UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EVALUATION OF THE EFFECTS OF LAKE AUDUBON ON GROUND- AND SURFACE-WATER LEVELS IN THE LAKE NETTIE AREA, EASTERN MCLEAN COUNTY, NORTH DAKOTA

By C. A. Armstrong

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1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
821 East Interstate Ave.
Bismarck, ND 58501

For sale by:

Open-File Services Section
Distribution Branch
U.S. Geological Survey
MS 306, Box 25425
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CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	2
Well-numbering system	5
Previous investigations and acknowledgments	5
Climate	5
Hydrogeology	8
Fort Union Formation	8
Glacial drift	8
Lake Nettie aquifer	9
McClusky Canal area	31
Conclusions	37
Summary	39
Selected references	41

ILLUSTRATIONS

			Page
Figure	1.	Map showing physiographic divisions in North Dakota and location of study area	3
	2.	Hydrograph showing water-level fluctuations of Lake Audubon	4
	3.	Diagram showing location-numbering system	6
	4.	Bar diagram showing monthly and annual precipitation at Turtle Lake	7
	5.	Map showing potentiometric surface of the Lake Nettie aquifer, lower and middle units, and the Turtle Lake aquifer, 1970	10
	6.	Geologic section of the Lake Nettie aquifer	13
	7.	Hydrograph showing water-level fluctuations in well 148-082-23BBB	15
	8.	Hydrograph showing water-level fluctuations in well 148-081-18DCD1	17
	9.	Hydrograph showing water-level fluctuations in well 148-081-18DCD2, Crooked Lake, and Lake Nettie	18
	10.	Map showing the rise of ground-water levels in the Lake Nettie aquifer, Turtle Lake aquifer, and near the McClusky Canal attributed to the raising of Lake Audubon's stage or the filling of the canal, or both, 1981	23
	11.	Hydrograph showing water-level fluctuations in well 148-080-19CCC1	24
	12.	Hydrograph showing water-level fluctuations in well 148-080-31AAA1	25

		Page
Figure 13.	Hydrograph showing water-level fluctuations in well 147-080-13CCC	26
14.	Hydrograph showing water-level fluctuations in well 148-082-13BBB and in Slough No. 1	29
15.	Hydrograph showing water-level fluctuations in well 148-082-15BBB	30
16.	Hydrograph showing water-level fluctuations in well 147-082-13CCC	33
17.	Hydrograph showing water-level fluctuations in well 147-082-13CAA1	34
18.	Hydrograph showing water-level fluctuations in well 147-081-18DAD	36
19.	Hydrograph showing water-level fluctuations in well 147-081-28ADD	38

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM OF UNITS (SI)

For those readers who may prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are given below.

Multiply inch-pound unit	By	To obtain SI unit
Acre	0.4047	hectare
Foot	0.3048	meter
Foot per day (ft/d)	0.3048	meter per day
Foot per mile (ft/mi)	0.1894	meter per kilometer
Foot squared per day (ft^2/d)	0.0929	meter squared per day
Inch	25.4	millimeter
Mile	1.609	kilometer
Square mile (mi^2)	2.590	square kilometer

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula: °C = (°F-32)x5/9.

Milligrams per liter (mg/L) is a unit expressing the concentration of a chemical constituent in solution as weight (milligrams) of solute per unit volume (liter) of water.

National Geodetic Vertical Datum of 1929 (NGVD of 1929) is a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

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ABSTRACT

Water logging and flooding of some roads and agricultural lands have become a problem in the Lake Nettie area of eastern McLean County. Part of the flooding is caused by the raising of Lake Audubon about 13 feet from an elevation of about 1,835 feet to 1,848 feet and its effect on ground-water levels in the upper unit of the Lake Nettie aquifer by way of leakage from the lower unit. The major part of the flooding is caused by the greater than normal precipitation and the resulting runoff.

Recharge to the aquifer is from the direct infiltration of precipitation and snowmelt, the lateral percolation of water from the adjacent Fort Union Formation and glacial-drift aquifers, and from Lake Audubon. Discharge is by evapotranspiration and by ground-water movement into undrained surface-water basins in the Lake Holmes-Lake Williams area and southward through Lake Ordway or westward to Lake Audubon.

Trends shown on hydrographs indicate that near equilibrium between recharge and discharge has been reestablished in the lower unit of the Lake Nettie aquifer in the area between Lake Audubon and Lake Nettie, but east of Lake Nettie water levels are still rising. As of 1982, water-level rises caused by the raising of Lake Audubon are as much as 4 feet in the lower unit of the Lake Nettie aquifer and are between 1 and 2 feet in the upper unit of the Lake Nettie aquifer, which is hydraulically connected to Lake Nettie, Crooked Lake, and Slough No. 1. There is a rise in Slough No. 1, about 2 miles east of Lake Audubon, that can be attributed to the higher levels of Lake Audubon. Apparently rises also have occurred in many other sloughs.

Water levels have risen in the Turtle Lake aquifer both as a result of raising the water level in Lake Audubon to an elevation of about 1,848 feet and the McClusky Canal to an elevation of about 1,844 feet. Water levels have risen as much as 6 feet near the canal, but generally less than 1 foot at distances of about 0.5 mile.

INTRODUCTION

Questions have been raised concerning the cause of water logging of some agricultural land east of Lake Audubon and the reports of some roads becoming too soft for safe passage. Climatic data indicate that increased precipitation has not been the sole cause of the problems. Therefore, this study was undertaken to determine the cause of the high water levels.

A ground-water divide and flow regime in the three units of the Lake Nettie aquifer was established in the study area before the Missouri River was dammed. When Lake Sakakawea (separated from Lake Audubon by a dam) and Lake Audubon were filling, ground-water flow patterns began to change and affect water levels in the Lake Nettie area. The quantity of change due to the initial filling of the lakes cannot be estimated because ground-water-level data do not exist for this period. Therefore, the study is applied only to those changes that have occurred since ground-water records began to be collected between 1967 and 1970.

The study of the effects of Lake Audubon on both ground- and surface-water levels in the Lake Nettie area was begun by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation in October 1982. The study encompasses a 260-mi^2 area east of Lake Audubon (fig. 1), and is referred to in this report as the Lake Nettie area. The area of concern to the U.S. Bureau of Reclamation includes about 105 mi^2 in Tps. 147 and 148 N., Rs. 81 and 82 W. and is within 11 miles of Lake Audubon when the lake is at the level of 1,847 to 1,848 feet above NGVD of 1929.

The level of Lake Audubon was maintained at elevations between about 1,833 and 1,836 feet above NGVD of 1929 from 1968 to 1975 by controlling the flow between Lake Sakakawea and Lake Audubon. The lake level was raised to about 1,848 feet in 1975, primarily by pumping from Lake Sakakawea into Lake Audubon, and the level generally has flucutated between 1,847 and 1,848 feet since 1975 (fig. 2). The McClusky Canal was filled to a controlled elevation of between 1,843 and 1,844 feet in 1979. Water levels in wells in the Lake Nettie aquifer have risen as much as 6 feet between 1970 and 1982.

Purpose and Scope

The purpose of this investigation is to describe changes in the ground-water levels and levels of surface-water bodies and to ascertain whether those changes can be ascribed to the raising of the level of Lake Audubon, or to the subsequent filling of the McClusky Canal, or both. The changes will be determined by analysis of water-level records obtained from observation wells.

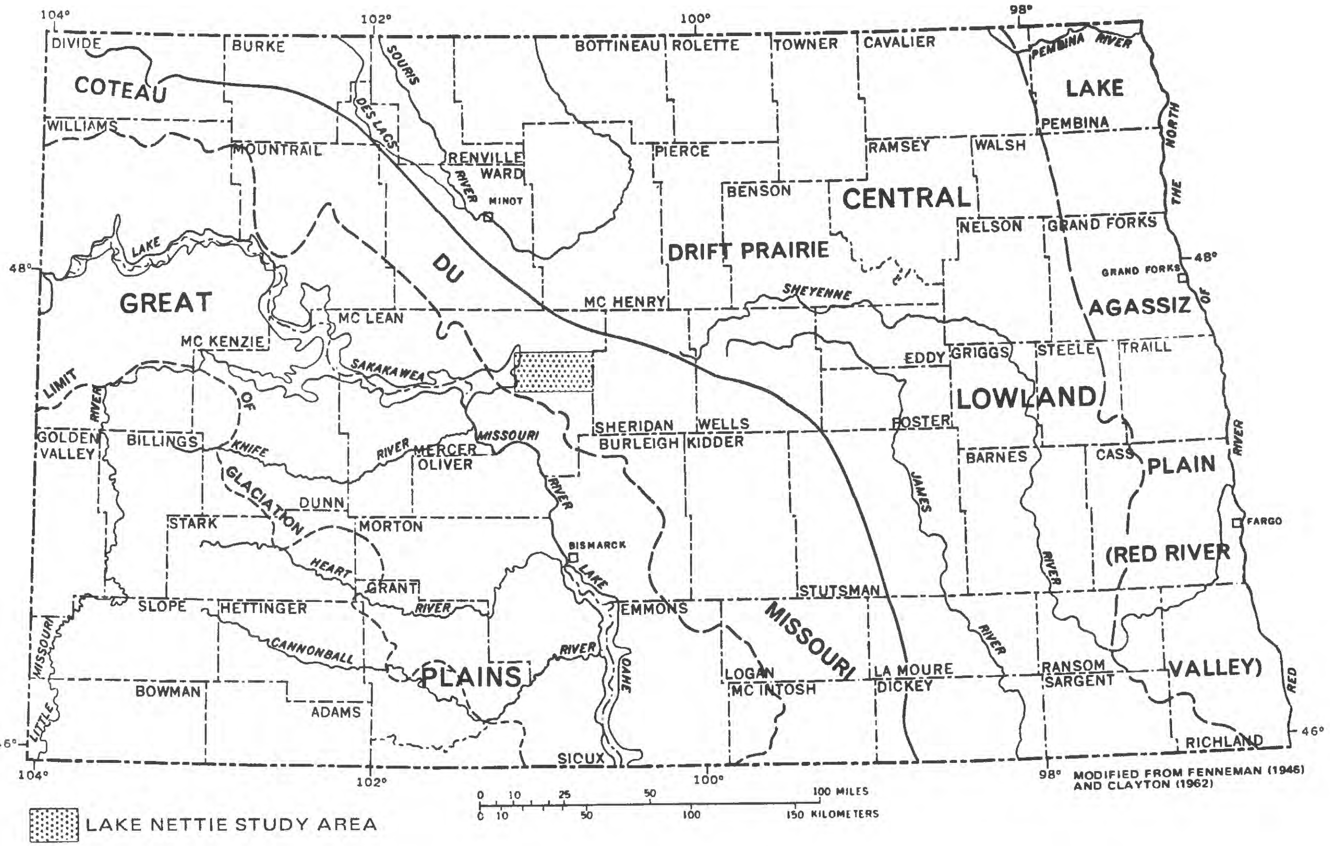

FIGURE 1.—Physiographic divisions in North Dakota and location of study area.

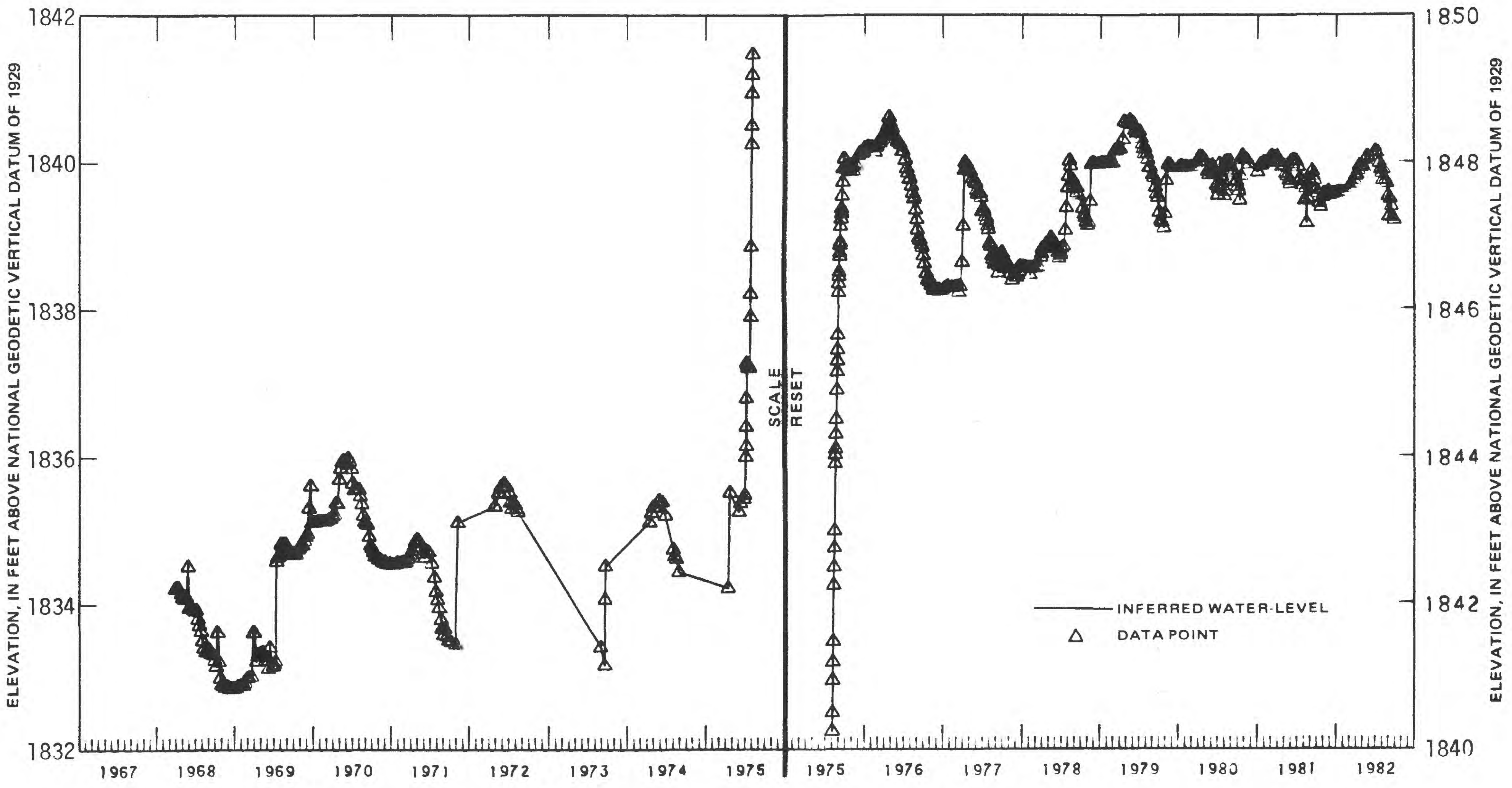

FIGURE 2.—Water-level fluctuations of Lake Audubon (Data furnished by U.S. Army Corps of Engineers).

Well-Numbering System

The wells, test holes, and small areas mentioned in this report are numbered according to a system based on the public land classification of the U.S. Bureau of Land Management. The system is illustrated in figure 3. The first number denotes the township north of a base line, the second number the range west of the fifth principal meridian, and 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). For example, well 147-082-15ADC is in the SW1/4SE1/4NE1/4 sec. 15, T. 147 N., R. 82 W. Consecutive terminal numbers are added if more than one well or test hole is recorded within a 10-acre tract.

