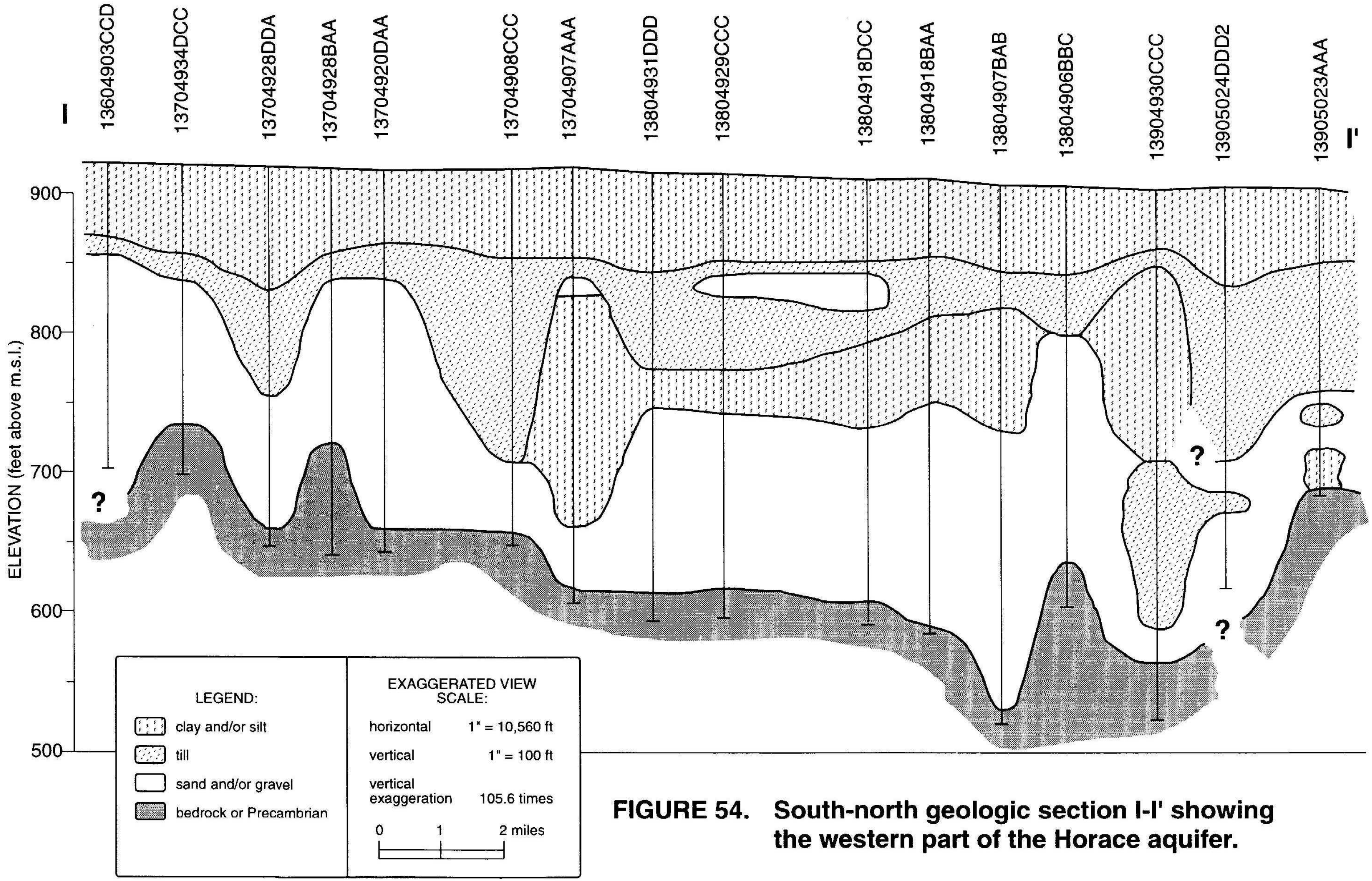


FIGURE 54. South-north geologic section I-I' showing the western part of the Horace aquifer.

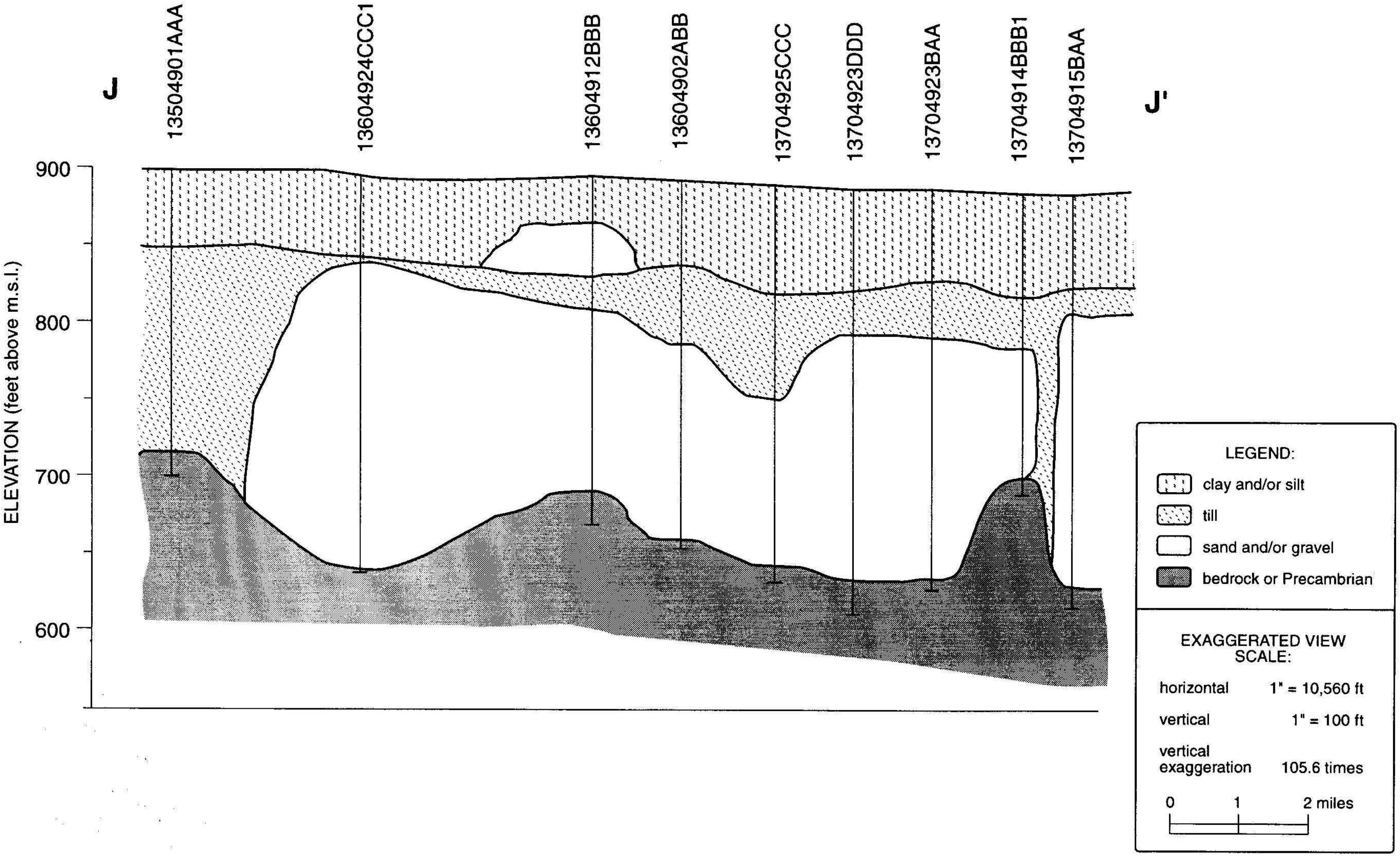


FIGURE 55. South-north geologic section J-J' showing the eastern part of the Horace aquifer.

The western portion of the Horace aquifer (figure 54) also has the more irregular aquifer bottom. The average bottom of the aquifer is about 240 feet below land surface in the western portion of the Horace aquifer, whereas it is only about 207 feet below land surface on the average to the bottom of the eastern portion of the Horace aquifer.

About 40 percent of the sites have an overlying sand and gravel unit that appears to be connected to the underlying Horace aquifer. These units range from 5 feet to 48 feet. Over the entire area of the Horace aquifer they average about 6 feet in thickness. The average thickness of the main Horace aquifer including the overlying sand and gravel layers is about 103 feet. With an average thickness of 103 feet, and an area of about 26.8 square miles, the approximate volume of the Horace aquifer is about 77 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

Aquifer water use and water-level history

It is likely that in the area overlying the Horace aquifer the development of farmsteads and wells began in the late 1800s. There are some shallow sand units that could have provided water from shallow wells, however, it is likely that some of the early wells were deep enough to reach the Horace aquifer. These early wells very likely flowed when they were first installed. As the population grew and water use increased, the water levels approached land surface and then dropped below land surface. Unlike some of the other aquifers (that have no water use records that reflect little significant historic water use), there may have been moderately significant use made of the Horace aquifer before water-use data is available beginning in 1978.

The communities of Christine, Hickson, and Horace overlie, or lie very near to, the Horace aquifer. In the late 1800s and the early 1900s these communities drew concentrated settlements that would have needed water, the use of which would have caused small water-level declines. Because of the concentrated nature of the withdrawals, these small water-level declines would have been a little more significant than they would have been had there been only dispersed farmsteads in the area. Additionally, the Wild Rice and Sheyenne Rivers are located above the Horace aquifer for extended distances. This resulted in a greater than normal density of farmsteads than is observed in some of the other parts of this study area. Not counting the communities in the area, there probably were 75 to 125 homes overlying the Horace aquifer through the 1900s.

In 1933 a Census Bureau estimate listed the population of the communities of Christine, Hickson, and Horace as 175, 75, and 250, respectively. At an estimated 60 gallons per person per day, these communities would have used something on the order of 10,000,000 gallons per year (10 Mg/y). If there were also about 100 farmsteads deriving their water supply from the Horace aquifer, and there were an estimated five people per farmstead, the rural population would have used an estimated 10 Mg/y. This estimate is made to compare the magnitude of the water use from the Horace aquifer, to the magnitude of the water use from the Fargo aquifer.

During the time period of the late 1930s and the 1940s, figure 25 shows that the Fargo aquifer produced an average of about 15 Mg/y. An estimated 20 Mg/y was withdrawn from the Horace aquifer during this same time period. The impacts of this magnitude of water use, however, would have been significantly different for each of these two aquifers for a couple of reasons. The Horace aquifer is over 100 times larger than the Fargo aquifer, and because the Horace aquifer is so much larger, the impacts of the water diversion would be much less noticeable in the Horace aquifer. The water use shown in figure 25 is derived from one well, whereas the use that was likely made of the Horace aquifer during this time period is estimated from the cumulative effects of many wells spread over a large area.

Figure 56 shows a hydrograph of three observation wells located in the Horace aquifer, and one well each, located in the West Fargo North and the West Fargo South aquifers. The hydrograph begins in the early 1960s, when water-level measurements that were associated with the Cass County ground-water study were initiated. A summary of the available water use data for the Horace aquifer is found in Table 5I on pages C230-1 in Volume C of the data report for this study. Figure 57 shows a bar chart of the annual water use from the Horace aquifer. The bar chart shows no documented water use until 1978.

As stated earlier, there was likely an additional 20 Mg/y of water use that was undocumented until about 1983 to 1984. This is when the cities of Christine and Horace began to report their water use associated with the water permits that were issued in 1980 and 1983. After 1984, there is an estimated 10 Mg/y additional water use derived from the numerous individual wells overlying the Horace aquifer that do not submit annual water use reports. The key aspect of this discussion is that while water use has likely grown from about 40 Mg/y in the early 1980s to about 110 Mg/y in the mid 1990s, this increase in the rate of water use is not the most significant factor in the water-level declines observed in the water levels of the Horace aquifer.

Initially, Figure 56 shows that by the early 1960s the water levels in the Horace aquifer were in a slow steady decline. The lowest water levels were not located near the wells of the city of Horace and the other small communities, but rather they were located at the north end of the Horace aquifer where ground-water withdrawals were minimal. Figure 53 shows the proximity of 139-050-23AAA to the 94/10 aquifer, and the proximity of the northern end of the Horace aquifer to the WFN aquifer.

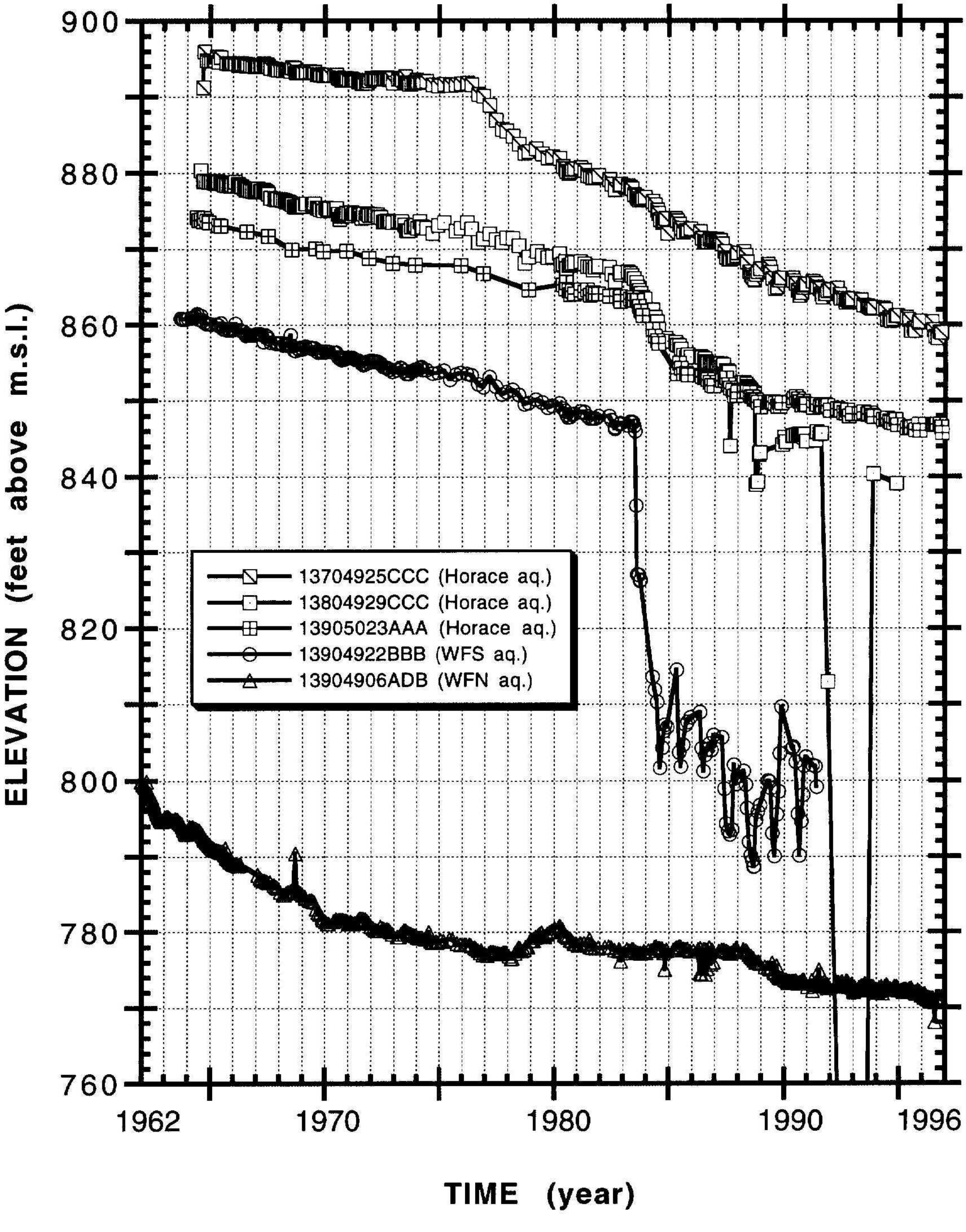


FIGURE 56. **Hydrograph of observation wells in the Horace, WFN, and WFS aquifers.**

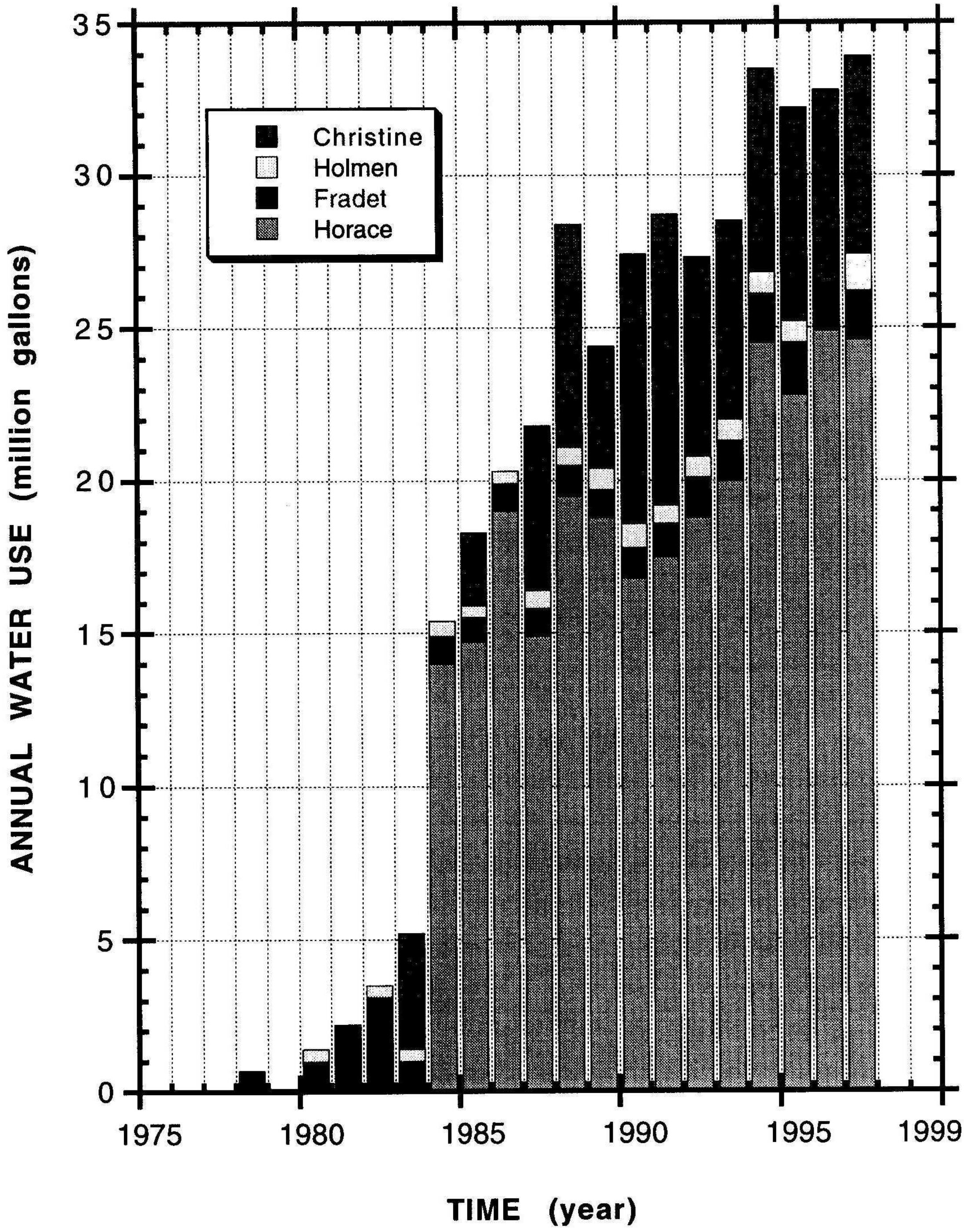


FIGURE 57. Graph of annual water use from the Horace aquifer.

There are no water-level measurements for the 94/10 aquifer before the 1980s. Thus, there is no data to show that the water use from the WFN aquifer that caused the low water levels observed for observation well 139-049-06ADB shown in figure 56, also caused lower water levels in the 94/10 aquifer. It is likely, however, that withdrawals from the WFN aquifer did cause lower water levels in the 94/10. Thus, the low water levels in either the 94/10 aquifer or the WFN aquifer (or a combination of the two) caused water levels to decline in the Horace aquifer because water from the Horace aquifer was draining into them from the north end of the Horace aquifer.

Prior to the development of the Cass Rural Water and city of West Fargo well fields in the WFS aquifer, figure 56 shows that the annual rates of decline were about 0.5 to 0.8 feet per year for the three different Horace observation wells. After the development of the rural water and municipal well fields in the WFS aquifer, the annual rates of decline increased to as much as 2.5 feet per year for a 5-year time period. Over the 14 years shown on Figures 58 and 59, the annual rate of water-level decline has been about 1.0 to 1.5 feet per year. The last seven years shown on figures 58 and 59 show an annual rate of decline of about 0.4 to 0.9 feet per year.

Aquifer water chemistry

Figures 15 to 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The third aquifer shown in each figure is the Horace aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. There are 27 sites with chemical data available, and this size of data set allows for a good representation of the general character of the water quality for the Horace aquifer.

Figure 15 shows that the Horace aquifer is in the high range of calcium concentration in comparison to the other aquifers in the area. Only the West Pleasant aquifer has a higher median value of calcium concentration of any of the other aquifers in the WFAS. There are no EPA standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water

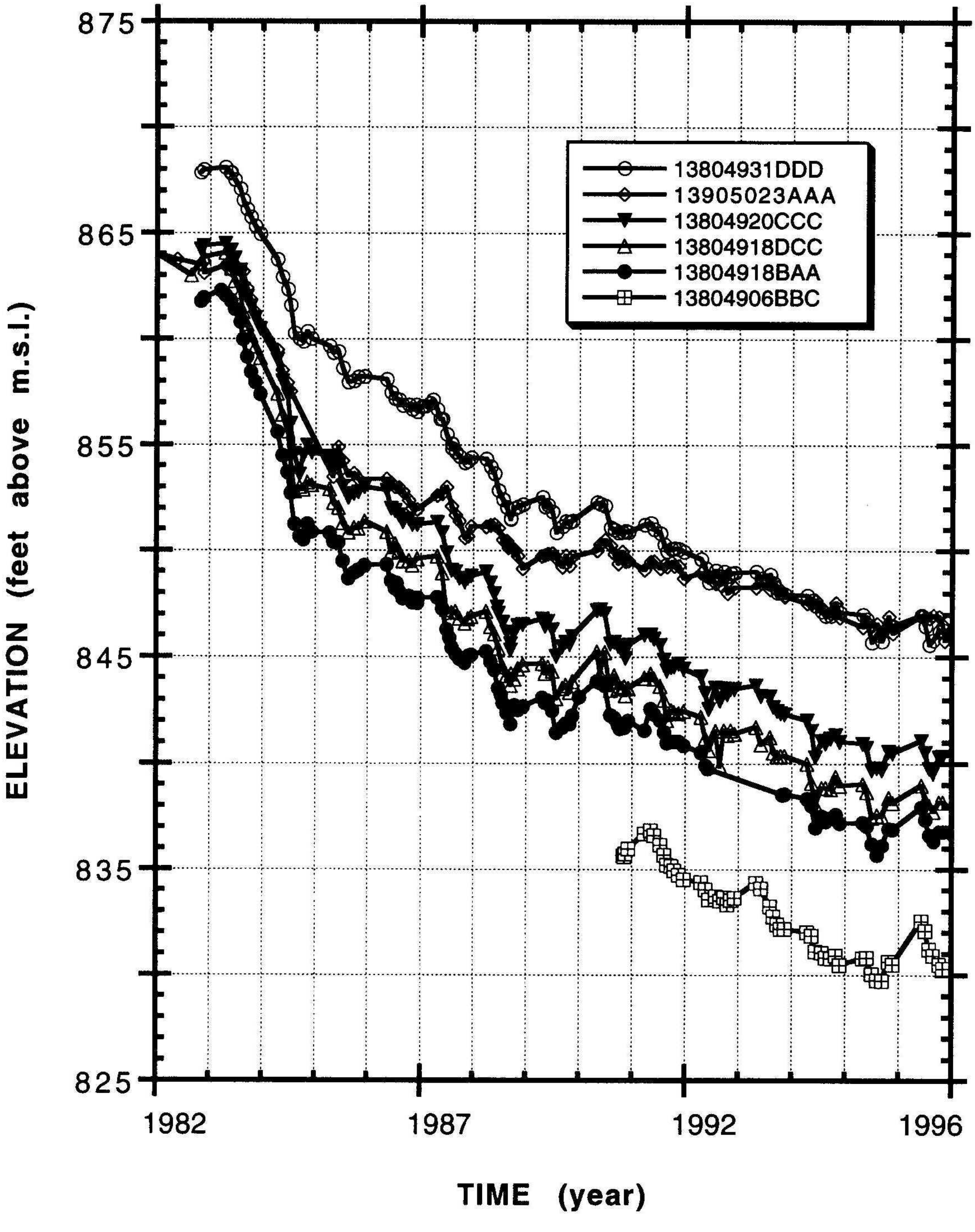


FIGURE 58. Hydrograph of selected observation wells in the north part of the Horace aquifer.

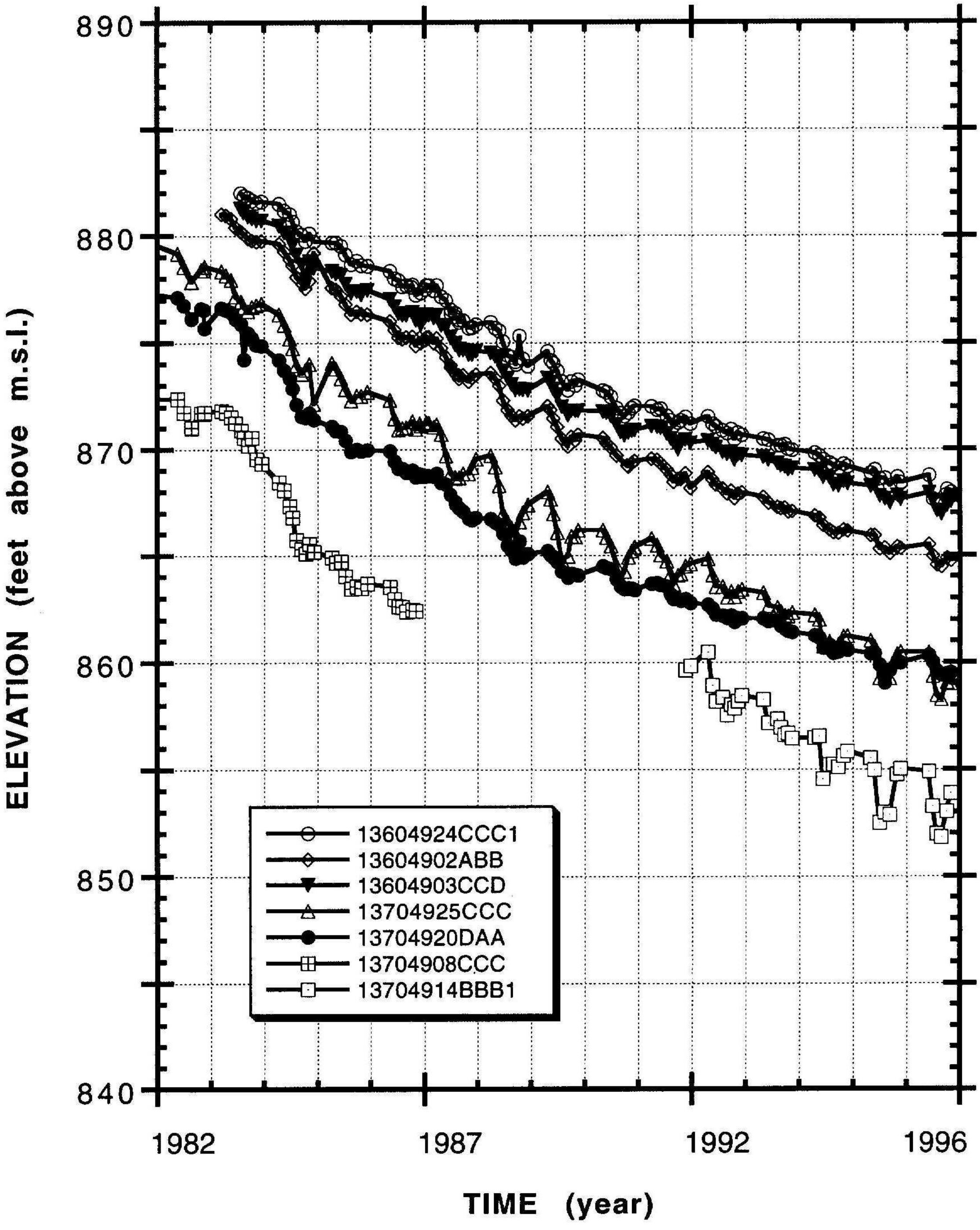


FIGURE 59. **Hydrograph of selected observation wells in the south part of the Horace aquifer.**

hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the Horace aquifer is low in chloride concentration in comparison to other aquifers in the area. Only the WFS aquifer is lower in the median value of chloride concentration than the Horace aquifer. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride, and only a few outliers among the samples from the Horace aquifer exceed this value. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes. Only one sample analysis for chloride concentration for the Horace aquifer showed values over the 400 mg/liter level.

Figure 17 shows that the Horace aquifer is among the highest in the group of nine aquifers with respect to hardness. Only the West Pleasant aquifer has a higher median value of hardness. All but one sample from the Horace aquifer had hardness values that are in the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the Horace aquifer is among the lowest of the group of nine aquifers with respect to the sodium concentration. Only the WFS aquifer is lower in sodium concentration than the Horace aquifer. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the Horace aquifer is among the highest in comparison to other aquifers in the area with respect to sulfate concentration. Only the West Pleasant aquifer has a higher median value than the Horace aquifer. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. The median value for the Horace aquifer is about the equivalent of the SMCL, and only three outliers have values that exceed the EPA Drinking Water Standard. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present. The same three outliers exceed 600 mg/liter.

Figure 20 shows that the Horace aquifer is in the middle range of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. All sites that were sampled from the Horace aquifer and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants. A significant portion of the water from the Horace aquifer is suitable for plants.

The water in the Horace aquifer varies in its character dependent upon location. The eastern portion of the aquifer tends to be a sulfate-type water with no dominant cation. The western portion of the aquifer tends to be a calcium-type water with no dominant anion. The total dissolved solids range from between 500 to 2,000 mg/liter, and the water is mostly very hard. The water is suitable for most purposes.

Figure 60 shows the relationship between stable isotopes of ground water in the Horace aquifer and precipitation at Oakes, ND. The 11 sample sites had a $\delta^{18}O$ value that ranged from -17.7 to -21.6, and a $\delta^{2}H$ value that ranged from -132 to -168. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in North Dakota have shown values of approximately -18 to -25.

The Horace aquifer samples all are in the "snowfall" range. This range of values for $\delta^{18}O$ is quite cold in its signature. Values like these do not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values for water samples collected from Horace aquifer wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the Horace aquifer.

Ground-water movement

The predevelopment ground-water movement pattern for the Horace aquifer is very likely the same as what was described for the West Fargo North aquifer. It is probable that before the development of this area in the late 1800s, most or all of the aquifers in the area had water levels at or above land surface. The very limited

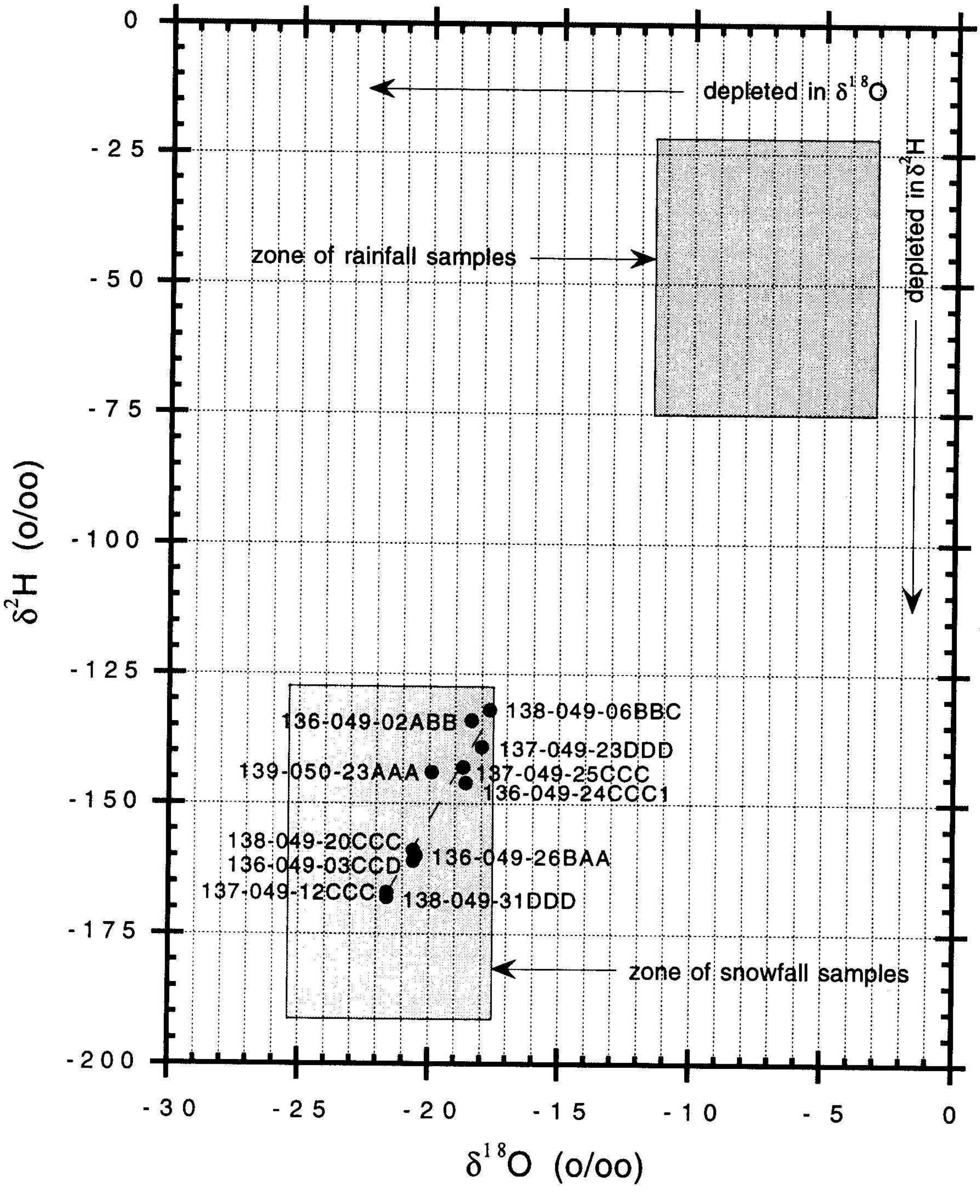


FIGURE 60. **Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the Horace aquifer and precipitation at Oakes, N.D.**

available data suggests that the above-land-surface water levels were the result of Pleistocene water that was trapped by the tills deposited by glaciers, and by the clays deposited at the bottom of Lake Agassiz.

