THE GEOHYDROLOGY of EAST-CENTRAL McLEAN COUNTY, NORTH DAKOTA

By
Kevin D. Swanson

North Dakota Ground-Water Studies
Number 105 - Part II
North Dakota State Water Commission
David Sprynczynatyk, State Engineer

Prepared by the
North Dakota State Water Commission
In cooperation with the
McLean County Water Resource District

ND State Water Commission

1996

THE GEOHYDROLOGY of EAST-CENTRAL McLEAN COUNTY, NORTH DAKOTA

NORTH DAKOTA GROUND-WATER STUDIES
Number 105 - Part II

By
Kevin D. Swanson
Hydrogeologist

Prepared in co-operation with the
McLEAN COUNTY WATER RESOURCE DISTRICT

Published by the
North Dakota State Water Commission
900 East Boulevard Avenue
Bismarck, North Dakota 58505

1996

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The investigation of the hydrologic system of East-Central McLean County was conducted cooperatively by the North Dakota State Water Commission (SWC) and the McLean County Water Resource District. The study received support from the U.S. Corps of Engineers, the U.S. Bureau of Reclamation and the U.S. Fish and Wildlife Service. Results of the investigation are presented in two parts. Part I is a compilation of the hydrologic data and part II is an interpretive report describing the dynamics of the of the hydrologic system in East-Central McLean County. Part I, published in 1994, makes available the hydrologic and geologic data collected during the investigation and serves as a reference for Part II. This report (Part II) provides a description and analysis of the data presented in Part I as well as the interpretation of the dynamics of the hydrologic system in the study area. Methods of data collection were presented in Part I.

The investigation was initiated in response to reports from area residents regarding water logging of agricultural land, deterioration and flooding of county and township roads, and an increase in size of some lakes and sloughs in Eastern McLean County from Lake Audubon eastward to Brush Lake. Rising water levels in some observation wells in this area had been noted when the water level record of the late 1960's to early 1970's was compared to that of the 1980's (Armstrong, 1983). The probable cause of these conditions was uncertain. It had been variously attributed, without substantiation, to Lake Audubon (especially to its 13 foot rise in operating elevation in 1975), to the McClusky Canal, and to Lake Sakakawea. It was also recognized that climatic patterns had also influenced surface water and groundwater levels.

PURPOSE AND SCOPE

The purpose of this investigation was to develop a hydrologic data base sufficient to allow quantification of the water level changes in the study area and an assessment of the relative importance that the man-made perturbations and the climatic patterns have had in causing the changes in water levels. Specific objectives of the study included:

1) developing a conceptual model of the groundwater flow systems in the glacial drift aquifers,
2) examining the interaction between groundwater and surface water systems,
3) evaluating the propagation of different climatic patterns through other components of the hydrologic system, and
4) assessing the degree to which human activities may have influenced components of the hydrologic system.

The scope of the study included:

1) definition of the geometry of the glacial drift aquifers and geologic correlation (stratigraphic relationships) of the upper, middle and lower units of the Lake Nettie aquifer system,

2) potentiometric analysis of groundwater flow directions, delineation of recharge and discharge areas, boundary conditions and groundwater divides,

3) analysis of the January through April 1985 Lake Audubon Response Test and July through September 1987 Lake Nettie Water Level Control Project to provide additional insight into the conceptual model and understanding of human impacts on the groundwater flow system;

4) analysis and quantification of long term (mid-1960's through mid-1990's) groundwater level trends with comparison to climatic patterns, and

5) assessment of monitored surface water level changes in the study area.

This study expands on the work of Armstrong (1983) and is primarily focused toward the Lake Nettie and Turtle Lake aquifer systems which were described in the McLean County ground-water study (Bluemle, 1971, and Klausing, 1971 and 1974). These glacial drift aquifers underlie much of the area between Lake Audubon and the McLean - Sheridan county border to the east.

LACK OF NUMERICAL SIMULATION

The original objectives for this study included limited two-dimensional numerical simulations of parts of the flow system to evaluate the feasibility of an additional detailed study using a numerical model to simulate the entire hydrologic system of the study area. Emphasis was to be placed on a two-dimensional profile (or vertical slice) model to simulate the effects of stage level rises in Lake Audubon on groundwater levels in areas of concern. Such a profile model would have been oriented from Lake Audubon to the east along the approximate aquifer axis. Once calibrated the model would have been used to simulate the response of the aquifer to changes in reservoir stage.

A profile model assumes that all flow occurs parallel to and in the plane of the profile, with no flow component at an angle to the profile. Potentiometric analysis of groundwater level data compiled during this study indicated that a profile model encompassing Lake Audubon and areas of interest to the east could not be oriented parallel to flow, especially in the lower and middle aquifer units where a predominant north to south component of flow is evident, as will be shown in subsequent sections of this report. If the profile is not oriented along a flow line, there would be errors in the numerical model results because the model can not simulate components of flow at an angle to the cross-section (Anderson and Woessner, 1992). In order to generate a numerical simulation with meaningful results, a full three-dimensional or quasi three-dimensional model would be required. Because of the geometric complexity of the system, an appropriate numerical model would necessarily be more sophisticated than the generalized two-dimensional models incorporated in the original objectives of this study. Additional data collection pertaining to the distribution of hydraulic conductivity and hydraulic heads in the confining beds would be necessary to calibrate such a numerical model.

The major objective of the study, the assessment of the relative importance of man-made influences versus climatic influences on water levels, has been largely fulfilled through the quantification of aquifer response during the Lake Audubon response test in 1985 and the measurement of water level variation across extreme wet and dry climatic conditions. As data analysis progressed and the conceptual model of the physical system was refined, the need to address the numerical modeling objective diminished. A detailed three-dimensional model would provide insight into the details of the dynamics of the geohydrologic system and better evaluation of probable historic groundwater flow directions in the lower aquifer unit prior to the filling of Lake Audubon and Lake Sakakawea. However, given the predominant influence of climatic conditions on determining groundwater and surface water levels, the ability to use a calibrated numerical model in a predictive mode would be largely dependent on the ability to predict future variations in climatic conditions. Future development of a three-dimensional numerical model may be warranted if operating levels of reservoirs were to be changed substantially.

ACKNOWLEDGMENTS

Appreciation is expressed to Arden Mathison and other members of the U.S. Bureau of Reclamation for their help in gathering, obtaining, and compiling data for this study. Appreciation is also expressed to the U.S. Corps of Engineers, the U.S. Geological Survey, and the U.S. Fish and Wildlife Service for furnishing data used in this report.

Particular recognition is due the following present and former employees of the North Dakota State Water Commission (SWC): G. Calheim and D. Sorge for drilling test holes and installing observation wells; A. Comeskey and D. Larson for logging test holes; G. Muri and M. Osborn for chemical analysis of water samples; M. Hove, K. Kunz, J. MacArthur, M. Osborn and M. Skaley for collection of water samples, collection of water level measurements and compilation of water level and water quality files; and to C. Bader for development of the database programs used in preparation of this report. Appreciation is expressed to Bob Shaver and Milton Lindvig of the SWC for critical review of this report. Recognition is also extended to the commercial well drillers who furnished well logs and to farmers and ranchers who allowed access to their land.

LOCATION-NUMBERING SYSTEM

Wells, test holes and other data collection points used in this study are numbered according the federal system of rectangular surveys of public lands as illustrated in Figure 1. The first and second series of numbers denote the township north of a base line and range west of the Fifth Principal Meridian, respectively. The third series of numbers designates the section within the

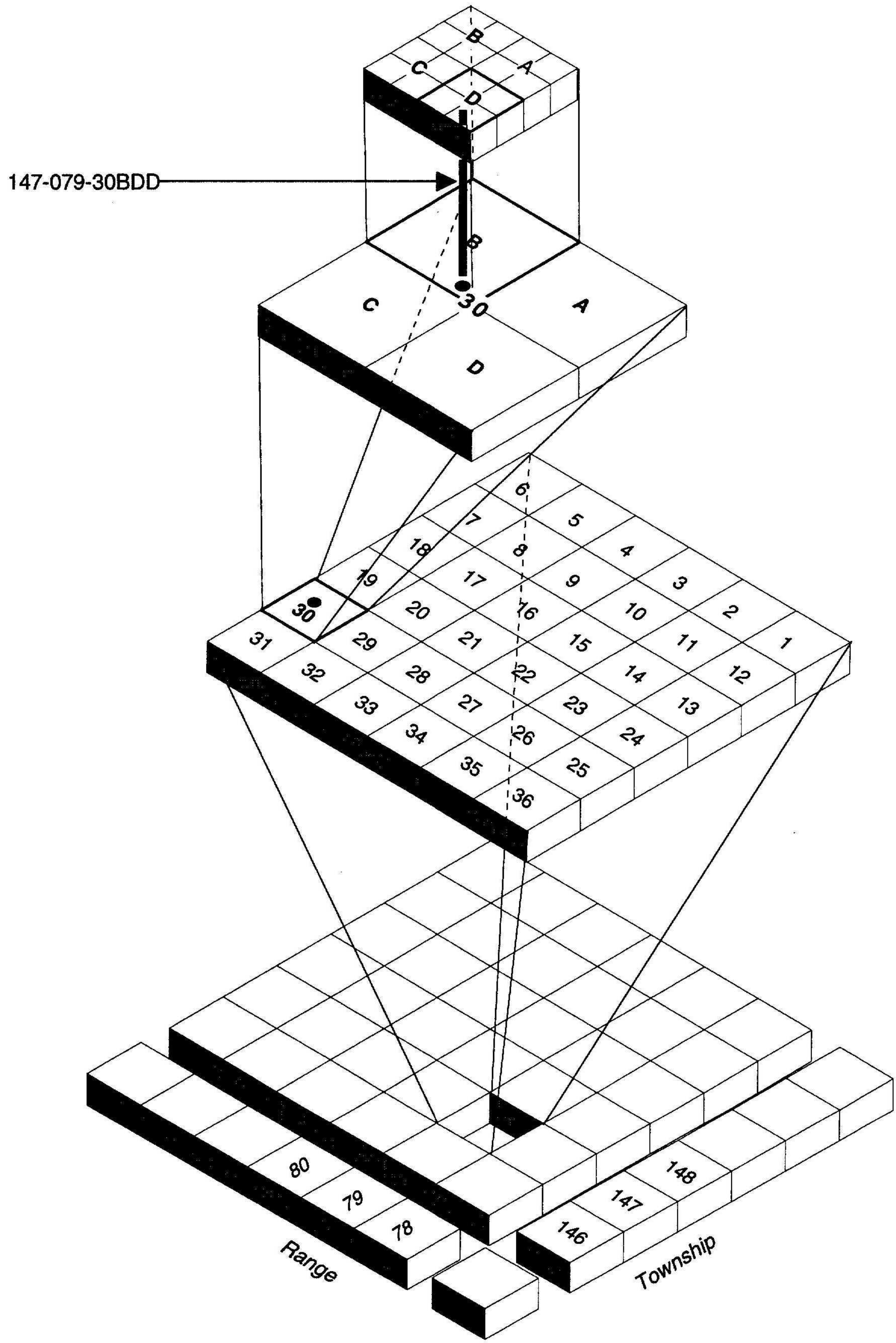


Figure 1. Location-numbering system.

township. The first, second, and third letters after the section number indicate, respectively, the quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). The letters A, B, C, and D respectively designate the northeast, northwest, southwest and southeast quarter of the tract. For example, a location given as 147-079-30BDD (Fig. 1) is in the SE1/4 of the SE1/4 of the NW1/4 of Section 30, Township 147 North, Range 79 West. Consecutive terminal numbers are added after the letters if more than one well or other data collection point is located in a particular 10-acre tract.

For the purposes of brevity an abbreviation convention is adopted in subsequent sections of this report for referring to Township locations. The abbreviation "Twp. 148-82" will refer to Township 148 North, Range 82 West while "Twp. 147-79" will refer to Township 147 North, Range 79 West, and so forth.

PREVIOUS INVESTIGATIONS

The geology and water resources of the study area have been described in several previous studies which were more regional in scope than this study.

Simpson (1929) briefly described the topography of the part of McLean County in which the study area is located. He noted that the rough and hilly morainal region of the eastern part of the county abounds with many lakes, sloughs, and undrained areas. Simpson briefly described the occurrence of groundwater in the bedrock and overlying glacial drift, summarizing information about the domestic wells and aquifer materials that comprised the water supply for the towns of Mercer and Turtle Lake. Simpson noted that the shallow wells in Turtle Lake yielded hard water and the deep wells yielded soft water.

Much of the previous work pertains to the surficial geology of McLean County, and is summarized by Bluemle (1971). The McLean County groundwater study (North Dakota County Ground-Water Studies Number 19) presented the results of the investigation of the geology and water resources of the county. Test drilling and water level collection for the county study occurred primarily from 1967 through 1970, and represents the earliest reliable groundwater level data for the study area, except for one observation well (148-80-33CCC), for which water level data dating to 1963 is available. The study consists of three parts:

Part I - Bluemle (1971) described and interpreted the surface and subsurface geology, the geomorphology, and geologic history of McLean County. He included a geologic map of the county showing the location and extent of various lithostratigraphic and geomorphic units. He also included a county map depicting the topography of the bedrock surface.

Part II - Klausing (1971) presented the basic data for the McLean County ground-water study. Included in Part II are logs and other data for test holes and wells, water-level measurements, information about springs in the county, and water-quality analyses for both groundwater and surface water.

Part III - Klausing (1974) discussed the hydrogeology of the bedrock and glacial-drift aquifers located in McLean County. He emphasized the aquifers that occur in the glacial drift because of their greater potential for ground-water development. For the glacial-drift aquifers, he described the location and areal extent, thickness and lithology, hydrologic character, the quantity of water in storage, water-level fluctuations, quality of water, and the utilization and the potential for development of the ground-water resource, including a map summarizing the estimated potential yield of the glacial-drift aquifers.

After the county groundwater study data collection was largely completed in 1970, periodic monitoring was performed in a few selected wells by the United States Geological Survey (USGS). However, groundwater monitoring was generally infrequent and involved few wells. In observation wells installed during the county groundwater study that are still intact, there is typically a water level data gap between the end of 1970 and 1977, across the time when Lake Audubon was raised 13 feet.

Armstrong (1983) described changes noted in observation-well hydrographs as well as stage-level records of several lakes and sloughs in an area between Lake Audubon and State Highway 41. Armstrong considered changes in water levels that occurred between the time that the McLean County groundwater study was completed (1971) and 1982. Armstrong concluded that the rising water levels in the observation wells and surface water bodies were in part the direct result of the construction and operation of both Lake Audubon and the McClusky Canal.

The conclusions reached by Armstrong (1983) were based on an earlier data set with a shorter period of record (mid-1960's through 1982). Armstrong's conclusions regarding the effect that the 13-foot increase (in 1975) in Lake Audubon had on water levels in lakes, sloughs and the upper unconfined units of the Lake Nettie aquifer system are inconsistent with additional data collected for this study across more extended periods of climatic cycling.

Beaver (1985) described the hydrology of the chain of lakes area between Lake Brekken and Brush Lake in east-central McLean County (parts of Twp. 147-79 and Twp 147-80) and discussed the hydrologic relationship of the shallow unconfined aquifer and the lakes in his study area with Lake Audubon, the McClusky Canal, and the underlying Lake Nettie aquifer. Beaver assessed the potential for change in the level of the lakes in his study area due to the management of Lake Audubon and the McClusky Canal, concluding that the lakes and the shallow, unconfined aquifer in his study area were hydraulically isolated from the Lake Nettie aquifer system and any effects from Lake Audubon and the McClusky Canal.

DESCRIPTION OF THE STUDY AREA

The study area encompasses approximately 500 square miles in eastern McLean County, extending from near the Snake Creek Embankment that forms Lake Audubon on the west to the Prophets Mountains on the east, as shown on Figure 2. Lake Audubon is the supply reservoir for the McClusky Canal which traverses the southwest quarter of the study area. The Snake Creek Embankment separates Lake Audubon from Lake Sakakawea, the reservoir formed by Garrison dam which is located 9 miles southwest of the Snake Creek Embankment. Construction of Garrison dam was completed in 1954 with diversion of the main Missouri River channel accomplished in April 1953.

POPULATION AND ECONOMY

Three small communities are located in the study area. The population of these communities according to the 1980 and 1990 censuses is as follows:

Community	1980 Census	1990 Census
Turtle Lake	802	681
Mercer	134	104
Coleharbor	150	88
Total	1,086	873

Agriculture forms the economic base of the study area. Irrigation development has occurred in the study area on a limited basis. Water based recreation is locally important. A high density of summer cabins has developed around Brush Lake in the eastern part of the study area. Similar development has occurred to a lesser extent at Blue Lake which is adjacent to Brush Lake, at Crooked Lake in the north-central part of the study area, and along the north side of Lake Audubon. Several wildlife management and wildlife refuge areas have been established in the study area.

PHYSIOGRAPHY

The study area lies within the Glaciated Missouri Plateau section of the Great Plains Province of Fenneman's (1931) physiographic classification (Fig. 3), and within the Missouri Coteau and the Coteau Slope districts in McLean County as described by (Bluemle, 1971). The boundary between the Missouri Coteau and the Coteau Slope has been defined as the contact between integrated and non-integrated drainage. The boundary between the two districts in the study area is not very distinct. The following generalized discussion regarding the physiography of the area is adopted from the more detailed descriptions provided by Bluemle (1971) and Klausing (1974).

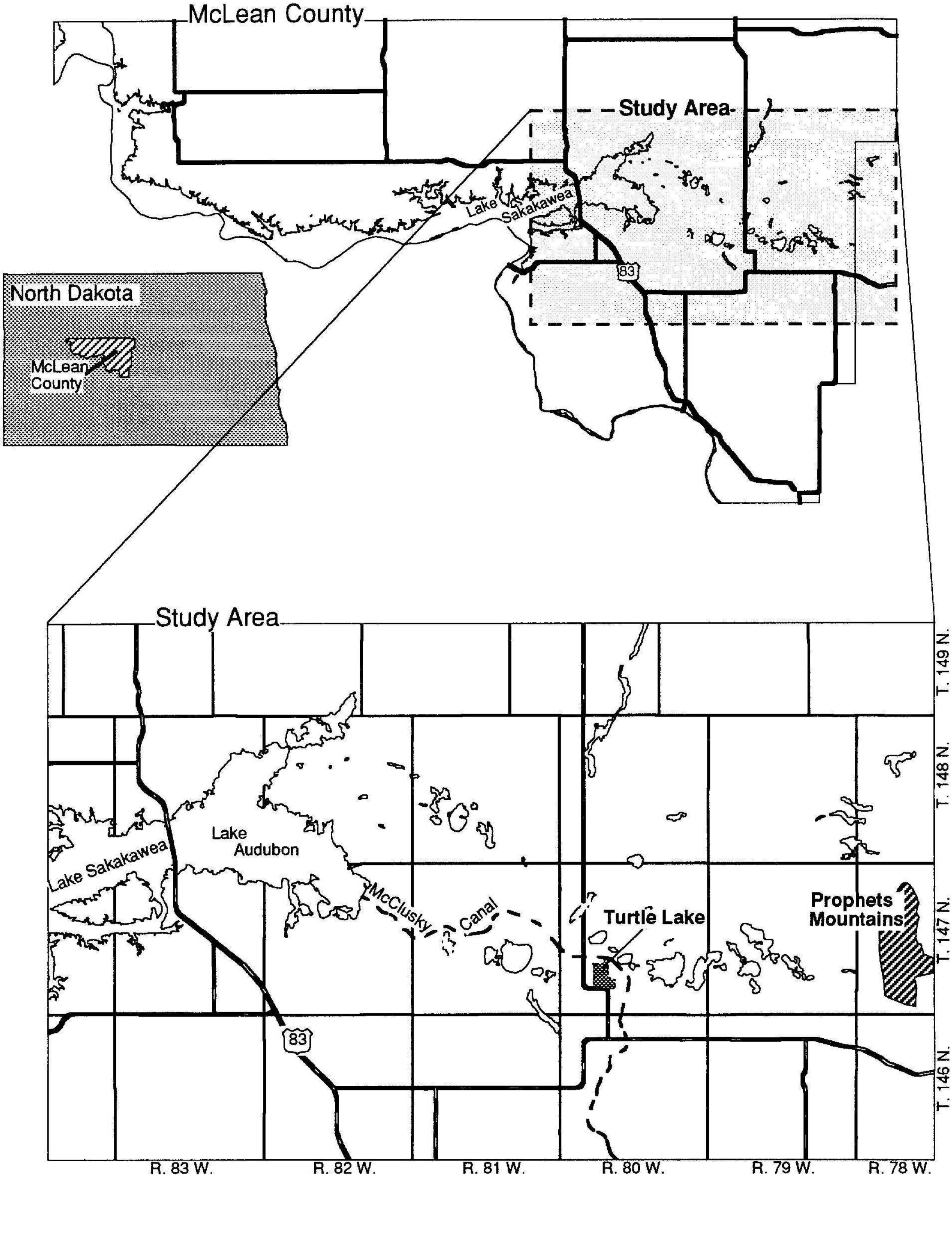


Figure 2. Location of McLean County, North Dakota and the East-Central McLean County hydrologic systems study area.

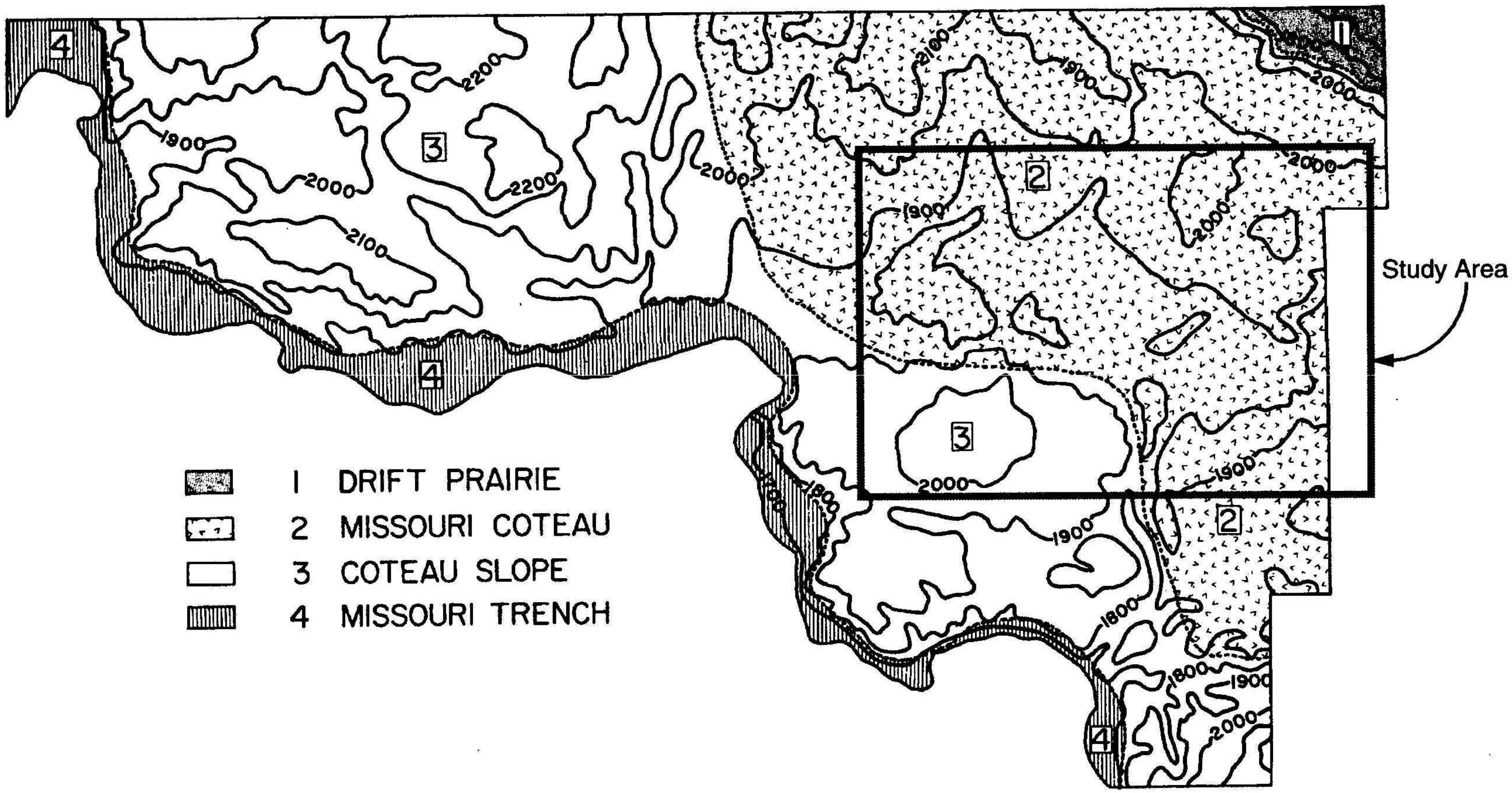


Figure 3. Topographic and physiographic map of McLean County (from Bluemle, 1971).

The Missouri Coteau district occupies most of the study area. The Missouri Coteau is an area of hilly topography characterized by moderate to high local relief. Bluemle (1971) notes local relief averages about 30 to 35 feet between lows and the adjacent highs. The Missouri Coteau is a landscape of constructional glacial features. The district is undrained to poorly drained and characterized by numerous sloughs and lakes of various sizes. The largest of the lakes have been named, such as the series of lakes around the city of Turtle Lake. A few, relatively short, intermittent streams are found in the Missouri Coteau district, but none transect it. Topographic relief tends to become less severe and the slopes more gentle toward the boundary with the Coteau Slope district.

The Coteau Slope district lies in the southwest corner of the study area to the south and west of the Missouri Coteau district (Fig. 3). Topography in the Coteau Slope district is undulating to rolling, and is mainly stream dissected bedrock with a veneer of glacial deposits. The district is characterized by moderate local relief, generally less than 25 feet between lows and the adjacent highs. Local topographic relief becomes somewhat more severe near some of the deeper valleys. These valleys carry small, intermittent streams across the Coteau Slope district to the Missouri River. Drainage in the district is youthful and moderately to well developed. Only a few lakes and sloughs occur in the area, and these are small compared to those in the Missouri Coteau district. Some limited areas of non-integrated drainage occur within the Coteau Slope district.

CLIMATE

The climate of the study area is semiarid and characterized by short summers, long winters, slight to moderate precipitation and wide fluctuations in temperature. The occurrence and pattern of precipitation varies considerably both during any one particular year and also from year to year. 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 winter precipitation generally falls as snow, some of which remains on the ground until the spring thaw which may result in considerable runoff. The runoff usually starts in March or April of most years and results in the filling of the lakes, sloughs and ephemeral prairie potholes in the area. The amount of runoff, if any, from summer storms will vary with the intensity and duration of the storm as well as antecedent soil moisture conditions.

The mean annual precipitation recorded at the city of Turtle Lake was 16.45 inches for the period 1912 through 1992, and was 17.03 inches for the period 1940 through 1992 (NOAA data, included in Table 8 of Part I of this study). The highest recorded total annual precipitation at the city of Turtle Lake was 24.56 inches in 1927 while the lowest was 5.20 inches in 1936. Since 1960, the highest and lowest annual precipitation totals have been 23.77 inches in 1982 and 8.45 inches in 1988. The 23.77 inches in 1981 and 8.45 inches in 1988 represent the third highest and third lowest annual totals since data collection began in 1912 (the years

1929, 1930, 1932, 1950, and 1956 were excluded from consideration because of missing monthly values). Thus, the period of water level record considered in this study (mid-1960's to mid-1990's) includes periods of both high and low annual precipitation extremes.

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 are usually warm with average daily temperature ranging from 62°F to 72°F. The amount of annual evapotranspiration in a given year will vary with average temperature, cloud cover and wind speed. On average, potential evapotranspiration at land surface in the region is about 36 inches per year (U.S. Department of Commerce, 1982), which exceeds the average annual rainfall by about 19 inches. The evaporation measuring station closest to the study area is at the Mandan Experiment Station, located about 52 miles south of the study area. Total April through September pan evaporation measured at the Experiment Station for 1985, 1986, 1987, 1988 and 1989 was 39.1, 38.9, 40.6, 51.5 and 44.5 inches, respectively (NOAA, 1985-1989).

Climatic patterns play a dominant role in the hydrologic cycle. Because the hydrologic cycle is a dynamic system, pronounced deviations from the average for climatic parameters will cause responses in other elements of the cycle, such as changes in groundwater levels, stream flow, and stage levels of lakes and sloughs. The amount of precipitation and evapotranspiration greatly affect the amount of water moving through the surface and groundwater components of the hydrologic cycle. During hot dry periods, evapotranspiration from areas of shallow water table and from lakes and sloughs may exceed recharge from all sources and water levels will be lowered. During extended wet periods some of the precipitation infiltrates through the unsaturated soil zone to recharge the groundwater system and some will become runoff that increases stream flow and raises the stage level of lakes and sloughs.

GEOLOGIC SETTING

TERTIARY ROCKS

The bedrock formations directly underlying the glacial drift in the study area are Tertiary rocks of the Fort Union Group which include, in ascending order, the Cannonball, Bullion Creek and Sentinel Butte Formations.

The Cannonball Formation consists of carbonaceous and lignitic siltstones and shale, lignite, claystones and friable sandstones. The Cannonball Formation is as much as 300 feet thick in the western and southern parts of McLean County but thins northeastward to less than 100 feet thick (Bluemle, 1971).

The Bullion Creek and Sentinel Butte Formations of Paleocene age, the youngest bedrock formations in the McLean County, directly underlie the glacial drift in the study area. The Bullion Creek and Sentinel Butte Formations were formerly called the "Tongue River"

Formations. The formations are exposed where the glacial drift is thin or absent. Maximum thickness of the two formations is about 800 feet in western McLean County. The contact between the Bullion Creek and underlying Cannonball Formation is at an elevation of about 1500 feet; therefore the maximum thickness of the Bullion Creek and Sentinel Butte Formations in the study area is about 400 to 500 feet. The formations are thinner where preglacial stream valleys were developed. The two formations consist of sands, silts and clays that range from poorly to fairly well cemented. Lignitic zones and lignite beds are commonly associated with the clay and silt beds (Bluemle, 1971).

PLEISTOCENE SEDIMENT

Pleistocene age glacial deposits cover the underlying bedrock formations over almost all of study area. The deposits range from a few feet to about 400 feet in thickness. These unconsolidated glacial drift deposits consist of fragments of older rock that has been eroded, transported and deposited by continental glaciers. The glacial sediments belong to the Coleharbor Formation and were deposited during the ice age from several hundred thousand to about 9,000 years ago (Bluemle, 1971)

The Coleharbor Formation consists of thousands of alternating beds but only three main facies: 1) interlayered bouldery, cobbly, pebbly, sandy, silty clay (boulder-clay); 2) sand and gravel; and 3) silt and clay. The following description of the types of glacial sediments in the study area is adapted from Bluemle (1971) and Klausing (1974).

Boulder Clay Facies

The boulder-clay facies of the Coleharbor Formation covers about 70 prcent of the study area (Fig. 4). The boulder-clay is a relatively uniform, nonbedded mixture of approximately equal parts of sand, silt and clay sized fragments together with small percentages of pebbles, cobbles and boulders as much as several feet in diameter. The boulder-clay facies is mainly till, a nonsorted, nonstratified sediment deposited from glacial ice by dumping, pushing, lodgement and ablation. Blocks of locally derived bedrock, such as shale and sandstone, are incorporated into the till in places. Because of its clay content, till has a low permeability and does not transmit significant quantities of groundwater. Shallow till near the land surface may have somewhat higher permeability imparted by fractures generated by weathering.

Sand And Gravel

The sand and gravel facies of the Coleharbor Formation occurs as isolated thin layers and lenses within the boulder-clay (till) facies and as thick continuous sequences independent of the boulder-clay. The thick continuous sequences were deposited mainly by rivers and streams during glacial time and occur as: 1) sediments in pre-glacial and interglacial stream valleys that were subsequently buried by till; 2) sediments in meltwater channels; and 3) surficial outwash sediments. The deposits range from sandy gravel and gravelly sand that is relatively free of finer material to very "dirty" gravel with high percentages of silt and clay. The sand and gravel facies is usually highly permeable and can yield significant quantities of groundwater.

Silt and Clay

The silt and clay facies of the Coleharbor Formation occurs in layers and lenses. Only a small percentage of the surface area is silt and clay but considerable thickness of it occur in buried valleys. The facies commonly has horizontal layering a fraction of an inch in thickness. Sand is uncommon and there are very few pebbles. The Coleharbor silt and clay exposed at the surface in the study area was deposited in lakes that were at least partly enclosed by glacial ice. The subsurface silt and clay that is confined to buried valleys was probably deposited in large lakes that formed when easterly flowing rivers were dammed by the advancing glacial ice.

POSTGLACIAL SEDIMENTS

Holocene sediments have been deposited throughout McLean County since the ice age, especially beneath stream valley flood plains and slough floors. Holocene deposits in the study area consist of alluvial sediments and slough sediments.