Previous Investigations and Acknowledgments

Simpson (1929, p. 166-169) briefly described the occurrence of ground water in McLean County and stated that shallow wells near the city of Turtle Lake yielded hard water and deep wells yielded soft water. Bluemle (1971) described the geology of McLean County and included a geologic map that shows considerable detail in the Lake Nettie area. Klausing (1971) compiled a basic-data report for McLean County. The report includes logs of wells and test holes, water-level measurements, and quality-of-water analyses. Klausing (1974) also described the hydrology of McLean County and included a detailed description of the Lake Nettie aquifer system, part of which underlies much of the study area.

Appreciation is expressed to Everett L. Wright, Larry E. Freed, and other members of the U.S. Bureau of Reclamation for their help in obtaining and compiling data for this study. Appreciation also is expressed to the U.S. Army Corps of Engineers for furnishing the Lake Audubon data.

Climate

The climate in the report area is semiarid. According to the U.S. Department of Commerce (1968-83), the mean annual precipitation at Turtle Lake is 17.22 inches. The maximum recorded annual precipitation of 23.64 inches occurred in 1982. About 75 percent of the precipitation generally falls from April through September when it is most needed for crops. Most of the summer precipitation is from thunderstorms and is extremely variable. The distribution of monthly and annual precipitation for 1967-82 is shown in figure 4. The winter precipitation generally falls as snow, some of which remains on the ground until the spring thaw and may result in considerable runoff. The runoff usually starts in March or April of most years and results in the filling of

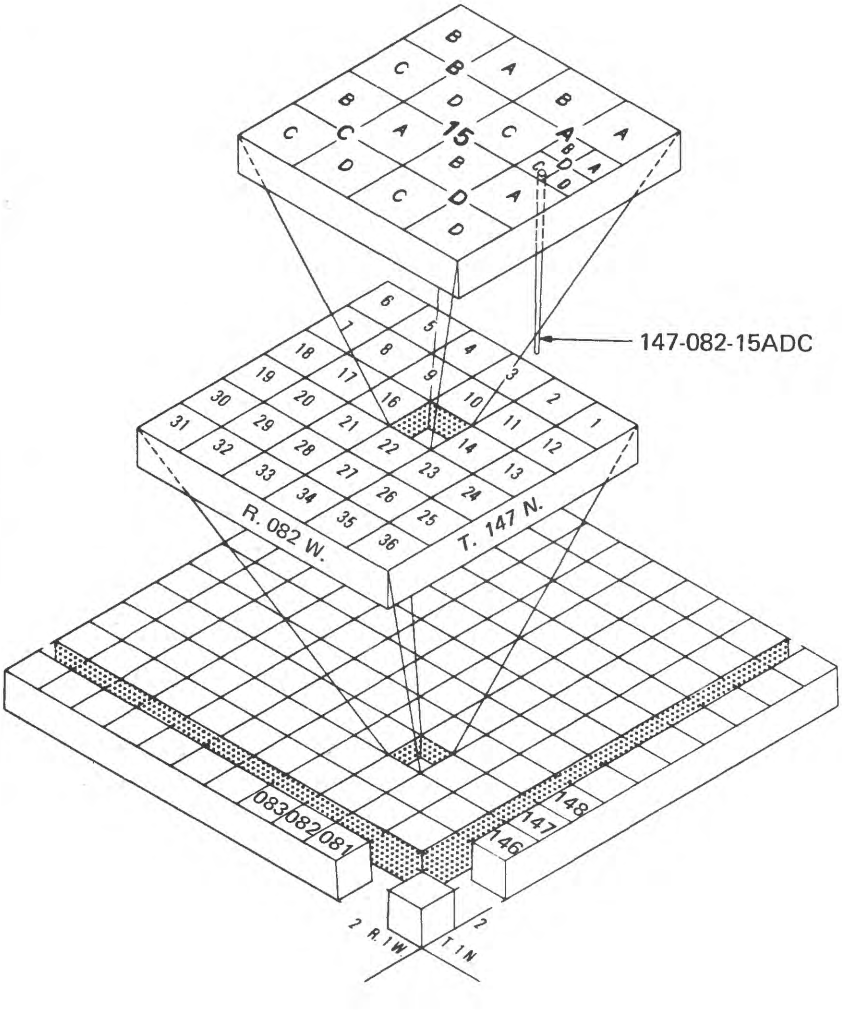

FIGURE 3.—Location numbering system.

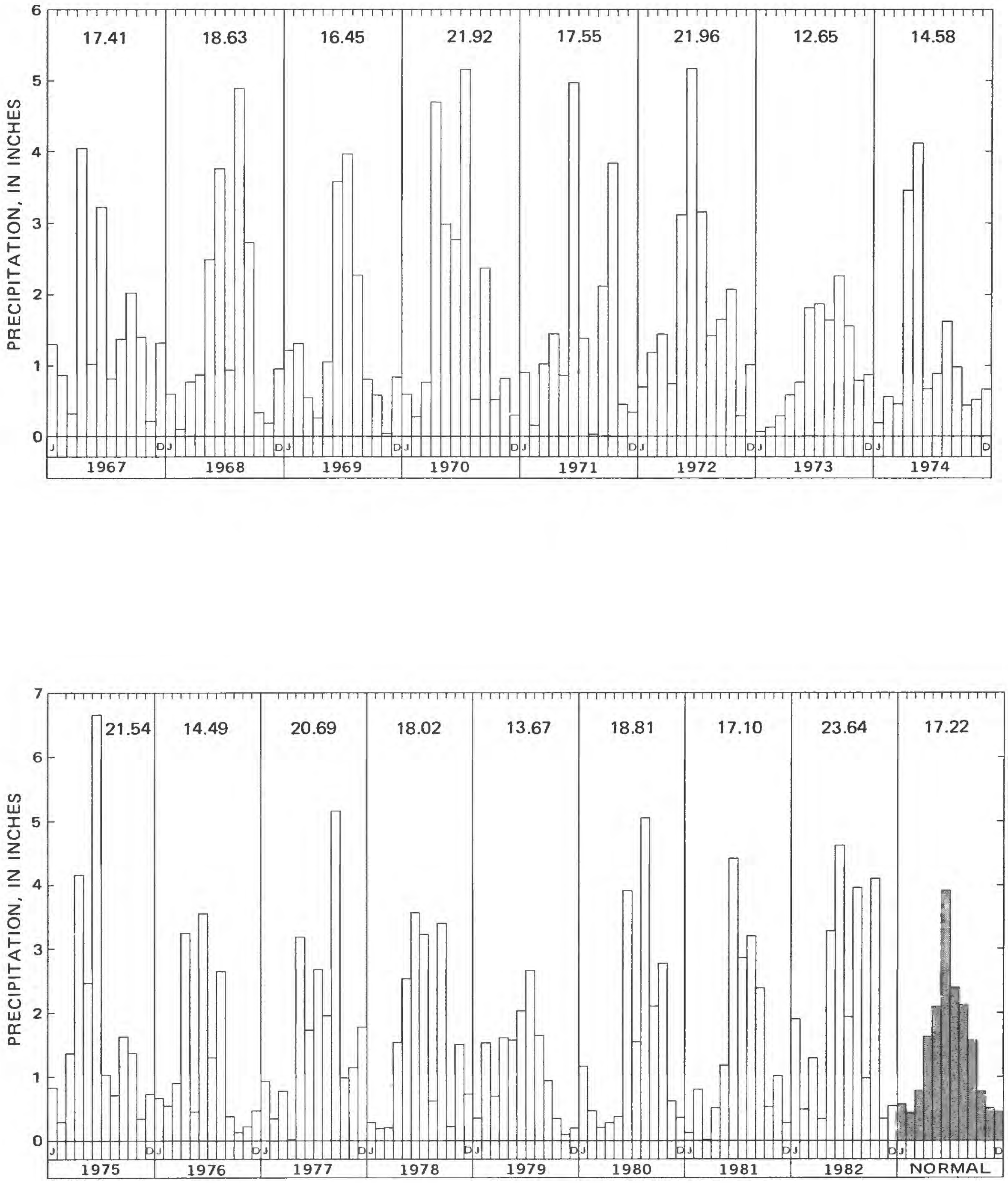

FIGURE 4.–Monthly and annual precipitation at Turtle Lake.

lakes, sloughs, and prairie potholes that abound in the area. Runoff from summer storms usually occurs only when a single storm or closely spaced storms drop more than an inch of precipitation on an area.

Temperatures in the area are extremely variable. Temperatures may be as low as -40°F in the winter and exceed 100°F in the summer. Summers usually are warm--average daily temperatures range from 62°F to 72°F.

HYDROGEOLOGY

Fort Union Formation

The Fort Union Formation, which is covered by glacial drift, underlies the study area at depths that range from about 9 to 293 feet. The formation consists of interbedded silt, siltstone, clay, shale, generally poorly consolidated sandstone, and lignite. The sandstone predominantly is very fine to fine grained and has a small hydraulic conductivity. Therefore, ground-water percolates slowly through the sandstone. Locally, lignite beds are fractured and small quantities of water also slowly percolate through these beds.

Water levels in aquifers in the Fort Union Formation (Klausing, 1971, table 1) north of the Lake Nettie aquifer generally are higher than water levels in the Lake Nettie aquifer. Therefore, ground-water movement apparently is from the aquifers in the Fort Union Formation to the Lake Nettie aquifer.

Only a few water levels are available from wells completed in the Fort Union Formation south of the Lake Nettie and Turtle Lake aquifers. Generally these water levels indicate that ground water is moving vertically downward, but there is an indication that some water is moving northward toward the Lake Nettie aquifer and Turtle Lake aquifer.

Areas where the Fort Union is within a few tens of feet of the land surface generally are topographically high and ground water does not rise close enough to the land surface to cause problems that are of concern in this report.

Glacial Drift

Glacial drift in the study area generally consists of till and glaciofluvial deposits. The till is composed of an unsorted mixture of clay, silt, sand, pebbles, and boulders. The mixture results in deposits that have small hydraulic conductivity. The till generally is not considered to be an aquifer. The glaciofluvial deposits predominantly are composed of sand and gravel lenses, although the deposits do contain lenses of silt and clay. The glaciofluvial deposits form the major aquifers in the Lake Nettie area.

Klausing (1974, p. 14) classified the glaciofluvial deposits in McLean County into four main groups of aquifers: (1) Aquifers associated with buried valleys; (2) melt-water-channel aquifers; (3) surficial-outwash aquifers; and (4) undifferentiated sand and gravel aquifers. Most of the glacial aquifers in the study area are contained within or overlie buried valleys, which were formed during Pleistocene time. Even though the larger aquifers in the area are associated with buried valleys, they may contain some melt-water-channel or outwash deposits.

The aquifers in the study area are part of the Lake Nettie aquifer system, which underlies about 166 mi^2 in east-central McLean County. Klausing (1974, p. 16) reported that aquifers in the system differ in mode and time of origin, but that all are interconnected. The individual aquifers have been named Lake Nettie, Turtle Lake, Horseshoe Valley, and Strawberry Lake aquifers. Definite boundaries between the aquifers cannot be established because the hydraulic connection throughout the system generally is good. The Lake Nettie and Turtle Lake aquifers underlie much of the study area (fig. 5). The Horseshoe Valley and Strawberry Lake aquifers, for the most part, are to the north and out of the study area, but both apparently discharge into the Lake Nettie aquifer. The junction of the Horseshoe Valley aquifer and the Lake Nettie aquifer is about 2 miles north of Lake Nettie (fig. 5). The apparent junction of the Strawberry Lake aquifer and the Lake Nettie aquifer is about 5 miles east of Lake Nettie (fig. 5); however, the southern end of the Strawberry Lake aquifer may be blocked with till and a good hydraulic connection may not exist.

Two Crooked Lakes are present in the study area. To avoid confusion with the Crooked Lake in secs. 19 and 20, T. 148 N., R. 81 W., the Crooked Lake that overlies part of the Strawberry Lake aquifer in secs. 4, 5, and 11, T. 148 N., R. 80 W., and secs. 26 and 35, T. 149 N., R. 80 W., is not further referred to in this report.

Lake Nettie Aquifer

The Lake Nettie aquifer extends from beneath Lake Audubon eastward beyond the McLean County border. It is about 2 miles wide at the edge of Lake Audubon and widens eastward to about 4 miles in width. The aquifer consists of three units--upper, middle, and lower. Each unit is composed of sand and gravel lenses. Klausing (1974, p. 6) reported that the upper unit ranges in thickness from 2 to 74 feet. The upper unit is exposed at the surface in the vicinity of Lake Nettie, but further west it may be buried beneath as much as 80 feet of till. The middle unit ranges in thickness from 0 to 97 feet. The middle unit is not present throughout the entire aquifer; however, where it is present, it is separated from the upper unit by at least 10 feet of till. The lower unit consists of one to four sand and gravel

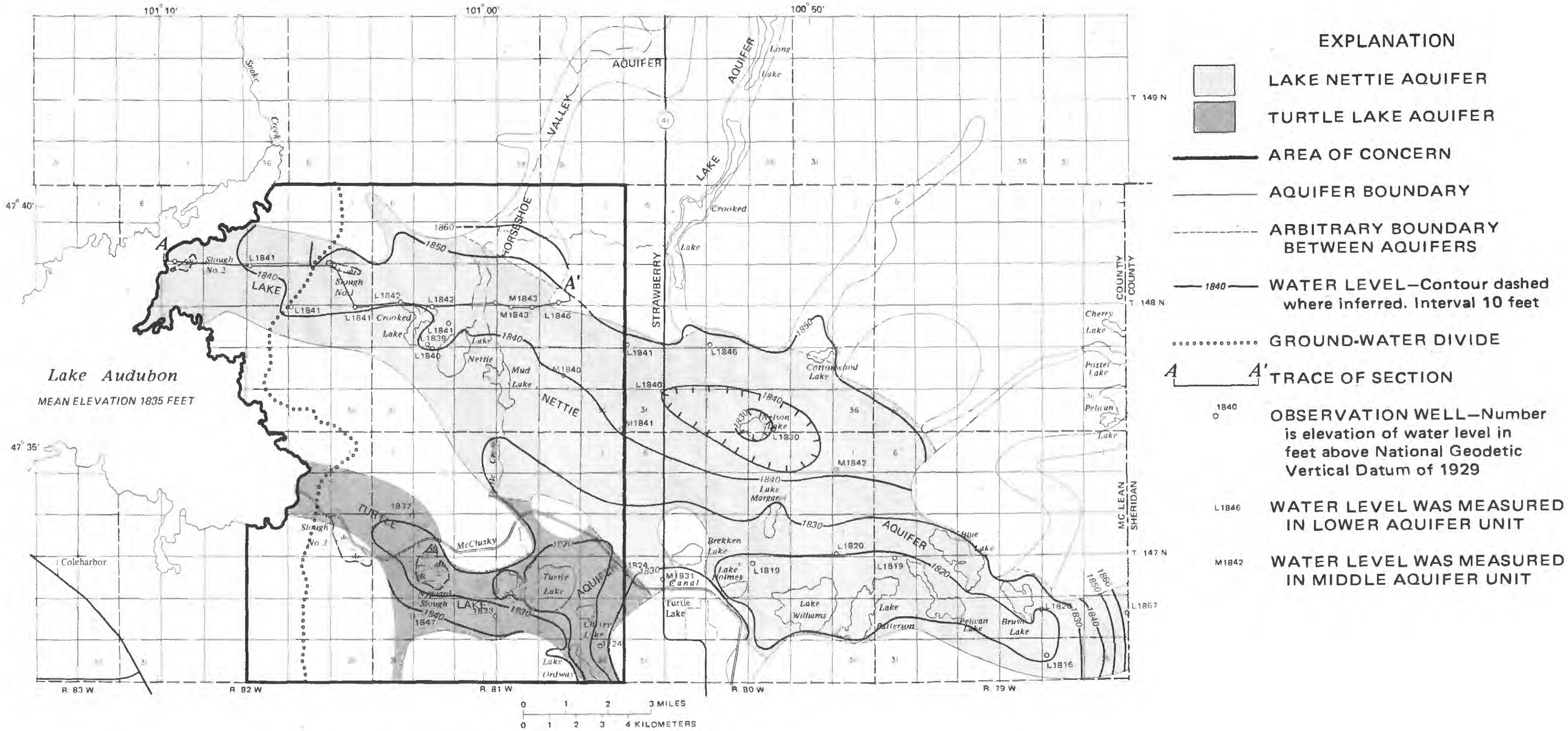

FIGURE 5.—Potentiometric surface of the Lake Nettie aquifer, lower and middle units, and Turtle Lake aquifer, 1971.

lenses that have an aggregate thickness of as much as 132 feet. The lower unit apparently is separated from the middle unit by at least 20 feet of till. However, the indication of leakage between the two units during a 5-day aquifer test implies that the separating till either may be thinner than shown in lithologic logs or is more permeable than other till in the area.

