The Hydrogeology of the

Spiritwood Aquifer System

Dickey and Parts of LaMoure and Sargent Counties, North Dakota

By

Robert B. Shaver

North Dakota Ground Water Studies

Number 91, Part II

North Dakota State Water Commission

THE HYDROGEOLOGY OF THE SPIRITWOOD AQUIFER SYSTEM, DICKEY COUNTY AND PARTS OF LAMOURE AND SARGENT COUNTIES, NORTH DAKOTA

NORTH DAKOTA GROUND-WATER STUDIES
NUMBER 91 - Part II

By
Robert B. Shaver, Hydrogeologist
North Dakota State Water Commission

Published By

North Dakota State Water Commission
State Office Building
900 East Boulevard
Bismarck, North Dakota 58505

1984

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The Spiritwood aquifer system underlies an area of approximately 110 square miles in southeastern LaMoure, northeastern Dickey and northwestern Sargent Counties in southeastern North Dakota (fig. 1). As of 1984, the State Engineer has approved the appropriation of 6,625.5 acre-feet of ground water from the Spiritwood aquifer in this area to irrigate 4,769.5 acres of land. Additional appropriations amounting to 2,900.3 acre-feet of ground water to irrigate 1,914.6 acres of land have been deferred. These appropriations have been deferred due to the lack of an adequate conceptual model of the aquifer system. In particular, the distribution and rate of natural recharge and discharge have not been defined. The objectives of this report are threefold: 1) to describe the present conceptual model of the aquifer system, 2) to determine which aspects of the conceptual model require further investigation, and 3) to propose a future work plan. The purpose of future study is the development of an acceptable aquifer management program.

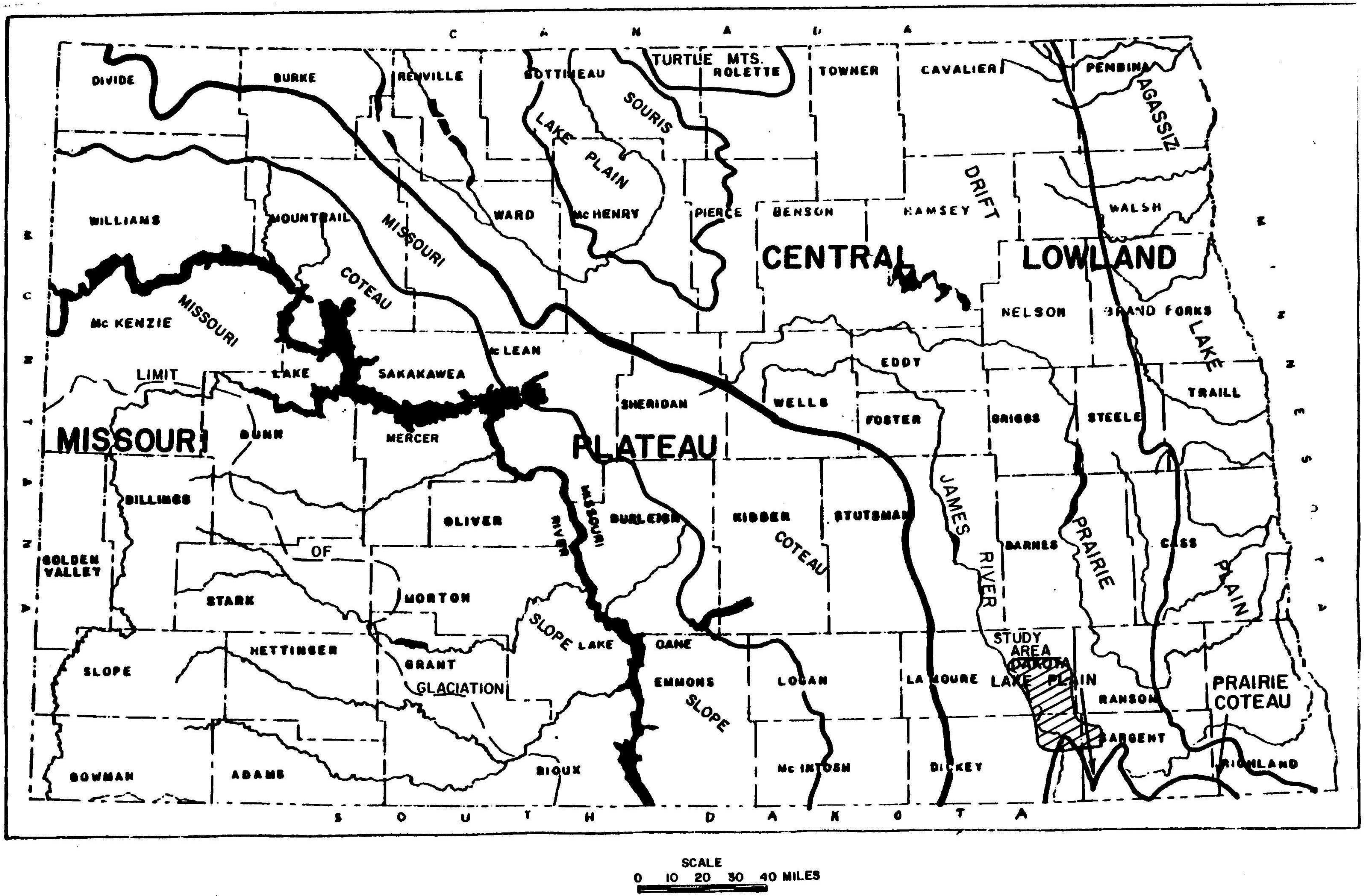


FIGURE 1.—Study area location

LOCATION-NUMBERING SYSTEM

The location-numbering system is based upon the location of a well or test hole in the Federal system of rectangular surveys of public lands (fig. 2). The first number denotes the township north of a baseline and the second number denotes the range west of the Fifth Principal Meridian. The third number indicates the section in which the well or test hole is located. The 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). Thus well 131-59-12AAA would be located in the NE¼NE¼NE¼ Section 12, Township 131 North, Range 59 West. Consecutive terminal numerals are added if more than one well is located within a 10 acre tract.

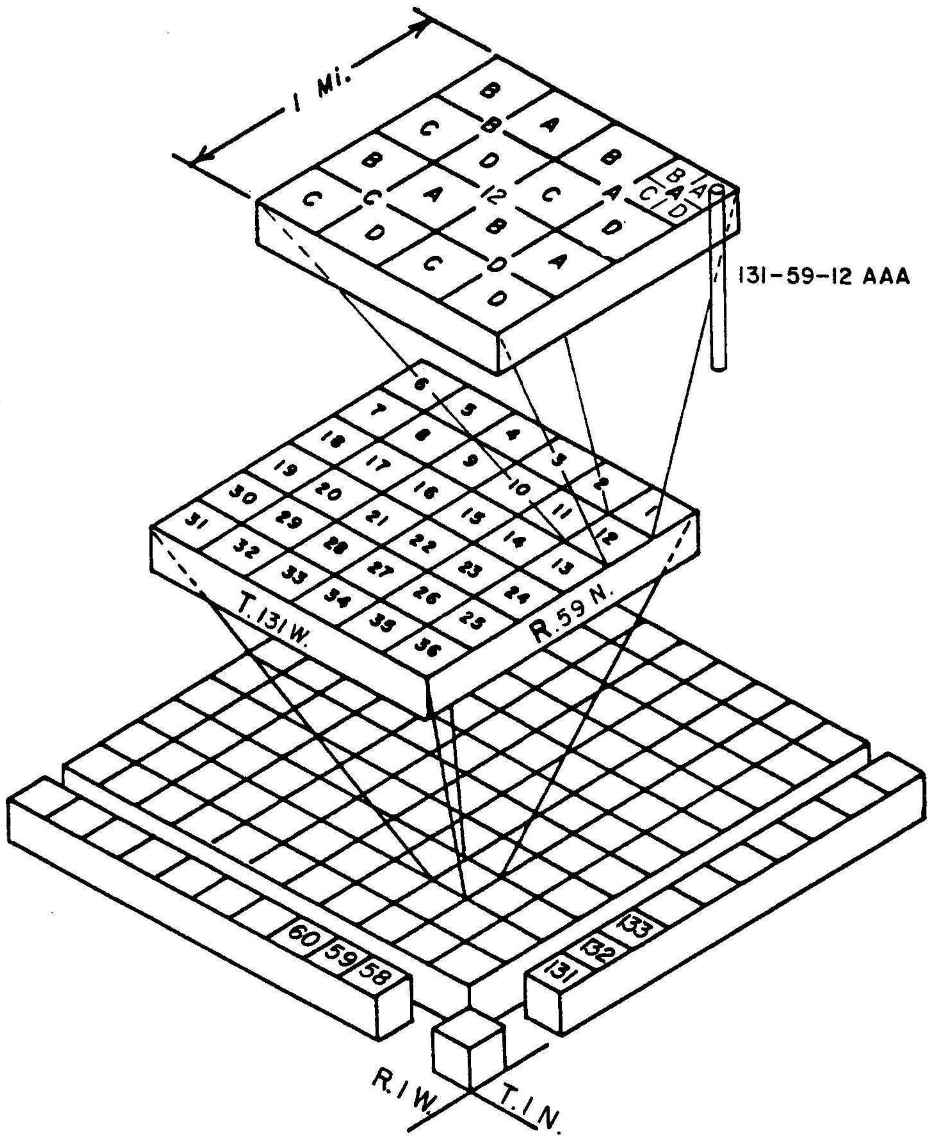


FIGURE 2.—Location-numbering system

PREVIOUS WORK

The geology and water resources of the Edgeley and LaMoure quadrangles (30 minute) were investigated by Hard (1929). The geology and ground-water resources of Dickey and LaMoure Counties are described in a three part report prepared by the U. S. Geological Survey in cooperation with the North Dakota Geological Survey, the North Dakota State Water Commission and the Dickey and LaMoure County Water Management Districts. Bluemle (1979) describes the geology in part I. Armstrong and Luttrell (1978) present the ground-water data in part II. Armstrong (1980) describes the ground-water resources in part III.

The geology and ground-water resources of Ransom and Sargent Counties are described in a three part report prepared by the U. S. Geological Survey in cooperation with the North Dakota Geological Survey, the North Dakota State Water Commission and the Ransom and Sargent County Water Management Districts. Bluemle (1979) describes the geology in part I. Armstrong (1979) presents the ground-water data in part II. Armstrong (1982) describes the ground-water resources in part III.

METHODS OF INVESTIGATION

Field work for the cooperative ground-water studies was completed in December 1976. Since that time, the State Water Commission has drilled additional test holes and installed additional observation wells throughout the Spiritwood aquifer system in the study area. Forward mud-rotary drilling rigs were used to drill all test holes. A lithologic log was prepared by the driller and by the site geologist. At some sites, borehole geophysical logs were made. These include, electric (resistance-spontaneous potential), gamma and neutron logs.

The observation wells were constructed using 20 foot lengths of 1¼-inch diameter plastic pipe, and 1¼-inch diameter plastic or galvanized steel screen. Screen lengths generally varied from 3 to 5 feet. An 0.018-inch slot screen was commonly used. A check valve was attached to the bottom of the screen. The plastic casing, screen and check valve were assembled prior to insertion into the drill hole. Once inserted, the hole was "back-flushed" through the screen to clean the formation. After "back-flushing" the hole was blown with air to collapse the formation around the screen. Drill cuttings were then shoveled into the well annulus.

During the summer of 1982, two nests of three piezometers each were completed in the Spiritwood aquifer system. The nests are located at 131-59-5BAA and 132-59-17CDC. For each nest, one well was completed in the Spiritwood aquifer, one was completed in the glacial till above the Spiritwood aquifer and one was completed in an overlying, glaciofluvial sand. Each well screen was packed with silica sand. Bentonite pellets were inserted down the annulus using a tremie pipe to seal the top of the sand pack. Cement was pumped into the annulus to provide a continuous seal to land surface. The construction procedure was used for each piezometer so that an accurate vertical head profile could be determined at the nest site.

Aquifer/response tests have been conducted on five irrigation wells completed in the Spiritwood aquifer in the study area. Water levels in observation wells were measured using Keck water-level sensing instruments, Stevens recording devices, and chalked steel tapes. Discharge was measured continuously using a Barton flowmeter coupled with a modified Cox Pitot tube. Various analytical methods were applied to the data obtained from these tests to determine aquifer hydraulic properties and, in some cases, boundary configurations.

Water samples were collected from most of the observation wells completed in the study area. Water samples were also collected from domestic/stock wells known to have been completed in the Spiritwood aquifer. The State Water Commission observation wells were sampled by air lifting the water out of the well using a small diameter rubber hose attached to a portable air compressor. The specific conductance and water temperature were measured at each sampling site. The water temperature was measured at land surface and does not represent an in-situ temperature. Three samples were collected from each well.

1) 250 milliliter - raw
2) 500 milliliter - filtered
3) 500 milliliter - filtered and acidified

A 0.45 micron filter was used to remove suspended sediment, and a 2-milliliter ampule of concentrated nitric acid was added to prevent the precipitation of metals. The samples were collected in plastic bottles and sent to the State Water Commission Laboratory in Bismarck for major anion-cation analysis.

The State Water Commission currently monitors monthly water levels in observation wells in the study area. Hydrographs have been prepared for each observation well and are periodically updated.

Annual water use for each appropriator was determined from data submitted on water use report forms of the State Water Commission. In some instances, the appropriator failed to return the form or the data reported was inaccurate. Kilowatt-hour and average monthly demand data from the rural electric cooperatives were also utilized to determine water use.

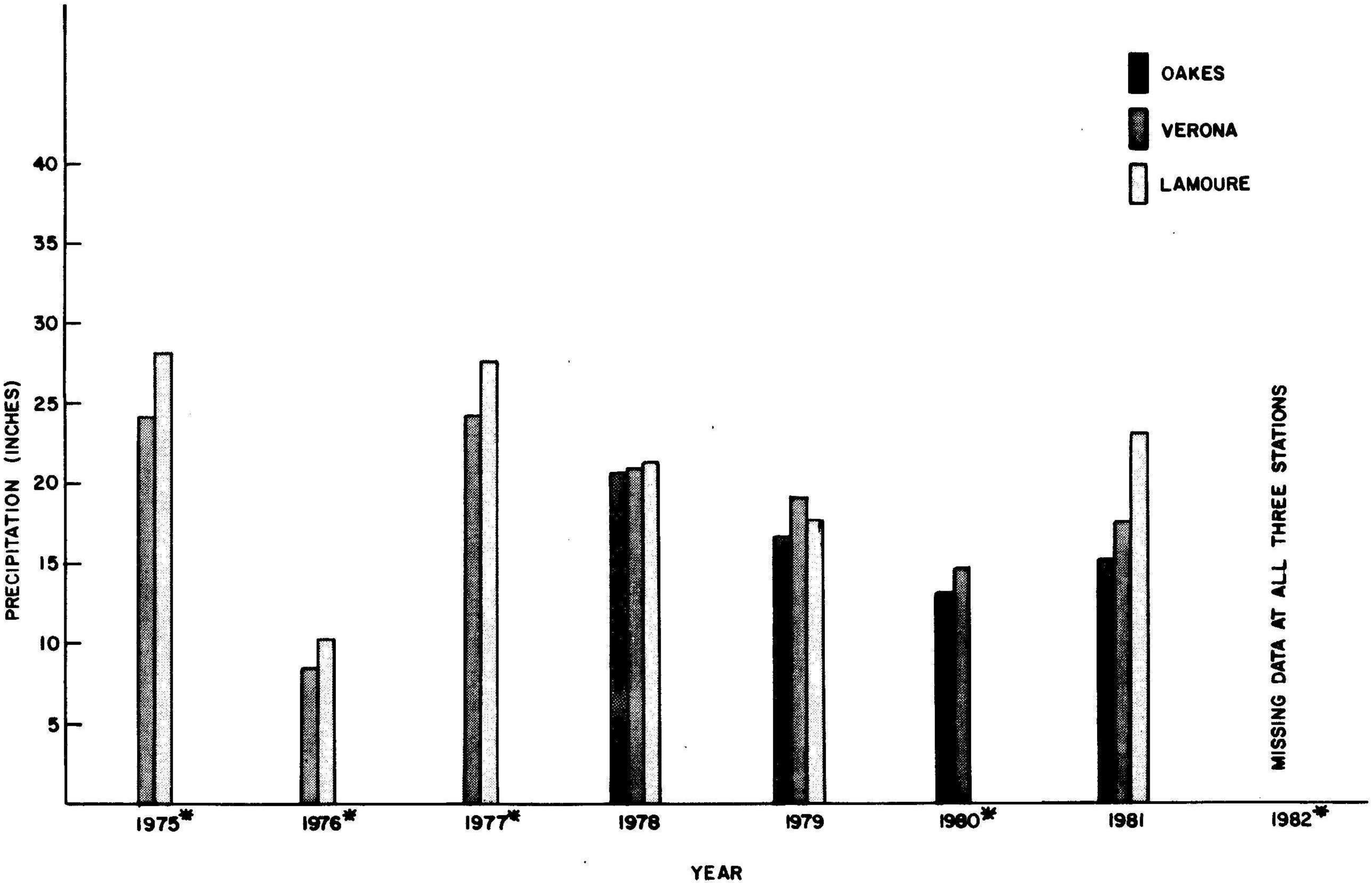
Beginning in 1972, State law has required that drillers submit completion reports for all drill holes and wells completed in North Dakota. The commercial completion reports provide additional lithologic data within the study area. Summaries of all State Water Commission and commercial completion reports pertinent to the study area are in Part 1 of this report. The location of all test holes and observation wells are shown on plate 1.

PHYSIOGRAPHY

The study area is situated in the Drift Prairie district of the Central Lowland province (fig. 1). The study area is flanked to the west by the James River Valley and is partially drained by Bear Creek (pl. 1). The land surface in the northern part of the study area is rolling with kettles. Drainage is partially integrated to non-integrated. Relief is 30 to 60 feet locally. The land surface in the central and southern part of the study area is gently undulating to undulating. Drainage is poorly integrated. Relief is generally less than 10 feet (Bluemle, 1979a, b). Land surface elevations are highest (approximately 1450 feet above mean sea level) in the northwestern part of the study area between Twin Lakes and the James River Valley. Land surface elevations are the lowest (approximately 1300 feet above mean sea level) in the vicinity of Oakes and within the James River Valley. There is an overall decline in land surface elevation from northwest to southeast in the study area.

CLIMATE

The climate of the study area is semiarid to subhumid. The National Oceanic and Atmospheric Administration (NOAA) received precipitation data from gauging stations located at Oakes, Verona and LaMoure, all within the vicinity of the study area. Annual values of precipitation from 1975 through 1982 for Oakes, Verona, and LaMoure were compiled (fig. 3). Over the period from 1975 through 1982 the maximum annual precipitation was 28.07 inches at LaMoure in 1975 and the minimum annual precipitation was 8.41 inches at Verona in 1976. About 70 percent of the precipitation generally falls from April through August (Armstrong, 1980). Summers are warm with temperatures commonly exceeding 90°F. Winters are cold with temperatures commonly falling below 0°F. Relative humidity, particularly during the summer months, is low.



*DUE TO MISSING DATA, PRECIPITATION IS NOT SHOWN AT SOME STATIONS

FIGURE 3.–Annual precipitation at LaMoure, Verona and Oakes

GEOLOGY

The Niobrara Formation of Cretaceous Age unconformably underlies the Pleistocene deposits of the Coleharbor Group in the central and southern part of the study area and conformably underlies the Pierre Formation in the northern part of the study area (pl. 2). The Niobrara Formation is a brown shale with light gray calcareous inclusions. Samples from the formation strongly effervesce in dilute hydrochloric acid, leaving a dark brown residue. The Niobrara Formation is a marine sediment.

In the vicinity of Twin Lakes and Verona, the Pierre Formation of Cretaceous Age unconformably underlies the Pleistocene deposits of the Coleharbor Group. The Pierre Formation is a dark black shale with occasional light-gray bentonite layers. The shale is non-calcareous and has a smooth greasy texture. The Pierre Formation is a near shore marine sediment.

The Coleharbor Group unconformably overlies the Cretaceous shales. Bluemle (1979) divides the Coleharbor Group into three main textural facies:

1) till
2) silt and clay
3) sand and gravel

The till facies consist of a non-stratified, non-sorted mixture of clay, silt, sand, gravel, pebbles, cobbles, and boulders. The clay and silt generally make up the matrix. The coarse-grained materials are generally angular to subrounded and consist of igneous, metamorphic, carbonate and shale fragments. The till facies predominates over most of the study area.

The silt and clay facies is glaciolacustrine. The lithology ranges from clay to silt to fine sand and can occur as a mixture of the above grain sizes. The silt and clay facies occurs just north of Oakes in both outcrop and in the subsurface.

The sand and gravel facies is glaciofluvial and consists of variable portions of subangular to rounded, poor- to well-sorted sand and gravel with occasional thin layers of silt and/or clay. Stratification is common. Surficial exposures of the sand and gravel facies in the study area occur as eskers, as uncollapsed floodplains, and as terrace deposits within the James River Valley. The sand and gravel facies also occurs in the subsurface as an extensive buried-valley complex (Spiritwood aquifer) and as less extensive deposits scattered throughout the till facies.

The Oahe Formation of Holocene age overlies the Coleharbor Group in scattered areas throughout the study area as:

1) pond and slough sediment (clay facies),
2) colluvial sediment (bouldery, gravelly, clay facies),
3) river sediment (sand and silt facies),
4) windblown sediment (sand and silt facies).

GROUND-WATER HYDROLOGY

Aquifer Composition and Geometry

The Spiritwood aquifer consists of variable portions of sand and gravel with occasional, thin, interbedded silt and clay layers. The sand and gravel is angular to well-rounded and consists of a mixture of Canadian shield silicates, carbonates and shale. Lignite fragments are common. Stratification is indicated by the response of the deposits to drilling.

Aquifer thickness ranges from less than a foot on the flanks of the buried channels to more than 274 feet thick at test hole 134-60-29BBB. The average thickness based on 163 test holes is 33 feet.

An isopach map of the Spiritwood aquifer is shown in plate 3. Geohydrologic sections indicate a complex stream-channel pattern (plates 4, 5, and 6). In areas where test drilling was spaced at one-half mile intervals, the channel pattern is braided and occasional long narrow bedrock ridges separate the individual channels.

Two main channel systems occur north of the Dickey-LaMoure County line (pl. 3). The eastern channel trends north-northwest from the Dickey-LaMoure County line toward the city of Grand Rapids. Southwest of Verona, the eastern channel bifurcates and continues southward toward the Dickey-LaMoure County line. A narrow bedrock ridge separates these two channels (geohydrologic section G-G', pl. 5). Channel width varies from approximately 1½ miles east of Twin Lakes to approximately 1 mile just north of the Dickey-LaMoure County line. The channel appears to be truncated by a low-transmissivity barrier which underlies the James River Valley near Grand Rapids. The water level in 134-61-4DDD is approximately 30 feet higher than the water levels in any of the observation wells completed in the Spiritwood aquifer west and north of the James River in the vicinity of Grand Rapids.