Ground-water flow would have been upward out of the Horace aquifer through the overlying glacial till and lake clay. This flow moved very slowly, but eventually would have reached the land surface. At the land surface this slow seepage would most likely have been removed by evapotranspiration, however some small accumulations could have occurred in the low-lying areas at the land surface, especially in the winter and early spring time periods. There may have been a northward ground-water flow component because the north part of the aquifer is overlain by a topographically lower land surface.

The earliest water-level data available for the Horace aquifer is from a time period around the turn of the century. Hall and Willard (1905) include data that shows that around 1900, the Horace aquifer water levels ranged from 8 to 24 feet below land surface in Cass County. In the northern end of Richland County, however, there was a Horace aquifer well that still flowed at that time. This data would suggest that water levels were dropping, however, it would also suggest that the water levels in the northern part of the Horace aquifer were dropping at a greater rate than were the water levels in the southern part of the aquifer. Implied in this perspective is that ground-water movement within the Horace aquifer might well have been to the north, and that this rate of movement was greater than it had been before development.

Very little Horace aquifer water-level data exists from the time of the Hall and Willard publication until the time of Klausing's publication (1966). As stated earlier there were a few small communities, and a moderate density of farmsteads. This likely resulted in approximately 20 Mg/y being removed from the Horace aquifer in the first half of the 1900s. While there would have been some local ground-water movement towards some of the community well fields, the data available in the early 1960s indicates that a more major component of the ground-water movement probably consisted of ground water moving from south to north in both the eastern and the western portions of the Horace aquifer.

Figure 56 shows three Horace aquifer observation wells that have records that date back to 1964. The figure also shows two other observation wells, one is 139-049-06ADB, a well located in the WFN aquifer, and the second is 139-049-22BBB, a well located in the WFS aquifer. As seen in Figure 53, the Horace aquifer sites are about 7 to 8 miles apart, and 137-049-25CCC is in the eastern portion of the Horace aquifer.

On a cursory glance, figure 56 shows ground-water movement from south to north based on the hydraulic gradients, however, it is likely that the gradient at 25CCC was not north and west along the Horace aquifer towards 138-049-29CCC, but rather north towards the WFS aquifer. It is also likely that there may be other operative factors in the western channel, because it is not likely that the hydraulic gradient between 29CCC and 139-050-23AAA would be as low as 0.6 feet per mile. The evidence for the northward movement from observation well 25CCC will be examined first.

Taking a closer look at the north end of the eastern part of the Horace aquifer, figure 61 illustrates a plan view showing the approximate spatial relationship of the Horace and WFS aquifers. Figure 61 also shows the locations of three observation wells that are within a couple of miles of the Cass Rural Water Users, Inc. well field. The well field is at the south end of the WFS aquifer. Figure 62 shows the water levels for the same three observation wells. Two of them are in the WFS aquifer (137-049-03BDD and 137-049-15BAA) and the third well is in the Horace aquifer (137-049-14BBB1).

There is approximately 12 to 15 feet difference in water-level elevation between each of the three wells. The distance between them is different, however. The distance between 3BDD and 15BAA is about 1 1/2 miles, and results in a hydraulic gradient of about 8 to 10 feet per mile. In this instance, because 3BDD is so close to the well field (see figure 61) and the steep part of the cone-of-depression, the 8-to-10-foot hydraulic gradient is not indicative of a discontinuity of the aquifer. The distance between 15BAA and 14BBB1 is about 1/2 mile, and the hydraulic gradient between these two wells is about 25 to 30 feet per mile. This large hydraulic gradient suggests a zone of small hydraulic conductivity between these two areas, causing a significant aquifer discontinuity.

However, a look at the pattern of the hydrograph in figure 62 shows that 14BBB1 is a subdued image of the pattern for 15BAA. The lowered water levels in the WFS aquifer are definitely impacting the water levels in the eastern part of the Horace aquifer. Thus it is believed that the hydraulic gradient in the 1960s from 25CCC (about 3 miles south of 14BBB1) indicated that ground-water flow was north toward 14BBB1, and eventually went from the north end of the eastern portion of the Horace aquifer into the south end of the WFS aquifer.

Returning the discussion back to the ground-water movement in the western portion of the Horace aquifer in the 1960s, it appears that the hydraulic gradient may have had both a north and east component. Indirect evidence presented in the section on the ground-water movement of the 94/10 aquifer suggested that there was a ground-water hydraulic gradient indicating flow from the Horace aquifer to the 94/10 aquifer. There is most probably an area north of 139-049-29CCC and south of 139-050-23AAA where there also has been ground-water flow from the Horace aquifer to the Ponderosa aquifer.

Possible evidence for this flow is the increased rate of annual water-level decline in observation well 139-050-12CCC (94/10 aquifer) that occurred in the mid 1980s (see

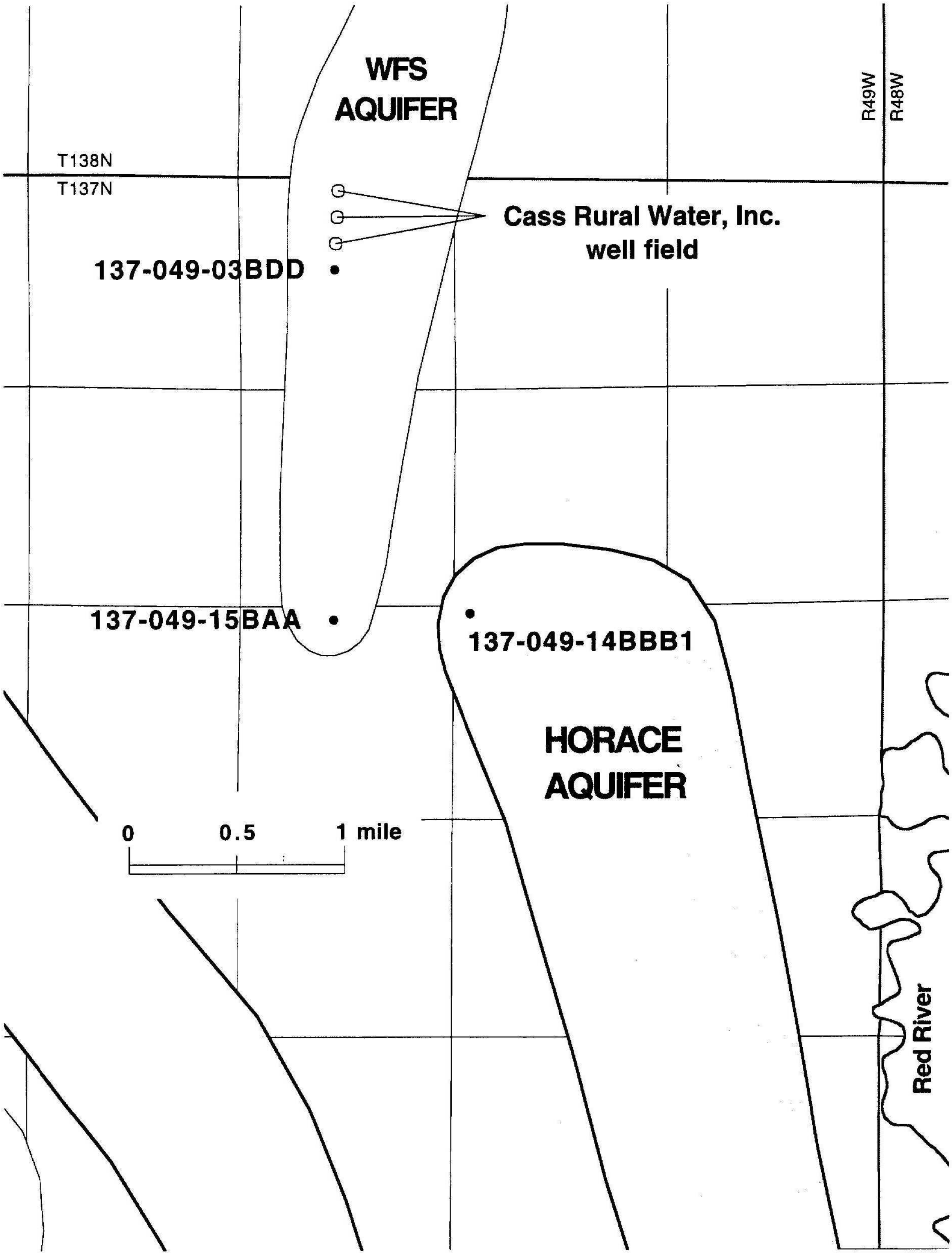


FIGURE 61. Approximate spatial relationship between the West Fargo South and Horace aquifers.

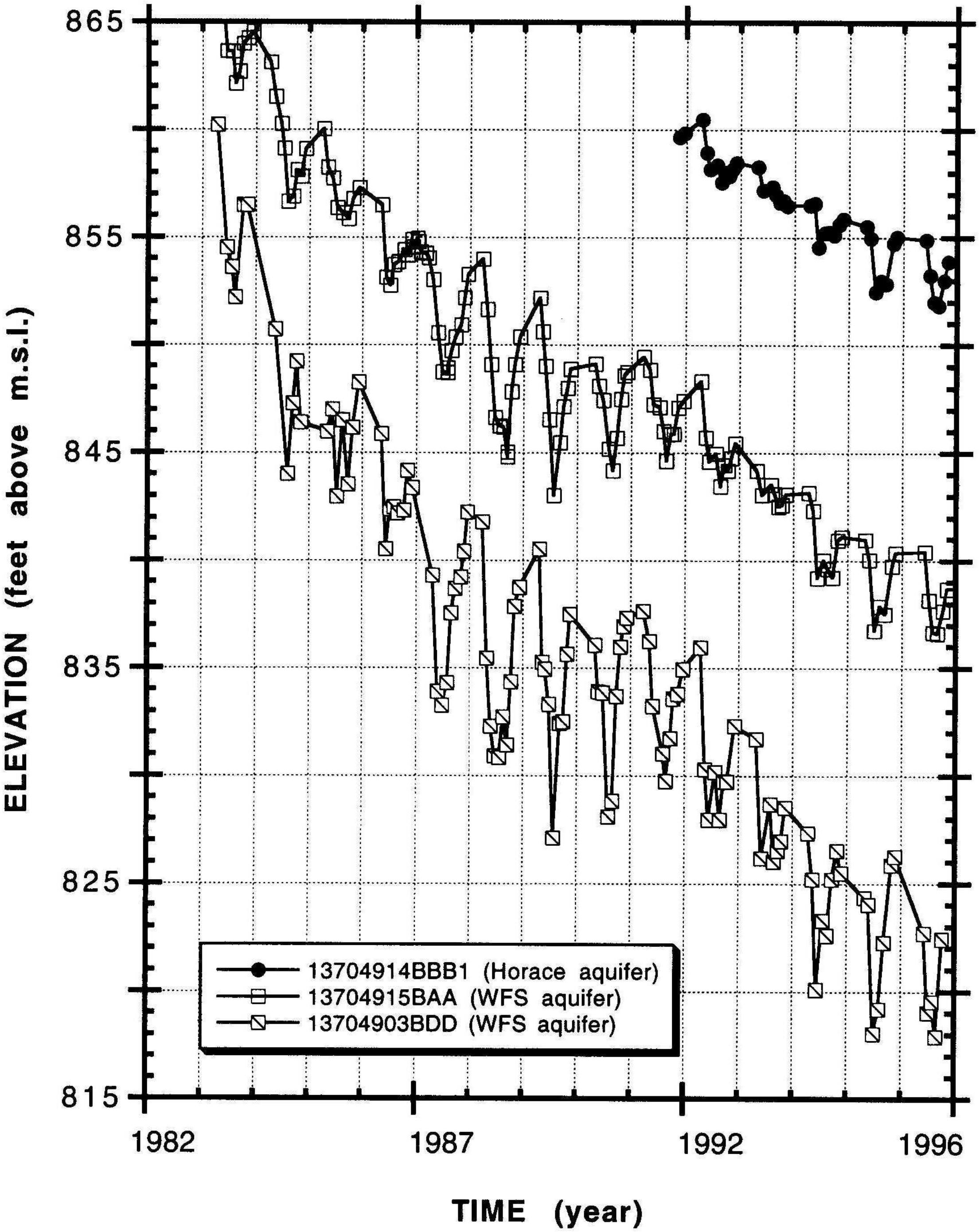


FIGURE 62. Hydrograph of selected wells in the Horace and WFS aquifers.

figures 39 and 56), apparently after the larger increased rate of decline in the water level in 23AAA. This greater rate of decline in 23AAA decreased the hydraulic gradient between the Horace and 94/10 aquifers, and probably resulted in less flow from the Horace aquifer to the 94/10 aquifer. The movement of ground water from the Horace aquifer to the 94/10 aquifer likely still continues in 1998, but at a lesser rate than prior to 1983, because of the smaller hydraulic gradient.

This lesser rate of ground-water movement from the Horace aquifer to the 94/10 aquifer is likely the result of a connection with the WFS aquifer (through the Ponderosa aquifer) that diminishes the ground-water movement from the north end of the Horace aquifer to the 94/10 aquifer. The ground-water movement is diminished because significant utilization of the WFS since 1983 by the city of West Fargo has lowered the water levels in the WFS and Ponderosa aquifers. As a result the hydraulic gradient between the Ponderosa aquifer and the Horace aquifer increased. This increased hydraulic gradient results in greater ground-water movement out of the Horace aquifer near the Ponderosa aquifer, and consequently less ground-water movement out of the north end of the Horace. However, during the 1960s this flow into the Ponderosa aquifer was likely also occurring (only at a lesser rate), and resulted in some of the northward ground-water flow being diverted from the northward direction, to the northeast.

While figure 56 (starting in 1983) clearly shows the effect of the significantly lowered water levels in the WFS aquifer upon the water levels in the Horace aquifer, this is probably not the first indication of the interconnection. Figure 56 also shows that in 1976 a significant change in the rate of annual water-level decline occurred in observation well 137-049-25CCC. In a much more subtle way, a similar increase in the annual rate of water-level decline occurred in three of the other observation wells shown in figure 56.

Those three wells are 138-049-29CCC, 139-050-23AAA, and 139-049-22BBB. The subtle change can be seen by placing a ruler or straight edge on the water-level curve for these three wells for the years from 1971 to 1976. In all three instances the curves after 1976 will fall beneath an extension of the straight line of the ruler. The likely cause of this change in the rate of annual water-level decline in the Horace aquifer was the development in the WFS aquifer of a well field in 1976 for Cass Rural Water Users, Inc. It would appear that the utilization of the Cass Rural Water Users wells in the WFS aquifer well field also impacted water levels in the Horace aquifer.

Besides the movement of ground water from the Horace aquifer to the WFS, Ponderosa, and 94/10 aquifers, there are likely other indirect outflows to the WFN aquifer. The likely area of this indirect leakage would be the area located to the southeast of the 94/10 aquifer, to the south and southwest of the WFN aquifer, and to the north of the Ponderosa aquifer (see figure 53). The likely route would be through discontinuous lenses of sand and gravel.

One other significant ground-water discharge from the Horace aquifer results from the pumping of water from wells screened in the Horace aquifer. Figure 57 shows the reported annual water use (close to 35 Mg) associated with water permits. However, there may be another 6 to 7 Mg/y of unreported water use associated with individual wells screened in the Horace aquifer that do not require a water permit.

Movement of ground water into the Horace aquifer likely occurs from the flow of ground water from the West Pleasant aquifer, and from the glacial sand and gravel bodies that occur relatively close to the Horace aquifer along the extensive boundary of the aquifer that extends in two lobes for up to 22 miles. An additional possible source of inflow is from the Cretaceous sandstone, if the sandstone is hydraulically connected to the Horace aquifer. There is also additional water coming into the Horace from the drainage of fine-grained materials that surround the aquifer. This drainage would be very slow because the surrounding tills and clays are characterized by small hydraulic conductivity.

PONDEROSA AQUIFER

Aquifer size and location

The map in figure 63 shows the area that is underlain by the Ponderosa aquifer and its relationship with the Horace and West Fargo South aquifers. The aquifer extends north and south for about 2 1/2 miles. The aquifer also extends for about 1 to 1 1/2 miles in an east-west direction. The location of geologic section K-K' is also shown in figure 63. A discussion of the limits of the Ponderosa aquifer shows the difficulty of both determining where the aquifer boundaries end, and also whether two nearby aquifers are connected or not.

In the northeast quarter of section 32, T139N, R49W, a 100-foot deep domestic well was replaced because the water level was declining. Figure 64 shows the location of that well with the star symbol that is the westernmost of the three star symbols. A test hole was drilled about 400 feet east of the 100-foot deep well, because the lithologic log for that 100-foot well showed no sand or gravel lens thicker than 5 feet beyond a depth of 165 feet. This test hole is represented in figure 64 as the middle star symbol, and did not show a sand or gravel lens of over 6 feet beyond a depth of 145 feet. A second test hole was drilled another 300 feet to the east, and this test hole is where the replacement domestic well was installed. This test hole showed a 10-foot section of sand and gravel at a depth of 232 to 242 feet below land surface. The location of this test hole is indicated in figure 64 with the easternmost star symbol.

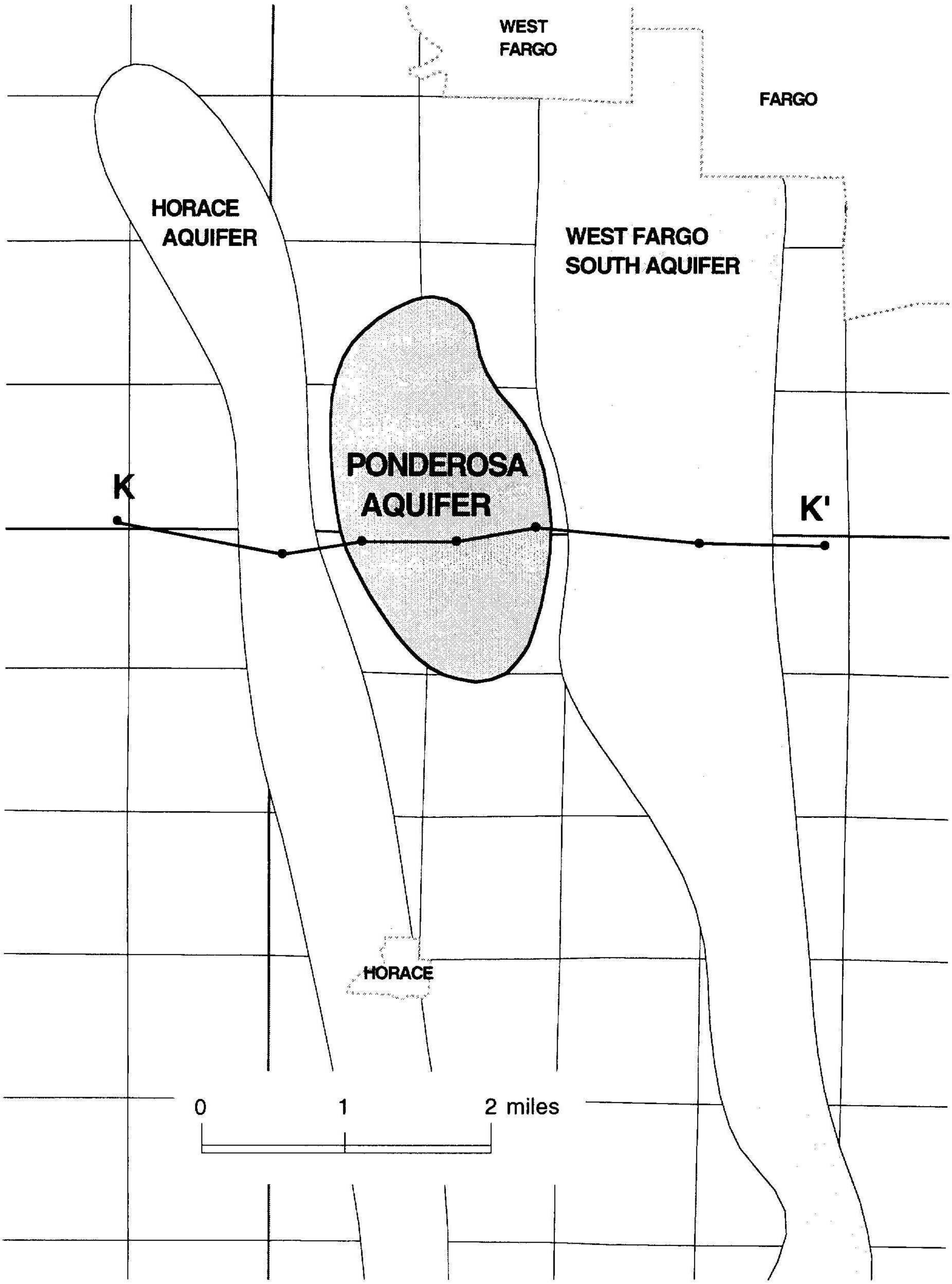


FIGURE 63. Location of the Ponderosa aquifer and geologic section K-K'.

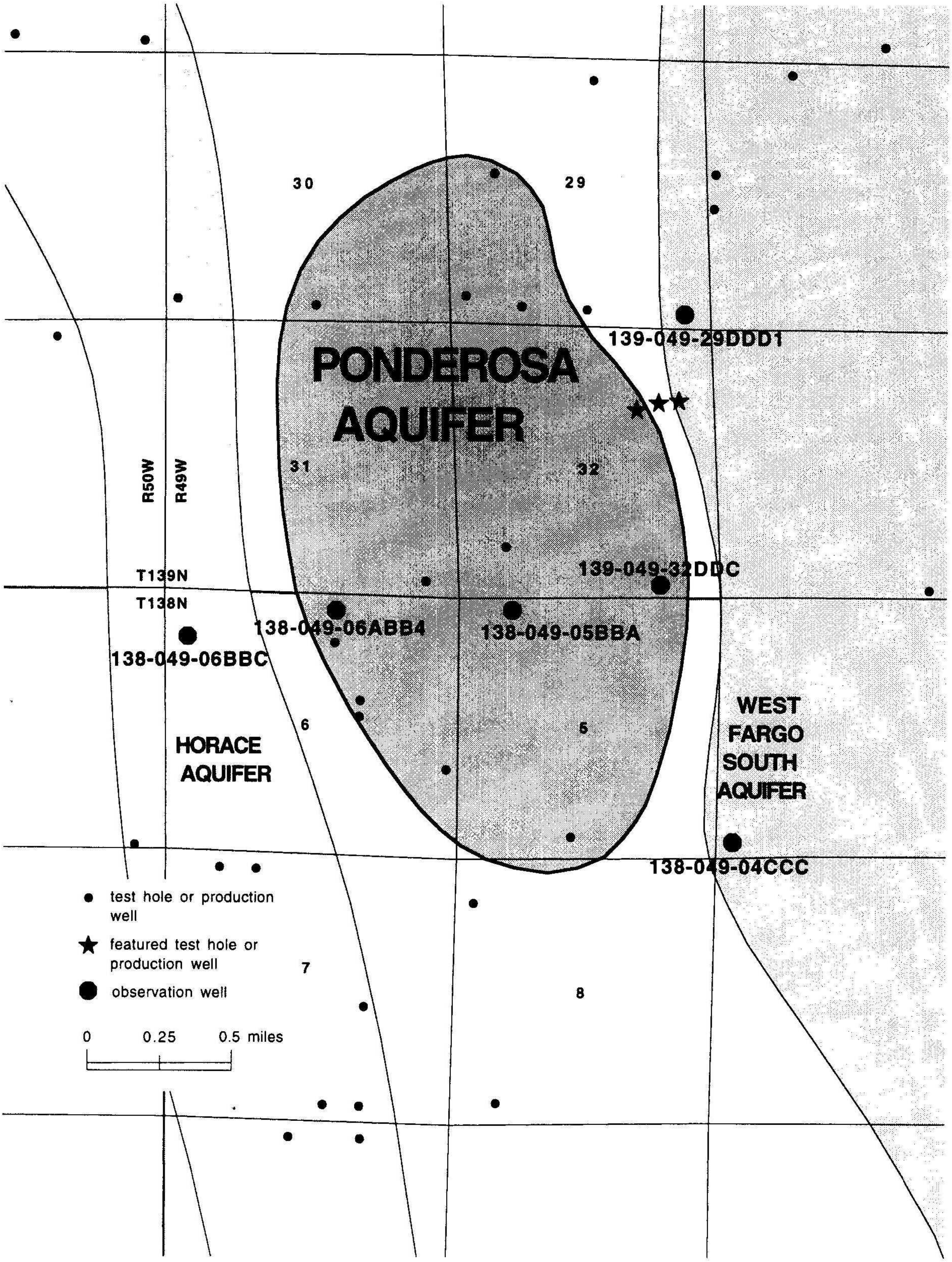


FIGURE 64. Location of the Ponderosa aquifer and selected well and test hole locations.

The lithologic logs for all three drill holes indicated numerous, but discontinuous, sand layers. These data indicate there is not an abrupt change from the Ponderosa aquifer on the west to the West Fargo aquifer on the east. The linear boundaries shown in figure 64 do not exist as drawn. Rather, the change is gradational, lenticular, and very subjective. In some settings, these subtle differences in the vertical location and distribution of the sand lenses would not result in a differentiation into two different aquifers. The additional consideration of water levels, however, results in the conclusion that the Ponderosa aquifer is subtly distinct (hydraulically) from the WFS aquifer.

Figure 65 shows a hydrograph for six observation wells. Three of the wells are screened in the Ponderosa aquifer, two in the WFS aquifer, and one in the Horace aquifer. The locations of these wells are shown in figure 64. Between wells 138-049-06BBC and 138-049-06ABB4 (about a half mile apart) there is about a 12 to 14 foot water-level difference. The hydraulic gradient between these two wells is about 20-25 feet per mile, showing a distinct, low-flow, small-hydraulic-conductivity zone between the two aquifers.

The proximity of the curves on figure 65 between the Ponderosa and the WFS aquifers do not show the elevation difference that the curve for the Horace well shows. The water levels for 138-049-04CCC (WFS) and 139-049-32DDC (Horace) are very similar, and they are over a mile apart. However, there is a subtle aspect that needs to be considered. The lowest water levels among the wells shown in figure 65 are observed in 139-049-29DDD1. This well is closest to the West Fargo aquifer production wells of the city of West Fargo, and as a result is closest to the lowest part of the cone of depression. If 32DDC were a well-connected part of the WFS aquifer, the water levels in 32DDC would be lower, not higher than the water levels in 4CCC. There must be some sort of transmissivity reduction to make it more difficult for water to flow one mile from 32DDC, than it is for the water to flow 2 miles from 4CCC.

Much more detailed drilling and water-level measurement would have to be done so that an accurate Ponderosa-WFS aquifer boundary could be drawn. This boundary is estimated based on the three logs in the northeast of section 32. If the best connection of the Ponderosa and the WFS aquifers is in this area, and a water-level difference of several feet takes place over a distance of about 1000 feet, this would result in a hydraulic gradient of about 10 to 20 feet per mile. If on the other hand the connection is at the south end of the Ponderosa aquifer, the Ponderosa could easily be considered as part of the West Fargo South aquifer.

Test holes to the north (in section 29), and to the south (in section 8) of the Ponderosa aquifer show little or no sand or gravel sections. It is possible that the Ponderosa aquifer extends further to the southeast in the eastern part of section 8, and

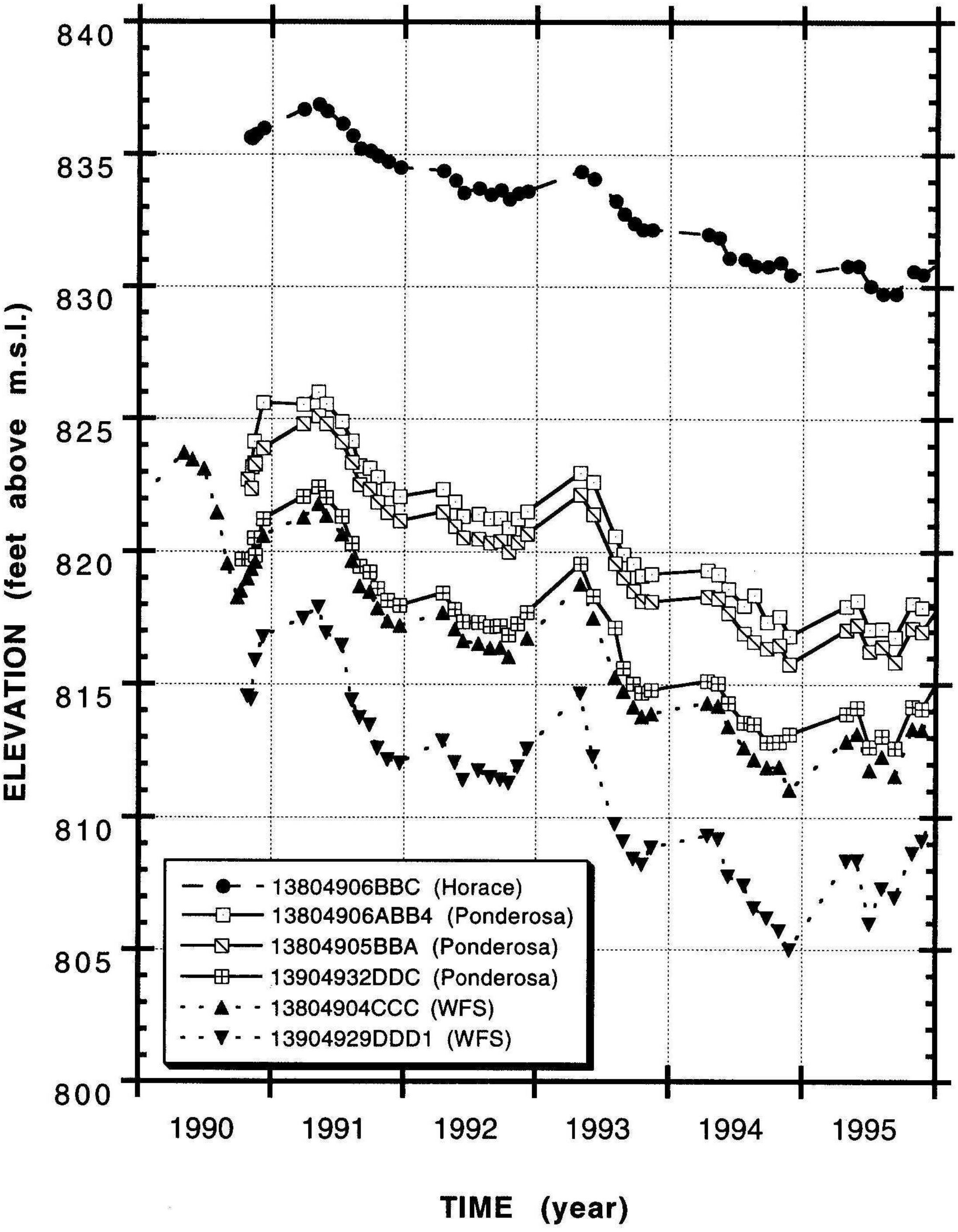


FIGURE 65. Hydrograph of observation wells in the Ponderosa, Horace and West Fargo South aquifers.

also that it extends further to the north-northwest in section 30. It is unlikely that the Ponderosa aquifer connects well to the Horace aquifer, but it is possible that the Ponderosa is part of the WFS aquifer.

The Ponderosa aquifer, as depicted in figure 64, underlies an area of about 3 square miles. Figure 66 shows a west-to-east geologic section K-K'. This geologic section shows the Ponderosa aquifer in the middle, with the Horace aquifer on the west, and the West Fargo South aquifer on the east. The question marks indicate the poorly understood nature of the boundaries of or transitional area between the aquifers.

There are 16 test holes and wells located in the Ponderosa aquifer that were investigated. Of these, 12 had lithologic descriptions for a significant portion of the aquifer interval. The lithology described varied from sand to coarse gravel. About half of the lithologic logs indicate gravel in the aquifer interval, with the gravels consisting of up to 195 feet in thickness. The thickest aquifer intervals tended to have significant sections of gravel. The thickest section of sand without gravel was 124 feet.

The average depth to the top of the Ponderosa aquifer is about 92 feet below land surface. The top ranges from 75 to 122 feet below land surface. This includes the overlying sand lenses that occur in about half of the test holes. The overlying lenses of sand are included in these thickness calculations because they are probably hydraulically connected to some degree to the main sand and gravel sections of the aquifer. The average depth to the bottom of the Ponderosa aquifer is about 247 feet. A large number of the test holes did not drill through the bottom of the aquifer. In those seven test holes that did penetrate the bottom of aquifer, the depth ranges from 173 to 308 feet below land surface.