Two aquifer tests have been made in the Lake Nettie aquifer; one in the upper unit and the other in the lower unit (Klausing, 1974, p. 17). The test in the upper unit was made using irrigation well 148-080-33CBD as the pumped well. Seven observation wells were located 60 to 1,450 feet from the pumped well. Analysis of the test indicated a transmissivity of 8,600 ft^2/d and a storage coefficient of 0.14. The average hydraulic conductivity of the aquifer at the test site was about 225 ft/d, which probably is a good representative hydraulic conductivity value for the central part of the upper unit.

The test on the lower unit was made using well 148-081-20CCD5 as the pumped well. Some observation wells were completed in each of the aquifer units. Analysis of the test indicated a transmissivity of 44,000 ft^2/d and a storage coefficient of 0.0002. The storage coefficient indicates that artesian conditions exist in the lower unit. The calculated hydraulic conductivity ranged from about 930 to 980 ft/d; mean hydraulic conductivity was about 950 ft/d. When the test was concluded after 5 days of pumping, drawdowns ranged from 1.3 to 1.5 feet in observation wells 4 to 5 miles on either side of the production well. The test indicated leakage from the middle to the lower unit, but did not indicate any leakage from the upper unit. However, the test was run for only 5 days, so the results do not preclude the possibility of leakage between all three units.

The two tests indicate large differences in transmissivity within the aquifer, but both indicate that relatively large transmissivities can be expected throughout the thicker parts of the aquifer. Because of the large transmissivities and confined storage coefficient, changes in artesian hydraulic head are transmitted rapidly through the middle and lower units of the aquifer. Water-level fluctuations in the upper aquifer unit, for the most part, depend on actual movement of water rather than artesian head changes. Increased pressure in the lower aquifer unit increases upward leakage.

Recharge to upper unit of the Lake Nettie aquifer is from infiltration of precipitation and snowmelt, upward leakage from the middle or lower units, and lateral movement of ground water principally from the north from glacial-drift aquifers and aquifers in the Fort Union Formation. Prior to 1975, when the stage of Lake Audubon generally was below an elevation of 1,836 feet (fig. 2), the lower aquifer unit discharged into Lake Audubon. Presently (since 1975), recharge to the lower unit of the Lake Nettie aquifer is from Lake Audubon and the percolation of water from adjacent Fort Union and glacial aquifers, which in turn are recharged in part from precipitation and snowmelt. The Horseshoe Valley aquifer and probably the Strawberry Lake aquifer are believed to contribute considerable water to the Lake Nettie aquifer, although the quantity of recharge from each source is not known.

Discharge from the Lake Nettie aquifer is by movement downgradient and by evapotranspiration in areas where water is near or above land surface. Prior to the changes made by man, a ground-water divide was established in all three aquifer units approximately along the ground-water divide shown in figure 5. This divide also approximates the surface-drainage divide in the area. Discharge west of the divide was toward Snake Creek (now under Lake Audubon). East of the divide discharge was, and is, east-southeast into the closed basin in the Lake Holmes-Lake Williams area and southward through Lake Ordway. Data are not sufficient to locate the present ground-water divide in the upper aquifer unit. However, it probably is still east of Lake Audubon because water levels in observation well 148-082-08CDC2, which was finished in the upper unit, are above the level of Lake Audubon. Water levels in the lower unit rose when the level of Lake Audubon was raised and the ground-water divide in the lower unit moved westward to Lake Audubon. The general movement of water in the aquifer is shown in figure 6.

Potential evapotranspiration at land surface averages about 36 inches per year (U.S. Department of Commerce, 1982). During hot dry periods, evapotranspiration from the near-surface water table or from connecting ponds or sloughs may exceed recharge from all sources, and water levels are lowered. During wet periods some of the rainfall or snowmelt that once would have infiltrated to the water table now becomes runoff, thus adding to the depth of water in sloughs and lakes.

Changes in land-use practices also affect the amount of precipitation that becomes recharge. For example, summer fallow uses less water than crops so more precipitation is available for recharge. Alfalfa, on the other hand, uses more water than most crops so less precipitation is available for recharge. These land-use practices, which have not been recorded or quantified, all affect recharge and runoff and make a complicated problem more complex.

The water level in the Lake Nettie aquifer at any particular site and at any particular time is due to the cumulative effects of recharge and discharge. A change in either recharge or discharge will cause fluctuations of the water levels. Large volumes of precipitation and runoff may have a large and nearly immediate effect on water levels in the upper aquifer unit, especially in those areas where the aquifer is in direct hydraulic

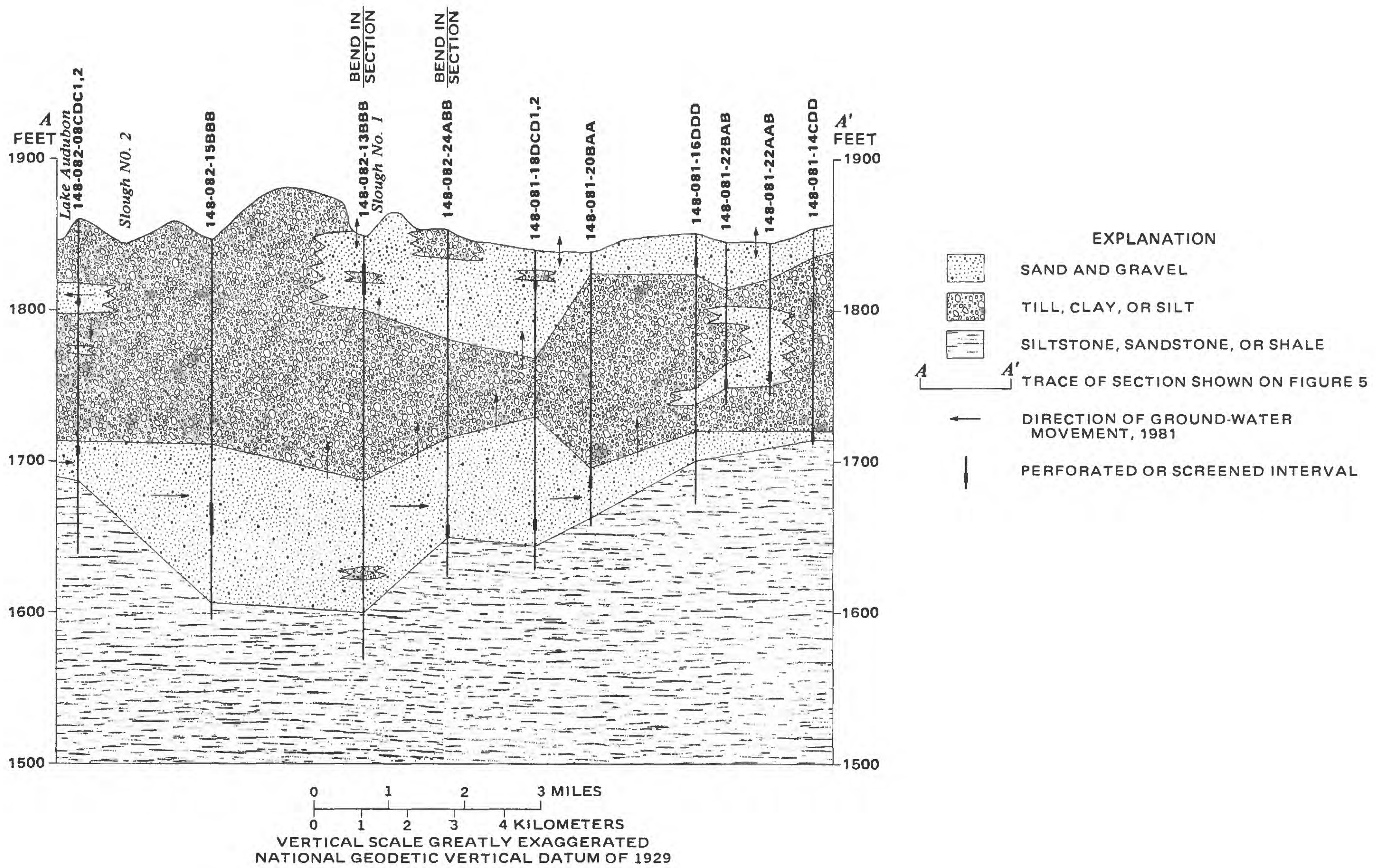

FIGURE 6.–Geologic section of the Lake Nettie aquifer.

connection with a slough or small lake. These events also affect water levels in the middle and lower aquifer units, but the effects are dampened and may be delayed for as much as 3 months. Thus, in the Lake Nettie area, the effects of precipitation and runoff greatly mask the effects of Lake Audubon, which has been held at an elevation between 1,846 and 1,848 feet in recent years.

After the Lake Audubon level was raised to an elevation of 1,848 feet in 1975, the ground water that previously would have discharged into the lake at the lower lake level could no longer discharge; consequently, ground-water levels in the Lake Nettie aquifer rose. The rising water levels in the lower aquifer unit were caused primarily by pressure changes due to the higher hydraulic head in the lake, which has some hydraulic connection with the lower unit of the Lake Nettie aquifer. The pressure, which moves as a wave, was transmitted through the lower unit thence upward into the middle unit and to some extent to the upper unit.

Movement of water from the lake to the aquifer took place near the lake. Movement in the upper unit probably did not extend more than several hundred feet away from the lake. After the divide in the lower unit moved westward to Lake Audubon, the movement of water through the aquifer started, but at a slow rate. The average particle velocity through the aquifer is defined by the following equation:

$$\overline{V} = -\frac{K\frac{dh}{dl}}{\theta},$$

where $\overline{V}$ = average particle velocity,

K = hydraulic conductivity,

$\frac{dh}{dl}$ = hydraulic gradient,

θ = porosity, and

$-$ = negative direction, or downgradient.

Therefore, the actual movement of a given particle of water in the lower aquifer unit from the lake eastward would be

$$\overline{V} = \frac{(950 \text{ ft/d}) \left(\frac{2 \text{ ft}}{(2 \text{ mi} \times 5{,}280 \text{ ft/mi})}\right)}{0.35} = -0.5 \text{ ft/d or } 180 \text{ ft/yr}.$$

In the 7 years between 1975 and 1982, a particle of water would have migrated eastward about 1,260 feet in the lower unit of the Lake Nettie aquifer.

Water levels in observation well 148-082-23BBB (fig. 7) were measured at irregular intervals between December 1969 and

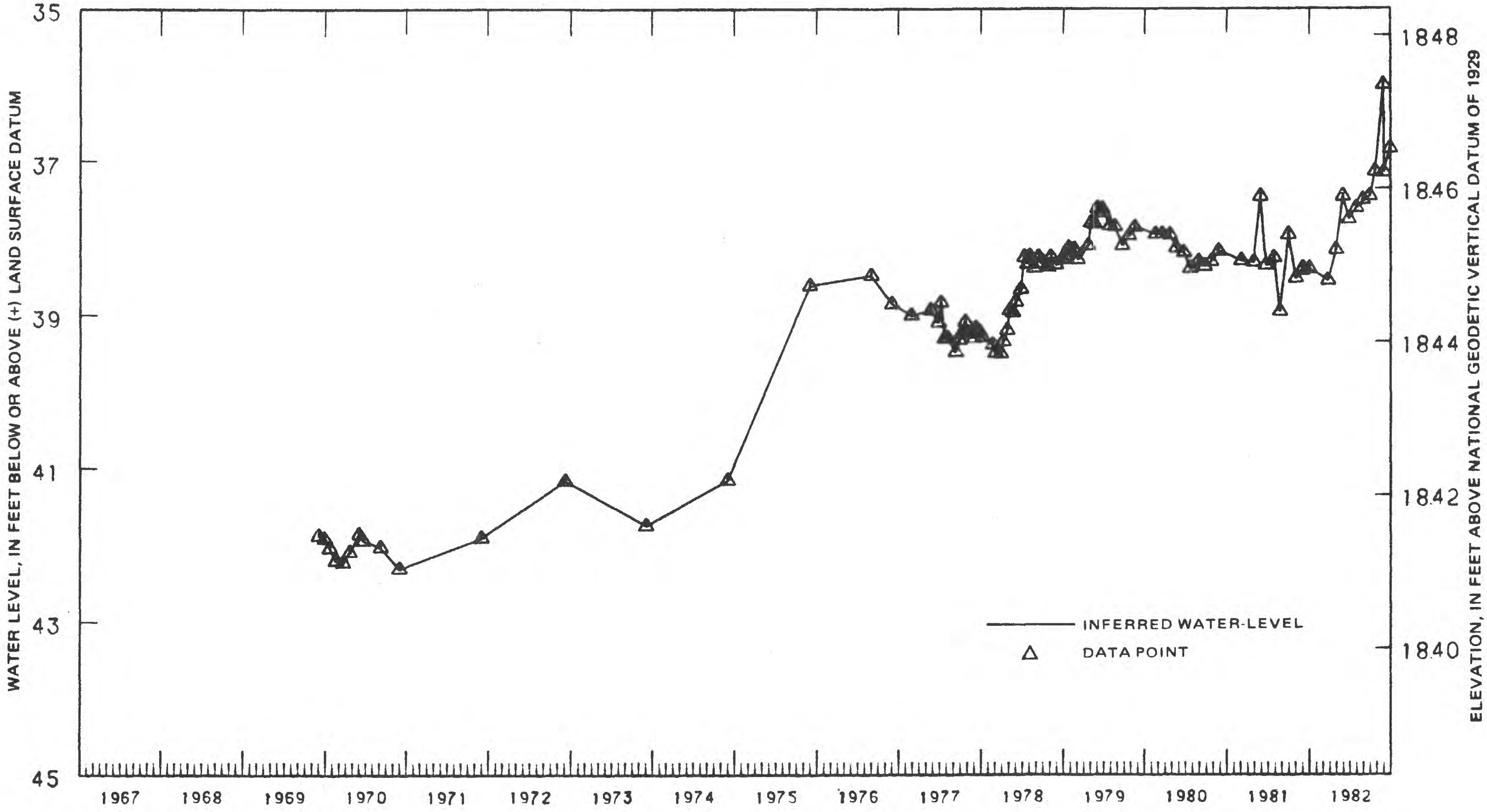

FIGURE 7.—Water-level fluctuations in well 148-082-23BBB.