Alluvial Sediments

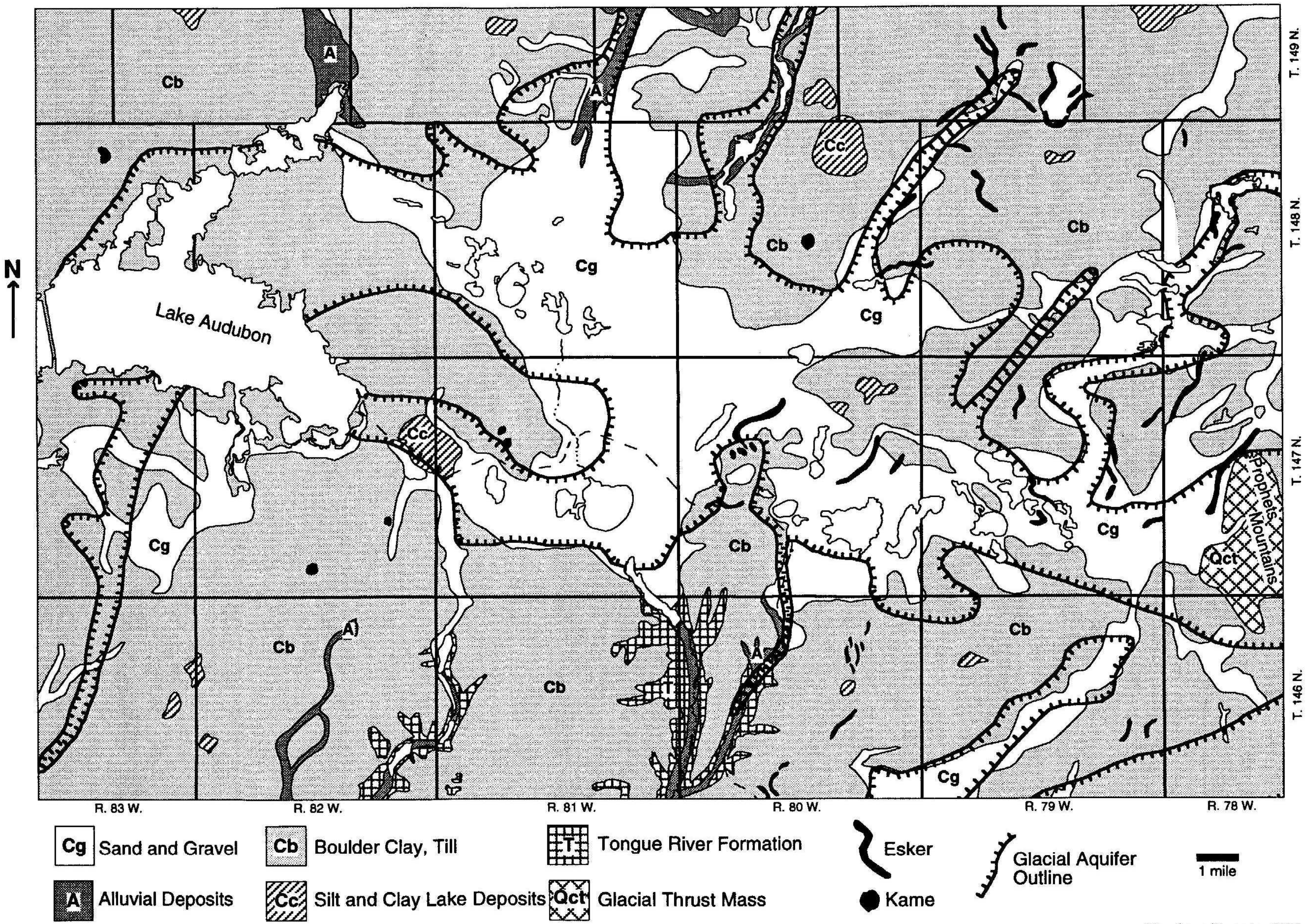
Alluvial sediment occurs along stream channels throughout McLean County. It is sometimes difficult to distinguish modern alluvial sediments from the underlying fluvial and lacustrine sediments of glacial age. The alluvial sediments in the study area consist mainly of clay, silt and fine sand. Alluvium is also present in many of the meltwater channels, where it commonly overlies sand and gravel deposits of glacial origin. Locally the alluvium may be as much as 20 feet thick.

Slough Sediments

The sediments in the bottoms of sloughs may be a few tens of feet thick and consist of dark brown and black clays with a high organic content. Most of the slough sediments are located in the hilly area in the eastern and northeastern parts of McLean County. The deposits consist of material washed into the lower areas from adjacent hill-slopes by runoff water.

GEOMORPHOLOGY

The landscape of the study area is characterized predominantly by hummocky topography of the Missouri Coteau formed by processes occurring along the margin of the last continental ice sheet to occupy the area. Stagnant glacial ice, covered with a thick blanket of superglacial sediment, remained in place when the ice sheet retreated from the area. Because of the insulating effects of the superglacial sediment, the stagnant ice melted slowly. Clayton et al. (1980a) interpret the hummocky topography to be the result of the superglacial sediment subsiding or collapsing as the ice supporting the sediment melts.



Map from Bluemle, 1971

Figure 4. Geologic map of the study area.

A portion of the surface geologic map developed by Bluemle (1971) is reproduced in Figure 4 . The distribution of the sand and gravel facies (map unit Cg) generally corresponds to the surficial, unconfined units of the glacial drift aquifers in the area. However, in some areas the thickness of the surface sand and gravel mapped by Bluemle is insufficient to constitute an aquifer. Bluemle notes that a small fraction of the material was deposited as outwash by glacial meltwater. Most of the material is stream sediment deposited by water derived from local precipitation during and immediately following glaciation.

Two surface glacial features that have been mapped in the area merit attention here because of the effect they have on the groundwater flow system. The first feature is the Prophets Mountains located in the southwest quadrant of Twp. 147-78, one to three miles east of the McLean County - Sheridan County border. The Prophets Mountains are located over the axis of the main body of the Lake Nettie aquifer. The "mountains" are ice thrust hills a few hundred feet higher than the bordering land. The elevation of the hills is sufficient to form a potentiometric divide in this area of the aquifer that represents the eastern boundary of the flow system in the study area.

The second feature is the hilly area in the south part of the northwest quadrant of Twp. 147-80 (about 2 miles north of the city of Turtle Lake), which where mapped as kames by Bluemle (Fig. 4). This hilly area was mapped as ice-thrust hills by Clayton et al. (1980). Analogous to the Prophets Mountains, these hills are of sufficient elevation (100 to 150 feet higher than the surrounding areas) to have an effect on the groundwater flow system. The presence of the hills causes groundwater flow in the aquifer to diverge around the hills.

GEOLOGIC HISTORY

The occurrence and geometry of the glacial drift aquifers results from the geologic history of the study area. A brief summary of recent geologic history relevant to the this study is provided here. Bluemle (1971) provides a more detailed description of the geologic history which includes preglacial and glacial drainage development with detailed figures depicting probable drainage patterns during various stages of the most recent glaciations.

DRAINAGE DEVELOPMENT AND DEPOSITION OF VALLEY FILL

The occurrence of deeper confined units in the Lake Nettie and Turtle Lake aquifers is mainly a result of preglacial drainage patterns and their alteration by continental glaciation. Prior to glaciation, general drainage patterns in the area were to the east and northeast, with flow ultimately into Hudson Bay. River valleys were eroded into the bedrock sediments. As glaciers advanced and retreated over the area major drainages were diverted, resulting in the cutting of new diversion trenches. Pre-existing river valleys were filled with various types of sediment: sand and gravel derived from meltwater running off the glaciers, sand and gravel carried by streams flowing in the bedrock valleys during interglacial periods, silt and clay deposited in pro-glacial and ice-dammed lakes occupying the bedrock valleys, and glacial till deposited during periods where the ice advanced over the area. The array of buried valleys in McLean county and other areas of North Dakota indicates that drainages followed many different routes during the various glaciations and the intervening interglacial stages. Because of the number of buried valleys that have been found, it is difficult to precisely identify the drainage pattern that may have existed at any particular time prior to the present.

BEDROCK SURFACE TOPOGRAPHY

The general pre-glacial and glacially modified drainage patterns in the study area are reflected in the elevation contours of the top of the buried bedrock surface shown in Figure 5. The bedrock contour map was prepared using bedrock elevations determined from test hole logs published in Part I of this study. The bedrock surface depicted in Figure 5 resulted from both glacial and nonglacial processes acting on the Fort Union Group bedrock, which underlies the glacial deposits in the study area.

The bedrock surface in the study area was influenced by the ice sheets during some or all of the four major ice advances which are recognized in the upper midwest. It was also subject to weathering during the interglacial periods. The deep bedrock valleys across the study area are the result of geomorphic processes occurring in the glacial and interglacial periods which modified the preglacial drainage system of the area.

Several narrow bedrock valleys are found in the study area. These valleys are typically not incised as deeply into the bedrock as the bedrock valleys described above. Bluemle (1971) interprets the origin of these valleys as meltwater trenches, formed when drainage was diverted by an ice sheet.

Due to the spacing of control points, various interpretations of the buried bedrock surface can be inferred from the same set of data points. Thus, there were discrepancies between the contoured surface of Bluemle (1971) and Klausing (1974), even though the two authors used the same data set. A significant discrepancy between Klausing and Bluemle's interpretations existed with respect to a north trending bedrock valley occupied by the Weller Slough aquifer, south of Lake Audubon. Klausing inferred that the bedrock valley turned to the northwest a few miles south of Lake Audubon, extended beneath Mallard Island and became tributary to the major east-west trending bedrock valley west of the Snake Creek Embankment. Bluemle inferred that the same north trending bedrock valley turned to the north-northeast a few miles south of Lake Audubon and became tributary to the major east-west trending bedrock valley near the east shore of Lake Audubon.

The bedrock topography depicted in Figure 5 (which is based on a larger data set than was available to Klausing and Bluemle) is generally consistent with that depicted by Bluemle (1971). Additional test drilling performed along an east-west transect south of Mallard Island indicates that the bedrock valley inferred by Klausing as trending to the northwest beneath Mallard Island does not exist.

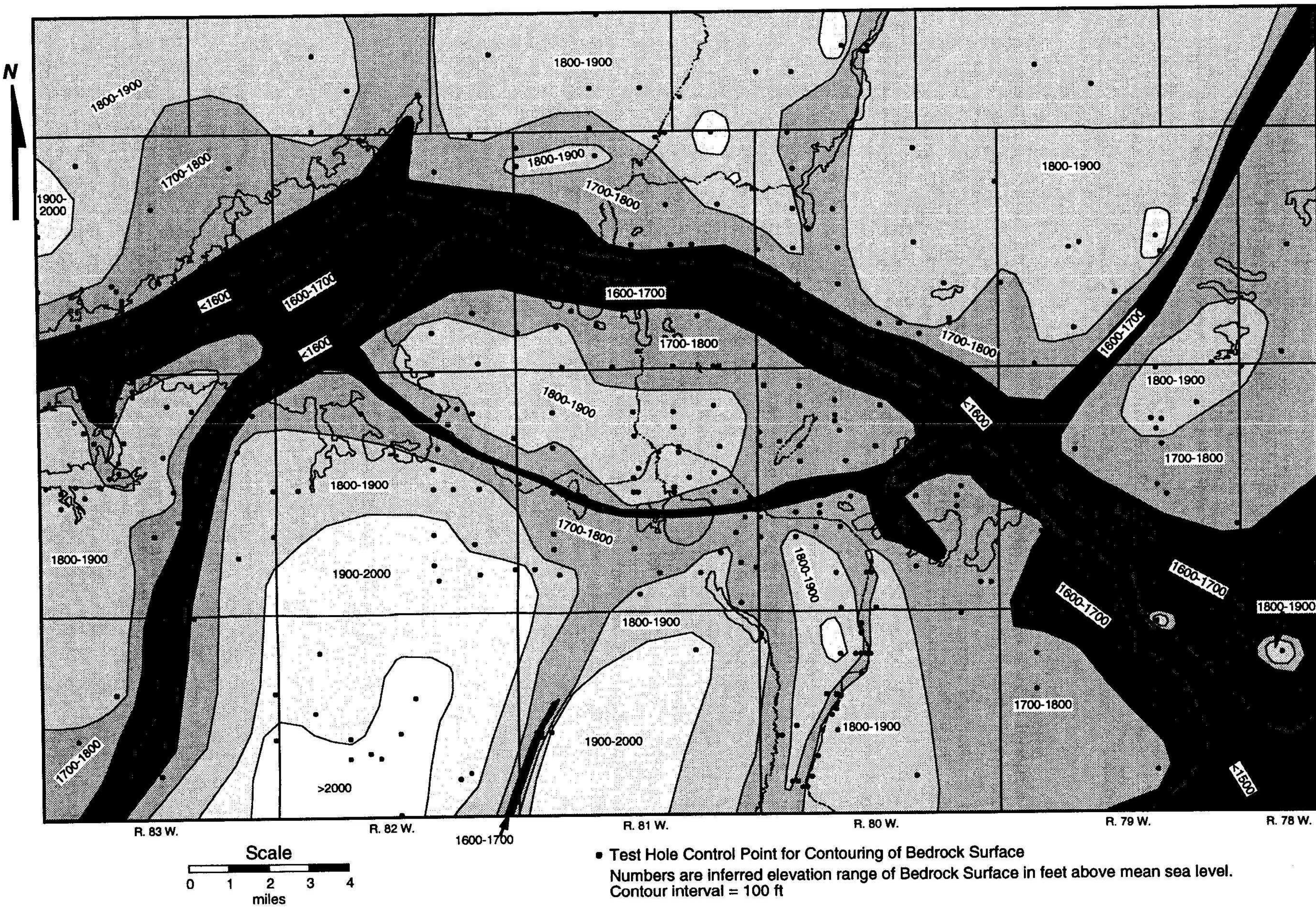


Figure 5. Bedrock topographic map.

GENERALIZED HYDROGEOLOGY OF THE STUDY AREA

The glacial drift aquifers in the study area were initially delineated by Klausing (1974). The following general discussion of general hydrogeology is adapted from the work of Klausing (1974), with the incorporation of additional information provided by the data collected for this study. Additional insights into the hydraulic character of the aquifers gained from data collected for this study will be developed in subsequent sections of this report.

GLACIAL DRIFT AQUIFERS

The Lake Nettie aquifer system is the major aquifer system occurring within the glacial deposits of the study area. This aquifer system consists of several separately defined, hydraulically interconnected aquifers, including the Lake Nettie, Turtle Lake, Horseshoe Valley, and Strawberry Lake aquifers. Parts of the Weller Slough - Wolf Creek aquifer and the Mercer aquifer also occur within the study area. The distribution of glacial drift aquifers within the study area is illustrated in Figure 6.

LAKE NETTIE AQUIFER SYSTEM

The Lake Nettie aquifer system underlies an area of about 175 square miles in the study area (Fig. 6). The individual aquifers in the system form a hydraulically related complex. The individual aquifers in the system were named the Lake Nettie, Strawberry Lake, Horseshoe Valley and Turtle Lake aquifers by Klausing (1974). The Strawberry Lake and Horseshoe Valley aquifers are tributary to the Lake Nettie aquifer. Cross-sections depicting the distribution of the buried and surficial sand and gravel deposits that make up the aquifer are presented in Plate 1.

Lake Nettie Aquifer

The Lake Nettie aquifer extends from Lake Audubon east-southeastward into Sheridan County. The aquifer consists of an upper, middle and lower unit. The sand and gravel bodies which comprise the aquifer were deposited during multiple periods of glacial and interglacial deposition. The lower and middle units of the aquifer occupy the major pre-glacial bedrock valley than transects the central portion of the study area (Fig. 5). The lower and middle units extend west beneath Lake Audubon and the eastern arm of Lake Sakakawea. The upper unit extends beyond the lateral boundaries of the lower and middle aquifer units.

The nature of the glacial and interglacial process that deposited the aquifer material generated a heterogeneous distribution of the sand and gravel bodies that comprise the aquifer (see cross-sections, Plate 1). As a result, all three aquifer units are not necessarily present in every mapped area of the aquifer. In some areas the distinction between the upper, middle and lower units of the aquifer is somewhat arbitrary, with the upper part of the middle unit merging into the upper unit or the lower part of the middle unit merging into the upper part of the lower unit. However the upper and lower units appear to remain separate from each other. The

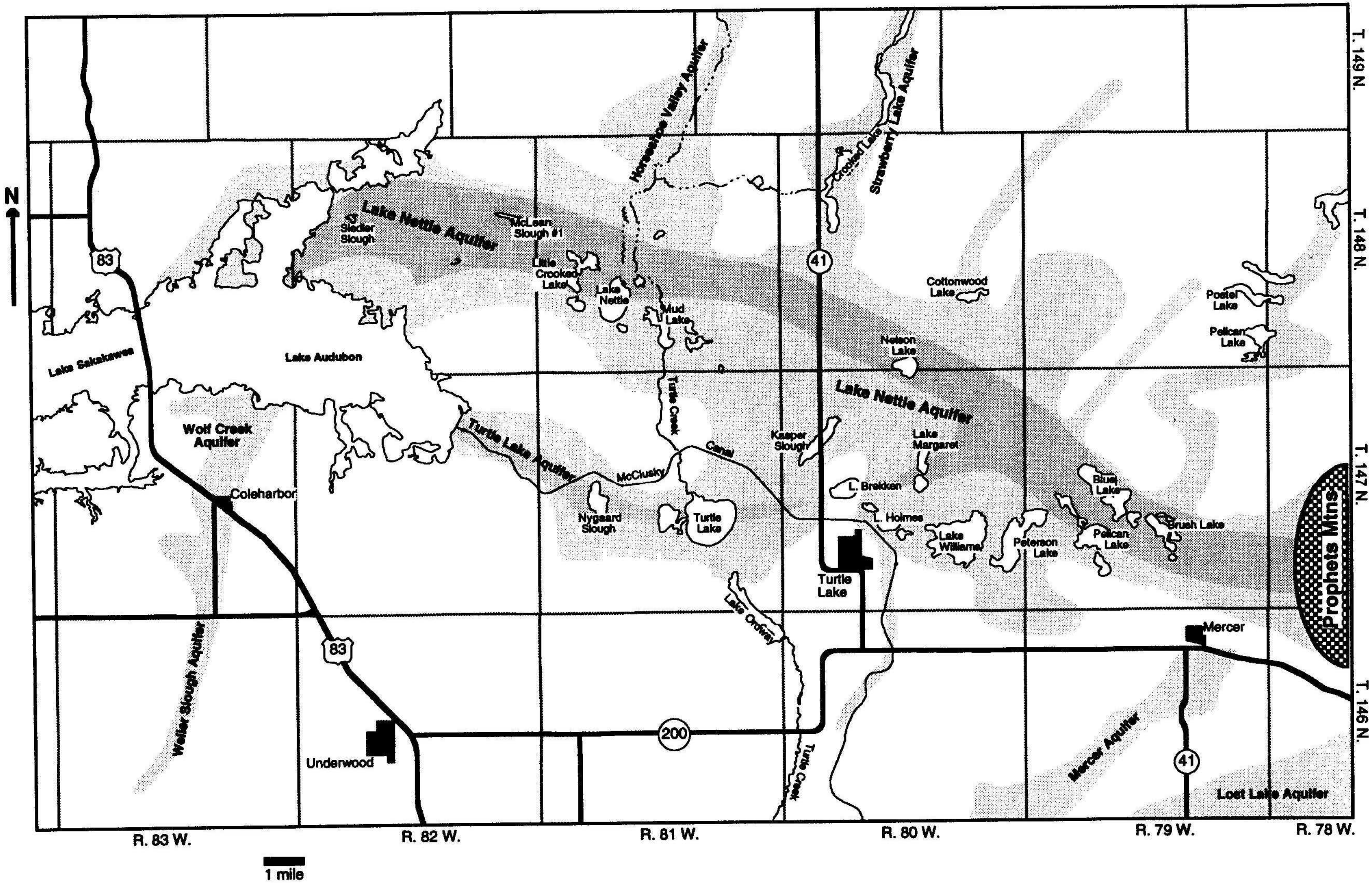


Figure 6. Major glacial drift aquifers and surface water bodies.

general working distinction between the three aquifer units that will be used for this report is as follows:

- the upper unit exists above about 1800 feet in elevation,
- the middle unit exists between about 1800 and about 1700 feet in elevation, and
- the lower unit below about 1700 feet in elevation.

The vertically distinct units of the aquifer are separated by varying thicknesses of low permeability till and lacustrine silt and clay.

Upper Aquifer Unit

The upper aquifer unit ranges from a few feet to about 70 feet in thickness. It is comprised mostly of sand mixed with gravel, but may locally consist of either sand or gravel. Where the upper unit is present, the saturated thickness is typically in the range of 10 to 40 feet. The upper unit is usually unconfined and exposed at the surface, but it may be confined or partially confined locally and overlain by as much as 50 feet of glacial till.

Two large relatively continuous areas of the surficial aquifer are present in the study area: 1) the western portion extending from the area about 3 to 4 miles west of Lake Nettie eastward to the area 5 to 6 miles east-southeast of Lake Nettie and southward to Turtle Lake; and 2) the eastern portion extending from the Nelson Lake area southeastward to the chain of lakes area (Lake Williams, Lake Peterson and Pelican Lake) east of the city of Turtle Lake (see cross-sections D-D', E-E', K-K', L-L' and M-M', Plate 1). The westernmost extent of the upper aquifer unit is about 3 miles east of Lake Audubon (see cross-sections J-J', K-K', L-L', M-M', Plate 1).

Cross-section M-M', oriented approximately along the axis of the main buried valley, suggests that the western and eastern parts of the upper aquifer unit are partially separated from each other. The two portions of the upper unconfined aquifer unit generally correspond to the surficial sand and gravel facies delineated by Bluemle (1971). According to Bluemle's surficial geologic map (Fig. 4), there is a peninsular area of till in the west part of Twp. 147-80 that is about 1 to two miles wide and extends about two miles north from the city of Turtle Lake. The portion of the till "peninsula" north of Lake Brekken is a locally elevated area approximately 150 feet higher than the surrounding land that was mapped by Clayton et al. (1980a) as a glacial thrust mass. This elevated area functions as a local groundwater flow divide causing flow to diverge around the area, partially dissecting the main western and eastern parts of the upper aquifer unit.

A 5-day aquifer test was performed in 1970 in the upper aquifer unit using an irrigation well located in 148-80-33CBD. The 17-inch inside diameter well screened from 39 to 51 feet was pumped at a constant rate of 510 gpm (gallons per minute) for 7,200 minutes starting on November 4, 1970. Water level response was monitored in seven observation wells. Analysis of the aquifer test data indicated a transmissivity of 8,600 ft^2/day (feet squared per day) and a storage coefficient of 0.14 (Klausing, 1974). The saturated thickness of the upper aquifer unit in the area of the pump test averages about 30 feet. Thus the 8,600 ft^2/day yields a hydraulic conductivity estimate of about 290 ft/day for the aquifer in the vicinity of the pumped well.

Middle Aquifer Unit

The middle aquifer unit is confined and usually separated from the upper aquifer unit by 10 to 30 feet or more of till. In some areas the separation between the upper and middle aquifer units is indistinct (e.g. the area between Nelson Lake and Pelican Lake shown on cross-section M-M', Plate 1). Where it is present, the middle aquifer unit consists of one, two or occasionally three individual layers of sand or gravel or a mixture of both. Cumulative thickness of the sand and gravel layers ranges up to 70 feet, but is typically on the order of 30 to 40 feet.

Lower Aquifer Unit

The lower aquifer unit is confined and typically separated from the middle unit by 20 to 40 or more feet of till or lacustrine clay. However, in local areas there is 10 feet or less of low permeability material separating the lower and middle units and in other areas the separation of the two units is indistinct. The lower unit appears to transect the entire study area, extending beneath Lake Audubon and the Snake Creek embankment to the west and beneath the Prophets Mountains to the east. The lower unit consists of one to five layers of interbedded and intermixed sand and gravel. Thickness of the individual beds ranges from a few feet to more than 100 feet. Aggregate thicknesses of greater than 200 feet were encountered in boreholes completed by the U.S. Corps of Engineers for the Snake Creek Embankment.

An aquifer test was performed in 1970 on the lower aquifer unit using a well located at 148-81-20CCD (between Lake Nettie and little Crooked Lake) completed with a 10-inch diameter 50-slot screen set from 162 to 190 feet. The well was pumped at a constant rate of 1450 gpm for 7,200 minutes (5 days) starting on September 28, 1970. Water level response was monitored in 29 observation wells. Analyses of the test data indicated a transmissivity in the aquifer of 44,000 ft^2/day with a storage coefficient of 0.0002 (Klausing, 1974). Deviation from the drawdown versus time type curve indicated the presence of a lateral boundary of less permeable material which was attributed to a flanking wall of the buried bedrock valley. The test data indicated leakage from the middle aquifer unit to the lower unit. The absence of response of water levels in three observation wells screened in the upper aquifer unit indicated no leakage from the upper unit to the middle or lower unit during the pump test. The hydraulic conductivity in the lower unit calculated from the transmissivity and aquifer thickness in the area is about 950 ft/day.

<u>Strawberry Lake Aquifer</u>

The Strawberry Lake aquifer (Fig. 6) occupies a buried bedrock valley that extends northward from its junction with the Lake Nettie aquifer into McHenry County. Klausing (1974) noted that the aquifer consist of several sand and gravel beds that range in thickness from 3 to 150 feet, with an average aggregate thickness of about 65 feet. At its confluence with the Lake Nettie aquifer near the south end of big Crooked Lake, the Strawberry Lake aquifer consists of two buried beds of sand and gravel with an aggregate thickness of about 70 feet. The elevation of the shallower bed approximately corresponds to the upper unit of the Lake Nettie aquifer, while the deeper bed approximately corresponds to the elevation of the middle unit of the Lake Nettie aquifer in this area (cross-section F-F', Plate 1).

Groundwater flow in the Strawberry Lake aquifer is southward along the axis of the buried valley toward the Lake Nettie aquifer. There appears to be hydraulic continuity between the two aquifers with groundwater flow "discharging" from the Strawberry Lake aquifer into the Lake Nettie aquifer. The base of the buried bedrock valley occupied by the Strawberry Lake aquifer is about 150 to 200 feet higher in elevation than the base of the larger buried valley occupied by the Lake Nettie aquifer.

Horseshoe Valley Aquifer

The Horseshoe Valley aquifer occupies a glacial meltwater channel that extends southward from the northern boundary of McLean County northwest of Ruso to its confluence with the Lake Nettie aquifer in the area northeast of Lake Nettie and little Crooked Lake. The aquifer is unconfined in the study area, consisting mainly of coarse sand and gravel deposits from the land surface to depths of about 50 feet. The saturated thickness of the sand and gravel is typically on the order of about 30 feet.

An aquifer test was performed in November 1973 in the Horseshoe Valley aquifer using an irrigation well located at 150-80-34A, about 9 miles north of the confluence of the Horseshoe Valley and Lake Nettie aquifers (outside of the study area). The well was pumped at a constant rate of 600 gpm for 4,500 minutes (75 hours). Analysis of the test data indicated a transmissivity of about 20,000 ft^2/day and a storage coefficient of 0.15 (SWC aquifer test open file reports). The saturated thickness of the unconfined aquifer in the vicinity production well is about 38 feet, yielding a hydraulic conductivity for the tested area of the aquifer of about 520 ft/day.

In the northern part of Twp. 148-81, to the northeast of Lake Nettie and little Crooked Lake, the Horseshoe Valley aquifer is 2 to 3 miles wide (Fig. 6) and extends beyond the confines of the meltwater trench mapped by Bluemle (1971). The boundary between the Horseshoe Valley and Lake Nettie aquifers is arbitrary. The sand and gravel deposits of the Horseshoe Valley aquifer are continuous with those of the upper unit of the Lake Nettie aquifer northeast of Lake Nettie (see cross-sections D-D' and D_2-D_2', Plate 1). Good hydraulic continuity exists between the two aquifers with the Horseshoe Valley aquifer acting as a tributary to the to the upper unit of the Lake Nettie aquifer.

Turtle Lake Aquifer

The Turtle Lake aquifer underlies an area extending southeastward from the southeast arm of Lake Audubon to an area about 1 mile west of the city of Turtle Lake (Fig. 6). The aquifer occupies an eastward trending buried bedrock valley several miles south of the larger buried valley occupied by the Lake Nettie aquifer. The buried valley appears to continue eastward to a junction with the buried valley occupied by the Lake Nettie aquifer in the northeast part of Twp. 147-80 (Fig. 5). However the spacing of test holes is such that precise delineation of the narrow deepest parts of the valley is tenuous.

The main western segment of the upper unit of the Lake Nettie aquifer is continuous with an upper unconfined layer of the Turtle Lake aquifer east of Turtle Creek between Lake Nettie and Turtle Lake (see cross-section E-E', Plate 1). The deeper confined intervals of the Turtle Lake aquifer are separated from the middle and lower units of the Lake Nettie aquifer by an intervening area of higher land surface topography and higher Fort Union Group bedrock surface topography (Figs. 5 and 6, and cross-sections C-C', D-D' and E-E', Plate 1).

The top of the sand and gravel deposits that form the aquifer lie from 0 to 80 feet below land surface. The aggregate thickness ranges from 12 to 120 feet and is typically about 40 feet. the aquifer consists of very fine to very coarse sand intermixed with fine to coarse gravel.

WELLER SLOUGH - WOLF CREEK AQUIFER

Weller Slough aquifer occupies a buried valley that extends north-northeastward in Twp. 146-83 and Twp. 147-83, in the area south of Lake Audubon (Fig. 7). The buried valley varies from less than 1/2 mile to about one mile in width. In the study area the aquifer consists of a layer of sand and gravel about 20 feet thick the top of which lies about 130 to 140 feet below land surface. Sand and gravel bodies of the aquifer extend to depths as great as 300 feet south of the study area. Based on test drilling completed after the McLean County Groundwater study, the northwest trend of the buried bedrock valley and Weller Slough aquifer beneath Mallard Island and Lake Sakakawea as inferred by Klausing (1974) is inaccurate. Instead, the buried valley appears to extend northeastward beneath Lake Audubon, as depicted by Bluemle (1971).

The Wolf Creek aquifer consists of sand and gravel bodies about 20 feet in thickness, the top of which is located 25 to 40 feet below land surface in the area north of Coleharbor. The sand and gravel deposits of the Wolf Creek aquifer extend beyond the lateral boundaries of the buried bedrock valley aquifer occupied by the deeper Weller Slough aquifer. The physical relation of the sand and gravel bodies of the Wolf Creek and Weller Slough aquifers is depicted in Figure 7. Klausing (1974) referred to an upper unit (30 to 42 feet below land surface) and a lower unit (about 130 feet below land surface) of the Wolf Creek aquifer.

The lower unit of the Wolf Creek aquifer referred to by Klausing is referred to here as the Weller Slough aquifer. The historic distinction of the Weller Slough and Wolf Creek aquifers is a result of Klausing's (1974) interpretation of the bedrock topography which has been refuted by subsequent test drilling. The Wolf Creek Aquifer consists of sand and gravel bodies that were deposited above and laterally beyond the buried valley that constrains the deposits of the Weller Slough aquifer.

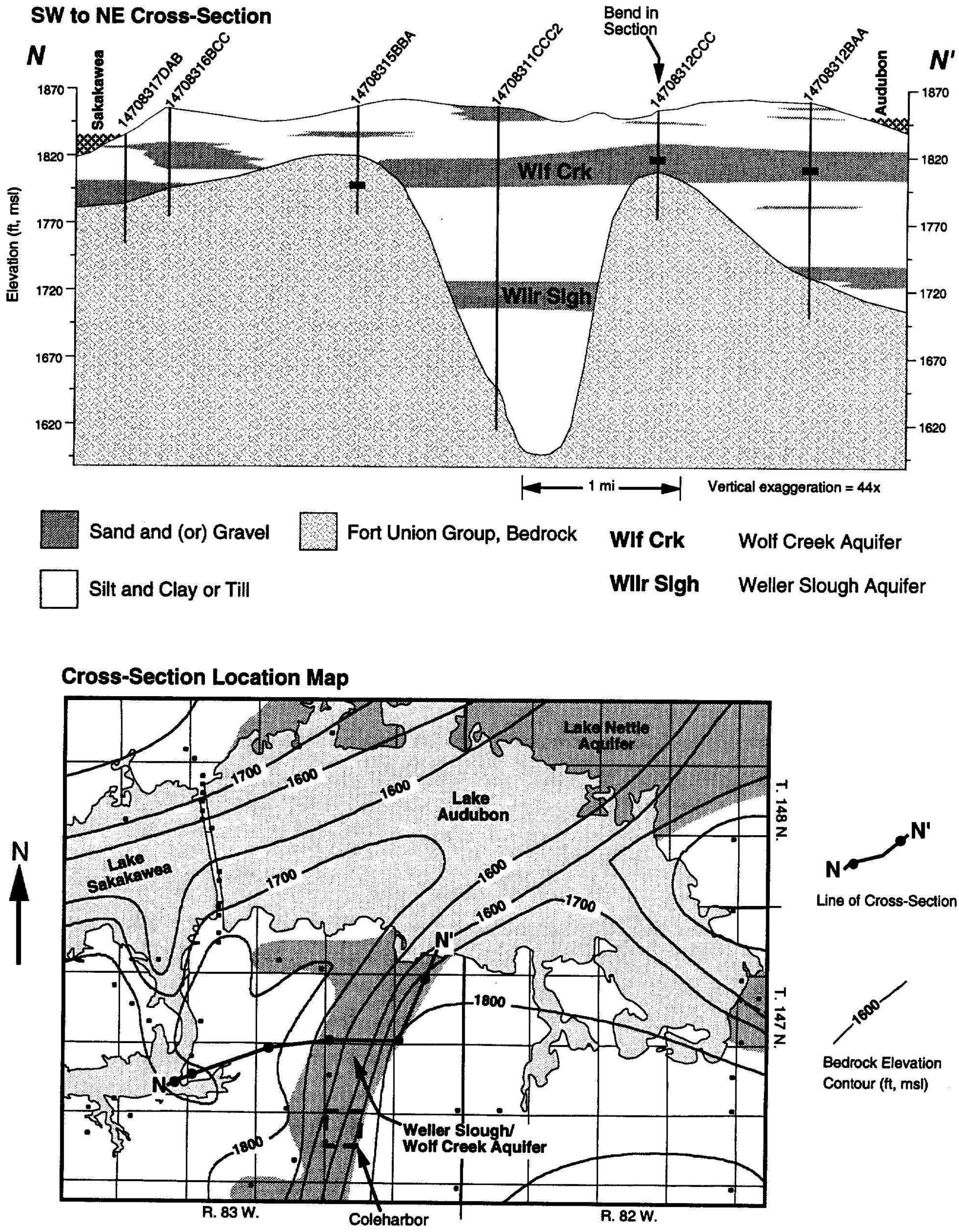


Figure 7. Southwest to northeast cross-section through the Wolf Creek - Weller Slough aquifer.