The western channel also trends north-northwest of the Dickey-LaMoure County line toward the Twin Lakes area. Channel width varies from approximately 2 miles south of Twin Lakes to 5 miles just north of the Dickey-LaMoure County line. The channel appears to be truncated by a low-transmissivity barrier east and south of Twin Lakes. A continuous narrow bedrock ridge separates the two main channel systems from Twin lakes southeast to the Dickey-LaMoure County line (geohydrologic section G-G', pl. 5). The continuity of the bedrock ridge is inferred from the following:

1) water-level differentials between the eastern and western channel systems particularly in the northern and central areas of these channel systems (pl. 7)

2) drawdown differentials between the eastern and western channel systems during the 1983 irrigation season (pl. 8).

South of the Dickey-LaMoure County line the eastern and western channel systems merge into one channel. The merged channel continues to the southeast just north of the city of Oakes.

At least three transverse low-transmissivity barriers are located approximately two, four and six miles southeast of Bear Creek. The location and extent of these barriers were determined by:

1) abrupt changes in hydraulic head (pl. 7)

2) maximum drawdown during the 1983 irrigation season (fig. 4)

3) residual drawdown over a period from April 14, 1982 to April 27, 1983 (fig. 5)

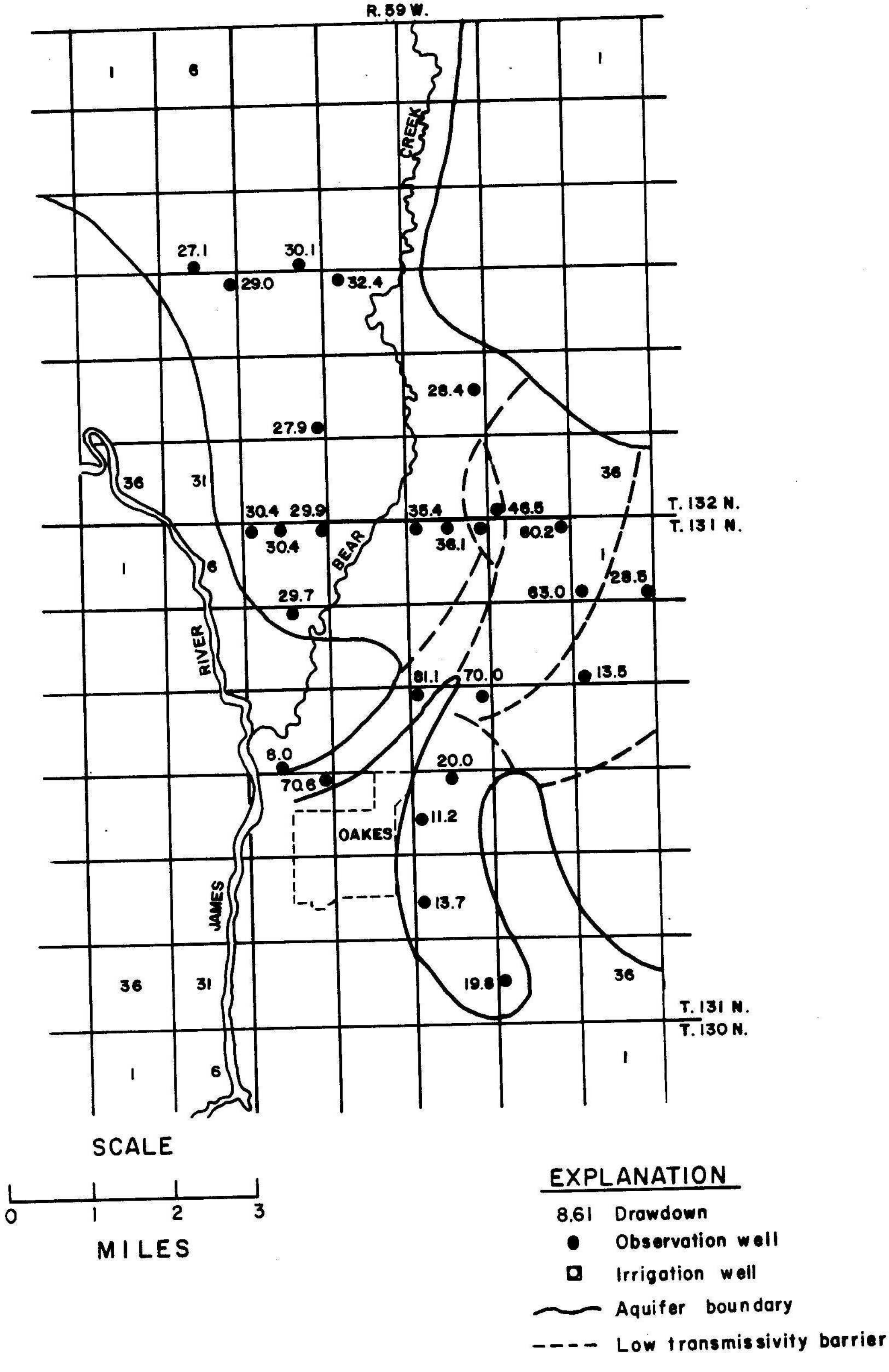


FIGURE 4.-Maximum drawdown, 1983 irrigation season

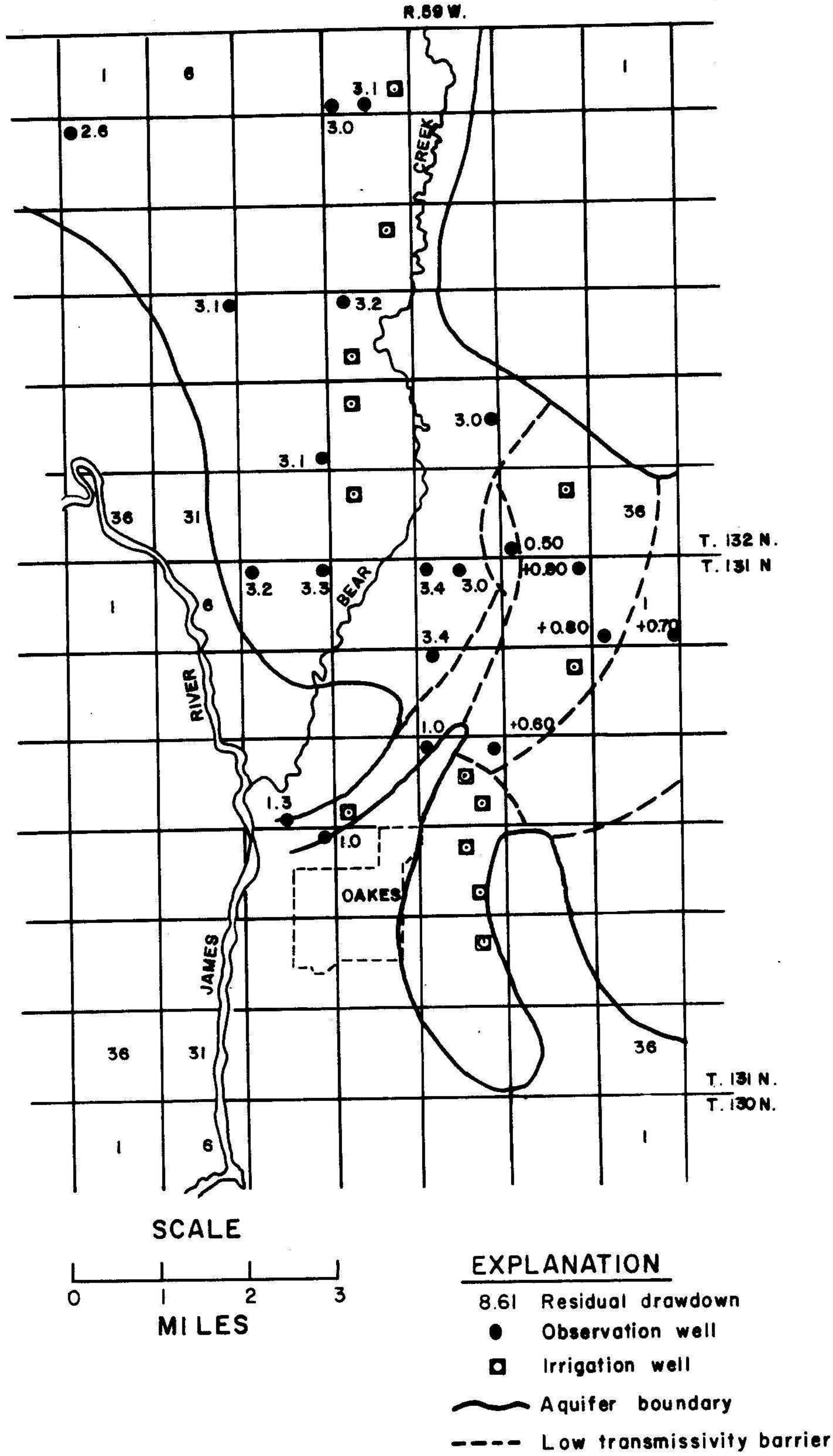


FIGURE 5.-Residual drawdown, April 14, 1982 to April 27, 1983

4) response-test drawdown distribution (fig. 6) (see discussion of Vculek irrigation - well response test under Hydraulic Properties)

5) observation well hydrograph analysis (figs. 7-12)

The hydraulic head distribution (pl. 7) and the drawdown distributions (figs. 4-6) require no discussion. Observation well hydrograph analysis requires further explanation. During October 1979, irrigation well 132-59-28BCA was pumped to irrigate a third crop of alfalfa and was the only well in operation during that time period. The hydrographs of observation wells 131-59-3BBB (fig. 7) and 131-59-5BBB (fig. 8) show the effect of this pumping. The hydrographs of observation wells 131-59-1DDA (fig. 9), 131-59-2AAA (fig. 10), 131-59-15AAA (fig. 11) and 131-59-15BBB (fig. 12) are not affected by this pumping. The response of these and other observation wells throughout this area during October 1979 provided additional evidence for the occurrence of at least one transverse low-transmissivity barrier southeast of Bear Creek.

The channel system continues southeast from the Dickey-Sargent County line toward the city of Cogswell. The geohydrologic data in this area of the aquifer is not adequate to determine in detail the channel geometry.

Occurrence and Movement

Water in the Spiritwood aquifer occurs under confined conditions. The confining lithologies consist of Cretaceous shales below the aquifer and glacial drift above the aquifer. Over most of the study area, the glacial drift consists primarily of till. Glaciofluvial and glaciolacustrine deposits comprise a significant percentage of the drift in the area

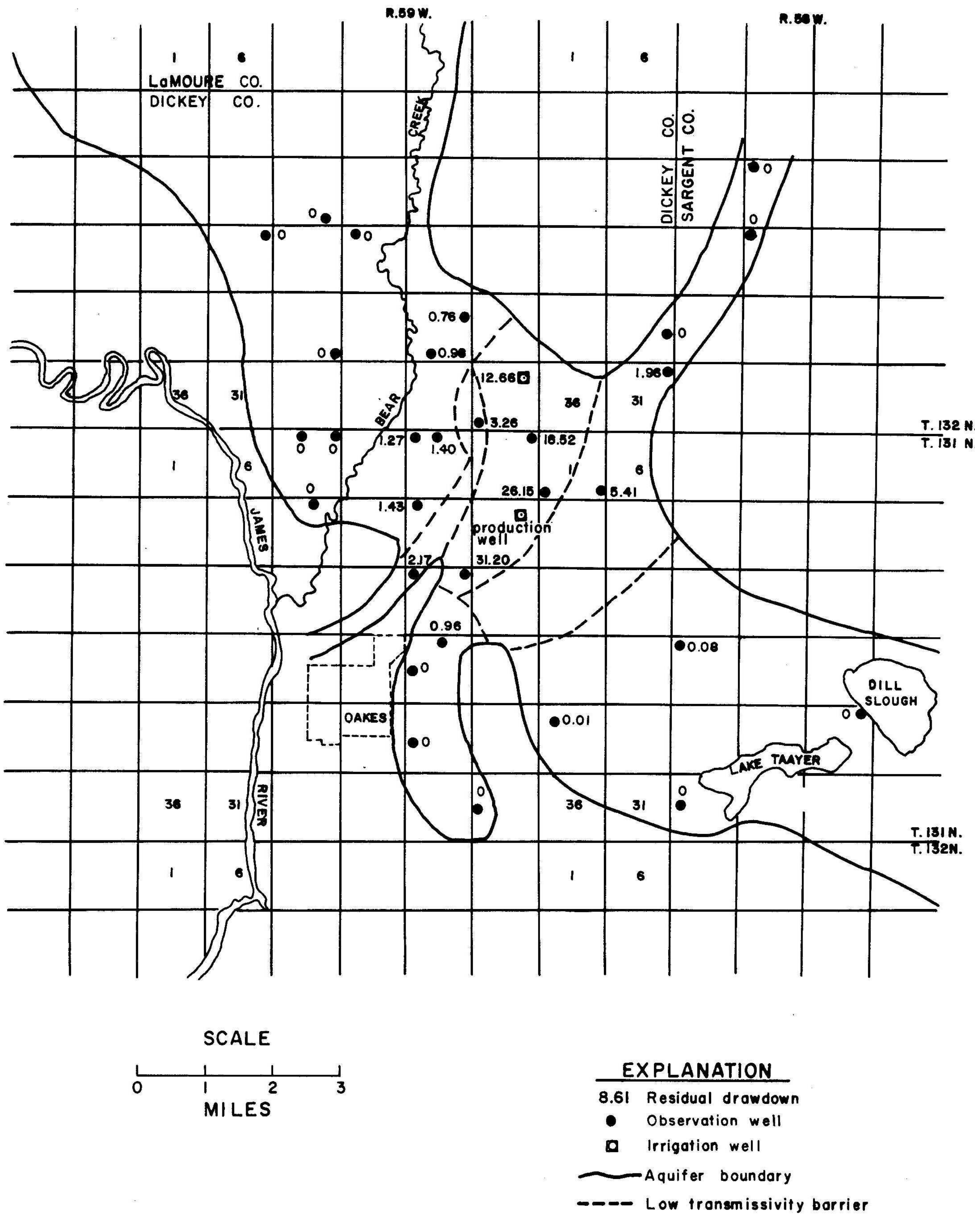


FIGURE 6.–John Vculek response test: drawdown distribution after 6,120 minutes of pumping