December 1970. Measurements were then made annually through 1976, and then (with a few gaps) monthly or biweekly through 1982. Water levels in most other observation wells in the area were not measured in 1975 during the critical time when the level of Lake Audubon was increasing. Therefore, it was necessary to use indirect methods of estimating inferred changes at locations when measurements were not made. For example, the water-level trends shown on the hydrograph of observation well 148-082-23BBB (fig. 7), which is completed in the lower aquifer unit, are similar to the water-level trends of record shown on the hydrograph of observation well 148-081-18DCD1 (fig. 8), also completed in the lower aquifer unit. Therefore, it is assumed that the general water-level trends would have remained similar during the period of no measurements in well 148-081-18DCD1. No attempt to reconstruct individual water levels was made. A comparison of water-level trends on the hydrograph of observation well 148-081-18DCD2 (fig. 9), completed in the upper aquifer unit, was then made with the trends on the hydrograph of observation well 148-081-18DCD1. The comparisons indicate that the raising of the level of Lake Audubon has affected the water levels in both the lower and upper units of the Lake Nettie aquifer.

The hydrograph of well 148-082-23BBB (fig. 7) shows water-level fluctuations and trends in such a way that an analysis of the effects of various influences of recharge and discharge can be largely, but not exactly, separated as to causes. The water levels generally indicate a small rising trend with fluctuations from December 1969 to 1975 apparently due to fluctuations in recharge and discharge. The probable cause of the rising trend has not been determined. It may have been caused by the original filling of Lake Audubon to the pre-1975 level, but it also may have been the accumulated influences of recharge from the slightly greater than normal precipitation that occurred between 1967 and 1974. However, the 1970 water levels shown in figure 7, which do not show a rising trend, when compared to the monthly distribution of precipitation, indicate that precipitation was not the major cause of the rising trend. The total precipitation for the year was 21.92 inches, or 4.70 inches more than normal, but August and October were considerably drier than normal. The level of Lake Audubon also was gradually lowered about a foot in the last half of the year. The result of the combined influences was that the lowest measured water level for 1970 in well 148-082-23BBB (fig. 7) occurred on December 2.

Precipitation during 1971 was 0.33 inch above normal. However, precipitation was below normal during most of the year with somewhat more than 3 inches greater than normal falling in September and October. The level of Lake Audubon in the latter part of 1971 was about a foot lower than in 1970. Therefore, the higher December water level in well 148-082-23BBB apparently was caused primarily by the greater than normal precipitation in September and October 1971.

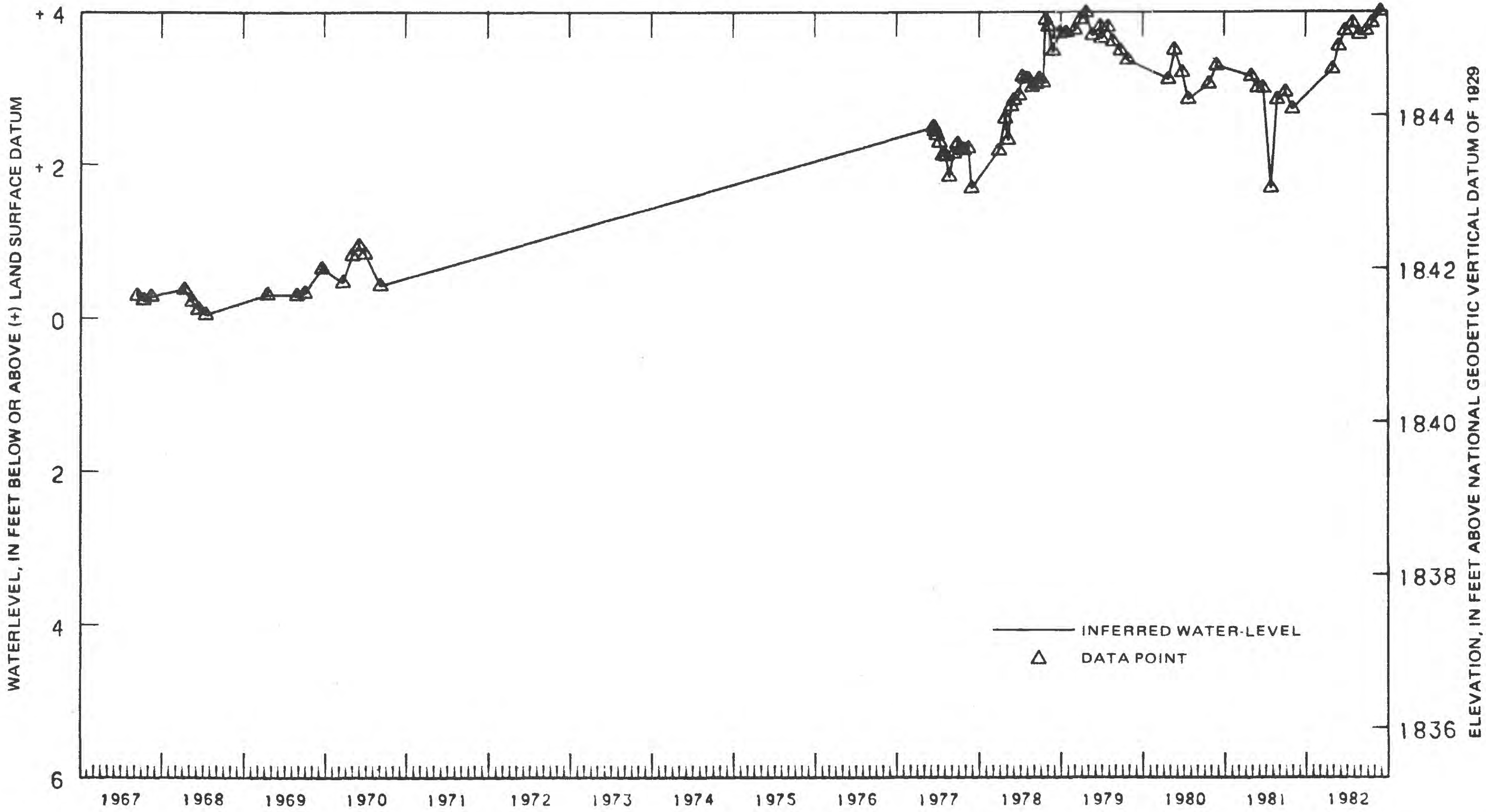

FIGURE 8.—Water-level fluctuations in well 148-081-18DCD1.

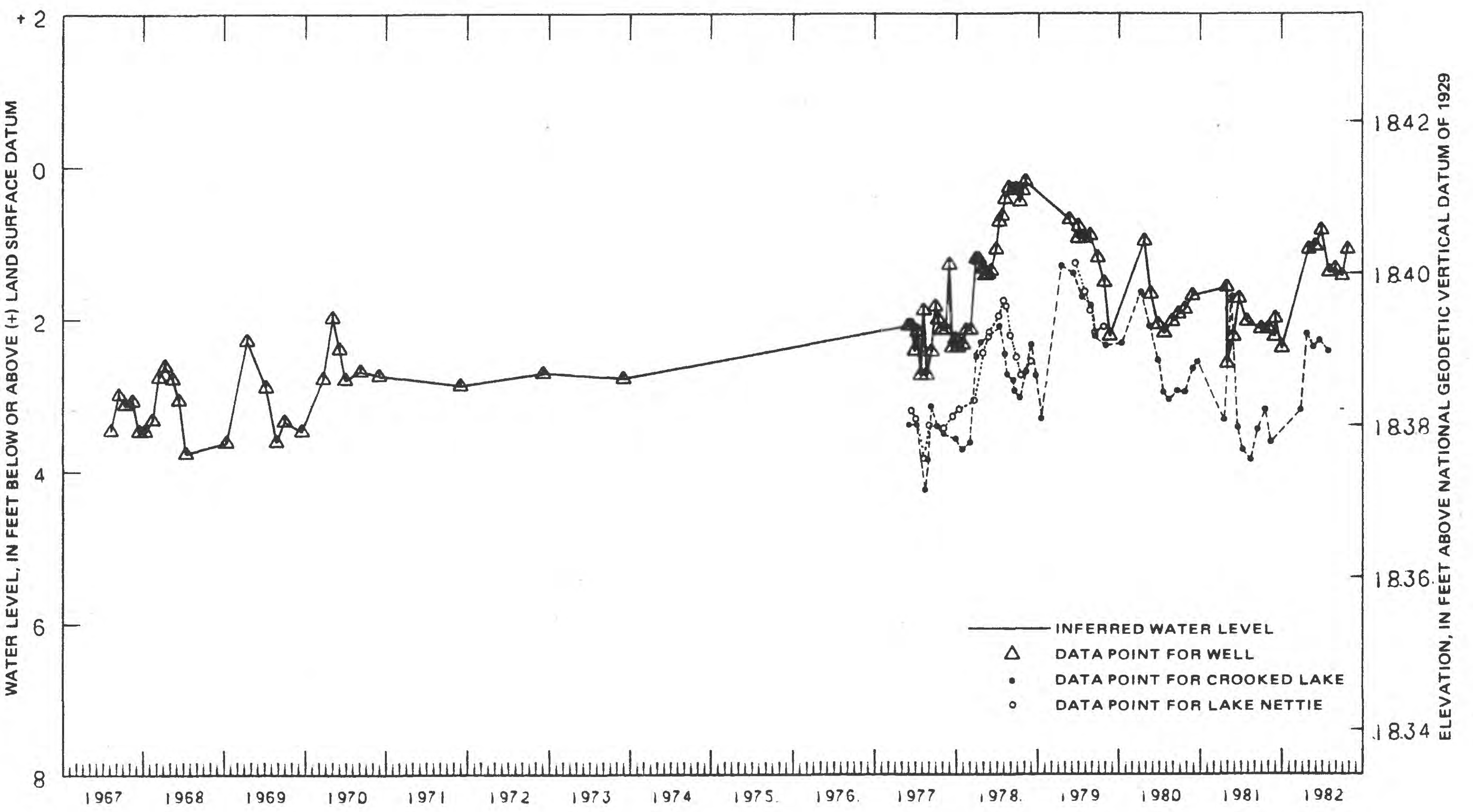

FIGURE 9.–Water-level fluctuations in well 148-081-18DCD2, Crooked Lake, and Lake Nettie.

Precipitation during 1972 was 4.74 inches greater than normal with about 1.3 inches of the excess occurring in October. Lake Audubon's level in August (the last reported lake level in 1972) also was about the same as the level in December 1971. The higher water level in well 148-082-23BBB in December probably was due in part to the greater than normal precipitation, but also may have been influenced by the lake level, which may not have receded much by December.

Precipitation during 1973 was about 4.5 inches less than normal, but all of the deficit occurred during the first 8 months of the year. There was somewhat greater than normal precipitation during the last 4 months. Lake Audubon's level in September was 0.74 foot lower than the last measured 1972 level. The December water level in well 148-082-23BBB was about 0.6 foot lower than the 1972 level. Either the precipitation deficit or the lower lake level may have caused the lower water levels in the well.

Precipitation during 1974 was greater than normal during April and May and near normal to considerably below normal for the remainder of the year, for a deficit of 2.64 inches. The water level in Lake Audubon on August 29, 1974, was 1.02 foot higher than the August 28, 1973, measurement. The December 2 water level in well 148-082-23BBB was at an elevation about 0.59 foot higher than the 1973 level. Either the early precipitation or the higher level of Lake Audubon may have caused the higher water level in the well.

Precipitation during 1975 was 4.32 inches greater than normal, but nearly all of the excessive precipitation fell during April, May, and June. The water level in Lake Audubon was at an elevation of 1,835.24 feet on June 5, 1975, and was raised at a nearly constant rate to an elevation of 1,848.05 feet at the end of September. The lake level then fluctuated slightly as it was lowered to about 1,847.95 feet near the end of November. The water level in well 148-082-23BBB on December 2, 1975, was at an elevation of 1,844.39 feet or 2.14 feet higher than it was on December 2, 1974. The greater than normal precipitation during the early part of 1975 may have caused an early rise in water levels in the well (no data available), but the higher Lake Audubon levels apparently were the primary cause of the much higher water levels in the well in December.

Precipitation during 1976 was 2.73 inches less than normal, but during April, about 1.6 inches more than normal fell. The water level in Lake Audubon varied to some extent, but generally rose to a high elevation of 1,848.61 feet on April 26. The lake level then declined to 1,847.22 on August 31. The rate of decline then increased and the level was down to an elevation of about 1,846.25 feet during the last half of November and December. The water level in well 148-082-23BBB on August 31 was at an elevation of 1,844.87 feet. The water level declined to an elevation of 1,844.50 feet on December 2. This is only 0.11 foot less than the December 2, 1975, measurement, and may reflect either the effects of Lake Audubon or the lack of precipitation.

Precipitation in 1977 was 3.47 inches greater than normal with most of the excess occurring in September. The elevation of Lake Audubon remained within a few hundredths of the 1,846.25-foot level until March 15, and then rose to 1,848.0 feet by April 15. The lake level then slowly declined to an elevation of 1,846.49 on September 12. The lake then rose to 1,846.77 feet on September 30, and then declined during October and remained within 0.15 foot of the 1,846.50-foot level for the remainder of the year. Water levels in well 148-082-23BBB fluctuated to some extent throughout the year, but the levels generally remained within 0.15 foot of the 1,844.4-foot elevation until June and then declined to near the 1,844.0-foot level. The water-level trends in the well followed, within a few weeks, the levels of Lake Audubon.

Precipitation in 1978 was 0.80 inch greater than normal. An excess of 1.83 inches occurred in September, but this followed a deficit of 1.57 inches in August; a net difference of 0.26 inch. The level of Lake Audubon remained within about 0.1 foot of the 1,846.5-foot elevation until the middle of March and then rose to within about 0.15 foot of an elevation of 1,847 feet by the middle of July. The lake further rose to the 1,848-foot level in August and fluctuated between 1,847 and 1,848 feet through the remainder of the year. Water levels in well 148-082-23BBB remained near an elevation of 1,844 feet until the spring thaw and then rose to about 1,845.1 feet by July and remained within 0.2 foot of this level throughout the remainder of the year. The water-level trends in the well generally followed the trends of the lake level, but apparently did not reflect the drop that occurred in the lake level during the latter part of the year possibly due in part to the September precipitation.

Precipitation during 1979 was 3.55 inches less than normal, and was less than normal in every month except February. The water level of Lake Audubon remained near 1,848 feet until early March and then rose to 1,848.55 feet by April 25. The lake level then remained within 0.15 foot of the 1,848.50 level until July when the lake level began to decline to a level of 1,847.09 on October 25. The level then rose to with 0.1 foot of the 1,848-foot level by November 15, and with small variations remained at that level for the remainder of the year. Water levels in well 148-082-23BBB remained near the 1,845.1-foot level until May and then rose to about 1,845.75 feet in July. The water level then declined to about 1,845.4 feet in October and then slowly rose to about 1,845.6 feet near the end of the year. In 1979, the water levels in the well generally followed the water level in Lake Audubon and did not show any appreciable effects of recharge from precipitation.