The effective average thickness of the Ponderosa aquifer is about 100 feet. The thickness is as small as it is (average top = 92 ft, and average bottom = 247 ft) because there are numerous interlayered clays and tills within the sand and gravel interval in several locations. With an average thickness of 100 feet, and an area of 3.2 square miles, the approximate volume of the Ponderosa aquifer is about 8.9 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

Aquifer water use and water-level history

It is likely that in the area overlying the Ponderosa aquifer the development of farmsteads and wells began in the late 1800s. There are some shallow sand units that could have provided water for shallow wells, however, it is likely that some of the early wells were deep enough to reach the Ponderosa aquifer. These early wells very likely flowed when they were first installed. As the population grew, and water use increased,

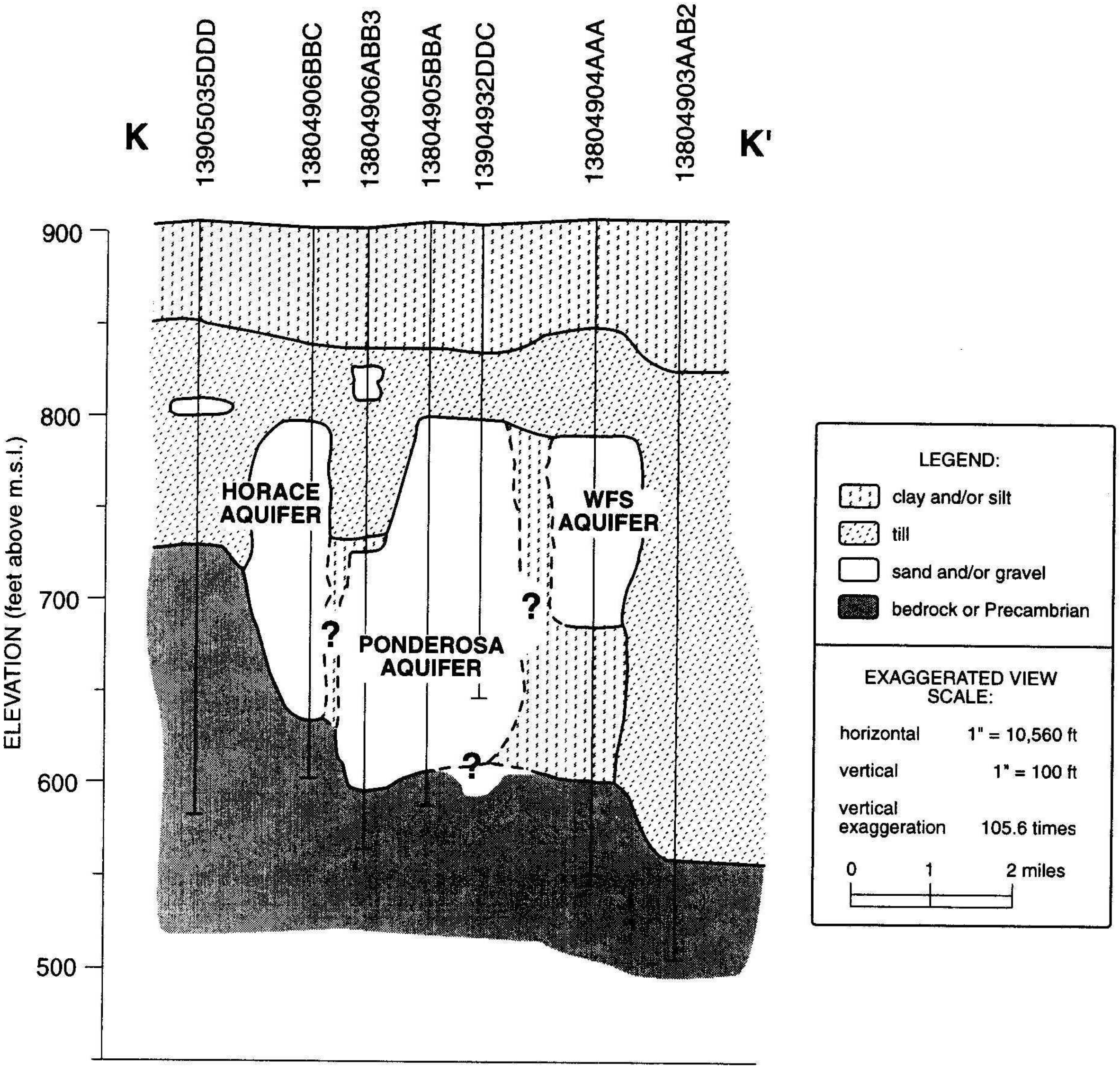


FIGURE 66. West-east geologic section K-K' showing the Horace, Ponderosa, and West Fargo South aquifers.

the water levels very likely approached land surface, and then dropped below land surface.

There is no documented water use data for the Ponderosa aquifer. The aquifer extent is small and historically there have only been a few farmsteads overlying the aquifer. Because a few miles of the Sheyenne River overlie a portion of the aquifer, a few homes have been nestled in the trees along the river, and the density of dwellings is a little larger than normal. Through the 1950s and possibly the 1960s about 15 to 20 overlying homes may have tapped the aquifer for a water supply. There are no significant uses that have been made of the Ponderosa aquifer other than local domestic wells. Overall water use from the aquifer has been quite small. Even with a greater density of homes than normal for the area, annual water use would only be about 1 or 2 million gallons per year at most. It is likely that almost all of the water-level decline that has occurred in the Ponderosa aquifer is due to leakage into the WFS aquifer.

Figure 65 shows three of the four Ponderosa aquifer observation wells for which there are regular water-level measurements. The water-level pattern of these three wells is similar to the water-level pattern displayed by the WFS aquifer well 139-049-29DDD1. The only difference is that water levels in the Ponderosa aquifer occur at a higher elevation, and the pattern of water-level fluctuation is a subdued image of the pattern shown by 29DDD1. There are no regular water-level measurements from any observation wells in the Ponderosa aquifer that predate 1990, because no observation wells had been installed in the aquifer until 1990. Over the six years shown on figure 65 the Ponderosa observation wells show an annual rate of water-level decline of about 1 foot per year. Earlier Ponderosa aquifer water levels could be estimated by investigating earlier Horace and WFS aquifer water levels in the area.

Aquifer water chemistry

Figures 15 to 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The fifth aquifer shown in each figure is the Ponderosa aquifer. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The Ponderosa aquifer is one of these aquifers, with only six sites being represented.

Figure 15 shows that the Ponderosa aquifer is in the high range of calcium concentration in comparison to the other aquifers in the area. Only the West Pleasant and Horace aquifers have a higher median value of calcium concentration among any of the other aquifers in the WFAS. There are no EPA standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the Ponderosa aquifer is medium to high in chloride concentration in comparison to other aquifers in the area. Only the Prosper, 94/10, and the West Pleasant aquifers are higher in chloride concentration than the Ponderosa aquifer. The EPA has a Secondary Maximum Contaminant Level (SMCL) of 250 mg/liter for chloride, and this value is very close to the median value of chloride for the Ponderosa aquifer. There is no regulation of this SMCL, and numerous public water supplies exceed this level. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes.

Figure 17 shows that the Ponderosa aquifer is among the highest in the group of nine aquifers with respect to hardness. Only the West Pleasant and Horace aquifers have a higher median value of hardness. Most of the samples from the Ponderosa aquifer had hardness values that are in the USGS category of "very hard" water, which is generally above 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the Ponderosa aquifer is in the middle among the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the Ponderosa aquifer is in the middle range of values in comparison to other aquifers in the area with respect to sulfate concentration. The West Pleasant, Prosper, and Horace aquifers have a higher median value than the Ponderosa aquifer. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form.

aquifer are below the SMCL. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the Ponderosa aquifer is in the middle range of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The SMCL is such that only some of the sites in the West Fargo South aquifer have TDS lower than 500 mg/liter. All sites that were sampled from the Ponderosa aquifer and all other aquifers in the WFAS have values for TDS that exceed this SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants. A significant portion of the water from the Ponderosa aquifer is suitable for plants.

The water in the Ponderosa aquifer is a sodium type, with no dominant anion, although anion concentrations in the water samples tend towards chloride as the dominant anion. The total dissolved solids generally range from 800 to 1300 mg/liter, and the water is generally very hard. The water is suitable for most purposes.

Figure 67 shows the relationship between stable isotopes of ground water in the Ponderosa aquifer and precipitation at Oakes, ND. The two sites had a $\delta^{18}O$ value that ranged from -19.5 to -20.5, and a $\delta^{2}H$ value that ranged from -144 to -151. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in ND have shown values of approximately -18 to -25.

The Ponderosa aquifer samples are both in the "snowfall" range. This range of values for $\delta^{18}O$ is quite cold in its signature. Values like these do not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values for water samples collected from Ponderosa aquifer wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the Ponderosa aquifer.

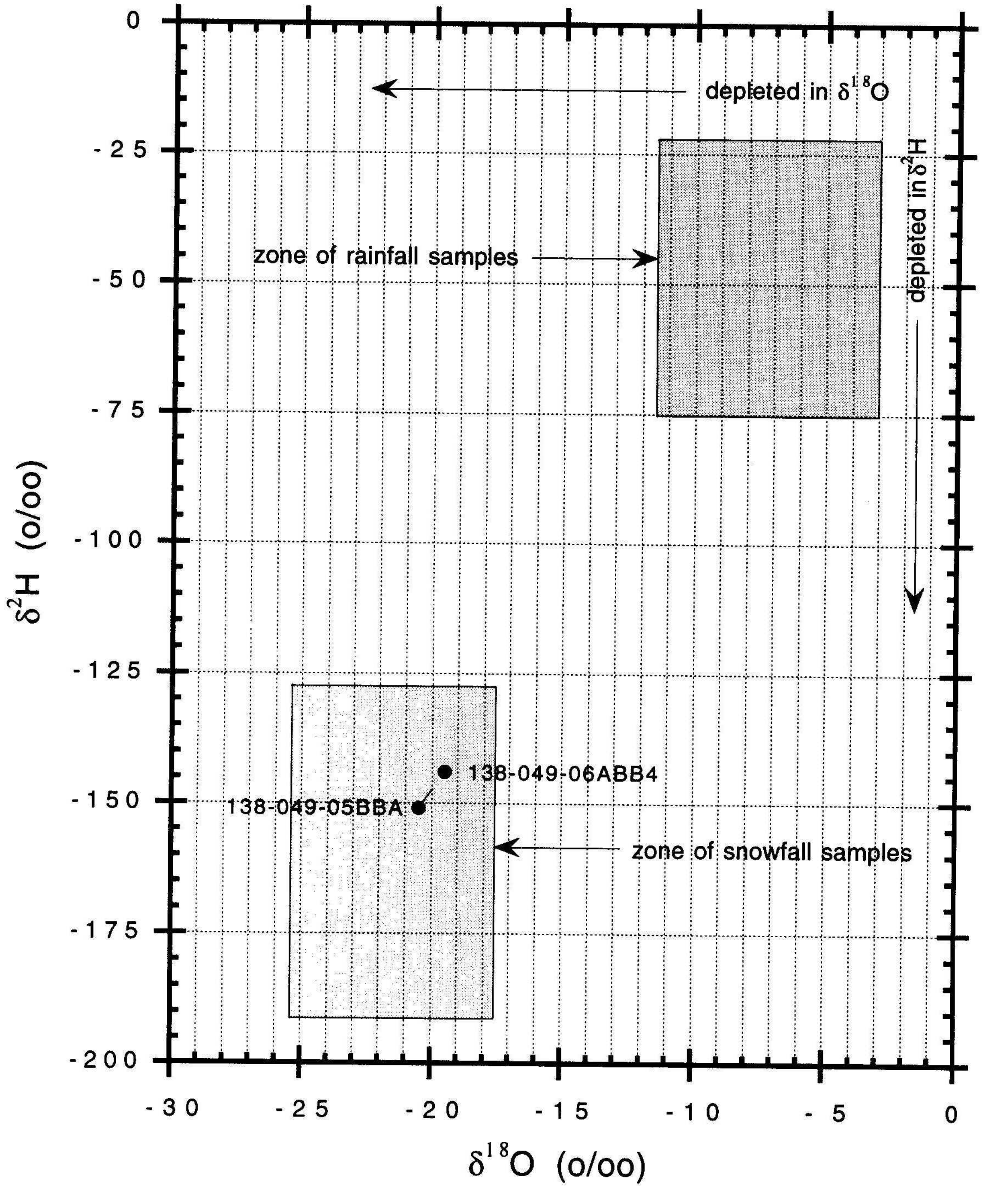


FIGURE 67. Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the Ponderosa aquifer and precipitation at Oakes, N.D.

Ground-water movement

Very little pre-1990 water-level data exists for wells screened in the Ponderosa aquifer. As a result, very little can be said with much assurance about the ground-water movement in the Ponderosa prior to the 1990s, other than relating to the water-level histories observed in the Horace and WFS aquifers. The previous discussion of the ground-water movement in the Horace aquifer addresses part of the historical movement of ground water in the Ponderosa aquifer.

It is probable that before the development of this area in the late 1800s, most or all of the aquifers in the area had water levels at or above land surface. Inference from other water-level data in the area suggests that the water levels were probably above-land-surface before settlement of the area began. Thus, the movement of the ground water would have been upward from the Ponderosa aquifer through the overlying glacial tills and lake clays. This ground water moved very slowly, but eventually this flow would have reached the land surface. At the land surface this slow seepage would most likely have been removed by evapotranspiration, however some small accumulations could have occurred in the low-lying areas at the land surface, especially in the winter and early spring time periods.

Once utilization of the aquifers in the area began in the late 1800s, a persistent decline of water levels began. Initially the Fargo aquifer and then the WFN aquifer were the most utilized aquifers in the area, and they experienced the greatest early water-level declines. Other aquifers (secondary in this context) that were connected to those two aquifers would have had declining water levels as a result of the connection. In turn, a tertiary set of aquifers not connected to either the Fargo or the WFN aquifers, but instead connected to the secondarily affected aquifers, would have had declining water levels as a result of the connection to the secondary aquifers. This was likely the situation for the Ponderosa aquifer, whereby the Ponderosa would be considered a tertiary aquifer.

In 1976 when Cass County Rural Water Users began using the WFS aquifer, and even more so in 1983 when the city of West Fargo began using the same aquifer, the Ponderosa aquifer began experiencing more direct (but still secondary) water-level decline impacts. These impacts are not documented with water-level measurements. As a result, the impacts cannot be shown on a hydrograph. However, the current relationship between the Horace, Ponderosa, and WFS aquifers, in combination with past water-level measurements of wells screened in the Horace and WFS aquifers, indicates that ground-water movement would have occurred from the Horace aquifer to the WFS aquifer through the Ponderosa aquifer. This is probable at least since the 1970s. In the early 1900s, and especially after the 1930s (but before the 1970s), it is quite possible that ground-water movement was from the Ponderosa to both the Horace and the WFS aquifers.

At this point in time, it is clear that significant ground-water inflow for the Ponderosa consists primarily of inflow from the Horace aquifer. Some minor inflow occurs as a result of leakage from adjacent tills and clays. Most movement of ground water out of the Ponderosa is into the WFS aquifer. Numerous wells also account for a moderate amount of outflow, however many of the overlying, recently-built, homes are supplied by rural water. The outflow exceeds the inflow, resulting in a declining water-level trend.

WEST FARGO SOUTH

Aquifer size and location

The map in Figure 68 shows the area that is underlain by the West Fargo South (WFS) aquifer. The aquifer extends for about 13 miles in a north-south direction. The aquifer generally ranges between 1 to 2 miles in width, although there are places where the aquifer might be less than a half mile in width. Figure 68 also shows the location of geologic sections K-K' (a west-to-east geologic section) and L-L' (a south-to-north geologic section).

The discussion of the aquifer boundaries for the WFS aquifer will begin on the east side of the far south end of the WFS aquifer, because this area has been discussed earlier in the discussion of the Horace aquifer. As mentioned earlier, near the center of Pleasant Township there are two observation wells that are about one-half mile apart and each well has historically had water-level elevations that are about 7 to 8 feet different. This results in a hydraulic gradient of about 15 feet per mile, and indicates a significant zone of small hydraulic conductivity material between the two wells. The two aquifers are related based upon the similarities between the patterns of water-level response in these two wells (one in each aquifer). However, a hydraulic gradient of 15 feet per mile indicates that there is a hydraulic discontinuity between the two wells, and hence a separation between the two aquifers.

On the east side of the south half of the WFS aquifer, there is very little lithologic information that is within one mile of the aquifer boundary as drawn in figure 68. The boundary is drawn as it is in figure 68 on the basis of lithologic descriptions of test hole and well logs that are located within the aquifer. It is conceivable that the WFS aquifer boundary occurs east of where it is depicted as being in figure 68.

In the north part of T138N, R49W (Stanley Township) and in T139N, R49W (Barnes Township) there are several lithologic logs of test holes and wells that indicate an absence of significant comparable sands and gravels on the east side of the WFS aquifer. In sections 2 and 3 of Stanley Township there is a deep sand unit ranging from

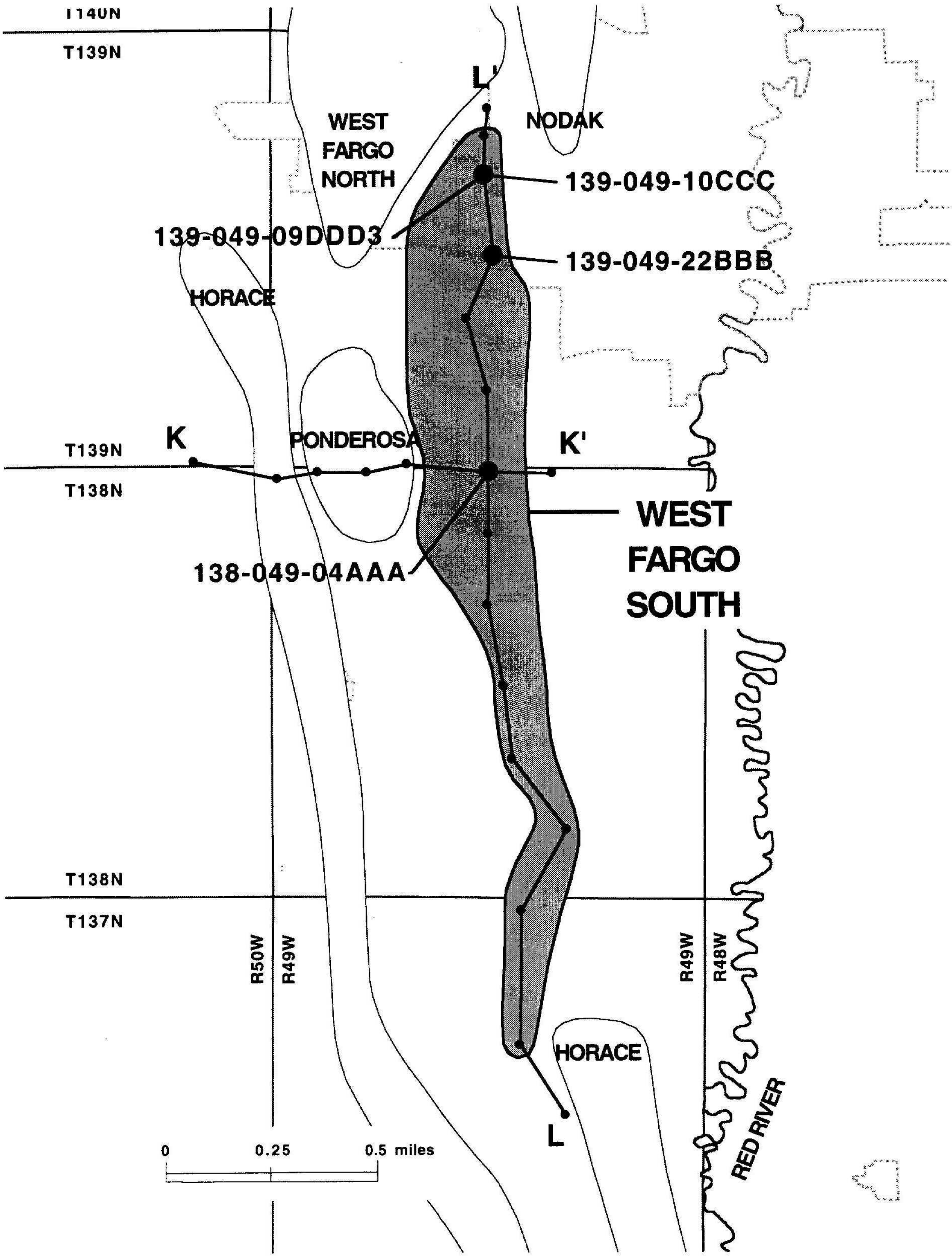


FIGURE 68. Location of the West Fargo South aquifer and geologic sections K-K' and L-L'.

300 to 400 feet in depth that appears to be a bedrock sand. The sand is generally finer in texture, and deeper than the sand and gravels of the WFS aquifer in that area. In southeast quarter of section 22 of Barnes Township there are several test holes. At the far west edge of the quarter, test holes show sand and gravel intervals with 60 to 90 feet of thickness, however test holes east of the west edge of the southeast quarter of section 22 show very limited sand intervals.

On the northwest side of the WFS aquifer lies the WFN aquifer. Earlier studies of the area depicted these two aquifers as one, however, Armstrong (1983) shows the two aquifers as being separate. Water-level elevations measured in observation wells in the two aquifers, and in the area between the two aquifers support this interpretation. Before the development of the WFS aquifer well field by the city of West Fargo, there was a 75-foot difference between the northernmost observation well in the WFS aquifer, and the southernmost observation well in the WFN aquifer. The distance between these two wells was about 3.5 miles, and this results in a hydraulic gradient of over 20 feet per mile. Because of the location of the older observation wells, and because of the loss of some of the older observation wells to construction in this rapidly developing area, it is difficult to compare same-time water-level measurements that are closer than 3.5 miles apart before the WFS well field was developed. By comparing trends of other observation wells in the area, however, it is possible to see that hydraulic gradients probably exceeded 45 feet per mile between the two aquifers. While related, these two aquifers are distinctly separated by a hydraulic discontinuity.

On the north end of the west side of the WFS aquifer the boundary is difficult to accurately determine. Very little lithologic or water-level information is available. The aquifer boundary is drawn on the basis of connecting the boundary near the WFN aquifer with the boundary near the Ponderosa aquifer in a relatively straightforward way. The means by which the boundary of the WFS aquifer is determined in the vicinity of the Ponderosa aquifer is discussed in section on the Ponderosa aquifer size and location. Because that discussion is extensive, the reader is referred to that section for details. The difference in water-level elevations and the lithologic logs of three close test holes result in the depiction of the boundary as seen in figure 68.

The south half of the west boundary of the WFS aquifer is determined with the help of numerous nearby lithologic logs. Logs of test holes in sections 16, 21, 27, 28, and 34 in Stanley Township, and also lithologic logs in sections 3 and 9 in Pleasant Township show little or no sand or gravel intervals. This data in combination with lithologic logs and water-level data for nearby test holes and observation wells located within the WFS aquifer boundary allow for a fairly accurate depiction for the WFS aquifer west boundary in the south half of the aquifer.

The WFS aquifer as depicted in figure 68 underlies an area of about 13.8 square miles. Figure 69 shows the south-to-north geologic section L-L'. The geologic section shows a moderately irregular top of aquifer, and a very irregular bottom of aquifer. It may be that east or west of the test holes shown in the geologic section there are locations where the irregularity of the top and bottom of aquifer might be less. It may also be that these irregularities are as extreme as they appear in the geologic section across the full width of the aquifer.

There are 55 test holes and wells located in the WFS aquifer that were investigated. Of these, 44 had lithologic descriptions for a significant portion of the aquifer interval. The lithology described varied widely from very fine sand to coarse gravel with boulders. Only about a third of the lithologic logs contained descriptions of gravel. The north and south ends of the aquifer both contain predominantly fine sands, according to the available lithologic logs. Most intervals containing gravel tended to become coarser with depth. A surprising number of test holes had intervals greater than 100 feet of fine sand. This was not observed in any of the other aquifers in this study.

The average depth to the top of the WFS aquifer is about 150 feet below land surface. The top of the aquifer ranges from 79 to 252 feet below land surface. The average depth to the bottom of the aquifer is about 235 feet below land surface. The bottom of the aquifer ranges from 153 to 332 feet below land surface. About 15 percent of the sites have an overlying sand and gravel unit that appears to be hydraulically connected. These units range from 13 to 49 feet in thickness. The average thickness of the WFS aquifer and the overlying units is about 90 feet. With an average thickness of about 90 feet, and an areal extent of 13.8 square miles, the approximate volume of the WFS aquifer is about 34.7 billion cubic feet. A discussion later in the report will address the relationship between the volume of the aquifer, and the amount of water that is stored in this aquifer volume.

A response test was run in a city of West Fargo well located at 139-049-16BDC, that was completed in the WFS aquifer. The test was conducted in September, 1983. This municipal well is called city well #7. The municipal well was pumped continuously for 96 hours at a rate of 715 gallons per minute. Calculated transmissivities varied from 3,600 to 7,000 feet squared per day. The open file report (Reiten, 1983) did not indicate most probable values of transmissivity and specific storage. No evaluation was made on the aquifer boundaries that are very close to this test location to the north and to the west.

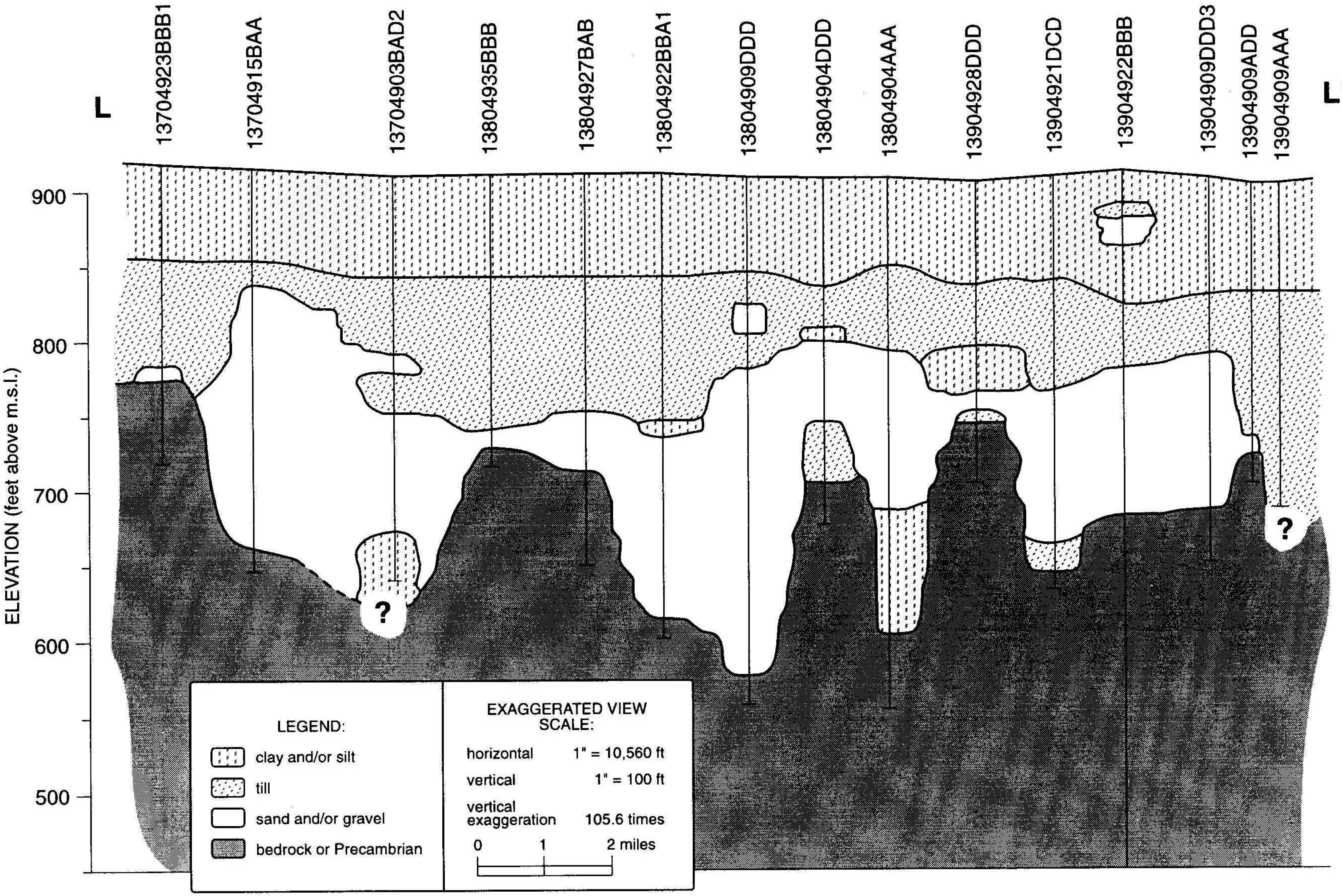


FIGURE 69. North-south geologic section L-L' showing the West Fargo South aquifer.

Aquifer water use and water-level history

It is probable in the area overlying the West Fargo South aquifer that the development of farmsteads and the utilization of wells in that area began in the late 1800s. There are some shallow sand units that could have provided water from shallow wells; however, some of the early wells were deep enough to reach the WFS aquifer. These early wells very likely flowed when they were first installed. As the population grew and water use increased in the area, the water levels approached land surface, and then went below land surface.

The early water-level data found in reports like Hall (1905), any of the USGS water-level reports (1937-69), and Dennis et al (1949) was extremely limited for the WFS aquifer. The time period up until the mid 1960s, when Klausing reported water levels for the north end of the WFS aquifer, yields little data on water levels or water use. Subsequent analysis of water-level data has shown that the low water levels in the WFN aquifer were probably the major cause of the lowering of water levels in north end of the WFS aquifer. It appears likely that water levels in the WFS aquifer dropped below land surface a number of years after water levels dropped below land surface in the WFN aquifer. Additionally, water levels dropped below land surface at the north end of the WFS aquifer first, and then later at the south end of the WFS aquifer. This would likely parallel the WFN aquifer in reverse (WFN going from south to north) only later in time, because the early water use in the area was from the WFN aquifer, and from other aquifers that were better connected to the WFN aquifer.

Development of the WFS aquifer was quite limited until the 1970s. There were probably no more than 35 to 40 homes or farmsteads that were located over the aquifer, and there were no communities of significant size. The estimate of 35 to 40 homes and farmsteads includes the homes that are located in the small community of St. Benedict. Total annual water use from the WFS aquifer was likely only a few million gallons at most, until the 1970s. Significant use of the WFS aquifer did not begin until the Cass Rural Water Users' (CRWU) well field went on line at the end of 1976. Figure 70 shows recorded annual water use for the WFS aquifer. As seen in Figure 70, there was one significant increase in annual water use at the very end of 1976, and a second significant increase in the summer of 1983, when the city of West Fargo began using the first of their new wells that was located in the WFS aquifer.

Early water-level information for the WFS aquifer is quite limited. Figure 71 shows a hydrograph of the three WFS aquifer observation wells that were measured for water levels prior to 1981. Early reports (turn of the century to the 1960s) that included a few water levels for some of the other aquifers had little information for the WFS aquifer. Even though there is limited data, Figure 71 supports the idea that the apparently small amount of water use from the WFS aquifer would not result in the

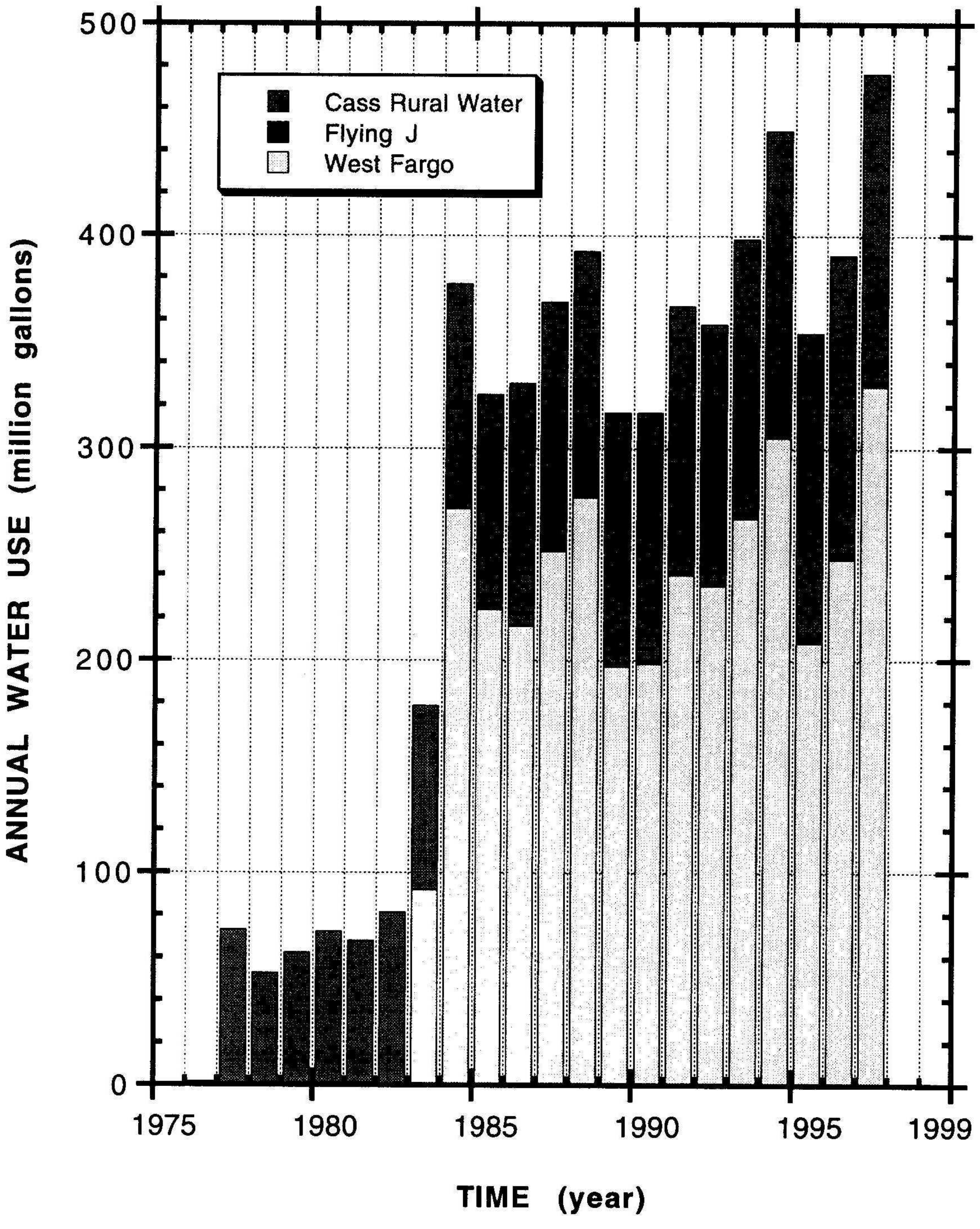


FIGURE 70. Annual water use from the West Fargo South aquifer.