MERCER AQUIFER

The Mercer aquifer underlies an area of about 8 square miles, consisting of surficial outwash deposits mostly in Twp. 146-79 in the area southeast of the city of Mercer (Figs. 2 and 4). The aquifer has a thickness of about 18 to 28 feet and generally consists of medium to very coarse sand intermixed and interbedded with gravel. The Mercer aquifer is hydraulically separated vertically and laterally from the Lake Nettie aquifer by intervening deposits of till and lacustrine silt and clay (see cross-section I-I', Plate 1).

FORT UNION GROUP AQUIFER

The Fort Union Group consists of interbedded silt, siltstone, clay, shale, sandstone and lignite. The beds vary in thickness and are generally not continuous over an extensive area. The sandstone beds are the major water bearing units and are predominantly very fine to fine grained. The sandstone beds range from a few feet thick to a maximum known thickness of 225 feet in test hole 146-82-32CDC (Klausing, 1974). Lignite beds, ranging from 0.5 to 20 feet thick, provide local water sources for domestic and livestock wells.

This study is directed toward glacial drift aquifers but there appears to be a good hydraulic connection between the glacial drift aquifers and the upper portion of the Fort Union Group aquifer. Water levels in observation wells completed in the upper 50 feet of the Fort Union Group sediments show trends similar to those in nearby Lake Nettie aquifer and Turtle Lake aquifer observation wells. There will be some amount of groundwater movement between the glacial drift aquifers and vertically or laterally adjacent sandy beds of the Fort Union Group aquifer. In localized areas where the sand and gravel aquifer units are bounded by low permeability till or silt and clay, an adjacent sandy bed of the Fort Union Group could constitute the most permeable local source or sink for groundwater flow into or out of the glacial drift aquifer.

GROUNDWATER USE

Groundwater is the primary source for rural domestic and livestock and municipal public water supply in the study area. Groundwater from the Lake Nettie, Strawberry Lake and Horseshoe Valley aquifers is also use to supply a minor amount of irrigation. The McLean-Sheridan Joint Water Resource Board rural water system well field in 147-80-08A has supplied domestic water supplies from the upper unit of the Lake Nettie aquifer to users in much of the study area since 1990.

Reported annual groundwater use since 1977 for valid water permits is shown in Figure 8. Reported water use in the Lake Nettie aquifer has fluctuated between about 400 and 900 acre-feet since 1977. After peaking at about 1700 acre-feet in 1984, reported use from the Horseshoe Valley and Strawberry Lake aquifers (including parts of the aquifers beyond the boundaries of the study area) declined to 500 to 600 acre-feet in 1987 through 1992. Reported use from the Turtle Lake aquifer was about 100 acre-feet from 1977 to 1990. After 1990 reported use from the Turtle lake aquifer dropped to zero when the city of Turtle Lake began obtaining its supply from the McLean-Sheridan Joint Water Resource Board rural water system.

The drop in reported water use in the Horseshoe Valley and Strawberry Lake aquifers after the mid-1980's is due to the fact that a significant percentage of irrigated land was removed from production by enrollment in the Conservation Reserve Program (CRP). Reported irrigated acres from the Horseshoe Valley and Strawberry Lake aquifers dropped from a high of 1500 acres in 1985 to 1200 acres in 1986, to about 750 acres in 1987 and fluctuated between 400 and 800 acres from 1988 through 1994. Reported irrigated acres from the Lake Nettie aquifer fluctuated between 800 and 1200 acres from 1977 to 1994.

In addition to the reported annual groundwater use associated with State of North Dakota water permits, numerous small capacity domestic and stock wells in the Study area obtain their supply from the glacial drift aquifers and Fort Union Group aquifer. There has been no measurable long term effect on groundwater levels from development in the area because the total volume of groundwater use is small compared to the size of the groundwater system. A few localized areas show minor irrigation season drawdown with complete static water level recovery in the off-irrigation season.

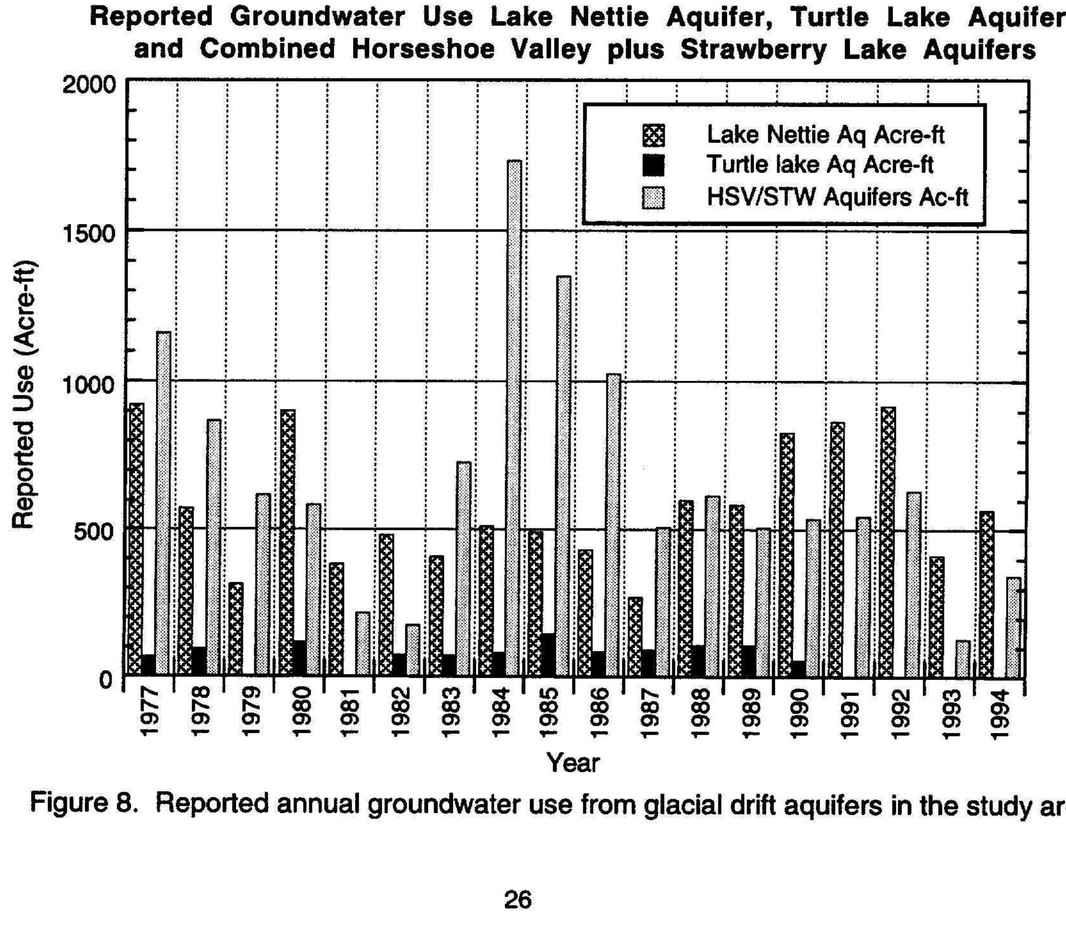


Figure 8. Reported annual groundwater use from glacial drift aquifers in the study area.

GENERALIZED GROUNDWATER RECHARGE AND DISCHARGE

The buried pre-glacial bedrock valley results in a "topographic sag" in the overlying land surface. The land surface overlying the Lake Nettie aquifer system is within 30 feet of 1850 feet in elevation, except for higher land surface elevations (1900 to 2000 feet) in areas overlying the tributary Horseshoe Valley and Strawberry Lake aquifers. The "topographic sag" over the aquifer system with rising land surface laterally beyond the aquifer deposit boundaries is evident on the cross-sections that traverse the aquifer system (Plate 1). The topographically higher areas to the north, south, and east combined with a land surface divide 1 to 3 miles east of Lake Audubon serve to create flow boundaries and a nearly closed basin drainage system in the study area. Parts of the study area that are not drained by Turtle Creek constitute true closed basin conditions. Except for groundwater discharge into Turtle Creek, which will remove water from the study area by flow to the south, groundwater discharge from the study area occurs only through evapotranspiration. Groundwater recharge to the glacial drift aquifers is from direct infiltration of precipitation and snowmelt, and leakage from and through overlying and underlying confining units. More detailed consideration of recharge and discharge is presented in subsequent sections of this report.

SURFACE WATER

The distribution of major surface water bodies within the study area is shown in Figure 9. The base map and hydrology shown on Figure 9 was developed from U.S. Bureau of Census TIGER/Line files which were generated by digitizing information from 1:100,000-scale maps of the USGS topographic map series (U.S. Department of Commerce, 1991). Areas with high densities of ephemeral or semi-permanent sloughs and wetlands as mapped on USGS 7.5-minute series topographic maps (1:24,0000-scale) are outlined on Figure 9 . These areas typically have 10 to 20 or more small wetland areas mapped per square mile. The high density wetland areas are typically found on hummocky areas with surficial glacial till and are areas of non-contributing surface drainage. Except for the portion of the study area drained by Turtle Creek, the study area is a closed basin with surface water flow in ephemeral streams toward the "topographic sag" in land surface overlying the buried valley occupied by the Lake Nettie aquifer system.

Based on topographic maps the headwaters of Turtle Creek are in the central part of the Horseshoe Valley, about 6 miles north of the Lake Nettie area. Turtle Creek exits the Horseshoe Valley in the south half of 148-81-09 and flows through the Lake Nettie National Wildlife Refuge in sections 16, 21, 28 and 34 of Twp. 148-81. Mud Lake is located on the mainstem of Turtle Creek. Turtle Creek flows south from Mud Lake, crosses under the McClusky Canal through a culvert and empties into Turtle Lake in the northeast quarter of 147-81-22. Water flows from Turtle Lake into Lake Ordway through canal "I", constructed by the USBR in the 1980's. When stage levels are sufficiently high water exits the study area via surface flow from Lake Ordway to the south down Turtle Creek.

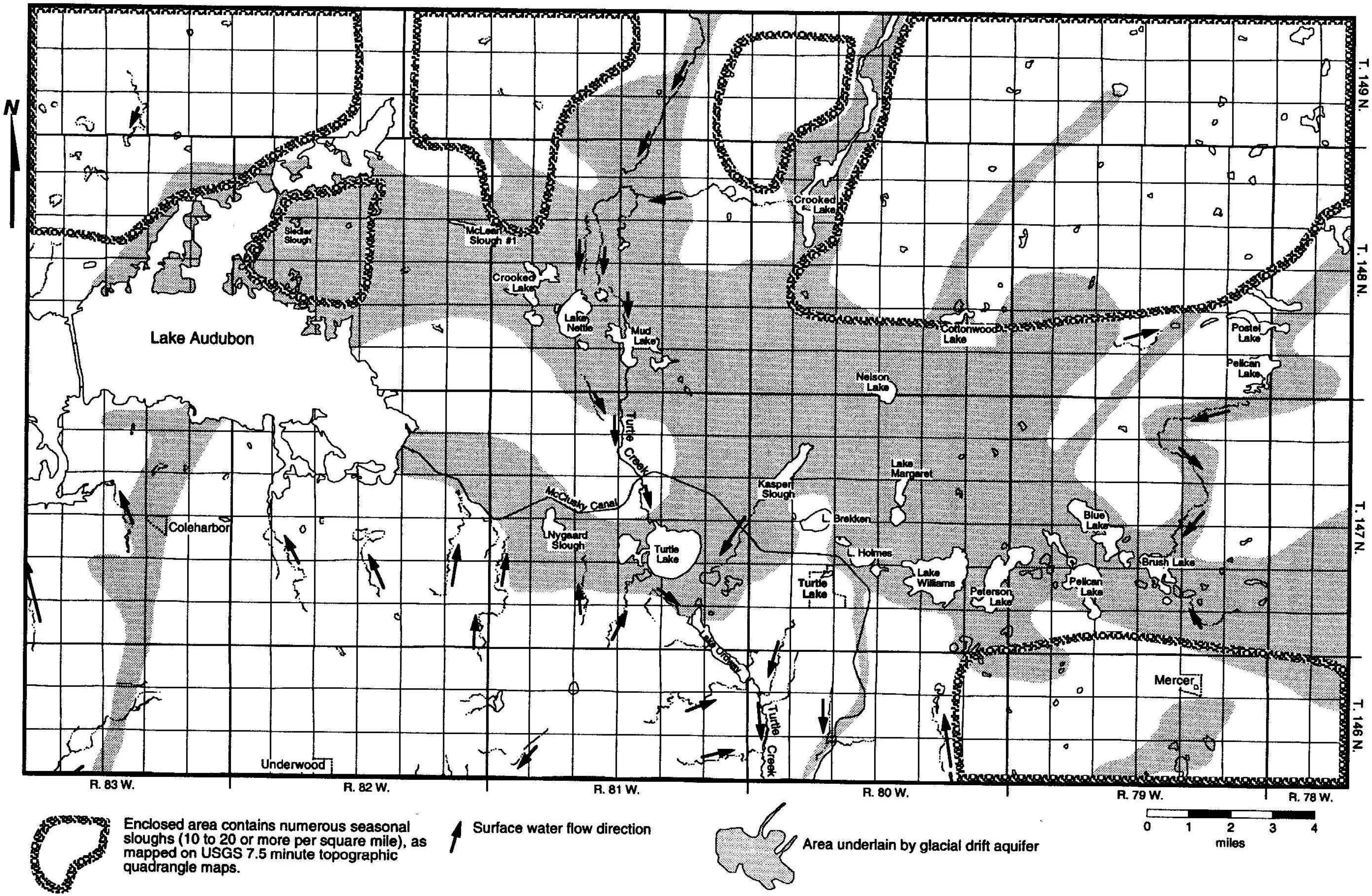


Figure 9. Distribution of surface water bodies and surface water flow direction in the study area.

There are two reservoirs in the study area: 1) Lake Sakakawea (Garrison Reservoir) formed by Garrison dam on the Missouri River, and 2) Lake Audubon (Snake Creek Reservoir) which is separated from Lake Sakakawea by the Snake Creek Embankment.

Construction of Garrison dam was completed in 1954 with diversion of the main Missouri River channel accomplished in April 1953. Lake Sakakawea is usually maintained between about 1835 and 1847 feet elevation above mean sea level (msl), but water surface levels have fluctuated with regional climatic cycles. During the last 30 years Lake Sakakawea elevation has been as high as 1854 feet in 1976 and has been below 1820 feet in 1991 and in early 1993.

The water surface elevation of Lake Audubon was maintained between about 1833 and 1836 feet from 1968 to 1975 by controlling the flow between Lake Sakakawea and Lake Audubon. The lake level was raised to about 1848 feet in 1975 by pumping from Lake Sakakawea into Lake Audubon. Lake Audubon forms the headwaters of the McClusky Canal. Construction of Reach 1 of the canal, which transects the southern portion of the study area, was begun in 1972 and was completed in 1975. The canal was filled to a controlled elevation between 1843 and 1844 feet in 1979.

Lake Audubon has been maintained at a normal operating elevation between 1847 and 1848 feet since 1975. Beginning in 1984 the water elevation of the lake has been lowered by two to three feet each fall and returned to normal operating level in the spring to help alleviate salinization problems. Lowering of Lake Audubon level in the Fall is accomplished by releasing water into Lake Sakakawea through a 7-foot x 10-foot gated conduit through the embankment near the Snake Creek Pumping Plant. In the Spring water is pumped from Lake Sakakawea into Lake Audubon to return the lake to normal operating level. A hydrograph showing the water level history of Lake Audubon, Lake Sakakawea and the McClusky Canal is shown in Figure 10.

Located within the study area are two lakes named "Crooked Lake". The larger of the lakes is about 5 miles long with its southern end located in 148-80-17, about 7.5 miles north of the city of Turtle Lake. The second and smaller Crooked Lake lies mostly within sections 19 and 20 of Twp. 148-81, about 8 miles northwest of the city of Turtle Lake. In this report the larger of the Crooked Lakes (with the southern end in 148-80-17) will be referred to as "Big Crooked Lake". While the smaller lake in 148-81-19 & 20 will be referred to as "Little Crooked Lake" or simply "Crooked Lake".

The lake named "Turtle Lake" lies in Sections 22, 23, 26 and 27 of Twp. 147-81, about 3 miles east of the city of Turtle Lake, which is located in 148-80-29. For this report the lake will be referred to as "Turtle Lake" and the city will be referred to as "the city of Turtle Lake".

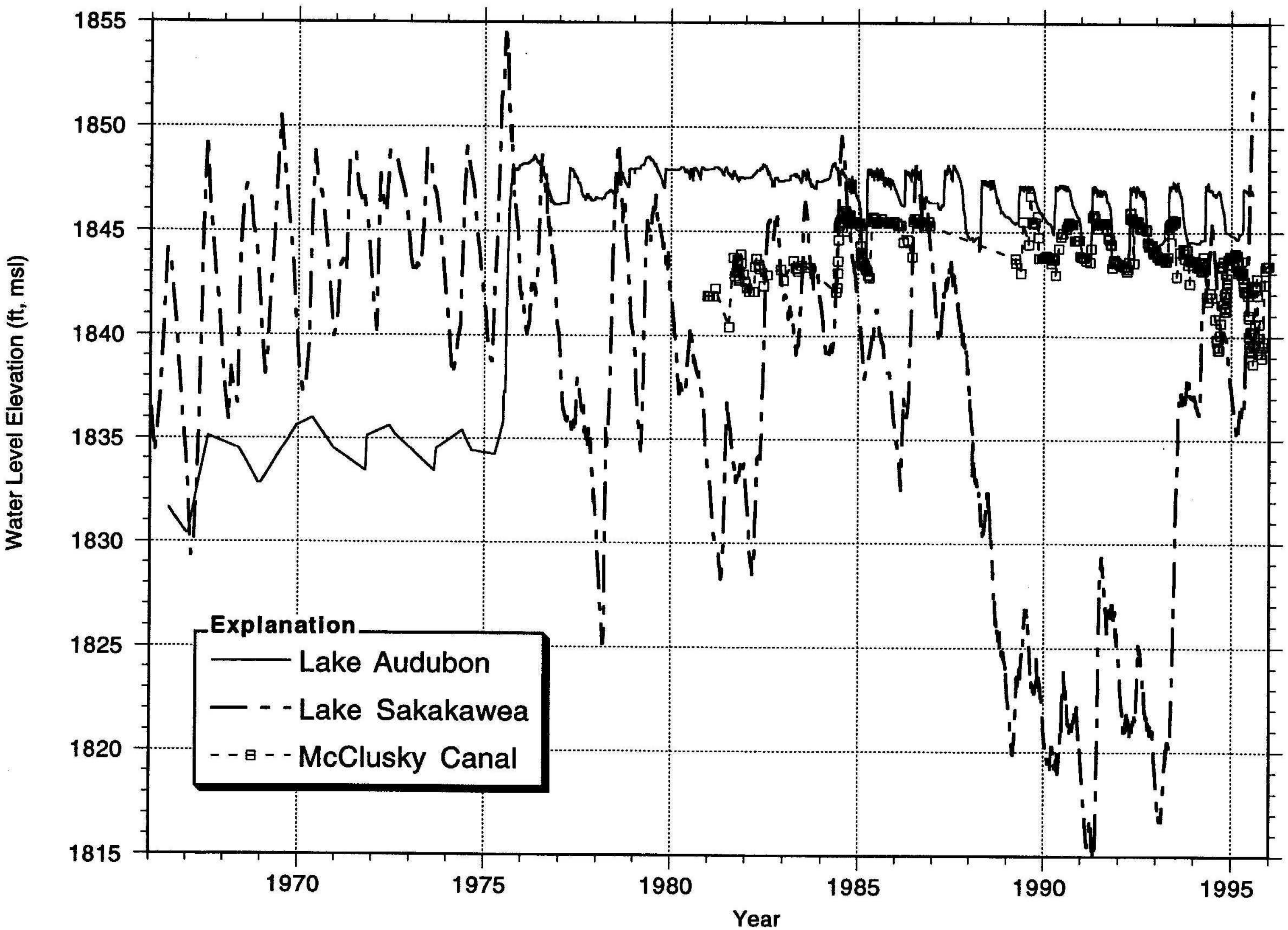


Figure 10. Water level history of Lake Audubon, Lake Sakakawea and the McClusky Canal.

GROUNDWATER FLOW SYSTEMS

The potential for and direction of groundwater flow, and possible interaction with surface water bodies can be determined from a potentiometric analysis of the lateral and vertical hydraulic head relations. The following section discussion focuses on the regional flow systems although it is recognized that smaller local flow systems may be superimposed on the regional flow system.

LAKE NETTIE AQUIFER SYSTEM - UPPER UNIT

PRE-RESERVOIR FLOW PATTERNS

No studies of the groundwater flow system were conducted in the study area prior to the construction of the Garrison Dam and the filling of Lake Sakakawea and Lake Audubon. However, general regional shallow groundwater flow patterns can be reasonably inferred from the elevations of surface water bodies in an area because of the hydraulic connection that typically exists between surficial aquifer systems and surface water bodies.

U.S. Geological Survey 15-minute topographic quadrangle maps are available for the area prior to the construction of the reservoir system. The following 15-minute quadrangle maps were inspected for surface water elevations:

ND Garrison Quadrangle	Edition of 1922
Coleharbor Quadrangle	Edition of 1929
Turtle Lake Quadrangle	Edition of 1947

Each of the maps use a 20 feet contour interval and include the water surface elevation of larger sloughs and lakes at the time of mapping. The area covered by the three quadrangle maps extends from the pre-reservoir Missouri River (about 7 mile southwest of the Snake Creek embankment) to the Blue Lake area (about 6 miles east of the city of Turtle Lake). These topographic quadrangles were inspected for reported elevations of surface water bodies. Elevations of major streams were also estimated at points where the stream crosses land surface elevation contours. A depiction of the estimated pre-reservoir regional groundwater elevation contours in the surficial aquifers (inferred from the pre-reservoir topographic maps) and inferred groundwater flow direction units is presented in Figure 11.

Prior to construction of the reservoirs, Snake Creek flowed from the northeast to southwest in the area now occupied by the northern arm of Lake Audubon. Snake Creek then turned to the west-southwest in the area now beneath the main body of Lake Audubon and continued to the southwest to its confluence with the Missouri River. Lake Audubon and the easternmost extension of Lake Sakakawea have filled the valley formerly drained by Snake Creek. The topographic low areas now occupied by the reservoirs formerly contained large areas of sloughs and ephemeral wetlands. Prior to the filling of the reservoirs groundwater flow in the upper aquifer unit, where present, in the western part of the study area was toward these

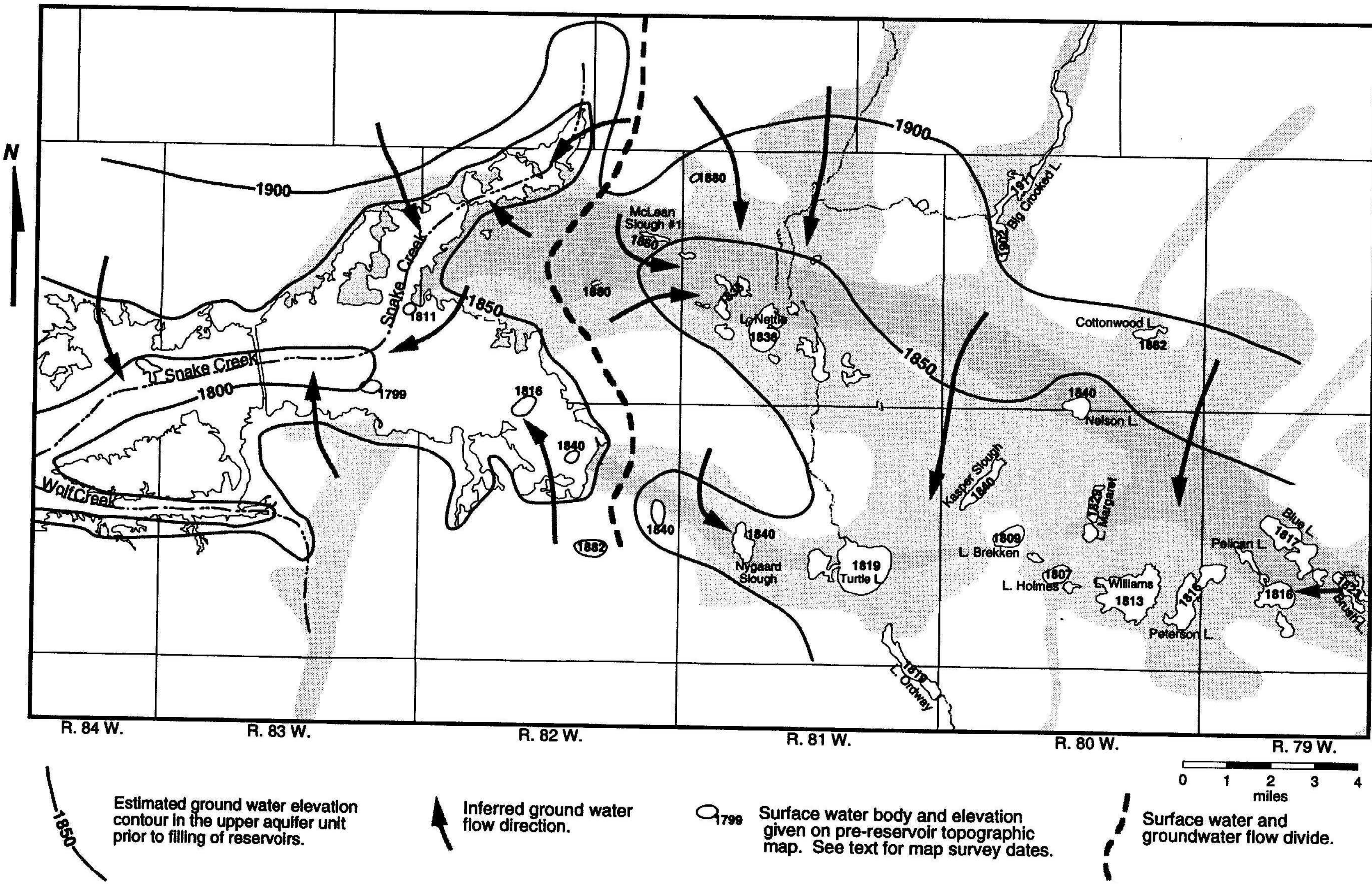


Figure 11. Estimated pre-reservoir water level contours of the upper unconfined aquifer/ water table.

topographically low areas with discharge into Snake Creek and the wetland areas occupying the topographic lows.

A north to south trending groundwater and surface water flow divide existed approximately 1 to 3 miles east of the eastern edge of Lake Audubon in the center of Twp. 148-82 and the east part of Twp. 147-81 (Fig. 11). The flow divide coincided with a land surface topographic upland area. The lowest land surface elevation of the topographic divide is approximately 1880 feet in sections 10, 11 and 15 of Twp. 148-82 overlying the Lake Nettie Aquifer and 1880 feet again in section 11 of T. 147N., R. 82 W. overlying the Turtle Lake aquifer. In other areas the divide exists in areas greater than 1900 feet in elevation.

West of the divide groundwater and surface water flow was focused toward Snake Creek (Fig. 11). East of the divide the pre-reservoir estimated water level contours indicate the following major groundwater flow patterns in the upper aquifer units:

- flow focused toward Lake Nettie and the Turtle Creek drainage area from the north, northeast, west and southwest in Twp. 148-81 and the eastern part of Twp. 148-82. This flow pattern suggests that groundwater discharged into the Lake Nettie and Turtle Creek drainage areas;
- flow from north to south in Twp. 147-80 with discharge to the chain of lakes east of the city of Turtle lake; and
- flow toward and groundwater discharge into Turtle Lake and Lake Ordway from the northwest in the Turtle Lake aquifer and from the northeast in the Lake Nettie aquifer north of Turtle Lake.

POST-RESERVOIR FLOW PATTERNS

Figure 12 presents the water elevation contours and flow directions for the upper units of the Lake Nettie aquifer system based on observation well and surface water stage data for April 1987. Measured groundwater level elevations indicate flow patterns in the upper aquifer similar to the general patterns inferred from the pre-reservoir topographic quadrangle maps. The groundwater flow divide in Twnps. 148-82 and 147-82 is still maintained. Groundwater flow in the western part of Twp. 148-82 is westerly toward Lake Audubon, which now covers much of the former Snake Creek drainage area. Whereas flow in the eastern part of Twp. 148-82 is easterly toward the Lake Nettie area. The position of the 1850 foot water elevation contour east of the flow divide is substantially equivalent to that inferred from the pre-reservoir topographic quadrangle maps (Fig. 11).

Three main subregions of groundwater flow can be identified east of the groundwater flow divide in Twnps. 148-82 and 147-82:

- the region associated with discharge to the Lake Nettie area,
- the region associated with discharge to the chain of lakes east of the city of Turtle Lake, and
- the region associated with groundwater discharge into Turtle Lake and Lake Ordway.

These groundwater flow subregions are discussed separately below.

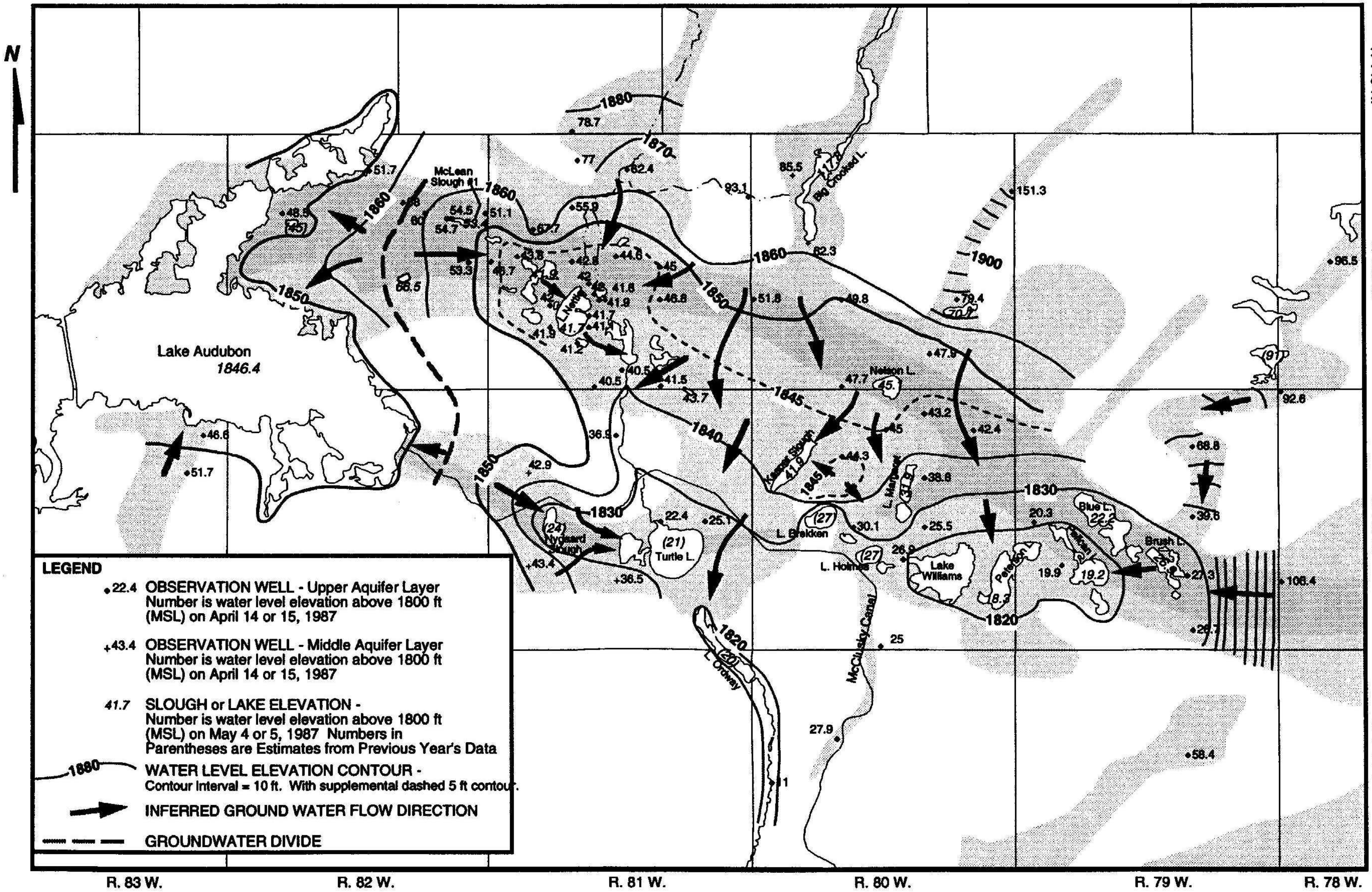


Figure 12. Potentiometric surface of the upper aquifer units in the Lake Nettie and Turtle Lake aquifers, April 1987.