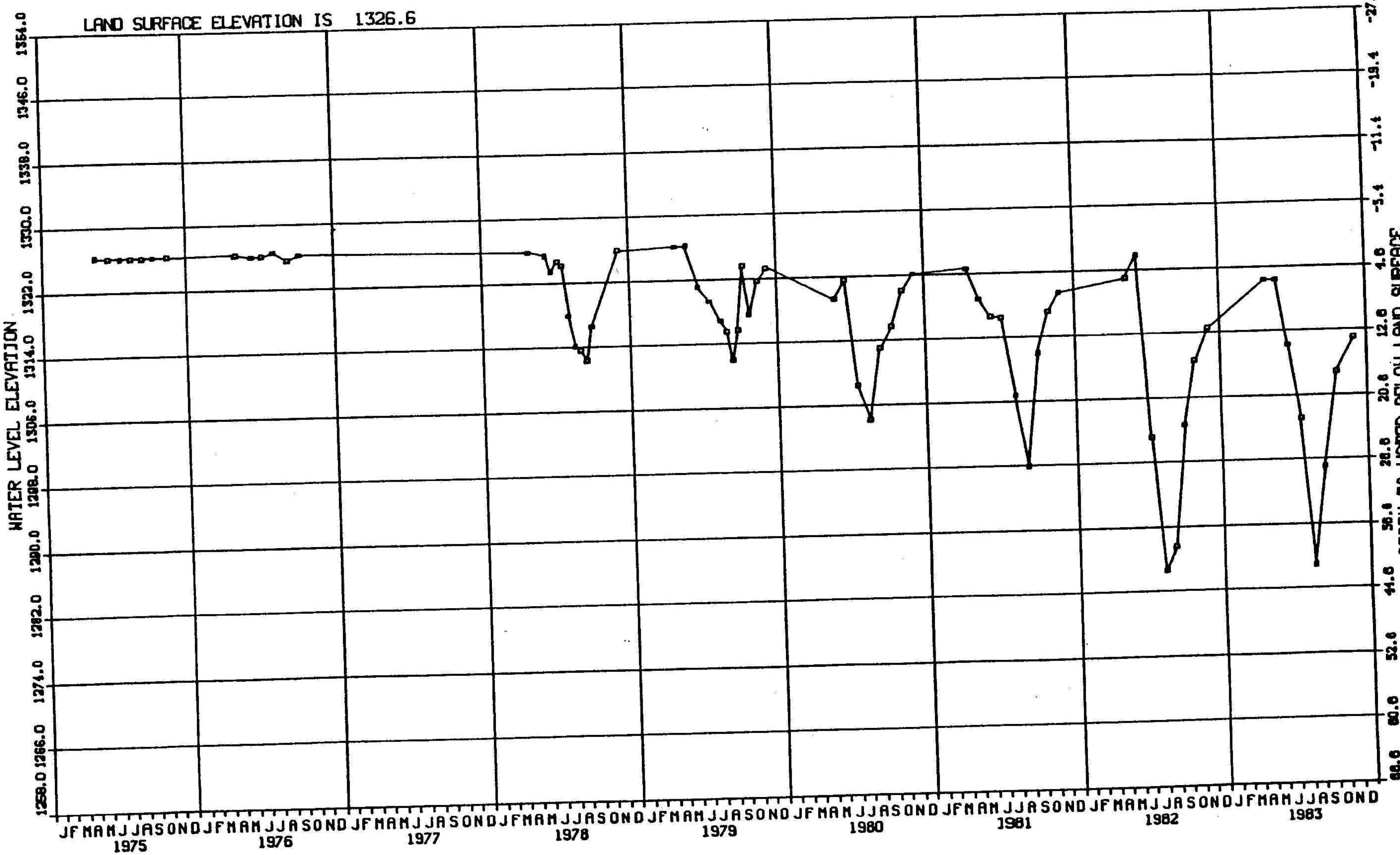


FIGURE 7.—Hydrograph of observation well 131-59-03BBB

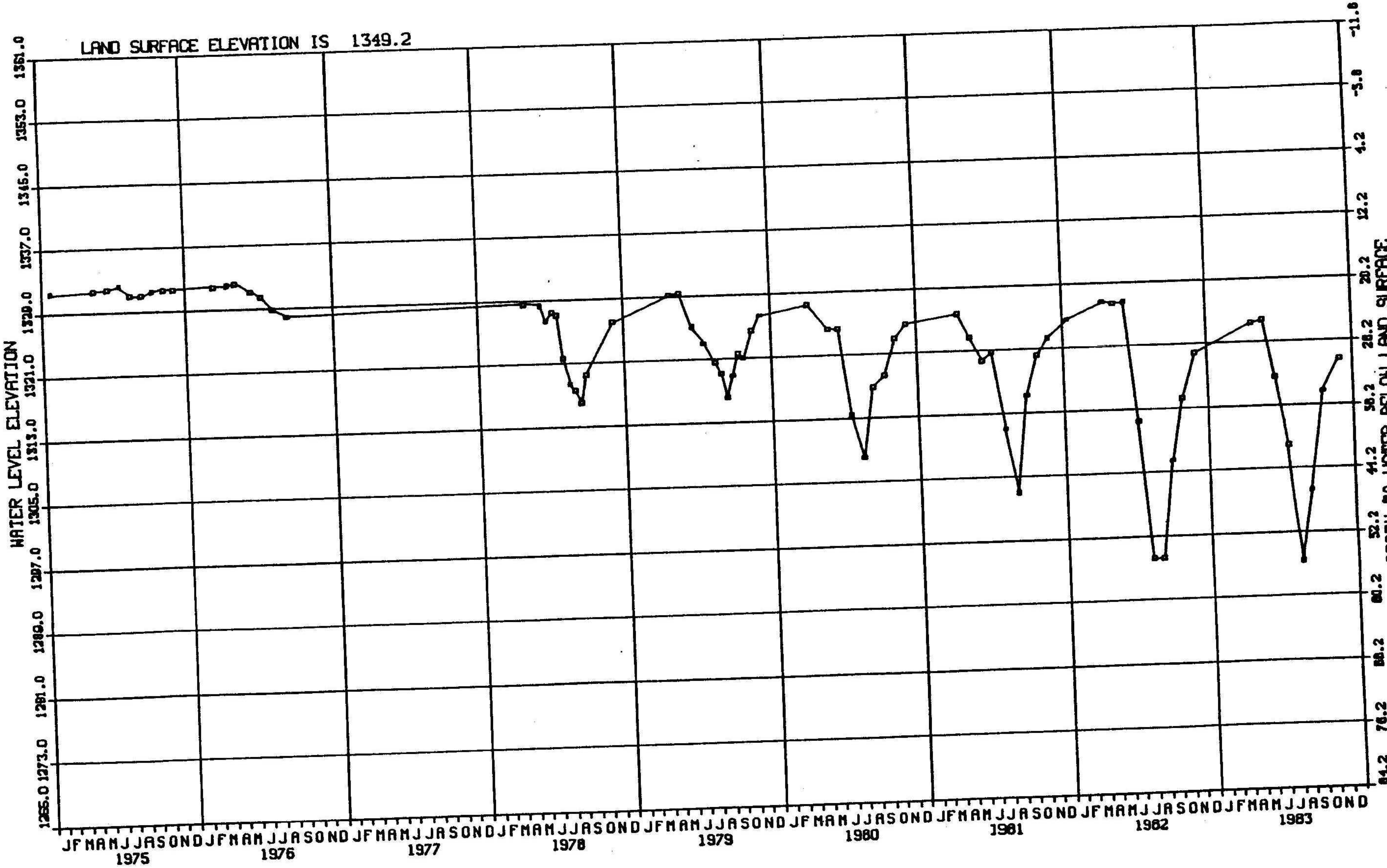


FIGURE 8.—Hydrograph of observation well 131-59-05BBB

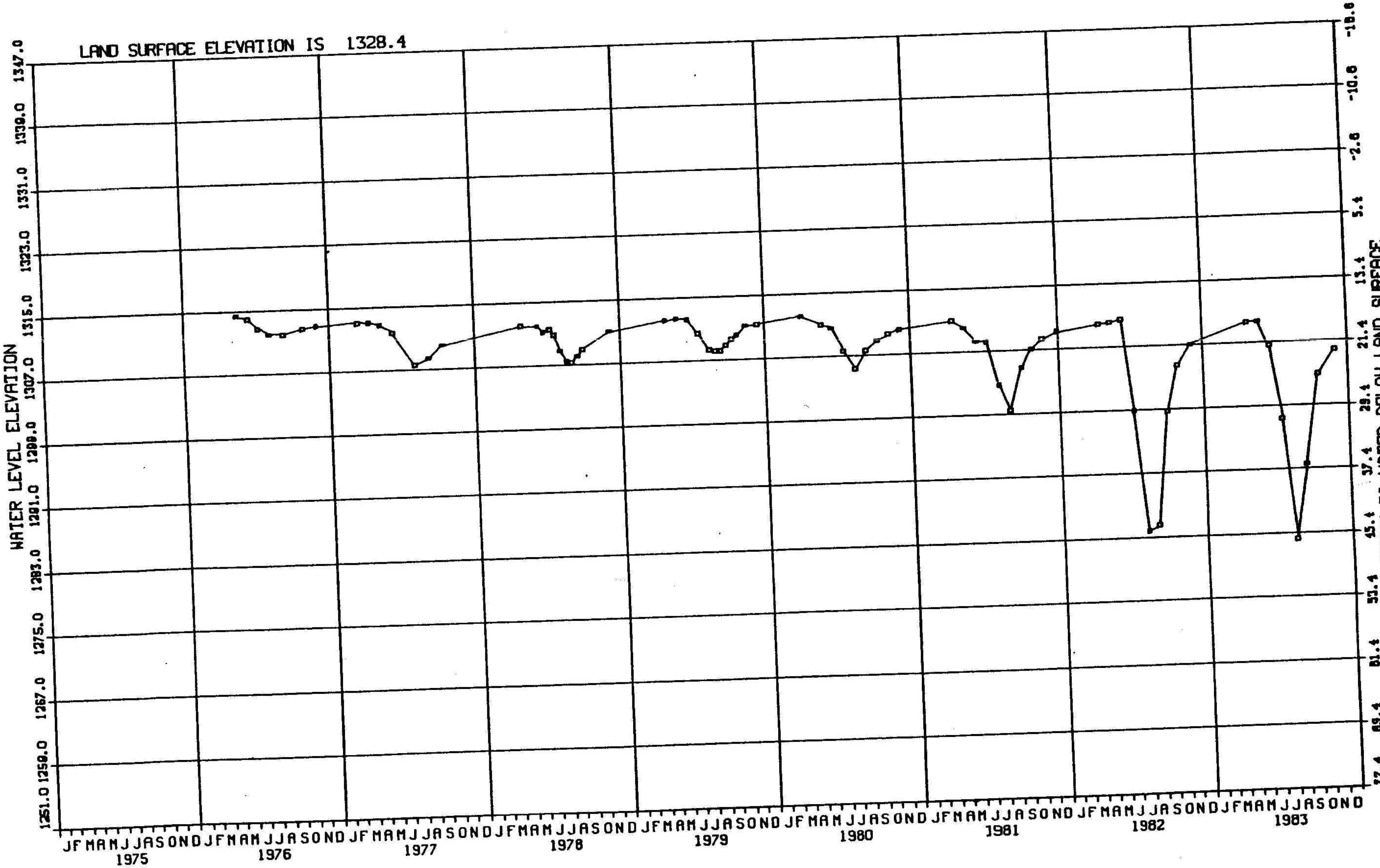


FIGURE 9.- Hydrograph of observation well 131-59-01DDA

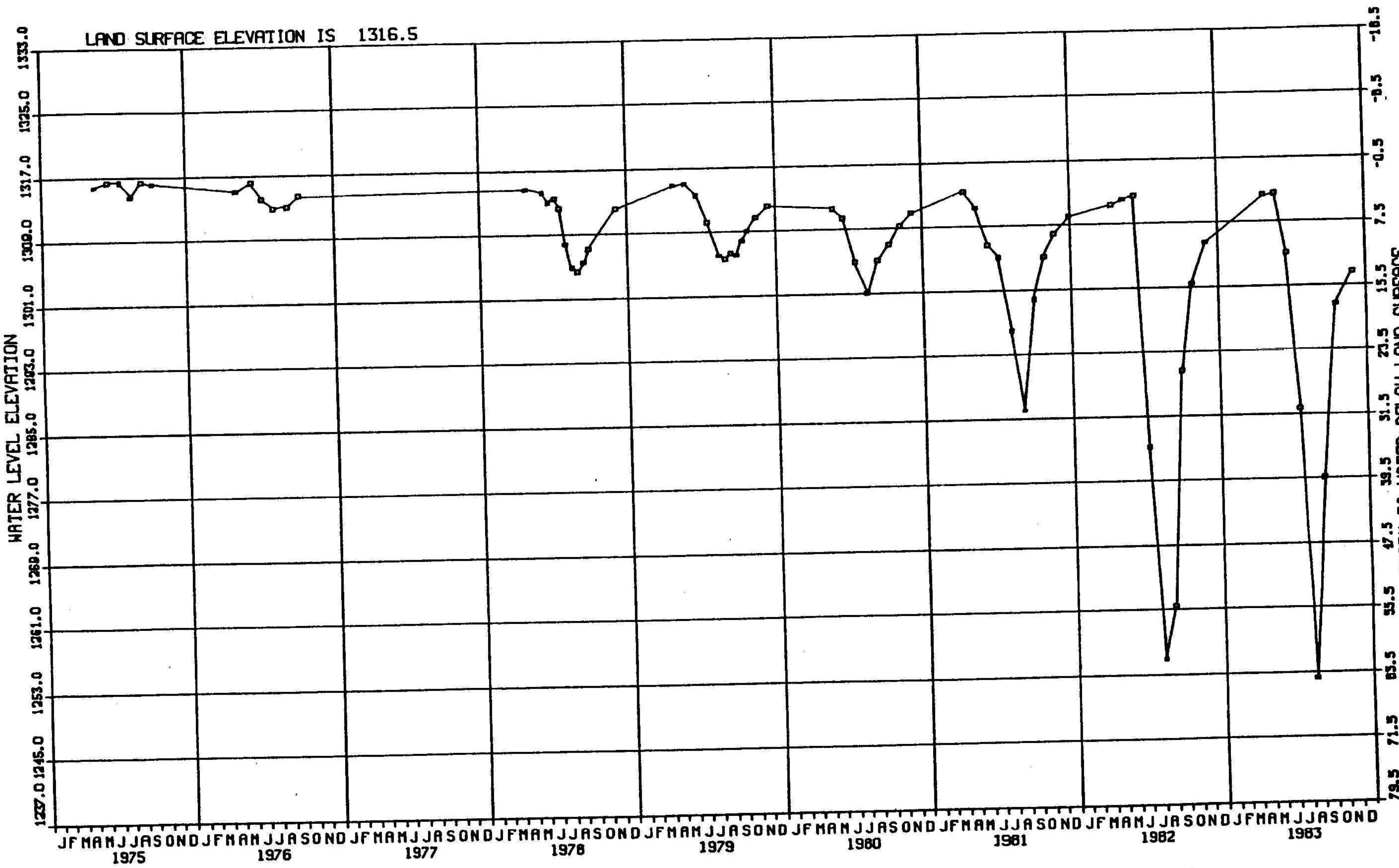


FIGURE 10.–Hydrograph of observation well 131-59-02AAA

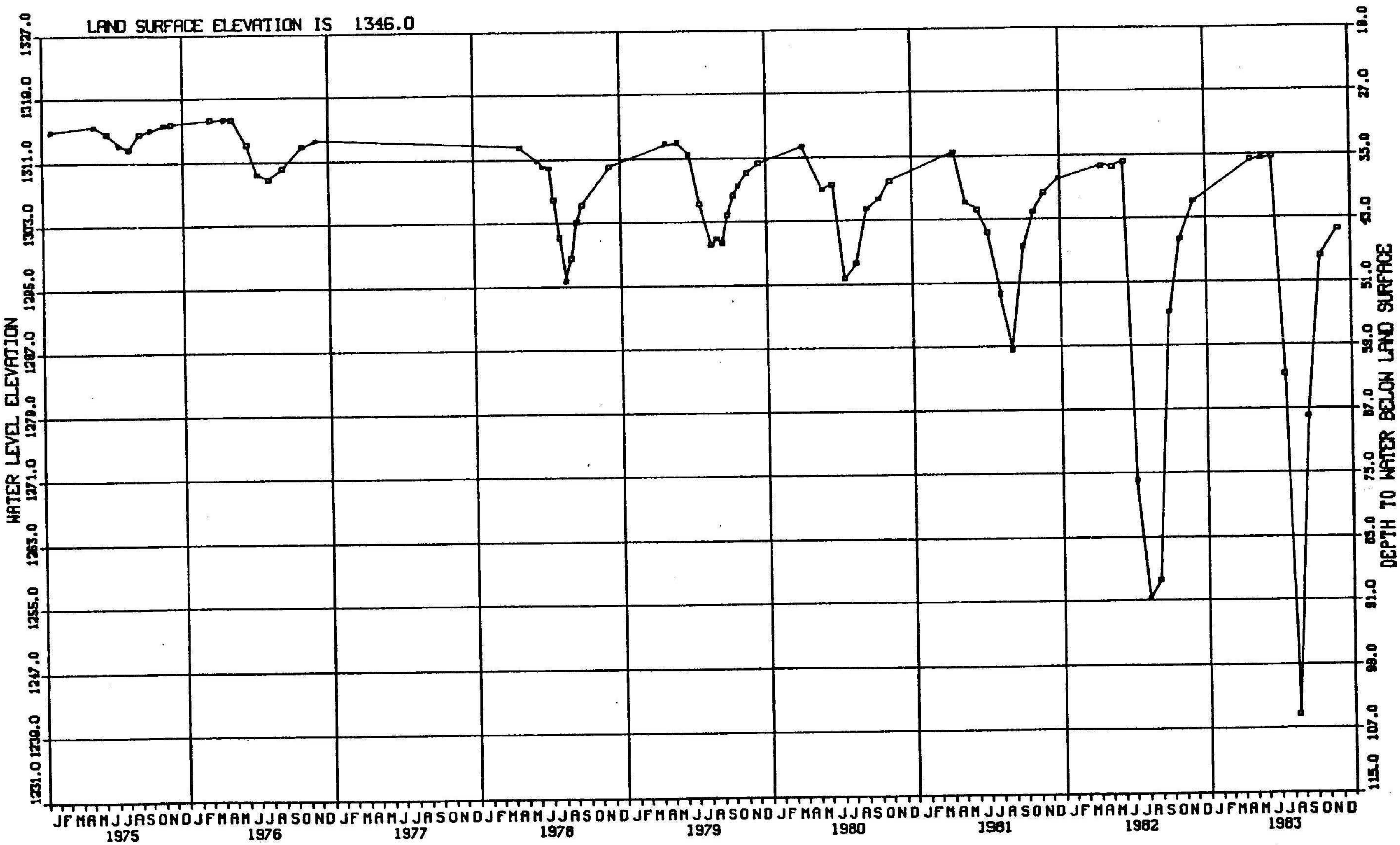


FIGURE 11.-Hydrograph of observation well 131-59-15AAA1

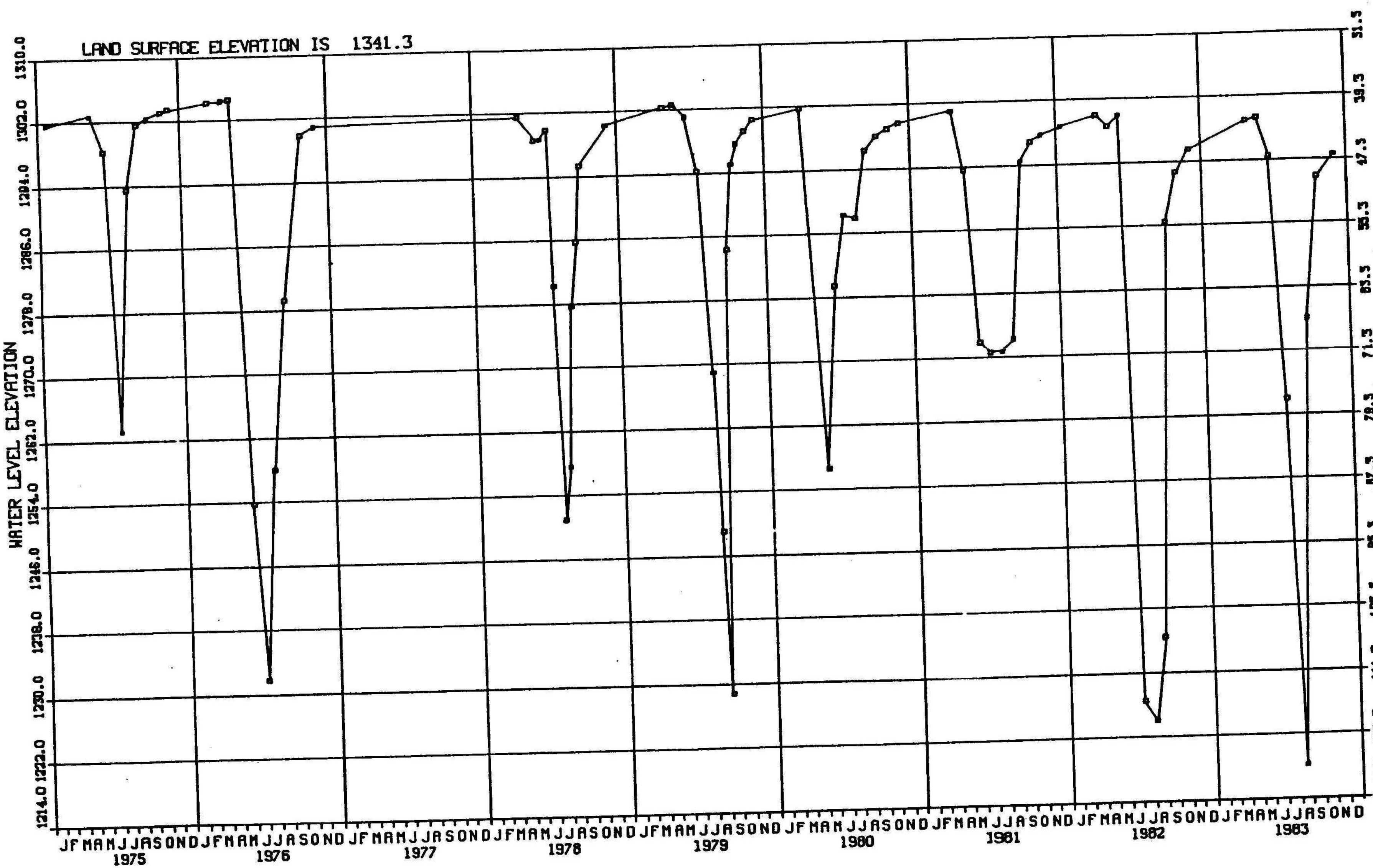


FIGURE 12.-Hydrograph of observation well 131-59-15BBB

north of Oakes and south of the Dickey-LaMoure County line.

The potentiometic surface map is based on water levels measured April 27-28, 1983 (pl. 7). For the most part, ground water flows from northwest to southeast. A ground-water divide is located between observation wells 134-61-14DDD and 134-61-4DDD (Area A). The ground-water divide corresponds to a topographic divide.

Additional observation wells were completed in areas A, B, and C during the summer of 1983 (pl. 7). A potentiometric surface map including these wells was not prepared because water levels were still significantly affected by ground water withdrawals for irrigation. Preliminary interpretation of the water level distribution from these new wells (not shown in pl. 7) during the winter of 1983-1984 indicates the existence of a transverse low-transmissivity barrier just east and south of the Twin Lakes area. The direction of ground-water flow in Area A is to the southwest toward the James River valley (not shown in pl. 7). The inferred low transmissvity barrier just east and south of Twin Lakes impedes water moving to the southeast. As a result, ground water moves to the southwest toward the James River valley. The difference in hydraulic head between the Spiritwood aquifer (Area A) and the LaMoure aquifer which underlies the James River valley is approximately 50 feet and suggests a limited hydraulic connection.

In the northern portion of the eastern channel system (Area B), the hydraulic gradient is less than one foot per mile. Southward, the hydraulic gradient increases to approximately five feet per mile. The increase is probably the result of a decrease in aquifer transmissivity. The areal drawdown distribution during the 1983 irrigation season also suggests a transmissivity decrease in the southern portion of the eastern channel system (pl. 8). The water levels are also affected by discharge to Bear Creek valley on the eastern flank of the channel.

The hydraulic gradient in the northern portion of the western channel system (Area C) is less than one foot per mile. In area D, the hydraulic gradient increases to approximately 4 feet per mile (pl. 7). The increase in hydraulic gradient is probably the result of a decrease in cross-sectional transmissivity (section D-D', pl. 4). The merging of the eastern and western channels just south of the Dickey-LaMoure County line also probably affects the water levels in that area.

The hydraulic gradient increases in the vicinity of Bear Creek (pl. 7). A trough in the potentiometric surface occurs along Bear Creek valley. Wells completed in the Spiritwood aquifer along Bear Creek valley will flow. Bear Creek is a local discharge area.

Several abrupt changes in hydraulic gradient occur southeast of Bear Creek (area E). These changes are due to the occurrence of low-transmissivity barriers.

In the vicinity northwest of Lake Taayer the hydraulic gradient is less than one foot per mile. Southeast of Dill and Pickell sloughs the hydraulic gradient increases to approximately 6 feet per mile. The available hydrologic data does not make it possible to determine if a change in recharge, discharge or transmissivity causes the change in hydraulic gradient.

Hydraulic Properties

Three aquifer tests and two response tests have been conducted on five irrigation wells completed in the Spiritwood aquifer within the study area.

William Huether Aquifer Test

The aquifer test using the William Huether irrigation well located in 134-60-36CCB was conducted for 4,560 minutes (76 hours). A constant discharge rate of 1,258 gallons per minute was maintained throughout the test. The irrigation well was drilled to a depth of 225 feet and is screened from 200 to 225 feet below land surface. Water levels in the production well and 13 observation wells were monitored during the test. The location of the observation wells and the drawdown in each well at the end the pumping period are shown in figure 13. The drawdown distribution approximately defines the continuous barrier boundary separating the eastern and western channels. Note that no drawdown was observed at observation wells 134-60-34DDD, 134-60-35CCC, and 133-60-1DDD, all of which are located in the western channel.

Observation well 134-60-16CCC also did not respond to pumping. The water level is approximately 38 feet higher than any of the other observation wells in the vicinity. The long-term hydrograph of this well is anomalous in comparison with the long-term hydrographs of all other observation wells in the vicinity. The anomoly suggests that observation well 134-60-16CCC is completed in an isolated deposit of sand and gravel.

Observation well 133-59-15CCC showed a maximum water-level fluctuation of .13 foot during the test. Barometric effects and the large radial distance of the observation well from the production well make it inconclusive as to whether a pumping response occurred in this observation well.

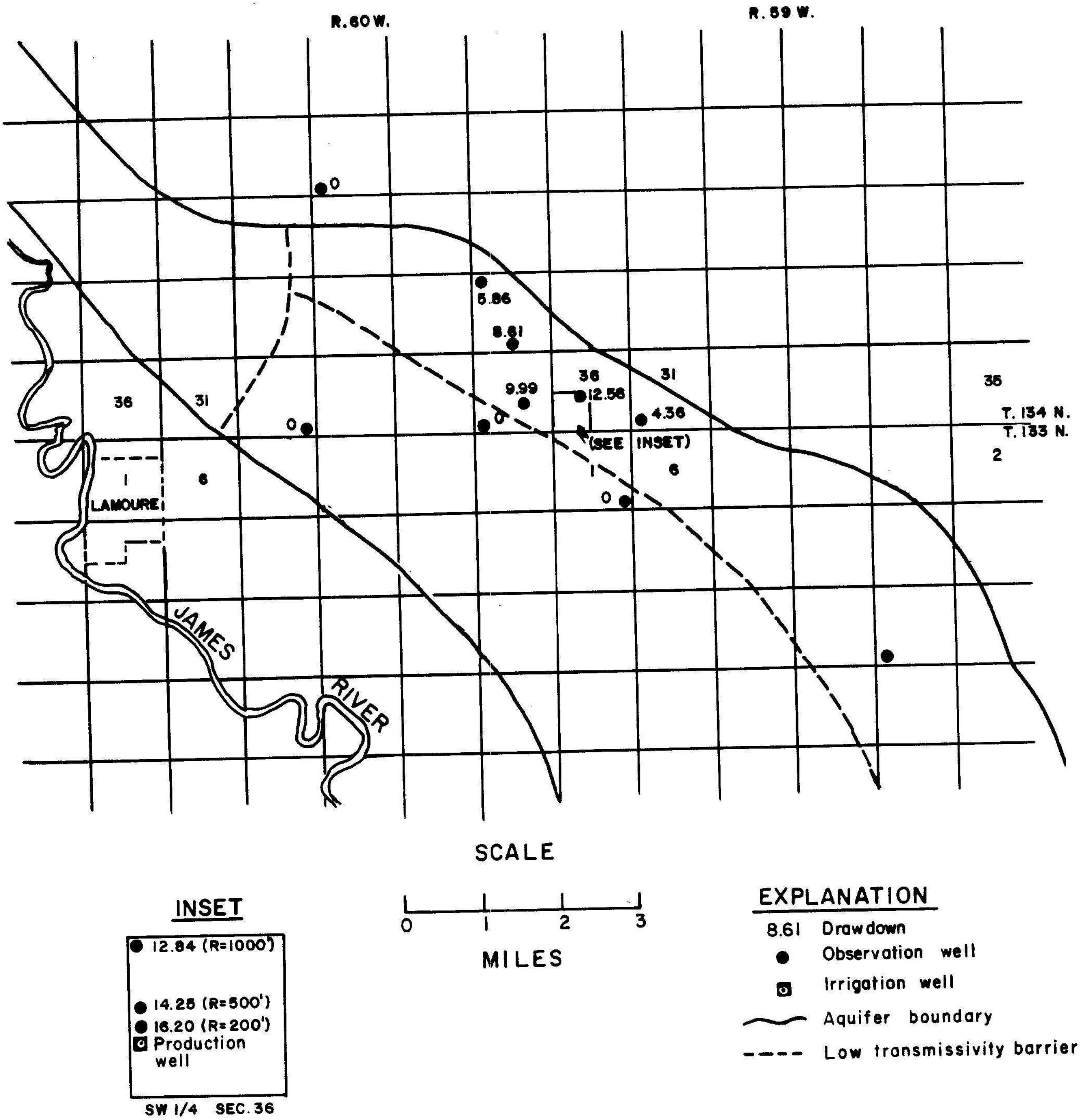


FIGURE 13–William Huether aquifer test: drawdown distribution after 4,560 minutes of pumping

The hydraulic properties of the aquifer were calculated using water level data measured at three observation wells located 200, 500, and 1000 feet north of the production well. Due to the close proximity to a barrier boundary, only the early-time data was used to calculate the hydraulic properties. Theis (log-log) and Jacob (semi-log) methods were used to analyze both time-drawdown and distance-drawdown data. Transmissivity calculated from the distance-drawdown plot was 18,500 ft^2/day. Based on an average saturated thickness of 49 feet, the hydraulic conductivity was calculated at 380 ft/day. The storage coefficient was .0004.

Curt Knutson Aquifer Test

The aquifer test using the Curt Knutson irrigation well located in 132-59-21CBD was conducted for 6,000 minutes (100 hours). A constant discharge rate of 1,043 gallons per minute was maintained throughout the test. The irrigation well was drilled to a depth of 210 feet and is screened from 195 to 210 feet below land surface. Water levels in the production well and 20 observation wells were monitored during the test. The location of the observation wells and the drawdown in each well at the end of the pumping period are shown in figure 14. The drawdown distribution approximately defines a transverse barrier boundary northeast of the city of Oakes. No response to pumping was observed at observation wells 131-59-01DDA, 131-59-01CCC, and 132-59-35ABD. The drawdown distribution also confirms the merging of the eastern and western channels just south of the Dickey-LaMoure County line.