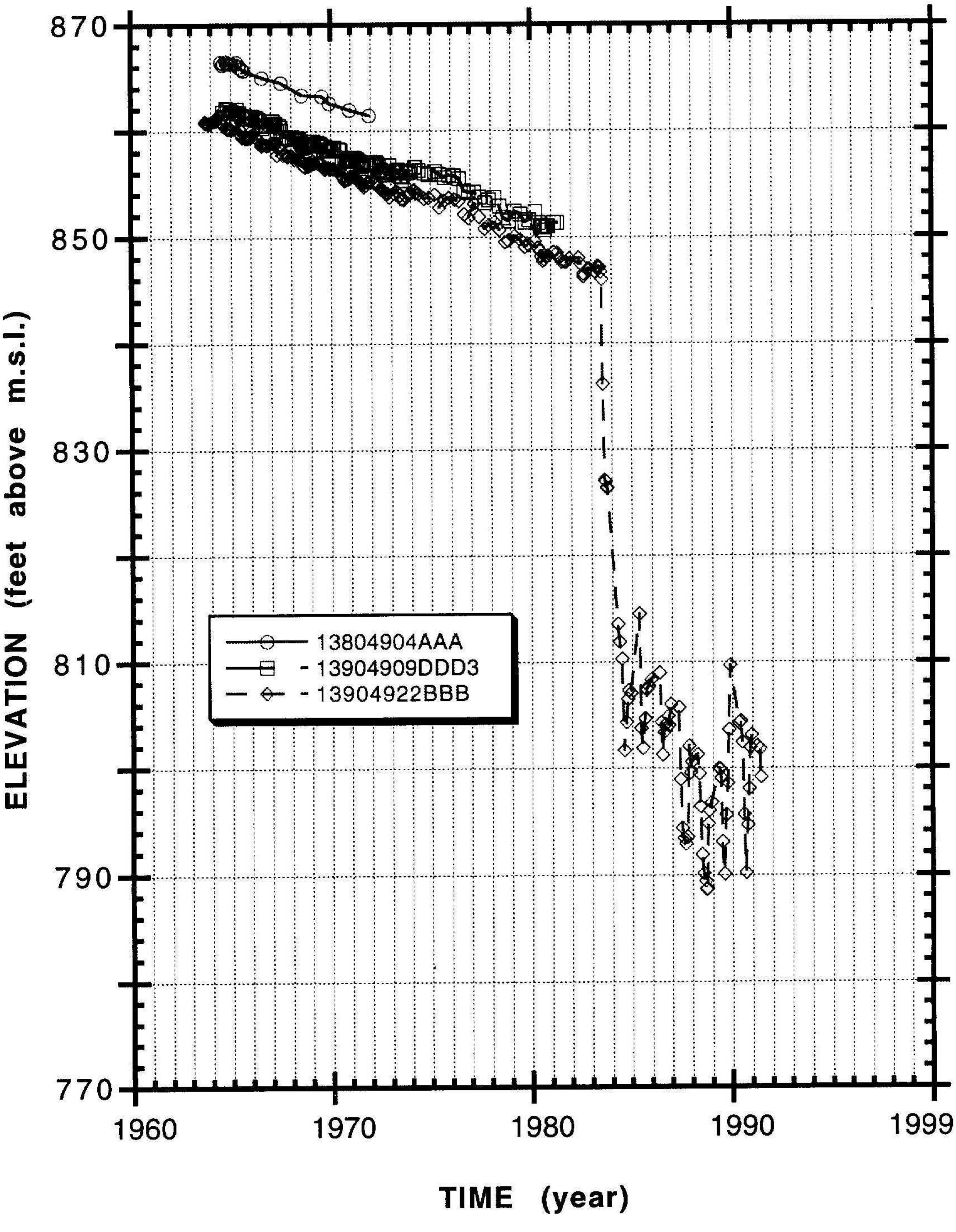


FIGURE 71. Hydrograph of WFS aquifer observation wells installed in the 1960s.

somewhat significant amount of water-level decline. Observation well 139-049-22BBB had water levels of about 50 feet below land surface when first installed in 1963, and continued to decline at a rate of about 0.7 feet per year through the 1960s.

A water-level decline of the magnitude of 50-plus feet as a result of the withdrawal of a few million gallons per year of water from an aquifer as large as 13.5 square miles does not seem likely. There may be some unknown withdrawals that would result in more than 2 or 3 million gallons being withdrawn per year from the WFS aquifer, however that likelihood also seems remote. It is more likely that the WFS aquifer was being affected by pumping from other nearby aquifers, with the lower water levels that result from significantly more water use. Very little is known about the water levels in the southern part of the WFS aquifer before 1981. Figure 71 also shows that none of these three WFS observation wells that go back in time the furthest, have water-level records that continue past 1991. Because of growth in the area, the sites for these three wells were no longer available for observation wells in 1971, 1982, and 1991. Thus, water levels were no longer available from these sites after those times.

Figure 72 shows a hydrograph for more recent observation wells in the WFS aquifer. The changing landscape of south Fargo has resulted in the loss of two of the six wells shown in figure 72, although there is enough of a historical record of these two terminated wells to be of value. Figures 71 and 72 give evidence of the impact of water use from aquifers in the area. Figure 71 shows the steady decline of water levels in both 139-049-09DDD3 and 139-049-22BBB. The same is true for 138-049-04AAA, however the water-level record is not long enough to show what the other two wells show. Initially, in the mid 1960s, the water levels of all three wells in figure 71 were declining at a rate of about 0.9 feet per year. By 1975 the rate of decline for the period of 1972-75 for the two remaining observation wells had lessened to 0.3 feet per year.

By the end of 1979, after more than three years of pumping on the part of Cass Rural Water User's (see figure 70), the rate of annual, water-level decline for the time period of 1976-79 for the two observation wells still being measured was 1.1 to 1.3 feet per year. Well 139-049-22BBB is about 9 to 10 miles north of the CRWU well field, and well 139-049-09DDD3 is about 10 to 11 miles north of CRWU well field. The effect of this change in the rate of water-level decline is a subtle feature because of the scale of figure 71. Because the city of West Fargo's (WF) well field is much closer to 139-049-22BBB, and because the total annual use is greater (see figure 70), the impact of the start up of the WF well field is much greater as seen in figure 71 (note the increase in the rate of water-level decline of 1976 as compared to 1983). The first WF well that was located in the WFS aquifer (well #7) was less than 1 mile from observation well 139-049-22BBB.

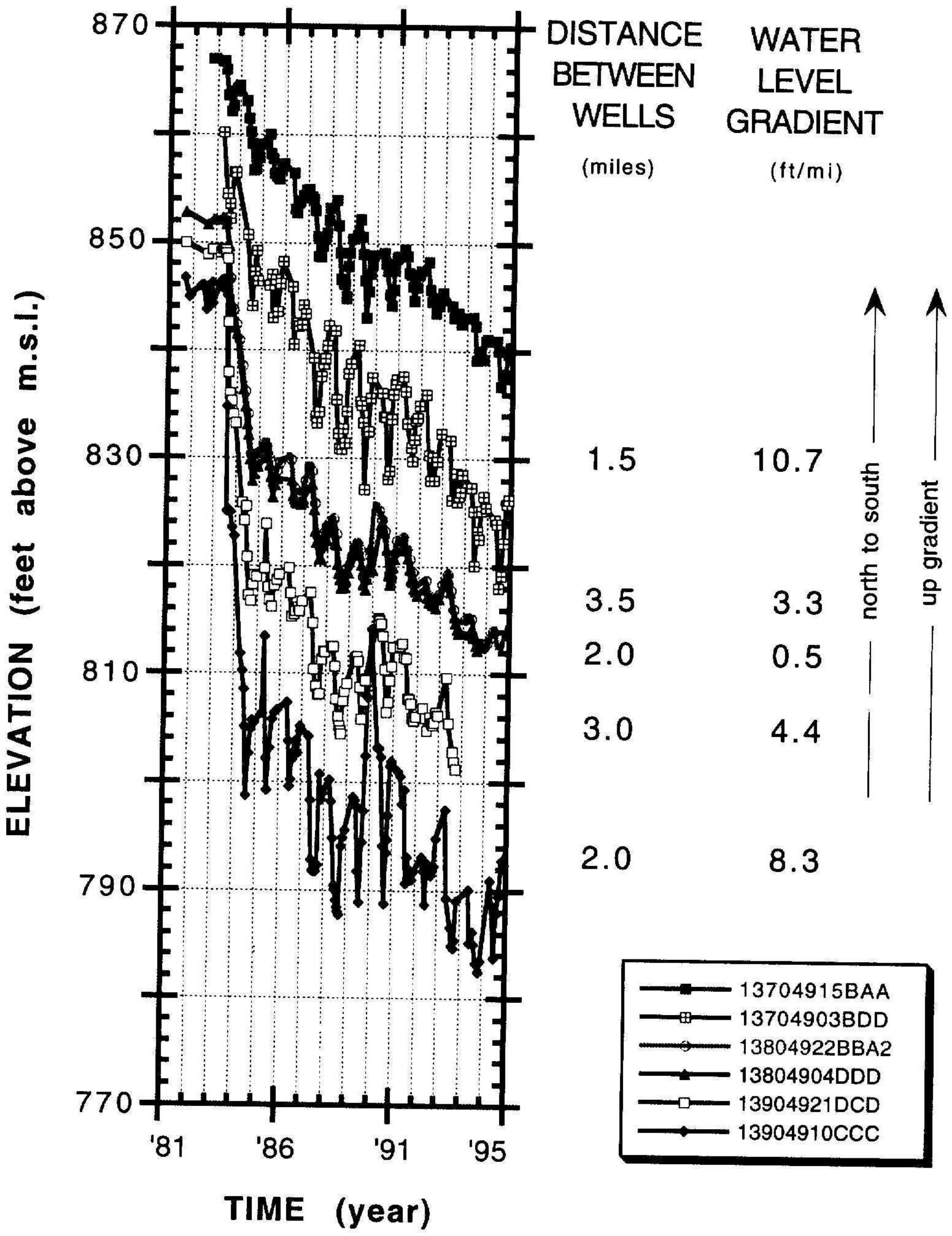


FIGURE 72. **Hydrograph of selected observation wells in the West Fargo South aquifer showing the hydraulic gradient between the observation wells.**

Figure 72 shows the impact of the two well fields since 1981. At the top of figure 72 are the observation wells located at the south end of the WFS aquifer, and at the lower part of the figure are the wells located in the northern part of the aquifer. The distances between the observation wells and the hydraulic gradients are listed on the right side of the figure, much like what was done in figure 14 for the WFN aquifer. With the start up of the WF well field in 1983, there was a very significant increase in the annual rate of water-level decline. That increase, however, can only be observed in the three northern (lower in the figure) wells in figure 72, because the three southern wells were not installed until late 1982 or 1983. By 1984-85 a somewhat consistent, although not steady, rate of annual decline developed. The water use from the WF well field has had more annual variation than the water use from the CRWU well field. See Tables 5C for CRWU annual water use, and 5F for WF annual water use (pages C221 and C227, respectively).

The rate of water-level elevation decline for the four northern and central observation wells listed in figure 72 has been about 1.6 feet per year for the time period 1985-95. Observation wells 137-049-15BAA and 137-049-03BDD (the two southernmost wells) show variations in the rate of annual water-level decline over the 13 years of record. During the early to mid 1980s the rate of decline was about 3.6 feet per year. During the time period 1986-90 the rate decreased to about 1.4 feet per year. From 1991 to 1995, the rate increased slightly to 2.2 feet per year.

A careful look at the water use of the CRWU well field shows that from 1983 to 1985 the annual use varied from 87.1 to 105.1 Mg with an average rate of water use of about 97.5 Mg per year, and a year-by-year increasing annual volume. The variation in water use from 1986 to 1990 was minimal, ranging from 113.6 to 118.1 Mg/y. This resulted in the lessening rate of annual water-level decline over this 5-year time period. Since 1991, and up to 1995, the annual use has ranged from 120.8 to 141.7 Mg in a generally increasing pattern year by year. This has resulted in the slight increase in the annual rate of water-level elevation decline.

Figure 72, as mentioned earlier, is similar in design to figure 14. Figure 14 was used to show why it is likely that there are discontinuities in the transmissivity of the WFN aquifer. The wide variation of hydraulic gradients observed in figure 72 also indicates that there are very significant variations in the aquifer properties of the WFS aquifer. Figure 72, however, is much more difficult to interpret in the same way as figure 14, because there are differences in the relationship of the well fields with the observation wells, and in the rates of water-level elevation changes. In the setting of the WFN aquifer, all of the observation wells are to the north of the WFN pumping center, and the water levels were changing slowly through time, because the pumping had started so long ago, and was not increasing at a large rate through recent time. In the setting of the WFS aquifer, there are two pumping centers, some of the observation wells are located on both sides of the pumping centers, and there have been significant increases in the rates of pumping in recent years. The aspect of aquifer discontinuities will be covered in more detail in the section on ground-water flow later in the discussion.

Prior to the development of the Cass Rural Water and city of West Fargo well fields in the WFS aquifer, figure 71 shows that the annual rates of decline were about 0.8 feet per year from 1963 to 1970, and about 0.3 feet per year from 1970 to 1976. After the development of those well fields in the WFS aquifer, the annual rates of decline increased significantly. From 1983 to 1991 water levels in observation well 139-049-22BBB dropped at a rate of about 6 feet per year. Most of this decline was in the first year, and from 1984 to 1991 the water levels in 22BBB declined at a rate of about 2 feet per year. Over the 15 years shown on Figure 72 the annual rate of water-level decline has been about 2.0 to 2.5 feet per year. The last seven years shown on figures 71 and 72 show an annual rate of decline of about 1.4 to 2.0 feet per year.

Aquifer water chemistry

Figures 15 through 20 show the concentrations of six different constituents for nine aquifers in the WFAS. The eighth aquifer shown in each figure is the West Fargo South aquifer, listed as WFS. Each aquifer has a variable number of different sites from which samples were collected for analysis, and each site has a variable number of samples that were collected from that particular site. Figures 15-20 depict only one representative sample from each site. The number of sites for each aquifer represented in figures 15-20 is as follows:

Aquifer	94/10	Fargo	Horace	Nodak	Ponderosa	Prosper	WFN	WFS	W Pleasant
No. of sites	4	3	27	4	6	19	39	22	5

The depiction of the chemical character of several aquifers is limited, because there are six or fewer sites. The WFN, however, is well depicted with 22 different sites represented by one or more chemical analyses of samples from those sites.

Figure 15 shows that the WFS aquifer is the lowest in calcium concentration in comparison to other aquifers in the area. There are no U.S. Environmental Protection Agency (EPA) standards, advisories, or regulations regarding calcium concentrations in public water supplies. Calcium, along with magnesium cause water hardness, and with certain other constituents can form scale on utensils, water heaters, boilers, and pipes.

Figure 16 shows that the WFS aquifer is the lowest among the group of nine aquifers with respect to chloride concentration. The EPA has a Secondary Maximum

Contaminant Level (SMCL) of 250 mg/liter for chloride. There is no regulation of this SMCL, and numerous public water supplies exceed this level. All WFS aquifer sites showed calcium values less than the SMCL. A salty taste is imparted by concentrations above 400 mg/liter, which may impair water's usefulness for drinking and some other purposes.

Figure 17 shows that the WFS aquifer is the lowest of the group of nine aquifers with respect to hardness. The median value of the WFS hardness (about 160 mg/liter) falls into the USGS category of "hard" water, which is bounded by the values of 121 and 180 mg/liter. There are no EPA standards, advisories, or regulations regarding hardness in public water supplies. Calcium and magnesium are the principal cause of hardness, which exhibits the characteristics of requiring greater quantities of soap to produce lather as the hardness increases.

Figure 18 shows that the WFS aquifer is the lowest of the group of nine aquifers with respect to the sodium concentration. The EPA health advisory for sodium concentration is called a "guidance", and is listed at 20 mg/liter. This value of sodium concentration is below each and every one of the sodium concentrations for every one of the 545 analyses that were performed on the all of the samples taken from the WFAS. There are very few sites in all of North Dakota that produce samples with sodium concentrations as low as 20 mg/liter.

Figure 19 shows that the WFS aquifer is the lowest in sulfate concentration in comparison to other aquifers in the area. The EPA has both a Drinking Water Standard (500 mg/liter) and a SMCL (250 mg/liter). The Drinking Water Standard is proposed and is in draft form. All sites and all samples from all sites in the WFS aquifer had sulfate concentrations below the lower SMCL sulfate value of 250 mg/liter. Laxative effects can be experienced with water having sulfate concentrations above 600 mg/liter, particularly if much magnesium or sodium is present.

Figure 20 shows that the WFS aquifer is the lowest of the group of nine aquifers with respect to the total dissolved solids (TDS) concentration. Sometimes referred to as 'salinity', TDS consists mainly of the total of the dissolved mineral constituents in the water. The EPA has a SMCL of 500 mg/liter. There is no regulation of this SMCL. The median value of TDS for the WFS aquifer is about equivalent to the SMCL. The major effect of salinity is that the osmotic pressure of a soil solution becomes too large with increasing salinity. Water containing excessive dissolved solids should not be used for plants. Many waters in the state with TDS between 500 and 1000 mg/liter are used for plants.

The water in the WFS aquifer is a sodium-bicarbonate type. The total dissolved solids generally range from 400 to 600 mg/liter, and the water is generally hard. It is suitable for most purposes. The best water quality in the study area is consistently found in the WFS aquifer.

Figure 73 shows the relationship between stable isotopes of ground water in the WFS aquifer and precipitation at Oakes, ND. The seven sites had a $\delta^{18}O$ value that ranged from -19.6 to -22.1, and a $\delta^{2}H$ value that ranged from -149 to -168. When water shows large negative values for $\delta^{2}H$ and $\delta^{18}O$, it is a sign that the water was emplaced under colder climatic conditions, and is described as having a "cold signature". As shown in figure 21, samples of rainfall in North Dakota have shown values of approximately -4 to -10 for $\delta^{18}O$ and samples of snowfall in ND have shown values of approximately -18 to -25.

The WFS aquifer samples all are in the "snowfall" range. The WFS aquifer samples as a group have the coldest signature of any of the aquifers in the area. It is interesting to note that the aquifer that has the water with the lowest values of various inorganic dissolved constituents also has the water with the lowest $\delta^{2}H$ and $\delta^{18}O$ values. This range of values for $\delta^{18}O$ in the WFS aquifer is extremely cold in its signature. Values like these do not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values for water samples collected from WFS aquifer wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the WFS aquifer.

Ground-water movement

There is no available data that shows any WFS aquifer water levels above land surface. One of the reasons for this is that none of the early reports on this study area listed any water-level measurements predating the 1930s. The first repetitive water-level measurements on record start in 1963. Much of the following discussion on the WFS aquifer flow system before the 1960s is based on inference, and on prior discussions of other nearby aquifers. This is also the last of the aquifers to be individually discussed, and the discussion of the WFAS as a whole, has, in essence, come full circle from the first aquifer discussion of the WFN aquifer.

A greater part of the early water usage (late 1800s to early 1900s) in the study area was from aquifers that were more closely related to the WFN aquifer. A very significant part of the subsequent increase in water usage through the mid-1900s (especially in the 1930s) was derived from the WFN aquifer. Because of this, it is most likely that the water levels (from the late 1800s to the mid-1900s) declined much more

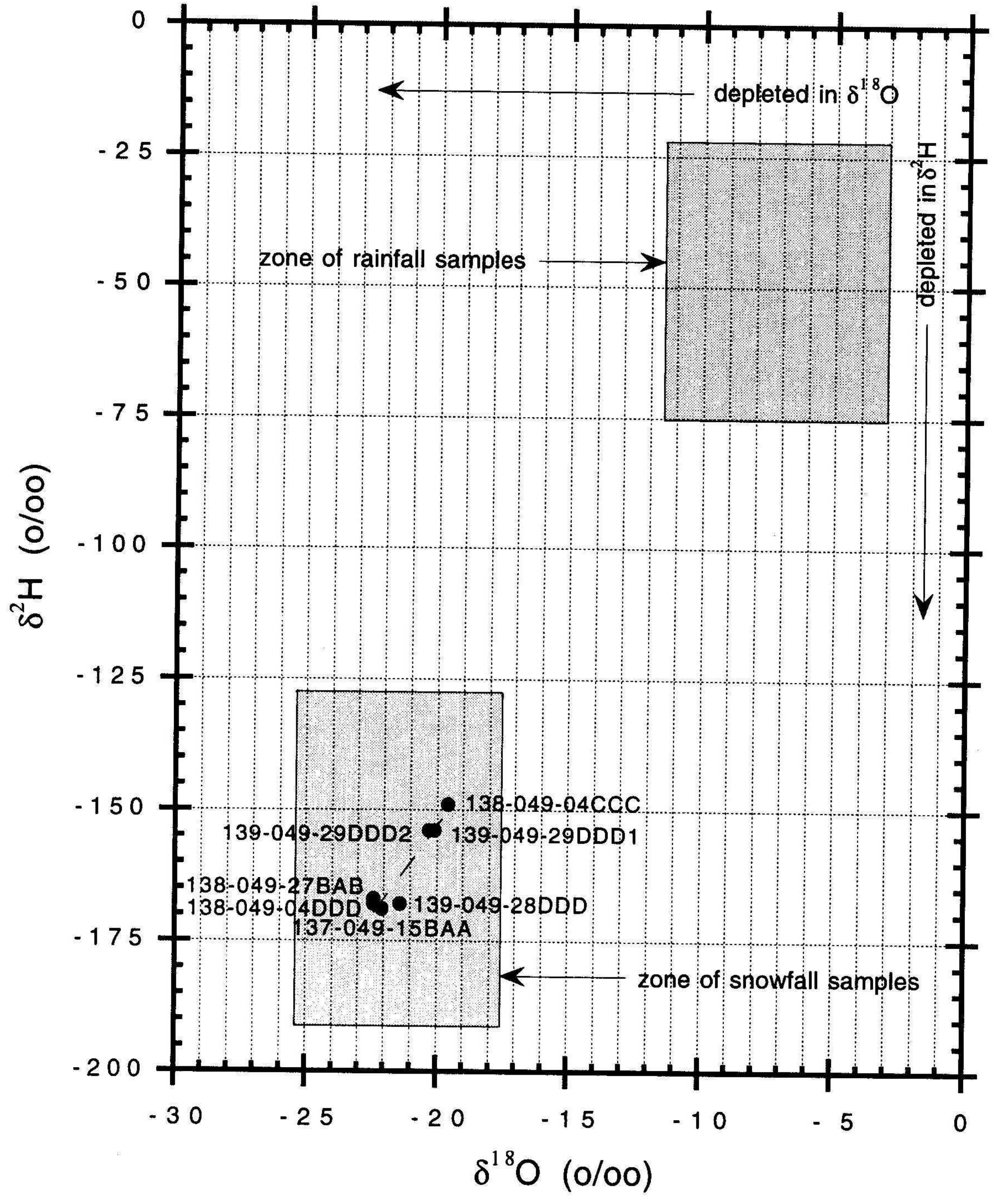


FIGURE 73. **Relationship between stable isotopes (deuterium and oxygen-18) in ground water from the West Fargo South aquifer and precipitation at Oakes, N.D.**

quickly in the WFN aquifer than did the water levels of the WFS aquifer. There are no data, however, to document how much more quickly.

While the timing of water-level declines is in doubt, there is little doubt that the pattern of water-level decline for the WFS aquifer is a similar, but delayed, pattern in comparison to the water-level patterns for WFN aquifer wells. The predevelopment ground-water movement pattern for the West Fargo South aquifer is likely the same as what was described for the West Fargo North aquifer. It is probable that before the development of this area in the late 1800s, most or all of the aquifers in the area had water levels at or above land surface. Ground-water movement would have been upward from the WFS aquifer through the overlying till and lake clay. This flow moved very slowly, but eventually this flow would have reached the land surface. At the land surface this slow seepage would most likely have been removed by evapotranspiration, however some small accumulations could have occurred in the low-lying areas at the land surface, especially in the winter and early spring time periods, when evapotranspiration processes would have been minimal. There may also have been a northward ground-water flow component because the north part of the aquifer is overlain by a topographically lower land surface.

Once ground water began to be utilized in the 1870s, water levels in the study area began to decline. The initial center of development would have been in the area around the downtown areas of Fargo and Moorhead. As the region grew in population, more wells were located in this area, more water was used, and the size of the populated area expanded. Ground-water levels in the area changed from being above land surface to being at land surface, and finally being below land surface. First the Fargo aquifer (probably between 1880 and 1885), and then the south end of the WFN aquifer (probably between 1890 and 1900) had wells screened in them that had water levels that went below land surface. Given the large hydraulic gradient that existed between the WFS and the WFN in the 1960s, the limited amount of use from the WFS aquifer in the early 1900s, and the fact that the water levels in the WFN aquifer did not decline at a significant rate until the 1930s, it is likely that water levels in the WFS aquifer dropped below land surface somewhere in the time period before the 1930s (possibly the early 1900s for the north end of the WFS aquifer, and the 1920s for the south end of the WFS aquifer).

While some of the above information cannot be documented directly with supporting data, the inference of flow from the WFS aquifer to the WFN aquifer seems reasonable because there does not appear to have been any other sources of outflow from the WFS aquifer. Once records were kept of water levels and water use in the WFS aquifer, it appears likely that well discharge (prior to the 1960s) from the WFS aquifer was not large enough to cause the water-level decline that was observed. For the time period when records of water use and water levels for the WFS aquifer began (mid-1960s), until the first significant volume of water was withdrawn (1976), it was clear that WFS water levels were declining at a slow rate (less than one-half foot per year). Water use from the WFS aquifer was minimal, and this decline was probably due to leakage to the WFN aquifer.

In a similar way, it is also likely that ground-water flow was from the WFS aquifer to the Nodak aquifer. However, the relative amounts cannot be estimated, because of the limited amount of historical water-level data for both the Nodak and the WFS aquifers.

During the 1960s, a more systematic pattern of measuring and recording water levels began for the WFS aquifer. As seen in Figure 71, the measurements showed a steady lowering of water levels in the WFS aquifer. Figure 68 shows the locations of these three wells. The data in figure 71 shows that water levels in observation well 139-049-09DDD3 are higher than water levels in observation well 139-049-22BBB. The patterns of water-level changes in the two wells are very similar. This suggests that flow in this part of the WFS aquifer would be from 9DDD3 to 22BBB, which is located a mile to the south of 9DDD3. Other evidence shows that this southerly flow does not occur. Several paragraphs of explanation are needed as to why there are conflicting sets of data with respect to the flow direction, before this discussion of WFS ground-water flow can continue.

Figure 74 shows a hydrograph of three observation wells in the north end of the WFS aquifer. Figure 68 shows the location of these three wells. This figure is used to point out two problems that are found in some water-level elevation records. While an inordinate amount of time was spent analyzing (and correcting, where possible) data problems, there still remain a few uncorrectable, and/or undetected data problems. There are no easy or difficult solutions for some of these problems. One of these problems is the difference in water-level elevations between 139-049-09DDD3 and 139-049-10CCC.

In 1981 major construction in the vicinity of 13th Avenue and 45th Street resulted in the need to permanently eliminate 9DDD3. Later that year a replacement well, 10CCC, was installed a few hundred feet to the east (east of the improved 13th Avenue). The depth of the eliminated well, 9DDD3, was 178 feet, and the depth of the replacement well, 10CCC, was 181 feet. There is every reason to believe that these two wells are in very well connected portions of the WFS aquifer. A comparison of these two wells with a third well, 22BBB, however, shows an unusually large difference in water levels across a distance of just a few hundred feet. The water-level elevations in 9DDD3 appear to be consistently about 2 1/2 to 3 feet higher than the water-level elevations in well 22BBB for any given date up to early 1981. Starting in late 1981 and afterwards

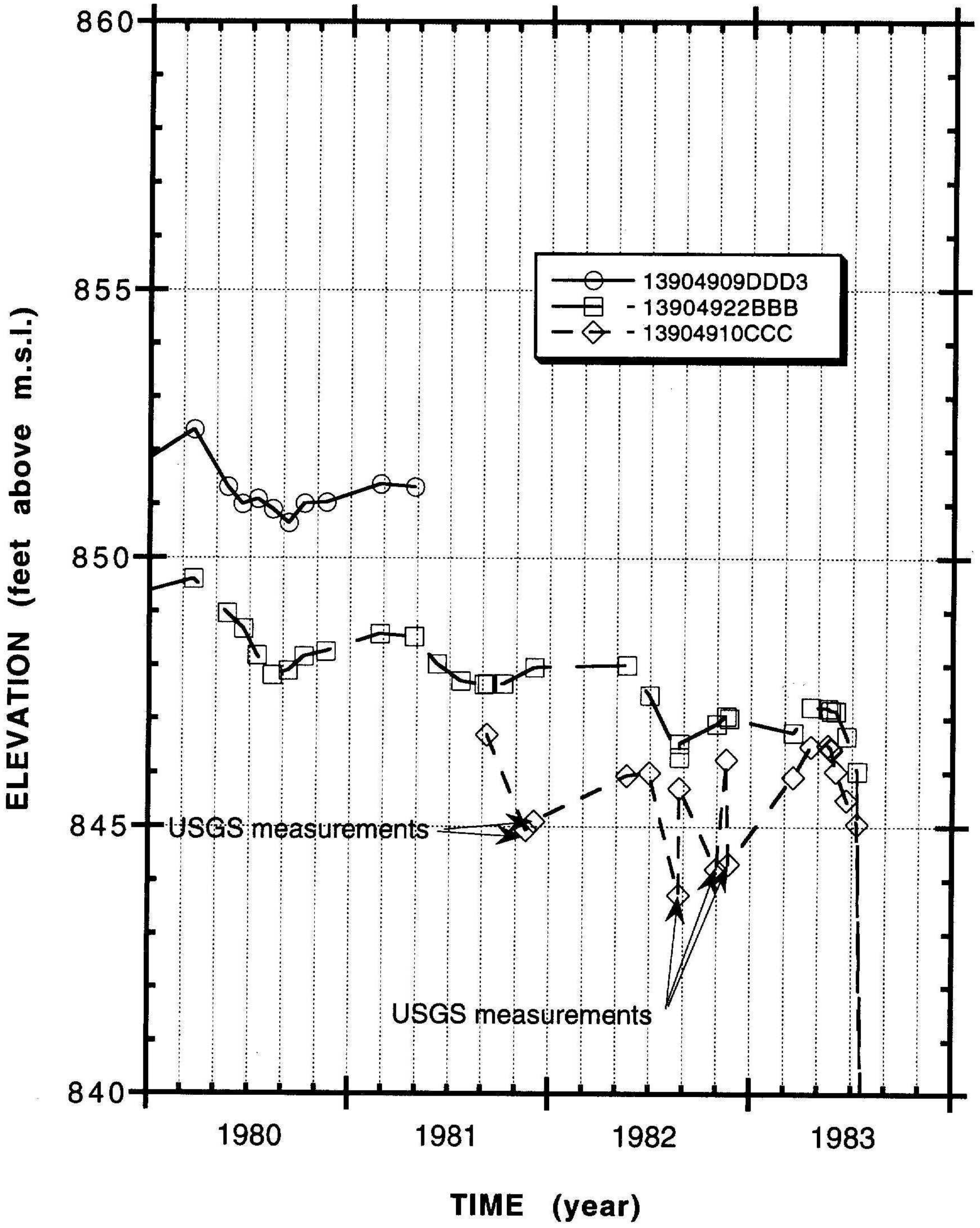


FIGURE 74. Hydrograph of three West Fargo South aquifer observation wells showing probable elevation problems.

for any given date the water-level elevations in 10CCC appear to be about 1 to 1 1/4 feet lower than the water-level elevations measured in 22BBB.

Because neither the elevation of the land surface nor the elevation of the measuring point for 139-049-09DDD3 were surveyed, it is believed that water-level elevations for 139-049-10CCC (which had been surveyed) are more indicative of the actual water-level elevations in the WFS aquifer in this immediate area. While there is insufficient information (the landscape of site of 9DDD3 was totally altered) to change the water-level elevations for 9DDD3, it is likely that the elevations for 9DDD3 are 3 1/2 to 4 1/4 feet lower than depicted in figure 71. This would also be true for the water-level elevations as listed on page C168 in Table 2, of Volume C, in the ground-water data report. The water-level measurements are most likely accurate, but the elevations of the land surface, and measuring point for 9DDD3 are probably not.

The second problem that is observed on figure 74 is the rather rapid 2-foot change observed for certain measurements in the 1981-82 time period for observation well 139-049-10CCC. Except for five measurements, all of the water-level measurements for 10CCC were made by SWC personnel. The five exceptions were measurements made by USGS personnel, and are noted with arrows on figure 74. They are generally 1 1/2 to 2 feet lower than the SWC measurements. This is probably because the measuring point was tabulated by each agency as being at a different elevation. A concerted effort was made to correct these discrepancies, however there was not always the supporting evidence with which to do so. In some instances, as in this one, it is very likely that some of the data should be adjusted to be compatible with the rest of the data. These problems are being pointed out to show the limits of the use of the available data. For the purpose of interpreting ground-water flow in the WFS aquifer, the SWC measurements for 10CCC will be assumed to be the best data to use.

Based on the above, it appears that figure 71 shows the water-level elevation of 139-049-09DDD3 as being about 3 1/2 to 4 1/4 feet too high. With such an adjustment, the ground-water flow in the WFS aquifer would appear to be from the area around 138-049-04AAA (the area with the highest water-level elevations of these three wells) to the area around 139-049-22BBB and then to the area around 139-049-09DDD3 (see figure 68). Ground-water flow from the aquifer around 22BBB would probably have been towards the northwest, because it is believed that the area to which most of the water of the WFS aquifer was flowing was toward the WFN aquifer. It is further believed that the connection between the WFS aquifer and the WFN aquifer occurs over a zone of less than one-half mile. In this one-half mile zone is material characterized by a small hydraulic conductivity that extends across a length of about 2 to 3 miles and is located northwest of 22BBB and 10CCC (see figure 68).

A summary of the flow system in the WFS aquifer for the time period from early development in the area (1870s) to the mid-1970s would consist of northward flow in the entire aquifer. Initially most of the flow would be caused by the lower land surface to the north, but as development of the area in the late 1880s increased, water use would have increased. This increased water use from aquifer units other than the WFS aquifer would cause water levels to decline in those units, and this would eventually induce leakage of water from the WFS aquifer to those other units. This leakage would cause water levels to decline in the north end of the WFS aquifer, and this would increase the ground-water flow from the southern part of the WFS aquifer.