Precipitation during 1980 was 1.59 inches greater than normal, but precipitation was considerably below normal in April, May, and July and greater than normal in August and October. The level of Lake Audubon fluctuated, but remained near the 1,848-foot level until June and then declined to near an elevation of about 1,847.5 feet by August 5. The lake level then rose to 1,848 feet by August 8. The level then declined during September to a low of 1,847.47 feet on October 10, and then rose to about 1,848 feet by October 24. The water level in well 148-082-23BBB remained near an elevation of 1,845.6 feet until April and then declined to a low of about 1,845.2 feet in June. The water level remained near that level, but did rise a few tenths of a foot in August, October, and November. The water level in the well generally followed the lake level except in April, May, and June when the decline of water level in the well preceded the decline of the lake level. The lack of recharge from the snowmelt, and less than normal April and May precipitation probably were the primary causes of the decline in the well during the April to June period.

Precipitation during 1981 was 0.12 inches less than normal. However, there was a significant deficit in March, April, and May and a surplus in June, August, and September. The level of Lake Audubon remained within 0.1 foot of the 1,848-foot level until May 10, and then declined to 1,847.69 feet by May 29, and recovered to 1,848 feet by June 5. The lake level again began to decline early in June and reached a low of 1,847.16 feet on August 14. After a brief rise to 1,847.87 feet in September, the level declined to about 1,847.5 feet and remained within 0.15 foot of that elevation for the remainder of the year. Water levels in well 148-082-23BBB generally remained within 0.2 foot of the 1,845-foot elevation, with the possible exception of May, August, and September. The water-level observations indicated an apparent rise of about 1 foot in May, but precipitation in both April and May was less than normal and the level of the lake was declining, so there is no apparent cause for the rise. However, there may have been sufficient ponded snowmelt from the preceeding winter to have been the source of the recharge. Precipitation was greater than normal in August, but the lake level had declined and may have been the primary cause of the low water level in August. Precipitation also was greater than normal in September and the level of Lake Audubon also rose. The combined effect of the precipitation and the lake level rise may have been the cause of the higher water level in the well in September.

Precipitation during 1982 was 6.42 inches greater than normal, with less than normal precipitation occurring in April, July, and September. Water levels in Lake Audubon slowly rose from the 1,847.5-foot level to near the 1,848-foot level in April and remained near there until July 21, after which the level slowly declined to about 1,847.2 feet by September 28 (the end of the record). The water level in well 148-082-23BBB apparently remained slightly below an elevation of 1,845 feet until April, when the effects of recharge from snowmelt began to appear. The rise of the water level in the well, except in July, then continued until November. The rise in the water level in the well apparently was due primarily to recharge from snowmelt in the spring followed by recharge from the greater than normal precipitation throughout the remainder of the year.

A month-by-month examination of figures 2, 4, and 7 have led to the following conclusions: (1) The raising of the stage of Lake Audubon to the 1,848-foot level during the summer of 1975 caused a water-level rise of somewhat more than 2 feet to near 1,845 feet in well 148-082-23BBB. (2) Lake-level fluctuations of more than a few weeks duration cause a proportional change in the water level in the well. (3) Recharge from precipitation and snowmelt causes water-level fluctuations in the well, but such fluctuations generally are small during the hotter summer months. (4) A significant rise of the water level in the well generally occurs following the spring snowmelt whenever precipitation in January, February, or March is sufficient to indicate a widespread snow cover.

A similar month-by-month analysis was made using the hydrographs of 17 other wells in the area. The effects of the raising of the Lake Audubon water level in each of the 18 observation wells were then estimated by establishing water-level trends. Various water-level fluctuations caused by recognizable contributing factors of recharge, discharge, and runoff were subtracted. The maximum estimated water-level rises in the Lake Nettie aquifer that were attributed only to the higher levels of Lake Audubon prior to late 1981 are shown in figure 10.

An analysis of the hydrographs indicates that as of 1982, water levels in the lower aquifer unit in the western part of the aquifer vary with temporal influences, but are at near equilibrium with the present lake level. The water-level trends for wells 148-080-19CCC1 and 148-080-31AAA1, shown in figures 11 and 12, and in other wells in the lower aquifer unit in the central part of the aquifer indicate that water levels from about Crooked Lake to North Dakota Highway 41, apparently have risen between 1 and 2 feet because of the effects of Lake Audubon. The rises in the above wells due to Lake Audubon appear to have ceased by 1979, but precipitation influences are masking the lake influences to such an extent that water levels in the area still may be rising because of the lake. Water-level trends, such as in well 147-080-13CCC (fig. 13), east of North Dakota Highway 41 indicate a small rising trend, but with the data available little or no effects in the wells can be attributed to the 1975 increased water level in Lake Audubon.

Crooked Lake apparently is separated from the upper unit of the Lake Nettie aquifer by only a few feet of mud on the lake

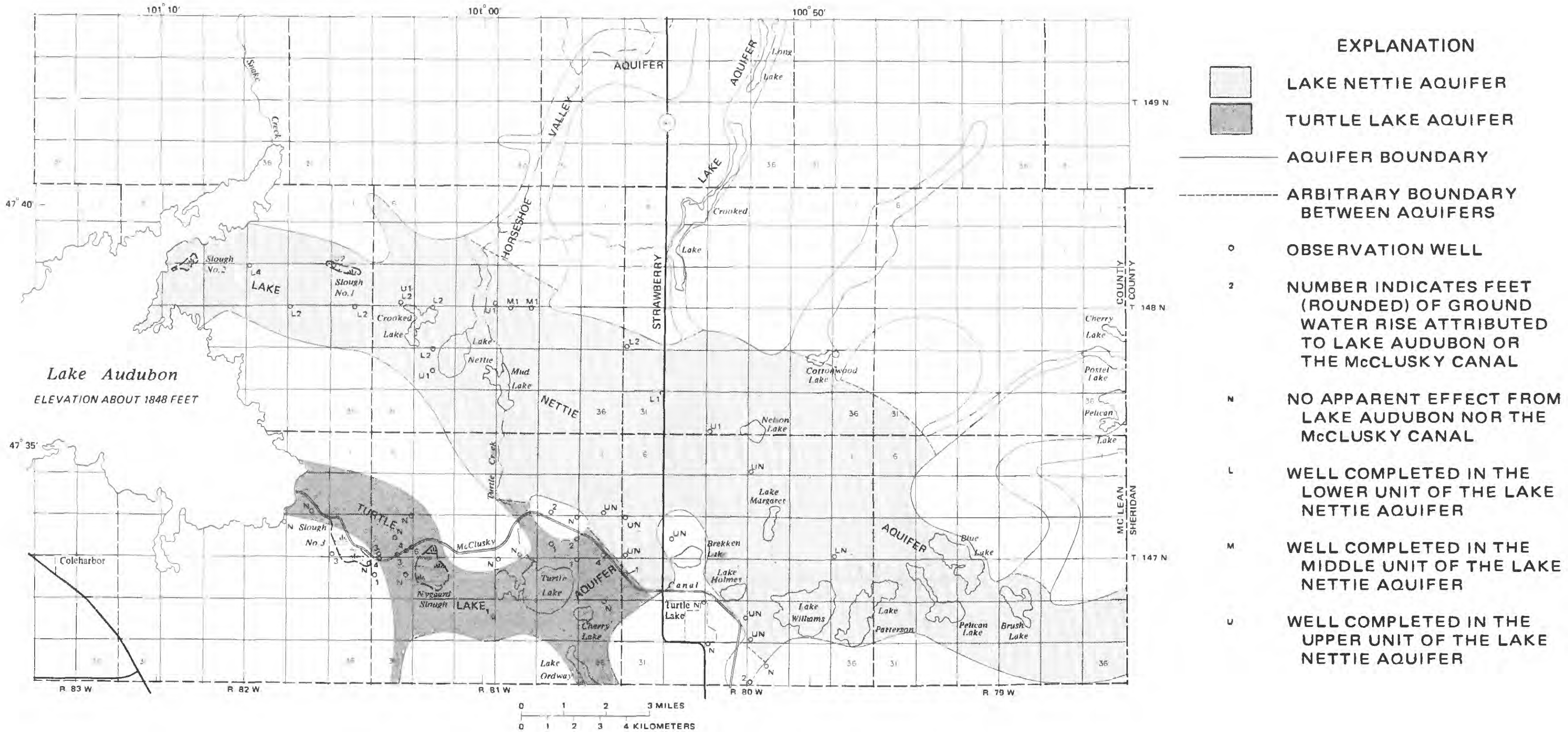

FIGURE 10.—Rise of ground-water levels in the Lake Nettie aquifer, Turtle Lake aquifer, and near the McClusky Canal attributed to the raising of Lake Audubon's stage or the filling of the canal, or both, 1981.

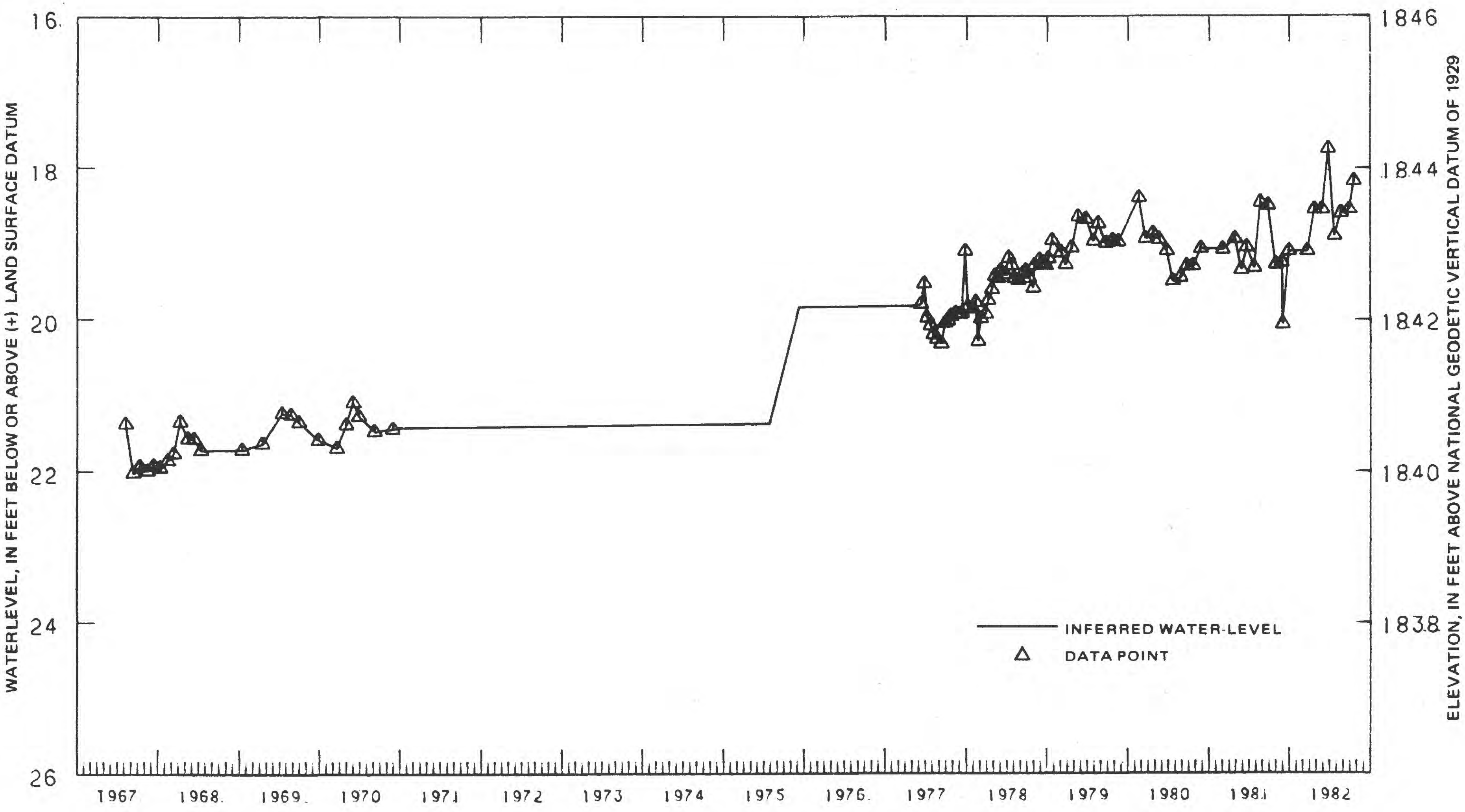

FIGURE 11.—Water-level fluctuations in well 148-080-19CCC1.

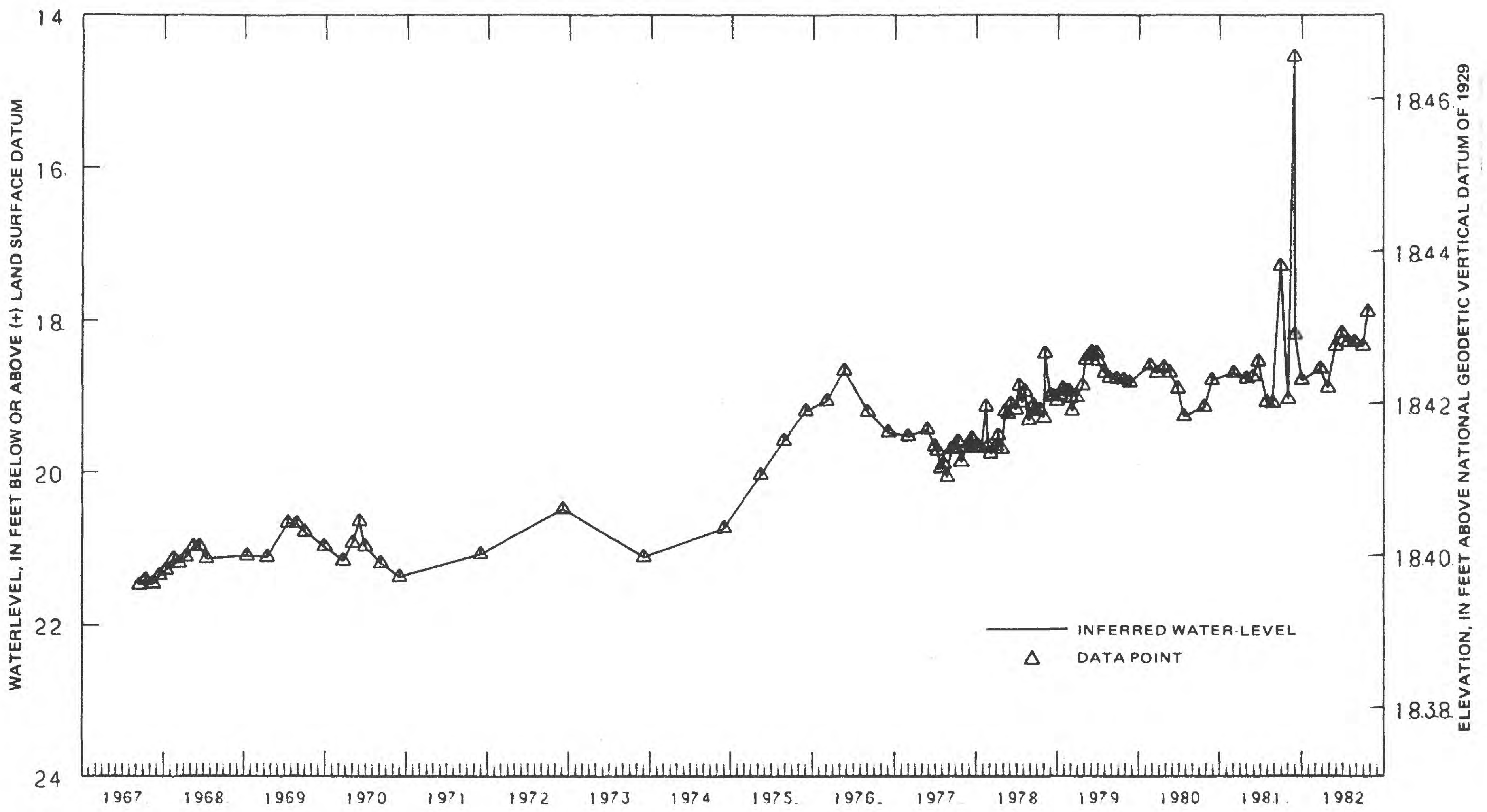

FIGURE 12.—Water-level fluctuations in well 148-080-31AAA.