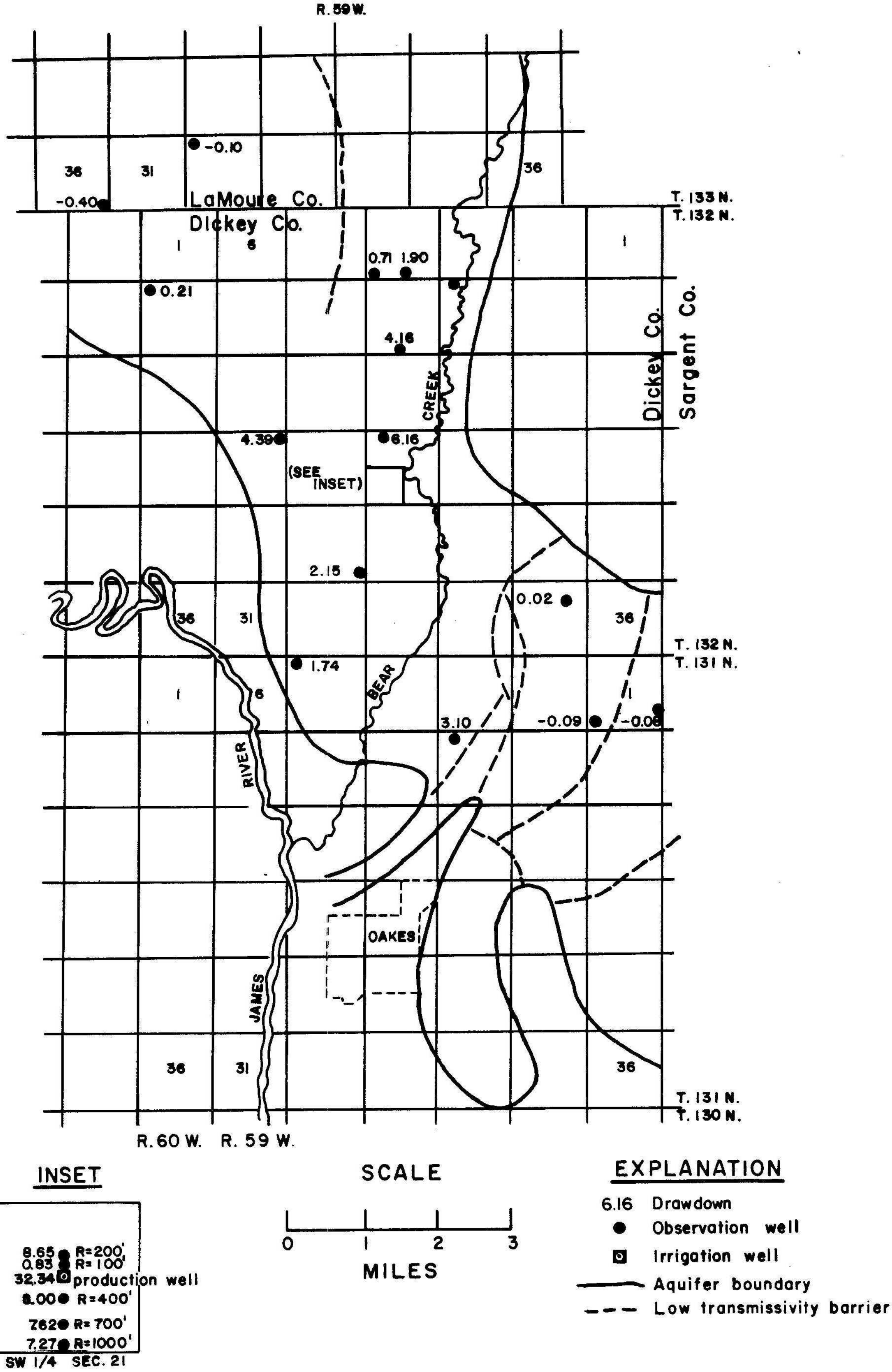


FIGURE 14.-Curt Knutson aquifer test: drawdown distribution after 6,000 minutes of pumping

The hydraulic properties of the aquifer were calculated using water level data measured at four observation wells located 200 feet north and 400, 700, and 1000 feet south of the production well. Due to the close proximity to a barrier boundary, only the early time data (first 60 minutes), was used to calculate hydraulic properties. Theis (log-log), Jacob (semi-log), and Chow (semi-log) methods were used to analyze both time-drawdown and distance-drawdown data. The Theis recovery method was also used. Based on the analytical methods and a computer simulation allowing for variation of aquifer coefficients and parallel barrier boundary configuration, a transmissivity of 37,700 ft^2/day and a storage coefficient of .0002 were calculated. The close barrier boundary is located 5,000 east and the far barrier boundary is located 8,000 feet west. Based on an estimated saturated thickness of 90 feet, a hydraulic conductivity of 420 ft/day is calculated.

Observation well 132-59-21CCA$_2$, located 100 feet south of the irrigation well, is screened from 105 to 111 feet below land surface in a sand and gravel deposit which lies above the Spiritwood aquifer. The Spiritwood aquifer and the overlying sand and gravel deposit are separated by approximately 35 to 40 feet of glacial till. The drawdown measured at this well after 6,000 minutes of pumping was 0.83 feet, indicating leakage of water from the overlying sand and gravel deposit to the Spiritwood aquifer. Due to the effect of barrier boundaries on water-levels, analytical methods were not utilized to assess leakage and aquitard properties.

Orrin Streich Response Test

The response test using the Orrin Streich irrigation well located in 131-59-16CCC was conducted for 2,670 minutes (46 hours). A constant discharge rate of 2,339 gallons per minute was maintained throughout the test. The irrigation well was drilled to a depth of 208 feet and is screened from 164 to 204 feet below land surface. Water levels in the production well, six observation wells and three irrigation wells were monitored during the test. The location of the observation wells and the drawdown in each well at the end of the pumping period are shown in figure 15. Observation well 131-59-15BBB is the only well that responded sufficiently to indicate a direct hydraulic connection. Observation wells 131-59-1CCC and 131-59-10BBA showed no response to pumping. All other wells showed subdued responses indicating limited hydraulic connections through leakage. The drawdown distribution defines a narrow buried channel trending northeast-southwest.

The hydraulic properties of the aquifer were calculated using water level data measured at the production well and the observation well located in 131-59-15BBB. The early time-drawdown data was affected by a close barrier boundary. Thus, aquifer hydraulic properties could not be calculated by the standard Theis (log-log) and Jacob (semi-log) analytical methods. Computer simulations were made and the output was matched with the actual time-drawdown data measured at the production well and the observation well located in 131-59-15BBB. A transmissvity, storage coefficient and aquifer width of 18,000 ft^2/day, .0002 and 1000 to 1500 feet, respectively, achieved the best fit. Based on an estimated saturated thickness of 43 feet, the hydraulic conductivity is calculated at 420 ft/day.

Dennis Roney Aquifer Test

The aquifer test using the Dennis Roney irrigation well located

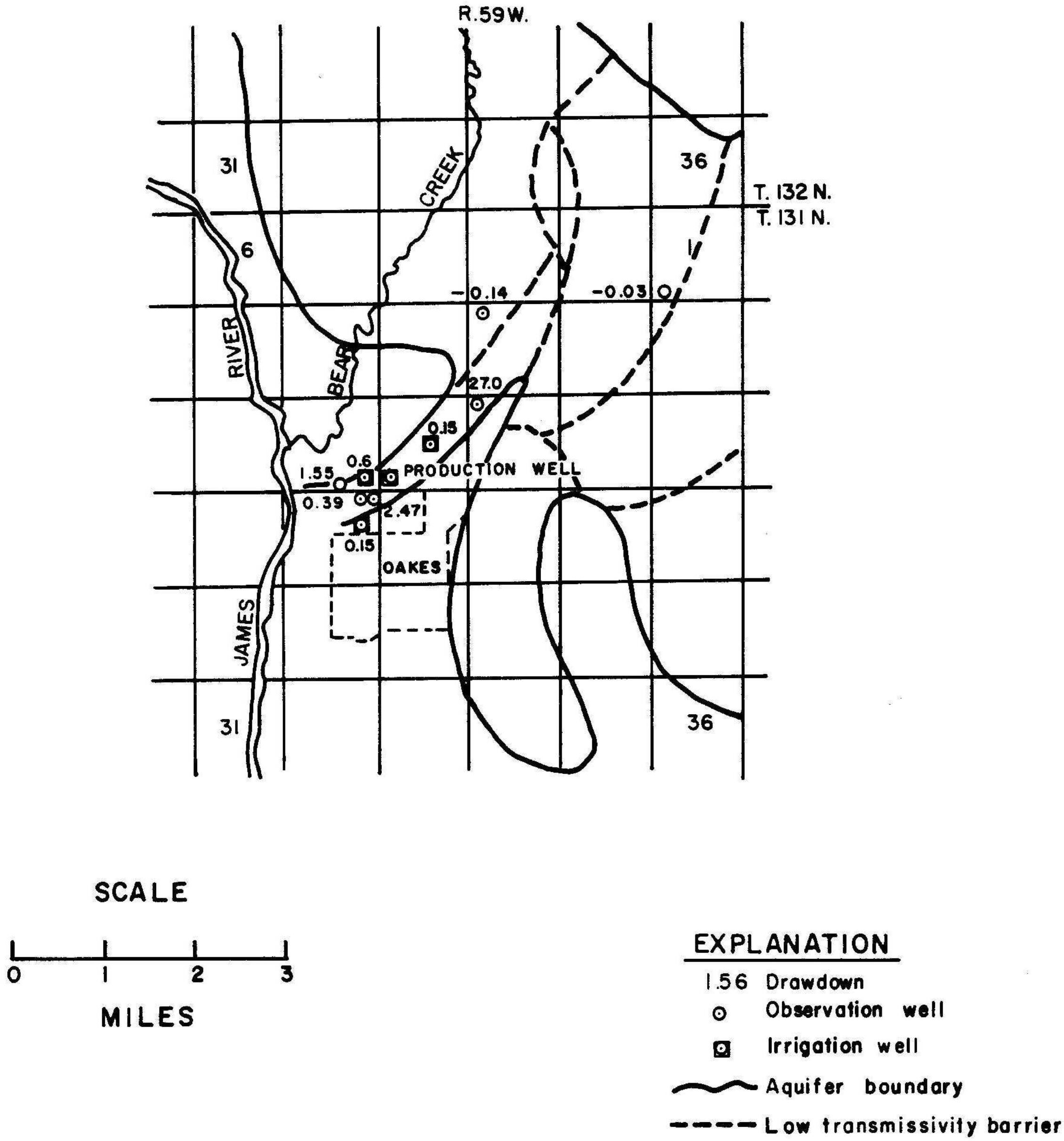


FIGURE 15.-Orrin Streich response test: drawdown distribution after 4,560 minutes of pumping

in 131-59-22BDA, was conducted for 6,000 minutes (100 hours). A constant discharge rate of 870 gallons per minute was maintained throughout the test. The irrigation well was drilled to a depth of 224 feet, and is screened from 199 to 224 feet below land surface. Water levels in the production well, ten observation wells and two irrigation wells were monitored during the test. The location of the observation wells and drawdown in each well at the end of the pumping period are shown in figure 16. The drawdown distribution approximately defines a transverse barrier boundary northeast of the city of Oakes. No response to pumping was observed at observation wells 131-59-03BBB, 131-59-05BBB, 131-59-15BBB, 131-59-20AAA, and irrigation well 131-59-21ACD.

The hydraulic properties of the aquifer were calculated using water level data measured at four observation wells located 100 and 500 feet south and 250 and 1000 feet north of the production well. Based on the production well completion report and the four observation well lithologic logs, the aquifer thickness ranges from 29 to more than 63 feet. Available test-drilling data indicates two roughly parallel barrier boundaries (bedrock highs) approximately 2000 feet east and west of the production well. The production well is completed in a tributary aquifer to the Spiritwood aquifer. Sandy silts and/or silty sands overlie the sand and gravel tributary channel.

Theis (log-log) and Jacob (semi-log) time-drawdown and distance-drawdown methods were applied to the water level data from the four observation wells and production well. The Theis recovery method was also applied. Due to the effects of leakage, barrier boundaries, variable aquifer thickness and recovering water levels, only the early time data (first 12 minutes) was used to calculate aquifer hydraulic properties. The

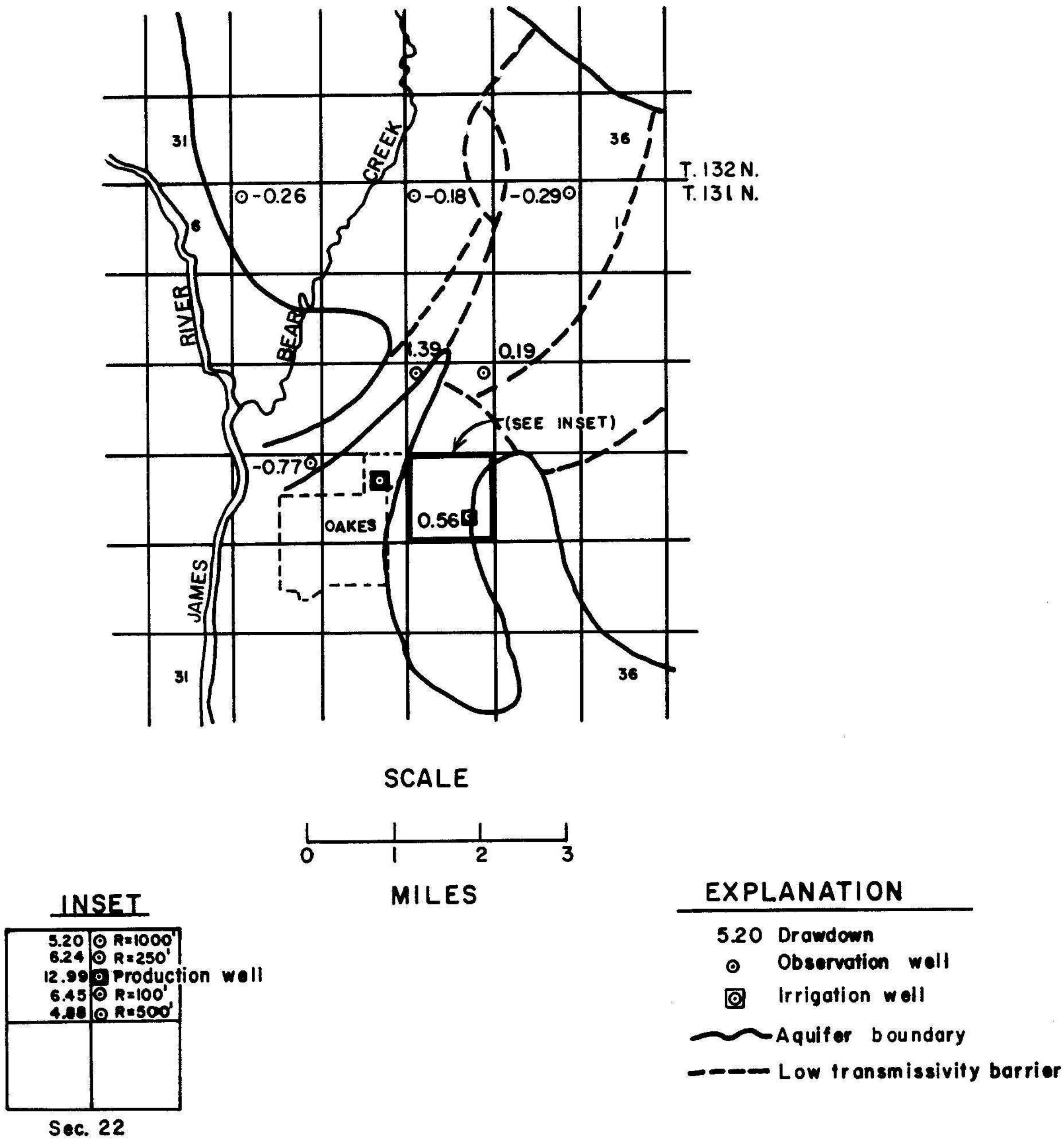


FIGURE 16.—Dennis Roney aquifer test: drawdown distribution after 6,000 minutes of pumping

calculated transmissivities and storage coefficients ranged from approximately 20,000 to 30,000 ft^2/day and .0001 to .0004 respectively. An average transmissvity of 25,000 ft^2/day and storage coefficient of .0002 was calculated. Based on an average saturated thickness of 42 feet, an average hydraulic conductivity of 600 feet/day was calculated.

John Vculek Response Test

The response test using the John Vculek irrigation well, located in 131-59-11AAC was conducted for 6,120 minutes (102 hours). The discharge rate varied from approximately 1,490 gallons per minutes at the beginning of the test to 1,350 gallons per minute at the end of the test. The irrigation well was drilled to a depth of 214 feet and is screened from 184 to 214 feet below land surface. Water levels in the production well were not measured due to oil in the measuring tube. Water levels were monitored in 30 observation wells and one irrigation well.

The location of each of the observation wells and the drawdown in each well at the end of the pumping period are shown in figure 6. The low-transmissivity boundary configuration is inferred from the drawdown distribution. Additional evidence to support this boundary configuration is shown by the maximum drawdown measured during the 1983 irrigation season (fig. 4) and the residual-drawdown distribution over the period from April 4, 1982 to April 27, 1983 (fig. 5).

A digital model was developed to simulate this response test. The transmissivity of the barriers ranged from 10 to 250 ft^2/day. The transmissivities of the aquifer ranged from 2000 to 20,000 ft^2/day. The storage coefficient was kept constant at 2.4×10^{-4}. The simulated drawdown distribution compared favorably with the actual measured drawdown distribution. For the most part, the measured late-time drawdowns were less than the simulated drawdowns, and thus suggests leakage into the aquifer. Due to the complexity of the simulated area, no attempt was made to quantify leakage.

Natural Recharge and Discharge

The Spiritwood aquifer deposits are not exposed within the study area and are buried by a 150 to 250 foot thick layer of glacial drift. As a result, the Spiritwood aquifer is not in direct contact with the hydrological processes occurring at or near the land surface. Thus, recharge to and discharge from the Spiritwood aquifer occurs by leakage through the overlying glacial drift and underlying Cretaceous shales.

The glacial drift consists primarily of till over most of the study area. Available lithologic data indicates numerous, thin (less than 5 feet thick) glaciofluvial deposits of silt, sand and gravel scattered throughout the till. Glaciofluvial and glaciolacustrine deposits comprise a significant percentage of the drift in the area north of Oakes and south of the Dickey-LaMoure County line. Glaciofluvial deposits and fractures and joints within the till probably allow recharge to move more rapidly downward to the Spiritwood aquifer.

The rate and volume of water derived or lost from leakage is a function of the hydraulic properties of the aquitards and the vertical hydraulic gradient established between the aquifer-aquitard system. The hydraulic properties are of two types, matrix and bulk. The matrix properties are intergranular. The bulk properties are associated with fractures and other secondary structures such as root channels and worm burrows. Included in the bulk properties of glacial till are the numerous small glaciofluvial deposits of silt, sand and gravel.

Currently, the natural recharge-discharge relationships of the Spiritwood aquifer are inadequately defined. Vertical hydraulic gradients indicate downward movement of ground water relative to the water table (recharge) over most of the study area. Due to the lithologic and structural heterogeneity of the glacial till and the occurrence of other glaciofluvial and glaciolacustrine deposits within the drift, variations in recharge rates should occur over the study area.

A significant recharge area is located in the vicinity of Sections 25 and 26, T133N-R60W. A local topographic high occurs in this area and provides the driving force for the downward movement of ground water. The surficial lithologies consist of windblown silt and sand and possibly glaciofluvial sand to depths of up to 50 feet. The surficial silts and sands, with high infiltration capacities provide a good catchment area. An 80 or more foot thick glaciofluvial unit of clayey silts, sand and gravel also occurs to a depth of 152 feet below land surface at test hole 133-60-27DDD. The occurrence of a deeper thick glaciofluvial deposit provides a conduit for rapid downward movement of recharge to the Spiritwood aquifer. The potentiometric surface (pl. 7) and water quality (pl. 9) further substantiates this location as a significant recharge area.

Another significant recharge area occurs in a narrow-buried tributary channel of the Spiritwood aquifer north of Oakes (refer to discussion of Orrin Streich response test). This narrow tributary channel is bounded on all sides by low transmissivity barriers. The channel is overlain in some areas by sand and gravel and lacustrine silt. Observation well 131-59-15BBB is completed in the tributary channel. The water level fluctuations at this observation well are primarily due to the pumping by irrigation well 131-59-16CCC (fig. 12). The geometry of this tributary channel limits the amount of ground water storage in the aquifer. A large residual drawdown should occur in this narrow channel due to annual irrigation withdrawals. The hydrograph of observation well 131-59-15BBB shows small annual residual drawdowns. The small residual drawdown indicates that a significant amount of ground water in this tributary channel is derived through leakage from the overlying glacial drift.

Within Bear Creek Valley and in the numerous topographic lows southeast of Bear Creek towards the city of Cogswell (Lake Taayer, Dill Slough, Pickell Slough), the vertical hydraulic gradient indicates upward movement of ground water relative to the water table (discharge areas). As mentioned previously, the trough in the potentiometric surface north of Oakes is aligned with Bear Creek Valley (pl. 7). Wells completed within the Spiritwood aquifer in Bear Creek Valley will flow. The shape and configuration of the potentiometric surface in this area indicates that Bear Creek is a discharge area. As with recharge areas, large variations in discharge rates should occur over the study area.

In order to quantify recharge and discharge rates, the heterogeneities within the glacial drift should be mapped and both the primary (matrix) and secondary (bulk) hydraulic properties should be determined. A future work plan is proposed at the end of this report to address the mapping of recharge and discharge areas.

WATER USE

The Spiritwood aquifer is a major aquifer in terms of ground-water irrigation development. No municipal or industrial wells are completed in the Spiritwood aquifer within the study area. The aquifer also provides water for a number of domestic/stock wells. Discharge from these wells is considered negligible. The first irrigation well was completed in the study area in 1973.

Annual irrigation withdrawals and corresponding acres irrigated were compiled (fig. 17). The data used to compile annual water use comes from annual water use reports completed by the irrigator and annual kilowatt hour and demand readings compiled by the electric cooperatives. Prior to the beneficial use of water, a metering device to measure flow rate must be installed properly within the discharge system. During the winter, each water permit holder receives a water use report form which is to be completed and returned to the Hydrology Division of the State Water Commission. On this form, the permit holder reports (1) meter readings at the beginning and end of the irrigation season (2) pumping rate, (3) estimated hours of system operation and (4) number of acres irrigated. The accuracy of the annual water use data based on meter readings is questionable. In some instances, the meters are improperly installed, thereby giving inaccurate pumping rates. In many cases, the meters break down during the irrigation season and only estimates of water use are reported. Some irrigators fail to submit their annual water use reports.