The development of the Cass Rural Water Users, Inc. well field in 1976 altered this north-flowing ground-water regime at the south end of the WFS aquifer flow system. Figure 56 shows the top curve (observation well 139-049-25CCC) as a slowly declining depiction of the water levels in that well from 1964 to 1976. This well is located in the Horace aquifer, but it is most probable that had there been an observation well located in the south end of the WFS aquifer at that same time, that this non-existent assumed observation well would have had a very-similar, slightly-lower, water-level-response pattern.

From 1976 until 1983, the curve of well 25CCC showed an initial, significant steepening followed by a gradual lessening of the annual rate of additional water-level decline with each additional year (until conditions again changed in 1983). In a more subtle way, observation well 139-049-22BBB (fourth curve down) shows the same gradual decline until 1976, when the utilization of the WFS aquifer on the part of CRWU caused a slight increase in the rate of annual water-level decline. These comparisons show that the Horace aquifer is fairly well connected to the WFS aquifer, and that utilization of wells in section 3 of T137N, R49W affected the water-level response in an observation well 9 to 10 miles to the north.

Figure 75 shows two observation wells that are located in the Horace aquifer, and three observation wells located in the south end of the WFS aquifer. Figure 75 is similar to figure 62, except for figure 75 showing a longer time period and two additional water-level curves. As mentioned earlier in the discussion on the ground-water flow system of the Horace aquifer, the 15-foot difference between 137-049-14BBB1 and 137-049-15BAA (one-half mile apart) shows a significant decrease in the transmissivity of the aquifer material. The hydraulic gradient between these two wells is about 30 feet per mile. This is the basis for determining that the two observation wells are in different aquifers. The hydraulic gradient between 15BAA and 139-049-03BDD is about 9 feet per mile, and is steeper than it would be if 03BDD were not so close to the well field. The hydraulic gradient between 03BDD and 138-049-35BBB is about 6 feet per mile.

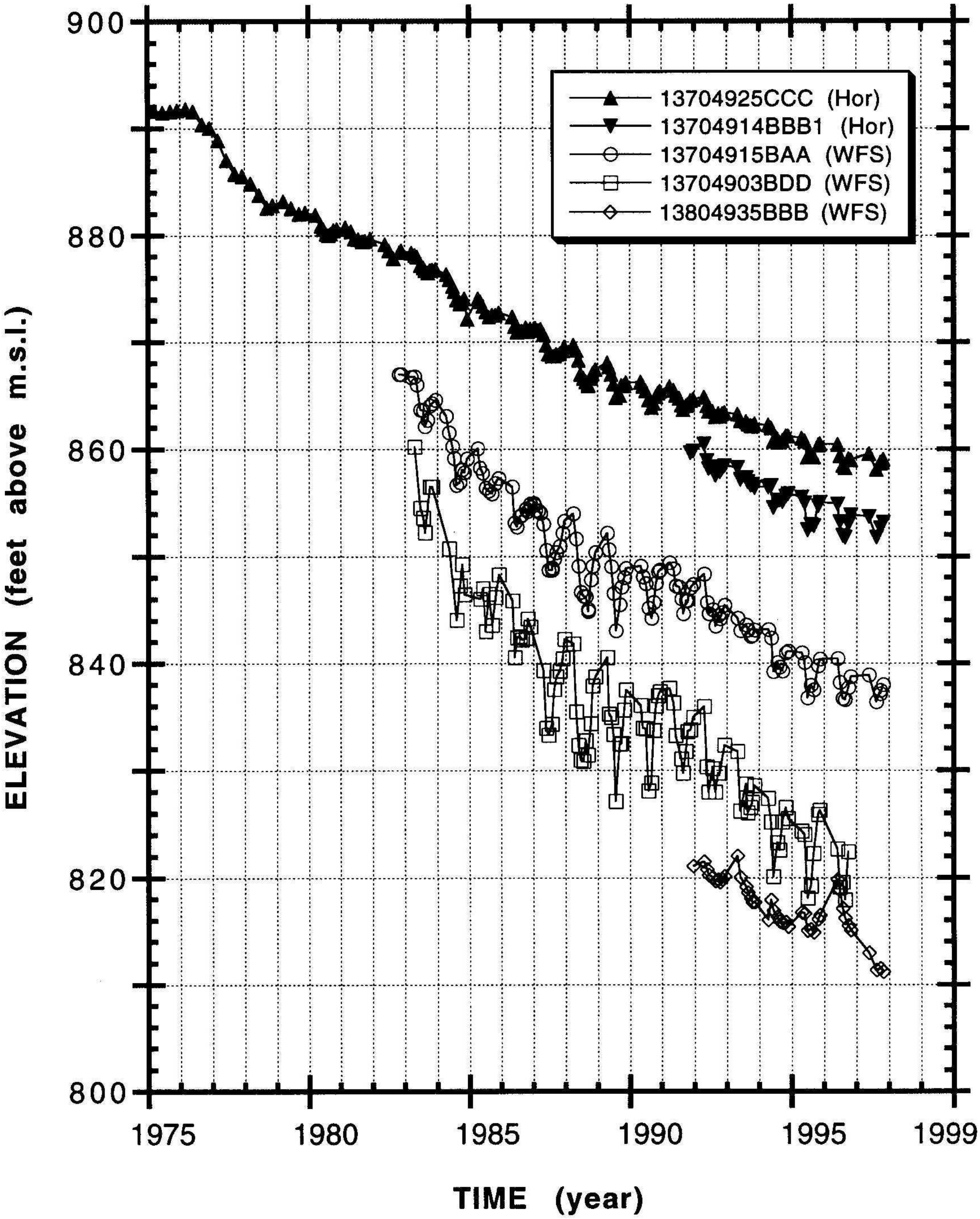


FIGURE 75. **Hydrograph of observation wells in the south portion of the WFS aquifer and the north portion of the northeast part of the Horace aquifer.**

This low hydraulic gradient is the basis for assigning these two wells to the same aquifer.

However, when the water-level data is analyzed more closely to ascertain ground-water flow directions, there appears to be another possibility. This was not mentioned earlier, because things were confusing enough at that point in the discussion. However, this perspective needs to be mentioned now, to more fully understand the complexity of the system, and the different possible ramifications of different management decisions.

Figure 76 shows a map view of the area with the aquifers in the area being depicted differently than they have been in any other map in this report. Figure 76 depicts a separate sub aquifer at the south end of what has been called the WFS aquifer. A second look at figure 75 shows that the general pattern of the water levels through time for 15BAA and 03BDD are very similar, with the main difference being that 15BAA pattern is a subdued image of the 03BDD pattern with higher water-level elevations. The same relationship is not found between the water-level patterns of observation wells 03BDD and 35BBB.

Although the water-level records for 35BBB only start in late 1991, the comparison with 03BDD water-level records shows that they are not similar. The annual cycles of 35BBB show steadily gradual water-level declines followed by a smaller, short, winter-spring, water-level rebound. The pattern for both 03BDD and 15BAA shows a large abrupt spring-summer decline, followed by a relatively abrupt, fall rebound and a more steadily gradual winter rebound until the next spring decline caused by increased spring-summer water use from the Cass Rural Water Users, Inc. well field. Figure 77 shows a hydrograph for observation wells located in the south-central portion of the WFS aquifer. Figure 78 is a map view of a part of the WFS aquifer, and shows the location of the four wells depicted in figure 77.

The key element to note from figure 77 is the strong similarity of the curves of the water-level measurements through the 1990-1994 time period. The small time period is displayed so that the very similar nature of the curves can be seen. A comparison of two figures (75 and 77) shows that 35BBB is closer in pattern and in actual water-level elevation to observation well 138-049-04DDD (which is over 4 miles from 35BBB) than it is to 03BDD (which is only about 1.5 miles from 35BBB). Earlier discussions presented this sub aquifer at the south end of the WFS aquifer in which the CRWU wells are found, as being part of the WFS aquifer. Because there is no nearby, water-level history that predates the development of the CRWU well field, this sub aquifer was included as being part of the WFS aquifer. It is possible that had there been water levels measured in this area before the 1976 startup of CRWU well field, that a significant water-level drop, and consequently large hydraulic gradient would

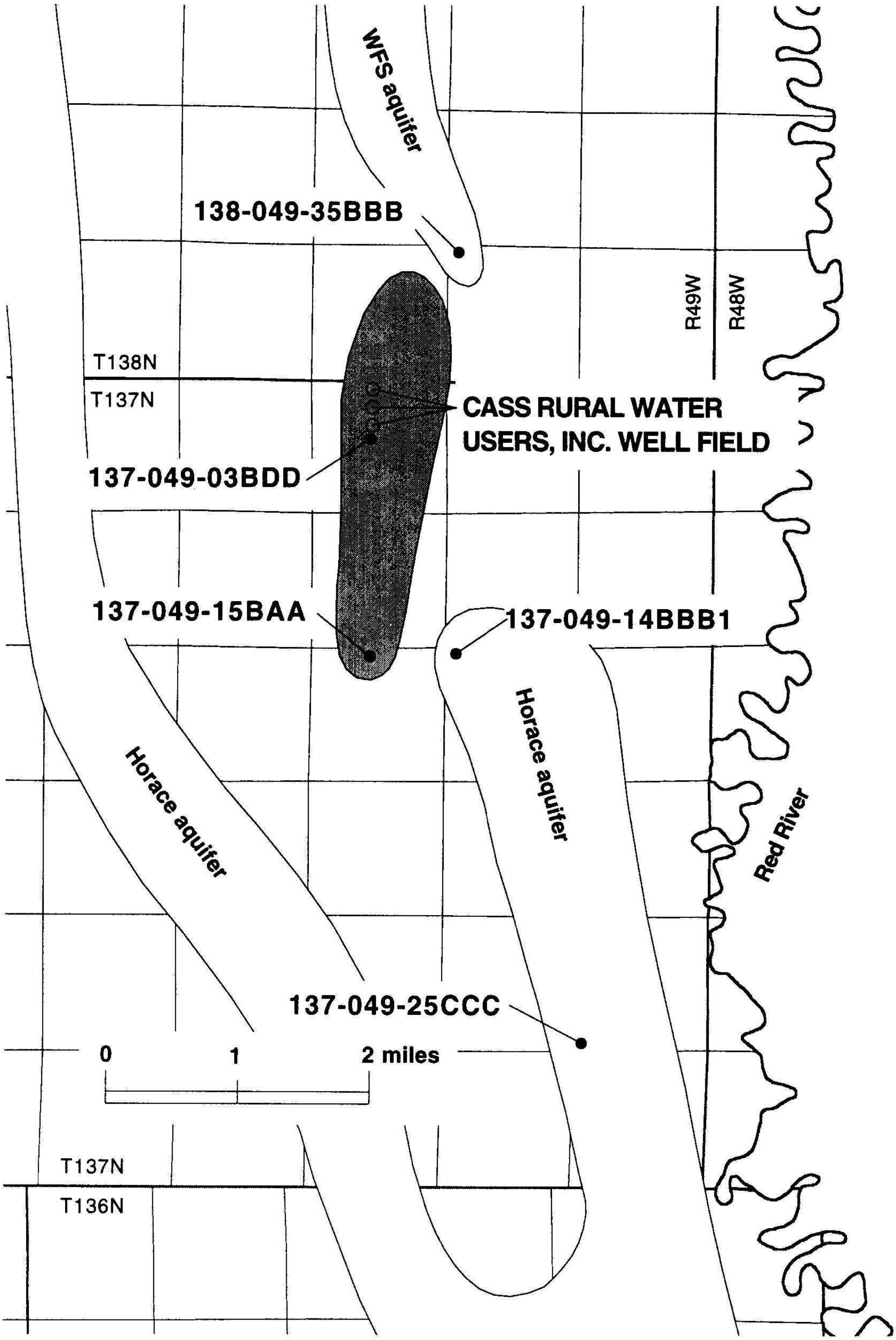


FIGURE 76. Possible configuration of the south part of the West Fargo South Aquifer near Cass Rural Water User's well field.

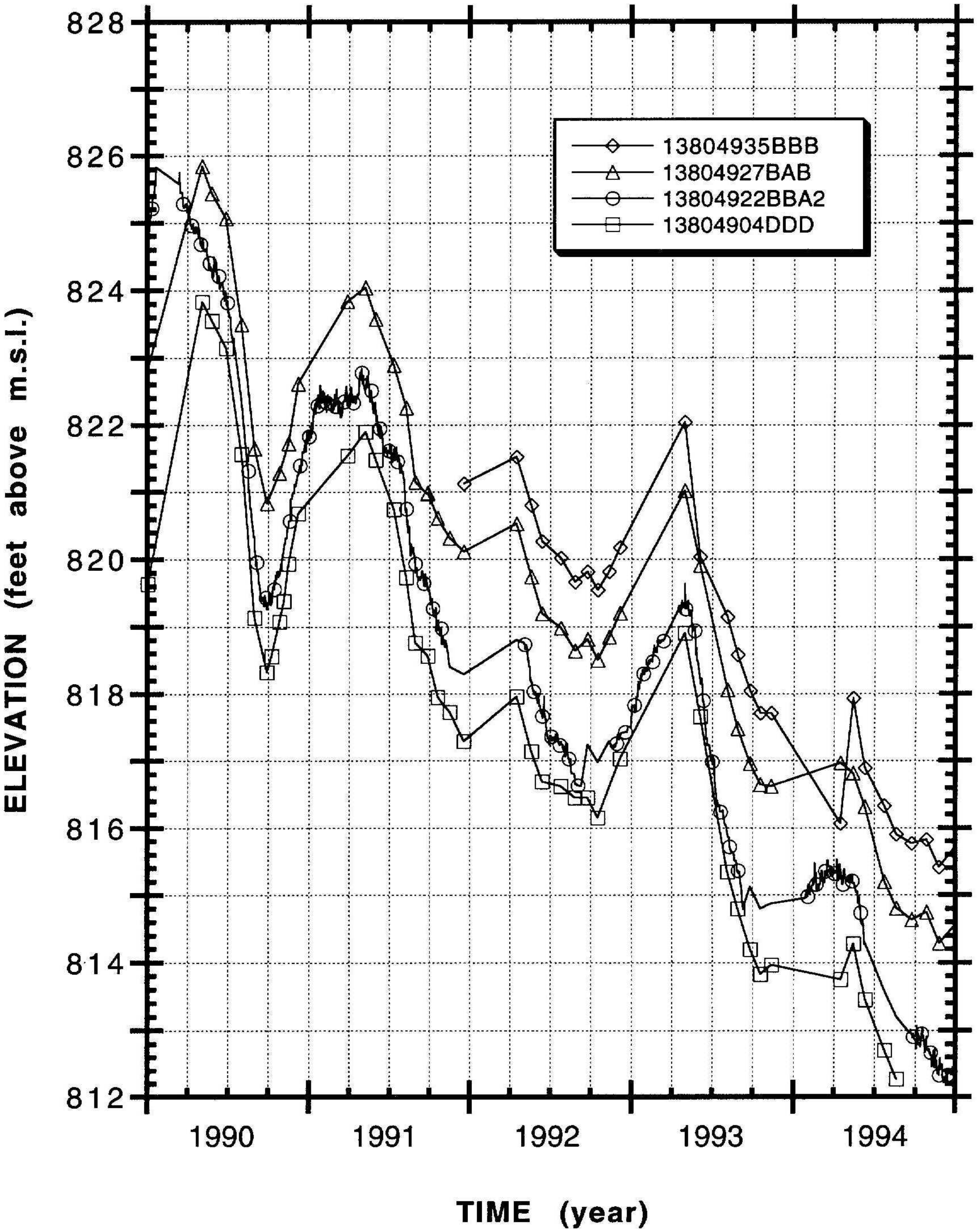


FIGURE 77. Hydrograph of observation wells in the south-central portion of the West Fargo South aquifer.

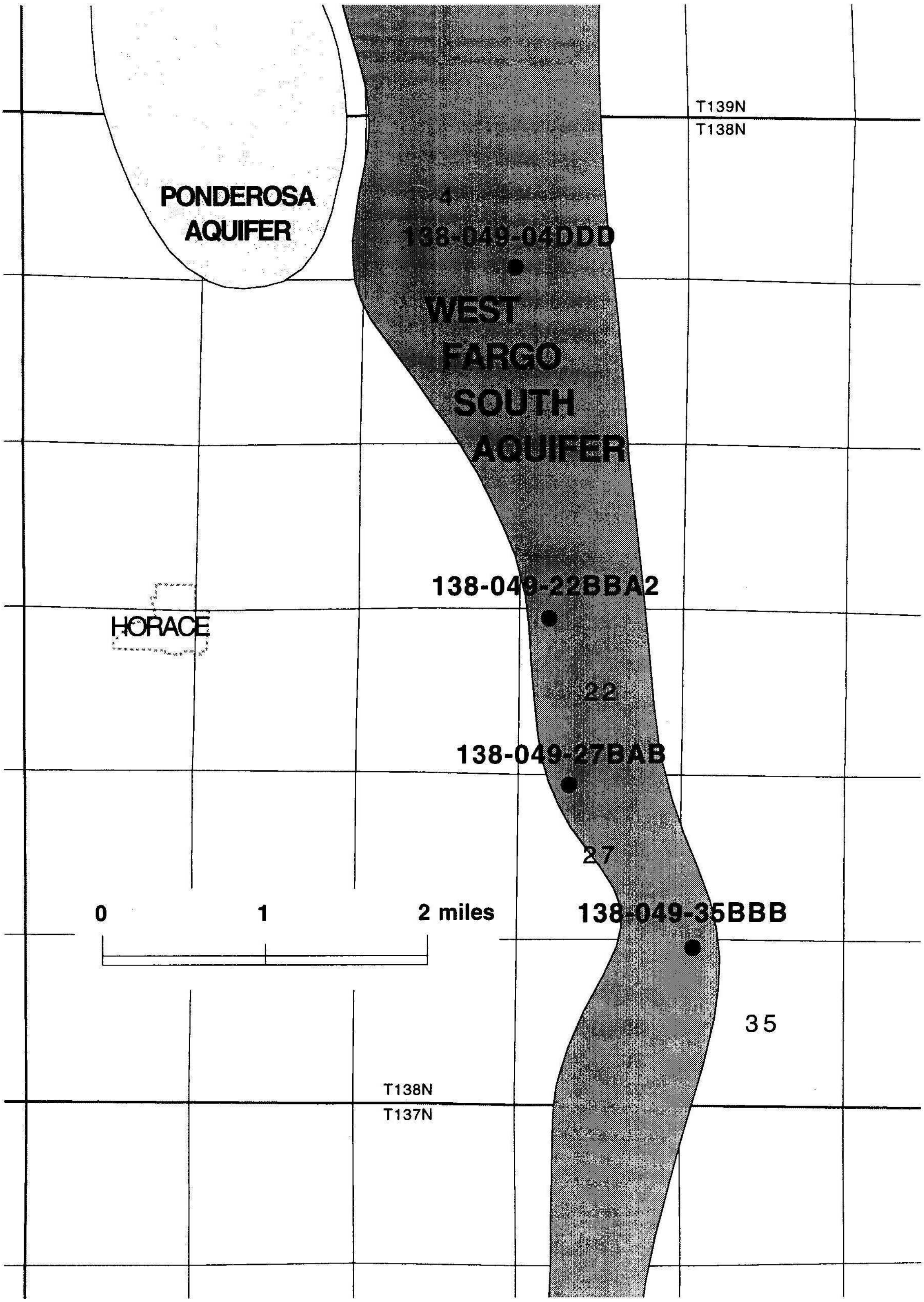


FIGURE 78. Location of observation wells shown in figure 77 hydrograph.

have existed somewhere in the region between the CRWU well field and 35BBB. Currently it appears that the pumping at the city of West Fargo well field in the WFS aquifer (about 8 1/2 miles away) causes a greater lowering of water levels in observation well 35BBB than does the pumping of the CRWU well field (about 1 1/2 miles away).

On the one hand, the greater similarity of the water-level history of 35BBB with the histories of the wells to the north suggests an aquifer configuration like the one presented in figure 76. On the other hand, the fact that WFS aquifer wells (as much as 10.5 miles to the north of the CRWU well field) have historic water-level patterns that were influenced by the CRWU well field, suggests that this apparent sub aquifer is, in fact, part of the WFS aquifer. This suggests that the aquifer configuration should be depicted as they are in all of the other figures showing the WFS aquifer. Utilization of the CRWU well field resulted in some ground-water movement that had been flowing to the north to be deflected towards the well field, into the wells, and out of the WFS aquifer.

Figure 78 shows the location of the four observation wells that have water levels graphed on figure 77. The distance between 138-049-35BBB (southernmost well in figure 78) and 138-049-04DDD (northernmost well in figure 78) is about 4 to 4.25 miles. The water-level difference between these two wells generally varies from 3 to 3.75 feet. This is an extremely small hydraulic gradient (0.8 to 0.9 feet per mile). This value would be small for any of the aquifers in this study area. It is probable that the aquifer transmissivity is quite high in places, which could account, in part, for this extremely small hydraulic gradient. However, some portions of the aquifer in this 4- to 5-mile reach do not have adequate thickness (150 to 200 feet) that would be indicative of very high transmissivities. Figure 69 shows a few thin sections of aquifer from 138-049-35BBB to 138-049-04DDD that are much less than 150 to 200 feet.

Part of the reason for the small hydraulic gradient in this area, is part of the ground water that is flowing north into the north end of the WFS aquifer, is coming into the WFS aquifer from the Ponderosa aquifer that is located north and west from the observation well at 138-049-04DDD. This ground-water in-flow from the Ponderosa aquifer (which comes from the Horace aquifer) reduces ground-water flow from the south end of the WFS aquifer, and therefore results in a lower hydraulic gradient. This additional ground-water flow coming in from the west from the Horace aquifer through the Ponderosa aquifer, and finally into the WFS aquifer is discussed in the ground-water flow sections of the Horace and Ponderosa aquifers. Figures 55 and 65 show the water-level elevations that indicate ground-water flow into the WFS aquifer from the Horace aquifer through the Ponderosa aquifer.

Figure 79 shows a hydrograph of WFS observation wells from 4DDD northward to the far northern tip of the WFS aquifer at observation well 139-049-09ADD. The time

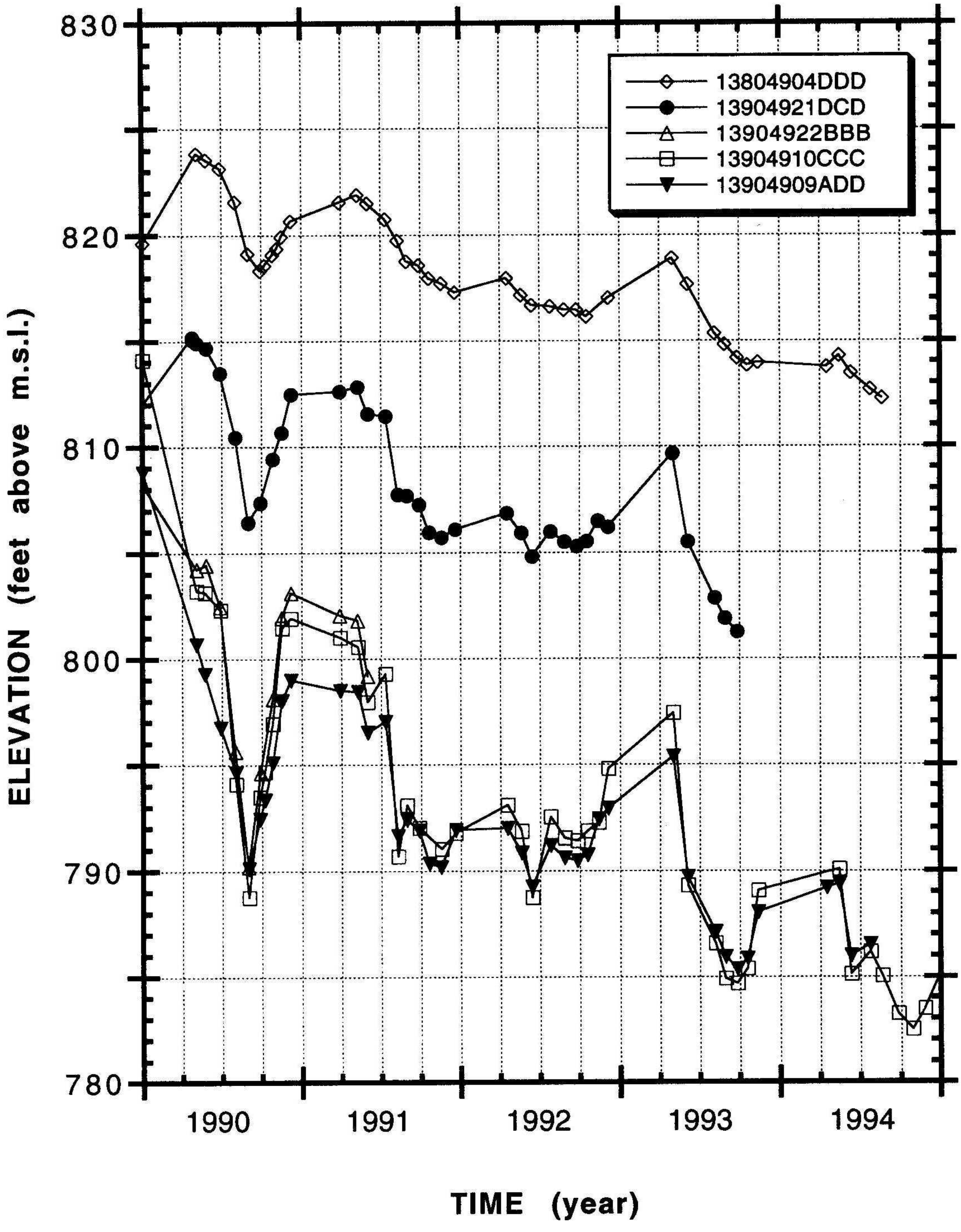


FIGURE 79. **Hydrograph of observation wells in the north portion of the West Fargo South aquifer.**

period from 1990 to 1994 is used on this figure, because it is the only time period in which a comparison between these wells can be made. By the end of 1994, only observation well 139-049-10CCC remained in place, and even that well is a redone, redesigned site near the newly-built, but now defunct, Builder's Square site. The hydrograph shows the north flow of ground water in the WFS aquifer, up to the very northern tip of the aquifer. At the north tip, however, a detailed look at the elevation relationship of water levels of observation wells 9ADD and 10CCC shows a periodic annual reversal. In the winters 10CCC shows water levels with elevations higher than the water-level elevations observed in 9ADD. In the summers, however, 10CCC shows water levels with lower elevations than the water levels of 9ADD.

As discussed in the ground-water flow section of the Nodak aquifer discussion earlier in this report, it is during the summertime (in this 1990-94 time period), when the water levels in the WFS aquifer were lowered. The WFS water-level elevations were lowered by the increased pumping resulting from the heavier summer water demand, and a reversal resulted whereby the previous flow from the WFS aquifer to the Nodak aquifer became a flow that went from the Nodak aquifer to the WFS aquifer. Presently, the water levels in the WFS aquifer are almost always lower than the water levels in the Nodak aquifer (see figure 34). Also observed in figure 34 is the fact that the water levels in the WFN and the Fargo aquifers are currently the lowest of all the systems in the area. Because the Nodak aquifer lies between the WFS and the Fargo aquifer (see figure 3), there is very likely no direct interaction between the Fargo aquifer and the WFS aquifer. Thus it is likely that any outflow from the WFS aquifer, other than to the production wells located in the WFS aquifer, flows into the WFN aquifer.

The significant in-flows to the WFS aquifer are the leakage from the Ponderosa aquifer in the vicinity of an area about 2 1/2 miles north of Horace, and the Horace aquifer in the vicinity of an area about 2 miles northwest of Hickson. Since the 1990s the Nodak aquifer may be contributing some water to the WFS aquifer especially during the summers. There may also be additional in-flow from some nearby, small, sub aquifers. Another possible source of some water to the WFS aquifer would be leakage from the aquitards that surround the WFS aquifer.

The significant ground-water out-flows from the West Fargo South aquifer are the approximately 500 million gallons per year (Mg/y) being pumped from the aquifer, and the leakage into the West Fargo North aquifer. The volume leaking into the WFN aquifer is difficult to determine. However, it can be said that the leakage in the 1990s is less than it was before the 1983 start-up of the city of West Fargo well field. Prior to the well field start-up, the hydraulic gradient from the WFS to the WFN aquifers was significantly larger than it was after the start-up.

ESTIMATED WEST FARGO AQUIFER SYSTEM WATER BUDGET

WATER BUDGET CAVEAT

The previous aquifer discussions (about the size, properties, water levels, chemistry, and ground-water flow of those aquifers) communicate some of the complexities of the West Fargo aquifer system. Any effort to assimilate the large volume of available data into this complexity in order to quantify the long-term availability of water from the WFS aquifer system is fraught with problems. This means that any estimates of the volume of water, and the potential yields from this system must be viewed as being very general.

The degree of accuracy of estimates that can be made of the quantitative aspects of the water budget, however, is better than the degree of accuracy of estimating potential water quality impacts on the system as a result of current or increased rates of water use. While this report characterizes the water quality of the different aquifer units, little is known as to why those differences in water characteristics occur. Additionally, little is known as to what changes in future water quality characteristics might occur at any given site, as a result of water use at lesser rates, current rates, or increased rates of withdrawal. Having water in storage is different than having good quality water in storage. Naturally occurring water quality changes in the future could change the desirability of the available ground water before declining water levels change the actual availability of that ground water. This is an important consideration in future water management.

INITIAL WATER IN STORAGE

The sum of the estimates of aquifer volumes for the nine discussed aquifers is about 225 billion cubic feet. All of the aquifers discussed are glacial aquifers, and are composed predominantly of sands and gravels, with minor amounts of clays and silts. The grains of the material in the aquifer are unconsolidated. There are spaces between these grains of unconsolidated material, and water can fill these spaces. When the water level is above the top of the aquifer all of the space between these grains is filled with water.

The percentage of space in unconsolidated material varies, depending on grain size, the degree of sorting of material, the degree of compaction, the shape of the grains, and other factors. However, the percent of pore space relative to the total volume for unconsolidated sand and gravel aquifers generally ranges between 35 to 45 percent.

Not all of the water in the pores of the aquifer material can be removed from storage. Drainage of a saturated porous material will yield only a portion of the water stored in the pore spaces. A certain amount of water will be retained in the pores adjacent to the sand and gravel particles. The percentage of pore-space water that can be derived from a saturated glacial aquifer varies, depending on several of the previously mentioned factors. The term for this aquifer property (the amount of water that can be drained from the porous medium) is specific yield. Specific yield values for the types of aquifer materials found in the WFAS generally range from 20 to 35 percent. For the purpose of making a volumetric estimate of the amount of retrievable water in storage in the West Fargo Aquifer System, the aquifer-wide specific yield will be estimated at 25 percent.

The estimate of 25 percent for the specific yield is based on the water level occurring at or below the top of the aquifer. When the water level is below the top of the aquifer, the aquifer is in an unconfined condition. In the previous aquifer discussions, the evidence is clear that each of the aquifers in the WFAS had water levels above the top of the aquifer. While only some of the aquifers have direct evidence that shows that they once had water levels above land surface, it is most probable that all of the aquifers had water levels that were (at one time) at, or above, land surface. Any estimate of the volume of water that results from the water level being above the top of the aquifer would have to be made with an additional assumption different than the assumption of 25 percent of the aquifer volume being specific yield.

When there is a confining layer overlying the top of an aquifer, and the water level is above the top of the aquifer, the pore space is already full. There is no more pore space in the aquifer that the water can fill. The aquifer is surrounded by confining material, and with the water level above the top of the aquifer, pressure is exerted within the aquifer. The higher that the water level is above the top of the aquifer, the higher the pressure that results.

An aquifer has a slight elasticity (a property that allows for expansion and contraction), and water has a slight compressibility. As a result, the pressure in the aquifer results in an expansion of the aquifer skeleton and a compression of the water such that there is a small amount of additional water in storage that results. It is as if the aquifer is an extremely stiff balloon. Different aquifers have different degrees of elasticity, and there is a term that incorporates the elasticity of an aquifer. The term is specific storage.

Specific storage of an aquifer is defined as "....the volume of water which a unit volume of the aquifer releases from storage because of expansion of water and compression of the aquifer under a unit decline in the average head within the unit volume of the aquifer" (Walton, 1970). This term represents a ratio of the volume of water that is withdrawn for each unit decline in height of the water level (i.e. one foot) for that given unit volume (i.e. cubic foot). When the aquifer is highly pressurized (water levels are a large distance above the top of the aquifer) the specific storage can be quite small. An example of a small value would be a specific storage of 0.000005. When the water level is slightly above the top of the aquifer, the specific storage of the aquifer could likely be a value of about 0.005. As long as the water level is above the top of the aquifer, the aquifer is in a confined condition.

An example of this difference in the value of specific storage is demonstrated by the difference in the values for the storage coefficient resulting from the two aquifer tests that were performed on the WFN aquifer. These tests were discussed in the section on the WFN aquifer size and location. The storage coefficient values derived from those aquifer tests can be divided by the aquifer thickness to derive the value for specific storage. The thickness of the aquifer in the location of the two aquifer tests is fairly similar (91 feet for 139-049-06DCD1 compared to 116 feet for 139-049-09BBA). This is about a 25 percent difference in thickness. If the specific storage were fairly similar, the storage coefficient should vary by about 25 percent. However, this is not the case.

For the 1963 aquifer test (139-049-06DCD1) when the water levels were higher, the aquifer storage coefficient was estimated to be 0.0007. For the 1972 aquifer test (139-049-09BBA) where the water levels were lower, the aquifer storage coefficient was estimated to be 0.07. This difference is accentuated by a second factor, namely the location of the top of the aquifer. The 1963 test utilized a production well in which the top of the aquifer was about 130 feet below land surface and about 30 feet below the water level at the time of the test. The 1972 test utilized a production well in which the top of the aquifer was about 100 feet below land surface and about 10 feet above the water level at the time of that test. These two tests were located in two different parts of the aquifer, and the properties and boundaries of the aquifer may have differed slightly. However, most of this difference in specific storage values probably is due to the difference in the relationship between the elevation of the top of the aquifer and the elevation of the water level.