LAKE NETTIE AREA

This subregion encompasses almost all of Twp. 148-81 and the eastern part of Twp. 148-82. Groundwater flow in this area converges on the Lake Nettie area (Little Crooked Lake, Lake Nettie and Mud Lake) from the west, northeast, southwest and from the Horseshoe Valley aquifer which is tributary to the Lake Nettie aquifer approximately 2 miles northeast of Lake Nettie. The flow system in this subregion of the upper aquifer unit is shown Figure 13. The relation between groundwater and surface water elevations indicates that the lakes and wetlands in the Lake Nettie area form a continuum with the surficial unconfined sand and gravel bodies which form the upper unit of the Lake Nettie aquifer. Groundwater discharges to the lakes, wetlands and intermittent streams in this relative topographic low. Their relative surface water elevations in November 1987 suggest that Lake Nettie and Mud Lake are the terminal groundwater discharge areas for this aquifer subregion. However, in November 1987, the water surface in Lake Nettie was actually depressed about 0.5 feet relative to its characteristic relation with surrounding groundwater elevations due to lingering effects of the June through September 1987 Lake Nettie pumpdown project.

Contouring of water level data for other dates, including both high and low water level conditions, produces contour patterns in the Lake Nettie area that are fundamentally the same as those shown for November 1987 in Figure 13. The only perceptible difference being that Lake Nettie elevation is characteristically a few tenths of a foot higher than groundwater in the upper aquifer on the lake's southeast side. This indicates that Lake Nettie is a groundwater flow through type lake with groundwater discharging into its west, north and south sides. Lake water in turn seeps into the groundwater system on the southeast side of the lake with flow toward Mud Lake.

Mud Lake was 0.5 to 2 feet lower in elevation than Lake Nettie when measured in 1987 and 1988, during times when area water levels were not affected by the Lake Nettie pumpdown. This relation, coupled with the surficial aquifer potentiometric surface, indicates that Mud Lake is the terminal groundwater discharge area for this subregion. A portion of the groundwater discharge leaves the system through the intermittent Turtle Creek outlet from Mud Lake while the remainder is lost to the atmosphere via evapotranspiration. Mud Lake also receives surface water from the northern reach of Turtle Creek during periods of high runoff.

The groundwater chemistry in the upper aquifer between Lake Nettie and Crooked Lake and southeast of Lake Nettie is consistent with the groundwater flow through nature of these lakes. Groundwater sampled at wells 148-81-29CAA (screen depth 34-48 feet) and 148-81-29BAA2 (screen depth 54-59 feet) located 500 to 1000 feet west of Lake Nettie (upgradient side) has total dissolved solids concentrations (TDS) of between 2,000 and 3,000 mg/L, compared to the 500 to 800 mg/L that typifies water quality in the upper aquifer in the area.

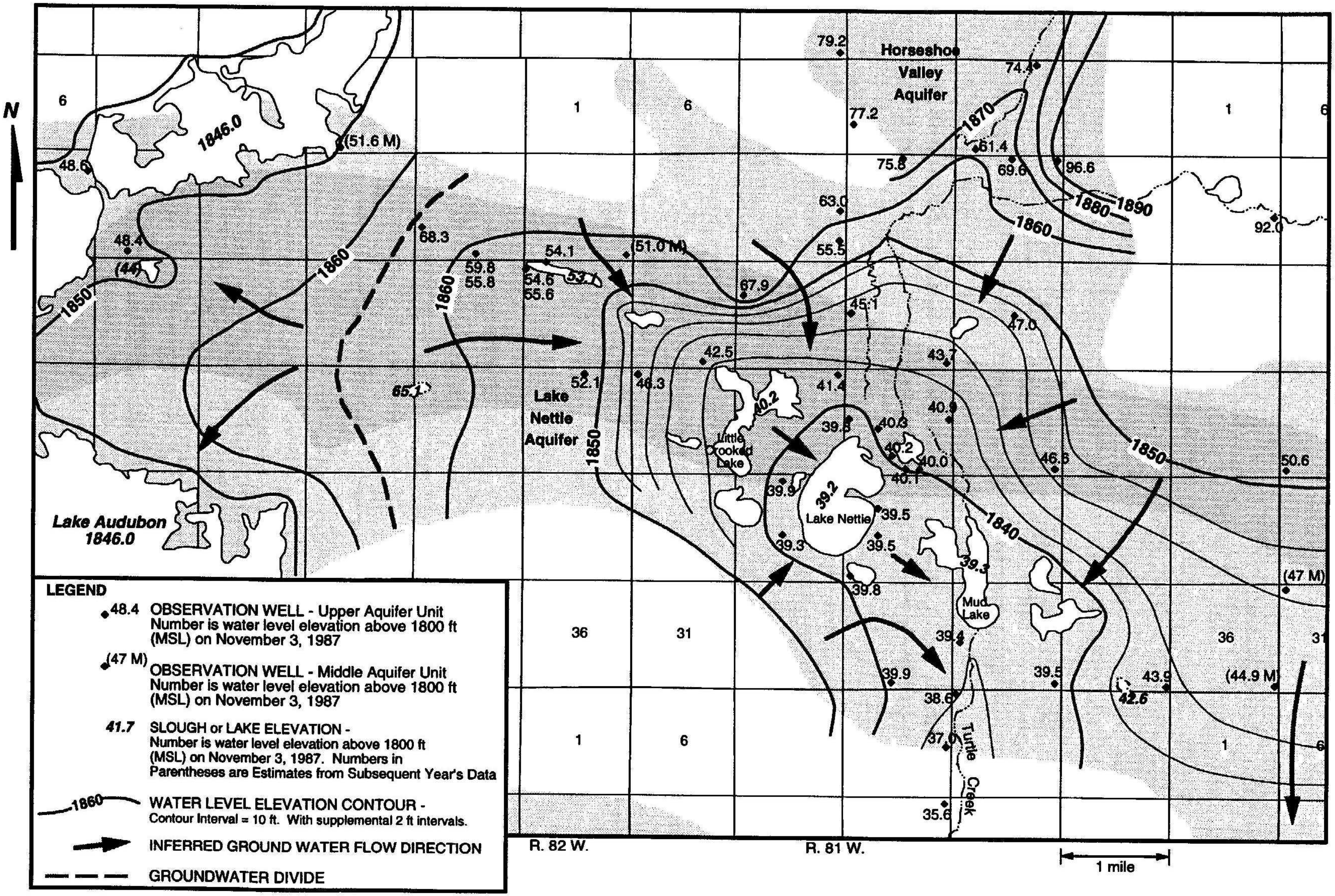


Figure 13. Potentiometric surface of the upper Lake Nettie aquifer unit near Lake Nettie, November 1987.

The groundwater from these wells also has elevated chloride and sodium concentrations relative to other major cations indicating an evaporative signature. Groundwater sampled from well 148-28CAB (screen depth 32-37 feet) about 500 feet southeast of Lake Nettie (downgradient side) also has sodium and chloride that indicate evaporative effects and TDS concentrations of 2,400 to 2,600 mg/L. It is clear that a portion of the groundwater in the upper aquifer in the area was once lake water that has seeped out of the downgradient side of the lakes. TDS concentrations in Crooked Lake and Lake Nettie, which are elevated due to evaporation, ranged from 1,500 to 2,000 mg/L in 1986 and 1987 to 3,200 mg/L in Lake Nettie and 6,500 mg/L in Crooked Lake in 1992. Because groundwater with an evaporative lake signature is found at depths of greater than 50 feet, it is clear that the flow through nature of the lakes has been a consistent phenomenon for a long period of time, possibly encompassing most of the time period since deglaciation of the area.

The groundwater drainage area for the Lake Nettie area encompasses the tributary Horseshoe Valley aquifer to the north, extends west to the groundwater divide 3.5 miles west of Little Crooked Lake, south to the topographic high area beginning about 1 mile southwest of Lake Nettie and east to approximately the eastern border of Twp. 148-81 (where a smaller groundwater flow divide separates southwesterly flow toward Mud Lake and southerly flow toward Turtle Lake). Thus, the land surface area underlain by the upper aquifer unit that may ultimately contribute groundwater discharge to Lake Nettie and Mud Lake encompasses greater than 30 square miles.

CHAIN OF LAKES AREA

This subregion encompasses all of Twp. 147-79 the east half of Twp. 147-80, and approximately the southeast quadrant of Twp. 148-80 (Fig. 12). Groundwater flows toward the chain of lakes predominantly from the north and east. Higher land surface elevation to the north drives flow southward to the chain of lakes from Twnps. 148-79 and 148-80. A topographic high area (mapped as a glacial ice-thrust mass by Clayton et al., 1980) dissects the southern portion of the aquifer in the southern part of the northwest quadrant of Twp. 147-80, causing a divergence of groundwater flow around it. A portion of the flow is directed to the southwest toward Kasper Slough and a portion is diverted to the southeast toward Lake Williams.

The Prophets Mountains on the east side of the chain of lakes create a steep gradient that generates westerly flow toward Brush Lake. There is also a surficial glacial meltwater channel extending from north Pelican Lake to Brush Lake in the northeast quadrant of Twp. 147-79. Groundwater flow in the meltwater channel is along the axis of the channel toward Brush Lake (Fig. 12).

It is likely that a small amount of south to north groundwater flow also occurs on the south side of the chain of lakes. Observation well data points are sparse south of the chain of lakes, but a rise in land surface elevation and the presence of low permeability sediments (mostly till) prohibit flow to the south from the south side of the chain of lakes.

The chain of lakes constitute a closed basin near the southern limit of the Lake Nettie aquifer. The chain of lakes consists of (from east to west) Brush Lake, Blue Lake, south Pelican Lake, Peterson Lake, Lake Williams, Lake Holmes and Lake Brekken. There are no significant surface water inlets or outlets from the chain of lakes. Thus, the main sources of water to the lakes are direct precipitation, contributing runoff and groundwater discharge. The highly saline nature of some of the lakes (TDS as high as 84,000 mg/L) indicate that they function as hydrologic evaporative "discharge pans". Prior to the construction of the Brekken-Holmes Recreation area the chain of lakes decreased in elevation and increased in salinity from east to west. Topographic quadrangle map elevations ranged from 1823 feet for Brush Lake on the east to 1805 feet for Lake Holmes, which formerly constituted the lowest hydrologic point for the eastern part of the study area. Since the construction of the Brekken-Holmes Recreation area, the two former lakes have been maintained as one lake at approximately elevation 1827 to 1828 feet by supplying water from the McClusky Canal. Since the filling of Brekken-Holmes, Lake Williams is the lowest point of the closed basin system, and constitutes the terminal discharge area for the eastern part of the study area.

TURTLE LAKE - LAKE ORDWAY AREA

Groundwater flow in the Turtle Lake aquifer east of the major groundwater divide in the northeast quadrant of Twp. 147-82 is from the north and south toward the axis of the Turtle Lake aquifer and then southeasterly along the axis of the aquifer. Nygaard Slough, and Hanson Slough are groundwater flow through areas with groundwater discharge into the west side of Turtle Lake (Fig. 12). Groundwater flow is also focused from the northeast into the northeast side of Turtle Lake in the segment of the Lake Nettie aquifer in the east part of Twp. 147-81.

The northern edge of Lake Ordway is located about 1/2 mile southeast of the south edge of Turtle Lake. The USBR constructed canal "I" in the 1980's to provide a surface outlet from Turtle Lake to Lake Ordway. When stage levels are sufficiently high water exits the study area via surface flow from Turtle Lake to Lake Ordway and down Turtle Creek.

Prior to the construction of canal "I" there was no surface water stream connecting the two lakes. However, a portion of the water in Turtle Lake exited the southeast side of the lake into the surficial sand and gravel groundwater system and eventually discharged into the north side of Lake Ordway. The water surface elevation in Turtle Lake is about 1.5 feet higher in elevation than that of Lake Ordway (water surface elevations recorded by staff gages in 1985 were 1820.0 to 1820.6 feet for Turtle Lake and 1818.2 to 1819.0 for Lake Ordway).

Drainage south through Turtle Creek constitutes the only natural non-evaporative removal of water in the otherwise closed hydrologic basin of the study area. Except for the small percentage of the study area's water budget that exits through Turtle Creek, all other water loss is by evaporation from surface water bodies, evaporation from the shallow soil zone and transpiration by plants.

INFLUENCE OF THE McCLUSKY CANAL

The McClusky Canal has not affected the flow system in the upper aquifer on a regional scale. The canal could, however, act as a local line sink or line source in the upper aquifer unit. However, the canal does not appear to have perturbed the potentiometric contours in the upper aquifer unit. If the canal bottom fully penetrated the upper aquifer unit, then natural groundwater flow would have been impeded creating a rise in water levels and a bunching of groundwater level contours near the canal in Twp. 147-81. There is no evidence on a regional scale of a bunching of contours (Fig. 12). USBR canal construction drawings indicate that the bottom of the canal intersects but does not fully penetrate the sand and gravel layer of the upper aquifer unit northeast of Turtle Lake in Twp. 147-81.

The presence of the McClusky Canal has produced localized effects on surface water levels and groundwater levels in certain areas adjacent to the canal. Armstrong (1983) determined that the canal caused water level rises as much as 6 feet in areas adjacent to the canal but that water level rises were less than 1 foot at distances greater than 0.5 miles from the canal. Armstrong (1983) also noted that the higher water levels generally resulted in more water in sloughs near the canal.

The USBR has recognized localized problems in the area overlying the Turtle Lake aquifer west of Turtle Lake. Remedial action was taken by constructing pipe drains and minor canals to improve surface drainage in the Nygaard Slough - Turtle Lake area in the west part of Twp. 147-81 and east part of Twp. 147-82. Because of the potential line sink or line source nature of a canal, any potential affect of the canal on groundwater or surface water levels in other areas would be limited to local areas immediately adjacent to the canal. Delineation of such localized effects, if any, would require a monitoring well system beyond the scope of this study.

LAKE NETTIE AQUIFER SYSTEM - MIDDLE UNIT

POST-RESERVOIR FLOW PATTERNS

Figure 14 presents the water elevation contours and flow directions for the middle (confined) unit of the Lake Nettie aquifer system based on observation well data for April 1987. The observation well data indicate groundwater flow in the east half of the study area converging on the chain of lakes area east of the city of Turtle Lake in a pattern similar to that of the upper unconfined aquifer. The data also indicate north to south flow in the Strawberry Lake aquifer with this aquifer acting as a tributary aquifer to the Lake Nettie aquifer.

A groundwater flow divide exists in the middle unit of the Lake Nettie aquifer in Twp. 148-82, similar to that of the upper aquifer unit. The divide separates flow toward Lake Audubon in the west part of Twp. 148-82 from possible flow away from Audubon in the east part of Twp. 148-82.

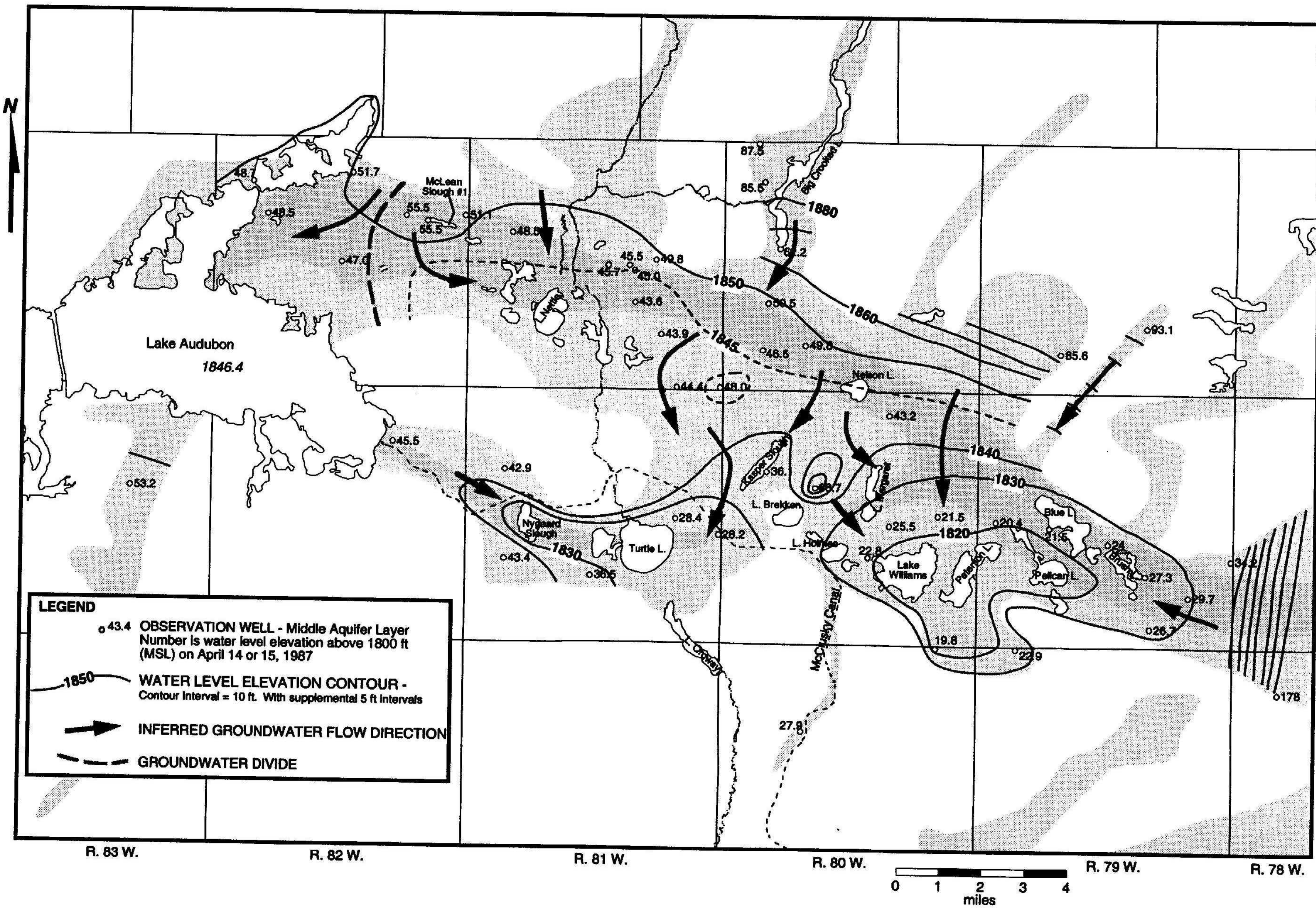


Figure 14. Potentiometric surface of the middle aquifer unit in the Lake Nettie and Turtle Lake aquifers, April 1987.

East of the groundwater divide, flow in the Lake Nettie aquifer in the western part of the study area is predominantly north to south, but the gradient in the middle aquifer unit is not as steep as in the upper unit. Although the water level contours in the southeast quadrant of 148-81 seem to suggest a component of flow from the northeast toward Lake Nettie and Mud Lake, it is unlikely that the middle aquifer unit results in upward leakage and discharge from the northeast into the Mud Lake area. Water levels at well nest 148-81-22DDD1,2,3 (approximately 3/4 mile northeast of Mud Lake) indicates downward movement of water from the upper to the middle aquifer unit. Water level elevations in the upper unit at this site (well 148-81-22DDD3) are 2.5 to 3 feet higher than those of the middle aquifer unit (well 148-81-22DDD2) (see hydrograph 17, plate 2). Groundwater flow in this area more likely continues to the south between Lake Nettie and Turtle Lake in the area east of Turtle Creek, ultimately discharging upward in the Turtle Lake/Lake Ordway area. Some amount of water movement may also occur through hydraulically connected relatively permeable layers of the Fort Union Group sediments.

The groundwater divide mapped in the upper portion of the Turtle Lake aquifer in the northeast quadrant of Twp. 147-82 does not appear to exist in the deeper confined unit of the Turtle Lake aquifer, which corresponds in elevation to the bottom part of the Lake Nettie aquifer middle unit or the top part of the Lake Nettie aquifer lower unit. Water elevations in wells 147-82-11BDB (Turtle Lake aquifer) and 147-82-02DCC (Fort Union aquifer) which are located about 1/4 mile east of Lake Audubon are consistently lower than the water elevation of Lake Audubon as shown in Figure 15. The hypothesized flow divide that probably existed in the confined aquifer unit in this area may have been moved west beneath Lake Audubon when it was raised to elevation 1847-1848 feet in 1975. Flow in the deeper confined units of the Turtle Lake aquifer is southeasterly along the axis of the aquifer toward Turtle Lake.

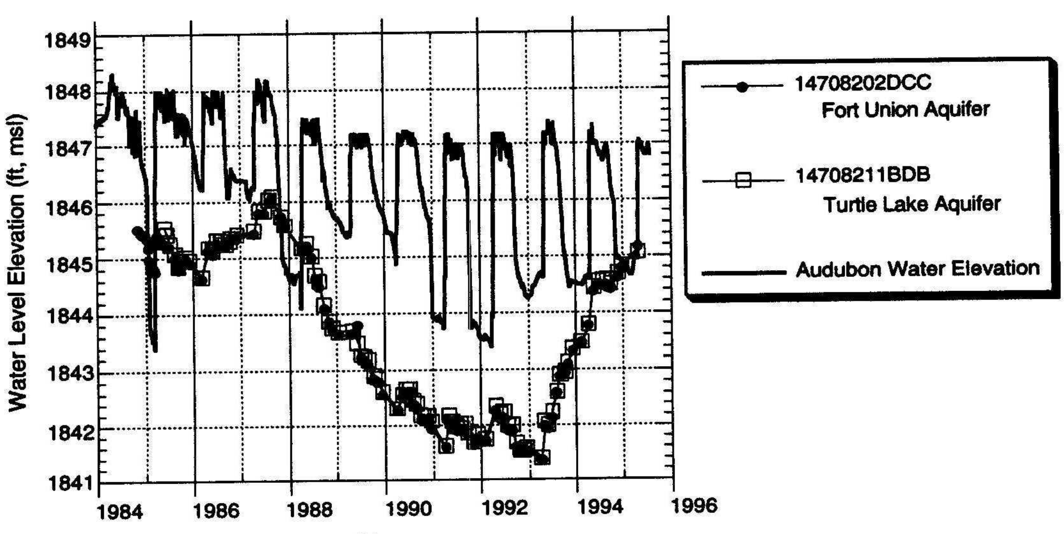


Figure 15. Hydrograph Showing Water Level Elevations in Lake Audubon and in Observation Wells 147-82-02DCC and 147-82-11BDB.

LAKE NETTIE AQUIFER SYSTEM - LOWER UNIT

POST-RESERVOIR FLOW PATTERNS

Figure 16 presents the water elevation contours (potentiometric surface) and flow directions for the lower confined unit of the Lake Nettie aquifer system based on observation well data for April 1987. Groundwater flow in the lower aquifer unit is generally to the south from the northern edge of the aquifer and then southeasterly toward the chain of lakes area east of the city of Turtle Lake. The north to south flow is driven by the higher land surface topography north of the aquifer. Flow also converges from the east and south on the chain of lakes in Twps. 147-79 and 147-80, driven by the higher elevations of the Prophets Mountains to the east and the general rise in topography to the south.

Southeasterly flow toward Turtle Lake occurs in the deeper confined units of the Turtle Lake aquifer. The flow toward Turtle Lake from the northeast that could be inferred from the water level contours is hypothetical as the contours shown on Figure 16 extend beyond the limits of the lower unit of the Lake Nettie aquifer and are shown for continuity.

Determination of groundwater flow patterns in the lower aquifer unit in Twp. 148-82 and the southern two thirds of Twp. 148-81 is difficult because of the extremely flat potentiometric surface in the area. The groundwater flow divide recognized near the center of Twp. 148-82, which separates westerly flow toward Lake Audubon and easterly flow toward Lake Nettie in the upper and middle aquifer units, is not defined by the water level data measured in the lower aquifer unit observation wells. Although hydraulic head in the lower unit of the aquifer in Twp. 148-82 in April 1987 was higher than the surface water elevation of Lake Audubon, net westerly flow in the lower unit toward Lake Audubon is not likely. Since the operating elevation of Lake Audubon was raised to 1847 feet in 1975, water level elevations in the lower aquifer unit in Twp. 148-82 have characteristically been lower than the elevation of Lake Audubon as shown on the hydrograph in Figure 17. April 1987 represents the end of wet period through the early and mid-1980's when groundwater recharge was probably large and resulted in unusually high groundwater levels.

Prior to 1975 when Lake Audubon was operated at an elevation of 1835 feet, a groundwater divide may have existed near the center of Twp. 148-82 with westerly flow toward and potential upward leakage into Lake Audubon in the west half of Twp. 148-82, as suggested in Figure 18, which illustrates the potentiometric surface of the lower and middle units of the Lake Nettie aquifer in September 1970. However, the spacing of observation well data points is such that precise delineation of the hypothesized flow divide and flow patterns in Twp. 148-82 prior to 1975 is not possible.

Generally similar patterns of groundwater flow in the lower aquifer are indicated by the 1970 data (prior to the 13 foot increase in Lake Audubon elevation) and the 1987 data (figs. 16 and 18). It is also apparent from the September 1970 data that the potentiometric surface in Twps.

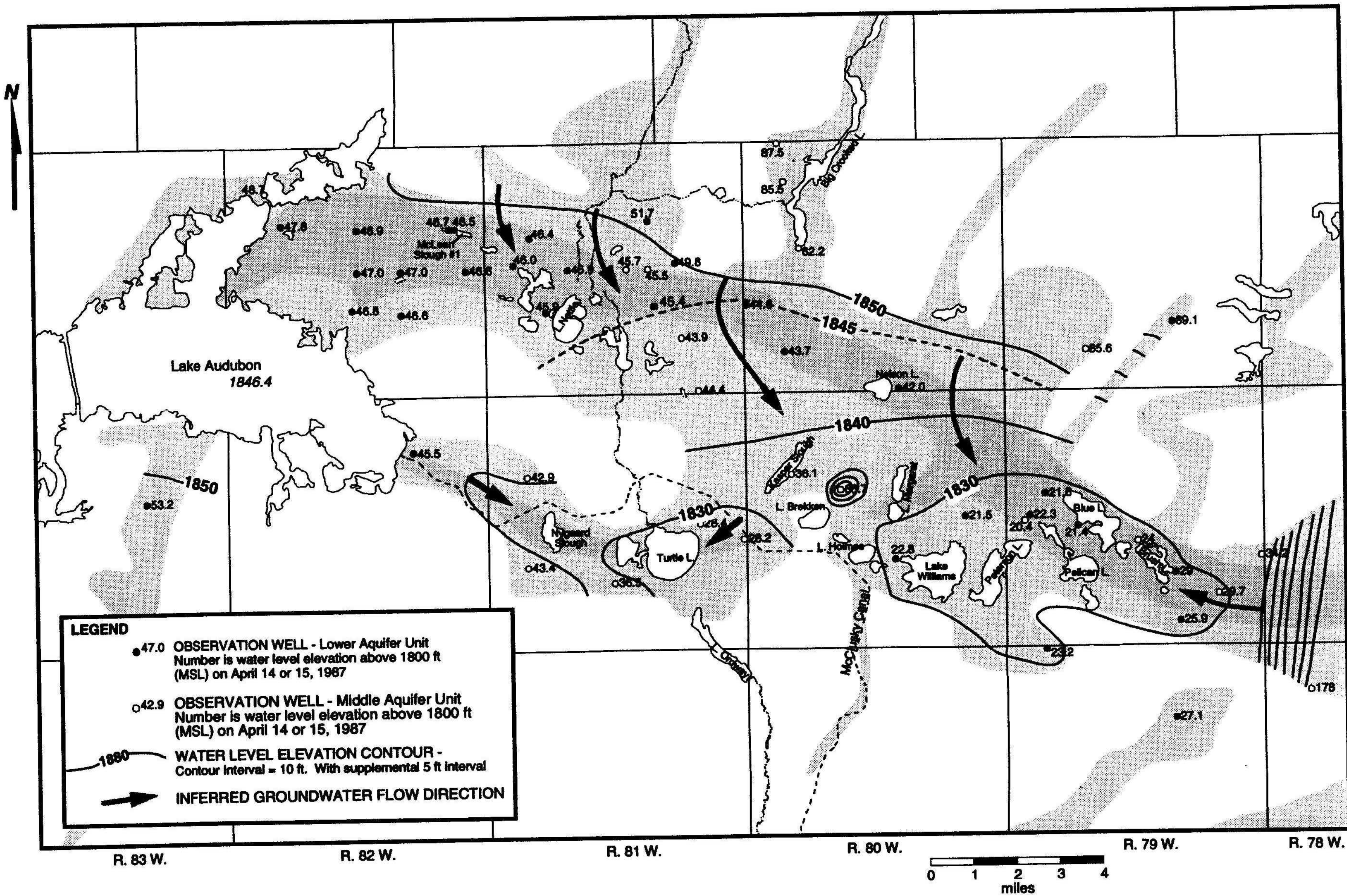


Figure 16. Potentiometric surface of the lower aquifer unit in the Lake Nettie and Turtle Lake aquifers, April 1987.

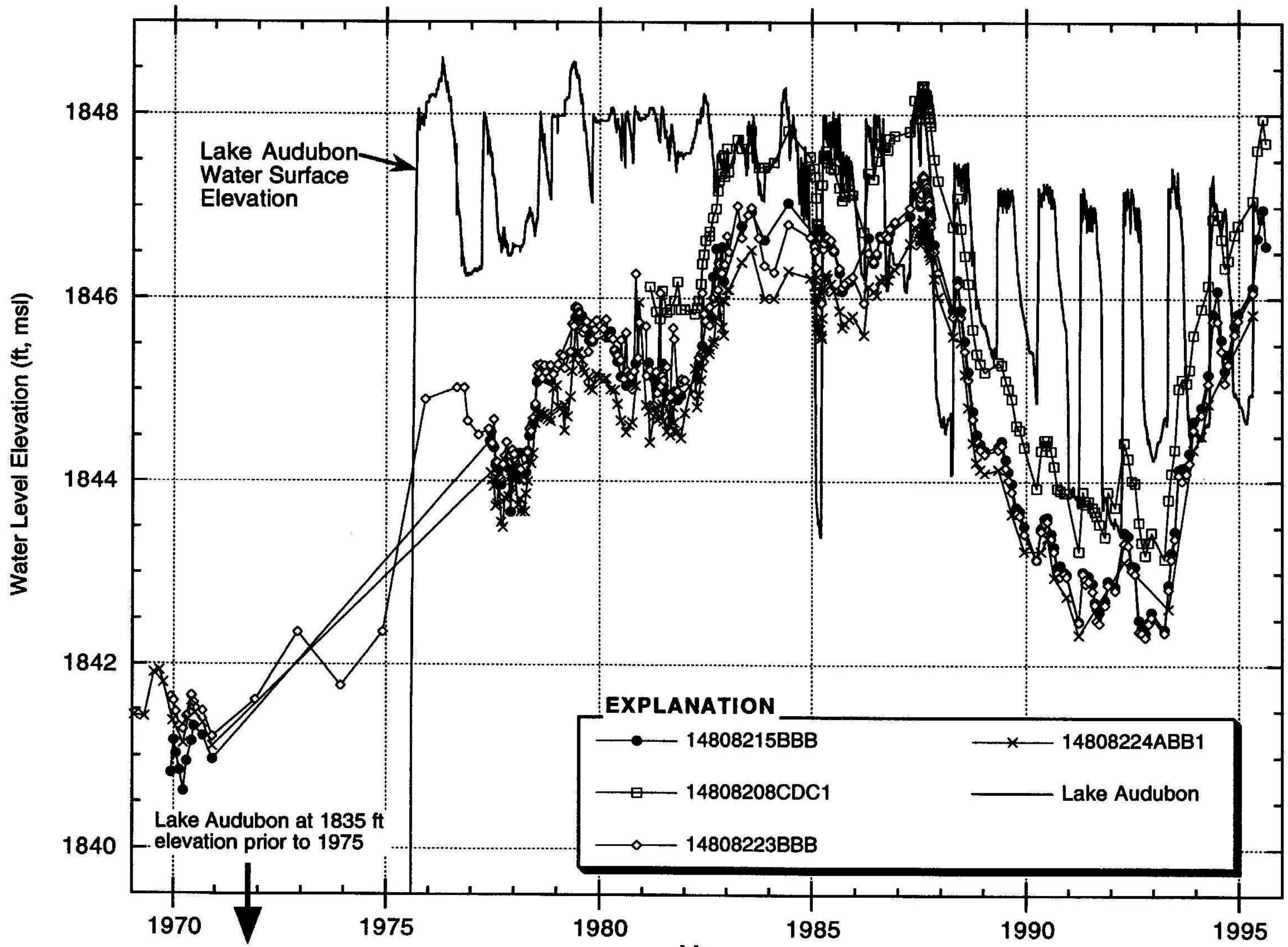


Figure 17. Water level fluctuations in Lake Audubon and in wells screened in the lower Lake Nettie Aquifer unit in Township 148-82.