The second source of water use data is the rural electric cooperatives. All of the irrigation-capture systems within the study area are powered electrically. The electric cooperatives maintain records of the total

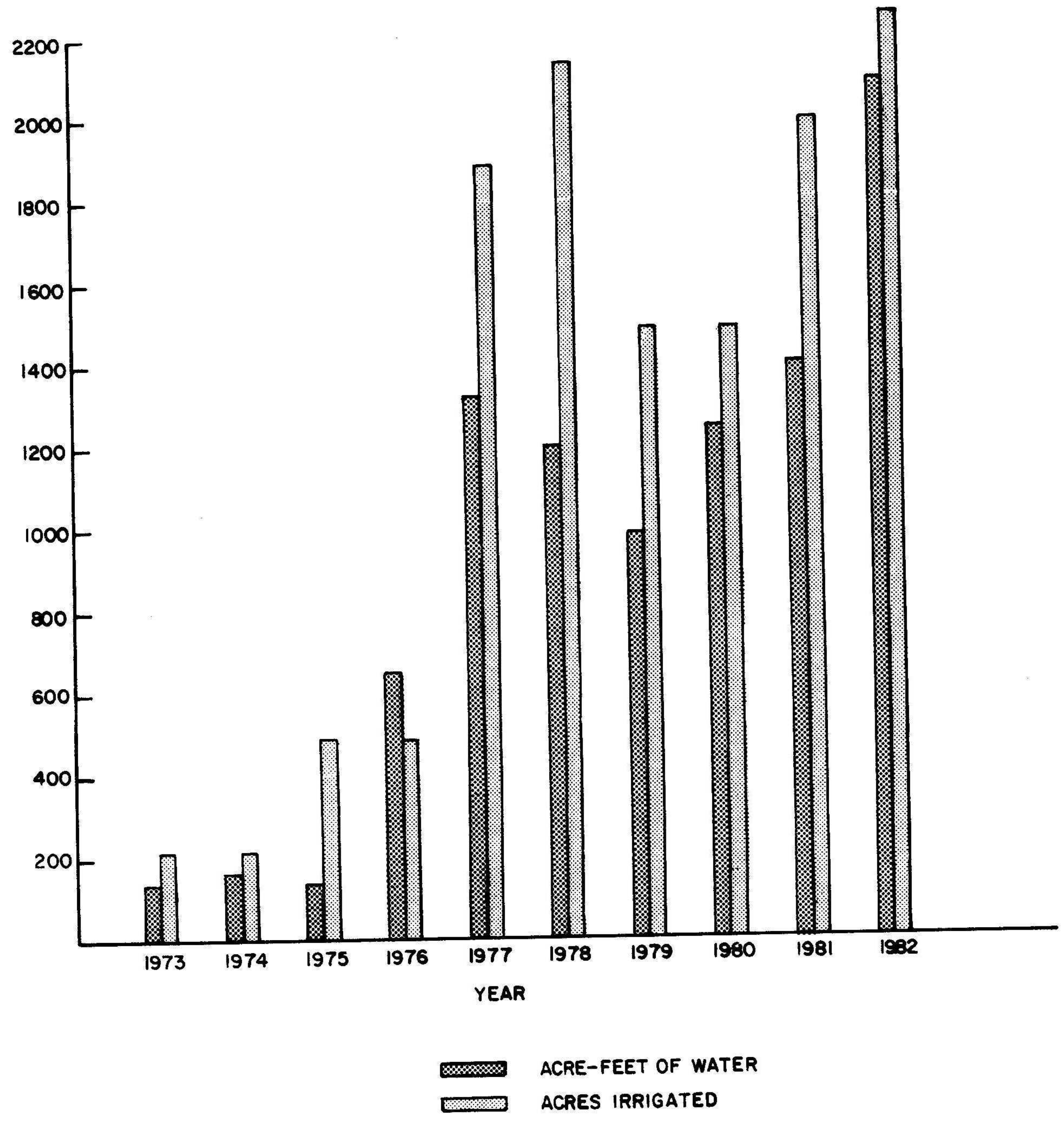


FIGURE 17.—Annual water use

kilowatt hours used and average monthly demand readings. The total kilowatt hours divided by the average monthly demand gives the total number of hours operated. The total number of hours multiplied by the estimated pumping rate gives the total volume of water pumped.

The pumping rate is the water use variable that is the most poorly defined. Currently, the State Water Commission is utilizing a Clampitron flow meter to more accurately measure irrigation-well pumping rates. The pumping rates of all irrigation wells within the study area are scheduled to be measured with this device by the end of the 1985 field season.

The annual water use data is based primarily on kilowatt hour and demand data received from rural electric cooperatives (fig. 17). Annual water use data for water permit #1816 (well location 131-59-16CCC) is not currently available and is therefore not included on the graph. The abrupt increase in irrigated acres in 1977 followed by the abrupt decline in acres irrigated in 1979 was due to the operation and later abandonment of a four quarter-section irrigation development in the north-central portion of the study area. Otherwise, a steady annual increase in ground water withdrawals has occurred.

The impact of irrigation development on aquifer-water levels within the study area was determined (pl. 8, figs. 7-12, and 18-24). Plate 8 also shows the following:

1) location of water permits (pending - approved not developed - approved and developed),

2) total drawdown measured during the 1983 irrigation season, and

3) residual drawdown at selected observation wells measured over a period from May 1976 to May 1983.