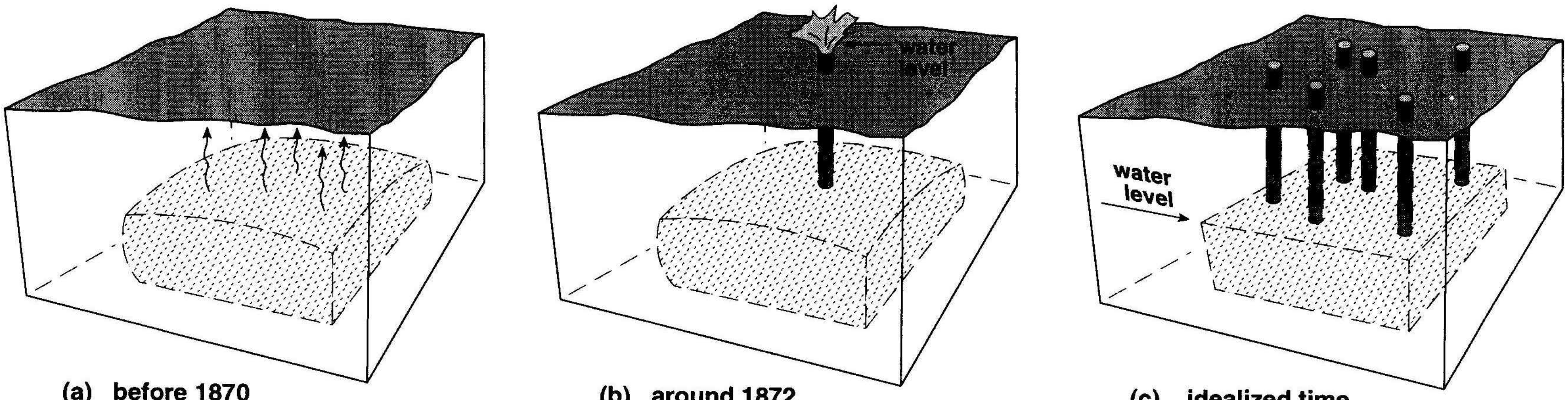
The elevation of the top of the WFAS is highly irregular and is much less predictable than the elevation of the water level. While the water-level elevation can be fairly well predicted between known data points in a connected aquifer, the elevation of the top of the aquifer cannot be as easily predicted. This makes it difficult to predict the storage coefficient at a given time for a given water level. For aquifer areas where the water level is above the top of the aquifer the storage coefficient is small (about 0.0005), and for areas where the water level is below the top of the aquifer the specific yield is relatively larger (0.25). To determine how much water is released from storage at a given time it is necessary to determine how much of the water is being withdrawn from elastic storage, and how much is being withdrawn from drainable storage. These values represent estimates of the range of values for storage coefficient and specific yield in glacial unconsolidated sand and gravel aquifers. With water levels well above the top of the aquifer the value is small. As the water level falls beneath the irregular top of the aquifer in some parts of the area of interest and not in other parts of the aquifer, the storage coefficient for the area of interest will become larger and larger.

For the purpose of an estimate of the initial volume of storage in the WFAS before development, a value of 0.0005 will be chosen for the storage coefficient, at the time water levels were at, or slightly above, land surface. Using a value of 0.0005 for the storage coefficient for an aquifer that has a volume of about 225 billion cubic feet results in a water volume of about 0.1 billion cubic feet. This amounts to about 0.8 billion gallons. The drainable water stored in the aquifer pore spaces when the water level is at the top of the aquifer is 0.25 times 225 billion cubic feet, or about 56.25 billion cubic feet. This amounts to about 421 billion gallons. The water in elastic storage when water levels are above the top of the aquifer (0.8 billion gallons) is quite small when compared to the drainable water in storage in the pore spaces of the aquifer (421 billion gallons).

Figure 80 is a schematic diagram of the WFAS showing the conditions: a) before 1870; b) soon after 1870; and c) an idealization of the time at which the aquifer is in a condition where the water level is right at the top of the aquifer. Condition "c" never occurred, and isn't possible given the complexity of the WFAS. Condition "c" is used to compare the storage volume of an aquifer in a confined condition with an aquifer in an unconfined condition.

Figure 80a shows a schematic diagram of the WFAS with no wells tapping the water supply in the aquifer. Discharge from the confined aquifer occurs by upward leakage into the overlying till and clay. The overlying till and clay units are characterized by a small hydraulic conductivity. As a result of this small hydraulic conductivity, upward leakage constitutes a small volume of discharge. Eventually the small volume of discharge reaches the land surface, and is lost to evapotranspiration.

Figure 80b shows that same aquifer soon after the first wells penetrated the top of the aquifer and released the water held under pressure by the surrounding confining materials. All pressure has been released in figure 80c, and the release of that pressure (the lowering of the water level from above land surface to the top of the aquifer) would hypothetically result from removing about 0.8 billion gallons of water.



(a) before 1870

(b) around 1872

(c) idealized time when water level is at top of aquifer.

EXPLANATION:

Figure (a) shows a schematic diagram of the WFAS before any wells were installed.

Figure (b) shows the same aquifer shortly after the first few wells were installed, and began releasing the water pressure.

Figure (c) shows when all pressure has been released, and the water level lowered to the top of the aquifer.

VOLUME OF WATER (in billion gallons)	for (a) and (b)	for (c)
unconfined aquifer storage	420.75	420.75
confined aquifer storage	0.84	none
total storage	421.59	420.75

FIGURE 80. Schematic diagram of the WFAS at three different times in history, demonstrating water storage concepts.

CURRENT WATER IN STORAGE

Estimating the volume of water in storage in the WFAS before the water utilization of the 1870s began is relatively easy compared to attempting to estimate the current water in storage. If one were to take the average current water level for the WFAS (about 80 feet below land surface) and the average depth to the top of the WFAS (about 140 feet), it would be a simpler calculation to estimate the volume. However, the water level has declined to below the top of the aquifer in some places, and is more than 100 feet above the top of the aquifer in other places.

As discussed in the previous section, the volume of water taken out of storage is much greater per foot of water-level decline in those areas where the water level is below the top of the aquifer, than it is in those areas where the water level is still above the top of the aquifer. The irregular shape of the tops of the aquifers as seen in the aquifer geologic sections (see figures 8, 9, 24, 28, 36, 41, 48, 54, 55, 66, and 69) makes it practically impossible to determine where the WFAS occurs under unconfined conditions. Figure 81 depicts an estimate of those areas where the WFAS is probably under unconfined conditions. These areas comprise about 20 percent of the overall area of the WFAS. In most of these areas the water level is just a few feet below the top of the aquifer. However, in parts of the WFN aquifer the 1998 water levels are nearly 40 feet below the top of the aquifer. Those shaded areas in figure 81 that do not lie in the WFN aquifer generally have water levels that are about 1 to 10 feet below the top of the aquifer with an average of about 5 feet. The shaded areas in the WFN aquifer are estimated to have water levels that average about 20 feet below the top of the aquifer. Using these estimates about 3 percent of the WFAS volume is unconfined. This results in an aquifer volume of about 219 billion cubic feet of aquifer that is saturated.

It would seem that with these estimates the volume of water currently in storage could then be estimated. However, the complicated nature of the storage coefficient and specific yield has a dominant influence on the difficulty of this calculation. The nature of the storage coefficient is that as water levels drop below the top of the aquifer, the storage coefficient value becomes larger. Choosing an average value for a large, static, full aquifer system is difficult. Choosing an average value for a large complicated aquifer system with a dynamic, changing water level is extremely difficult.

The selection of a value for specific yield is no easier. The value of 0.25 is based upon a very long time period (many years) of drainage, whereby the pore spaces are almost entirely drained. Currently drainage is occurring in the upper portions of some parts of the WFAS. However, the process is only partially complete, and the upper parts of the WFAS that are draining still have some water in the pore spaces that have yet to

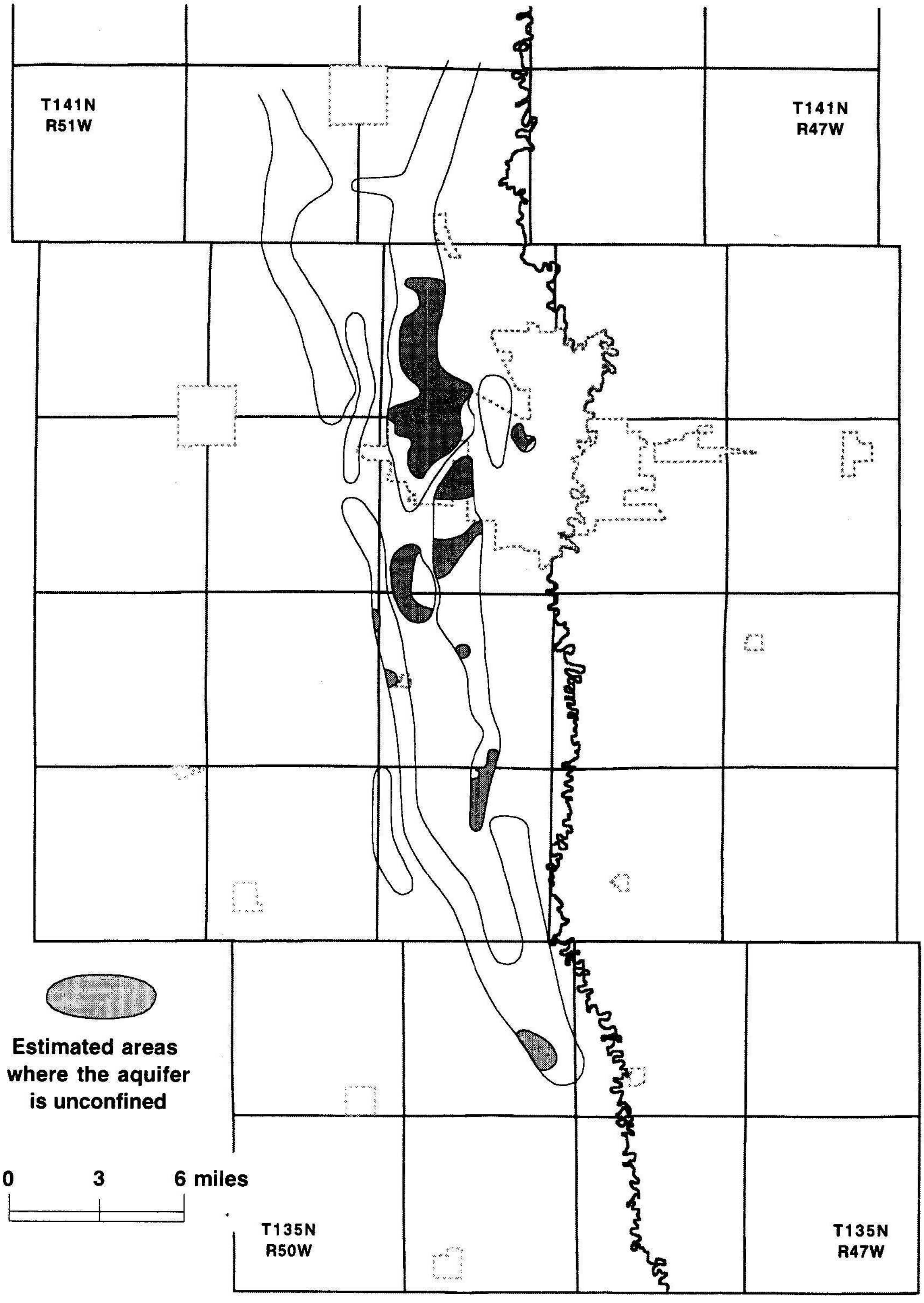


FIGURE 81. Estimate of areas of the West Fargo Aquifer System where the aquifers are unconfined in 1998.

drain out. Exactly, or even approximately, what percent of pore space within the top of the unconfined portions of the WFAS is yet filled with water is, again, extremely difficult to estimate.

For the purposes of a very general estimate, the assumption will be that half of the water in elastic storage has been removed in the last 125 years. A second assumption is that half of the water represented by drainable storage in the aquifer has been removed in the last 125 years.

The estimate of the water currently in storage is then comprised of three parts. The water stored in the saturated part of the aquifer system. This is the water that is stored in 219 billion cubic feet of aquifer with a specific yield of 0.25. This would be 410 billion gallons of water. The second part would be the unconfined portion of WFAS which is estimated to have one-half of the 10 billion gallons of water still draining into the saturated portion of the aquifer. This would be about 5 billion gallons of water. The third part is the water that is represented by the specific storage (the pressurization of the aquifer by the water levels that are above the top of the aquifer), about half of which (estimated) still remains from before the 1870s. This would be 0.4 billion gallons of water. All totaled, this would be about 415 billion gallons that is estimated to be in storage in 1996.

TOTAL WATER USE (1870-1995)

Estimating total water use for the West Fargo Aquifer System is difficult because of the system complexity and lack of water use records. However, with certain assumptions an effort can be made to fill in the gaps in the water use records. This effort has value, because the estimate of the volume of water withdrawn can then be compared to the change in volume of water stored in the WFAS in 1870, and in 1995.

The first assumption is that no meaningful use was made of any part of the WFAS prior to 1870. The railroad reached Fargo in 1872, and conjecture about where the railroad would cross the Red River brought some of the first settlers into the area in 1871. Records show that by 1872 wells were drilled into the WFAS.

The second assumption is that growth in this area was rapid in the 1870s and 1880s. Railroad and steamboat traffic brought much commerce and many people to the area in the 1870s, and this was also the time of the development of the bonanza farms in this area. By 1890 Fargo had a rolling mill, foundry, stockyards, and carriage shops (Robinson, 1966). The Fargo community will be assumed to have used ground water until about 1890. Non-Fargo eastern Cass County inhabitants (those overlying the WFAS) are assumed to have used ground water from early times to recent times when water use data collection began.

Estimates of rural populations that overlie the WFAS are made from old maps showing farmsteads and past farmsteads. These population estimates are compared to census figures for Cass County minus Fargo, and a ratio is used to estimate the percent of rural Cass County population that overlies the WFAS. Daily per capita water use rates are estimated starting at 20 gallons a day in 1870, and ending at 100 gallons per day in 1965. Estimates of water use are blended into actual water use records, as the actual water use records become available for the various entities in the area that overlie the WFAS. These yearly estimates are then combined into 10-year increments (except for the 1990-95 time period) and shown in TABLE 1.

TABLE 1. ESTIMATE OF WATER USE BY DECADE IN THE WEST FARGO AQUIFER SYSTEM

TIME SPAN	ESTIMATE OF GROUND-WATER WITHDRAWN FROM THE WEST FARGO AQUIFER SYSTEM (million gallons)	ESTIMATE OF CUMULATIVE GROUND-WATER WITHDRAWN FROM THE WEST FARGO AQUIFER SYSTEM (million gallons)
1870-1879	22	22
1880-1889	95	117
1890-1899	205	322
1900-1909	283	605
1910-1919	295	900
1920-1929	367	1268
1930-1939	647	1914
1940-1949	2343	4257
1950-1959	3627	7884
1960-1969	5005	12889
1970-1979	6465	19354
1980-1989	8126	27480
1990-1995	5521	33001
TOTAL	33001	

This estimate of 33 billion gallons looks large, however a tabulation of Table 5I in Volume C of the accompanying data report shows about 24 billion gallons. That data report lists only documented water use figures.

The main point of this total WFAS water use estimate is to show that more water has been withdrawn from the aquifer system than appears to be missing. The estimate of the water in storage in 1870 in the WFAS was about 422 billion gallons. The estimate of the water in storage in 1995 in the WFAS was about 415 billion gallons. This estimated difference is only about 7 billion gallons. The estimated 33 billion gallons of water that may have been removed from the aquifer system may be too large of an estimate. However, whatever the actual use is, the actual use is clearly more than the 7 billion gallons that have been estimated to have been removed from the aquifer. In essence an estimated 20-25 percent (7 billion gallons) of the water used to date has come from the WFAS, and the remainder (26 billion gallons) from other sources.

Either the water being withdrawn is being replaced (recharge) or the water is being derived from places other than the aquifer system. Currently there is no evidence that recharge is occurring to any significant degree. There is, however, evidence that water is being drained from places other than the aquifers that comprise the WFAS.

WATER DRAINAGE FROM LOW-PERMEABILITY MATERIALS

As stated earlier, all of the aquifers in the WFAS are surrounded by aquitards, usually in the form of lake clay, till, or bedrock material. Two piezometer nests (locations with multiple piezometers) have been installed into these units. The first location is in the south end of the WFN aquifer at site 140-049-32BBB. The location of this site is shown in figure 6, and geologic sections are shown in figures 8 and 9. The second location is in the north end of the WFS aquifer at site 139-049-21AAA and very near site 139-049-22BBB. The location of this site is shown in figure 68, and a geologic section is shown in figure 69.

Figure 82 shows a two-dimensional view of the WFN aquifer at 140-049-32BBB. This view shows where the WFN aquifer bottom and top are located at elevations of about 675 feet to about 725, respectively. This well (140-049-32BBB) was installed in 1963, and water levels have been measured since that time. In 1983 two small piezometer tubes were installed into the till material above the WFN aquifer. Figure 82 shows the openings of these two piezometers (140-049-32BBB2 and 140-049-32BBB3) were installed at elevations of about 770 feet and 800 feet. Superimposed in the same diagram are hydrographs of these two piezometers, and also a hydrograph of 140-049-32BBB.

The water level of 140-049-32BBB3 had three measurements taken in 1983 before the water level went below the bottom of the opening. These measurements are not indicative of the water level of the clay in the zone of the opening at this site. The

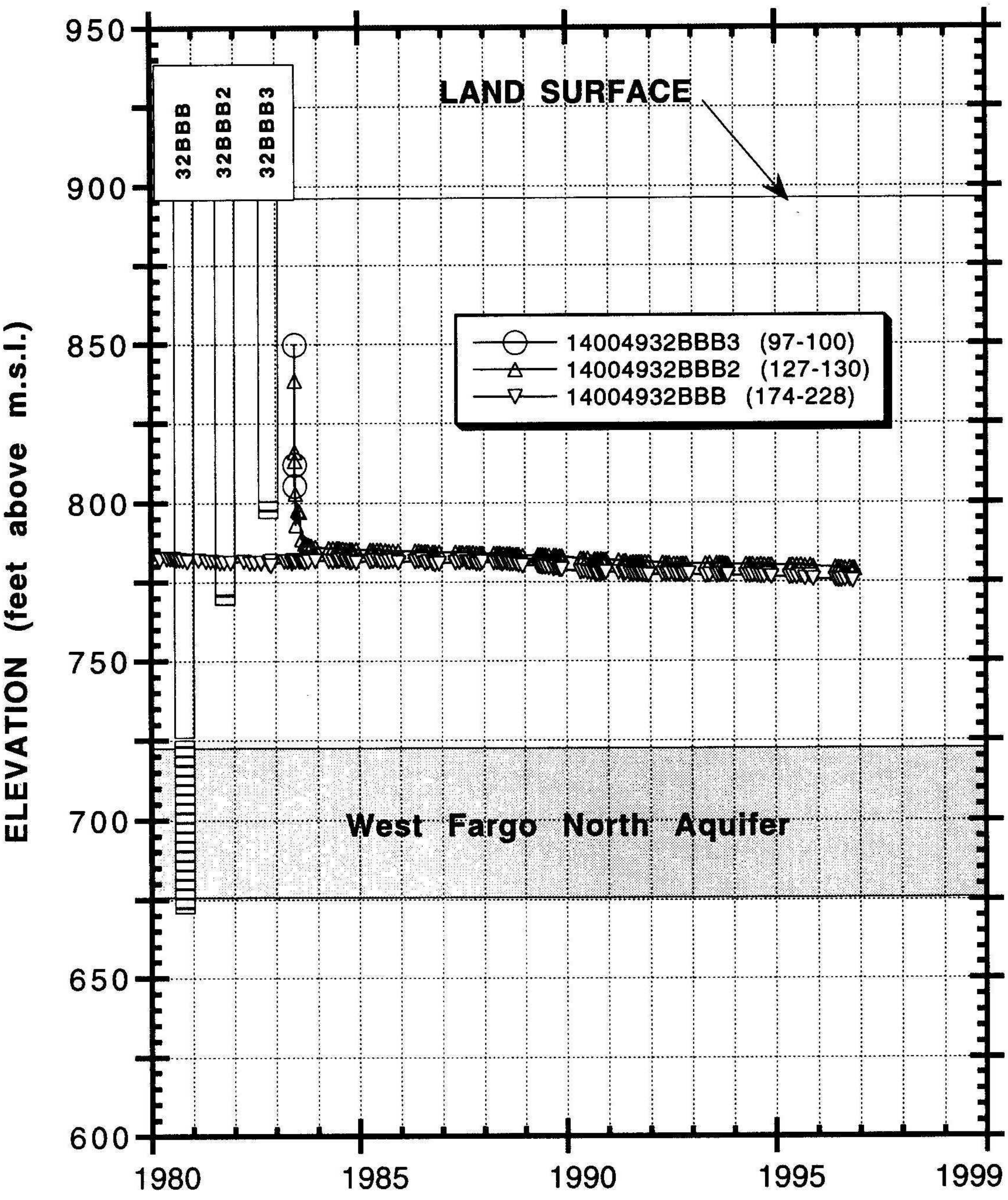


FIGURE 82. Combination hydrograph and geologic section showing well screen locations and water-level variations through time for piezometers at site 140-049-32BBB.

only thing known for sure is that the water level at the location of 32BBB3 is below the elevation of the opening of this piezometer.

The water level in 140-049-32BBB2, while being close to the bottom of the piezometer, has been measured since 1983. In this time period the close relationship of the hydrographs of both 32BBB2 and 32BBB indicates that they are likely hydraulically related. The water levels in 32BBB2 are generally about 3 to 4 feet higher than the water levels in 32BBB. Water is likely draining out of the overlying till, and into the WFN aquifer. Over the 13 years of record (1983-95) in which the water levels in both 32BBB and 32BBB2 have been measured the pattern of the water levels have been fairly similar.

At the second nested-piezometer location (139-049-21AAA) there were six openings at six different elevations. There were three openings that were located higher than the screened interval of 139-049-22BBB, and there were three openings that were located lower than the screened interval of 22BBB. Figure 83 shows a two-dimensional view of the WFS aquifer and a hydrograph of 22BBB along with hydrographs of the three openings that are placed higher than the screen for 22BBB. Figure 84 also shows a two-dimensional view of the WFS aquifer and a hydrograph of 22BBB, along with hydrographs of piezometers with the three openings that were placed lower than the screen for 22BBB at site 21AAA. Road construction for the development of the I-94 and 45th St. interchange resulted in the loss of 139-049-22BBB and 139-049-21AAA6 in 1991. However, by that time several things became clear.

First, the hydrograph in figure 83 shows that the water level for the observation well with the shallowest screen (21AAA6) did not display the declining pattern displayed in the other wells. This well was screened in a shallow 18-foot sand that appears relatively unconnected to any of the deeper wells. This type of shallow sand interval was rare in the lithologic logs of the study area that were gathered. There are few other such sand intervals overlying the WFAS, and this is the only such site where water levels have been steadily monitored for several years.

Over the seven full years in which regular water-level measurements of well 21AAA6 were made (1984-1990), there was a rising water level in five of the seven spring seasons. In six of the seven years a water-level decline was observed for the summer/fall season. In two of the seven years there was a slight increase in the elevation of the water level in the fall season. These water-level patterns suggest a connection to the near surface, whereby the water-level pattern is dominated by local climatic conditions. This pattern also suggests that the shallow sand layer is not well connected to the WFAS. It is unfortunate that this observation well was not in place during the wet cycle that began in 1993.

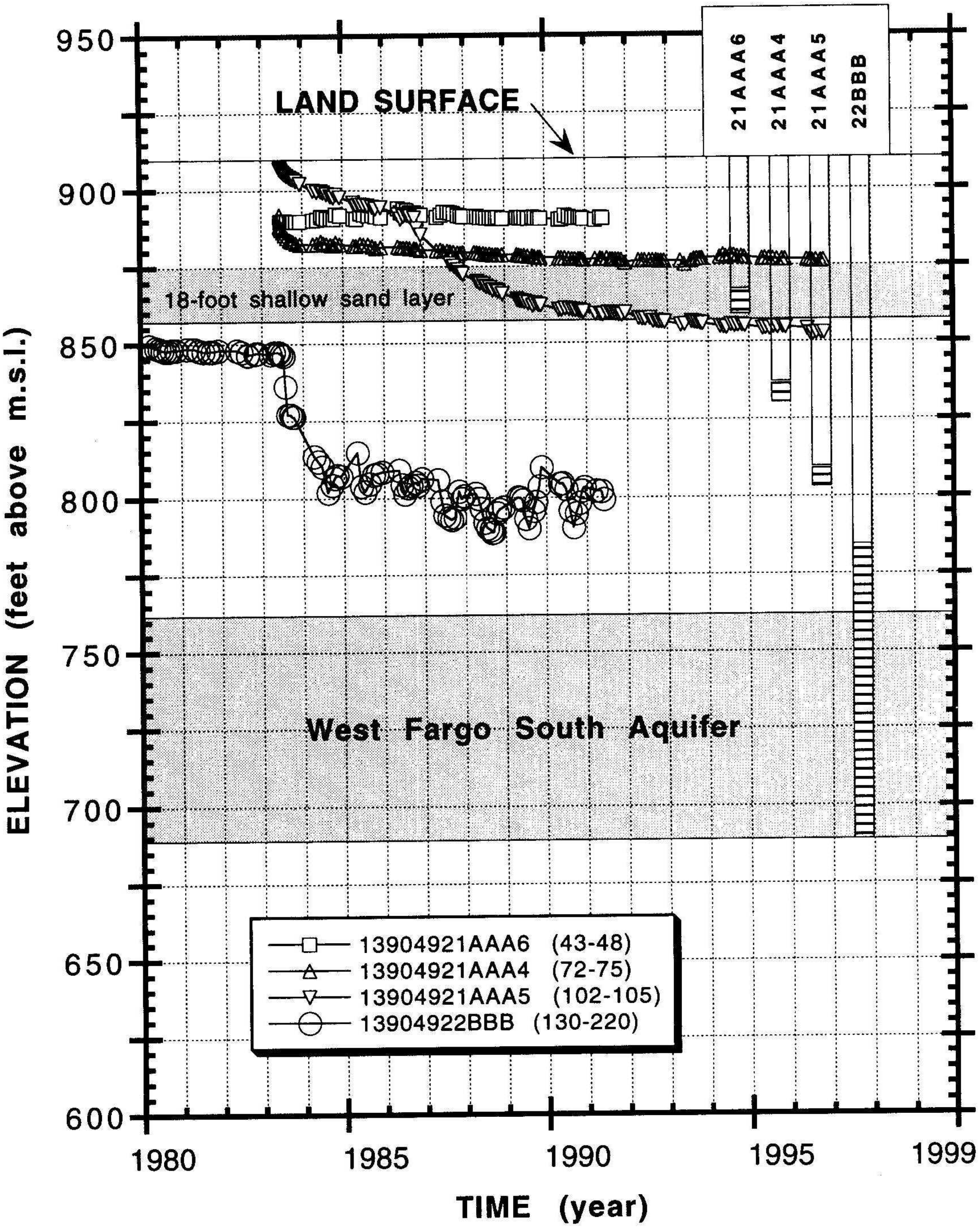


FIGURE 83. Combination hydrograph and geologic section showing well screen locations and water-level variations through time for piezometers above observation well 139-049-22BBB.

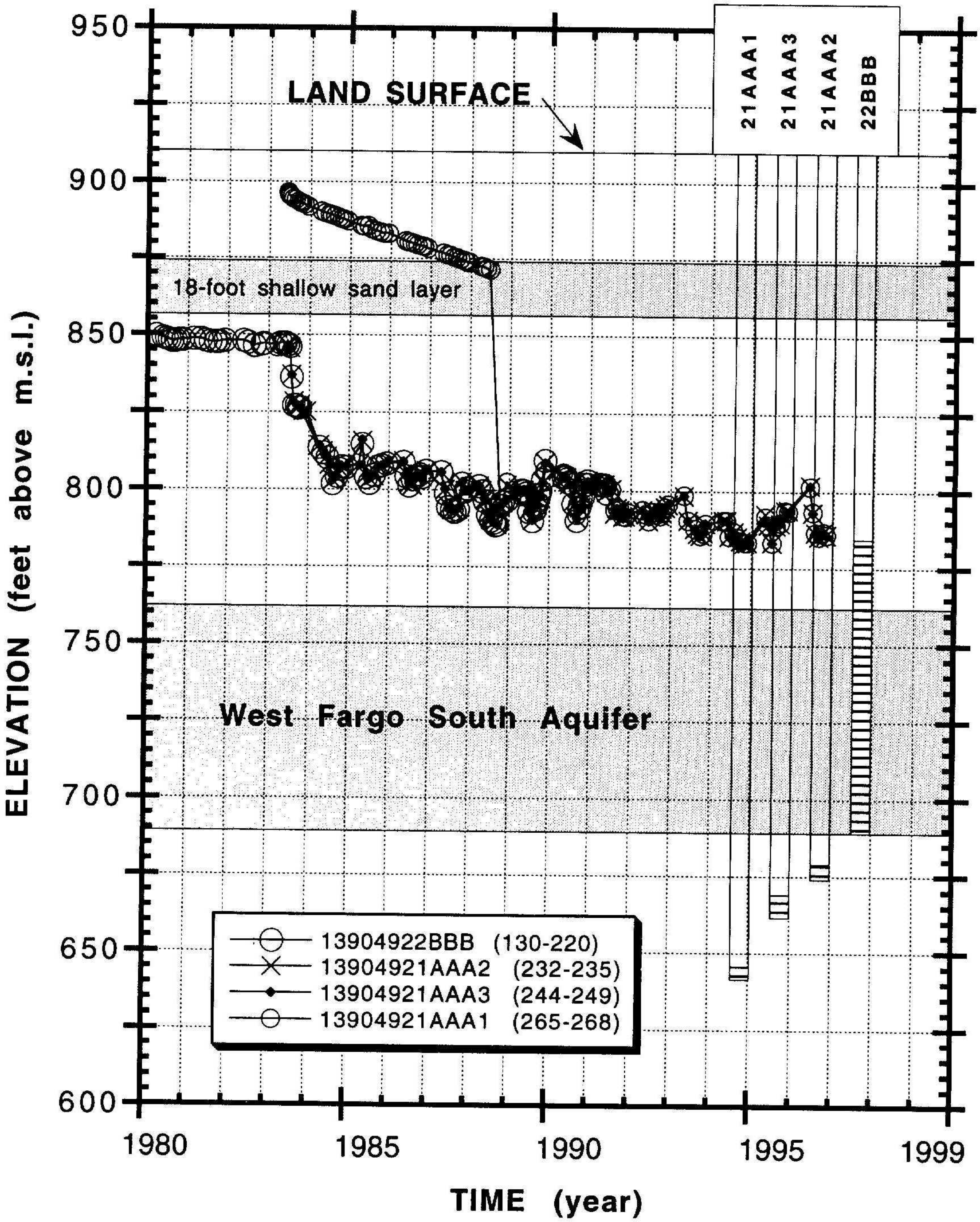


FIGURE 84. Combination hydrograph and geologic section showing well screen locations and water-level variations through time for piezometers below observation well 139-049-22BBB.

The second item of interest is that the three observation wells that had openings in the bedrock below the WFS aquifer, all had water-level patterns that were similar to the pattern of the water levels in 22BBB as seen in figure 84. The deepest piezometer (21AAA1) showed a steadily declining water-level pattern from 1983 until the summer of 1988. Sometime between June 24, 1988 and July 22, 1988, a blockage apparently became dislodged somewhere in the piezometer/opening interface. The water level then quickly dropped to where the water level was the same as it was for the other piezometers that were below the screen of 22BBB. It is likely that the water-level record of 21AAA1 is valid only after June 24, 1988.

There are two main possible reasons why the water levels in the four piezometers shown in figure 84 have been almost identical since 1988. The first possibility is that the low-permeability materials (in which the three lower piezometers are located) are in good connection with the WFS aquifer. This could be through fractures in the lower-lying material, or through laterally connected fine silt and sand layers that are inter-bedded with the clay layers. The second possibility is that the construction of the piezometers was not effective in connecting the screens to only a few feet of the bedrock material. While it is possible that the screens were not effectively sealed, it is also important to note that the screens of the higher piezometers (shown in figure 83) used similar construction procedures. The higher piezometers did show water levels that were different than the water levels of observation well 22BBB.

Although the amount of water-level data for the low-permeability materials surrounding the WFAS is limited, the data indicate a significant water-level decline in some of those materials. The assumption is that the lake clays, tills, and bedrock clays were fully saturated prior to the 1870s. The partial dewatering of these aquitards is a very significant possible source of water for the WFAS. The degree to which these materials are dewatered, and the areal extent of these dewatered, aquitards is poorly known. Quantification of the volume removed from these materials since the 1870s is not feasible with the limited available data. However, the range of possible volumetric values for the water drained from the aquitards surrounding the WFAS easily encompasses 26 billion gallons, and 26 billion gallons is the estimate of the water that appears to have come from somewhere other than the WFAS.

An estimate of the water stored in the aquitards can be made by estimating the volume of material overlying the WFAS and multiplying that estimate by the percentage of that volume that is water. It should be noted that this estimate would not include any water stored in materials that lie below or laterally adjacent to the WFAS. Using the sum of the areas of the aquifers of the WFAS (104.2 square miles), and the average depth to the top of the WFAS (140 feet), the volume of this material is approximately 41 billion cubic feet. Assuming that about 1/3 of this volume is comprised of water, the estimate would be that this material contains about 1 trillion gallons of water. Draining only 2 1/2 percent of this volume of water would result in 26 billion gallons of water. This estimate is within a realistic range, and especially so when considering that only the directly overlying material is used in this estimate.

There is a very significant concern resulting from the fact that 75 to 80 percent of the water withdrawn from the WFAS may be coming from the aquitards surrounding the WFAS. The drainage of water from the aquitards to the WFAS is predominantly a one-time event. The water-level decline trends observed in the few existing wells completed in the aquitards show that these materials are not being replenished. If this were so, the result would be that once most of the water has been removed from these materials, there would be less movement of water from the surrounding materials into the WFAS. This will eventually result in most of the water that is withdrawn from the WFAS coming directly from storage in the WFAS. This, in turn, means that the rate of water-level decline would increase. Quantifying the extent of the dewatering process in the materials surrounding the WFAS will take a significant effort. This is one of the dominant factors (if not the most dominant factor) in the attempt to predict future water levels as a result of current or future levels of water use. Any consideration of the WFAS must encompass the aquitards that surround the WFAS as it has been discussed to this point in this report. The low-permeability material that surrounds the West Fargo Aquifer System is, in fact, an integral part of the West Fargo Aquifer System.