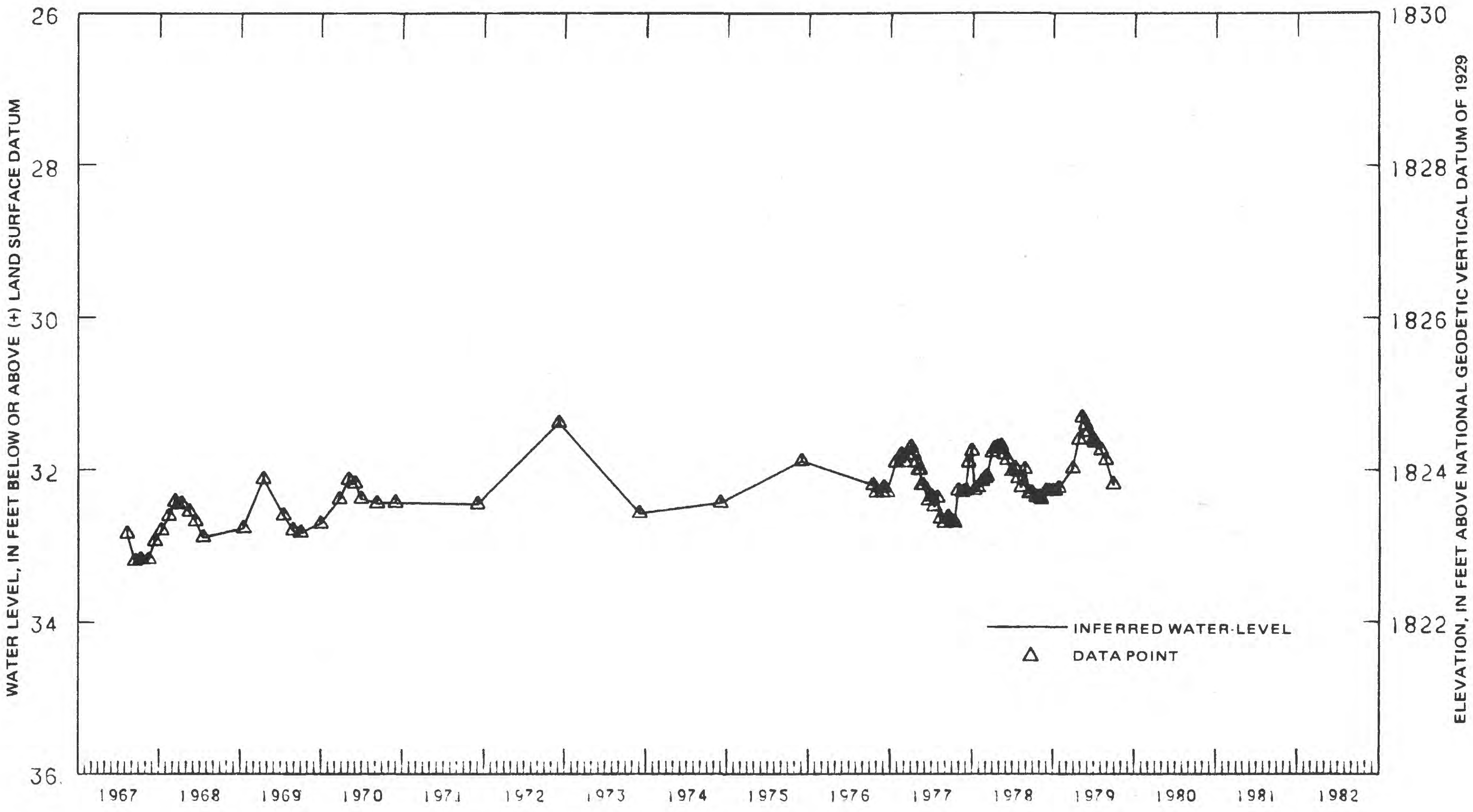

FIGURE 13.—Water-level fluctuations in well 147-080-13CCC.

floor. Therefore, at least a poor hydraulic connection between the lake and the aquifer probably exists. The hydrographs of Crooked Lake and well 148-081-18DCD2 (fig. 9) show a fair correlation when high evaporation periods are excluded. The lake generally is somewhat lower in elevation than water levels in the well, probably because of the evapotranspiration, but some subsurface leakage from Crooked Lake to Lake Nettie and Turtle Creek may occur. Water-level measurements in well 148-081-18DCD1 (fig. 8) show a fair correlation, but at an elevation about 3 feet higher, to those in well 148-081-18DCD2. Even though there is about 36 feet of till between the lower and upper aquifer units, the trends shown in the three hydrographs (figs. 8 and 9) are similar and indicate that as of 1981 about a foot of the water-level rise in well 148-081-18DCD2 reasonably could be attributed to the raising of the level of Lake Audubon. The magnitude of the rise due to Lake Audubon is questionable because of the many variable influences caused by runoff into and evaporation from nearby Crooked Lake. Some of the rise in Crooked Lake also could be attributed to the rise of Lake Audubon, but the greatest part of the rise in Crooked Lake probably is due to the accumulation of runoff and precipitaton.

A few stage measurements of Lake Nettie show that the stage in Lake Nettie varies, but generally is within 0.5 foot of the stage of Crooked Lake. Lake Nettie also is separated from the upper unit of the aquifer only by the mud on the lake floor, so it can be assumed that some of the water-level rise in Lake Nettie also can be attributed to Lake Audubon.

During times of large runoff, Lake Nettie and the marshy area that connects Crooked Lake and Lake Nettie at high water encroaches upon a few hundred feet of the county road in two low places. During years of normal to below normal precipitation, the lake and slough levels should recede to levels somewhat higher than the levels in existence before Lake Audubon was raised. If the level of Lake Audubon is raised to the 1,850-foot level, there probably will be a further rise in the ground-water heads in the lower aquifer unit and the rate of upward leakage will increase.

Slough No. 1 is located, for the most part, in 148-082-13B, and extends westward into 148-082-14AA and 148-082-11DD. It encroaches on the road near the northeast corner of section 14, and on at least one occasion in 1982 the water rose and covered part of the road. This slough overlies and is in direct hydraulic connection with about 42 feet of sand of the upper aquifer unit. The upper unit is separated from the lower unit at this location by about 116 feet of till and clayey silt. There is some upward leakage from the lower unit, but it is small. The upward leakage probably is less than at Crooked Lake because of the greater thickness of till between the upper and lower aquifer units.

Because water levels in Slough No. 1 were measured only during 1977, 1978, and 1979 (fig. 14), the record is too short for conclusive comparisons to be made. However, the record is long enough to show at least a rough correlation between water levels in the slough and in the 40-foot well at 148-082-13BBB (fig. 14), and a fair correlation with water levels in well 148-081-18DCD1 (fig. 8). A comparison of the hydrographs in figure 14 with the hydrographs in figures 8 and 9 (148-081-18DCD1 and 18DCD2) indicates that at least 1 foot and probably about 2 feet of the water-level rise in well 148-082-13BBB can be attributed to the increased stage of Lake Audubon. Because of the apparent hydraulic connection between the aquifer and the slough, some of the increased water level in the slough can thus be attributed to the increased stage of Lake Audubon. The remainder and greatest part of the increase and the fluctuations in the well are due to accumulation of precipitation and runoff, and to evapotranspiration variations.

Slough No. 2 is located, for the most part, in 148-082-17AB and 17BA, but extends northeastward into 148-082-08DC (fig. 5). During times of high water the slough may extend into the western part of section 17, and, during peak levels, water may rise to cover at least part of the road that has been built through the slough. No data are available to determine how much water in the slough can be related to Lake Audubon, which is about 0.5 mile to the west, but water levels in well 148-082-15BBB (fig. 15) in the lower unit of the aquifer have risen about 6 feet since 1970. However, only about 4 feet of this rise can be attributed to the raising of Lake Audubon. This is 2 to 3 feet more than the rise in wells farther east. The rise of approximately 4 feet probably would cause somewhat more upward leakage and contribute to higher water levels throughout the area. Ground-water levels on the west side of the ground-water divide in the upper aquifer unit are more directly influenced by Lake Audubon. Ground-water gradients that were reestablished after the rise to the 1,848-foot level would have been similar, but higher, than those established at the 1,833- to 1,836-foot levels. The amount of ground-water rise cannot be determined because records were not obtained. The theoretical maximum possible rise of about 13 feet probably will not be approached because of the increased evapotranspiration that takes place when water levels near the land surface, and the many topographically low areas near the lake that would limit rises. Even though water-level rises in the area cannot be quantified, water levels in problem areas near Slough No. 2 probably would have been several feet higher in 1982 than before the 1,848-foot level of Lake Audubon if sporadic pumping from this slough since 1979 had not reduced water levels in the slough.

Many small perennial sloughs and marshes shown on the 1981 Coleharbor 7½-minute topographic quadrangle map were shown as areas that contained intermittent sloughs, or were dry, on the

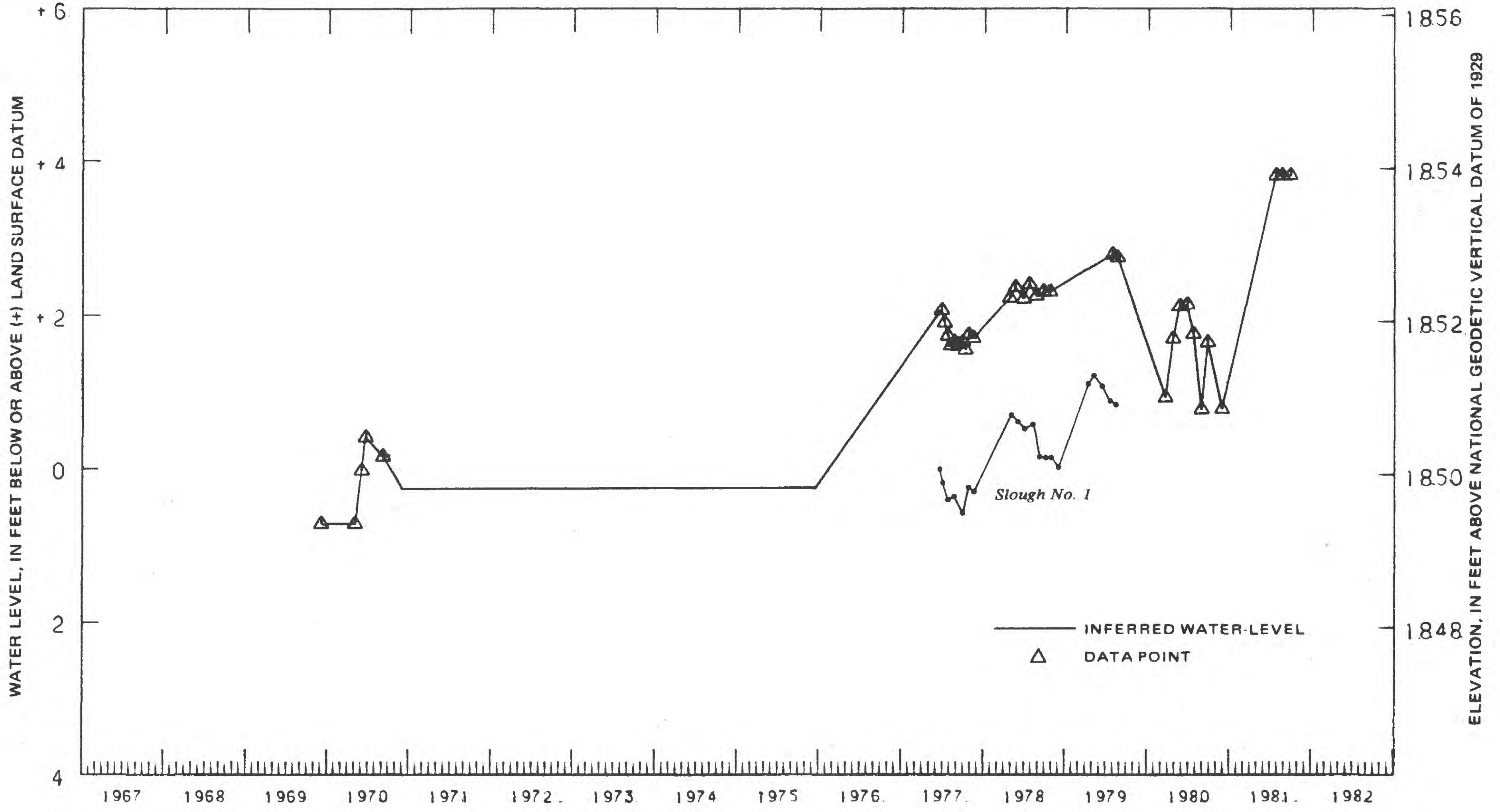

FIGURE 14.—Water-level fluctuations in well 148-082-13BBB and in Slough No. 1.