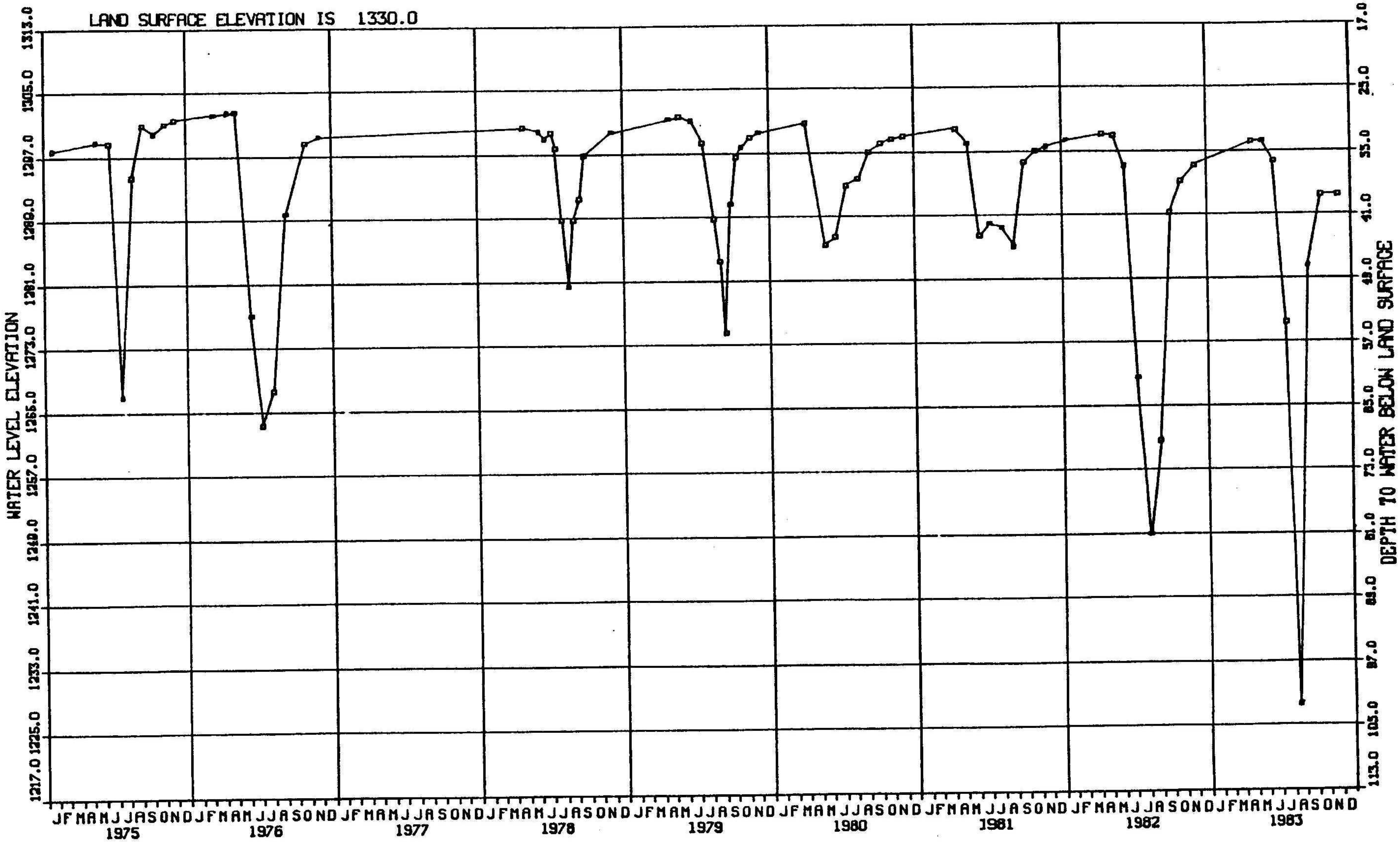


FIGURE 18.- Hydrograph of observation well 131-59-20AAA$_1$

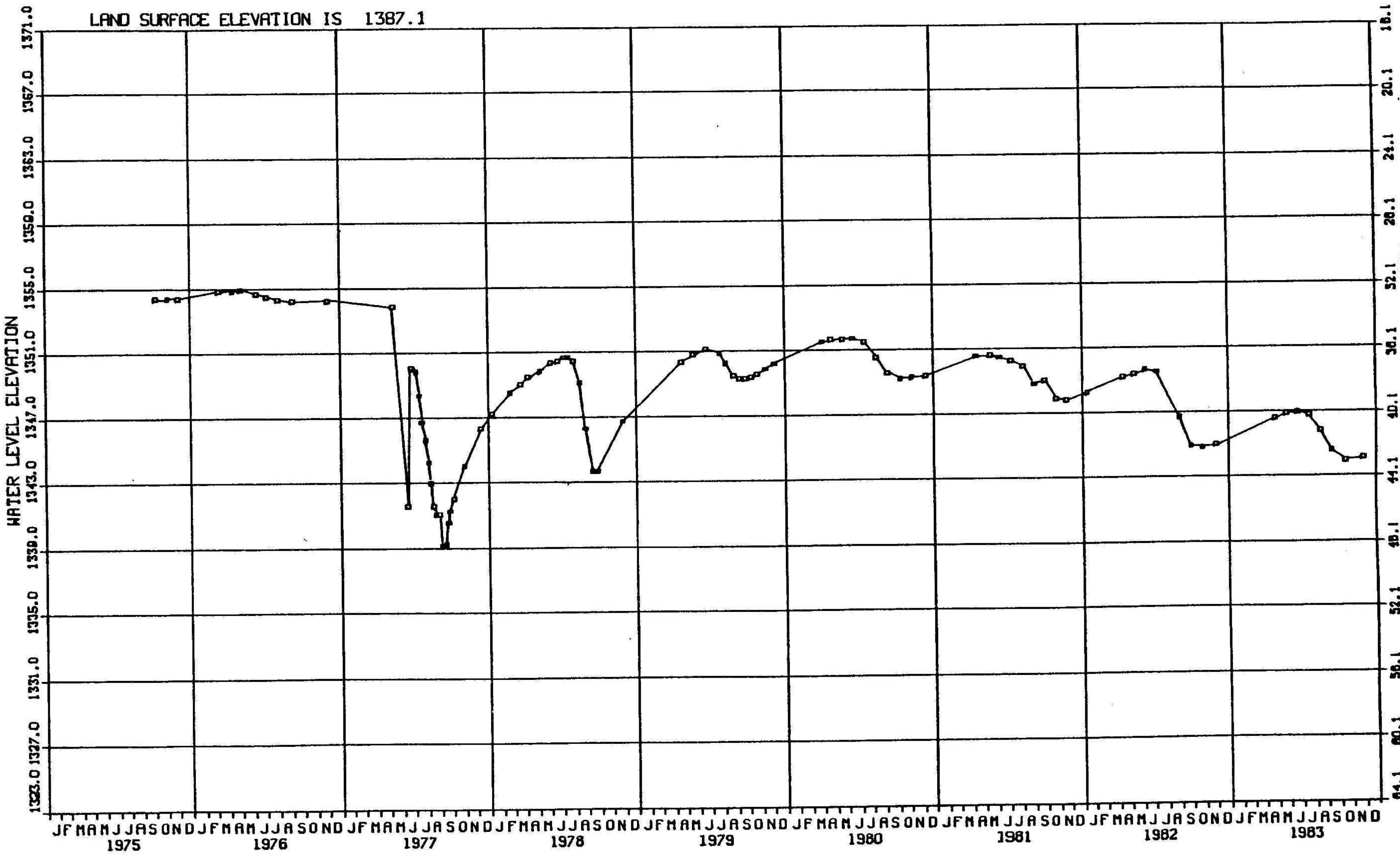


FIGURE 19.-Hydrograph of observation well 133-59-15CCC

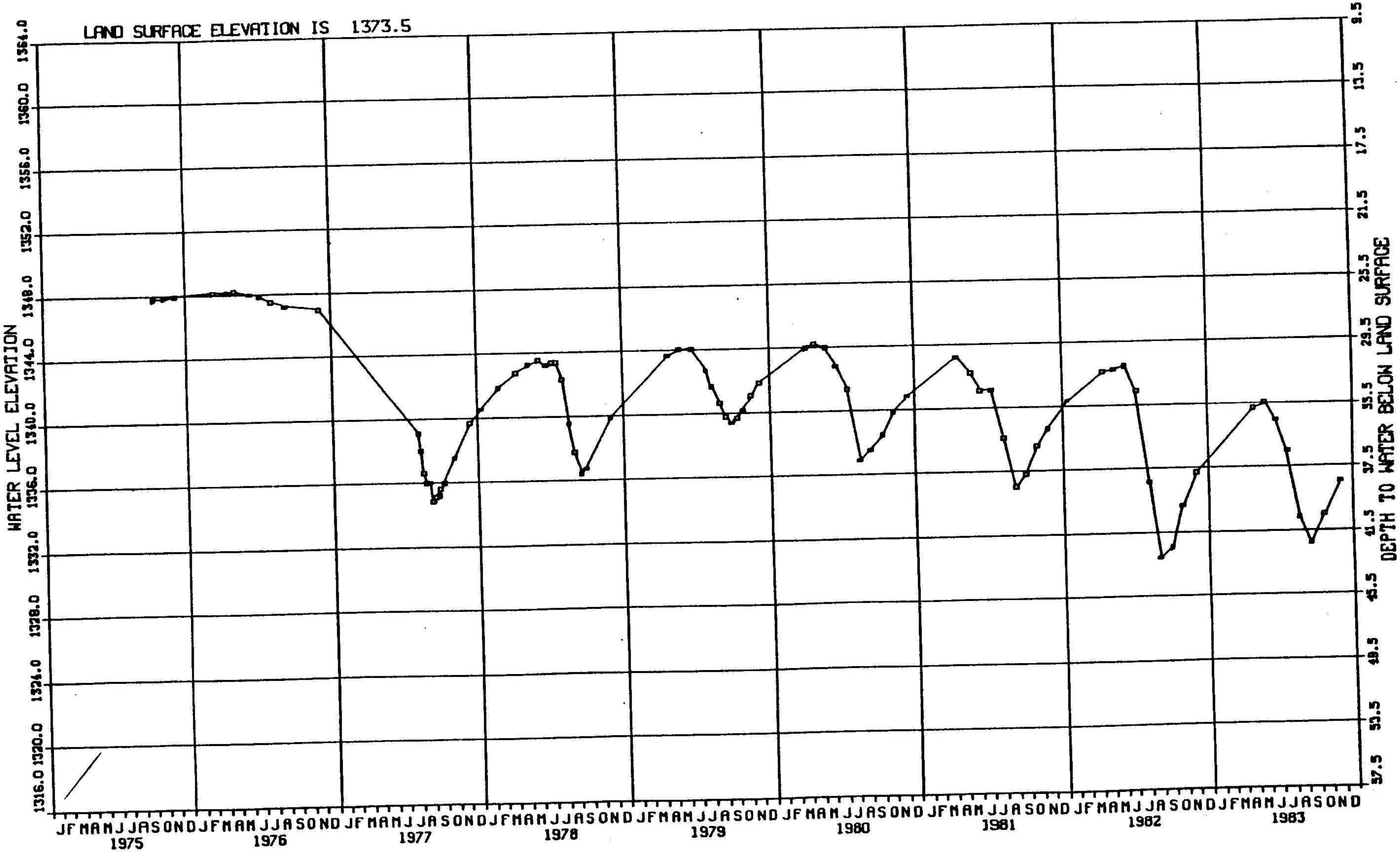


FIGURE 20.-Hydrograph of observation well 133-59-32BBB

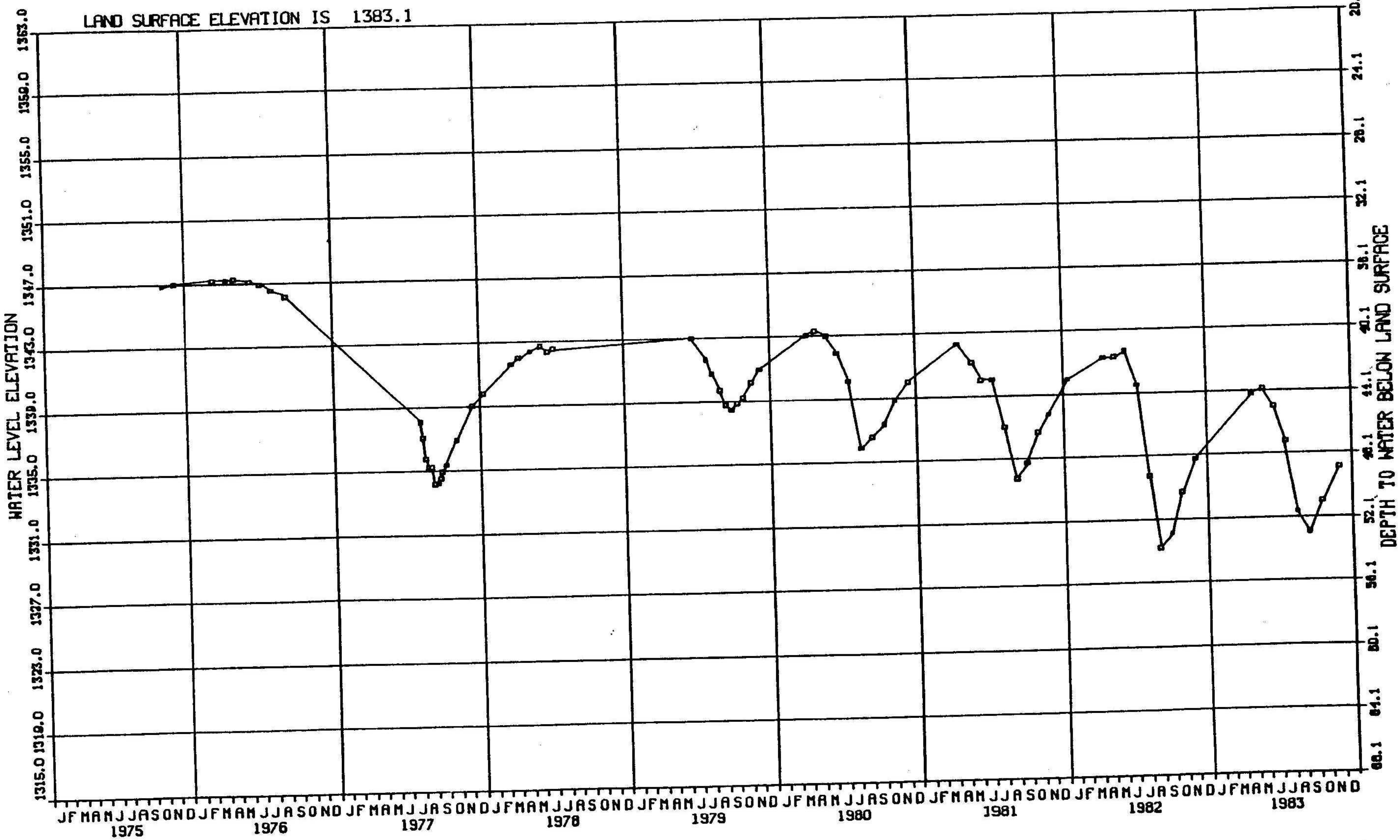


FIGURE 21.–Hydrograph of observation well 133-60-36DDD

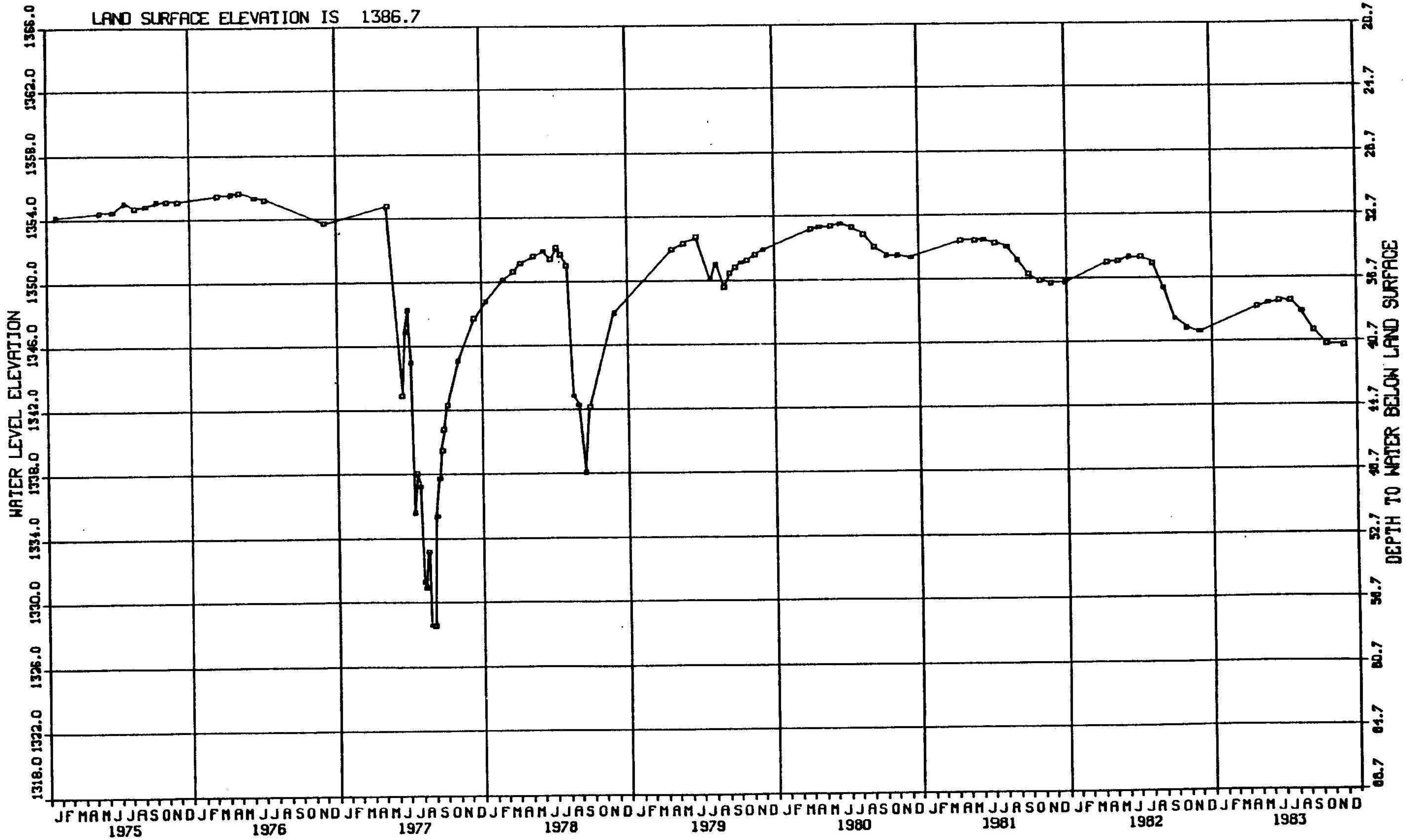


FIGURE 22.-Hydrograph of observation well 134-59-31CCC

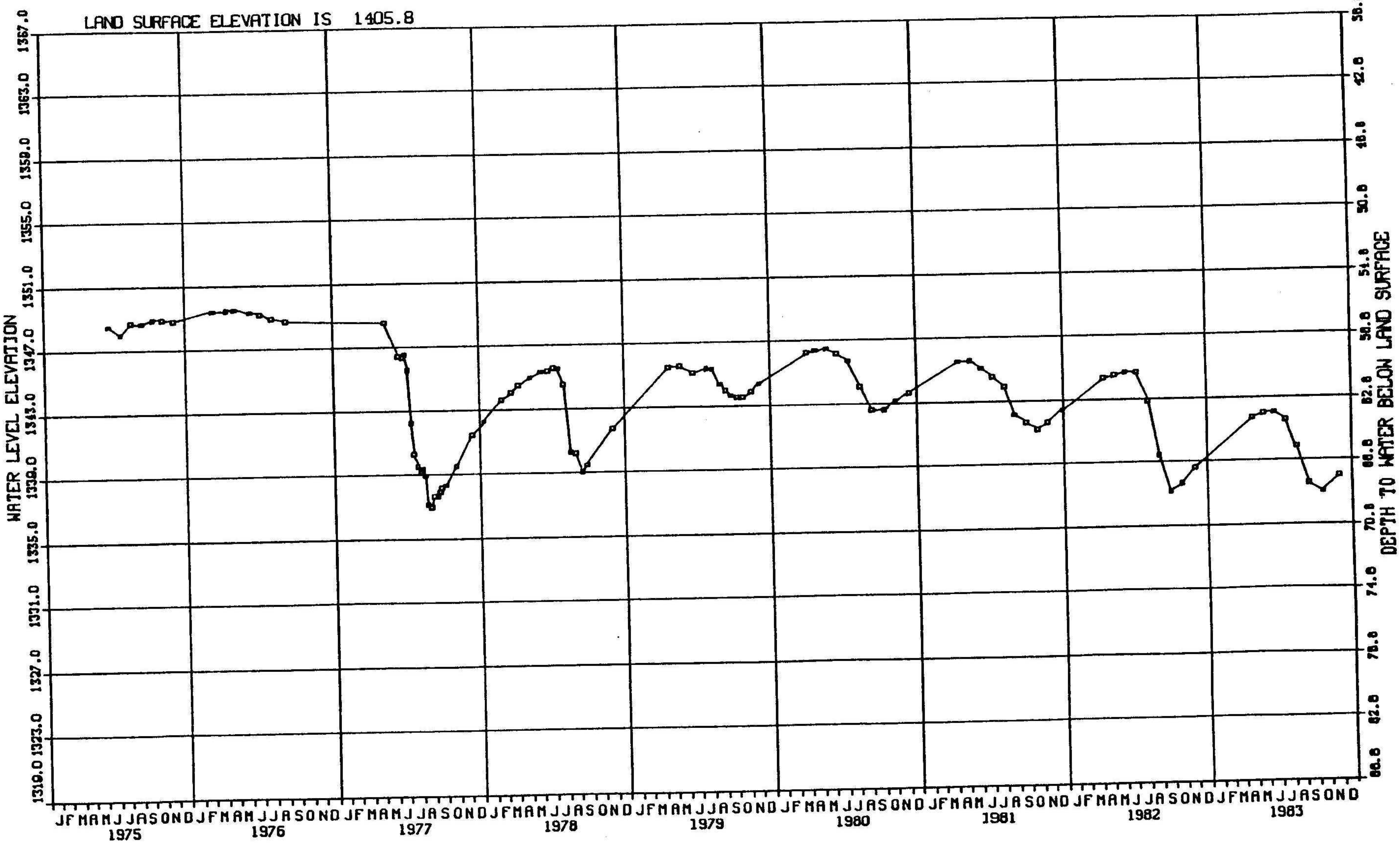


FIGURE 23.-Hydrograph of observation well 134-60-32DDD

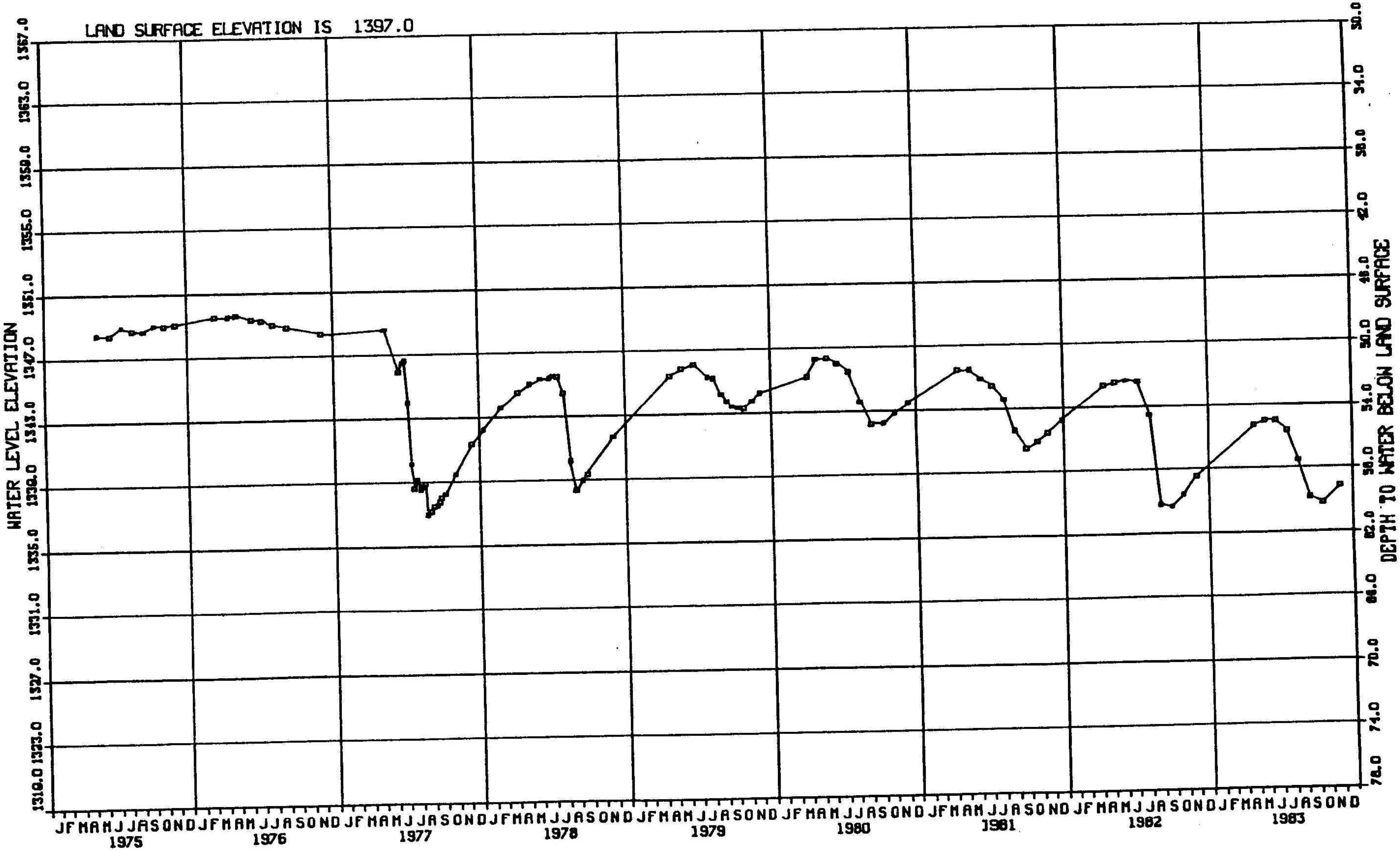


FIGURE 24.-Hydrograph of observation well 134-60-35CCC

The total drawdown measured during the 1983 irrigation season ranged from 2.2 feet at observation well 133-59-15AAA to 80.1 feet at observation well 131-59-15BBB (pl. 8). The largest drawdowns occurred northeast of Oakes in Dickey County where the developed irrigation appropriations are located. The smallest drawdowns occur in the central and northern parts of the study area where no irrigation appropriations are developed.

The total residual drawdown measured ranges from 3.8 feet at observation well 131-59-01DDA to 8.2 feet at observation well 133-59-32BBB (pl. 8). The steady increase in annual residual drawdown reflects the steady increase in annual water use.

The hydrographs prepared from observation wells throughout the study area indicate that highest water levels occur during April and May prior to each irrigation season (figs. 7-12, and 17-23). The lowest water levels occur during peak irrigation demand in August.

WATER CHEMISTRY AND QUALITY

Partial chemical analyses were made on samples gathered from 122 State Water Commission observation wells, 31 domestic/stock wells and 10 irrigation wells - all completed in the Spiritwood aquifer within the study area (table 1). The samples were analyzed at the State Water Commission Laboratory in Bismarck. The samples were collected and analyzed over a period from 1974 to 1984.

Histograms of total dissolved solids (calculated), calcium, magnesium, sodium, bicarbonate, sulfate and chloride were prepared (fig. 25). General statistical functions were calculated for each chemical parameter and are shown at the bottom of each figure. Based on the calculated mean and standard deviation, a normal distribution for each chemical parameter was synthesized. The synthesized normal distribution is shown on each histogram for comparative purposes.

Of the six major cations and anions, the bicarbonate distribution more closely approximates a normal distribution. In each case the actual distributions show a more compressed range in concentration (more peakedness) than the synthesized normal distributions. Bicarbonate has the smallest range, 9.32 epm and sulfate has the largest range, 45.80 epm. The total dissolved solids range from 12.72 epm (363 mg/l) to 111.95 epm (3640 mg/l).

Chemical analyses from the Spiritwood aquifer were plotted on Piper trilinear diagrams (fig. 26). The water ranges, for the most part, from a Ca-HCO_3 type to a Na-HCO_3-SO_4 type. The Na-HCO_3 type predominates.

Partial chemical analyses were made on samples gathered from seven State Water Commission observation wells, one domestic well and one irrigation well - all completed in glaciofluvial units above the Spiritwood

TABLE I -- Chemical analyses Spiritwood aquifer

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
130-57- 5BBB1	153-156	9-21-77	34	1.9	.56	98	26	110	7.4	436	0	230	14	0.2	1.0	.52	739	350	0	40	2.6	955	8.0
130-57- 8DDD1	143-146	4-26-78	32	2.1	.16	82	28	150	7.6	387	0	220	71	0.3	0.4	.68	785	320	3	50	3.6	1220	7.6
130-57-17BBB	198-201	7-24-80	37	1.5	.15	120	29	130	7.4	381	0	300	79	0.2	1.0	.14	893	420	110	40	2.8	1310	7.7
131-57-31CCC	198-201	7-24-80	45	.80	.07	84	34	140	7.3	506	0	220	28	0.4	0.5	.17	809	350	0	46	3.2	1170	8.0
131-58-20BBB	188-191	7-23-80	38	.40	.08	69	24	200	6.8	522	0	210	61	0.4	1.0	.44	868	270	0	61	5.3	1290	8.0
131-58-27AAA	208-211	11- 6-75	21	.25	.58	110	35	67	8.0	446	0	160	16	0.2	0.6	.48	639	420	54	25	1.4	1020	7.6
131-58-32BCC1	148-151	7-23-80	32	.38	.01	13	16	340	6.4	601	0	230	95	0.8	0.1	1.1	1030	100	0	87	15.0	1570	8.2
131-58-34BBB	158-161	11- 6-75	22	.87	.06	51	23	190	8.9	487	0	160	52	0.4	2.4	.88	752	220	0	64	5.6	1210	7.6
132-58-16BBA2	166-169	5-22-75	22	.84	.04	44	17	800	14	558	0	1.6	1080	0.9	3.0	2.2	2260	180	0	90	26	4100	8.1
132-58-21BBB1	178-181	5-21-75	20	3.2	.04	53	21	840	12	674	0	1.6	1090	1.0	1.0	.43	2380	220	0	89	25	4230	7.9
132-58-30DAA	147-152	10- 4-82	30	.32	.02	20	8.5	820	17	550	0	0.0	860	0.8	6.6	2.0	2040	85	0	94	39	3540	8.1
132-58-31AAA	150-155	10- 7-82	29	.22	.06	23	9.5	460	14	624	0	140	290	0.7	6.7	.67	1280	96	0	90	20	2150	8.2
131-59- 1DDA	163-166	5-14-76	32	1.3	.16	57	24	240	8.0	529	0	230	73	0.5	0.8	1.2	929	240	0	68	6.7	1460	7.7
131-59- 1CCC	172-175	10-27-76	29	1.6	.22	58	23	260	6.9	529	0	260	93	0.4	1.0	1.7	996	240	0	69	7.3	1470	8.2
131-59- 2AAA	158-161	9-27-74	19	2.1	.26	65	21	220	8.1	520	0	230	61	0.7	1.0	.98	890	250	0	65	6.1	1430	7.7
131-59- 2BCC	176-186	9-14-82	30	3.5	.34	54	17	250	12	520	0	210	72	0.6	4.5	1.5	911	205	0	71	7.7	1430	8.1
131-59- 2CCC	?	8- 4-83	31	1.0	.39	51	18	230	9.0	535	0	230	70	0.8	0.3	0.7	906	201	0	70	7.1	1450	7.8
131-59- 3BAA	197-200	9- 4-81	21	.44	.19	46	26	270	11	545	0	260	93	0.9	1.0	0.8	998	220	0	72	7.9	1460	8.0
131-59- 4AAD	151-157	8- 3-83	31	1.5	.21	52	18	250	9.7	532	0	250	46	0.6	0.1	.68	922	204	0	72	7.7	1410	7.7
131-59- 5AAA	187-190	9- 4-81	30	.71	.12	45	31	210	12	553	0	200	46	0.5	1.0	.68	849	240	0	64	5.9	1240	7.9
131-59- 5BAA1	166-171	9-22-82	27	.28	.19	40	19	220	13	509	0	180	33	0.5	7.6	.42	792	178	0	71	7.1	1250	8.1
131-59- 5BBB	158-161	10- 1-74	19	.29	.10	42	21	200	9.3	490	0	200	31	0.6	7.4	1.1	773	190	0	68	6.3	1220	8.0
131-59- 8ABB	155-160	9-21-82	29	.58	.03	36	16	230	12	501	0	190	38	0.6	6.2	.74	806	156	0	74	7.9	1250	8.0
131-59-10BBA	196-199	11-17-76	29	.92	.12	48	17	250	7.0	536	0	240	56	0.5	1.0	.89	914	190	0	73	7.9	1350	8.2
131-59-10ADD	TD=210	8- 2-83	31	0.1	.14	58	16	260	9.9	516	0	250	82	0.5	1.0	.81	963	211	0	72	7.8	1480	8.0
131-59-11AAC	184-214	8- 2-83	34	1.3	.17	58	22	260	9.9	512	0	250	85	0.5	0.2	.75	974	235	0	70	7.3	1500	7.9
131-59-12CCC1	211-231	8- 4-83	31	.95	.24	60	24	230	9.7	500	0	260	99	0.5	7.6	.68	970	248	0	66	6.3	1550	7.8
131-59-12CCC2	208-211	11-17-76	29	1.2	.24	57	21	270	7.3	521	9	250	89	0.4	1.0	1.1	993	230	0	71	7.7	1460	8.4
131-59-15AAA	188-194	9-27-74	26	.51	.24	61	21	240	8.6	560	0	210	78	0.7	8.3	1.2	932	240	0	68	6.7	1480	7.6
131-59-15BBB	178-184	9-25-74	19	2.1	.22	51	18	300	8.3	630	0	180	110	0.8	0.4	1.2	1000	200	0	76	9.2	1630	7.9
131-59-15DCA	161-186	7-15-77	13	.83	.18	58	18	130	6.8	440	0	110	33	0.4	1.0	.59	589	220	0	55	3.8	1010	8.1
131-59-16CCC	164-204	8- 3-77	23	1.6	.08	40	15	210	7.1	509	0	130	63	0.3	2.5	1.0	745	160	0	73	7.2	1180	8.3
131-59-17DCC	121-124	11- 5-76	28	.79	.48	82	23	100	7.1	439	0	120	41	0.2	1.0	.83	620	300	0	41	2.5	943	8.2
131-59-22ABB	197-200	9-21-82	28	.85	.29	82	18	67	7.2	369	0	46	12	0.2	3.6	.24	447	279	0	34	1.7	683	7.9
131-59-22BAA	196-199	9-15-76	32	.79	.34	59	18	40	5.5	304	18	33	4.9	0.1	1.0	.26	363	220	0	28	1.2	556	8.7
131-59-22BAD	213-216	9-15-76	33	.65	.24	55	15	100	6.2	377	20	66	17	0.2	1.0	.34	501	200	0	51	3.1	759	8.7

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
131-59-22BDA1	215-218	9-15-76	32	.69	.40	81	26	32	4.5	340	17	73	6.2	0.2	1.0	.23	441	310	3	18	0.8	661	8.6
131-59-22BDA2	212-215	9-15-76	30	.63	.52	80	27	20	4.9	330	11	65	4.4	0.0	1.0	.23	408	310	21	12	0.5	627	8.5
131-59-22BDA3	199-224	9-21-76	31	1.3	.44	78	23	86	6.2	423	0	110	24	0.1	0.2	0.3	569	290	0	39	2.2	858	8.2
131-59-22CCA	TD=172	7-27-76	31	1.4	0.6	81	29	9.6	5.9	381	0	40	2.5	0.6	1.0	.11	391	320	8	6	.23	527	8.2
131-59-22DCA	137-157	7-31-75	20	.44	.58	63	30	18	5.9	292	0	62	5.1	0.6	2.5	0.0	352	280	40	12	0.5	571	7.9
131-59-22CBB1	158-161	7-27-82	27	0.0	.42	60	17	95	8.6	384	0	96	12	0.4	1.0	.29	507	220	0	47	2.8	796	7.9
131-59-27CBB1	127-132	1-19-83	31	.32	.05	21	9.5	480	11	668	0	92	290	1.0	1.0	1.6	1270	92	0	91	22	2060	8.3
131-59-35BCC1	125-130	7-28-82	28	.42	.06	22	8.0	370	10	612	0	150	150	1.4	1.0	.74	1040	88	0	89	17	1040	8.2
132-59- 3CCC	118-121	10-30-74	21	.19	.72	63	25	260	11	550	0	310	60	0.4	0.3	1.2	1020	260	0	67	7.0	1700	7.6
132-59- 4BBA	165-170	7-29-83	32	2.6	.65	120	33	150	12	533	0	290	28	0.2	1.0	.57	933	435	0	42	3.1	1350	7.8
132-59- 4CCB	174-178	1- 3-84	27	.69	.54	89	29	83	10	487	0	100	14	0.3	1.0	.54	595	342	0	34	2.0	952	8.0
132-59- 4CCC	195-198	8- 1-79	29	.06	.22	69	24	260	9.4	516	0	330	67	0.4	1.0	.97	1050	270	0	67	6.9	1560	7.9
132-59- 4DCC	158-161	8- 1-79	29	.02	.44	87	25	230	9.5	558	0	330	35	0.3	1.0	1.2	1020	320	0	60	5.6	1500	7.9
132-59- 9CDD	162-165	7-23-80	30	.17	.32	91	30	210	8.8	540	0	290	39	0.5	0.4	.92	967	350	0	56	4.9	1430	7.9
132-59-17DCD1	188-193	9-22-82	29	.06	.14	36	15	270	12	513	0	200	71	0.7	8.5	.83	896	152	0	78	9.6	1420	8.1
132-59-18DCC	245-250	9-22-82	25	.73	.43	100	29	42	9.8	435	0	100	4.1	0.2	4.7	.22	530	369	13	19	0.9	845	7.9
132-59-19AAA	238-241	8- 1-79	29	.65	.24	36	15	270	8.9	540	0	230	45	0.5	1.0	1.2	903	150	0	78	9.6	1390	8.0
132-59-21BBA	213-216	7-12-79	7.9	.24	.44	93	29	84	8.9	452	0	130	13	0.2	1.0	.37	591	350	0	34	1.9	933	7.9
132-59-21BAA	150-165	9-14-82	29	.94	.22	49	22	270	13	527	0	250	73	0.6	0.3	1.6	970	213	0	72	81	1520	8.0
132-59-21C	195-210	7-14-77	13	1.1	.24	67	25	180	8.5	519	0	220	29	0.4	1.0	.94	802	270	0	58	4.8	1230	8.0
132-59-23BAB	155-165	9-15-82	32	.98	.05	32	21	330	13	586	0	210	120	0.7	5.5	.073	1050	167	0	80	11	1720	8.0
132-59-27ADD	156-159	7-23-80	32	.10	.15	56	22	290	7.7	593	0	290	69	0.5	0.6	.99	1060	230	0	72	8.3	1610	8.1
132-59-27CDC1	209-214	3- 8-83	31	.32	.21	45	14	370	10	484	0	380	150	1.3	1.0	.74	1240	170	0	81	12	1970	8.0
132-59-28B	200-225	7-14-77	13	1.2	.42	90	28	97	7.5	460	0	170	15	0.3	1.0	.31	651	340	0	38	23	1000	8.1
132-59-29DAA	183-188	9-14-82	29	1.4	.52	100	28	18	7.9	390	0	100	3.5	0.2	0.1	.18	481	365	45	9	0.4	762	7.8
132-59-33CBC	170-180	8- 3-83	34	1.4	.12	69	23	160	10	474	0	200	16	0.5	5.5	.62	753	267	0	55	4.2	1130	7.7
132-59-32CCC	177-182	9-14-82	31	1.4	.07	42	21	200	13	488	0	170	30	0.5	0.2	1.1	750	192	0	68	6.3	1190	8.0
132-59-33CCC	170-180	9-14-82	31	1.1	.12	51	25	200	14	518	0	200	25	0.6	7.8	1.1	812	230	0	64	5.7	1280	8.0
132-59-32DAA	203-208	8- 4-83	31	.91	.15	59	23	210	11	511	0	240	26	0.6	1.4	.62	856	242	0	64	5.9	1300	7.7
132-59-35CCC	177-180	9- 4-81	30	.31	.34	53	26	240	11	533	0	230	89	0.5	1.0	.85	945	240	0	67	6.7	1390	8.2
132-59-35ABC	172-187	8- 2-83	33	1.4	.34	64	26	260	10	548	0	240	74	0.4	0.3	0.7	980	267	0	67	6.9	1530	7.8
132-59-36BCC	154-157	8- 2-83	30	2.7	.16	57	21	260	9.9	574	0	250	76	0.5	4.8	.62	996	229	0	70	7.5	1550	7.7
133-59- 4AAA	342-345	8-27-81	30	.06	1.3	65	24	350	15	223	0	150	480	0.3	1.0	0.3	1230	260	77	73	9.5	2050	8.0
133-59- 4DCC	205-210	9- 7-83	32	.02	.16	68	28	260	13	416	0	390	100	0.5	1.3	1.2	1100	285	0	65	6.8	1730	8.0
133-59- 5CDD1	197-202	9- 7-83	32	.32	.17	51	19	250	9.9	479	0	320	36	0.5	1.0	1.1	957	205	0	71	7.5	1470	8.0
133-59- 6CBC	233-243	7-26-83	29	2.5	.25	57	26	190	9.5	511	0	220	48	0.4	0.1	.64	835	249	0	61	5.2	1300	7.8