Significant additional work needs to be done in the determination of the relationship between the aquitards surrounding the WFAS and the aquifers of the WFAS. Nests of vertically distributed piezometers need to be installed in carefully selected sites. Analysis of the data collected from these nests would aid in determining the nature of the flow system between the aquitards and the WFAS. Determinations could be made of the amount of water flowing from the aquitards to the aquifers, and if there is any significant recharge into the aquitard materials.

MANAGEMENT CONSIDERATIONS

RESOURCE SIZE COMPARED TO USE

The aquifers that are part of the WFAS have an estimated 415 billion gallons of water in storage. Currently about one billion gallons of water are being withdrawn annually from the aquifers of the WFAS. If the aquifers were like a bank account, the estimate would be that the supply would last about 415 years. The aquifers are not like a bank account, and the WFAS water supply will not last 415 years. There are four main factors that need to be discussed to put into perspective the size of the WFAS in comparison to water use. One of the factors discussed in an earlier section dealt with the "one-time" drainage of water into the WFAS from the surrounding aquitards. The ramification of this factor is that water levels may decline at a more rapid rate in the future, than they have to date.

A second factor impacting the rate of water-level decline is the conversion from confined to unconfined conditions in the aquifers. The ramification of this factor is that water levels may decline at a lesser rate in the future. The hydrographs presented in the aquifer discussions have shown a lesser rate of water-level decline in more recent years. The only exceptions have been in those cases where there has been an increase in water use in the vicinity of the observation wells showing an increase in the rate of water-level decline.

A third factor that diminishes the functional size of the WFAS is the consideration of the quality of the water in different parts of the aquifer. The city of West Fargo has abandoned well #4 and has no intention of replacing it with a new well in that area because of poor water quality. The quality of the water derived from well #4 is better than the quality of water available from many parts of the WFAS. Additional limitations could result from the utilization of wells with acceptable water quality that evolve through time into wells that yield poorer quality water.

The fourth factor is the efficiency of the wells that capture water from the aquifer. This factor will be discussed in detail in the following section. Three of these four factors diminish the timetable for the viability of the WFAS. The net effect of these factors is that extrapolation of past water use and observed water-level declines will not provide a reliable prediction of future water levels and water quality. The only realistic estimate that can be made with the available data is to look at the production wells currently in place, and to estimate the time remaining before pumping water levels drop below the tops of the well screens.

EFFICIENCY OF WELLS AND WELL FIELDS

The water supplies being produced from the WFAS are being provided by hundreds of wells. The pumping rate of these wells ranges from a few gallons per minute (gpm) up to about 800 gpm. In those instances where larger amounts of water are needed, two or more wells are used. Multiple wells are needed for two reasons. In some instances small communities or certain industries will install a second well, so that they have a backup. Even though one well is capable of providing the total water supply needed, the second well is installed so that in the case of a failure there is always a functioning well that can produce the necessary water supply.

A second reason for multiple wells is that the water supply needed is large enough that a single well cannot produce the required water. This is generally true because water cannot come into the well screen from the aquifer fast enough. A measure of the ease with which water moves from the aquifer through the well screen (the aquifer/well-screen interaction) is called specific capacity. Specific capacity is the yield of the well per unit of drawdown, expressed as gallons per minute per foot of drawdown (gpm/ft). The greater rate at which a well is pumped, the greater the drawdown. If the rate of pumping is high enough, the drawdown reaches the top of the well screen. More water cannot be pumped without the water level dropping into the screened interval. This can cause well damage and a deterioration of well efficiency. So there is a limit on the rate at which an individual well can be pumped, and if more water is needed, additional well(s) must be constructed.

Individual water supplies

Most of the wells that are completed in the WFAS serve single residences or farms, and are pumped at less than 25 gallons per minute. These water supplies do not require water permits because less than 12.5 acre-feet are used annually. Only rarely will such wells be unable to capture water in a situation of declining water levels. They may need well maintenance, the pump may need to be set deeper, or in a worst case, the well may need to be deeper. However, only in unusual geologic settings will a properly constructed well pumped at less than 25 gallons per minute be unable to capture the necessary water.

Small water systems

There are a few permitted wells that service small businesses, small communities, or small housing developments. These wells may produce up to 10,000,000 gallons per year at pumping rates of up to 100 gpm, however they generally are not characterized by large drawdowns. Only rarely will such wells be unable to capture water in a situation of declining water levels. They also may need well maintenance, the pump may need to be set deeper, or in a worst case, the well may need to be deeper, however, a properly constructed well will experience an inability to capture water only in an unusual geologic setting.

Intermediate-sized water systems

There are also a few wells that produce between 10,000,000 and 40,000,000 gallons per year for certain industries or municipalities. These wells are generally pumped at rates up to 300 gpm. Some of these wells may be located in areas where declining water levels could result in much lower pumping rates. Most of the wells in the area have specific capacities that range between 4 to 15 gpm/ft. A production well with a specific capacity of 10 gpm per foot of drawdown would need 30 feet of available drawdown above the top of the screen to produce 300 gpm. In some portions of the aquifer where the depth of the bottom of the aquifer is fairly shallow (less than 200 feet), the lowering water level may be a concern. Currently, communities like Horace and Harwood, as well as businesses like the stockyards, have well screens deep enough to avoid this problem for many years to come. The community of Oxbow, however, needs to be aware that its wells are shallow and that its well field will be one of the first to experience water supply problems due to declining water levels in the area. While a problem is not imminent, it does bear watching.

The community of Oxbow utilizes two wells to provide its water supply. The screened intervals for wells #1 and #2 are 130 to 138, and 128 to 148 feet below land surface, respectively. The static water level for well #1 was 22 feet below land surface in 1975 and 58 feet below land surface for well #2 in 1989. Based on the rate of decline of observation wells in the area from 1989 to 1999, an estimate of the depth to water at the well sites for 1999 would be about 75 feet below land surface. The specific capacities for wells #1 & #2 are 7 gpm/ft and 13 gpm/ft, respectively. The wells pump at about 60 gpm. Well #1 is a 6-inch well, and well #2 is a 5-inch well. With the lower specific capacity well #1 is the more vulnerable of the two wells.

Currently it is estimated that the pumping water level for well #1 is about 85 feet below land surface. This is about 55 feet above the top of the well screen. Because the water levels in this area are declining at rates between 1.0 to 2.0 feet per year, it is assumed that water levels in this well field may be declining at the same rate. At a rate of decline of 2 feet per year for the water-level surface, it is estimated that the water-level surface would be at the top of the well screen in about 25 to 30 years. If the well efficiency deteriorates, this time span will be shorter. If the rate of water-level decline in the area becomes less, the time span will be longer.

Because of the shallow depth of the well screens in relation to the depth to water, the pumping water levels should be monitored periodically to determine if they are getting close to the top of the respective screen. Among the options available to deal with a declining water level, would be to install a deeper well or install additional wells. The multiple-well option would likely be best for Oxbow, because these wells are located on a Precambrian ridge that is unusually high. Thus, locating a deeper well site in that immediate area is very unlikely. It is conceivable that at some future time the community of Oxbow may have to explore another area for a water supply, if the water levels were to drop so low as to make a multiple-well water-capture system no longer feasible.

Large water systems

The group of users with the most pressing time concern about the impact of declining water levels on their wells would be those entities that require large water supplies and high yield wells. They are the city of West Fargo, Cass Rural Water, Inc., Cargill, Inc., and Cass Clay Creameries, Inc. These entities have wells that generally pump at rates from 300 to 800 gpm, and produce up to 277 Mg/y of water from a single well. Well fields with the greatest likelihood of potential problems in the near future would be those with wells completed in a shallower portion of the aquifer and/or with wells that have relatively low specific capacities. The water supply of the city of West Fargo, and the wells it has utilized historically, can be used to discuss some of the management considerations resulting from the use of high yield wells to produce large water supplies in a declining-water-level situation. First, a brief history of the water supply for the city of West Fargo.

It is likely that there have been nine production wells utilized by the city of West Fargo up to 1999. Records on the first two wells are not complete. However, it is probable that wells #1 and #2 were the two wells (139-049-08BBA1 and 2) that C. J. Ferch constructed in 1937 near the intersection of 1st Av. and 1st St. These wells were used to provide the city of West Fargo with water beginning in 1938. They were within a few hundred feet of each other and were 132 and 135 feet deep. Klausing (1966) lists water levels measured in a city of West Fargo well that might have been one of these two wells, or may just have been another well in the very near proximity.

Well #3 (139-049-08BDA) is located near the swimming pool (about 1,500 feet southeast of the original wells), and is 164 feet deep. This well was drilled in 1954 and represents the first effort at spacing the wells over a larger area. This well was plugged in March of 2000.

City well #4 (139-049-07ABB2) was drilled in 1960 and was located about 3,000 feet west of the original wells, where the city of West Fargo shop facility is located. Well #4 was 204 feet deep, and is often referred to as the "Shop" well. Little is known of the water use from wells 1 through 4, other than the estimates found in the Dennis et al (1949) report, until 1965 when the first annual water use reports were submitted. From 1966 to 1973 well #4 provided 69 to 83 percent of the city's water supply, and well #3 provided the remainder. It is not known when wells #1 and #2 were no longer utilized. From 1966 to 1973 the community grew significantly, and so did its water needs. Well #4 produced about 120 Mg in 1973. This well was plugged in February of 1999.

In 1973 an additional well was constructed (well #5). Well #5 (139-049-09BBA) is located about 5,000 feet east of the original wells #1 and #2, and is 203 feet deep.

Well # 5 (called the "Sherman" well) was then used heavily through 1979. Well #5 produced 208 Mg in 1979.

Well #6 (the "12th Av." well) was added in 1976. Well #6 (139-049-08DCD) is located about 4,500 feet south-southeast from the original two wells, and is 223 feet deep. This well is very near the water tower on 12th Avenue. Well #6 was not used heavily until the early 1980s, when it was used heavily from 1980 until 1982. Well #6 produced 266 Mg in 1982.

Well #7 (about 1.75 miles southeast of the original two wells) was added in 1983, and was heavily utilized immediately, and water use from this well increased until 1988. Well #7 (called the "ABM" well) produced 277 Mg in 1988. Well #7 (139-049-16BDC) is 261 feet deep. Note that the wells were spread out more and more through time, and that the demand made on those wells also increased through time. It is also noteworthy that the newest wells were usually deeper than the older wells. As water levels have declined, there has been a need to place the production wells deeper. Given the depth of the recent wells and the depth of the deepest parts of the aquifer, there is little chance of constructing wells of greater depth.

The essence of this discussion is that the addition of new wells in a background of declining water levels can improve the capacity of the water supply. However, if any one well is used too much, two problems result. The first problem is that too much production is concentrated at one well site, resulting in a greater water-level decline at that location. A balance between all of the available production wells could result in more available water at peak times of demand, while no one well has a pumping water level that is below the top of the well screen.

The second problem is that overuse of new production wells has resulted in water levels declining into the well screen, and in the subsequent incrustation of the well screen. Incrustation of well screens has resulted in decreased production from those wells. Thus, additional wells may be needed more quickly than they would have been had the early use of the newest wells not been so heavy. Because several of the city of West Fargo wells were used quite heavily when they were new, the life expectancy of these wells may have been somewhat diminished. Except for the years of 1989, 1990, and 1994, every year from 1966 until 1997 the city well that was used the most, provided more than 50 percent of West Fargo's total water supply. A concerted effort to balance the withdrawals in five or more wells could reduce some of the loss of productivity of individual wells.

The city of West Fargo is somewhat limited in its ability to balance water use from the available wells, because of water quality differences between wells, and because of the preexisting network of waterlines. All city of West Fargo wells discharge directly into the city waterlines, after chlorination of the water at the well site.

Nevertheless, if new wells are strategically placed, pumped at appropriate rates, and if the older wells are either rehabilitated or replaced at or near their current locations, a better pumping balance could be achieved. An improved balance in the utilization of the wells could result in a longer life for most of the wells, and in an increased capacity to capture water in a declining water-level environment. The fact that the city has its wells located in two different aquifers means that there is less cumulative well interference than there would have been if all of the wells had been located in one aquifer. This increases the potential to blend more wells into the water supply system.

All of these factors that influence the rate at which water levels will decline in the future in the different parts of the WFAS do not change one overriding fact. The operation of the capture system for the city of West Fargo presents a difficult problem, and however the city manages the wells, it will likely be a relatively short time before most of its current wells would experience problems. Table 2 shows the wells that were available to the city of West Fargo for the production of its water supply in the summer of 1999.

TABLE 2. CITY OF WEST FARGO PRODUCTION WELL DATA (1998-99)

Well No.	Pumping rate (gpm)	Top of screen (ft)	Bottom of screen (ft)	Static water level (ft)	Pumping water level (ft)	Specific capacity (gpm/ft)
5	350	172	203	132.1	172.5	8.7
6	650	183	223	135.7	184.5	13.3
7	500	211	261	134.0	212.8	6.3
8	283	185	216	132.6	162.0	9.6
9	650	222	298	131.6	211.0	8.2

In the spring of 1998 or the summer of 1999 these five wells were tested for pumping rates and pumping water levels. Three wells (5, 6, and 7) had pumping water levels just below the top of the well screens. Well #9 (the interstate well) had a pumping level that was 11 feet above the top of the screen. Well #9 is constructed in the WFS aquifer. With water levels declining at about 1.5 to 2.0 feet per year the last seven years, the pumping water level would reach the top of the screen in about six to seven years. Well #8 (the Riverside well) had a pumping water level that was 23 feet above the top of the screen. Well #8 is constructed in the WFN aquifer. With the water level declining at about 0.2 feet per year the last seven years, the pumping water level would reach the top of the screen in about 100 years. This is the one well among the city's five wells that does not have a short time period before the pumping water level is below the top of the screen.

The city has recently (spring of 2000) had an extensive study done of its wells. The city of West Fargo is replacing wells #3 and #6 in the summer of 2000. Since well #3 has not been used to any significant degree in years, and because the replacement well for well #6 will be more productive than well #6 was, the city will have a greater pumping capacity, and thus, greater flexibility in producing its water supply. Additional wells may be added in the future, and there may be changes in pumping rates that would extend the length of time before the water level declines below the tops of the respective well screens.

Adding or replacing wells and sizing or resizing the pumps and pumping rates to optimal withdrawal rates will buy some additional time. Ultimately, however, it will become increasingly more difficult for the City of West Fargo to withdraw all of its water needs from the West Fargo Aquifer System. As the city gets larger, the problem will only become more severe.

The other large water users in the WFAS have less complicated, less vulnerable water supplies. The pumping water levels of the Cargill wells have been and are more than 100 feet above the top of the respective screens. With a recent (over the last 15 years) water-level decline rate in the WFN aquifer of less than 1 foot per year, this represents over 100 years under current conditions. The pumping water level of the Cass Clay Creamery well is about 12 to 15 feet above the top of the screen. With a recent (over the last 15 years) water-level decline rate in the Fargo aquifer of about 0.7 feet per year, this represents about 15 to 20 years under current conditions.

Cass Rural Water Users, Inc. has four wells that are located in the south end of the WFS aquifer (this well field is referred to as "Phase 1"). The first two wells were constructed in 1975, the third well was constructed in 1978, and the fourth well was constructed in 1999. In 1993 wells #1, #2, and #3 had static water levels of 90, 88, and 82 feet below land surface, respectively, and pumping water levels of 170, 165, and 122 feet below land surface, respectively. The rate at which the wells were pumped is not known. Historically, wells #1, #2, and #3 have been pumped at about 125, 300, and 450 gpm, respectively.

Production well #1 has a relatively shallow screened interval of 166 to 182 feet below land surface. This is the reason the well is pumped at a significantly lower rate than the other wells. Even though the well is pumped at a lower rate, the pumping water level is likely below the top of the screen any time the well produces more than about 110 to 115 gpm.

Well #2 has a screened interval of 217 to 257 feet below land surface. The specific capacity of the well is about 3.6, and the well pumps about 300 gpm. Based on past pumping records of well #2 and assumptions of approximately 2 feet per year of water level decline in the area, it is estimated that production well #2 should have pumping water levels above the top of the screen for about 15 more years.

Well #3 has a screened interval of 212 to 252 feet below land surface. The specific capacity of the well is about 6.8, and the well pumps about 460 gpm. Based on past pumping records of well #3 and assumptions of approximately 2 feet per year of water level decline in the area, it is estimated that production well #3 should have pumping water levels above the top of the screen for about 25 more years.

Because well #4 is new and pumping data is not available, no estimates are made on the amount of time before the water level will reach the top of the well screen of well #4.

The length of time that the Cass Rural Water Users, Inc. well field should be viable could be lengthened by careful selection of the pumping rates for the four wells. In a similar but less complicated setting as is observed in the city of West Fargo well fields, CRWU could pump its wells at rates designed to maximize the utilization of the well field. This would delay the time when pumping water levels start to drop below the tops of the respective well screens. It is, however, only a delay, and inevitably this portion of the WFAS water supply will need to be augmented or replaced. Current data indicates that lateral expansion of the CRWU well field is somewhat limited. If the well field is expanded to incorporate parts of the Horace aquifer, additional time could be available. However, the increase in additional time may not be large.

The above estimates are based on the most recent rates of water-level decline. In the future these rates of water-level decline could increase or decrease with no change in current rates of withdrawal. Alternative water supplies could be utilized or conservation measures enacted to reduce the volume pumped. The area could continue to grow and rates of use could increase.

GENERAL CONSIDERATIONS AND LIMITS TO LATERAL EXPANSION

The previous discussions are important to a declining water-level discussion, because the utilization of more wells pumping at lesser rates can spread the cones of depression out over a larger area. By locating more wells over a larger portion of the aquifer with balanced, but lesser, pumping rates, a greater portion of the water in the aquifer could be captured. There is, however, an economic benefit to having a few large capacity wells deliver a water supply for many homes and small businesses, and also for large plants to utilize one or two large capacity wells for the needed water supply. Balance needs to be found between the economic advantage of a few wells, and the hydrologic advantage of more wells with lower pumping rates. Even with the efforts towards spreading out more high-capacity wells, there are limits as to how effectively this can be done.

Aquifer boundary conditions, water quality considerations and pipeline expenses limit the degree to which water supplies requiring multiple well systems can be spread out laterally. The areas depicted in figure 3 as being where the aquifers are located limit the possible locations of sites for high-yield wells. In reality, there is some chance that high-yield wells could be located in areas where aquifers are not shown, and that high-yield wells could not be installed in places where aquifers are shown. Such is the nature of the knowledge of the aquifer system. Considering figure 3, however, there are limits as to how far any entity could spread out their wells in an effort to maximize the utilization of the WFAS. This is just on the basis of aquifer boundaries.

Additionally, certain aquifers and certain portions of other aquifers contain water of a quality that is marginal or unacceptable for many of the purposes for which certain entities use water. Most of the water of acceptable or suitable quality is found in parts of the WFS, the WFN, the Horace, the Ponderosa and the Fargo aquifers. Other aquifers have water quality that is suitable for only limited purposes.

Each entity also has an economic limit on the investment that can be made for infrastructure to capture and convey water to the location where it is needed. A municipality usually has a higher degree of flexibility than do most industries with respect to the area over which additional wells can be located. For each entity there are different limits as to how feasible it would be to utilize more wells spread out over a larger area to develop their water supply.

For any large volume user, utilization of the WFAS becomes a bigger and bigger problem as the volume of water needed increases. The larger the volume of water required, the larger the problems developing the water supply, until eventually the WFAS is no longer a feasible source for a large volume user. An industry, whose plant growth potential is limited, does not face this problem to the same degree that an entity that supplies water to a growing population.

MANAGEMENT OPTIONS

The water levels in the West Fargo aquifer system are declining, particularly in the aquifers in and around the city of West Fargo where the greatest use is occurring. This indicates that under the present rate of use, the sustained yield of the aquifer is being exceeded. In order to meet current needs over the long term and supply future growth, alternative water sources must be developed. These sources will either augment or replace the water supplies that are currently obtained from the West Fargo aquifer system. The following options are presented briefly to give some perspective (where possible) of the potential volume of water, and the potential ease with which the option could be utilized.

UNUSED PERFECTED AND CONDITIONAL SURFACE WATER PERMITS

The city of West Fargo currently holds three water permits that authorize the appropriation of water from the Sheyenne River and from Lake Ashtabula. They are perfected water permit #127, conditional water permit #921, and conditional water permit #921A.

Perfected water permit #127 has a priority date of November 7, 1918. The permit authorizes the appropriation of 200 acre-feet per year from the Sheyenne River. The point of diversion is specified as the northeast quarter of the southeast quarter of section 6, T139N R49W. Also in place is conditional water permit #921A, which has a priority date of July 25, 1961. This permit authorizes the appropriation of 1,460 acre-feet per year from the Sheyenne River. A total of 1,660 acre-feet per year is allocated to the city of West Fargo directly from the Sheyenne River.

Water permit #921 authorizes the appropriation of 954 acre-feet of water annually that is stored in Lake Ashtabula. Lake Ashtabula is a reservoir on the Sheyenne River that is created by Baldhill Dam and is located a short distance upstream from Valley City. The water can be released from the reservoir for use by the city of West Fargo. The priority date is July 25, 1961. This allocation in combination with the 1,660 acre-feet per year available directly from the Sheyenne River results in a total of 2,614 acre-feet per year (about 852 Mg/y) of water being allocated to the city of West Fargo.

Additionally, the Sheyenne River could also be a possible source of water for Cass Rural Water Users Inc. While it does not have any water appropriated from the Sheyenne River, there may be unappropriated water available from the river so that CRWU could replace or augment the water that they currently obtain from the WFAS. The combination of both the city of West Fargo and CRWU both using surface water would eliminate up to two-thirds of the ground-water diversions from the WFAS. This would have a profound impact on the declining water levels of the WFAS.

RELEVANT U.S. BUREAU OF RECLAMATION FEATURES

The U.S. Bureau of Reclamation (USBR) has prepared a comprehensive report appraising alternatives to meet projected water shortages in the Red River Valley. The report consists of five parts (U.S. Bureau of Reclamation 1998, 1999, 2000a, 2000b, and 2000c). Different methods to meet water shortages are presented as features, and these 21 features are presented in different combinations as alternatives. The alternatives are applied to the North Dakota side of the Red River valley water needs. In the context of this study area (which is a subset of the USBR study area), several of the USBR features have applicability in part or in whole.

The Water Supply Task Force Group of the Red River Basin Board also has prepared a draft Red River Basin Water Supply Report (Red River Basin Board 2000). This draft report expands the area of discussion to include the entire Red River basin, incorporating significant areas in Minnesota and Manitoba. The draft incorporates three of the USBR features. They are conservation practices, a treatment plant between the McClusky and New Rockford canals to transfer Missouri River water to the Red River valley, and aquifer storage and recovery (ASR). ASR has previously been referred to as artificial recharge.

This study will not address all of the 21 features in the USBR report. Five of the features are either structural surface water solutions or involve the management of surface water structures. These are outside the parameters of this study. One of the features (desalinization of the Dakota aquifer) was discussed as being utilized outside of this study area. Implementing this feature outside of the WFAS study area was likely done because the feasibility of this feature is reduced in this study area due to the highly limited occurrence of the Dakota aquifer within this WFAS study area.

Nine of the features are basin transfers of surface water, and while probably necessary for the long-term water needs of the study area and the basin as a whole, the features are outside the parameters of this study. While these nine features may be outside the parameters of this study, it should be kept in mind that some of these features could provide very significant amounts of water. Basin transfers consisting of 100 cfs or more would provide significantly more water to the study area than any of the six remaining features that will be discussed in this report.

The six remaining features that will be briefly discussed in the context of this study area are:

1) purchase existing surface water rights (Feature 6);
2) secure additional unappropriated ground water (Feature 7);
3) purchase existing ground-water rights (Feature 8);
4) use the WFAS for water storage and recovery (Feature 9);
5) reuse wastewater (Feature 11); and
6) increase water conservation measures (Feature 12).

The discussion of 1) and 3) will be combined in the following section called "existing water rights (surface and ground water)".

Existing water rights (surface and ground water)

The purchase of existing water rights for utilization by entities within the study area is a possible source of additional water. The water source for these purchases could be either ground or surface water. One additional limitation in this option would be that the purchased water rights may only be transferred to a superior use as determined by the order of priorities contained in section 61-04-06.1 of the North Dakota Century Code. The order of priorities is as follows:

1) domestic use;
2) municipal use;
3) livestock use;
4) irrigation use;
5) industrial use; and
6) fish, wildlife, and other outdoor recreational uses.

There are other parts of the country where water rights have been purchased and transferred. The cost of this practice is market driven and highly variable. This has been done in a very limited way in North Dakota, and the market value of such purchased rights is unknown.

If ground water were to be brought into this study area through such a process, it is likely that significant quantities would be necessary so that the expense of purchasing the water rights and building the pipeline would be cost-effective. For this reason it is likely that only two aquifers would be feasible to consider. These two aquifers would be the Sheyenne Delta aquifer and the Page aquifer. There are about 10 billion gallons per year (32,000 acre-feet) of water currently allocated from these two aquifers. If the costs associated with this option are not prohibitive, this is a physically feasible alternative for additional water.

Similarly, there are surface water rights on the Sheyenne River below Baldhill Dam that could be purchased. The market value for these rights is a total unknown. Surface water rights on the Sheyenne have the advantage of not requiring as much pipeline, if any at all. The Sheyenne River passes through the study area. There is one big difference in the surface water rights of the Sheyenne compared to the ground-water rights of the Page and Sheyenne Delta aquifers. The difference is that where over 90 percent of the ground water rights are irrigation allocations, less than 7 percent of the surface water rights are irrigation allocations. As a result there are probably only about 1.4 billion gallons per year (4,400 acre-feet) of water available for purchase, if one assumes that most of the non-irrigation allocations would not be available for purchase. Any change in purpose of use of existing water rights must be processed in the same manner as a new water permit application.

Additional unappropriated ground water

In the consideration of additional aquifers for use in North Dakota that are located within reach of the study area, the first logical limit is that any aquifers located in Minnesota, would not be viable alternatives. The combination of physical, legal, and political constraints make the plausibility of tapping into Minnesota ground water extremely small. In the North Dakota portion of the study area it is possible that there are significant unknown aquifers of good water quality that are not related to the WFAS. While it is possible, it is also unlikely. Past test drilling programs, in conjunction with numerous well drilling logs and water quality analyses show little opportunity for an unrelated aquifer of moderate size to be located within the study area.

Aquifers of moderate to significant size outside of the study area, but within feasible pipeline distances of water-using entities within the study area are few. Only two North Dakota aquifers appear to be of sufficient size that would allow for diversions of sufficient volume, so as to be worth the expense of a pipeline of 30 to 50 miles. Those two aquifers are the Page aquifer, and the Sheyenne Delta aquifer.

The Page aquifer is northwest of the study area. The 400-square-mile aquifer underlies portions of Cass, Steele, and Traill counties. While this aquifer contains a moderately large volume of water, the aquifer also has been significantly developed in terms of water allocation. The total allocation currently permitted from the aquifer is about 16,000 acre-feet per year. There may be some additional allocation potential from the Page aquifer. However, whatever additional allocation could be developed from the aquifer would be limited and the points of diversion developing this supply would have to be dispersed over a large area. Presently, there are pending permit applications in place that are awaiting evaluation as to whether there is additional water available for appropriation.

The Sheyenne Delta aquifer is the one ground-water source in North Dakota within 50 miles of the study area that may present a viable option for some additional ground water. The 750-square-mile aquifer underlies portions of Cass, Ransom, and Richland counties. The greatest concentration of development is in the western portion of the aquifer. The total allocation currently permitted from the aquifer is also about 16,000 acre-feet per year.

While the eastern portion of the Sheyenne Delta aquifer does have some development potential, there are a number of factors that limit the potential. The development potential is limited by:

- the effects on existing water rights;
- the effect on the base-flow of the Sheyenne River;
- the well yield limitations on the north and east parts of the Sheyenne Delta aquifer;

- the economic feasibility of constructing multiple well systems;
- the accessibility to the National Grasslands; and
- the impacts on the National Grasslands.

In spite of these limitations there may be potential for some additional water that could be diverted to the study area. The points of diversion developing this supply would have to be dispersed over a large area. All totaled, however, there is limited expansion capability with respect to ground-water resources in the area. An extensive study would be needed to accurately define the amount of water that might be available from the Sheyenne Delta aquifer. An estimate of the approximate volume available from this feature is not possible at this time.

West Fargo Aquifer System storage and recovery

The utilization of the West Fargo Aquifer System for the storage of surface water and the recovery of ground water is an additional water resource management option that merits consideration. The technique of artificial recharge has been utilized in many areas where ground-water resources are limited, and surface water resources are in surplus. The surplus surface water may only be available during certain times of the year, and/or only in certain years, but aquifer storage and recovery (ASR) can be effective given the right physical setting with available surplus surface water.

Generally the physical setting of an unconfined aquifer makes it easier to operate an ASR system than does the physical setting of a confined aquifer. This is true even after a confined aquifer is partially dewatered and converts to an unconfined aquifer with an overlying aquitard. The less-permeable materials of the overlying aquitard must be penetrated in some manner. With an unconfined aquifer natural depressions and/or man-made basins provide direct access to the aquifer. This usually means more water can infiltrate at less expense, and also means that ever-present clogging problems can be dealt with at the surface. Most recharge facilities are utilized in unconfined aquifers.

The WFAS is a confined aquifer that is converting to an unconfined aquifer in some places. Even where it is in unconfined conditions, there is an overlying layer of less-permeable material that generally has a thickness of more than 100 feet. There are places where the top of the aquifer is less than 100 feet below land surface, however the average depth to the top of the aquifer is about 140 feet below land surface. In physical settings like the WFAS the usual procedures are to construct either recharge wells or gravity shafts. The recharge well places a screen at the bottom of a well that penetrates through the confining layer into the receiving aquifer (same as a production well) and recharges water into the well. The gravity shaft places a column of coarse, permeable material through the confining layer into the aquifer. Water is driven through the shaft by gravity from the surface through the confining layer into the aquifer.

The advantage of the recharge well in the ASR system is that the well can be pressurized to drive more water into the receiving aquifer. The advantage of the gravity shaft in the ASR system is that the ever-present clogging problem can be dealt with at the surface. The recharge wells need to be rehabilitated to overcome the decrease in recharge rates that result from clogging. Eventually even with rehabilitative procedures, the recharge wells need to be replaced at significant expense. With gravity shafts, the rate of recharge is less, however the cost of rehabilitation is less, because the sand and gravel shaft can be rehabilitated at the surface much like the surficial features associated with unconfined aquifers.

As water levels decline in the WFAS, ASR systems will become a more viable solution to augment water supplies in the WFAS. The lower the water levels the greater the pressure differential between the surface and the level at which water is being introduced into the aquifer. Additionally, the lower the water levels in the WFAS, the greater the volume of water that could be recharged during times of surplus surface water availability.

A challenge of developing ASR systems in the WFAS would be determining how to allocate expenses of operating such a system among water users of the WFAS. The complexity of the WFAS has been described in earlier portions of this report. This complexity results in the fact that the recovery portion of an ASR system might result in only a portion of the recharged water being available to recover in that area of the WFAS in which the storage was implemented. It should be possible through cooperation to equitably address these issues in the design and implementation phases of a WFAS ASR system.

To put the possible quantity of recharge water into perspective, the following scenario is presented with numerous assumptions. Surplus surface water would be available for an average of two months out of each year (through a combination of surplus spring runoff and some limited storage). Gravity shafts would be utilized to conduct the surface water to the aquifers. Assume each gravity shaft would average about 100 gpm over the time period for each annual recharge cycle. (A Scottsdale, Arizona, recharge facility with 600 feet of head differential and very coarse aquifer material averages about 250 gpm/well). Assume 75 percent of the recharged water could be retrieved. A 20-well recharge system would provide about 130 Mg/y of water.

Reuse of wastewater

The reuse of water is also a technique that has been used in many areas where water is scarce. This technique generally requires a wastewater that has been gathered after use. This water will be changed in character from the original water supply, and generally needs treatment before being of use for additional purposes. The more uses to which the water could be put, the more water treatment that would be required. In some instances the treatment may be so comprehensive so as to be of a quality that could be used for virtually every purpose. The more comprehensive the treatment, the higher the cost. Additionally, some wastewater (no matter how much improved by treatment) would be controversial, if used for human consumption.

In the case of the WFAS water there is a distinct limit as to how much could be treated and recycled. The larger general categories of water use that result from the utilization of the WFAS are municipal, industrial, and domestic and rural water use. The largest municipal wastewater supply would be the estimated 400-500 Mg/y that flows through the West Fargo wastewater lagoons. The next largest wastewater supplies would be on the order of 20 Mg/y or less. Such small volumes would make recycling of wastewater less economically feasible.

Some industrial use consists of the water being incorporated into the product, and that water would not be reusable. An example would be livestock at the stockyards. There may be some potential to segregate wastewater streams in the plant setting, such that portions of the wastewater could be treated and reused. The maximum that could be reused is likely significantly less than half of the estimated 350 Mg/y of water that is used by industrial water users.

In a few instances rural water is provided to a small town and the water is returned to holding ponds after use. In most instances the rural water is provided to individual homes where the wastewater is dispersed back into the earth via a septic system, or some reasonable facsimile. A very small percentage of the 200 Mg/y of water used by rural water and individual homes could be feasibly recycled.

The net volume of recyclable wastewater is probably in the range of 500 Mg/y. However, there may not be feasible uses for 500 Mg/y of recycled water. The uses to which this water could be put would increase as the comprehensiveness of treatment increases; however, there still may be limits on delivering that water to prospective users.

Water conservation measures

In many areas where water is scarce, significant water conservation measures have been implemented. Sometimes the conservation is achieved solely through economics, (raise water costs high enough and the rate of water use drops), and sometimes the measures are specific programs or actions to limit water use or encourage conservation. There are a wide variety of conservation measures, and this study will not go into any detail on any of these measures. The main point of this discussion is to put any selected conservation measures into perspective with respect to potential impacts on the current rate of water diversion.