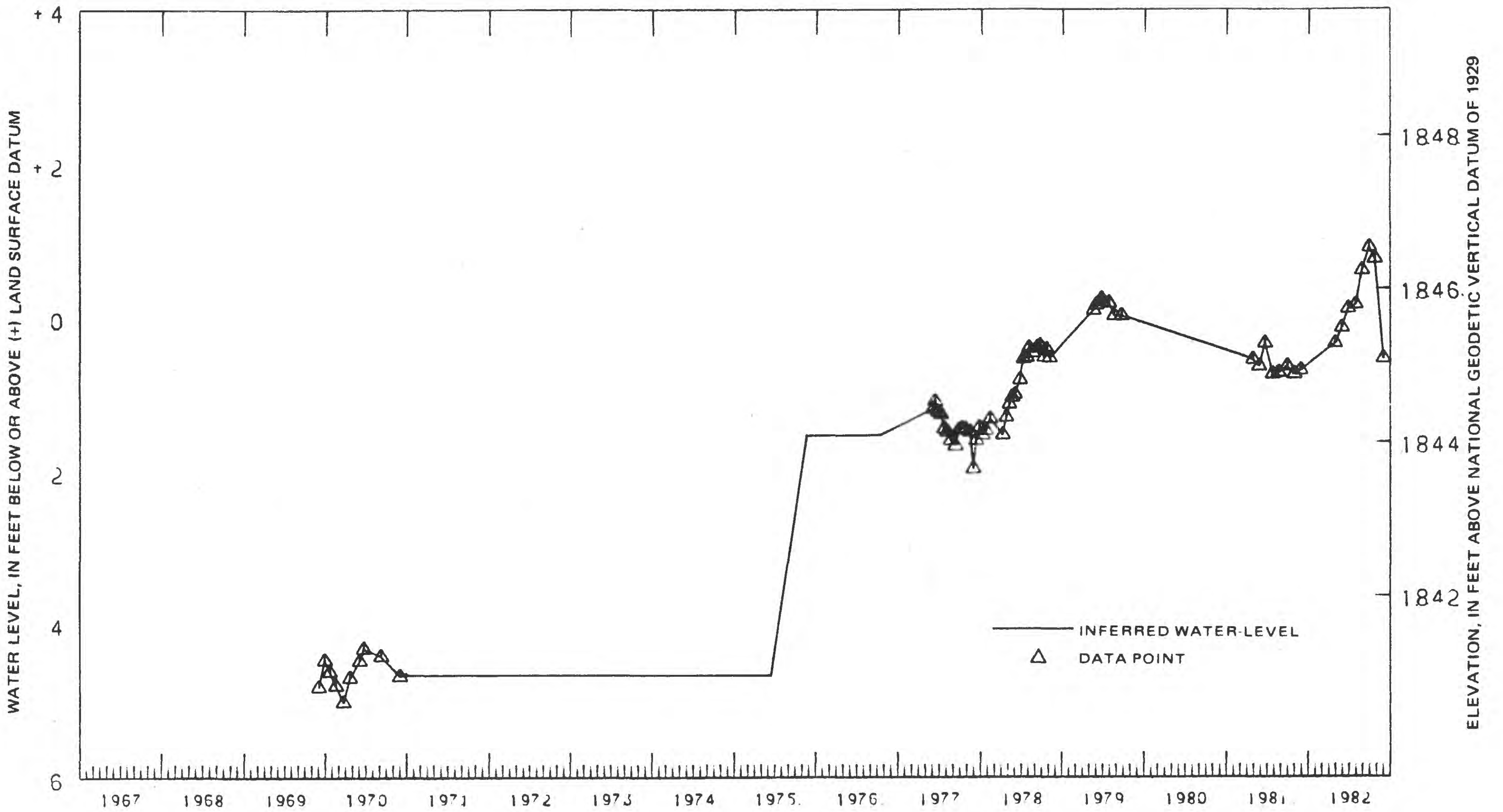

FIGURE 15.—Water-level fluctuations in well 148-082-15BBB.

1929 Coleharbor 15-minute topographic quadrangle map, before the raising of Lake Audubon. This may be an indication that the higher lake level has caused ground-water levels throughout the area to rise and has had some undetermined effect on many sloughs in the area. However, some of the higher water levels may have been caused by the initial filling of Lake Audubon to the near 1,835-foot level. There is no record of when the water levels began to rise. The effect has been most noticeable in those areas less than 1,850 feet in elevation between Lake Audubon and the ground-water divide east of Lake Audubon. Even though many of the sloughs have been influenced by the higher levels of Lake Audubon, the major cause of the flooding in most sloughs and small lakes probably is the excessive runoff that occurs in years of greater than normal precipitation, such as 1982.

Present plans call for raising the water level in Lake Audubon to an elevation of 1,850 feet. If the lake level is raised, water levels throughout the area of concern may also rise. Such rises should be monitored, especially within a few miles of the area where problems have been reported.

Analyses of water samples from the Lake Nettie aquifer (Klausing, 1974, p. 21-25) indicate that the water is very hard (more than 180 mg/L) and the quality varies considerably from place to place. The dissolved-solids concentrations in 29 samples from the upper unit ranged from 287 to 2,800 mg/L. The dissolved-solids concentrations in 13 samples from the middle unit ranged from 520 to 1,810 mg/L, and the dissolved-solids concentrations in 19 samples from the lower unit ranged from 565 to 1,550 mg/L. Seven wells (147-081-07DDD, 147-081-23AAA, 148-081-14CDD, 148-081-18DCD1, 148-082-15BBB, 148-082-23BBB, and 148-082-24ABB) previously sampled by Klausing (1971, table 4) were resampled in 1982. The analyses of all seven samples show that there has been no appreciable change in the quality of the water in the aquifer, and indicate that there probably has been no significant change in the sources of recharge.

McClusky Canal Area

Reach 1 of the McClusky Canal, which crosses the report area, was begun in 1972 and completed in 1975. The canal extends from its head in a southeast arm of Lake Audubon, southeastward to 147-080-33DCC where it leaves the area (fig. 5). The route of the canal was determined to a large extent by the topography of the area in order to reduce the cost of cutting and filling to a minimum. Consequently, the canal meanders across the area. The path of the canal is such that it overlies part of the Turtle Lake aquifer as well as undifferentiated glacial drift.

The canal was constructed principally in glacial till, but locally glaciofluvial sand or gravel was encountered. The undisturbed till generally has a hydraulic conductivity of considerably less than 0.6 ft/d. In areas where glaciofluvial materials were encountered, the canal was lined with clay that had a hydraulic conductivity of less than 0.6 ft/d. The small hydraulic conductivity of the till and clay liner retards but does not eliminate seepage into or from the canal. This is especially true where there is only the clay liner between the water in the canal and the underlying sand or gravel, which may be part of the Turtle Lake aquifer.

As construction of the canal proceeded, ponded water appeared in the canal. The source of the water is not known, but some probably was derived from precipitation and some was from ground water. The U.S. Bureau of Reclamation reported that they encountered "blow outs" (places where ground-water pressure was sufficient to cause the liner to rupture or leak) in some areas where sand was encountered. In areas adjacent to and lower than the canal, the leakage does contribute to the high water problems that occur.

Water-level trends in well 147-082-13CCC (fig. 16), which was finished in glacial drift and the Fort Union sandstone, and in a few other wells in the McClusky Canal area show rises that apparently resulted from raising the level of Lake Audubon. The water levels in well 147-082-13CCC generally were at an elevation of between 1,841 and 1,842 feet before Lake Audubon was raised in 1975. This is somewhat higher than the water levels in Slough No. 3, which was shown on a 1960 contour map to be at an elevation of less than 1,840 feet. The somewhat higher water level in the well and a low gradient toward the slough probably indicates a hydraulic connection between the well and the slough. If the connection is real, then water levels in the well would be a good indicator as to water levels in the slough. The hydrograph of well 147-082-13CCC (fig. 16) shows the water levels in the well before 1975 generally remained between 34.5 and 36 feet below land surface. About 5 feet of rise occurred in early 1975 followed by a drop of nearly 3 feet in the latter part of the year. The sharp rise in the early part of the year probably was caused by greater than normal precipitation and runoff into the slough. The drop in the latter part of the year was due to less than normal precipitation and large evapotranspiration rates. After the peak water level in 1975 had dissipated, water levels generally remained between 32 and 33.8 feet and show a slow rising trend until 1979. The water levels, which generally were about 2 feet higher than pre-1975 levels, and the rising trend probably were due to the effects of Lake Audubon. The rise in 1979 probably was caused by the effects of leakage from McClusky Canal, which was filled to an elevation of between 1,843 and 1,844 feet in 1979.

Water levels in other wells located between the canal and Slough No. 3, such as well 147-082-13CAA1 (fig. 17), also rose,

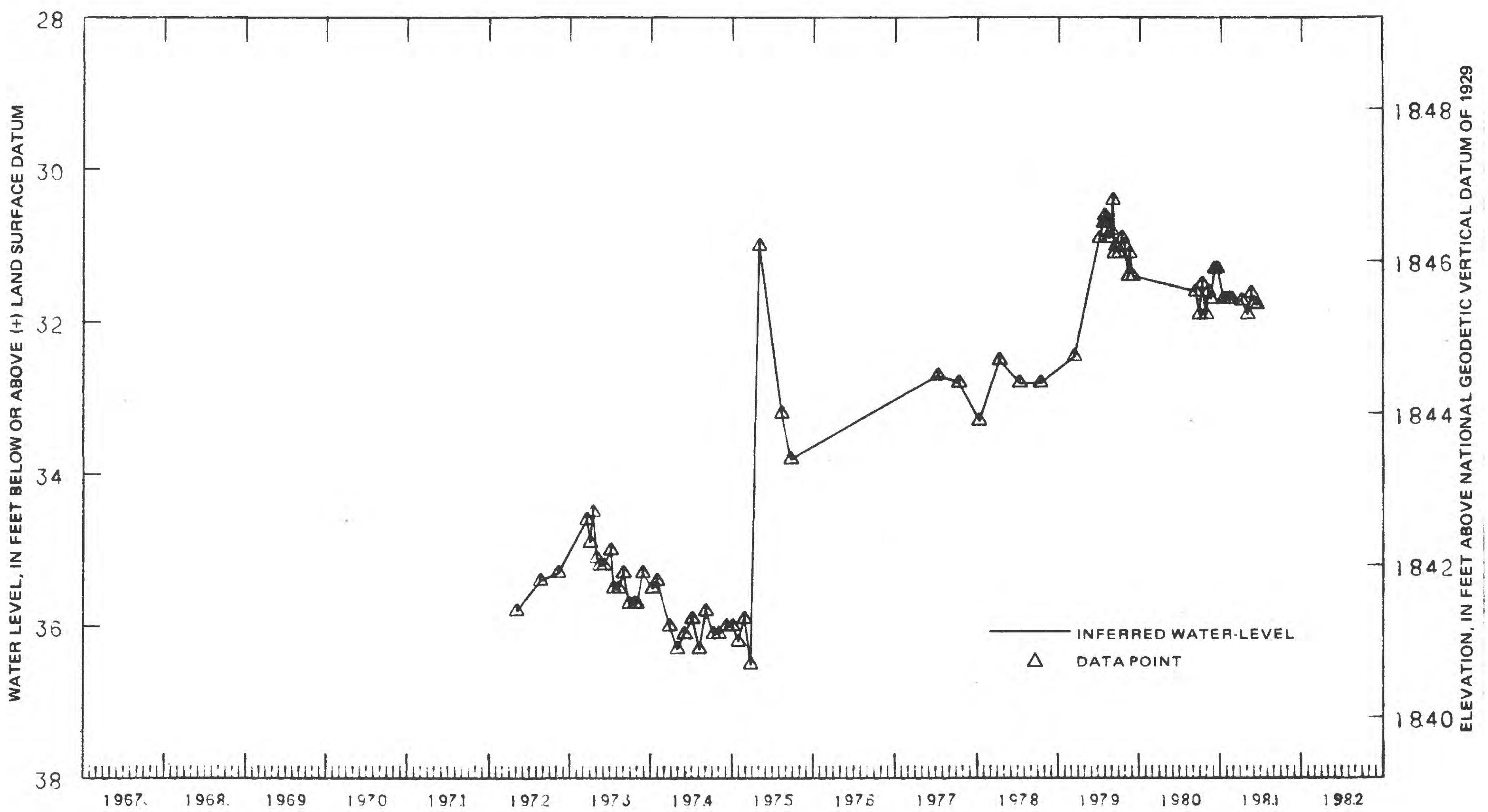

FIGURE 16.—Water-level fluctuations in well 147-082-13CCC.

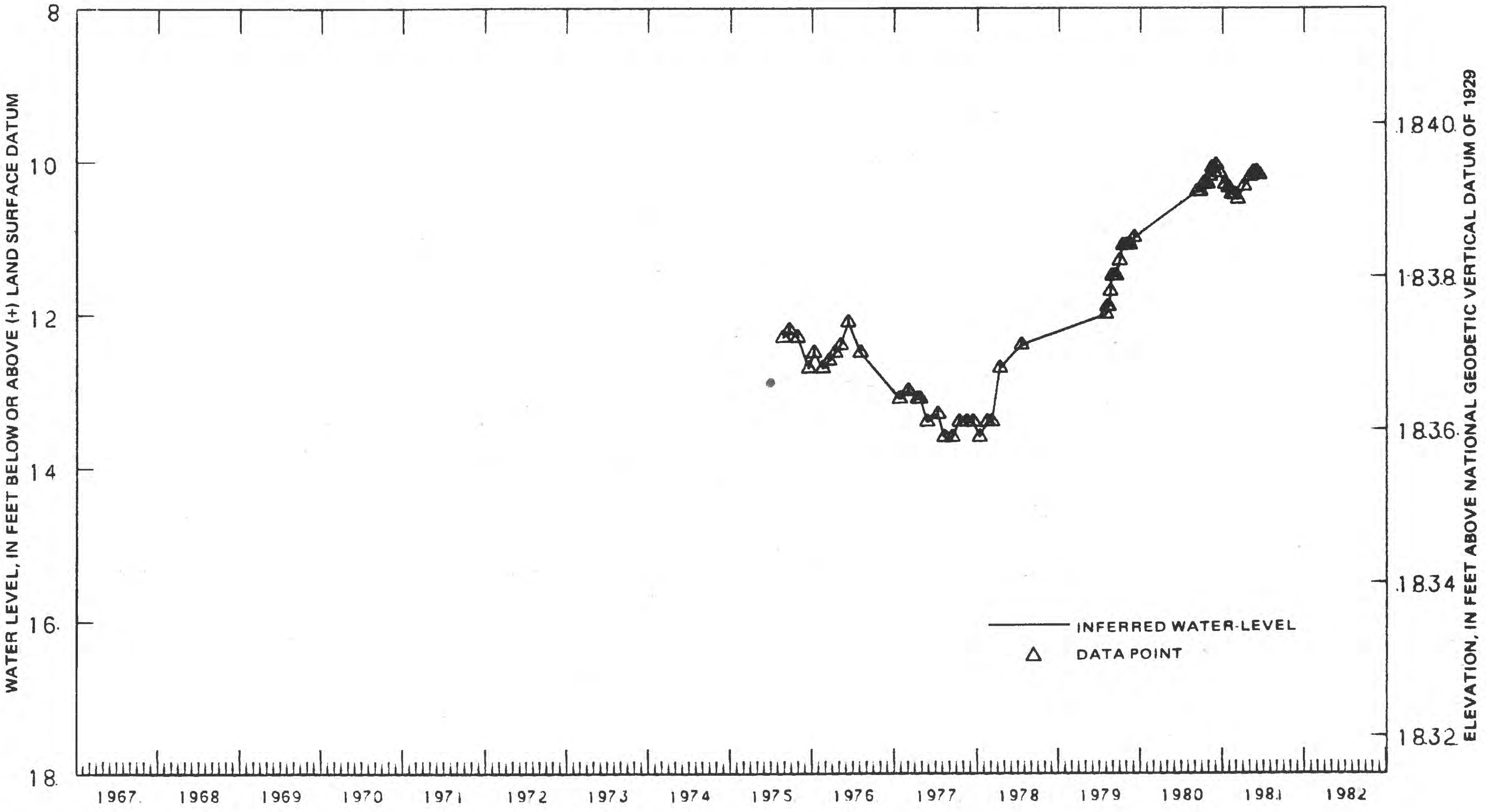

FIGURE 17.—Water-level fluctuations in well 147-082-13CAA1.

but only about 1 foot of rise might be attributed to the canal. Thus, the total effect of Lake Audubon and the canal on water levels in well 147-082-13CCC probably is about 3 feet. No data are available to establish the effects of the lake and canal on Slough No. 3, but the possible hydraulic connection between well 147-082-13CCC and the slough indicates that the effects might be similar. However, evapotranspiration would cause the water levels in the slough to be somewhat lower than in the well.