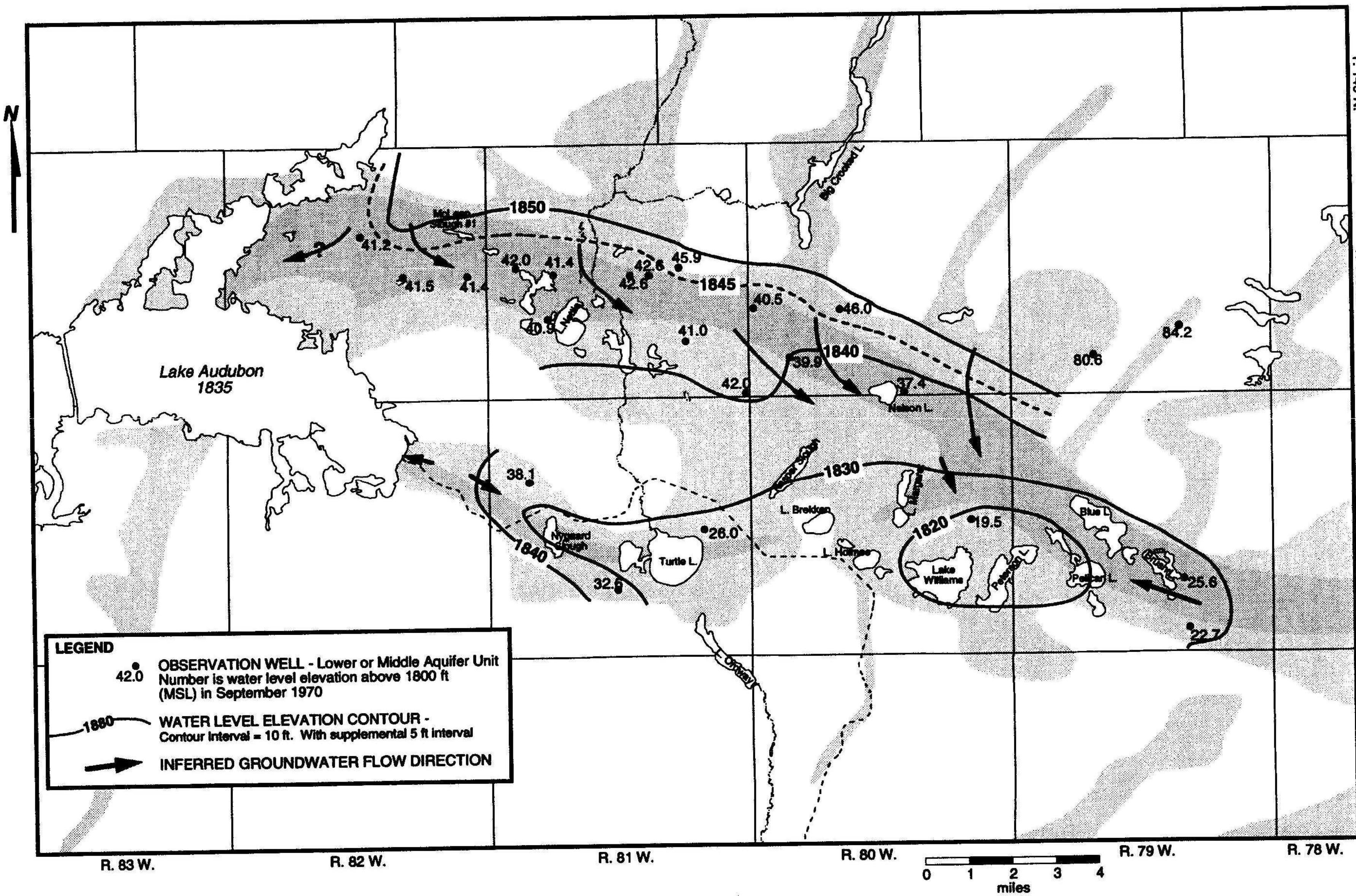


Figure 18. Potentiometric surface of the lower and middle aquifer units in the Lake Nettie and Turtle Lake aquifers, September 1970.

148-82 and 148-81 was also quite flat when Lake Audubon was at 1835 feet, below the elevation of the lower aquifer water levels. The water level data also suggest a stronger north to south component of flow than a west to east component. The main difference in the pre-1975 versus post-1975 potentiometric surface is the elevation relation relative to Audubon. Actual flow patterns suggested by the data do not differ for the pre-1975 and post 1975 data.

Comparison of the contoured groundwater elevations for April 1987 and September 1970 (figs. 16 and 18) suggests that the 1830, 1840 and 1845 foot contours were moved 1 to 2 miles south after Lake Audubon was raised from 1835 feet (1970 data) to 1847 feet (1987 data). However, the apparent movement of the potentiometric surface contours is largely an artifact of climatic fluctuations. The potentiometric surface for the lower aquifer unit in April 1991 is presented in Figure 19. Water levels in April 1991, after a period of drought, were generally 3 to 4.5 feet lower than they had been in 1987. Comparison of Figures 18 and 19 indicates that water level contour locations in April 1991 were fundamentally similar to those of September 1970.

Patterns in groundwater elevation data indicate that the Fort Union Group bedrock aquifer that forms the north and south lateral boundaries of the lower aquifer unit is in good hydraulic connection with the lower and middle aquifer units. However, it is anticipated that lateral flow in the lower unit would generally tend to be along the axis of the buried bedrock valley due to the much higher transmissivities of the sand and gravel bodies of the aquifer relative to that of the sedimentary bedrock units. To evaluate potential flow along the axis of the buried valley the April 1991 water level elevations of wells completed in the lower unit are contoured with a 1 foot contour interval in Figure 20. The groundwater elevation data included on Figure 20 are the same as those presented in Figure 19. However, water elevation contours in Figure 20 are restricted to the approximate area of the buried valley where the estimated buried bedrock surface is below 1700 feet in elevation.

The water level elevation contouring in Figure 20 illustrates the flatness of the potentiometric surface and lack of distinct flow patterns in the lower unit of the aquifer in Twp. 148-82, the aquifer area closest to Lake Audubon. Also illustrated is a distinct increase in the steepness of the potentiometric surface along the axis of the buried valley in Twnps. 147-80 and 147-79. The bunching of the contours is attributed to the blockage of southerly flow in the area south of the chain of lakes, which forces water movement upward through intervening less permeable sediments to terminal discharge into the chain of lakes. The aquifer is bounded in the area south of the chain of lakes by thick masses of till and rising land surface topography. It is also possible that narrowing and thinning of the lower aquifer unit contributes to the steepened gradient.

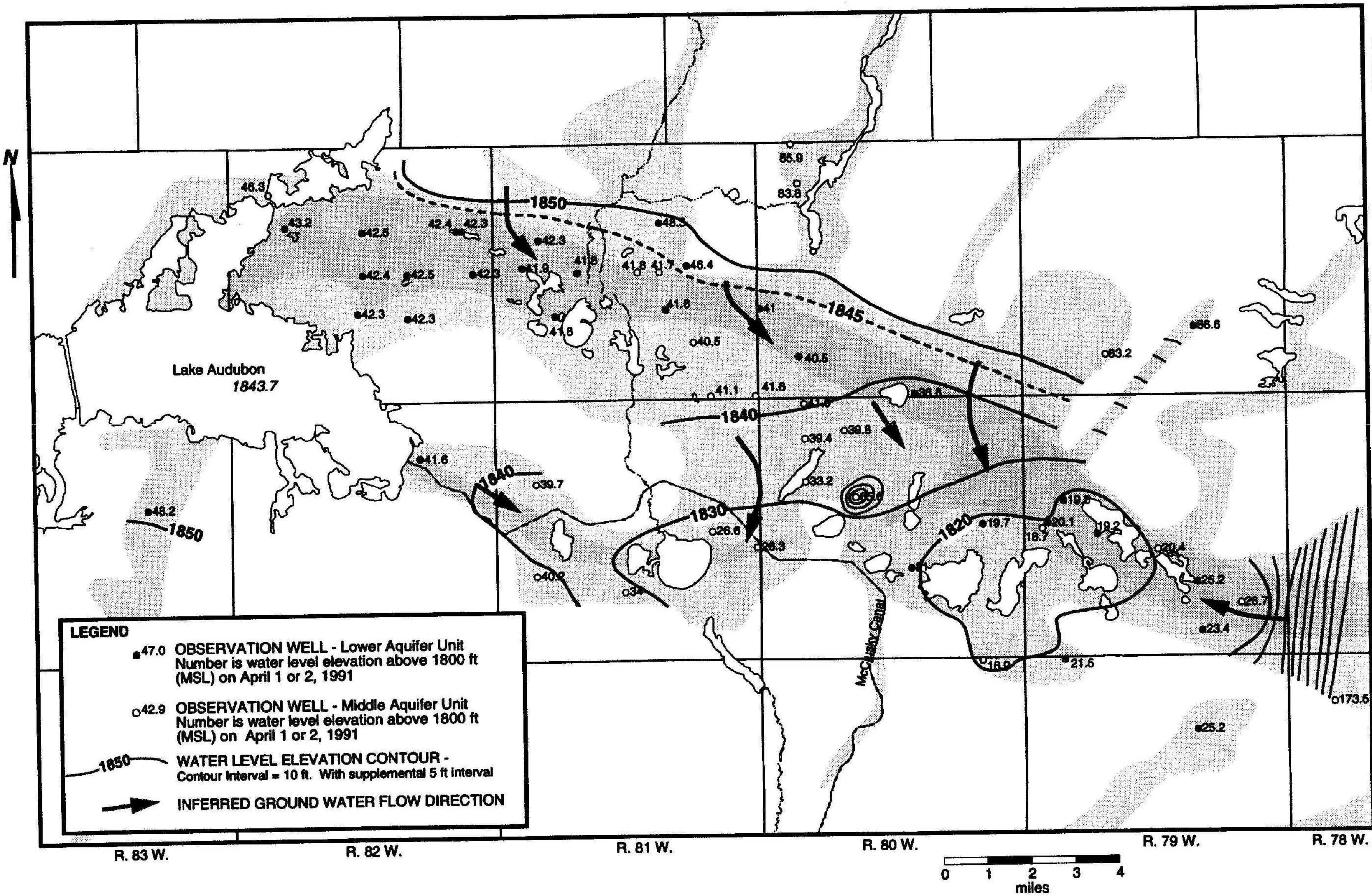


Figure 19. Potentiometric surface of the lower aquifer unit in the Lake Nettie and Turtle Lake aquifers, April 1991.

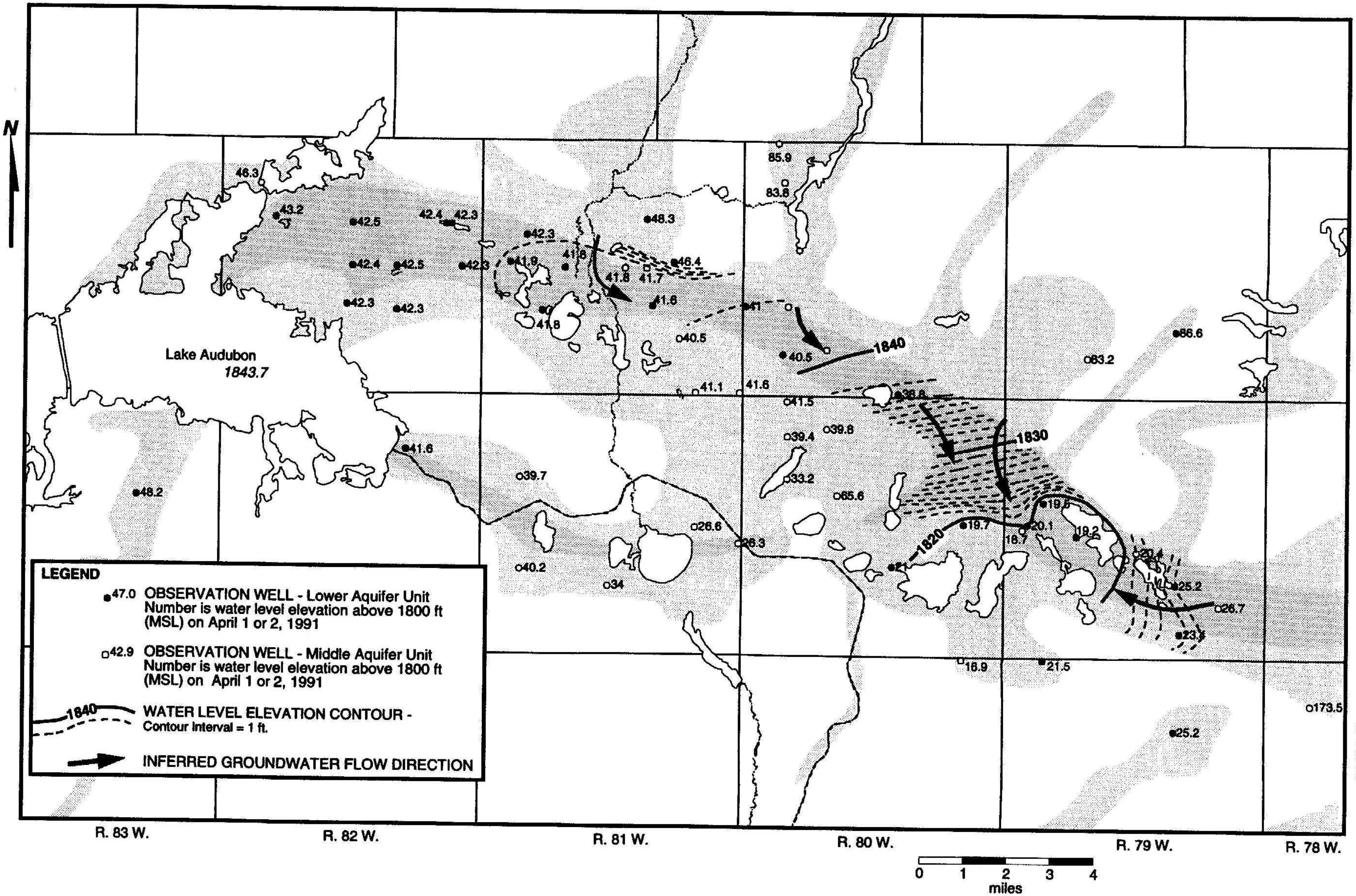


Figure 20. **Potentiometric surface of the lower aquifer unit in the Lake Nettie aquifer, April 1991. Water level contouring is constrained to main channel of pre-glacial bedrock valley.**

HYPOTHESIZED PRE-RESERVOIR FLOW PATTERNS

Detailed information regarding the flow systems in the lower and middle units of the Lake Nettie aquifer system prior to the construction of Garrison Reservoir and Lake Audubon is non-existent. However, reasonable conjecture can be made based on the nature of the present flow system, pre-reservoir topographic maps and piezometer information collected by the USCOE during construction of the Snake Creek Embankment, which separates Lake Audubon from Lake Sakakawea. The piezometers were located near the axis of the pre-reservoir Snake Creek valley.

Hydraulic head information was collected by the USCOE in 1950 from two piezometers installed in Snake Creek Embankment borings bearing USCOE numbers 138 and 182. Information from the USCOE regarding these two piezometers is given below:

USCOE Boring	Location	Land Elevation	Piezometer Depth	**Water Elevation**	Date Measured
No. 182	148-83-28cdb	1790.9	75 ft	**1794-1796**	Oct & Nov 1950
No. 138	148-83-33bdd	1802.2	115 ft	**1796-1798**	Sept & Nov 1950

The USCOE data indicate that the hydraulic head near the present day west edge of Lake Audubon was approximately 1800 feet in elevation prior to the construction of the reservoirs, similar to that mapped in Figure 11 for the upper unit. Current hydraulic head in this area would be within a few feet of the overlying Lake Audubon elevation and would also fluctuate with Lake Sakakawea elevation. Prior to the reservoirs, flow in the middle and lower aquifer units in Twp. 148-82 was likely similar to that depicted in the upper unit. A groundwater flow divide likely existed near the center of Twp. 148-82 (as exists currently in the upper unit, see for example Fig. 12). Groundwater movement was from the north to south toward the axis of the aquifer then split westward and eastward by the divide. Westward flow may have ultimately discharged into the now inundated Snake Creek valley. However, thick sequences of low permeability till that overly the lower aquifer unit in the area near Lake Audubon suggest that the amount of groundwater discharge by upward leakage from the lower units was likely minimal. Eastward flow probably continued to the east-southeast along the axis of the aquifer.

It is not clear whether the hydraulic gradient in the lower aquifer unit was better defined in Twnps. 148-82 and 148-81 prior to the construction of the Snake Creek Embankment than it is currently. Estimates of water elevations from pre-reservoir topographic maps and current vertical gradients observed in other parts of the aquifer, suggest that the hydraulic head in the lower aquifer in sections 7 and 18 of Twp. 148-82 (the area beneath the Snake Creek arm of Lake Audubon) was likely 1820 to 1830 feet in elevation. Thus, pre-1975 operation of the lake at 1835 feet elevation represented a 10 to 15 foot increase in the elevation of the possible discharge area for the lower aquifer. The 10 to 15 foot increase is similar in magnitude to the 13 foot increase in Lake Audubon elevation in 1975, which produced only a 2 to 3 foot rise in water levels in the lower aquifer in Twp. 148-82. The small increase in water levels suggests the potentiometric surface in most of the central portions of Twps. 148-81 and 148-82 may have been relatively flat prior to the existence of the reservoirs. The flatness would have been an artifact of relatively high transmissivities in the aquifer with most of the hydraulic head drop occurring near the discharge areas to drive flow through the less permeable sediments which confine the aquifer.

The initial filling of Lake Audubon to 1835 feet may have contributed to flattening the potentiometric surface by raising the base level to which the groundwater flowed in the lower aquifer unit. September 1970 data indicate a relatively flat potentiometric surface in the central portions of Twps. 148-81 and 148-82 (Fig. 18). Filling Lake Audubon first to 1835 feet then to 1847 feet may have first reduced then eliminated the potential for westerly or southwesterly flow in the west half of Twp. 148-82 that probably occurred in the lower aquifer unit prior to the construction of the reservoirs.

VERTICAL HYDRAULIC HEAD RELATIONS AND POTENTIAL LEAKAGE

The preceding sections focused on the lateral movement of groundwater within the flow systems. This section focuses on the apparent vertical components of groundwater flow and the potential for upward or downward leakage between the upper, middle and lower units of the Lake Nettie aquifer system. The potential for vertical movement of groundwater is determined by inspection of the vertical hydraulic gradient measured at well nest sites where observation wells are screened in different vertical units of the aquifer and lateral separation of the wells is negligible.

In areas where the water level (hydraulic head) in a well screened in a deeper aquifer unit is higher in elevation than that of the paired well screened in an overlying aquifer unit, there is a potential for upward movement of groundwater from the deeper layer to the shallower layer (upward discharge from the deeper unit). Conversely, where hydraulic head in the shallower layer is higher than in the deeper layer, there is the potential for downward movement from the shallower to the deeper layer (recharge to the deeper unit). The existence of a definable vertical head difference at a site only indicates the direction of potential vertical flow or leakage between different aquifer units. The actual amount of vertical flow, if any, will be controlled by the magnitude of the vertical hydraulic gradient and the hydraulic conductivity of the intervening materials that separate the aquifer units.

Figure 21 shows the distribution of the relative direction and magnitude of the vertical head differences between the upper aquifer unit and the lower or middle aquifer unit at 16 observation well nests in the study area. Hydrographs showing water level trends in the well nest sites are included on Plate 2. The hydrographs shown on Plate 2 indicate that the relative vertical head relations between the different aquifer layers are maintained through periods of increasing and decreasing water levels that result from varying climatic patterns.

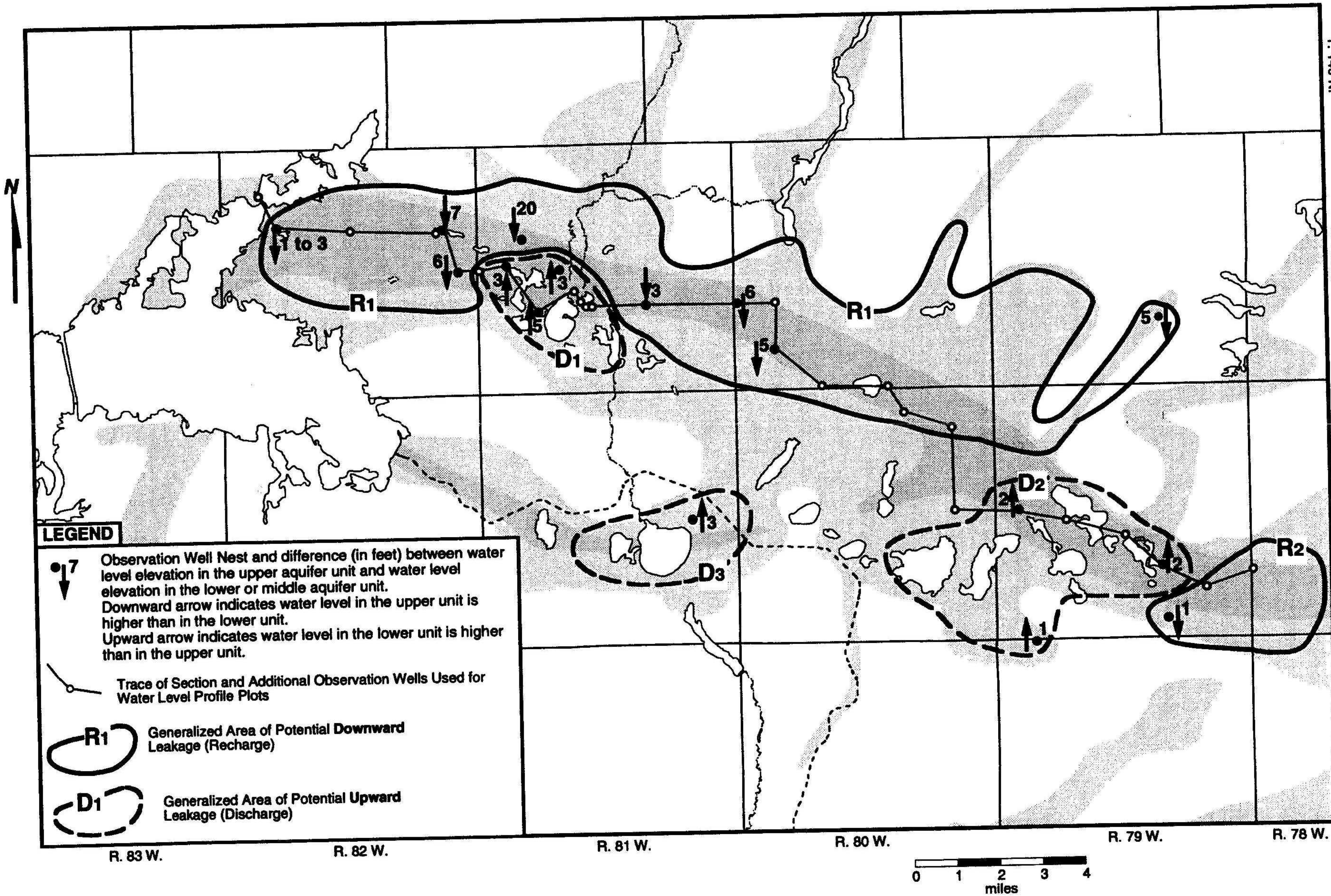


Figure 21. Vertical hydraulic head difference between the upper and the lower or middle aquifer unit at observation well nest sites.

Well nest site 147-80-22CDD, located between Lake Brekken-Holmes and Lake Williams was not included in Figure 21 because the filling of Lake Brekken-Holmes to about 20 feet above its "natural" elevation has created a local area of easterly leakage toward Lake Williams and has affected the water level in well 147-80-22CDD2. Well nest 148-82-13BBB2,3 also was not included. Both wells 148-82-13BBB2, and -BBB3 are completed in the upper aquifer unit but are separated by about 5 feet of till. The wells measure the vertical flow in a local flow system associated with McLean County Slough #1.

Approximated areas of potential downward leakage (recharge) and upward leakage (discharge) are also delineated on Figure 21, based on the measured vertical head differences at the observation well nest sites. The downward leakage area designated as area R_1 indicates that most of the northern portion of the aquifer system functions as a potential recharge area for the lower aquifer unit. The apparent downward leakage is topographically driven by higher land elevations in the northern part of the study area. The downward leakage area designated as area R_2 is also topographically driven by the presence of the Prophets Mountains which overlie the aquifer system in the southeast part of Twp. 147-78.

The vertical head distribution at well nest sites in the Lake Nettie area suggests an area of potential leakage from the lower aquifer unit to the upper aquifer unit (area D_1, Fig 21). However, the Lake Nettie area does not appear to function as a significant discharge area for the lower unit. The area of potential upward leakage is largely an artifact of the response of the upper aquifer system to the surface topography, which causes the Lake Nettie area to function as a discharge area for the groundwater flow in the upper aquifer unit. This is illustrated on Figures 22 and 23, which present the profiles of water level elevations in October 1986 (period of high water levels) and December 1990 (period of low water levels) in the upper, middle and lower units of the Lake Nettie aquifer in a transect approximately along the axis of the aquifer. The location of the wells which are used for generating the profile are included on Figure 21.

As shown on Figures 22 and 23, the potentiometric surface of the upper aquifer falls from west to east, dipping below the elevation of the lower unit's potentiometric surface in the Lake Nettie area (area D_1). The upper unit potentiometric surface then rises again east of the Lake Nettie area, before declining toward the Peterson Lake and Pelican Lake area in the eastern part of the profile (area D_2). The trough in the upper unit's potentiometric surface in area D_1 results from the relative topographic low in which Lake Nettie, Little Crooked Lake and Mud Lake are situated. The potentiometric surface of the middle aquifer unit also rises to the east of Lake Nettie. In contrast to the upper unit profile, there is no dip in the lower unit potentiometric surface nor focusing of flow into the Lake Nettie area. The lower unit's potentiometric surface instead declines only slightly to the east in the west half of the profile, ignoring the fall and rise of the potentiometric surface of the overlying aquifer units. The profiles during the high water level conditions on October 6, 1986 (fig. 22) and during the low water level conditions on December 12, 1990 (fig. 23) are virtually identical except for a uniform offset along the

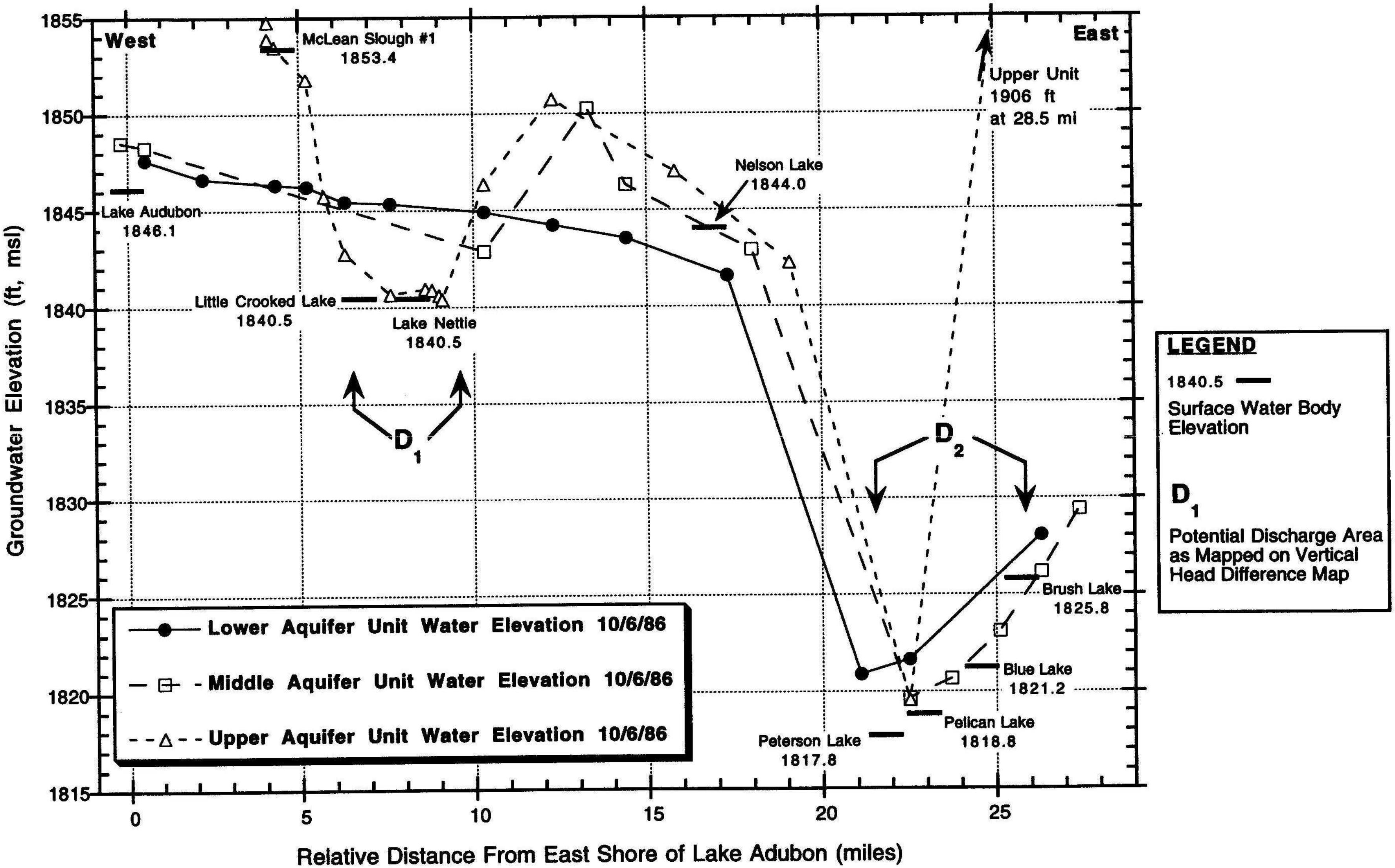


Figure 22. Water level elevation profile of the lower, middle and upper aquifer units along the approximate axis of Lake Nettie aquifer - October 6, 1986.

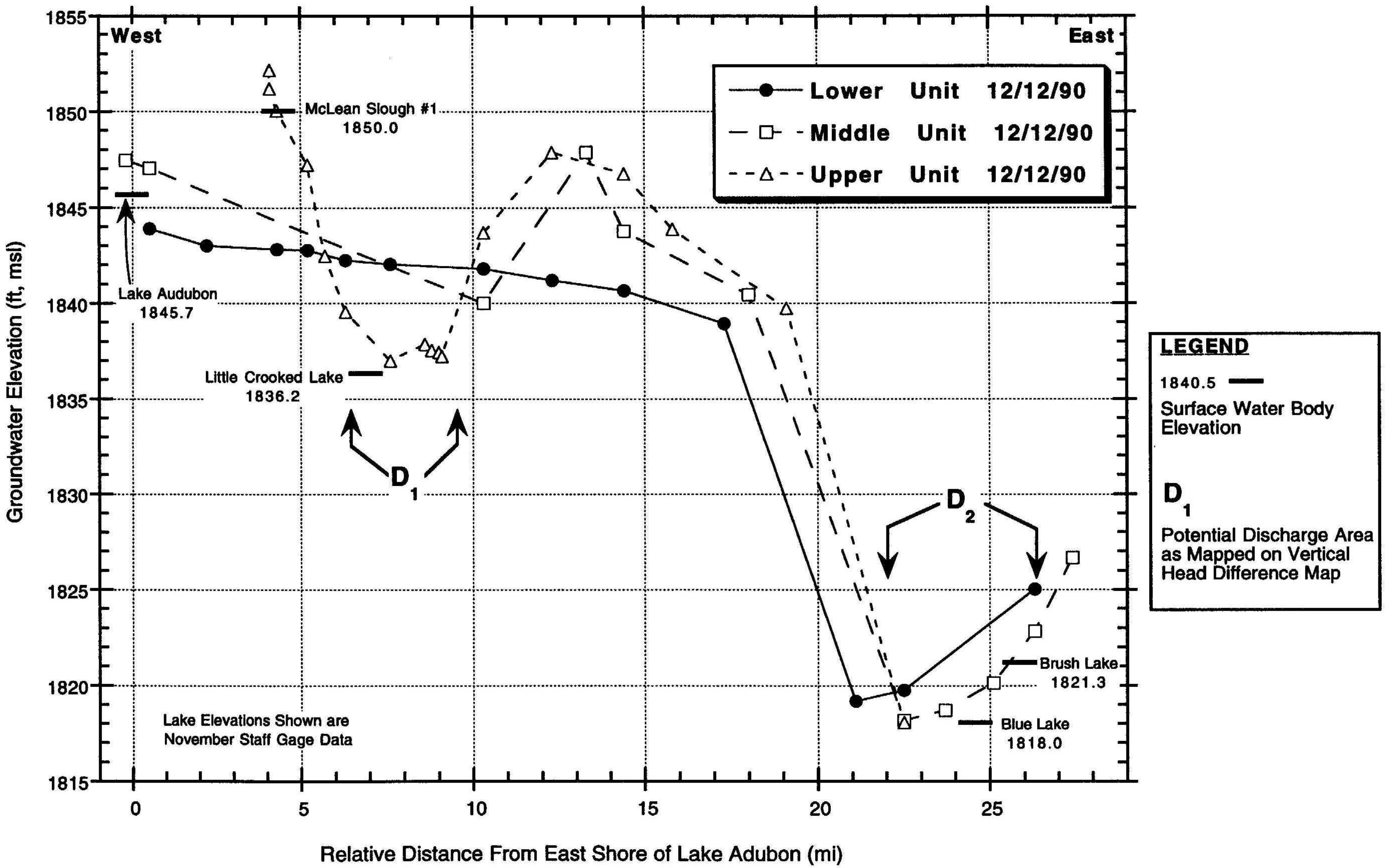


Figure 23. Water level elevation profile of the lower, middle and upper aquifer units along the approximate axis of Lake Nettie aquifer - December 12, 1990.

elevation axis, indicating that the relative positions of the upper unit's and lower unit's potentiometric surfaces are maintained through different climatic cycles.

If the Lake Nettie area constituted a significant discharge area for the lower aquifer unit with significant water loss by upward leakage, then it would be expected that a convergence of lateral flow would be discernible from the contouring of the potentiometric surface. No convergence of flow into the Lake Nettie area in the lower unit is discernible with the present data set (e.g. Figs. 16, 18, 19). The terminal discharge areas for the deeper confined aquifer units are the chain of lakes east of the city of Turtle Lake (area **D_2**) and the Turtle Lake - Lake Ordway area (**D_3**). In addition to the convergence of lateral flow into these two areas of the middle and lower aquifer units (Figs. 14, 16, 18, 19), vertical head relations indicate upward leakage from deeper units to shallower units to surface water bodies in area **D_2** and area **D_3** (Fig. 24).