The key concept is that any such measures would extend the time period in which the production wells and well fields would be viable. The more conservation measures that are implemented, and the more effective that those conservation measures are, the longer the time period before problems would be encountered. For large water supply systems conservation measures may delay the inevitable problems. However, under the current conditions, they cannot be avoided. A very effective conservation program can lower the per capita use, however the conservation measures will not necessarily limit growth of the area. With additional growth comes additional use, and thus conservation can only delay the day when water levels are low enough to make the capture of additional water cost prohibitive.

For example, water use from the WFAS was about 900 Mg/y in 1993. A 10-percent reduction in water use would reduce water use by about 90 Mg/y. A 10-percent reduction in water use across the entire spectrum of users of the WFAS would be significant. To put this conservation into perspective, it would be useful to look at the rate of growth of water use from the WFAS. Figure 85 shows a graph of the data tabulated in Table 1 that was presented in the section on the water budget. The figure shows a surprisingly consistent pattern of growth of water use. Since the late 1940s the growth in water use for the WFAS has generally been about 15 Mg per year. The estimated 90 Mg/y reduction in total water use resulting from a 10 percent decrease represents about six years of water use growth. In a time of low water levels, and difficulty in supplying water, this would be very significant. For the long-term viability of the WFAS water supply, however, this would only be a six-year delay. Greater reductions in use would result in longer delays.

The annual capability of the WFAS to supply water without water-level decline is not known. What is fairly clear, however, is that the annual capability to supply water without water level decline is significantly less than the current rate of annual use. It is unlikely that sufficiently austere conservation measures could be accomplished, such that current users could maintain utilization of the WFAS and achieve water level stability. Conservation measures can buy additional time, but the likelihood that conservation measures can bring water-level stability to the WFAS is quite small.

SUMMARY

The lower part of the geology of the study area consists of Cretaceous shales and siltstones deposited on top of an irregular Precambrian igneous rock base. There is an occasional sandstone layer interlayered in the Cretaceous material. This surface was

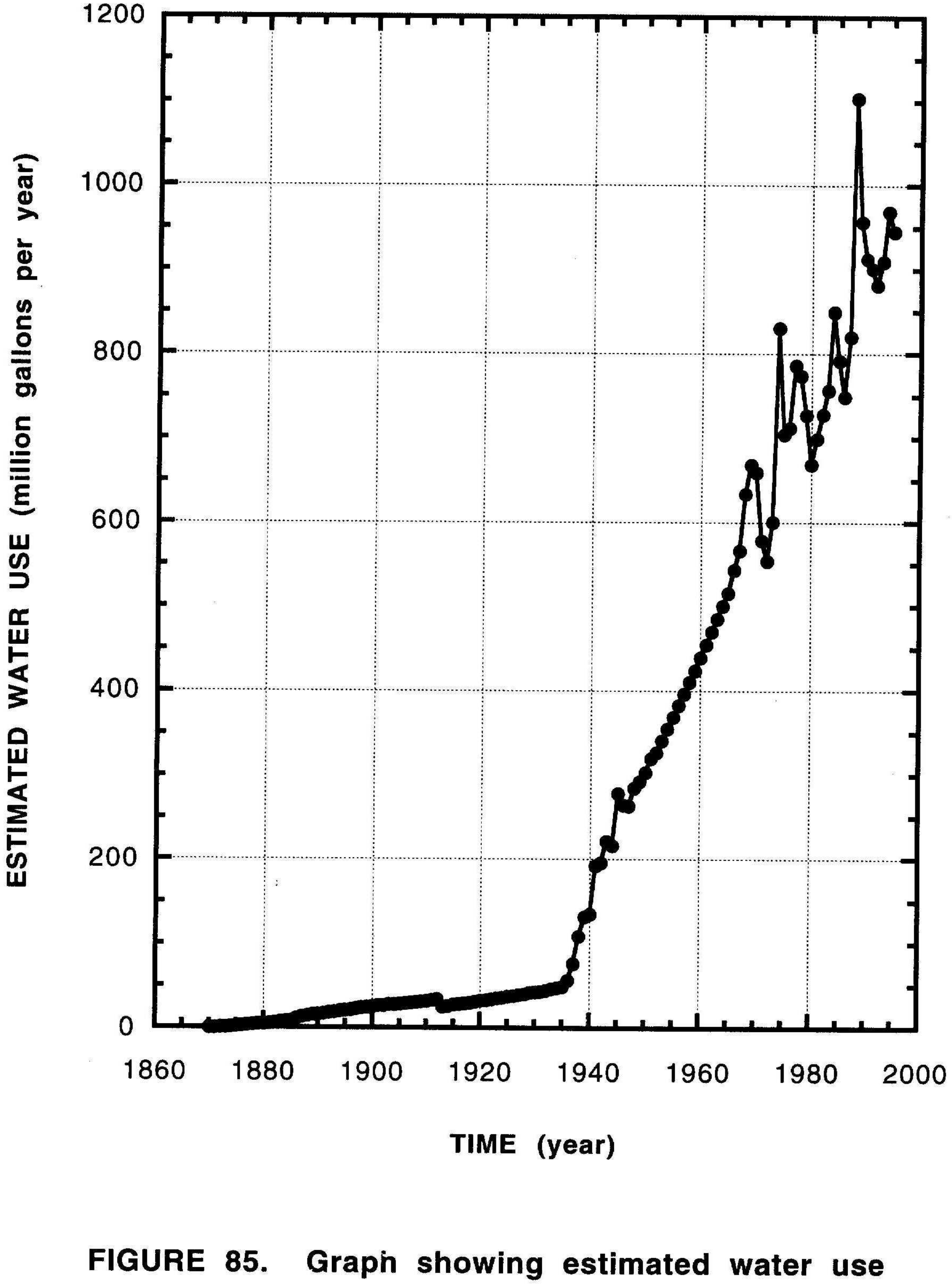


FIGURE 85. Graph showing estimated water use for the West Fargo Aquifer System.

eroded, and the resulting surface consisted of some Cretaceous and some Precambrian material at land surface. Repeated glacial events subsequently deposited tills, sands, gravels, and lake clays on top of the Cretaceous/Precambrian preglacial surface in very complex ways. Many sand and gravel bodies were formed in the study area, and nine significant aquifers comprise the aquifer system known as the West Fargo Aquifer System (WFAS). These sand and gravel bodies are surrounded by aquitards comprised of Cretaceous and Precambrian sediments, as well as glacial tills and clays.

All of the nine aquifers have been utilized as a source of ground water to varying degrees. Each of the nine aquifers is surrounded by aquitards. Even though the aquifers are enclosed in aquitards, these nine aquifers are interconnected in ways that resulted in ground-water level declines even in aquifers from which not much ground water has been historically withdrawn.

The West Fargo North (WFN) aquifer has been the most heavily used aquifer in the WFAS. The WFN is the second-largest aquifer in the WFAS. The WFN averages about 79 feet in thickness over an area of about 27 square miles. The water levels have declined about 0.5 feet per year in the last 15 years. The water is a sodium/chloride type with total dissolved solids generally ranging between 800 to 1,100 mg/l. The water is suitable for most purposes.

The Fargo aquifer was the first of the nine discussed aquifers in the WFAS to be utilized as a source of ground water. The Fargo aquifer averages about 40 feet in thickness over an area of about 0.5 square miles. The water levels have declined about 0.7 feet per year during the last 15 years. The water is a sodium type with no dominant anion. The total dissolved solids generally range between 700 to 800 mg/l. The water is suitable for most purposes.

The Nodak aquifer averages about 68 feet in thickness over an area of about 2.6 square miles. The water levels have declined about 1.1 feet per year during the last 15 years. The water is a sodium type with no dominant anion. The total dissolved solids generally range between 500 to 900 mg/l. The water is suitable for most purposes.

The 94/10 aquifer averages about 48 feet in thickness over an area of about 3.2 square miles. The water levels have declined about 0.5 feet per year during the last 15 years. The water is a sodium-chloride type with total dissolved solids generally ranging between 1,050 to 1,200 mg/l. The water is suitable for some purposes and marginal for other purposes.

The Prosper aquifer averages about 75 feet in thickness over an area of about 14.6 square miles. The water levels have declined about 0.4 feet per year during the last 15 years. The water is a sodium-chloride type with total dissolved solids generally ranging between 1,000 to 3,000 mg/l. The water is marginal for most purposes.

The West Pleasant aquifer averages about 57 feet in thickness over an area of about 3.2 square miles. The water levels have declined about 0.9 feet per year during the last 15 years. The water is a calcium type with no dominant anion. The total dissolved solids generally range between 1,000 to 3.000 mg/l. The water is marginal for most purposes.

The Horace aquifer is the largest aquifer in the WFAS. The Horace averages about 103 feet in thickness over an area of about 26.8 square miles. The water levels have declined about 1.3 feet per year during the last 15 years. The water in the eastern part of the aquifer is a sulfate type with no dominant cation. The water in the western part of the aquifer is a calcium type with no dominant anion. The total dissolved solids generally range between 500 to 2000 mg/l. The water is suitable for most purposes.

The Ponderosa aquifer averages about 100 feet in thickness over an area of about 3.2 square miles. The water levels have declined about 1.0 feet per year during the last six years. The water is a sodium type with no dominant anion. The total dissolved solids generally range between 800 to 1,300 mg/l. The water is suitable for most purposes.

The West Fargo South aquifer averages about 90 feet in thickness over an area of about 13.8 square miles. The water levels have declined about 2.3 feet per year during the last 15 years. The water is a sodium-bicarbonate type with total dissolved solids generally ranging between 400 to 600 mg/l. The water is suitable for most purposes. The WFS aquifer has the best water quality of any of the aquifers in the WFAS.

The ground-water flow pattern for the West Fargo Aquifer System has varied through time. The general historical pattern has been for the aquifer from which the most water is being withdrawn to have the water levels of that aquifer drawn down to the lowest levels. This generally causes water from nearby aquifers that are slightly hydraulically connected, to drain into the aquifer from which the most water is being withdrawn. Because the history of water use is different for each aquifer, because of the different spatial relationships between aquifers, and because the degree of connection between aquifers varies so much, the resultant ground-water flow patterns through time have been variable and quite complex.

Inadequate data currently exists to depict the ground-water flow interaction between the WFAS and the surrounding aquitards. Limited data does indicate that the surrounding aquitards are being dewatered. This suggests that there is significant movement of water from the aquitards into the aquifers of the WFAS. It is probable that this is a one-time occurrence. As more water is drawn out of the surrounding aquitards, less water will move from the aquitards into the aquifers, because the aquitards are probably being drained at a significantly greater rate than the rate at which they are being recharged. Additionally, inadequate data exists to characterize both the variable water chemistry and the reasons for that variability. Continued use of ground water could lead to changes in the water chemistry in any of the aquifers comprising the WFAS.

Stable isotope data (deuterium and oxygen-18) shows that almost all samples are in a "snowfall" range. This range of isotope values is strikingly cold in its signature. This range does not suggest modern-day recharge, unless there is a mechanism whereby only snowmelt recharges the aquifer. This is most unlikely. It is just as unlikely, that the aquifer is receiving any significant amount of meteoric water as recharge. Currently the isotopic values of water samples collected from WFAS wells indicate that the ground water was emplaced under colder than present climatic conditions. Analysis of the available isotope data leads to a conclusion that modern-day recharge is insignificant in the WFAS. The strong inference is that the ground water in the WFAS is predominantly trapped Pleistocene water.

Water budget estimates resulted in an estimate of about 422 billion gallons of water being contained in the nine aquifers comprising the WFAS in 1870. An estimate of water contained in the same aquifers in 1995 is about 415 billion gallons. An estimate of the total water use from these aquifers over that same time period is about 33 billion gallons. It appears that water is being derived from sources additional to the aquifers that comprise the WFAS. The major source for this additional water is likely the aquitards that surround the WFAS. The most critical additional work that needs to be accomplished to quantify the ground-water flow system, is the installation of numerous nested piezometers for the purpose of gathering data necessary to quantify ground-water flow in and through the aquitards.

Ground-water withdrawals exceed the leakage replenishment capacity of the aquitards, resulting in a steady water-level decline (of different rates) in all the aquifers in the WFAS. Leakage from the surrounding aquitards is merely reducing the rate of water-level decline in the WFAS. There are several management actions that could mitigate these water-level declines to varying degrees. Some possibilities are the purchase of existing water rights, appropriating unappropriated ground water rights, the reuse of wastewater, aquifer storage and recovery procedures, water conservation measures, and developing unused surface water allocations. Depending on the development costs, and the proportion of the available resources that could be developed, these possibilities could be significant options for additional water, rather than continuing the depletion of the WFAS. The potential for the utilization of currently-held, perfected and conditional surface-water allocations appears to be of sufficient volume and feasibility, such that this is the most promising available alternative to augment or replace water supplies currently obtained from the WFAS.

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APPENDIX A

BRIEF DISCUSSION OF REFERENCES

One of the first published papers covering geology and hydrology of the Red River basin was the comprehensive U.S. Geological Survey (USGS) monograph done by Upham (1895) describing the entire area once occupied by glacial Lake Agassiz. Additional work on the geology and artesian basin in this area of the Red River valley was done by Willard (1905) and by Hall and Willard (1905). The "Pleistocene artesian wells" are compared to "those deriving their supply from the Dakota sandstone" by Willard (1905). He pointed out that while the Dakota sandstone wells "furnish a seemingly unlimited amount of water", the Pleistocene artesian wells "have ceased to flow entirely and have to be pumped". Hall and Willard recorded some of the earliest test holes and wells installed in the area. Their discussion on the hydrology is insightful and very informative. Simpson (1929) has additional lithologic data and water levels for wells drilled in the early 1900s.

Insightful and informative discussions of the patterns of settlement of North Dakota are found in Lounsberry (1917). These discussions help formulate estimates of early water use in the study area. Similar historical perspectives are provided by Robinson (1966). Robinson includes some inferred information on water development and water use with respect to municipal and industrial startups, as well as settlement and farming patterns. Additional historical perspectives are given by Krenz and Leitch (1993). A full spectrum of Red River valley water issues is presented in this work.

Leverett (1932) did a comprehensive report on the Quaternary geology of Minnesota and parts of adjacent states. This report discusses many surficial features in the study area. Allison (1932) discussed the general geology and the chemical character of the waters of northwestern Minnesota, as well as discussing on a county-by-county basis the water resources of those northwestern counties.

In the 1930s the Works Progress Administration completed a statewide selective inventory of wells in North Dakota in conjunction with the North Dakota Geological Survey (193?). Well depths and 1930s water levels are available from this report.

Starting in 1938 and continuing through 1977, the USGS published a series of Water Supply Papers (WSP) that contained water-level and artesian-pressure measurements in observation wells for the years from 1937 to 1974. The WSPs of Meinzer and others (1938-40 and 1942-44 and 1946), Sayre (1947 and 1954-57), Paulsen (1948-49 and 1951-52), LaMoreaux (1959), Hackett (1964), McGuinness (1969), Hendricks (1973), and Cragwell (1977) list numerous wells located in the study area with corresponding water-level and piezometric-head measurements. The evolving descriptions found in these WSPs of well locations and measuring points help relate the observation wells and their measurements through time.

A progress report on a study of the ground-water resources of the Red River valley in the vicinity of Fargo, ND was completed in 1946 by Byers, et al (1946). The report contains a description of the resources, and a wealth of water quality, water level and lithologic data. Much of this data is included in Ripley (1997, 1997b, and 1997c). Subsequently a similar, but more extensive, report was published by Dennis et al (1949). This report is the first report to refer to specific glacial aquifers by name, and the first reference to the West Fargo aquifer is found in this report. The Fargo, West Moorhead, East Moorhead, Dilworth, and Maple Ridge aquifers are other glacial aquifers that are also mentioned. This report also has substantive historic water use data for the Fargo/Moorhead area.

Guyton (1957) reported on the ground-water conditions in the East Dilworth aquifer, but in reality, the report is actually about what is known today as the Buffalo aquifer, and in fact Guyton used parentheses to refer to the Buffalo once in the introduction. Guyton also referred to a report by Meyer (1955), that I have not found, but Guyton seems to be the first to discuss the Buffalo aquifer. In this same time period Bingham (1960) produced a report on the basic geology and ground-water data for Clay County, Minnesota. The data incorporated is extensive, but much of the information is found in the Dennis et al (1949) report. There is no interpretive work found in this report. A limited amount of data is found in Brookhart and Powell (1961) for the far northwest portion of the study area near Hunter, North Dakota. Paulson (1962) presented general ground-water concepts in a North Dakota setting with glacial descriptions applicable to the study area.

In the 1960s reconnaissance-level analyses of the ground-water resources of Cass and Richland counties were done. Baker (1966 and 1967) and Baker and Paulson (1967) in a three-part report presented the geology, water resource data, and an interpretive report on the ground-water resources of Richland County. The WFAS is not noted in the northeast part of the county in this study. Klausing (1966, 1968, and 1968b) in a similar three-part report presented the geology, water resource data, and an interpretive report on the ground-water resources of Cass County. These Cass County reports refer to both the West Fargo and the Fargo aquifers. Extensive water resource data and interpretations are found in these reports.

The conceptual model of the configuration of the WFAS has changed from the model that is presented by Klausing. Parts of the aquifer he presented as the West Fargo aquifer, are now considered to be parts of the Horace, the Nodak, the Ponderosa, the Prosper, the 10/94, the West Fargo North, the West Fargo South, and the West Pleasant aquifers.

Lindvig (1964) performed the first aquifer test on the WFAS during the Cass County study (Klausing, 1966, 1968 and 1968b). This test was run in the southwest part of the West Fargo North aquifer. Subsequent aquifer tests were performed in 1972, and in 1983. Schmid (1972) performed an aquifer test in the southeast part of the West Fargo North aquifer using one of the city of West Fargo wells. Reiten (1983 and 1983b) presents the results of an aquifer test in a two-part report. The first well that the city of West Fargo installed into the north part of the West Fargo South aquifer was used for this test.

In another three-part county report Bluemle (1967) described the geology of Traill County. The other two parts are a compilation of the basic ground-water resource data by Jensen (1967), and an intepretive report describing the ground-water resources of Traill County by Jensen and Klausing (1971). This county is not within the study area, but it is immediately adjacent to the study area. Some of the data and interpretations provide useful insights into the ground-water resources of the study area.

Eighteen papers are presented in Mayer-Oakes (1967) on different aspects of glacial Lake Agassiz. Five of the papers discuss some aspect of the ground-water resources in the study area, but only two of them discuss study-area resources in some detail. The Elson (1967) report provides a detailed history of glacial Lake Agassiz, and briefly refers to features in the study area. Winter (1967) discussed four subsurface, linear sand and gravel deposits in the Red River valley, one of which is currently called the Buffalo aquifer. It is referred to as "Unit C" in the Winter report.

Maclay et al (1969) showed the same aquifer as an unnamed "buried sand ridge aquifer". In their report they called the aquifer "unit A" in this atlas on the Buffalo River watershed. This report also shows historic water levels in the Moorhead East and West aquifers and depicted these aquifers as being part of "unit C" (different than "Unit C" of Winter's report). In a similar atlas on the Wild Rice River (Minnesota) watershed, Winter et al (1970) found no significant aquifers in that portion of the watershed that is located within the study area. A summary of all of the watershed atlases pertaining to Minnesota watersheds draining into the Red River is found in Maclay et al (1972). A regional hydrogeologic assessment of the southern part of the Red River valley on the Minnesota side is being done now by Trojan (in preparation).

Walton (1970) published a textbook on ground-water resource evaluation. Some of the definitions in his text are used in this report. Walton's textbook gives good, pragmatic examples of techniques to use to estimate various facets of ground-water resources.

In the 1970s many reports on the hydrology and glacial geology of the area were published. Bluemle (1972) discussed primarily landforms in southeastern North

Dakota that were formed from the glacial processes that occurred in that area. Bluemle (1988) is an updated version of that report. Bluemle (1972b) covers preglacial topography and then the subsequent Pleistocene drainage development in North Dakota giving insights into the drainage history of the Red River valley area. Bluemle (1991) is an updated version of the 1972 study on drainage development that concentrates on the Missouri River development, but that does have some additional insights on the eastern part of the state. In 1974 Bluemle presented a paper on the early history of Lake Agassiz. Bluemle (1974) presented the concept that early Lake Agassiz was predated by small ice marginal lakes that enlarged and coalesced to form Lake Agassiz.

Arndt and Moran (1974) presented an inventory of mineral, soil, and water resources in Cass and Clay counties. They briefly discussed the Fargo and West Fargo aquifers. The aquifers are depicted as they were in the Klausing (1968b) report. The aquifer they call the Moorhead is currently known as the Buffalo, and the Ridges aquifer was previously referred to as the Maple Ridge by Dennis et al (1949). They also refer to the Kragnes aquifer as a "vaguely defined buried sand and gravel deposit", and refer to Maclay and others (1969). I find no mention of the Kragnes aquifer in the Maclay report.

Harris, Moran and Clayton (1974) described late Quaternary sediments in the northern part of the Red River valley. The Sherack and Poplar River formations are two units described in their report that occur in this study area. While their report does not mention the Brenna formation as being in the study area, Arndt (1977) in his report on the stratigraphy of offshore sediment in Lake Agassiz did mention the Brenna formation as occurring in the study area. Arndt's report states that the contact between the Sherack and the Brenna formations is "difficult to recognize" south of Hillsboro, which would be in this study area. A broad overview of the ground-water resources of the Souris-Red-Rainy region is presented by Reeder (1978).

In the late 1970s and the early 1980s several studies were completed by engineering firms and students on water supplies and water resources in the area. Barr Engineering (1975) produced a report on the Moorhead water supply. The report evaluated the potential for expansion of the surface and ground water supplies for Moorhead. The report referred to Maclay et al (1969) and Winter et al (1970) for a significant portion of its ground-water information. Moore Engineering (1975) produced an engineer's report on test drilling with lithologic logs, water levels, water chemistry and test pumping in the West Fargo North aquifer. A subsequent report by Moore Engineering (1981) discussed the water supply for West Fargo with water use data for 1980 and parts of 1981.

McLain (1977) was the first since Dennis et al (1949) to differentiate the East and West Moorhead aquifers, and to give evidence for considering the two as separate, but related, aquifers. Additional history on Moorhead's water use (both surface and ground water) is also available from this report. Ulteig (1979, 1979b, and 1979c) is a three-part study that evaluated the potential for ground-water development to the south and southwest of Fargo in the southern part of Cass County. Ulteig Engineers in conjunction with Hickok & Associates incorporated geophysical testing, along with conventional test drilling, to delineate aquifers in the southeast part of Cass County. Two east-west trending systems are shown. The northern one (about 1-2 miles south of Horace) has subsequently been shown to be two different aquifers, and the southern one (about 1-2 miles north of the county line) has proven to not be continuous in the way it is depicted in this report.

Hickok (1982) prepared a report for the U.S. Corps of Engineers describing the water demand projections for the Fargo-Moorhead urban area. A fairly comprehensive discussion of the various water users in the area, and their water supplies and rates of use is included. Hickok (1982b) focuses on the surface water resources. A brief quantification of the Red River valley municipal water supply use and future needs is compiled in the report by the North Dakota State Engineer and the Garrison Diversion Unit Conservancy District (1990).

In the early 1980s several papers and a map were published on aquifer evaluations or the geology and/or hydrogeology of resources in the area. Wolf (1981) presented a comprehensive analysis of the Buffalo aquifer. The report discusses the location, possible origins, aquifer properties, quantity, water quality, water use, surface water interactions, and potential for aquifer recharge of the Buffalo aquifer. Hobbs (1982) published a geologic map of the Quaternary deposits of Minnesota. Hoganson and Harris (1982) evaluated the geologic and geohydrologic aspects of a waste site southeast of Sabin. A good summary of the most recent glacial history (the last 14,000 years) is included. The hydrology is drawn primarily from Arndt and Moran (1974), and the Buffalo is referred to as the "Moorhead or Buffalo Aquifer". Bluemle and Clayton (1983) discussed glacial processes in North Dakota. Brophy and Bluemle (1983) discussed the Sheyenne River and its relationship with glacial Lake Agassiz.

In the mid-1980s a report by Hickok (1984) prepared for the U.S. Army Corps of Engineers reviews available data, published reports, and in-progress work pertaining to water supply/conservation elements for the Fargo-Moorhead urban area. The report separates the West Fargo South from the West Fargo aquifer, enlarges the Fargo aquifer, and identifies the Kragnes aquifer as an aquifer located on the north side of Dilworth. In other portions of the report the West Fargo aquifer has a very similar configuration as that found in Klausing (1968b). The U.S. Army Corps of Engineers (1985) report is almost identical to the Hickok (1984). The U.S. Army Corps of Engineers (1985b) report provides a general overview of the water resources of the

Fargo-Moorhead urban area, as well as the physiographic, biological, and cultural elements of the area. This report presents the earlier Klausing (1968b) configuration of the West Fargo aquifer.

Armstrong (1985) studied the West Fargo aquifer system by reviewing previous work, and incorporating additional subsurface exploration. The result was a reconfigured model of the West Fargo aquifer that consisted of the West Fargo North, the West Fargo South, and the Horace aquifers, as well as the Fargo aquifer and an unnamed aquifer that was configured as occurring beneath the Sheyenne River from 5 miles northeast of Kindred to about a mile south of West Fargo. The report contains numerous geologic-sections, as well as potentiometric maps for 1963-64 and 1981.

In the late 1980s one publication presented the surface geology of the area, and another paper discussed deformation beneath glaciers. Harris (1987) published a map of the surface geology of the southeast corner of North Dakota including Ransom, Richland, Sargent counties as well as the southern half of Cass, and the southeastern fourth of Barnes counties. The map displays a description of the lithologies, interpretations of the age and origin of the sediments, and a description of the topography. Boulton and Hindmarsh (1987) presented experimental data and theory for subglacial deformation in Iceland. Drumlin and tunnel valley formation and the relationship of subglacial bed permeability to those formations are discussed in the report.

One of the first papers to discuss tunnel valleys in the upper Midwest (east-central Minnesota) was by Wright (1973). This paper gives a detailed discussion on tunnel valleys, and is one of the first papers presenting several mechanisms for the formation of tunnel valleys. Additional discussions of tunnel valleys can be found in Mooers (1989), Gorrell and Shaw (1991), and Patterson (1994). Harris et al (1996) discuss the Buffalo aquifer in terms of buried tunnel valleys.

Additional information on the Buffalo aquifer pertaining to a geo-electrical investigation using soundings can be found in Zohdy and Bisdorf (1979). Ulteig (1987) reports on test well drilling in the Buffalo aquifer, and evaluates hydraulic coefficients of the aquifer in the area of the drilling. A description of the Buffalo aquifer, a description of the hydraulic connections of the aquifer, and an estimate of both the sources of recharge and the volume of recharge to the Buffalo aquifer can be found in Schoenberg (1997).

A regional hydrogeologic assessment of the quaternary geology of the southern part of the Red River valley in Minnesota and North Dakota was completed by Harris et al (1995). This report has a lithostratigraphic map of the greater Red River valley. This publication also has a surficial geological map and Quaternary stratigraphy for the southern Minnesota portion of the study area.

Chemical and water-quality aspects of the study area, or chemical processes occurring in the study area are presented in several diverse reports. Hem (1985) presents a comprehensive discussion of the study and interpretation of the chemical characteristics of natural water. Shaver (1995) discusses the use of the stable isotopes of oxygen and hydrogen to assess recharge implications in North Dakota ground-water settings.

Downey (1986) describes a regional bedrock flow system that can impact the salinity of some of the Red River Valley ground-water systems. Strobel and Haffield (1995) discuss this same factor in a report on the salinity of surface water in the Red River of the North basin.

Stoner et al (1993) describes the physical, chemical and aquatic-biological characteristics of the regional water quality in the U.S. portion of the Red River basin (Red River of the North Basin Study Unit). The report provides baseline and historical information for the study unit. Stoner et al (1998) summarizes the major findings that emerged between 1992 and 1995 from the water-quality assessment of this Red River of the North Basin Study Unit. Cowdery (1998) uses a basin-wide sampling approach to depict the general character of water quality in this same study unit.

Numerous studies have been completed on the old and new Fargo landfill sites. A soils investigation of the new Fargo landfill site was done by Midwest Testing Laboratory (1979). Berreth (1986) investigated the potential for ground-water contamination resulting from leachate emanating from the old Fargo landfill. Donohue (1990 and 1990b) presents a comprehensive set of data on shallow subsurface information, including lithologic logs of the material, and hydraulic conductivities. Additional shallow subsurface information is available from two reports completed by Twin City Testing (1983 and 1990). A site suitability study by Olson and Greer (1995) also includes shallow subsurface data in the vicinity of the new Fargo landfill.

Significant subsurface data on the southern portion of the WFAS is available from the Ulteig (1979). Some of the interpretations in this report are based on electric log data, and subsequent test drilling has shown these interpretations to be misleading. The report does have substantial lithologic information, however.

The water-resource data associated with this report, Ripley (1997, 1997b, and 1997c) is the most comprehensive set of data available for the study area. This data includes lithologic logs, water levels, and water quality analyses, as well as water use. Water use data for Moorhead was reported by McLain (1996).

The U.S. Bureau of Reclamation (USBR) addresses water shortages and appraises alternatives to meet those projected water shortages in the Red River Valley in a report consisting of five parts (1998, 1999, 2000, 2000b, and 2000c). The different methods that could be used to meet water shortages are presented as features. These

21 features are presented in different combinations, and presented as alternatives. The eight alternatives are applicable to the North Dakota side of the water needs of the Red River valley. Additionally, the Water Supply Task Force Group of the Red River Basin Board (2000) has prepared a draft Red River basin water supply report. This draft report expands the USBR area of discussion to include the entire Red River basin, incorporating significant areas in Minnesota and Manitoba. This draft incorporates three of the USBR features. The three features are conservation practices, a treatment plant between the McClusky and New Rockford canals to transfer Missouri River water to the Red River valley, and aquifer storage and recovery (ASR).

APPENDIX B

DEFINITIONS

aquifer	A body of rock, gravel, or sand that is sufficiently permeable to conduct ground water and to yield economically significant quantities of water to wells and springs. An aquifer serves as a transmission conduit and as a storage reservoir.
aquifer boundary	A boundary usually is thought of as being delimited by a bounding or separating line. An aquifer boundary usually occurs as a zone in which material through which water moves easily transitions into material through which water does not move as easily.
aquifer coefficient	A number that serves as a measure of some property of the aquifer. Some examples would be specific storage, storage coefficient, and transmissivity.
aquitard	Material that retards, but does not prevent, the flow of water to or from an adjacent aquifer. It does not readily yield water, but may serve as a storage unit for ground water.
compressibility	A property of an aquifer whereby the aquifer skeleton is capable of being compressed.
cone of depression	A depression in the potentiometric surface or water table of a body of ground water, which has the shape of an inverted cone and develops around wells from which water has been withdrawn.
confined aquifer	An aquifer bounded above and below by beds of distinctly lower hydraulic conductivity than that of the aquifer itself; an aquifer containing confined ground water.
deuterium	The hydrogen isotope that is of twice the mass of ordinary hydrogen and that occurs in water. Deuterium is also called heavy hydrogen.
distance-drawdown analysis	A technique of pump test analysis that uses drawdowns at wells at various distances from the pumping well to complement time-drawdown analysis.
elasticity	The property of a strained body to recover its size and shape after deformation resulting from the strain.
heavy hydrogen	See the definition for deuterium.
heavy oxygen	See the definition for oxygen-18.
hydraulic conductivity	The capacity of a porous rock, sediment or soil to transmit fluid under unequal pressure.

hydrograph	In this report a hydrograph is a graph showing a plot of water-level elevation versus time.
isotope	Any of two or more species of atoms of an atomic element having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. The result of the different number of neutrons results in a different mass.
oxygen-18	The oxygen isotope that is 1.125 times heavier than the mass of ordinary oxygen and that occurs in water. Oxygen-18 is also called heavy oxygen.
per mil difference	A way of expressing the ratio of the concentration of the heavy isotope of hydrogen or oxygen in a sample to the concentration of the same isotope in a standard oceanic sample, called Standard Mean Ocean Water (SMOW). The ratio is multiplied by 1000 because of the small occurrence of the heavy isotopes in water.
piezometer	A well constructed so that the well screen portion of the well is in connection with only a small portion of the medium in which the hydrostatic pressure (water level) is being measured.
potentiometric lines	A line connecting points of equal potential (equal water-level elevation in unconfined aquifers). Ground water flows at right angles to the potentiometric lines.
potentiometric surface	An imaginary surface representing the total head of ground water and defined by the level to which water will rise in a well. The water table is a particular potentiometric surface for an aquifer that is unconfined.
residual-drawdown analysis	A technique of pump test analysis that plots time data on a logarithmic scale and drawdown data on a linear scale. The data plotted is data gathered during the recovery after the pumping of the well has stopped.
specific capacity	The rate of discharge of a water well per unit of drawdown, commonly expressed in gallons per minute per foot of drawdown.
specific storage	The volume of water which a unit volume of the aquifer releases from storage because of expansion of water and compression of the aquifer under a unit decline in the average head within the unit volume of the aquifer.
specific yield	The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass. This ratio is stated as a percentage. This is approximately the specific storage for an unconfined aquifer.
stable heavy isotope	An isotope that has an extra neutron, or extra neutrons, that makes the element heavier than normal, but that does not decay, and as a result remains stable (not radioactive).

storage coefficient	The product of specific storage and aquifer thickness for a confined aquifer.
sub aquifer	Used in this study to describe a body of sands and gravels of moderate to large hydraulic conductivity that are surrounded by materials of small hydraulic conductivity, but that also are related to other bodies of sand and gravel to a limited degree.
time-drawdown analysis	A technique of pump test analysis that plots time data versus drawdown data on either a log-log scale or a log-linear scale. These plots are used to determine aquifer properties when used in conjunction with various well functions.
transmissivity	The rate at which water is transmitted through a unit width of an aquifer under unit hydraulic gradient. While considered a property of the aquifer, the term also incorporates the properties of water.
trapped Pleistocene water	A term used to describe water that would have been emplaced during the end of the Pleistocene time period (about 10-20,000 years ago). The water is assumed to have been emplaced in places where flow was limited, and the water trapped.
unconfined aquifer	An aquifer that has ground water with a free water table, i.e. is not confined under pressure beneath material of small hydraulic conductivity.
water-level gradient	A measure of the decline in potential (water level in unconfined aquifers) per unit distance. The term is commonly expressed in feet per mile.