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
133-59- 6DDD	197-202	9- 8-83	31	.51	.09	45	21	270	9.5	512	0	260	100	0.6	1.0	.26	991	199	0	74	8.3	1600	8.0
133-59- $7BAA_1$	292-297	9- 8-83	32	.06	.28	56	28	270	9.7	573	0	160	150	0.6	1.0	.68	990	255	0	69	7.4	1620	8.2
133-59- $7BAA_2$	197-202	9- 8-83	34	.47	.32	51	24	250	9.5	468	12	160	150	0.6	1.0	.48	924	226	0	70	7.2	1510	8.4
133-59- 7DAA	216-225	10- 4-82	30	2.1	.32	51	25	240	10	481	0	290	32	0.7	7.3	1.2	927	230	0	68	6.9	1400	7.8
133-59- 9ADA	200-210	7-26-83	26	1.1	.23	75	22	250	13	450	0	400	64	0.5	0.0	.76	1070	278	0	65	6.5	1590	7.6
133-59- $9BBB_1$	211-216	9- 7-83	31	.20	.13	75	31	240	11	416	0	430	63	0.6	1.0	.64	1090	315	0	61	5.9	1640	8.1
133-59-14CCC	167-170	8-27-81	30	.58	.24	82	33	240	12	502	0	380	57	0.5	1.0	.68	1080	840	0	60	5.7	1520	7.9
133-59-14CDD	167-170	8-27-81	30	1.2	.56	96	36	230	13	475	0	340	100	0.4	1.0	.35	1080	390	0	55	5.1	1550	7.7
133-59-15AAA	167-170	8-27-81	31	.94	.37	82	38	230	14	480	0	330	100	0.4	1.0	.65	1060	360	0	57	5.3	1550	7.8
133-59-15CCC	188-191	9-25-75	21	1.5	.07	84	32	180	9.2	562	0	250	22	0.5	0.0	5.1	882	340	0	53	4.2	1350	7.7
133-59-19BAA	196-199	8-27-81	31	1.5	.16	86	43	130	12	530	0	210	33	0.3	1.0	0.0	809	390	0	41	2.9	1130	7.8
133-59-20BBB	197-200	8-25-81	30	.20	.13	56	32	270	12	550	0	240	120	0.5	1.0	.45	1030	270	0	67	7.2	1510	8.1
133-59-20ABB	197-200	8-25-81	30	.33	.32	78	40	180	12	555	0	240	40	0.4	1.0	.05	895	360	0	51	4.1	1290	7.9
133-59-21BAA	231-234	8-26-81	31	.27	.35	94	43	110	10	562	0	160	27	0.3	1.0	0.0	754	410	0	36	2.4	1070	8.1
133-59-26ADD	176-187	8-27-82	25	.50	.32	22	55	350	13	415	0	340	100	1.3	0.4	2.1	1060	78	0	89	17.0	1700	8.1
133-59-$27CCC_1$	164-169	8-26-82	28	.25	.12	55	19	300	20	472	0	410	44	0.5	0.5	1.5	1110	215	0	73	8.8	1680	7.9
133-59-$27CCC_2$	178-183	9-14-82	29	.80	.33	64	18	280	15	482	0	380	31	0.5	0.3	1.6	1060	234	0	71	8.0	1560	7.8
133-59-27DCC	168-173	8-26-82	28	1.1	.10	73	33	170	12	530	0	230	17	0.5	0.0	.74	826	318	0	53	4.1	1270	8.0
133-59-28CDD	204-209	8-27-82	26	.44	.08	54	27	220	13	490	0	250	50	0.7	7.5	1.2	891	246	0	65	6.1	1380	8.1
133-59-28CCC	195-200	8-27-82	27	.66	.11	53	25	250	13	498	0	210	110	0.6	0.2	1.2	936	235	0	68	7.0	1490	7.9
133-59-29DCC	198-203	9-23-82	28	1.2	.11	65	23	180	13	495	0	200	17	0.4	6.3	.95	779	257	0	59	4.9	1200	8.0
133-59-30CDD	214-219	9-23-82	29	1.4	.11	71	37	180	13	528	0	240	24	0.5	10.0	8.5	867	329	0	53	4.3	1330	8.0
133-59-30CCC	225-230	9-23-82	29	.43	.25	67	26	140	11	482	0	170	19	.05	5.0	.75	706	274	0	51	3.7	1090	8.1
133-59-31AAA	TD=223	9-15-82	29	5.2	.15	68	30	190	14	516	0	260	19	0.5	6.9	.69	877	294	0	57	4.8	1320	7.9
133-59-31DDB	TD=237	9-15-82	30	3.9	.13	62	32	190	14	516	0	260	26	0.5	7.7	.71	881	286	0	58	4.8	1340	8.0
133-59-32BBB	198-201	9-25-75	20	1.5	.20	61	29	190	10	496	0	250	19	0.5	4.2	4.5	834	270	0	59	5.0	1270	7.7
133-59-$34AAA_3$	TD=165	9-14-82	31	1.7	.24	77	28	200	12	527	0	270	28	0.6	4.9	1.2	915	307	0	57	4.9	1400	7.9
133-59-$34AAA_2$	168-173	8-26-82	27	1.2	.17	79	31	220	12	511	0	320	37	0.6	0.9	1.1	982	325	0	58	5.3	1490	7.5
133-59-35AAA	193-198	8-26-82	27	1.4	.30	70	28	250	12	420	0	350	59	0.7	0.0	1.1	1030	290	0	64	6.4	1590	8.3
133-59-35ABB	162-165	8-28-81	30	.84	.47	76	34	250	12	542	0	330	72	0.6	1.0	.58	1070	330	0	61	6.0	1550	7.9
134-59-31CBB	177-182	11- 2-83	28	.46	.04	28	11	280	11	475	0	300	23	0.5	11.0	1.2	928	115	0	83	11.4	1440	7.8
134-59-31CCC	178-184	5-22-75	21	.68	.04	33	21	260	6.8	486	0	300	39	.06	1.0	1.4	924	170	0	76	8.7	1430	8.1
132-60- 1DCC	203-208	9-23-82	28	.59	.09	57	30	220	15	515	0	260	28	0.5	11.0	.74	905	266	0	63	5.8	1390	8.0
132-60-10BAA	203-208	8-26-82	28	.03	.23	33	12	260	11	594	0	170	46	0.8	0.0	1.3	855	132	0	79	9.9	1340	8.1
132-60-11BAA	203-208	9-23-82	27	.08	.68	84	26	170	15	489	0	260	15	0.4	6.3	.61	846	317	0	52	4.1	1270	8.1
132-60-12BBB	210-216	8- 1-79	30	.06	.16	61	17	120	9.2	467	0	92	19	0.3	1.0	.67	580	220	0	53	3.5	902	8.0

TABLE 1.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
133-60- 1CCC	209-214	9- 8-83	32	1.8	.43	110	33	57	9.0	395	0	160	5.6	0.3	1.0	.20	605	410	0	23	1.2	893	8.1
133-60- 1DDD	193-196	11-16-76	31	.17	.26	63	25	230	7.6	554	12	140	110	.05	0.4	1.1	894	260	0	65	6.2	1370	8.4
133-60- 2BCC	230-240	10- 5-82	30	.63	.14	54	25	220	11	456	0	280	34	0.7	6.2	.96	888	238	0	66	6.2	1340	8.1
133-60- 2CDD	255-260	9- 8-83	32	1.1	.17	83	32	200	12	452	0	250	110	0.3	1.0	.51	945	339	0	55	4.7	1450	8.2
133-60- 4DCC	211-216	11- 2-83	28	.49	.06	46	24	230	12	473	0	270	29	0.5	0.7	.90	875	214	0	69	6.9	1370	7.8
133-60- 5DAA$_1$	217-222	1- 4-84	28	.23	.07	53	28	190	12	487	8	210	31	0.4	1.0	.71	802	247	0	61	5.2	1240	8.4
133-60-10ABB	220-225	7-28-83	32	.79	.09	58	32	180	11	472	0	270	32	0.5	0.0	.64	850	276	0	57	4.7	1290	7.8
133-60-10BBB$_1$	227-232	9- 8-83	32	.24	.08	52	25	210	13	443	0	320	23	0.4	1.0	1.1	896	233	0	65	6.0	1350	7.8
133-60-10DDC	204-210	9-15-82	27	1.1	.06	27	13	250	12	468	0	250	29	0.6	6.6	1.4	849	121	00	80	9.9	1320	8.0
133-60-11BBB	227-232	9- 8-83	33	.71	.10	50	25	200	11	485	0	240	28	0.5	1.0	.98	829	228	0	64	5.7	1250	7.9
133-60-12BAA	197-202	9- 8-83	29	.35	.67	110	32	67	11	365	0	180	9.3	0.3	1.0	.24	621	406	110	26	1.4	896	7.9
133-60-12CCC	215-225	9-15-82	30	5.1	.21	100	29	99	12	482	0	170	7.5	0.3	3.9	.46	694	369	0	36	2.2	1050	8.0
133-60-23AAA	217-220	8-25-81	31	.49	.17	88	39	140	11	517	0	210	41	0.3	1.0	.05	817	380	0	44	3.1	1140	8.0
133-60-23ABB	211-214	8-27-81	28	.03	.09	49	31	230	12	500	0	250	73	0.5	1.0	.70	921	250	0	65	6.3	1330	8.2
133-60-23BBC	215-219	7-28-83	32	.45	.06	215	11	280	11	488	0	260	44	0.6	0.4	.89	905	108	0	83	12	1380	8.1
133-60-24AAA	207-210	8-27-81	30	.02	.70	83	25	160	12	521	0	190	26	0.4	1.0	.45	786	310	0	52	4.0	1090	8.3
133-60-24BAA	217-220	8-27-81	31	2.0	.20	93	46	150	13	548	0	260	36	0.4	1.0	.30	903	420	0	43	3.2	1260	7.7
133-60-25BBB	218-221	8- 1-79	30	.41	.14	52	24	260	9.1	479	0	290	90	0.4	1.0	1.1	994	230	0	70	7.5	1500	8.0
133-60-25CCC	208-213	9-23-82	29	.14	.04	22	6.0	240	9.5	517	0	82	12	0.6	5.1	.71	662	80	0	85	12	994	8.1
133-60-26DCC	202-207	9-23-82	28	.88	.08	45	15	110	13	449	0	65	2.0	0.5	5.9	.53	507	174	0	56	3.7	809	8.2
133-60-36CCD	215-225	8-27-82	22	.18	.07	19	8.5	290	12	595	0	160	3.8	1.1	0.4	1.6	846	83	0	87	14	1350	8.2
133-60-36BAA	218-223	9-23-82	28	.13	.05	32	11	220	12	542	0	96	29	0.7	7.2	1.1	704	125	0	77	8.4	1090	8.2
133-60-36DDD	212-215	9-24-75	21	.19	.48	61	21	100	9.0	463	0	78	12	0.5	1.0	4.2	536	240	0	46	2.8	868	7.8
134-60-16CCC	212-215	11-16-76	28	1.4	.08	52	17	290	9.1	413	0	290	150	0.1	9.7	1.0	1050	200	0	75	8.9	1600	8.0
134-60-19BBB	233-253	7-26-83	32	.38	.74	79	23	88	9.2	462	0	91	12	0.4	3.8	.40	568	292	0	39	2.2	873	8.0
134-60-20ADD	317-322	9-28-83	29	.10	5.8	580	130	430	25	211	0	2200	130	0.3	1.0	.91	3640	1983	1800	32	4.2	4020	7.9
134-60-25DDD	200-205	11- 2-83	28	.58	.10	25	9.5	290	11	487	0	320	36	0.5	0.2	1.1	962	102	0	85	12.5	1540	7.7
134-60-26ABD	213-219	7-27-83	32	2.0	.05	22	8.5	280	11	455	0	300	25	0.4	8.9	.84	915	90	0	85	13	1380	8.0
134-60-26BBB	218-221	11-16-76	29	.69	.07	41	14	280	8.1	399	0	410	25	0.2	5.9	1.3	1010	160	0	78	9.6	1490	8.2
134-60-26CBB	225-230	9- 8-83	31	.21	.07	51	24	260	12	418	0	390	27	0.5	1.0	1.0	1000	226	0	70	7.5	1500	8.3
134-60-26DCC	198-201	111-17-76	28	1.2	.06	47	15	230	8.3	506	0	260	13	0.2	3.1	1.0	856	180	0	72	7.5	1300	8.2
134-60-28ADD	178-181	7-22-80	33	.41	.13	55	27	190	6.8	481	0	240	29	0.4	0.6	.48	820	250	0	62	5.2	1220	8.1
134-60-29AAA	238-241	7-22-80	31	.15	.21	68	32	160	5.8	481	0	210	28	0.3	0.5	.44	773	300	0	53	4.0	1160	7.8
134-60-29BBB$_2$	278-281	7-22-80	33	1.1	.16	73	21	95	6.1	453	0	90	21	0.3	0.1	.48	564	270	0	43	2.5	867	8.0
134-60-29DAA	217-222	9-29-83	34	.49	.47	89	32	120	10	462	0	140	23	0.4	0.0	.41	678	354	0	42	2.8	954	8.1
134-60-29DDD	207-212	9-29-83	28	.61	.13	73	22	120	10	415	0	140	20	0.3	4.4	.44	623	273	0	48	3.2	954	8.0

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
134-60-30BBB	230-235	9-28-83	29	.22	.10	71	23	100	10	438	0	110	15	0.3	3.6	.38	579	272	0	43	2.7	902	8.0
134-60-30CBB	205-210	9-28-83	33	.43	.11	59	21	140	11	479	0	110	22	0.4	0.2	.46	634	234	0	55	4.0	954	8.3
134-60-32DDD	218-224	11-14-74	18	1.3	.14	65	33	140	7.1	480	0	170	25	0.5	5.6	.55	702	300	0	50	3.5	1120	7.9
134-60-33BCC	217-222	9-29-83	27	.62	.14	64	21	130	10	426	0	150	22	0.3	4.9	.42	640	246	0	52	3.6	984	8.1
134-60-35BBB	190-195	9- 9-83	30	.07	.08	49	21	250	13	423	0	340	33	0.5	1.0	1.0	947	209	0	71	7.5	1400	8.3
134-60-35CBB$_1$	195-200	1- 4-84	28	.25	.10	47	23	230	10	451	0	320	24	0.6	0.8	1.3	907	212	0	69	6.9	1370	8.1
134-60-35CCC	255-261	11-14-74	18	1.8	.14	74	30	200	7.9	490	0	240	69	0.5	1.0	.63	884	310	0	58	4.9	1400	8.0
134-60-36ABD	185-200	8- 4-77	22	.75	.08	23	8.9	260	6.6	532	0	220	15	0.0	1.0	1.2	821	94	0	85	12	1260	8.3
134-60-36CCB	200-225	10-30-76	24	.56	.08	35	18	290	6.4	488	7	280	54	0.3	1.0	1.8	958	160	0	79	10	1400	8.4
134-61- 4AAA	263-266	9- 8-82	25	.02	.07	31	15	340	11	625	0	120	180	0.5	1.0	.69	1030	139	0	83	12	1730	8.3
134-61- 4DDD	256-259	8- 1-79	30	.20	.14	33	12	200	9.0	524	0	110	22	0.3	1.0	.33	676	130	0	75	7.6	1040	8.2
134-61-10CBB	237-242	7-14-83	29	.04	.12	31	13	200	11	526	0	120	24	0.3	0.0	.49	660	131	0	75	7.6	1090	7.8
134-61-13DAD	257-262	9-28-83	32	.01	.70	68	18	100	9.8	425	0	81	21	0.3	1.0	.36	541	244	0	46	2.8	836	8.0
134-61-14DDD	258-261	7-26-79	29	.63	.16	60	17	130	8.1	486	0	100	15	0.3	1.0	.63	601	220	0	55	3.8	942	8.2
134-61-24DAA	217-222	9-28-83	33	.59	.30	70	20	100	10	454	0	88	18	0.4	0.4	.36	565	257	0	45	2.7	872	8.1
134-61-24DCC$_1$	228-231	1- 3-84	32	1.5	.09	51	16	150	11	486	0	100	18	0.3	1.0	.54	620	193	0	61	4.7	983	8.1
134-61-24DCC$_2$	225-235	7-26-79	32	.51	.16	62	21	130	7.5	486	0	100	15	0.3	1.0	1.1	610	240	0	53	3.7	957	7.9
134-61-25DDD	209-214	9-28-83	30	.25	.05	38	16	170	10	486	0	110	16	0.3	5.3	.49	635	161	0	68	5.8	1000	8.1
134-61-36ADD	212-217	9-28-83	22	.07	.04	14	5.0	360	11	780	0	53	140	1.2	0.7	2.1	993	56	0	92	21	1680	8.3

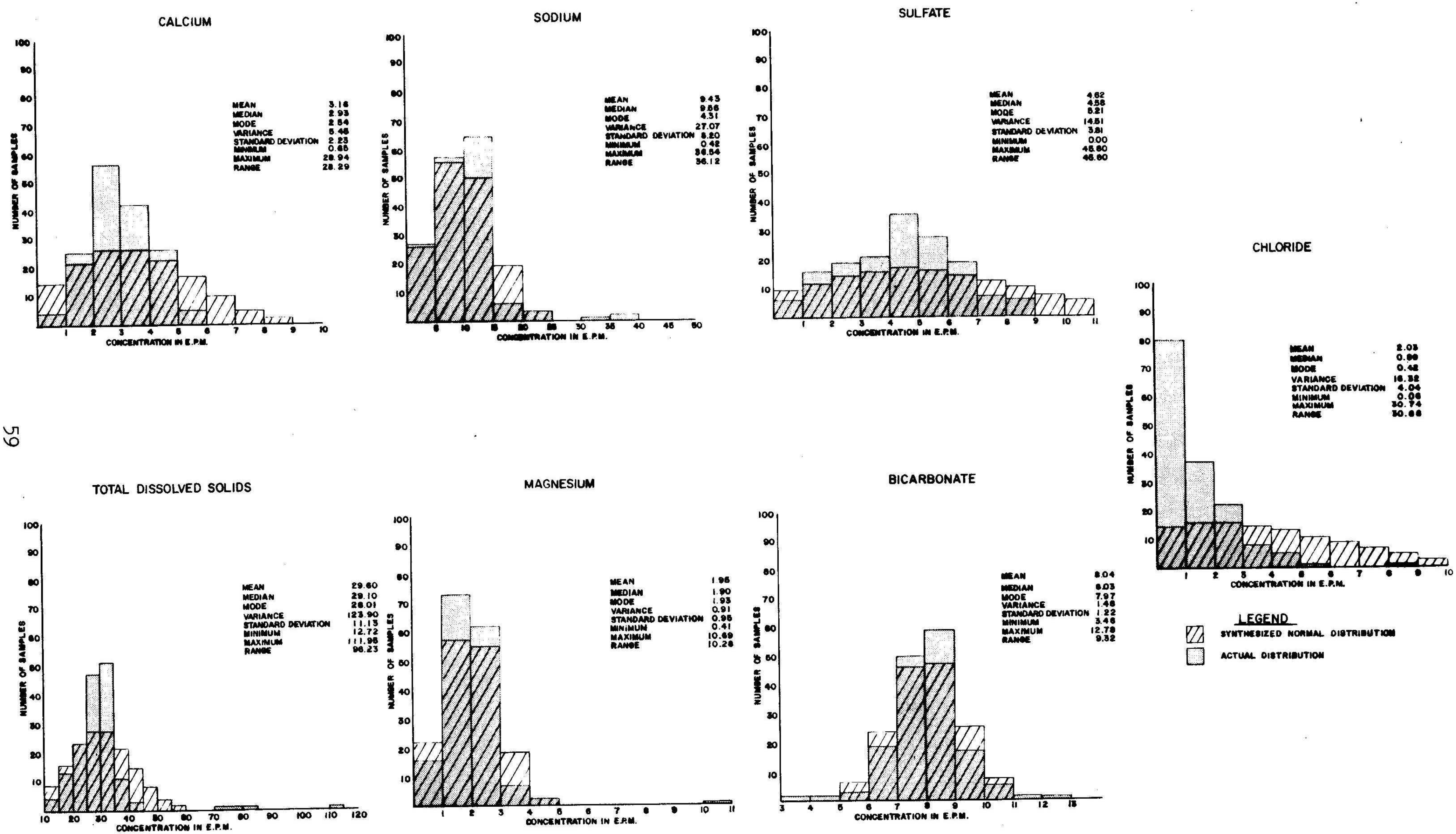


FIGURE 25.–Histograms and general statistical parameters for selected cations and anions

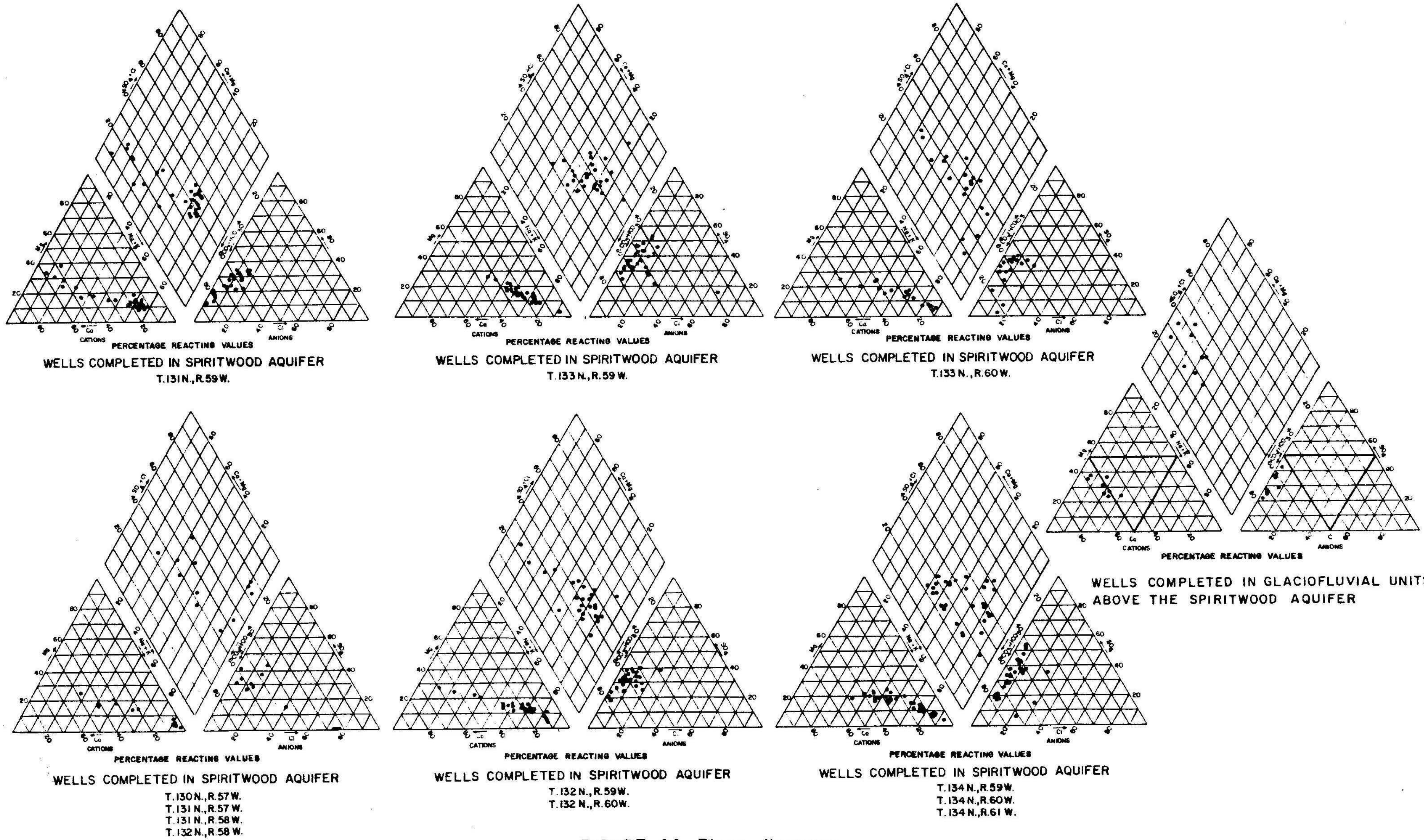


FIGURE 26.-Piper diagrams

aquifer (table 2). The depths of these wells are all less than 100 feet below land surface. Chemical analyses of samples collected from these wells were also plotted on a Piper trilinear diagram (fig. 26). The analyses all indicate a Ca-HCO_3 type of water. The total dissolved solids (calculated) range from 11.40 epm (315 mg/l) at well 131-59-9CCB to 24.02 epm (694 mg/l) at well 132-59-17DCD$_3$.