RATE OF POTENTIAL UPWARD LEAKAGE IN THE LAKE NETTIE AREA

Armstrong (1983) suggested that increased water levels in the lower unit of the Lake Nettie aquifer may have resulted in increased upward leakage into the upper unit and higher surface water elevations. Estimates of limits regarding of the amount of increased leakage that could reasonably occur will be developed in this subsection.

Groundwater level elevations suggest the potential for upward leakage from the lower to the upper aquifer unit in the Lake Nettie area (area **D_1**, Fig. 21). During a October 1970 pump test, well nests between Lake Nettie and Crooked Lake indicated that the lower aquifer was higher in elevation than the middle unit which was in turn higher than the upper unit, indicating the potential for upward leakage. The groundwater elevation data collected in October prior to the pump test indicated that the lower aquifer unit water level elevation was consistently 3 feet higher than the upper unit as follows:

Well Nest	Lower Unit	Middle Unit	Upper Unit
148-81-20ccd2,3,4	1840.6 ft	1839.3 ft	1837.6 ft
148-81-20cdc1,2,3	1840.6	1839.2	1837.5
148-81-29baa,caa	1840.8	xxx	1837.9

The 1985 Lake Audubon response test indicated that the 13 foot increase in Audubon elevation resulted in an approximate 1.3 foot water level increase in the lower aquifer at well 148-81-29BAA1. No water level information has been collected from the intervening middle aquifer unit in the area since Lake Audubon was raised in 1975. However, the Lake Audubon response test in 1985 did indicate a response in the middle aquifer unit in other locations more distant from the lake. It is reasonable to assume that the response seen in the lower unit was also transmitted through the middle unit, creating a stronger vertical gradient and increasing the rate of upward leakage.

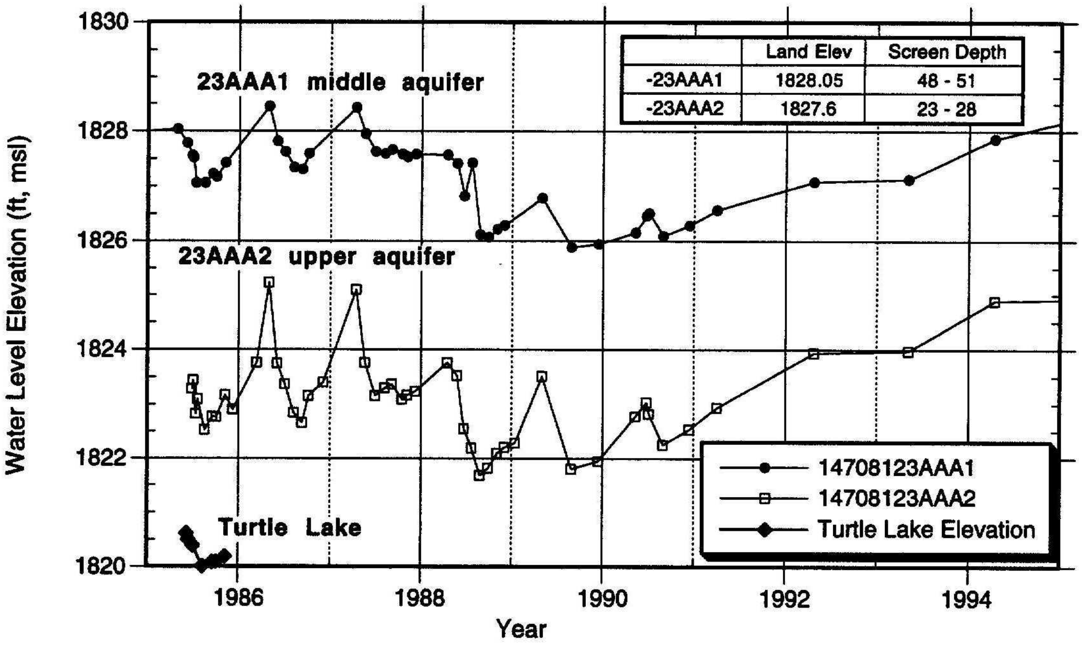


Figure 24A. Relation of water level elevations in well nest 147-81-23AAA to Turtle Lake. Relative elevations indicate the potential for upward leakage and discharge into Turtle Lake.

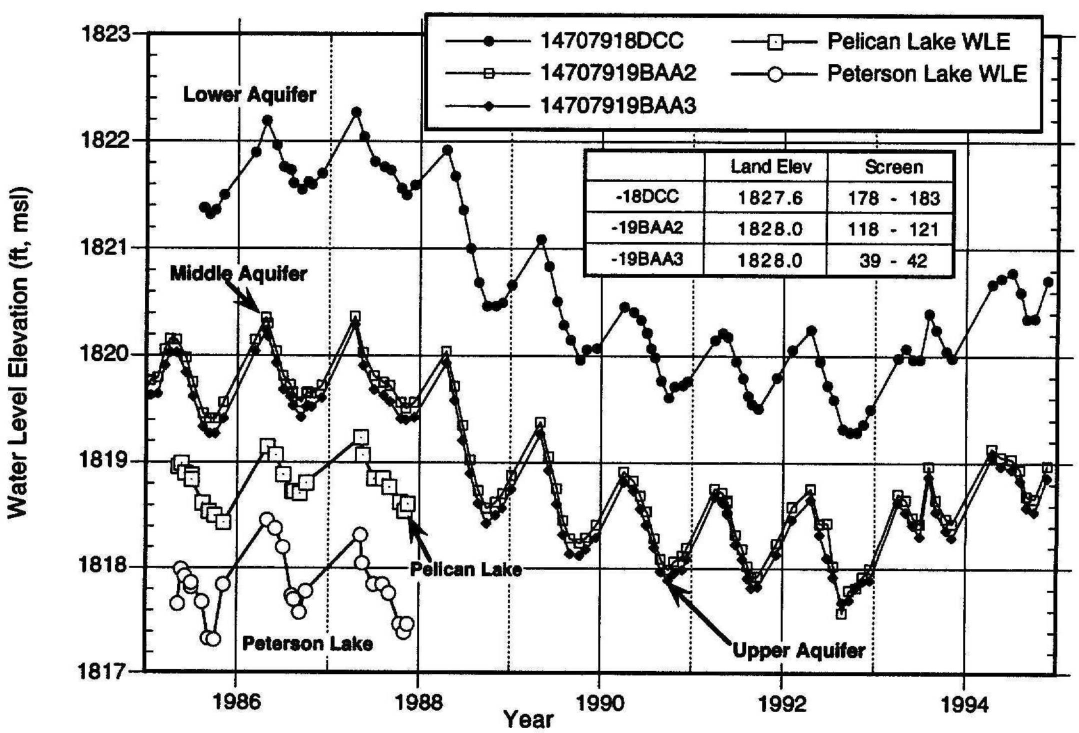


Figure 24B. Relation of water level elevations in well nest 147-79-18DCC/-19BAA to Pelican Lake and Peterson Lake. Relative elevations indicate the potential for upward leakage and discharge into the lakes.

The actual upward flux into the upper aquifer is determined by the gradient between the middle and upper units. Since there is no post-1975 water level information on the middle unit, the change in the gradient between the upper and lower units due to the response of the lower unit to the 13 foot increase in Lake Audubon in 1975 will be used in the calculation of increased flux. For the purposes of this illustration the 1.3 foot increase in the lower aquifer at 148-81-29BAA1 will be rounded up to 2. In October 1970 there was a three foot difference in water elevation between the lower and upper aquifer units, which are vertically separated by approximately 100 feet in the vicinity of Lake Nettie. Thus the 13 foot increase in Lake Audubon in 1975 caused the hydraulic gradient between the lower and upper aquifer layer to increased by about 0.02, from 0.03 to 0.05 (a 3 foot difference in 1970 versus about a 5 foot difference after 1975 between the lower and upper aquifer units divided by the 100 foot vertical separation).

In addition to the intervening middle aquifer unit the upper and lower units are separated by two to three layers of till, which are each 10 to 30 feet thick. The hydraulic conductivity of till in central North Dakota buried at depth is estimated to be on the order of 10^{-9} to 10^{-11} m/s (Robert Shaver, North Dakota State Water Commission, personal communication).

The increase in potential upward flux of water through a unit cross-sectional area can be estimated from the following relation:

$$q = Ki$$

where: q = water flux in units of length per time
K = hydraulic conductivity in units of length per time
i = hydraulic gradient in units of length per length

The estimated increased flux due to the 13 foot increase in Lake Audubon and the resultant total vertical flux between the lower and upper aquifer units in the **D_1** potential discharge area for a range of possible hydraulic conductivities is tabulated below:

K m/s	**K ft/d**	**q ft/yr**	**q in/yr**	**Δq ft/yr**	**Δq in/yr**
10^{-11}	2.83×10^{-6}	5.2×10^{-5}	0.00062	2.1×10^{-5}	0.00025
10^{-10}	2.83×10^{-5}	5.2×10^{-4}	0.0062	2.1×10^{-4}	0.0025
10^{-9}	2.83×10^{-4}	5.2×10^{-3}	0.062	2.1×10^{-3}	0.025
10^{-8}	2.83×10^{-3}	5.2×10^{-2}	0.62	2.1×10^{-2}	0.25
10^{-7}	2.83×10^{-2}	5.2×10^{-1}	6.2	2.1×10^{-1}	2.5

The calculated fluxes for the estimated range of buried till conductivities (10^{-9} to 10^{-11} m/s) is less than 1/4-inch per year and would not create a noticeable change in water levels. Even increasing the upper estimate of the till hydraulic conductivity by two orders of magnitude from 10^{-9} to 10^{-7} m/s yields an increased upward flux of only 2.5 inches, which would be readily consumed by evapotranspiration. Potential evapotranspiration at land surface in the area averages about 36 inches per year (U.S. Department of Commerce, 1982), about 19 inches greater than the area's average annual rainfall. If the calculated amount of increased potential upward flux caused by the increased water level in the lower aquifer was inflated to the many inches per year that would make a material difference in upper aquifer and surface water levels, the associated total potential upward flux would be unreasonably large.

Because of the low hydraulic conductivity of the sediments that separate the aquifer units in the Lake Nettie area it is unlikely that the 2 feet of head increase in the lower aquifer unit, which resulted from the 1975 increase in Lake Audubon elevation within the D_1 potential discharge area, resulted in a measurable increase in the actual upward flux of groundwater .

LACK OF POTENTIAL FOR LEAKAGE FROM LAKE AUDUBON

Armstrong (1983) postulated that Lake Audubon recharges the lower unit of the Lake Nettie aquifer since the lake operating level was raised from 1835 to 1847 feet in 1975. The hypothesis of recharge to the lower aquifer unit by leakage from Lake Audubon is contradicted by water level elevation data from observation wells 148-82-07AAD3 and well nest 148-82-08CDC1,2, which are located near the northern arm of Lake Audubon. Well 148-82-07AAD3 is screened in the middle aquifer unit a few hundred feet west of the west shore, while well nest 148-82-08CDC1,2 has wells screened in the middle and lower units about 1/4 mile east of the east shore of the lake.

The cross-section below (Fig. 25) shows the location of the well screens and aquifer units relative to Lake Audubon.

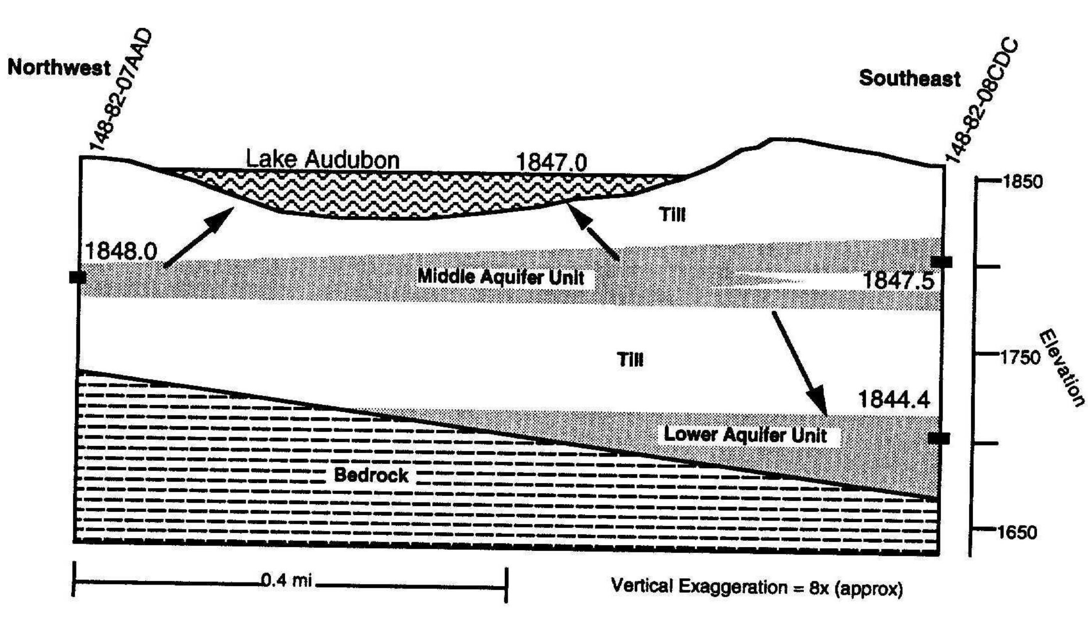


Figure 25. Cross-section from well 148-82-07AAD to well nest 148-82-08CDC1,2 across the northern arm of Lake Audubon. Water elevations in for May 10, 1990 are included (1848.0, 1847.5, and 1844.4 feet). Arrows represent direction of potential vertical groundwater leakage.

The hydrograph in Figure 26 shows the water level elevations for the period of record (1981 - 1995) for the observation wells together with the stage elevations of Lake Audubon. With the exception of periods of relatively high groundwater elevations (such as 1986-1987 and 1994-1995), the hydraulic head in the lower aquifer unit (well 148-82-08CDC1) is usually lower (0 to 3 feet) than the elevation of Lake Audubon, which would suggest the potential for leakage from Lake Audubon to the lower unit. However, the hydraulic head in the middle unit (wells 148-82-07AAD3 and 148-82-08CDC2) is always higher than both the elevation of Lake Audubon and the hydraulic head in the lower unit. The higher hydraulic head in the intervening middle unit physically prohibits both the downward leakage of water from Lake Audubon to the lower unit during periods when the lake elevation is higher than the hydraulic head of the lower unit, and also prohibits the upward discharge of water from the lower unit toward the lake during periods when the lake elevation is lower than the hydraulic head of the lower unit.

The lower aquifer unit is hydraulically isolated from Lake Audubon with regard to the actual leakage of water. The water elevation relations shown in Figure 26, considered together with the configuration of the potentiometric surfaces of the upper, middle and lower units, indicate that groundwater is discharged into Lake Audubon from the middle aquifer unit by upward leakage across the intervening till. In the area east of Lake Audubon downward leakage from the middle unit may provide recharge to the lower unit. Water levels in the lower unit have been affected by hydrostatic loading, where the weight of the water in Lake Audubon has increased the pressure in the underlying sediments. This aspect will be discussed in more detail in subsequent sections of this report.

Figure 26 shows that water level elevations in the lower aquifer fluctuated by 4.5 feet between 1981 and 1995 at well 148-82-08CDC1 even though Lake Audubon was maintained at an operational level of 1847 to 1848 feet (with winter drawdowns of 2 to 3 feet beginning in 1985). The fluctuations in water level at this well site are attributed to a combination of changes in Lake Sakakawea stage and climatic variation. The rise from elevation 1845.8 to about 1847.5 in 1982 coincides with a 17 foot rise in the elevation of Lake Sakakawea from 1829 to 1846 feet. However, annual rainfall recorded at the Turtle Lake NOAA station was 6.7 inches above normal in 1982. Similarly the almost 5 foot rise in the elevation of the water level in well 148-82-08CDC1, from a low of 1843.2 feet in early 1993 to almost 1848 feet in mid-1995, coincides with a rise in Lake Sakakawea of about 35 feet (from 1817 feet in early 1993 to 1852 feet in mid-1995). Above normal rainfall was also experienced in the area in 1993 through mid-1995. The factors contributing to fluctuations in water level elevations will be more thoroughly evaluated in subsequent sections of this report.

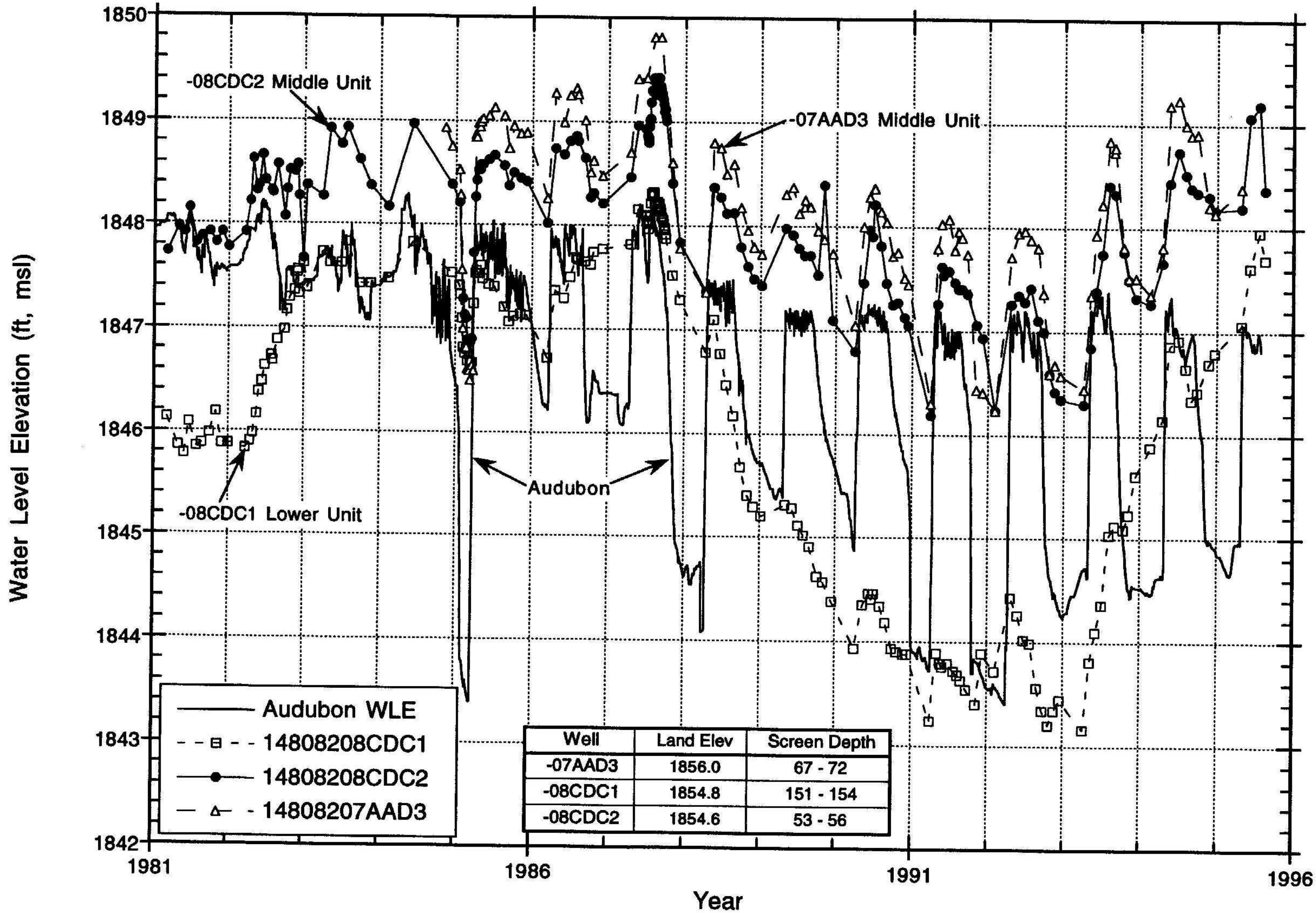


Figure 26. Water level elevations in Lake Audubon and in observation wells 148-82-07AAD3 and 148-82-08CDC1,2 located near the edge of Lake Audubon.

LAKE AUDUBON RESPONSE TEST

From January through April 1985 the water elevation of Lake Audubon was lowered approximately 3 feet to an elevation of 1843.5 feet then raised 4.3 feet to an operating elevation of 1847.8 feet. Water levels in several observation wells were monitored on a weekly basis across the drawdown and refilling period in order to evaluate the magnitude and timing of aquifer response to changing reservoir stage levels. Five of the wells were also equipped with continuous water level recorders during the Lake Audubon refilling phase of the test. In 1975 water levels in most observation wells were not measured with sufficient frequency to directly monitor the effect that the 13 foot increase in Lake Audubon elevation had on groundwater levels. Thus, the 1985 Audubon response test provides the only available data set with which to directly quantify the effect that changes in Lake Audubon elevation have on groundwater levels.

WATER LEVEL CHANGES IN LAKE AUDUBON

On January 21, 1985 the conduit gate between Lake Audubon and Lake Sakakawea was opened to begin the drawdown of Lake Audubon from an elevation of 1846.1. The gate was closed on February 4 at a lake elevation of 1843.8. Between February 4 and March 19, the level of Lake Audubon decreased an additional 0.4 feet, attributed to leakage loss to the McClusky Canal. On March 19, pumping began from Lake Sakakawea to raise the level of Lake Audubon. The Snake Creek pumping plant pumps were turned off on March 29, after raising Audubon level by 4.3 feet. A synopsis of the Lake Audubon elevations during this drawdown and refilling cycle is given below:

Date		**Lake Elev.** (ft, msl)	**Net Change** (ft)	**Net Rate of Change** (ft/day)
12/05/84		1846.8		
			-0.4	0.01
01/11/85		1846.4		
			-0.3	0.03
01/21/85	Drawdown Starts	1846.1		
			-2.3	0.16
02/04/85	Drawdown Ends	1843.8		
			-0.4	0.01
03/19/85	Refilling Starts	1843.4		
			4.3	0.42
03/29/85	Refilling Stops	1847.7		
			0.3	0.06
04/05/85		1848.0		

RESPONSE OF THE GROUNDWATER SYSTEM

The response of the groundwater system to the drawdown and refilling of Lake Audubon was monitored by measuring water levels in 19 observation wells in the Lake Nettie, Turtle Lake and Fort Union Aquifers on a weekly basis from January 15 to April 17, 1985. The locations of the monitored wells are shown on Figure 27. Figure 28 shows the distinct drawdown and recovery fingerprint on the hydrographs for several of the monitored wells. In addition to the weekly measurements, continuous recorders were installed in 5 of the wells from 3/5/85 to 4/17/85, across the refilling phase of the response test. The recorder well locations are included on Figure 27.

Of the 19 wells which were monitored, 18 are screened in the middle or lower confined units of the aquifers. The remaining well, 148-81-29CAA, is screened in the upper, unconfined unit of the Lake Nettie Aquifer. A summary of the well locations, construction information, and magnitude of water level changes in the wells during the response test is given in Table 1. Weekly water level data across the drawdown and refilling period is included in Table 2. Daily elevations of Lake Audubon across the response test period are included in the basic data report (Part I) of this study.

Water levels in 13 of the monitored wells screened in the confined lower or middle aquifer units showed distinct responses to the drawdown and refilling of Lake Audubon, with the amount of change ranging from 6% to 60% of the amount of change in the reservoir. The water level changes ranged from 2.3 feet near the shore of Audubon to 0.25 feet at a distance of about 14 miles from the lake. Hydrographs of water levels in observation wells which responded to the drawdown and refilling of the reservoir are shown with Lake Audubon elevation on Figure 29.

Water level responses to the drawdown and refilling of the lake were indistinct in 5 of the monitored wells. Although some apparent response to Audubon was discernible in these wells, the timing of the groundwater level changes in relation to the drawdown and refilling of Lake Audubon indicates that the groundwater levels in this group of wells were also responding to other factors. Hydrographs of water levels in this group of wells during the response test are presented with Lake Audubon elevation on Figure 30 Because of the uncertainty associated with separating the response due to Audubon from that of the other factors, this group of wells will be treated separately from the group that showed distinct responses in terms of quantifying the response.

MAGNITUDE OF AQUIFER RESPONSE TO LAKE AUDUBON CHANGES

The measured response of groundwater levels to the January through April 1985 drawdown and refilling of Lake Audubon can be used to calculate the amount by which groundwater level rose at the location of the well in response to raising the level of Lake Audubon from 1835 feet to 1848 feet in 1975. If the groundwater levels responded immediately to changes in lake level and there were no other concurrently operating factors that could affect groundwater levels, then a regression of water level elevation in a particular well versus reservoir elevation across a discreet time period would provide the most direct evaluation of the amount of groundwater rise to be expected for a given amount of lake elevation rise. However, there is a time lag between changes in Lake Audubon and the corresponding response in the confined aquifer units that

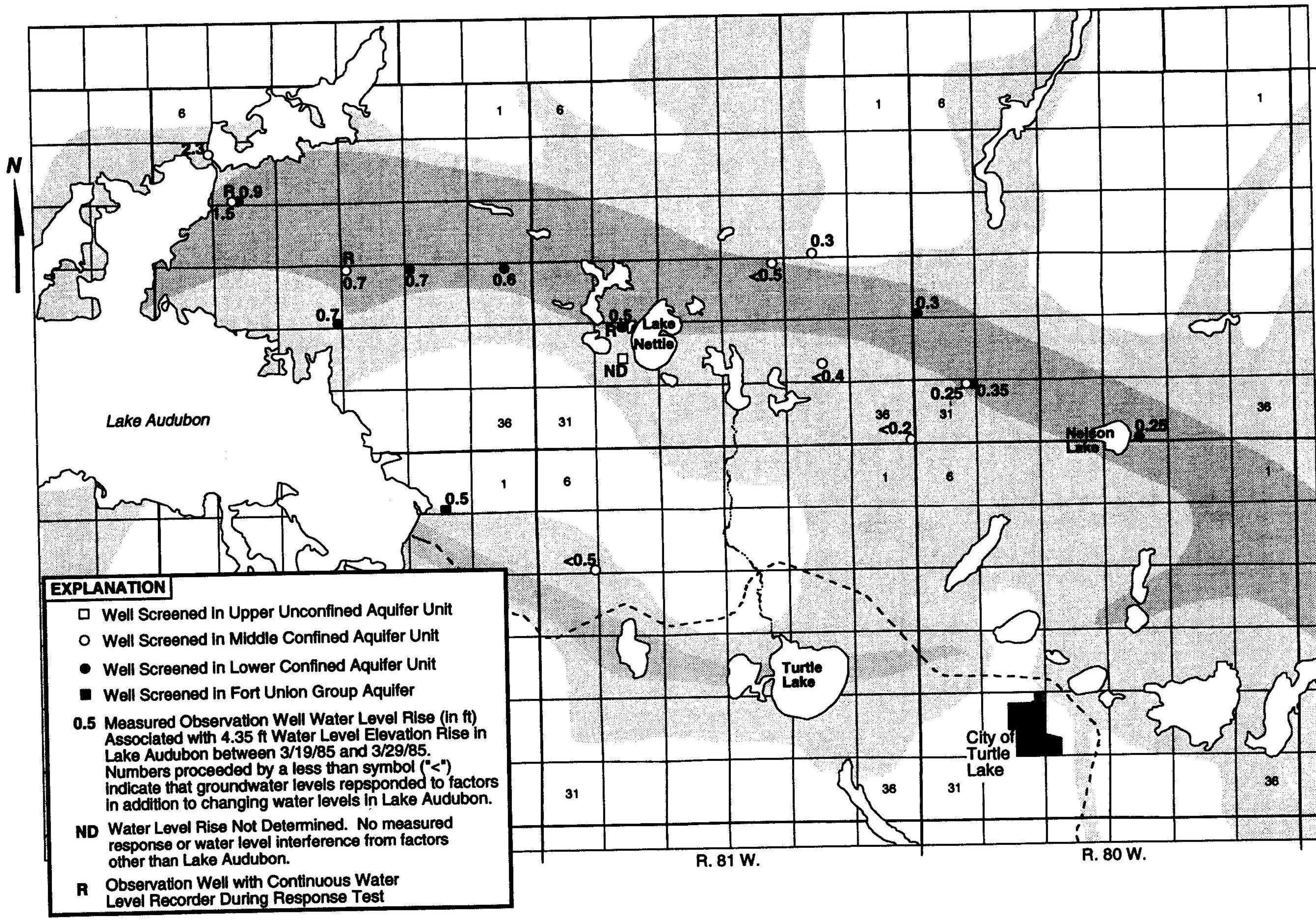


Figure 27. Map showing water level responses measured in observation wells during Lake Audubon response test, January - April 1985.

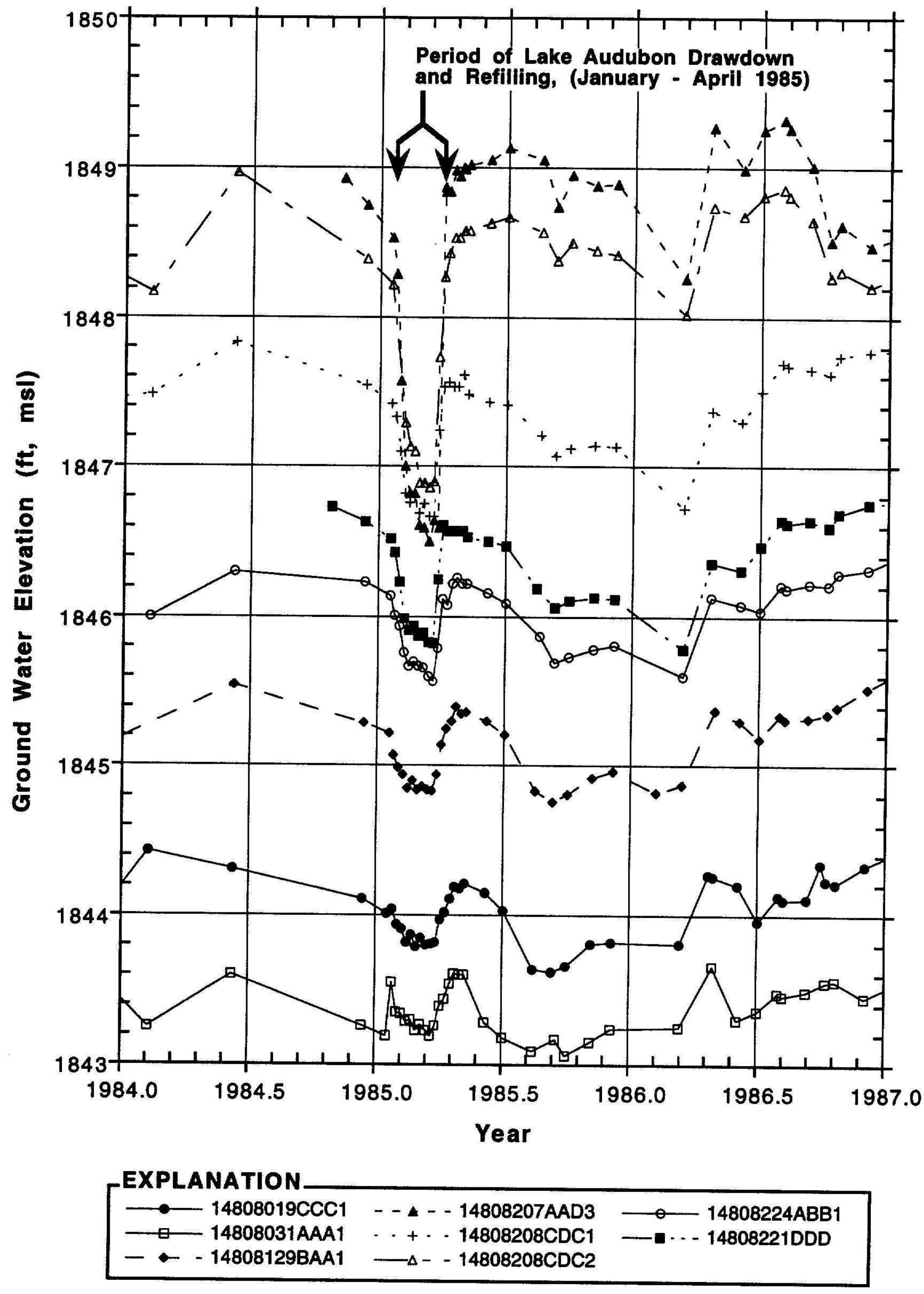


Figure 28. Representative responses of observation well water levels to partial drawdown and refilling of Lake Audubon.