Water levels in the area near the McClusky Canal respond to changes in recharge and discharge as they do elsewhere. However, the filling of the canal in 1979 to an elevation of between 1,843 and 1,844 feet, has had an effect on the hydrologic regime. The effect generally is most apparent in wells within about 0.5 mile of the canal, and in areas where the canal is higher than the adjacent land. Water levels in observation well 147-081-18DAD (fig. 18), which is about 120 feet south of the canal, fluctuated from natural causes at elevations between 1,832.9 and 1,835.6 feet in the years before the canal was constructed and filled. The filling of the canal resulted in raising the water level in the well approximately 5 feet to an elevation of about 1,840 feet within a few months of the filling. The fluctuations in 1980 and 1981 probably were the result of precipitation and evapotranspiration differences. If the water in the canal is raised to an elevation of about 1,849 feet (approximate proposed operation level) then water levels at the well should approach land surface. Evapotranspiration in the summer should keep water levels below land surface at the well, but nearby topographic lows probably will become boggy or contain water.

Water levels in well 147-082-13CAA1 (fig. 17), which is about 180 feet from the canal, rose somewhat more than 1 foot to an elevation of about 1,838.5 feet in 1979, and the effects of the canal still may be the cause of the rising water levels in 1980 and 1981. The patterns formed by the water levels in both figures 17 and 18 are similar and show that the canal has had a similar but not equal effect at both well sites. Water levels in well 147-082-13CAA1 during 1981 were at an elevation of nearly 1,839 feet. If the canal level is raised 5 or 6 feet to about 1,849 feet, the water level in the well probably will rise. However, because evapotranspiration, which averages about 2.5 feet per year at land surface, is a significant factor at depths of more than 5 feet, water levels in the well probably will not reach 1,844 feet, at least not as a result of the effects of water in the canal.

Further raising of water levels in the McClusky Canal and Lake Audubon will further raise the ground-water levels in the Lake Nettie aquifer and near the canal in the area of concern. In lower areas, the higher ground-water levels will cause areas presently containing ponded water to become larger. These areas should be monitored both before and after changes occur. An

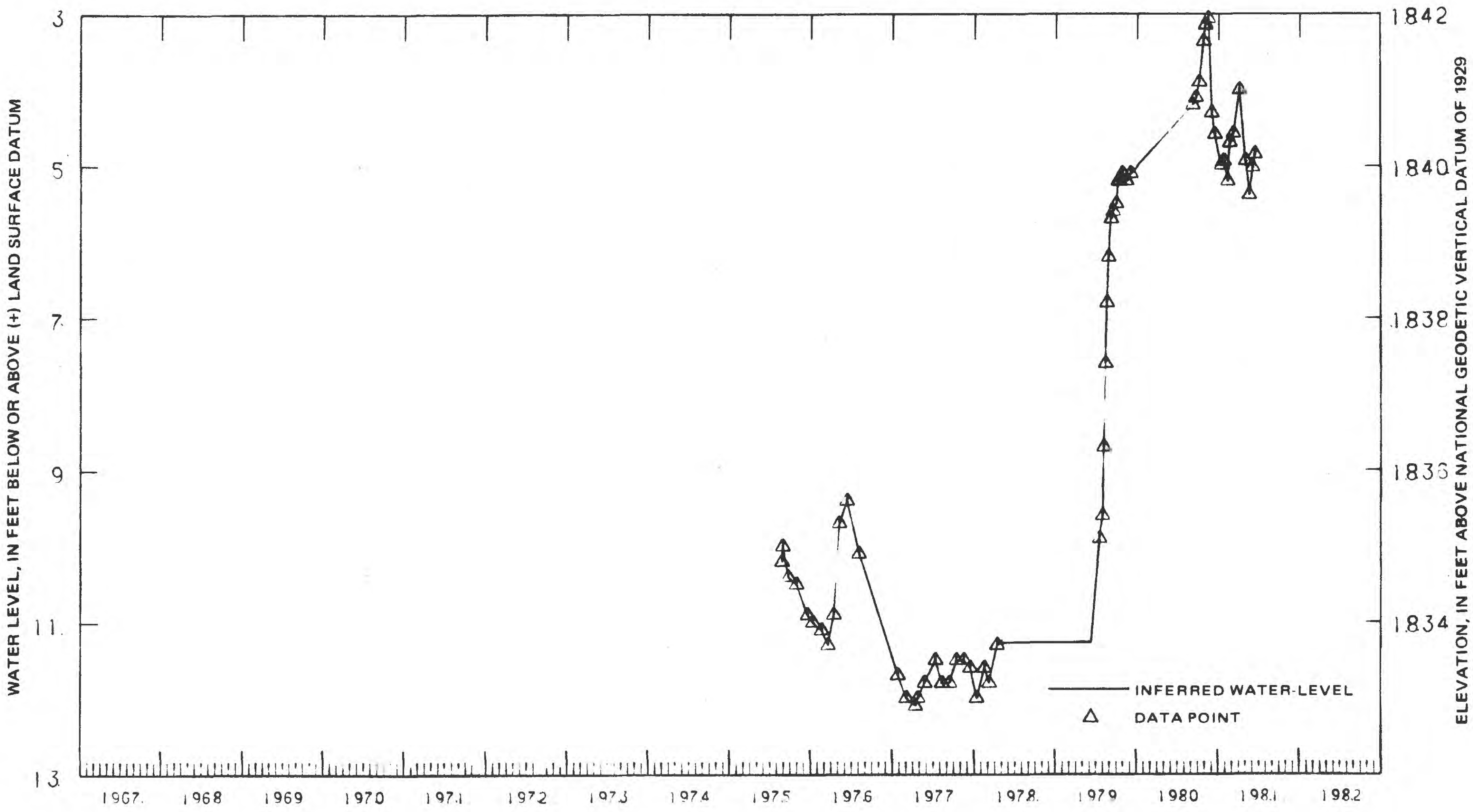

FIGURE 18.—Water-level fluctuations in well 147-081-18DAD.

examination of topographic maps of the area shows that nearly all of the area that has been or will be affected by the higher water levels in the canal lies in an undulating generally low area that extends from Slough No. 3, through Nygaard Slough, to Turtle Lake. However, the U.S. Bureau of Reclamation has recognized the problem and has taken remedial action by constructing pipe drains and a drainage ditch through the low area. Their construction is scheduled to be completed in 1983, so most of the effects of raising the water level in the canal should be eliminated. There also are a few small areas near and to the north of the canal that may be affected, such as in secs. 17 and 18, T. 147 N., R. 81 W., but as of 1982 have not been a problem. No records of ponded water-level rises in the low area are available, but verbal reports in 1981 and 1982 indicate that the water levels began to rise before 1982. Figure 10 shows water-level rises in wells that can be attributed primarily to the higher water levels in the canal.

Water levels in wells more than 0.5 mile from the canal or in areas considerably higher than the canal generally show little or no changes that can be attributed to filling of the canal. A possible exception is well 147-081-28ADD (fig. 19) in the Turtle Lake aquifer. The hydrograph of this well shows a gradual water-level rise that apparently started in 1967 and probably reflects higher water levels in Turtle Lake, which in turn may have been affected by Lake Audubon both before and after the 1975 stage, and later by filling of the canal. The effects of Lake Audubon and the canal may have increased the runoff in Turtle Creek, but measurements of flow in the creek have not been made since 1976 so the increased flow, if any, has not been determined.

CONCLUSIONS

Ground-water levels appear to have risen in the Lake Nettie aquifer west of Highway 41 as a direct result of raising the level of Lake Audubon to an elevation of about 1,848 feet. As of 1982, water levels in the lower unit of the Lake Nettie aquifer are estimated to have risen from about 4 feet about 1 mile southeast of the lake to between 1 and 2 feet at a distance of 11 miles. Further east, rises in the lower aquifer unit have been gradual or not apparent. The cause of these gradual rises, where apparent, has not been established.

Water levels in the upper unit of the Lake Nettie aquifer also have been affected, but generally through upward leakage from the lower unit and, except for areas west of the ground-water divide, not by direct hydraulic connection with Lake Audubon. The water-level rise in the upper unit varies from place to place because both the thickness and the hydraulic conductivity of the underlying material varies. Even though the upward leakage from the lower aquifer unit does vary considerably, water-level rises in the upper unit in the area of

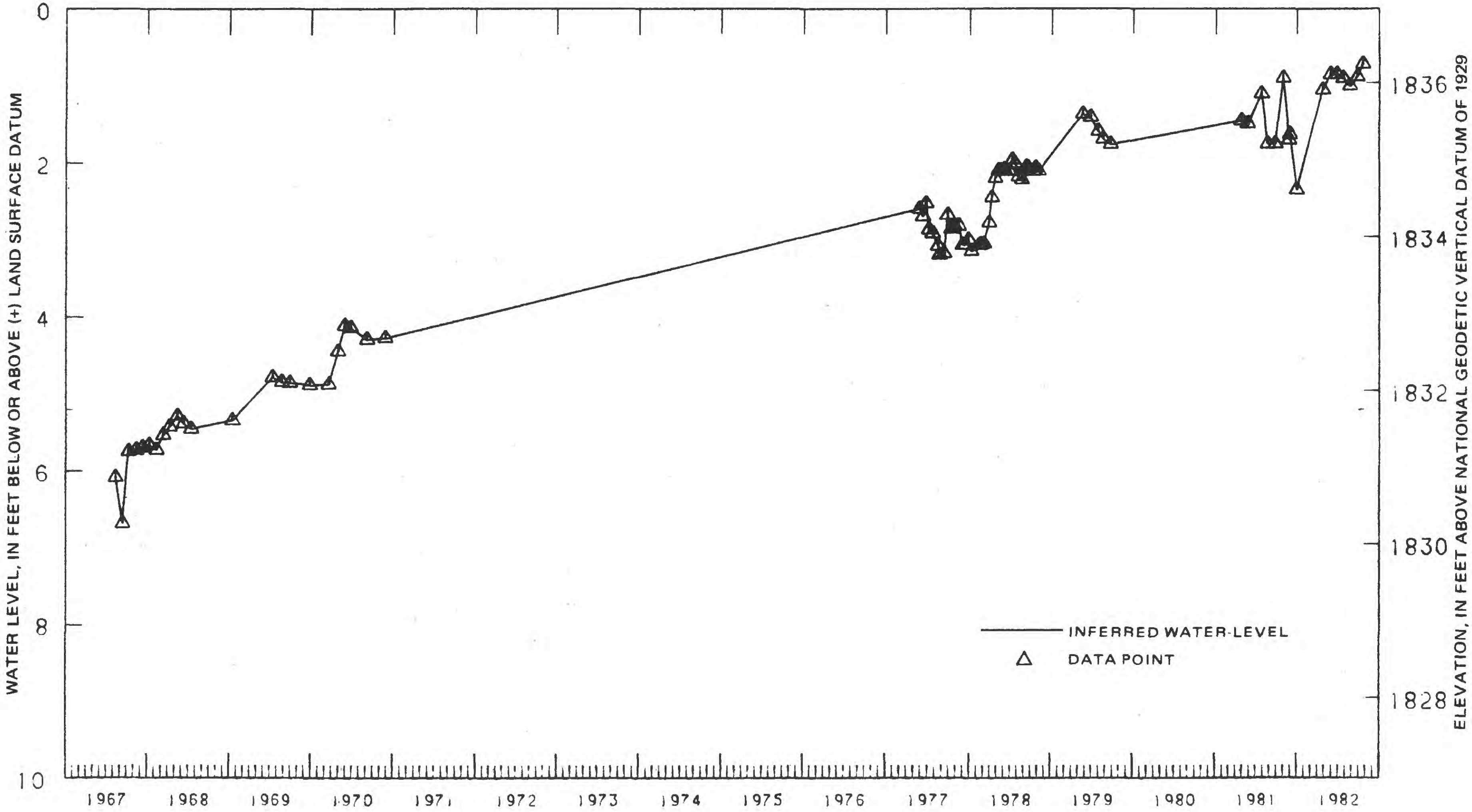

FIGURE 19.—Water-level fluctuations in well 147-081-28ADD.

concern due to the effects of Lake Audubon generally appear to be only 1 to 2 feet. Water-level rises in the area less than 1 mile from Lake Audubon may have been more. The 1- to 2-foot rise, however, is enough, when added to runoff and precipitation in some wet years, to contribute to the high water that is causing road damage in the Lake Nettie-Crooked Lake area and at Slough No. 1.

There are many small sloughs scattered throughout the area that may have or will have some flooding problems. Also, there are low areas where water levels may rise near the surface, especially in the spring when ground-water levels generally are the highest. These potential problem areas have not been identified as there are no data available.

Ground-water levels have risen near McClusky Canal. North of the canal where ground levels generally are high, rises have been small and no problems have been reported. There are, however, a few small areas where sloughs or marshy areas may develop such as the low area in secs. 17 and 18, T. 147 N., R. 81 W. South of the canal ground-water levels have risen and some flooding has occurred.

Raising the water levels in Lake Audubon and in the McClusky Canal to proposed operating levels probably will cause further flooding unless remedial control measures are implemented. Data are not presently available to quantitatively predict the extent of the problem areas, so an expanded observation network should be installed. The network should include most of the present wells and gages and include new gages on Lake Nettie, Sloughs No. 1, No. 2, and No. 3, and any other sloughs where a 2- to 4-foot rise would threaten a road. Also, a gage should be reestablished on Turtle Creek to determine the increased flow, if any, that may have resulted or perhaps will result from the higher water levels in the Lake Nettie aquifer. The expanded network should be measured for more than a year before operating levels are increased. A minimum of four measurements a year should be made and should include a measurement in November just before the lakes and sloughs freeze and another 2 to 3 weeks after the spring thaw is completed.

SUMMARY

Water logging and flooding of some roads and agricultural lands have become a problem in the Lake Nettie area of eastern McLean County. Part of the water logging and flooding is due to the raising of Lake Audubon from an elevation of about 1,835 feet to 1,848 feet and its effect on water levels in the lower unit of the Lake Nettie aquifer, which in turn affects water levels in the upper unit of the aquifer. However, the major cause of the flooding is excessive runoff that occurs in years of greater than normal precipitation, such as in 1982.

Aquifer recharge, which is the cause of the high ground-water levels, is from the infiltration of precipitation and snowmelt, the lateral percolation of water from the adjacent Fort Union Formation and glacial-drift aquifers, and from upward leakage from the lower unit of the Lake Nettie aquifer caused in part by the increase in hydraulic heads due to the filling of Lake Audubon to an elevation of about 1,848 feet.

Discharge is by evapotranspiration and percolation into the closed basins in the Lake Holmes-Lake Williams area and southward through Lake Ordway or westward to Lake Audubon. During hot dry periods, evapotranspiration rates are large, and exceed all sources of recharge. During such periods, water levels decrease.

Trends shown on hydrographs indicate that equilibrium between recharge and discharge has almost been reestablished in the Lake Nettie aquifer in the area between Lake Audubon and Lake Nettie, but east of Lake Nettie water levels may still be rising. At the present time (1982), water-level rises caused by the raising of Lake Audubon are as much as 4 feet in the lower unit of the Lake Nettie aquifer and generally are between 1 and 2 feet in the upper unit of the aquifer, which is hydraulically connected to Crooked Lake and Lake Nettie. There are assumed to have been rises, which have not been measured, in many sloughs.

Water levels have risen near the McClusky Canal both as a result of raising the water level in Lake Audubon and the filling of the canal. Water-level rises have been as much as 6 feet near the canal, but generally less than 1 foot at distances of more than about 0.5 mile. The higher water levels generally have resulted in more water in the sloughs near the canal.

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