Table 3 explains the significance of the various chemical constituents for domestic and municipal use. The data in table 1 used in conjunction with table 3 provides the framework to assess the suitability of the ground water in the Spiritwood aquifer for domestic and municipal use. The water quality of the Spiritwood aquifer is suitable for domestic and municipal use over most of the study area.

A map showing the areal distribution of total dissolved solids (calculated) in the Spiritwood aquifer was prepared (pl. 9). A map showing the areal distribution of the sodium adsorption ratio (SAR) was also prepared (pl. 10). The potential for an irrigation salinity and/or sodium hazard can be estimated at any location within the study area by using these two plates. Based on an irrigation classification developed by the U. S. Salinity Laboratory (1954), the Spiritwood aquifer generally has a high salinity hazard and a low to medium sodium hazard. A soil-water compatibility investigation is thus recommended prior to the development of any irrigation project within the Spiritwood aquifer.

The temporal and spatial distribution of chemical constituents may be used to identify time and place of recharge, place of discharge and residence time within the aquifer (Back and Hanshaw , 1971). The distribution of total dissolved solids and of major cations and anions are being investigated to determine areas of natural recharge and discharge.

TABLE 2 — Chemical analyses: glacio fluvial deposits above the Spiritwood aquifer

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
131-59- 4DB*	20-35 18-28	7-14-77	12	2.1	.30	83	30	7.5	3.1	278	0	100	5	0.2	22	0.0	402	330	100	47	0.2	749	8.3
131-59- 9CCB	22-30	8- 6-75	17	.23	.31	64	27	5.0	4.0	254	0	66	3.8	0.2	2.5	.04	315	270	62	4	0.1	524	7.9
132-59-17DCD$_3$	58-63	9-22-82	28	.10	.47	130	41	48	12	436	0	210	7.6	0.2	1.0	.27	694	494	140	17	0.9	1060	7.9
132-59-27CDD	49-54	10-29-82	27	.57	.43	120	52	45	5.9	369	0	220	10	0.2	1.0	0.1	664	514	210	16	0.9	989	8.0
133-59- 5CDD$_2$	54-59	9- 7-83	30	.09	.46	99	29	74	10	395	0	120	4.9	0.2	1.0	.29	564	36	43	30	1.7	816	7.7
133-59- 9BBB$_2$	60-65	9- 7-83	30	.47	.63	110	33	55	9.3	475	0	130	9.0	0.6	1.0	.17	613	410	21	22	1.2	948	8.1
133-60- 5DAA$_2$	60-65	9-29-83	28	2.6	.38	120	34	59	11	364	0	180	5.9	0.3	2.7	.31	623	440	140	22	1.2	883	7.9
133-60-10BBB$_2$	77-82	9- 8-83	32	.23	.67	120	32	50	10	345	0	160	4.1	0.3	1.0	.33	581	431	150	20	1.1	756	7.8
134-60-35CBB$_2$	65-70	1- 5-84	26	.03	.34	100	28	44	11	411	0	94	5.8	0.3	1.0	.26	513	365	28	20	1.0	798	8.1

*Composite sample at pivot from two wells

Table 3 -- Dissolved chemical constituents in water -- their effects upon usability and recommended concentration limits for domestic and municipal water supplies in North Dakota.

Constituent or Parameter	Effects of dissolved constituents on water use	Suggested limits for drinking water in North Dakota[1]	U.S. Public Health Service recommended limits for drinking water[2]
Silica (SiO_2)	No physiological significance		
Iron (Fe)	Concentrations over 0.1 mg/l will cause staining of fixtures. Over 0.5 mg/l may impart taste and colors to food and drink.		0.3 mg/l
Manganese (Mn)	Produces black staining when present in amounts exceeding 0.05 mg/l		0.05 mg/l
Calcium(Ca) and Magnesium (Mg)	Calcium and magnesium are the primary causes of hardness. High concentrations may have a laxative effect on persons not accustomed to this type of water.		
Sodium (Na)	No physiological significance except for people on salt-free diets. Does have an effect on the irrigation usage of water.		
Potassium (K)	Small amounts of potassium are essential to plant and animal nutrition.		
Bicarbonate (HCO_3) and Carbonate (CO_3)	No definite significance, but high bicarbonate content will impart a flat taste to water.		
Sulfate (SO_4)	Combines with Calcium to form scale. More than 500 mg/l tastes bitter and may be a laxative	0-300 mg/l - low 300-700 mg/l - high over-700 mg/l - very high	250 mg/l
Percent Sodium and Sodium Adsorption Ratio (SAR)	Indicate the sodium hazard of irrigation water.		
Chloride (cl)	Over 250 mg/l may impart a salty taste, greatly excessive concentrations may be physiologically harmful. Humans and animals may adapt to higher concentrations.		250 mg/l
Flouride (F)	Flouride helps prevent tooth decay within specified limits. Higher concentrations cause mottled teeth.	Limits of 0.9 mg/l to 1.5 mg/l	Recommended limits depend on average of daily temperatures. Limits range from 0.6 mg/l at 32°C. to 1.7 mg/l at 10°C.
Nitrate (NO_3)	Over 45 mg/l can be toxic to infants. Larger Concentrations can be tolerated by adults. More than 200 mg/l may have a deleterious effect on livestock health		45 mg/l
Boron (B)	No physiological significance. Greater than 2.0 mg/l may be detrimental to many plants		
Total dissolved solids	Persons may become accustomed to water containing 2,000 mg/l or more dissolved solids.	0-500 mg/l - low 500-1400 mg/l average 1400-2500 mg/l high over 2500 mg/l very high	500 mg/l
Hardness (as $CaCO_3$)	Increases soap consumption, but can be removed by a water-softening system.	0-200 mg/l - low 200-300 mg/l average 300-450 mg/l high over 450 mg/l very high	
pH	Should be between 6.0 and 9.0 for domestic consumption		
Specific Conductance	An electrical indication of total dissolved solids measured in micromhos per Centimeter at 25°C. Used primarily for irrigation analyses.		

1. Schmid, R. W., 1965, Water Quality Explanation: North Dakota State Water Commission, unpublished report, File No. 989.
2. U.S. Public Health Service, 1962, Public Health Service Drinking Water Standards: U.S. Public Health Service, Pub. No. 956, 61 p.

Three fundamental factors control the chemical character of ground water: 1) mineralogy 2) transmissivity and 3) regional topography. The previously-described recharge area located in the vicinity of Sections 25 and 26, T. 133N., R.60W. was identified using this approach. The low total dissolved solids found in the northwestern part of the study area is explained by this approach (pl. 9). This part of the Spiritwood aquifer is situated under a regional topographic high. In comparison to other areas of the Spiritwood aquifer, the residence time of ground water in this part of the aquifer is less (shorter flow path). Total dissolved solids generally are directly proportional to residence time. In this area, upward movement of higher total dissolved solids ground water from the underlying Pierre shale into the aquifer does not occur. The ground-water flow pattern is dominated by a regional discharge area (James River valley). Ground-water flow in the aquifer and underlying shale is toward James River valley to the southwest.

Many of the chemical analyses from the eastern channel system of the Spiritwood aquifer indicate SO_4^{2-} as the major anion. The spatial distribution of these analyses generally corresponds to areas where the Pierre Formation directly underlies the aquifer. The basal Pembina Member of the Pierre Formation contains appreciable amounts of gypsum and/or selenite (Tourtelot, 1962).

These examples illustrate the value of a hydrochemical approach to ground-water flow system analysis. A more detailed report describing the application of a hydrochemical approach to the Spiritwood aquifer in the study area is in preparation.

AQUIFER MANAGEMENT

Statement of the Problem

The management of buried-valley aquifers includes assessment of the following:

1) short-term irrigation well interference (well spacing)
2) permissible sustained yield, and
3) permissible mining yield

Data available over most of the study area provides sufficient definition of both aquifer geometry and aquifer hydraulic properties to assess short-term well interference in a single irrigation season. Thus, well spacing is for the most part adequately defined. Permissible sustained yield and mining yield are more difficult to assess. Permissible sustained yield is the maximum rate at which water economically and legally can be withdrawn perenially for beneficial purposes without bringing about some undesired result (Domenico, 1972). Permissible mining yield is the maximum volume of water in storage that can be extracted economically and legally and used for beneficial purposes without bringing about some undesired result (Domenico, 1972). The determination of these two yield values requires, in part, the quantification of long-term areal recharge, discharge and leakage rates. The overlying glacial drift is characterized by lithologic and structural (joints, fractures) inhomogeneities which create significant spatial variation in recharge, discharge and leakage. The spatial variation of these three parameters is inadequately defined. This precludes the development of any meaningful long term predictive management model.

Allocation of Ground Water

The right to appropriate ground water in North Dakota is derived from the doctrine of prior appropriation. Under the prior appropriation doctrine, the water and land are declared to be separate entities. The ground water is the property of the state. The individual appropriates a right to use a specified quantity of ground water provided the use is beneficial (Walton, 1970).

State law requires that a water permit be obtained for all uses with the exception of individual domestic or livestock. The permit is obtained by filing an application with the State Engineer. This application is processed in accordance with prescribed procedures. They include the notification of landowners within a one-mile radius of the designated point of diversion, legal notice in the official county newspaper and a hearing at which those who may have an interest in the application may state their views.

After the statutory procedures have been completed the State Engineer must evaluate the application in accordance with the following statutory criteria:

1. The rights of a prior appropriator will not be unduly affected.
2. The proposed means of diversion or construction are adequate.
3. The proposed use of water is beneficial.
4. The proposed appropriation is in the public interest.
    a. The benefit to the applicant resulting from the proposed appropriation.
    b. The effect of the economic activity resulting from the proposed appropriation.
    c. The effect on fish and game resources and public recreational opportunities.
    d. The effect of loss of alternate uses of water that might be made within a reasonable time if not precluded or hindered by the proposed appropriation.
    e. Harm to other persons resulting from the proposed appropriation.

f. The intent and ability of the applicant to complete the appropriation.

A number of statutes govern the appropriation of water and the administration of water permits. Some deal with procedure and others can be considered the foundation to a workable system. The key elements of the latter include:

1. The State Engineer may attach conditions to a permit to protect the rights of others and the public interest.

2. Priority in time gives the superior water right. However, priority of appropriation does not include the right to prevent changes in the condition of water occurrence, such as the increase or decrease of stream flow, or the lowering of a water table, artesian pressure, or water level by later appropriators if the prior appropriator can reasonably acquire his water under the changed conditions.

3. A conditional water permit must be developed within a specified period of time, usually three years. If it is not developed within the specified period the permit can be cancelled. Also, if a developed permit is unused for a period of three consecutive years, it is also subject to cancellation.

4. Water permits can be assigned only upon the approval of the State Engineer.

5. A change in the type of use for a water permit can go only from a lower to higher use. For example, irrigation use is superior to industrial use, thus a water permit issued for irrigation purposes cannot be transferred for industrial purposes.

6. The State Engineer has full power and authority to enforce and otherwise administer the provisions of the statutes.

7. Any action of the State Engineer is appealable to the District Court.

As of 1984, the State Engineer has approved the appropriation of 6,625.5 acre-feet of ground water from the Spiritwood aquifer in the study area to irrigate 4,769.5 acres of land. Action on additional appropriations amounting to 2,900.3 acre-feet of ground water to irrigate 1,914.6 acres of land has been deferred. The location and status of water permit applications in the study area are shown in plate 8.

Action by the State Engineer to defer or to hold a portion of a requested appropriation in abeyance is taken primarily to protect the rights of prior appropriators. As previously mentioned, management of the Spiritwood aquifer system includes the assessment of short-term irrigation well interference and long-term yield capabilities of the aquifer. Short-term well interference is an important consideration in the narrow tributary channels northeast of Oakes. In these areas of the Spiritwood aquifer well spacing is the most important criteria used to evaluate water permit applications. The well spacing problem in the narrow tributary channels is relatively easy to solve by test drilling and aquifer testing methods. Water permit applications which do not meet necessary well spacing requirements and which would unduly impact the rights of prior appropriators are denied by the State Engineer.

The long-term yield capability of the Spiritwood aquifer in the study area is much more difficult to assess. As previously mentioned, the glacial drift overlying the Spiritwood aquifer is characterized by lithologic and structural (joints, fractures) inhomogeneities which create significant spatial variation in recharge, discharge and leakage. The spatial variation of these three parameters is inadequately defined. The Hydrology Division of the State Water Commission has developed an approach to address the problem of determining the long-term yield capability of the Spiritwood aquifer in the study area. First, piezometer nests have been installed throughout the study area and water levels are being monitored on a monthly frequency. The objective of this phase of the investigation is to measure the response of the aquifer and overlying aquitards to existing irrigation withdrawals. Second, hydrochemical data are being analyzed to distinguish areas of recharge and discharge in the aquifer system. Third, areal and profile computer models are being developed to test and refine the existing conceptual model of the aquifer system. The ultimate goal is the development of a reliable long-term predictive management model. To adequately evaluate the hydraulic properties of the aquitards, requires a water level monitoring program that covers a long period of record. As a result, approval of additional appropriations in some areas of the Spiritwood aquifer may not be granted by the State Engineer for a period of several years or more. To expedite the evaluation process it is important that existing appropriators submit accurate annual water use reports and that water be applied to benefcial use as soon as possible after the State Engineer approves a water permit application.

Based on available hydrologic data, and the distribution of water permit applications as shown in plate 8, there are three areas of the Spiritwood aquifer where additional appropriations of ground water could be approved by the State Engineer. These areas include: 1) the segment of the aquifer south and west of Twin Lakes, 2) the eastern channel system extending southeast of Twin Lakes to the LaMoure-Dickey County line, and 3) the area in the vicinity of Lake Taayer between Oakes and Cogswell.

SUMMARY AND CONCLUSIONS

The Spiritwood aquifer occupies a braided buried-valley complex in parts of LaMoure, Dickey and Sargent Counties. The aquifer consists of variable portions of sand and gravel with occasional thin, interbedded silt and clay layers. The buried channels are subparallel and are separated by narrow bedrock ridges. Northeast of Oakes, numerous low transmissivity barriers occur which are oriented transverse to the aquifer. The barriers consist of silty clay.

Water in the Spiritwood aquifer occurs under confined conditions. The confining lithologies consist of Createceous shales below the aquifer and glacial drift above the aquifer. Over most of the study area, the glacial drift consists primarily of till. Glaciofluvial and glaciolacustrine deposits comprise a significant percentage of the drift in the area north of Oakes and south of the Dickey-LaMoure County line.

For the most part, ground water in the Spiritwood aquifer flows from northwest to southeast, in the study area. A ground-water divide occurs west of Twin Lakes. The ground-water divide corresponds to a topographic divide. In this area of the aquifer, ground water flows to the west and southwest toward the James River valley.

The average values of transmissivity, hydraulic conductivity and storage coefficient calcuated from the aquifer/response tests were 24,800 ft^2/day, 455 ft/day and .00025, respectively. The hydraulic conductivity ranges from 380 to 600 ft/day. Data from most of the aquifer/response tests indicated that leakage occurred from the overlying glacial drift. Each test indicated the existence of one or more low transmissivity barriers. The complex hydrogeologic setting precluded the quantification of leakage using available analytical techniques.

The natural recharge-discharge relationships of the Spiritwood aquifer are inadequately defined. Over most of the study area, the aquifer acts as a buried-line sink. Ground water flows downward into the aquifer from the overlying glacial drift and upward into the aquifer from the underlying Createceous shales. The overlying glacial drift is characterized by lithologic and structural (joints-fractures) inhomogeneities. As a result, there is a great deal of spatial variation in recharge and discharge. The inhomogeneities are not adequately mapped and the associated hydraulic properties are not defined.

Ground-water withdrawals for irrigation from the Spiritwood aquifer began in 1973 and show a relatively steady increase through 1982. 135 acre-feet of ground water was applied to beneficial use during 1973 and 2085 acre-feet was applied to beneficial use during 1982.

The water chemistry of the Spiritwood aquifer ranges from a $Ca-HCO_3$ type to a $Na-HCO_3-SO_4$ type. The $Na-HCO_3$ type predominates. Over most of the study area, the water quality of the Spiritwood aquifer is suitable for domestic and municipal use. Based on an irrigation classification developed by the U. S. Salinity Laboratory, the Spiritwood aquifer generally has a high salinity hazard and a low to medium sodium hazard. A soil-water compatibility investigation is recommended prior to the development of an irrigation project within the Spiritwood aquifer.

The inability to identify and quantify recharge, discharge and leakage precludes the development of any meaningful long term predictive management model. Until these parameters are defined, the appropriation of additional ground water in some areas of the aquifer will be curtailed.

This includes the western channel system just south of Twin Lakes which extends southeast to Bear Creek valley.

No additional appropriations will be approved northeast of Oakes in the narrow segments of the aquifer which are bounded by low transmissivity barriers. Aquifer geometry is the limiting factor for the appropriation of additional ground water in these segments.

Based on available hydrologic data, and the distribution of water permit applications as shown in plate 8, there are three areas of the Spiritwood aquifer where additional appropriations of ground water could be approved by the State Engineer. These areas include: 1) the segment of the aquifer south and west of Twin Lakes, 2) the eastern channel system extending southeast of Twin Lakes to the LaMoure-Dickey county line, and 3) the area in the vicinity of Lake Taayer between Oakes and Cogswell.

FUTURE WORK

Additional research is required to determine the natural recharge and discharge relationships of the Spiritwood aquifer system. Water moves into and out of the Spiritwood aquifer through leakage from the overlying glacial drift and underlying shales. The heterogeneous nature of the drift, both lithologically and possibly structurally (fractures-joints) creates a spatial variation in the rate of recharge and discharge. To quantify recharge and discharge rates, the lithologic and structural heterogeneities must be mapped. The hydraulic properties of these heterogeneities also must be defined.

The mapping of the lithologic and structural heterogeneities, particularly within the glacial drift, is at present, insurmountable. The detail needed in mapping is not economically feasible, because the small scale nature of the heterogeneities would require too many test holes. No borehole or surficial geophysical method is currently available which can adequately define these heterogeneities. The areal mapping problem currently cannot be solved.

A study to investigate glacial drift inhomogeneities should be initiated and should be restricted to a specific area of the aquifer in order to define in detail the recharge and leakage processes. Several significant recharge areas occur in the study area. One previously mentioned area is located in the vicinity of Sections 25 and 26, T133N, R60W. A glaciofluvial unit within the drift above the Spiritwood aquifer may act at a conduit for recharge to the Spiritwood aquifer. Additional test holes and observation wells to trace this fluvial unit are recommended at the following locations:

1) 133-60-26CDC
2) 133-60-35ADD
3) 133-60-27DAA
4) 133-60-27AAA

Water chemistry data, coupled with other hydrogeologic data can provide a basis for the definition of recharge and discharge areas within a ground-water flow system. The screened intervals of observation wells have been selected almost entirely from estimates of hydraulic conductivity. The coarsest part of the aquifer section is generally screened. Some observation wells therefore are screened at the base of the aquifer just above the bedrock contact and others are screened in middle or upper portions of the aquifer. Vertical variation of water chemistry within the aquifer has not yet been established. If vertical water chemistry variation is significant, then the screened interval becomes an important criteria in the interpretation of water-chemistry data. Ignoring the aquifer interval sampled could lead to major misinterpretation of the flow system.

Three sites within the study area have been selected to assess vertical variation in water chemistry within the Spiritwood aquifer. The first site is proposed at 133-60-02CDD. One observation well has been completed at this site, and is screened from 255 to 260 feet below land surface. The aquifer consists of variable portions of sand and gravel and occurs from 200 to 261 feet below land surface. An observation well should be completed near the top of the aquifer at 200 feet below land surface. Another optional observation well could also be screened at about 230 feet below land surface.

The second site is proposed at 133-60-36DDD. One observation well has been completed at this site and is screened in the upper part of the aquifer from 212 to 215 feet below land surface. The aquifer consists of variable portions of sand and gravel and occurs from 204 to 243 feet below land surface. An observation well should be completed near the base of the aquifer, at 240 feet below land surface.

The third site is proposed at 132-59-27CDC. Two observation wells have been completed at this site. One is screened from 105 to 110 feet below land surface within the till and the other is screened from 209 to 214 feet below land surface near the base of the aquifer. The aquifer consists of variable portions of sand and gravel and occurs from 147 to 218 feet below land surface. An observation well should be completed near the top of the aquifer, at 150 feet below land surface.

A profile modelling study is also recommended. The modelling would be a "knob turning" exercise to investigate the following:

1) the impact of glaciofluvial units above the Spiritwood aquifer on the flow system,

2) the impact of a dual porosity/permeability aquitard (fractured till) on the flow system,

3) the discharge area located in Bear Creek valley, and

4) the impact of topography on the flow system.

The knowledge gained from this study will provide a better insight into the selection of additional data-gathering sites. Ultimately, a three-dimensional model of the aquifer system should be developed and utilized as a management tool for the allocation of ground water.

REFERENCES CITED

Armstrong, C.A., and Luttrell, S.P., 1978, Ground water basic data for Dickey and LaMoure Counties, North Dakota: County Ground-Water Studies No. 28, Part II, 557 p.

Armstrong, C.A., 1979, Ground-water basic data for Ransom and Sargent Counties, North Dakota: County Ground-Water Studies No. 31, Part II, 637 p.

Armstrong, C.A., 1980, Ground-water resources of Dickey and LaMoure Counties, North Dakota: County Ground-Water Studies No. 28, Part III, 61 p.

Armstrong, C.A., 1982, Ground-water resources of Ransom and Sargent Counties, North Dakota: County Ground-Water Studies No. 31, Part III, 51 p.

Back, W., and Hanshaw, B.B., 1971, Geochemical interpretations of groundwater flow systems: Water Resources Bulletin, Vol, 7, No. 5, pp. 1008-1016.

Bluemle, J.P., 1979, Geology of Dickey and LaMoure Counties: County Ground-Water Studies No. 28, Part I, 72 p.

Bluemle, J.P., 1979, Geology of Ransom and Sargent Counties, North Dakota: County Ground-Water Studies No. 31, Part I, 83 p.

Hard, H.A., 1929, Geology and water resources of the Edgeley and LaMoure quadrangles, North Dakota: U. S. Geological Survey Bulletin 801, 89 p.

Tourtelot, H.A., 1962, Preliminary investigation of the geologic setting and chemical composition of the Pierre Shale Great Plains Region: U. S. Geological Survey Professional Paper 390, 74 p.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U. S. Department of Agriculture, Agriculture Handbook no. 60, 160 p.

Walton, W.C., 1970, Groundwater resource evaluation: McGraw-Hill, 664 p.