TABLE 1. 1985 Lake Audubon Response Test. Observation Well Information and Water Level Response Summary for Wells Monitored During Lake Drawdown and Refilling

Location	Water Level Change (ft)	Screen Depth (ft)	Aquifer Interval (ft)	Land Surface Elev (msl)	Elev Top Screen (msl)	Distance from Audubon (mi)	Aq Unit	Comments
Lake Audubon	4.35	---	---	(1847)	---	0		Lowered 2.3 ft from 1846.1 elevation between 1/21/85 and 2/4/85; raised 4.35 ft from 1843.39 elevation between 3/19/85 and 3/29/85
147-81 07DDD	<0.5	118-138	118-154	1912.9	1795	2.7	TL	Well in Turtle Lake Aquifer. Interference from City of Turtle Lake supply well pumping. Turtle Lake Aquifer
147-82 02DCC	0.5	113-118	91-?	1878.0	1765	0.2	FtU	Well screened in Fort Union Group Sandstone, overlain by till.
148-80 19CCC1	0.3	198 - 201	183-208	1861.85	1664	10	L	Delay of a few days in response to refilling of Lake.
148-80 31AAA1	0.35	208-211	195-218	1861.07	1653	11	L	Apparent response to refilling of Lake. Mid-January and early drawdown phase data internally inconsistent due to interference from well casing repair.
148-80 31AAA2	0.25	78-81	56-88	1861.07	1783	11	M	Apparent response to refilling of Lake only. Mid-January and early drawdown phase data internally inconsistent due to interference from well casing repair.
148-80 34DCC	0.25	198-207	190-240	1867.5	1670	14	L	Slightly delayed response.
148-81 14CDD	0.3	136-141	136-141	1858.57	1723	8.5	M	Apparent slightly delayed response to Lake drawdown. Well is screened in isolated(?) 5 ft thick sand and gravel lens.
148-81 22AAB	<0.5	85-87	58-89	1847.12	1762	7.9	M	Water levels rose (0.4 ft total) from 2/15/85 trough 3/20/85 during Lake drawdown phase of test.
148-81 26DBC	<0.5	78-81	60-88	1860.5	1783	7.8	M	Water levels rose (0.3 ft total) from 2/15/85 trough 3/20/85 during Lake drawdown phase of test.
148-81 29BAA1	0.5	158-178	153-203	1857.02	1699	5	L	Continuous Recorder Well
148-81 29CAA	ND	38-48	0-48	1851.0	1813	5	U	Screened in upper unconfined aquifer. Water levels rose (0.3 ft total) from 2/15/85 trough 3/20/85 during Lake drawdown phase of test.. Attributed to early snowmelt recharge.
148-81 36DDD	<0.2	78-81	50-90	1850.7	1773	8	M	Water levels rose (0.2 ft total) from 2/15/85 trough 3/20/85 during Lake drawdown phase of test.
148-82 07AAD3	2.3	67-72	62-80	1856.0	1789	0.1	M	Adjacent to Lake. Aquifer interval overlain by 62 ft of clay till.
148-82 08CDC1	0.9	151-154	147-187	1854.8	1704	0.3	L	Continuous Recorder Well
148-82 08CDC2	1.5	53-56	41-61	1854.62	1802	0.3	M	20 ft thick sand and gravel layer overlain by 40 ft of till; Continuous Recorder Well
148-82 21DDD	0.7	168-173	140-186	1869.03	1701	0.5	L	
148-82 22BBB	0.7	125-130	124-132	1875.32	1750	1.5	M	
148-82 23BBB	0.7	198-204	164-266	1883.56	1686	2	L	Continuous Recorder Well
148-82 24ABB1	0.6	198-201	140-205	1856.17	1658	3.5	L	

Water Level Change = Approximate magnitude of water level change which was detected in well as a response to lowering and raising of Lake Audubon during the response test

ND = none detected

Aquifer Interval = depth interval of permeable sand or sand and gravel layer in which well is screened

Land Surface Elev = Elevation of land surface, as surveyed, in feet above mean sea level (msl)

Elev Top Screen = Elevation of top of well screen, in feet above mean sea level (msl)

Distance from Audubon = Approximate distance of well from Lake Audubon (in miles), as measured along the aquifer axis

Aq Unit = Aquifer Unit: L = Lower, M = Middle, U = Upper unit of Lake Nettie Aquifer

Table 2. Water elevation data for Lake Audubon and observation wells monitored during Lake Audubon response test, January - April 1985.

Date	Year	Lake Audubon	147-81 07DDD	147-82 02DCC	148-80 19CCC1	148-80 31AAA1	148-80 31AAA2	148-80 34DCC	148-81 22AAB	148-81 26DBC	148-81 29BAA1	148-81 29CAA	148-81 36DDD	148-81 14CDD	148-82 07AAD3	148-82 08CDC1	148-82 08CDC2	148-82 21DDD	148-82 22BBB	148-82 23BBB	148-82 24ABB1
12/12/84	1984.948	1846.70	1842.17	1845.44	1844.11	1843.26	1845.84	1841.52	1844.39	1843.10	1845.29	1840.00	1844.17	1849.37	1848.75	1847.54	1848.39	1846.63	1846.64	1846.67	1846.23
1/15/85	1985.041	1846.19						1841.49													
1/16/85	1985.044	1846.18	1842.60		1844.01	1843.19	1845.78		1844.04					1849.26							
1/17/85	1985.047	1846.16		1845.34							1845.22	1840.07	1844.05		1848.53	1847.42	1848.22	1846.52	1846.56	1846.57	1846.14
1/23/85	1985.063	1845.78		1845.17	1844.04	1843.55		1841.51	1844.04	1842.92	1845.07	1840.04	1844.05	1849.29	1848.29	1847.33		1846.43	1846.47	1846.51	1846.01
1/30/85	1985.082	1844.72	1842.42	1844.96	1843.94	1843.35	1845.97	1841.48	1844.07	1842.91	1844.99	1840.01	1844.05	1849.18	1847.57	1847.10		1846.23	1846.24	1846.34	1845.94
2/6/85	1985.101	1843.79	1842.28	1844.86	1843.91	1843.34	1845.98	1841.43	1843.95	1842.84	1844.94	1839.95	1844.02	1849.18	1847.00	1846.82	1847.29	1845.99	1846.05	1846.14	1845.76
2/13/85	1985.121	1843.67	1842.28	1844.81	1843.82	1843.29	1845.94	1841.30	1843.87	1842.79	1844.85	1839.94	1844.00	1849.12	1846.82	1846.76	1847.13	1845.91	1845.98	1846.05	1845.67
2/14/85	1985.123	1843.66			1843.82																
2/20/85	1985.140	1843.56	1842.56	1844.88	1843.87	1843.30	1845.97	1841.38	1843.90	1842.81	1844.90	1840.02	1843.99	1849.12	1846.82	1846.80	1847.10	1845.94	1846.00	1846.08	1845.70
2/27/85	1985.159	1843.56	1842.34	1844.78	1843.79	1843.23	1845.90	1841.29	1843.92	1842.81	1844.84	1840.00	1843.96	1849.05	1846.61	1846.69	1846.89	1845.87	1845.89	1846.02	1845.67
3/6/85	1985.178	1843.48	1842.59	1844.80	1843.85	1843.27	1845.97	1841.36	1844.06	1842.90	1844.86	1840.10	1843.97	1849.09	1846.59	1846.75	1846.89	1845.89	1845.93	1846.03	1845.66
3/13/85	1985.197	1843.40	1842.30	1844.75	1843.80	1843.23	1845.86	1841.31	1844.11	1842.95	1844.84	1840.13	1844.02	1849.06	1846.50	1846.67	1846.86	1845.83	1845.87	1845.98	1845.60
3/20/85	1985.216	1843.82	1842.28	1844.75	1843.81	1843.19	1845.97	1841.30	1844.17	1842.99	1844.83	1840.20	1844.03	1849.01	1846.64	1846.67	1846.90	1845.82	1845.85	1845.95	1845.57
3/27/85	1985.236	1846.67	1842.38	1845.31	1843.82	1843.26	1846.05	1841.32	1844.28	1843.09	1844.94	1840.23	1844.05	1849.04	1846.59	1847.24	1847.73	1846.25	1846.24	1846.24	1845.79
4/3/85	1985.255	1847.73	1842.55	1845.42	1843.97	1843.39	1846.14	1841.42	1844.43	1843.47	1845.14	1840.34	1844.13	1849.13	1848.87	1847.53	1848.27	1846.61	1846.59	1846.54	1846.12
4/4/85	1985.258	1847.88						1841.45	1844.43						1848.84						
4/10/85	1985.274	1847.87	1842.48	1845.28	1844.02	1843.44	1846.14	1841.43	1844.52	1843.30	1845.25	1840.38	1844.16	1849.18	1848.84	1847.56	1848.43	1846.57	1846.60	1846.61	1846.08
4/17/85	1985.293	1847.74	1842.79	1845.28	1844.11	1843.54	1846.23	1841.55	1844.66	1843.38	1845.30	1840.46	1844.21	1849.26	1848.98	1847.53	1848.53	1846.57	1846.62	1846.66	1846.22
4/24/85	1985.312	1847.77	1842.48	1845.32	1844.19	1843.61	1846.29		1844.83	1843.48	1845.40	1840.55	1844.17	1849.36	1848.94	1847.53	1848.53	1846.57	1846.59	1846.69	1846.26
4/29/85	1985.326	1847.90						1841.58	1844.86						1849.00						
5/1/85	1985.332	1847.99	1842.51	1845.27	1844.18	1843.60	1846.28	1841.60	1844.86	1843.48	1845.35	1840.54	1844.37	1849.34	1848.99	1847.61	1848.58	1846.57	1846.60	1846.66	1846.22
5/8/85	1985.351	1847.80	1842.71		1844.21	1843.60	1846.19	1841.63	1844.82	1843.47	1845.36	1840.49	1844.38	1849.34	1849.02	1847.48	1848.58	1846.53	1846.59	1846.67	1846.22
6/6/85	1985.430	1847.64						1841.64													
6/7/85	1985.433	1847.71	1842.61	1845.26	1844.15	1843.28	1845.76		1844.71	1843.21	1845.30	1840.38	1844.00	1849.38	1849.05	1847.43	1848.63	1846.50	1846.64	1846.64	1846.16
7/2/85	1985.501	1847.79	1842.54																		
7/3/85	1985.504	1847.87		1845.21	1844.03	1843.18	1845.48	1841.48	1844.49	1842.94	1845.21	1840.23	1843.66	1849.28	1849.13	1847.41	1848.67	1846.47	1846.50	1846.53	1846.09

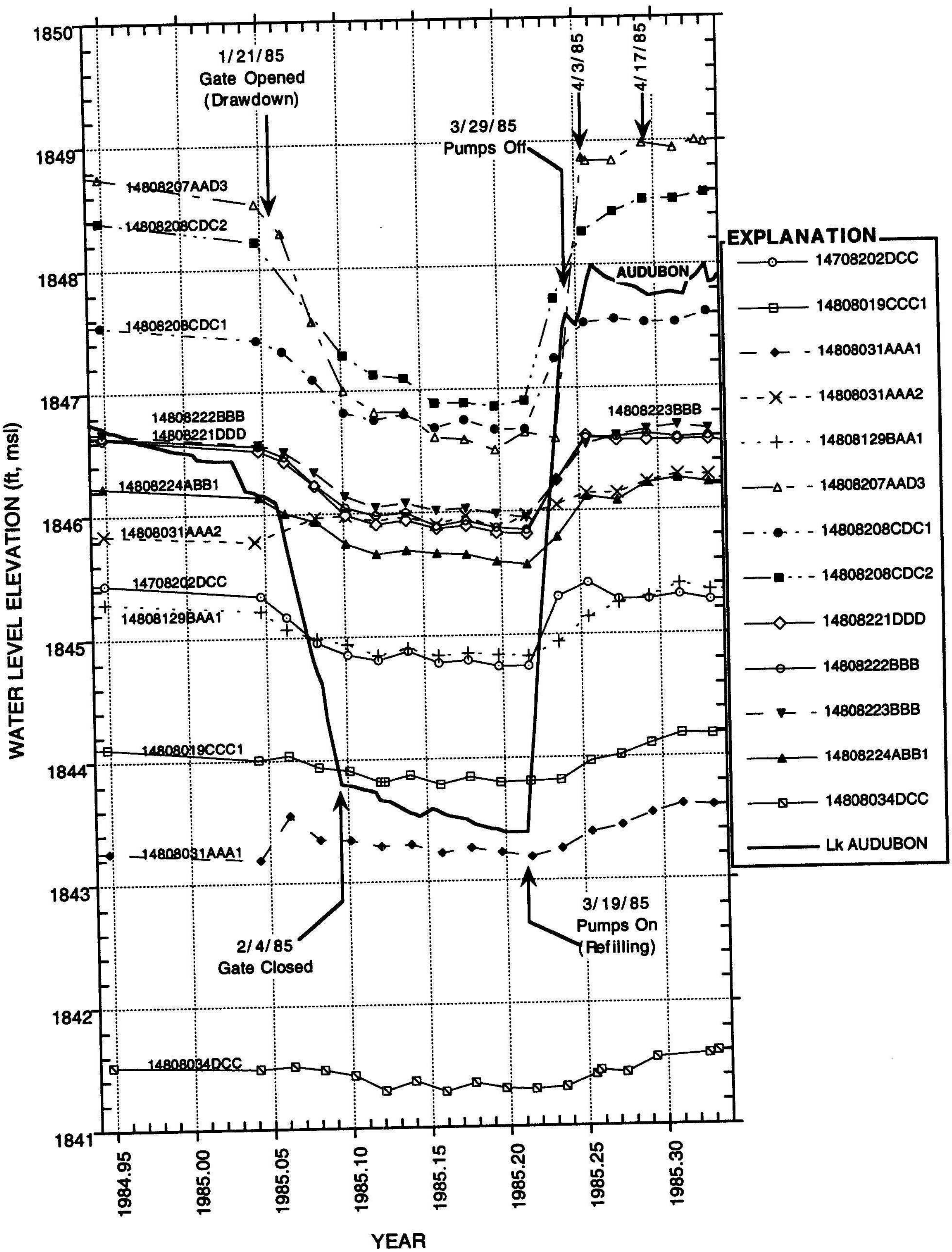


Figure 29. Water level changes in wells with distinct responses to partial drawdown and refilling of Lake Audubon.

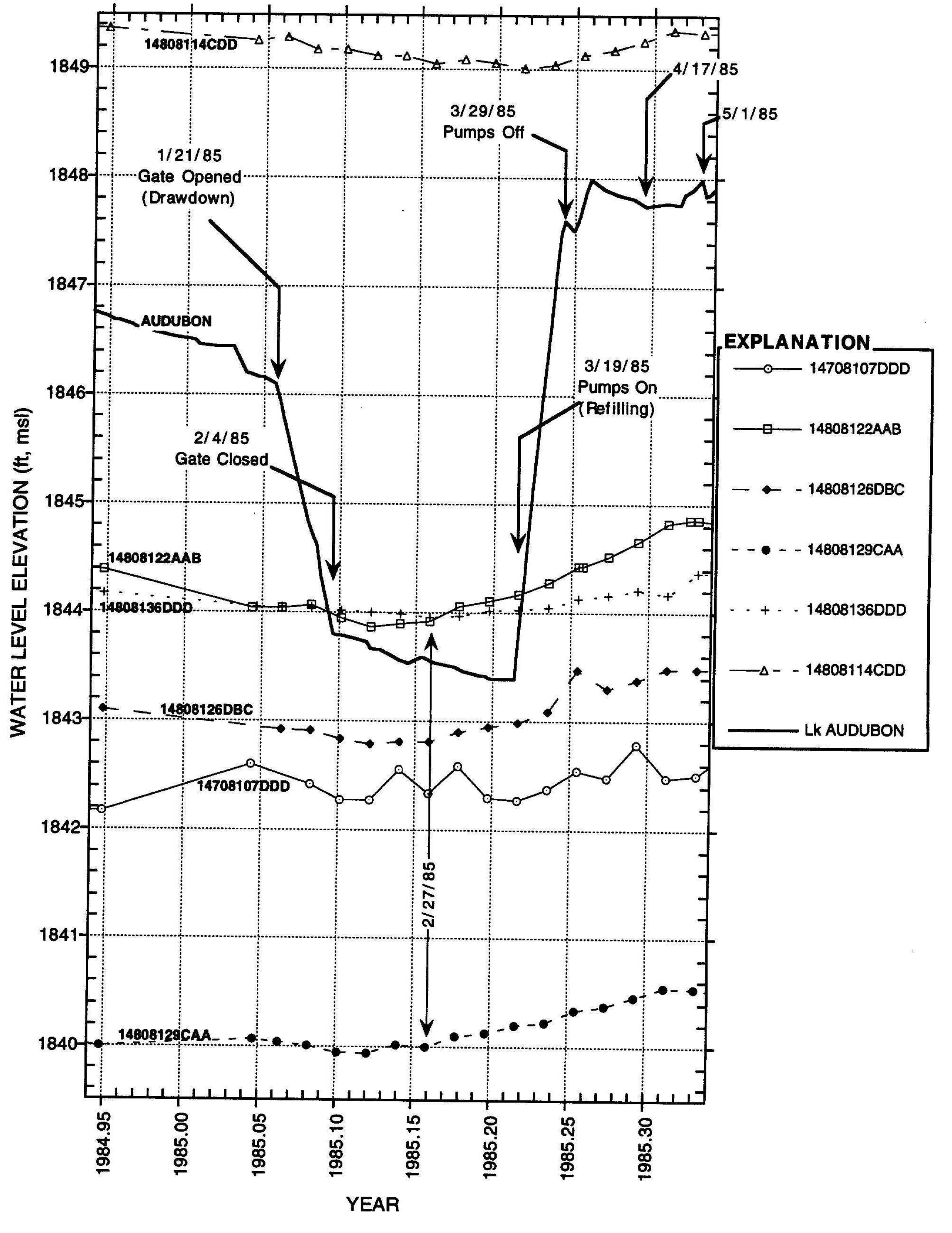


Figure 30. Water level changes in wells with indistinct responses to partial drawdown and refilling of Lake Audubon.

increases with distance from the lake. In addition, water level changes in some wells indicates that there was some response to climatic factors that was superimposed on the groundwater level changes induced by Lake Audubon.

In order to reduce the high or low bias that may be introduced by sole use of a particular method, several different calculation methods were used to quantify the ratio of aquifer water level change to Audubon water level change. These calculations provide estimates of the expected change in water elevation in the aquifer at the observation well per foot of change in Lake Audubon elevation. The calculations results are summarized in Table 3. The rational basis for each of the calculation methods is described below. The alphabetical letter at the beginning of each paragraph corresponds to the similarly lettered row in Table 3.

A. Ratio of water level change in well to change in Audubon during the primary lake drawdown period between 1/21/85 and 2/4/85. The observation well water level change between the monitoring dates of 1/15/85 and 2/6/85 was divided by the 2.37 foot drop in Audubon elevation between 1/21/85 and 2/4/85.

B. Ratio of water level change in well to change in Audubon during period between 1/21/85 and 3/19/85. This period includes the primary drawdown period as described in A, above, as well as the 6-weeks in which water levels in Audubon slowly declined due to leakage to the McClusky Canal. The observation well water level change between the monitoring dates of 1/15/85 and 3/20/85 was divided by the 2.77 foot drop in Audubon elevation between 1/21/85 and 3/19/85. Use of this extended drawdown period reduces the problems with time lag between drawdown of Audubon and timing of the response in monitoring wells more distant from the lake.

C. Ratio of water level change in well to change in Audubon during the lake refilling period between 3/20/85 and 4/17/85. The observation well water level change between the monitoring dates of 3/20/85 and 4/3/85 to 4/17/85 (date used dependent on when observation well water level had stabilized) was divided by the 4.35 foot increase in Audubon elevation between 3/19/85 and 4/3/85.

D., E., F. Regression Slope: The slope determined from a linear regression (least squares fit) of water elevation in the observation wells against Audubon elevation on the same date. The slope of the regression line represents the change in water elevation at the well per foot of change in Lake Audubon elevation. There is a degree of uncertainty introduced by using this method due to the time required for the lake level change signal to propagate through the aquifer-aquitard system to the observation well locations. Because of the time lag between change in Audubon elevation and response at the more distant wells, the water level record was broken into parts (drawdown period and refilling period) for the linear regression analyses. Rows D., E., and F. of Table 3 include slope of the regression line, the R-value of the line (a measure the data scatter about the best fit line), and the number of data points used in the regression. In Table 3 Row D. represents the line fit to the data of 12/12/84 to 2/6/85 (across the drawdown period); Row E. represents the line fit to the data of 3/13/85 to 4/17/85 (across the refilling period); Row

TABLE 3. Change in observation well water levels per 1 foot change in Lake Audubon elevation. Summary of calculations.

		OBSERVATION WELL													
		147-82 02DCC	148-80 19CCC1	148-80 31AAA1	148-80 31AAA2	148-80 34DCC	148-81 29BAA1	148-82 07AAD3	148-82 08CDC1	148-82 08CDC2	148-82 21DDD	148-82 22BBB	148-82 23BBB	148-82 24ABB1	Audubon
Water elevation	01/16/85	1845.34	1844.01	*	*	1841.49	1845.22	1848.53	1847.42	1848.22	1846.52	1846.56	1846.57	1846.14	1846.16
Water elevation	02/06/85	1844.86	1843.91	1843.34	1845.98	1841.43	1844.94	1847.00	1846.82	1847.29	1845.99	1846.05	1846.14	1845.76	1843.79
Water elevation	03/20/85	1844.75	1843.81	1843.19	1845.97	1841.3	1844.83	1846.64	1846.67	1846.9	1845.82	1845.85	1845.95	1845.57	1843.39
Water elevation	04/03/85	1845.42	1843.97	1843.39	1846.14	1841.42	1845.14	1848.87	1847.53	1848.27	1846.61	1846.59	1846.54	1846.12	1847.73
Water elevation	04/17/85	1845.28	1844.11	1843.54	1846.23	1841.55	1845.3	1848.98	1847.53	1848.53	1846.57	1846.62	1846.66	1846.22	1847.74
Change During Drawdown (ft)	1/16 - 2/6	-0.48	-0.10	—	—	-0.06	-0.28	-1.53	-0.60	-0.93	-0.53	-0.51	-0.43	-0.38	-2.37
Change During Drawdown (ft)	1/16 - 3/20	-0.59	-0.20	—	—	-0.19	-0.39	-1.89	-0.75	-1.32	-0.70	-0.71	-0.62	-0.57	-2.77
Change During Refilling (ft)	3/20 - 4/17	0.53	0.30	0.35	0.18	0.25	0.47	2.34	0.86	1.63	0.75	0.77	0.71	0.65	4.35
A. Ratio to Audubon Change - Drawdown (ft/ft)	1/16 -2/6	0.203	0.042	—	—	0.025	0.118	0.646	0.253	0.392	0.224	0.215	0.181	0.160	—
B. Ratio to Audubon Change - Drawdown (ft/ft)	1/16 - 3/20	0.213	0.072	—	—	0.069	0.141	0.682	0.271	0.477	0.253	0.256	0.224	0.206	—
C. Ratio to Audubon Change - Refilling (ft/ft)	3/20 - 4/17	0.122	0.069	0.08	0.04	0.057	0.108	0.538	0.198	0.375	0.172	0.177	0.163	0.149	—
D. Regression Slope (Well vs Audubon, ft/ft): DRAWDOWN 12/12/84-2/6/85	slope (ft/ft) R-value (# points)	0.206 .98 (5)	0.064 .939 (5)	NA	NA	0.0274 .916 (5)	0.121 .945 (5)	0.620 .998 (5)	0.244 .998 (5)	0.382 .999 (3)	0.217 .998 (5)	0.208 .999 (5)	0.178 .998 (5)	0.153 .980 (5)	—
E. Regression Slope (Well vs Audubon, ft/ft): REFILLING 3/13/85-4/17/85	slope (ft/ft) R-value (# points)	0.147 .969 (5)	0.0402 .836 (5)	.0479 .829 (7)	0.053 .805 (6)	0.0287 .872 (5)	0.0791 .907 (5)	0.539 .999 (4)	0.205 .995 (5)	0.341 .988 (5)	0.176 .983 (5)	0.168 .978 (5)	0.138 .963 (5)	0.115 .948 (5)	—
F. Regression Slope (Well vs Audubon, ft/ft): DRAWDOWN & REFILLING 12/12/84-4/17/85	slope (ft/ft) R-value (# points)	0.152 .948 (15)	0.0533 .876 (14)	NA	NA	0.0331 .715 (15)	0.0954 .943 (14)	0.542 .974 (14)	0.206 .961 (14)	0.340 .948 (12)	0.177 .937 (14)	0.168 .922 (14)	0.149 .949 (14)	0.126 .934 (14)	—
Rate of Water Level Change During DRAWDOWN Period 1/23/85-2/6/85	slope (rate of change, ft/yr)	-8.170	-3.426	-5.481	NA	-3.539	-3.425	-33.985	-13.43	-17.24	-11.59	-11.06	-9.745	-6.582	-58.25
G. Ratio to Audubon Slope ft/ft	DRAWDOWN	0.140	0.059	.094	NA	0.061	0.059	0.583	0.231	0.296	0.199	0.190	0.167	0.113	—
Rate of Water Level Change During REFILLING Period 3/20/85-4/4/85	slope (rate of change, ft/yr)	17.246	4.063	4.454	3.165	3.567	7.917	54.299	22.07	35.126	20.236	18.95	15.101	14.055	110.71
H. Ratio to Audubon Slope ft/ft	REFILLING	0.156	0.037	0.040	0.029	0.032	0.072	0.490	0.199	0.317	0.183	0.171	0.136	0.127	—

Notes: * = Water Level measured on 1/16/85 not used in analysis due to interference from well casing repair.

NA = Not Analyzed

Rows **A.** - **H.** correspond to the change in water elevation (in feet) in the observation well per foot of change in Lake Audubon elevation, as calculated by the method indicated. See text for description of calculation methods.

F. represents the line fit to the entire data record of 12/12/84 to 4/17/85 (across the drawdown and refilling periods). (In performing these direct regressions of water elevation at the observation wells versus Audubon elevation, the time lag will add uncertainty to the regressions for the more distant wells unless the water elevations are empirically shifted in time to match the time period in which Lake Audubon elevation was changing).

G.- H. Ratio of Water Elevation Rate of Change to Audubon Elevation Rate of Change. In this method, the slope of the line for water elevation in the observation well vs. date (rate of groundwater level change, feet/year) was divided by the slope of the line of Audubon water elevation vs. date (rate of Audubon change, feet/year). Row G represents calculations using the slopes during the Audubon drawdown period, while Row H represents the calculations using the slopes during the refilling period. The lines here were fit to data points in those portions of the hydrographs which correspond to water level change in the well induced by changes in Lake Audubon elevation. The slopes used for each well were from the best fit lines to data for the time period of greatest rate of change in response to the drawdown and then the period of the greatest rate of change corresponding to the refilling of Lake Audubon. Since the slope of the line of water elevation versus time is an interpolation between the weekly data points, this calculation method reduces the uncertainty that is introduced by the time lag between the changed elevation in Audubon and the corresponding response at the observation well into the direct regression of groundwater elevation versus Audubon elevation (methods D., E., and F., above)

As an example of this calculation method:

during refilling of Audubon the slope of the line representing the rate of water elevation change in well 148-82-23BBB between 3/20/85 and 4/3/85 (Fig. 29) is 15.1 feet/year. The corresponding slope for rate of water elevation change for the same period in Lake Audubon is 110.7 feet/year. Since the change in water elevation in the observation wells during this time period is attributed to the change in Lake Audubon elevation, the amount of change in the well per foot of change in Lake Audubon is determined as follows:

$$\frac{\text{148-82-23BBB slope}}{\text{Lake Audubon slope}} = \frac{15.1\ \text{ft/yr}}{110.7\ \text{ft/yr}} = 0.136\ \text{ft/ft.}$$

Where the units ft/ft indicate feet of water elevation change in the aquifer (at the monitoring well location) per foot of water elevation change in Lake Audubon.

Table 4 summarizes, for each calculation method, the estimated water level increase in the lower or middle aquifer unit at each observation well location which would have occurred in 1975 when the operating level of Lake Audubon was raised 13 feet. The minimum, maximum and mean estimates from the various calculation methods are also included in Table 4. The distribution of the estimated increases is shown on Figure 31. Predicted groundwater responses for a 13 foot change in Audubon ranged from 7.5 feet in well 148-82-07AAD3, located a few hundred feet from the shore of the lake, to about 0.5 feet at wells 148-80-31AAA2 and 148-80-34DCC, located 11 to 14 miles from the lake. At distances between 1 and 5 miles from the Lake, mean estimated increase in water elevation (for a 13 rise in Lake Audubon) ranged from 2.5 feet to 1.3 feet. These estimates assume a linear relation between the amount of change

TABLE 4. Predicted change* (feet) in water levels in the lower and middle aquifer units that would be caused by a 13-foot change in Lake Audubon elevation.

	Observation Well Location												
	147-82 02DCC	148-80 19CCC1	148-80 31AAA1	148-80 31AAA2	148-80 34DCC	148-81 29BAA1	148-82 07AAD3	148-82 08CDC1	148-82 08CDC2	148-82 21DDD	148-82 22BBB	148-82 23BBB	148-82 24ABB1
Distance from Audubon (mi)	0.2	10	11	11	14	5	0.1	0.3	0.3	0.5	1.5	2	3.5
Well Screen Depth (ft)	113-118	198-201	208-211	78-81	198-207	158-178	67-72	151-154	53-56	168-173	125-130	198-204	198-201
Elevation of Top of Screen (msl)	1765	1664	1653	1783	1670	1699	1789	1703	1801	1701	1750	1685	1658
Calculation Method*													
A. Ratio to Audubon Change - Drawdown 1/16/85 - 2/6/85	2.6	0.6	NA	NA	0.3	1.5	8.4	3.3	5.1	2.9	2.8	2.3	2.1
B. Ratio to Audubon Change - Drawdown 1/16/85 - 3/20/85	2.8	0.9	NA	NA	0.9	1.8	8.9	3.5	6.2	3.3	3.3	2.9	2.7
C. Ratio to Audubon Change - Refilling 3/20/85 - 4/17/85	1.6	0.9	1.0	0.5	0.7	1.4	7.0	2.6	4.9	2.2	2.3	2.1	1.9
D. Regression Slope: DRAWDOWN 12/12/84 - 2/6/85	2.7	0.8	NA	NA	0.4	1.6	8.1	3.2	5.0	2.8	2.7	2.3	2.0
E. Regression Slope: REFILLING 3/13/85 - 4/10/85	1.9	0.5	0.6	0.7	0.4	1.0	7.0	2.7	4.4	2.3	2.2	1.8	1.5
F. Regression Slope: DRAWDOWN + REFILLING 12/12/84 - 4/10/85	2.0	0.7	NA	NA	0.4	1.2	7.0	2.7	4.4	2.3	2.2	1.9	1.6
G. Ratio to Audubon; Drawdown Slopes 1/23/85 - 2/6/85	1.8	0.8	1.2	NA	0.8	0.8	7.6	3.0	3.9	2.6	2.5	2.2	1.5
H. Ratio to Audubon; Refilling Slopes 3/20/85 - 4/4/85	2.0	0.5	0.5	0.4	0.4	0.9	6.4	2.6	4.1	2.4	2.2	1.8	1.6
Minimum	1.6	0.5	0.5	0.4	0.3	0.7	6.4	2.6	3.9	2.2	2.2	1.8	1.5
Maximum	2.8	0.9	1.2	0.7	0.9	1.8	8.9	3.5	6.2	3.3	3.3	2.9	2.7
Mean	**2.2**	**0.7**	**0.9**	**0.5**	**0.5**	**1.3**	**7.5**	**2.9**	**4.8**	**2.6**	**2.5**	**2.2**	**1.9**

*Calculated as 13 times the water level change in the monitoring well per foot of Lake Audubon change during the response test (as given for **A - H** in Table **xxxLART 3**). Methods of normalizing the observation well water level response to 1 foot of stage level change in Lake Audubon are discussed in the text and are summarized below:

A. Water elevation change in well from 1/16/85 to 2/6/85 divided by change in Lake Audubon elevation during same period.
B. Water elevation change in well from 1/16/85 to 3/20/85 divided by change in Lake Audubon elevation during same period.
C. Water elevation change in well from 3/20/85 to 4/17/85 divided by change in Lake Audubon elevation during same period.
D. Slope from regression of water elevation in well vs Lake Audubon elevation on the same date between 12/12/84 and 2/6/85.
E. Slope from regression of water elevation in well vs Lake Audubon elevation on the same date between 3/13/85 and 4/10/85.
F. Slope from regression of water elevation in well vs Lake Audubon elevation on the same date between 12/12/84 and 4/10/85.
G. Ratio of slope of best fit line for period of greatest rate of change in water elevation in well to slope of best fit line for rate of change in Lake Audubon elevation during lake drawdown period (from 1/23/85 to 2/6/85).
H. Ratio of slope of best fit line for period of greatest rate of change in water elevation in well to slope of best fit line for rate of change in Lake Audubon elevation during lake refilling period (from 3/20/85 to 4/4/85).

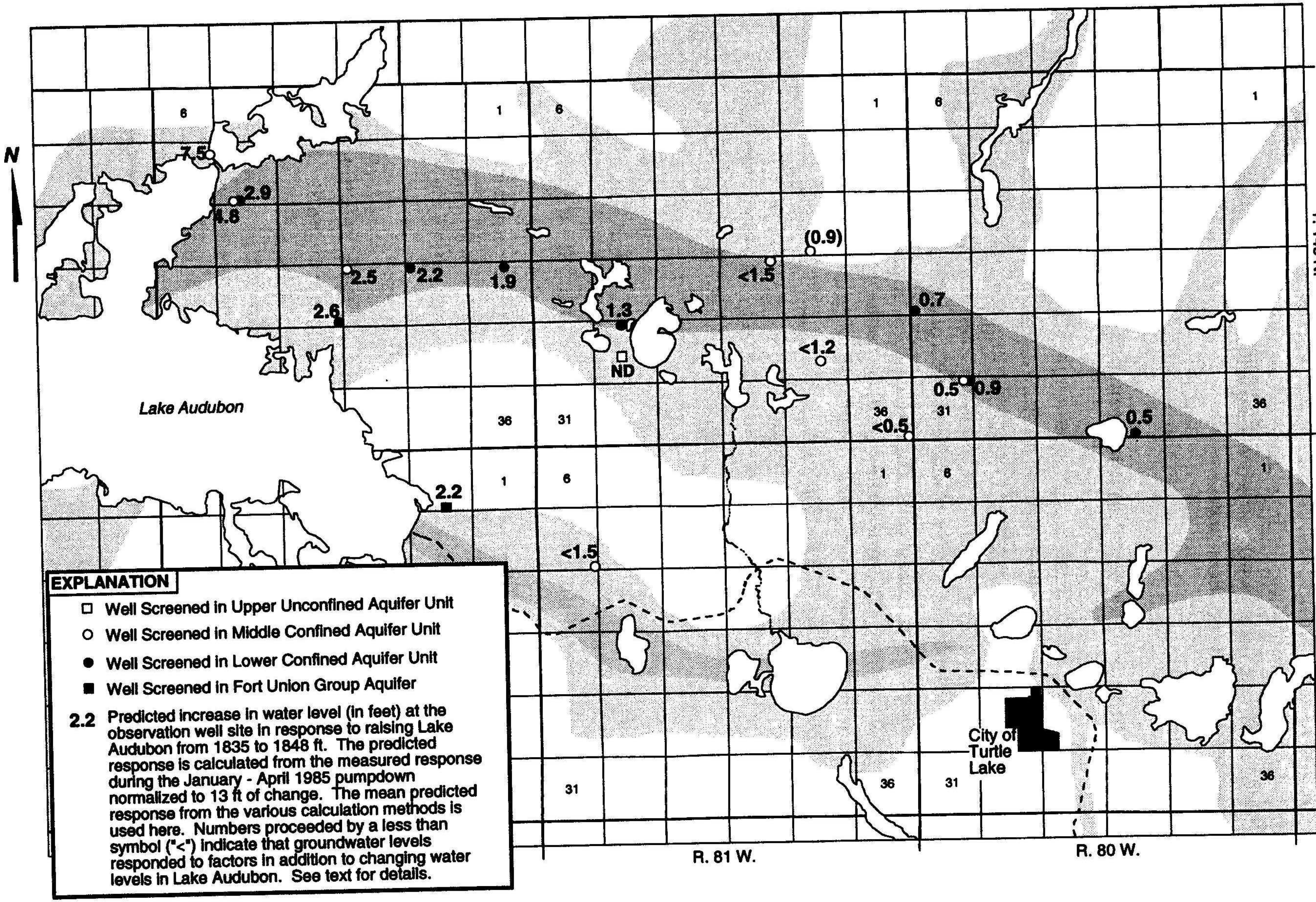


Figure 31. Calculated amount of water level rise in the middle and lower confined aquifer units that would have occurred in response to a 13 foot increase in Lake Audubon stage level.

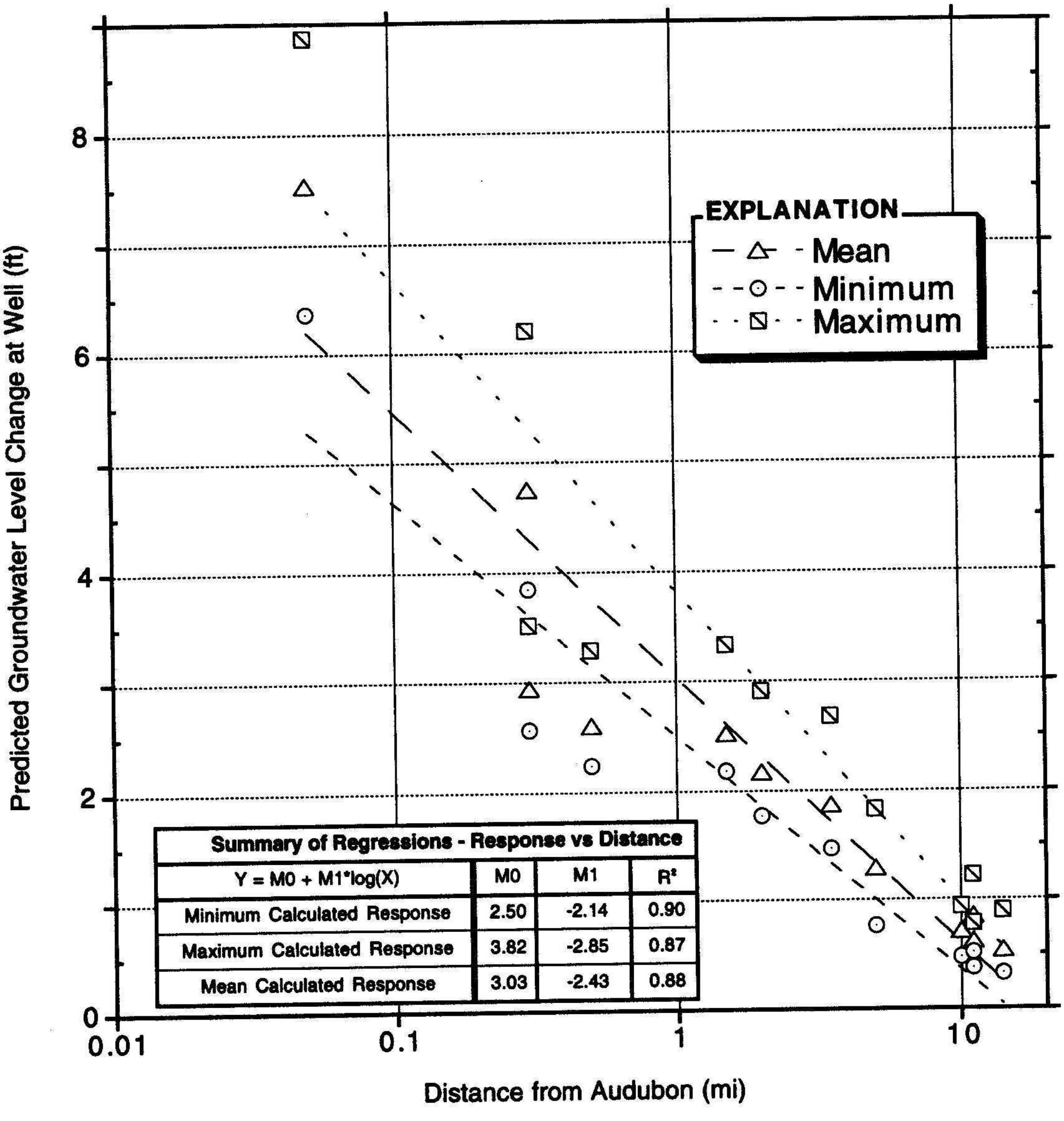
induced by the 4 feet of lake elevation change during response test and the amount that would have occurred in response to the larger 13 foot increase. Given the size of the system, and that the magnitude of Lake Audubon water level change during the response test was about 1/3 of the 13 foot change in 1975 (with the water level change occurring within the same elevation range), the linear approximation is considered valid.

RELATIONSHIP BETWEEN DISTANCE AND PREDICTED RESPONSE

Because the increased weight caused by the overlying lake water column is applied to the aquifer only in areas where it underlies the lake, the increased pressure caused by the lake dissipates with distance away from the lake. Thus the greatest water level response occurred at well 148-82-07AAD3, located only a few hundred feet from the lake in the upper part of the middle aquifer unit. The change in water levels in this well was about 58% of the corresponding change in Lake Audubon. The variation in water level in the next nearest well, 148-82-08CDC2 (also in the upper part of the middle aquifer unit), was about 37% of the corresponding change in Lake Audubon, while water level change in the deeper nested well in the lower aquifer unit, 148-82-08CDC1, was only about 22% of the corresponding change in Lake Audubon. The smaller water level change in the lower aquifer well, relative to that of the nested well in the middle unit, results from the fact that a portion of the pressure applied by the weight of the lake water column is carried by the aquitard materials that separate the middle and lower aquifer units.

The greater pressure change in the middle unit relative to that of the lower unit is only true very near the lake where the sand and gravel body in which wells 148-82-07AAD3 and 148-82-08CDC2 are screened appears to be continuous beneath the lake (Fig. 25). At greater distances from the lake (e.g. well nest 148-80-31AAA) the water level response in the middle unit is less than in the lower unit because the middle aquifer unit is not continuous to the east of the lake (see for example cross-section M-M', Plate 1). The pressure signal is propagated largely through the lower aquifer unit along the axis of the aquifer and then up into the overlying middle unit wherever it is present.

Predicted water level response in wells in the Lake Nettie Aquifer caused by a 13-foot change in Lake Audubon are plotted against the log of distance from Lake Audubon in Figure 32. The distances used are approximations of the distance from the shore of Lake Audubon to the well in a direction parallel to the axis of the aquifer. The distance - response relationship shown in Figure 32 and the distribution of the amount of response (Fig. 31) indicate that the expected water level response in the confined layers of the Lake Nettie Aquifer to the 13 foot increase in lake stage in 1975 would have been less than 3 feet at distances greater than one mile, less than 2 feet at distances greater than 3 miles, and less than 1 foot at distances greater than 10 miles from Lake Audubon.



Summary of Regressions - Response vs Distance			
$Y = M0 + M1*\log(X)$	M0	M1	R^2
Minimum Calculated Response	2.50	-2.14	0.90
Maximum Calculated Response	3.82	-2.85	0.87
Mean Calculated Response	3.03	-2.43	0.88

Figure 32. Predicted confined aquifer water level increase (in response to a 13 foot rise in Lake Audubon) versus distance from the Lake Audubon, as estimated along the aquifer axis.

Predicted rise is calculated from magnitude of water level change in the observation well during the 1985 Lake Audubon response test as tabulated in text.

WELLS WITH INDISTINCT RESPONSES TO LAKE AUDUBON

Of the 19 wells monitored for the response test, water level trends in 6 of the wells were not included in the analysis of aquifer response to changes in Audubon. As shown in Figure 30, water levels in 4 of these wells (148-81-22AAB, 148-81-26DBC, 148-81-29CAA, and 148-81-36DDD) declined about 0.1 feet between 1/15/85 and 2/13/85 (across the drawdown period). However, water levels in these 4 wells began rising between 2/27/85 and 3/6/85, while Lake Audubon was still drawn down, and 3 weeks prior to the onset of the refilling of Lake Audubon. The rise in water levels continued steadily until approximately 5/1/85. Water levels in these 4 wells were not included in the calculations to quantify the response of groundwater system to lake stage changes (Table 3) because their water levels were responding to factors other than the changes in Lake Audubon elevation. It is not possible to separate the amount of response in these wells due to changes in Lake Audubon stage from the amount due to other factors.

A portion of the rise in water levels in these wells probably due to an early period of above freezing temperature which began on 2/15/85 and extended through 3/31/85, as summarized below.

Average of Daily Maximum Temperatures
Reported for Turtle Lake (NOAA Data):

Time Period	Average of Daily Max Temperature (^oF)
01/01/85 - 01/15/85	19.4
01/16/85 - 01/31/85	14.8
02/01/85 - 02/14/85	6.2
02/15/85 - 02/28/85	39.2
03/01/85 - 03/15/85	37.1
03/16/85 - 03/31/85	47.4

The above average temperatures may have resulted in an episode of earlier than normal snow melt recharge that resulted in water level response in the wells. Well 148-81-29CAA is screened in the upper unconfined aquifer layer near the west side of Lake Nettie, 5 miles east of Lake Audubon. The remaining three wells in this group are screened in the upper part of the middle unit of the aquifer with well screens above 1760 feet in elevation where depth to the top of the screened aquifer unit is 60 feet or less. The three wells are all located in the southeast quadrant of Twp. 148-81, approximately 8 miles east of Lake Audubon (Fig. 27).

Figure 33 shows that the timing of the onset of the continued rise in water levels in the four wells (between the 2/13/85 and 2/20/85 measurements) corresponds to the period of when daily maximum temperatures first exceeded the freezing point. Snow melt recharge was apparently responsible for the rising trend in water levels in these 4 wells during the phase of the test in which Lake Audubon was drawn down and still declining slightly. Based on data from other wells, it is inferred that water levels in the middle aquifer unit wells would have varied by about 0.2 to 0.4 feet in response to Lake Audubon. The water level rise of 0.2 to 0.3 feet in the wells before the refilling of Audubon began masks or is added to any rise in water levels in these wells that could be attributed to Lake Audubon during the response test.

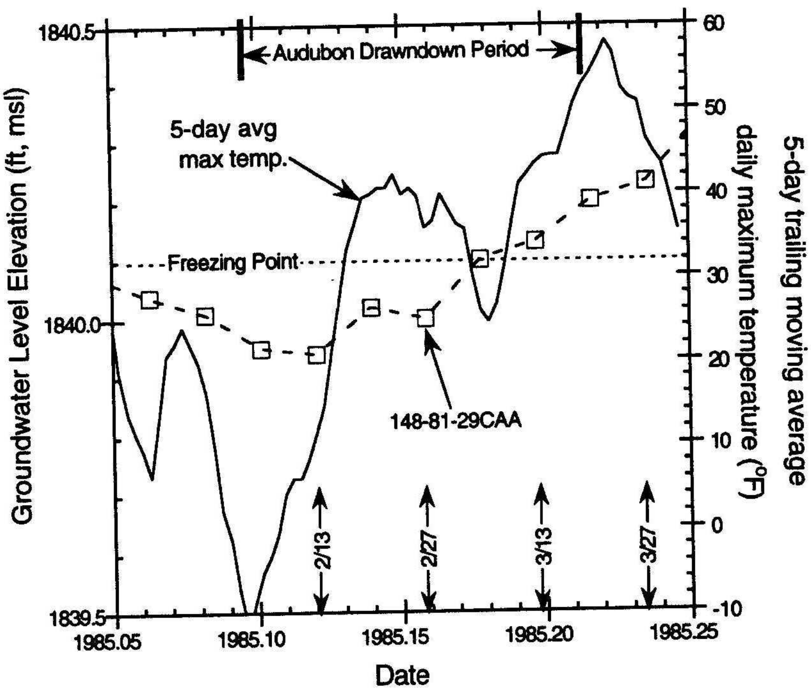


Figure 33. Partial hydrograph of water levels in well 148-81-29CAA and graph of the 5-day trailing moving average of maximum daily temperature at the Turtle Lake NOAA station. Note that the time at which the 5-day average maximum temperature exceeds the freezing point coincides with onset of rising trend in water levels.

Water levels in observation well 147-81-7DDD screened from 118 to 138 feet in the Turtle Lake Aquifer showed no distinctive response to the drawdown and refilling of Lake Audubon (Fig. 30). Water levels in the well appeared to decline about 0.3 feet during the drawdown phase of the test. The weekly water levels then oscillated up and down by 0.2 to 0.3 feet between 2/13/85 and 3/13/85 when Audubon was drawn down. Water levels did rise 0.5 feet during the refilling of Lake Audubon, but then dropped 0.3 feet between 4/17/85 and 4/24/85 while the reservoir was maintained at its operating level. These masking oscillations make it difficult to quantify water level changes due to Audubon.

Based on other observation well data, up to 0.5 feet of water level response during the test would be expected at 147-81-7DDD, due to the confined nature of the aquifer at this location and proximity to Lake Audubon (3 miles). The historic record for this well indicates that water levels oscillations of a few tenths of a foot over a period of 1 to 2 weeks are common in this well. The cause of the water level oscillations is not known with certainty, but may be partly attributable to pumping patterns from the City of Turtle Lake supply wells which obtained its supply from the confined units of the Turtle Lake Aquifer a few miles to the east between 1982 and 1990.

As shown in Figure 30, water levels in well 148-81-14CDD did exhibit a prolonged decline of 0.3 feet between 1/23/85 and 3/20/85, probably a sluggish response to the lowering of Lake Audubon. Water level in this well also exhibited a rise totaling about 0.35 feet which began within one week of the onset of Audubon refilling but which continued until about 3 weeks after Audubon had been refilled and maintained at a steady level. Well 148-81-14CDD is located approximately 8 miles east of lake Audubon and is screened in a 5 foot thick lens of sand and gravel immediately overlying Fort Union Group bedrock. This sand and gravel lens appears to be partially separated from the main sand and gravel bodies of the aquifer units, which may account for the delayed nature of the response. Because of the possibly isolated nature of the screened sand and gravel body and the sluggish water level response, this well was not included in the calculated estimates of response to a 13 foot change in Lake Audubon (Tables 3 and 4). However, based on the 0.35 foot increase in groundwater elevation after the refilling of Lake Audubon, the estimated groundwater response at this well to a 13 foot increase in Lake Audubon would be about 1.0 foot, which is consistent with other wells in the data set. The response of water levels in this partially isolated sand and gravel lens shows propagation of the pressure signal through the less permeable units.

The estimated responses of water levels in the wells with indistinct responses due to climatic interference, water level oscillations or sluggishness are tabulated below:

	147-81 07DDD	148-81 22AAB	148-81 26DBC	148-81 36DDD	148-81 14CDD	Lake Audubon
Water Level Change 1/16/85 - 2/13/85	-0.32 ft	-0.17	-0.13	-0.05	-0.17	-2.51
Response to 13 ft Change Based on Drawdown Response	1.6	0.9	0.7	0.3	0.9	
Water Level Change 3/20/85 - 4/17/85 or 4/24/85	<0.51	<0.49	<0.39	<0.18	0.35	4.35
Response to 13 ft Change Based on Refilling Response	<1.5	<1.5	<1.2	<.5	1.0	

The less than sign ("<") indicates that water level changes due to apparent snowmelt recharge are included in the measured water level rise. The water level rise attributable to Lake Audubon will be some fraction of the observed amount.

RATE OF AQUIFER RESPONSE TO CHANGES IN LAKE AUDUBON

In addition to the weekly measurements, continuous water level recorders were installed on 3/5/85 and monitored until 4/17/85 in the following 5 wells:

148-80-19CCC1
148-81-29BAA1
148-82-08CDC1
148-82-08CDC2
148-82-23BBB

Depth to water measurements obtained from the continuous recorders were corrected for the effects of atmospheric pressure changes by using barometric data obtained from a microbarograph which was set up at the Snake Creek pumping plant on 1/22/85 and operated until 4/14/85. Barometric efficiencies for the wells determined from data collected between 3/5/85 and 3/19/85 were as follows:

Well	Screened Interval	Aquifer Interval	Barometric Efficiency
148-80-19CCC1	198-201 ft	183-208 ft	14.2 %
148-81-29BAA1	158-178	153-203	13.5
148-82-08CDC1	151-154	147-187	13.5
148-82-08CDC2	53-56	41-61	23.0
148-82-23BBB	198-204	140-205	12.8

Selected points extracted from the continuous recorder data are plotted on Figure 34 together with Lake Audubon Elevation. The responses of water levels in the confined system were quantified by applying calculation methods **C** (ratio water level increase to Audubon change during refilling) and **H** (ratio of slopes of rate of change), as described above for Table 3, to the recorder data. The predicted groundwater level responses for a 13 foot change in Lake Audubon, as calculated from the recorder well data, are tabulated below. The mean of the calculated values from the weekly measurements (from Table 3) are also included below for comparison:

Predicted Water Level Change at Well for a 13 foot Change in Audubon

Well	Recorder Well Data		Weekly Data
	Ratio of Elev. Change	Ratio of Slopes	Mean
148-80-19CCC1	0.8 ft	0.7 ft	0.7 ft
148-81-29BAA1	1.3	1.0	1.3
148-82-08CDC1	2.7	2.7	2.9
148-82-08CDC2	4.6	3.8	4.8
148-82-23BBB	2.1	1.8	2.2

The values calculated for the recorder well data all lie within +/-20% of the mean calculated value for the weekly data summarized in Tables 3 and 4. Thus, it can be concluded that the weekly measurements made at the non-recorder wells adequately characterize the magnitude of the groundwater response at those wells, and that the associated predictive calculations performed with the data are reasonably reliable.

The continuous nature of the recorder data provides a means of evaluating the rate at which the groundwater levels respond to the elevation changes occurring at Lake Audubon. The onset of water level rise in the wells ranged from 30 hours to about 200 hours after the pumps were

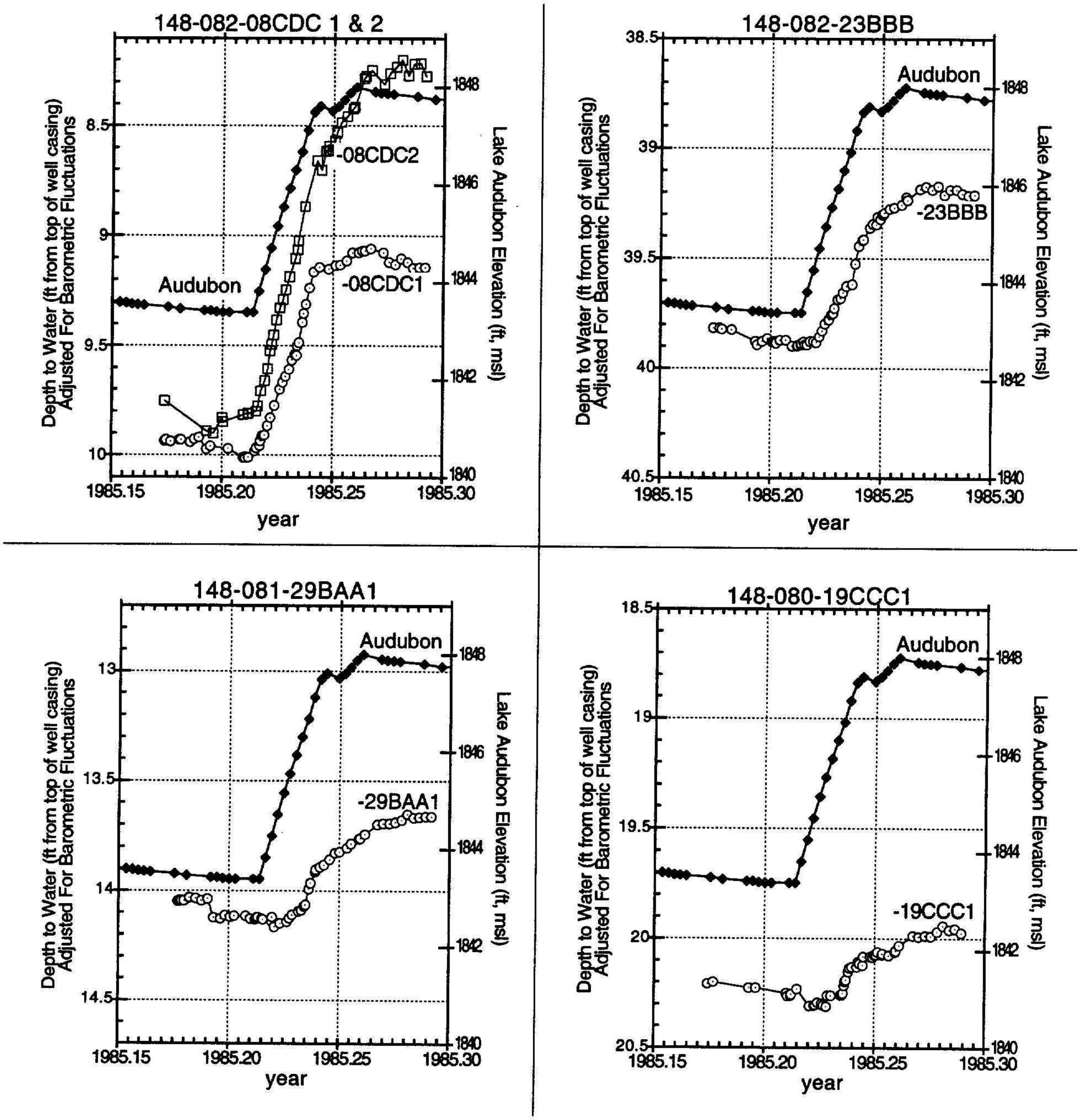


Figure 34. Continuous recorder well water level data and daily Lake Audubon elevations during refilling phase of Lake Audubon response test. Depth to water in wells has been corrected for barometric fluctuations. Depth to water axes are exaggerated by a factor of 4.5 relative to the Lake Audubon elevation axes.

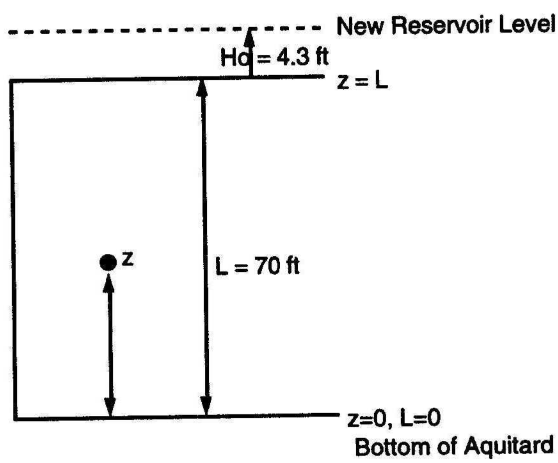
turned on to begin refilling the Lake, with the time lag increasing with distance from Lake Audubon, as summarized below:

Well	Distance	Onset of Rise
148-82-08CDC1	0.3 mi	30 hrs
148-82-08CDC2	0.3	30
148-82-23BBB	2	80
148-81-29BAA1	5	100
148-80-19CCC1	10	200

Lake Audubon would have risen only about 0.5 feet in elevation in the 30 hours between the start of pumping to refill the reservoir and the onset of rise at well nest 148-82-08CDC1,2. The rapid response of the aquifer water levels indicates that the cause of the rise in groundwater levels is the weight of the increased height of the column of lake water in areas overlying the aquifer. The increased load increases the downward pressure on the underlying material. A portion of the pressure load is born by the sediment particles in the till aquitard that underlies the reservoir and by the sediment particles of the aquifer matrix. The remainder of the load is carried by the water that exists in the pores of the aquifer and aquitard. The increased hydrostatic pressure results in an increased hydraulic head in the aquifer, resulting in an increase in the height of the water column in the observation well. A pressure change can propagate rapidly through the aquifer-aquitard hydraulic system, whereas actual movement of water leakage through the till that underlies the lake, if it occurred at all, would be at a rate much slower than was indicated by the timing of the observed water level response in the aquifer.

The stepped head analytical approach (Bredehoeft and Hanshaw, 1968) was used to evaluate the vertical distribution of the increase in hydraulic head through a till aquitard that would be caused by movement of leakage water due to an "instantaneous" increase in hydraulic head (raised reservoir stage) above the aquitard.

The system is schematically illustrated below:



The governing equation for the system is given by equation (1):

$$\frac{\partial^2 h'}{\partial z^2} = \frac{Ss}{K}\frac{\partial h'}{\partial t} \quad \text{where } 0 \le z \le L \qquad \text{(eq. 1)}$$

$$h'(z,0) = 0 \quad at\ t = 0$$

$$h'(0,t) = 0 \quad at\ t > 0 \ \text{(constant head boundary)}$$

$$h'(L,t) = H_0 \quad at\ t > 0$$

where the variables and associated units are:

h' = excess head (length)
z = depth (length)
Ss = aquitard specific storage (length^{-1})
Kv = aquitard vertical hydraulic conductivity (length/time)
L = aquitard thickness (length)
H_0 = constant stepwise change in head in reservoir (length).

The solution for equation (1), given by Bredehoeft and Hanshaw (1968) is:

$$h' = H_0 \sum_{n=0}^{\infty} \left[erf\left\{ \frac{(2n+1) + z/L}{(4Kt/SsL^2)^{1/2}} \right\} - erf\left\{ \frac{(2n+1) - z/L}{(4Kt/SsL^2)^{1/2}} \right\} \right] \qquad \text{(eq. 2)}$$

Equation (2) was used to evaluate the vertical distribution of increased hydraulic head in 70 feet of till between the reservoir bottom and the top of the lower aquifer unit at a time of 200 hours (8.33 days) after the reservoir was raised, assuming an "instantaneous" increase of 4.3 feet in the reservoir. The value of 70 feet for the aquitard thickness is the thickness of till separating the middle aquifer unit and lower aquifer unit at well 148-82-08CDC1 near the east side of Lake Audubon. The thickness of low hydraulic conductivity till between the bottom of the reservoir and the top of the lower aquifer unit may actually be in excess of 100 feet near the east side of Lake Audubon (cross-section M-M', Plate 1). The value of 70 feet provides a reasonably conservative estimate of the thickness of the low hydraulic conductivity unit. Values of input variables used in the analysis are:

H_0 = 4.3 feet
t = 8.33 day
Ss = $1.8\text{x}10^{-4}$ ft^{-1} ($6\text{x}10^{-4}$ m^{-1})
Kv = $2.8\text{x}10^{-5}$ to $2.8\text{x}10^{-2}$ ft/day ($1\text{x}10^{-10}$ to $1\text{x}10^{-7}$ m/s)

The value of $1.8\text{x}10^{-4}$ ft^{-1} for *Ss* (aquitard specific storage) is the mean value using data from consolidation tests performed by Porter and O'Brian Inc. (1962) on 108 till samples from ICBM missile silo sites in the Minot and Grand Forks North Dakota areas (Bob Shaver, SWC written communication).

The excess head (*h'*) versus depth (*z*) in the till aquitard calculated from an "instantaneous" 4.3 foot rise in Lake Audubon for the range of till hydraulic conductivity estimates is tabulated below:

z (ft)	h' (ft) $Kv = 2.8\text{x}10^{-5}$ ft/d	h' (ft) $Kv = 2.8\text{x}10^{-2}$ ft/d
70 (top of aquitard)	4.30	4.30
69	2.30	4.23
68	0.92	4.16
67	0.27	4.09
66	0.06	4.02
65	0.01	3.95
60	0.00	3.60
55		3.25
50		2.91
40		2.26
30		1.65
15		0.80
1 (bottom of aquitard)		0.05

The calculated increase in head in the aquitard due to actual transmittance of leakage water from the increased reservoir stage has propagated less than 10 feet into the till after 200 hours using a value of $2.8\text{x}10^{-5}$ ft/day (10^{-10} m/s) for till conductivity. Even using the generously high estimate for till hydraulic conductivity of $2.8\text{x}10^{-2}$ ft/day (10^{-7} m/s) results in a calculated excess head of only 0.05 feet at the base of the till aquitard. It is clear from the stepped head analysis that the response of water levels in the confined aquifer units resulted from a loading effect, because the water level in well 148-82-08CDC1 began responding to the increase in Lake Audubon elevation only 30 hours after refilling began, when the reservoir had risen about 0.5 feet. The aquifer and aquitard matrix sediments are "squeezed" by the weight of the increased water column in the overlying reservoir and a portion of the load is transmitted from the aquifer matrix to the pore water, causing increased pore fluid pressure and a rise in water levels in observation wells screened in the confined aquifer units.

By examining the hydrographs in Figures 29 and 34, it is evident that groundwater levels at wells within 5 miles of Lake Audubon had equilibrated with the changed lake elevation within a few days after stabilization of lake level had been achieved. Water levels at wells between 5 and 14 miles had equilibrated within 2 to 3 weeks after the stabilization of lake level had been achieved. Thus, it is reasonable to conclude that confined groundwater levels within 10 miles of Lake Audubon would have equilibrated by the end of 1975 with the 13 foot increase in operating elevation, which occurred from early July 1975 through the end of September 1975.

It should be emphasized that the estimated groundwater level increases discussed above pertain to only the confined lower and middle units of the aquifer system, where the pressure increase caused by the weight of the overlying reservoir water column is transmitted rapidly thorough the system. The magnitude of potential changes in water levels in the upper unconfined aquifer layers would be much less due to differences in storage terms and the timing would be much more sluggish because the actual transmission of leakage water (not just pressure) would be necessary to cause a water level change.

PREDICTED AQUIFER RESPONSE VERSUS RESPONSE MEASURED IN 1975

Measurement of water levels in observation wells in the study area during 1974 and 1975 was sparse. However some insight relative to the extent which Lake Audubon water levels affect the aquifer water levels can be gleaned from inspection of relevant hydrographs pertinent with reference to the information obtained from the Lake Audubon response test. Figure 35 presents the relevant water level measurements made in observation wells in 1974 through 1976.

Figure 35A indicates the magnitude to which water levels in the lower and middle aquifer units in the west part of the study area rose in response to Lake Audubon. Water levels in well 148-82-23BBB, and well nest 148-80-31AAA1,2 were also measured during the 1985 response test. A comparison of the measured differences in the water levels before and after the 1975 raising of Lake Audubon with those predicted from the results of the 1985 response test is tabulated below.

Well	Aquifer Unit	Measurement Dates	Measured Water Level Change	Predicted Water Level Change
148-82-23BBB	Lower	12/2/74 - 12/2/75	2.54 ft	2.2 ft
148-80-31AAA1	Lower	5/16/75 - 12/2/75	0.84	0.9
148-80-31AAA2	Middle	5/16/75 - 12/2/75	0.12	0.5

The agreement between the predicted and measured responses is quite good with the exception of the overprediction of the response in middle aquifer unit at well 148-80-31AAA2. However, the spacing of measurement dates in 1975 makes it difficult to strip out any climatic influences that may also have been occurring at this well. The poor agreement between the measured and predicted change in well 148-80-31AAA2 is possibly a result of seasonal climatic fluctuations that were superimposed during the 1985 response test. A small increase in groundwater level due to climatic response would have introduced a large relative error in the quantification of predicted response at this well as water levels varied only about 0.2 feet during the 1985 response test. Conversely, a small seasonal summer decline in water levels at the well in 1975 could have partially offset any groundwater level increase due to the raising of Lake Audubon.

Water levels in nested well 148-80-31AAA1 indicate that a slight rising trend may have started before 5/16/75 prior to the raising of Audubon. Water levels in the upper aquifer (well 148-81-33CDD) did not respond to changes in Lake Audubon Stage, but exhibited a typical annual cycle with a slight rise in the early spring through early summer, then declining through late summer and fall. The water levels in well 148-81-33CDD suggest that seasonal climatic variations in the groundwater levels were not extreme in 1975 and that the measured water level changes in wells 148-80-31AAA1 and 148-82-23BBB reasonably characterize the magnitude of aquifer water level response to the 13 foot increase in Lake Audubon stage. The

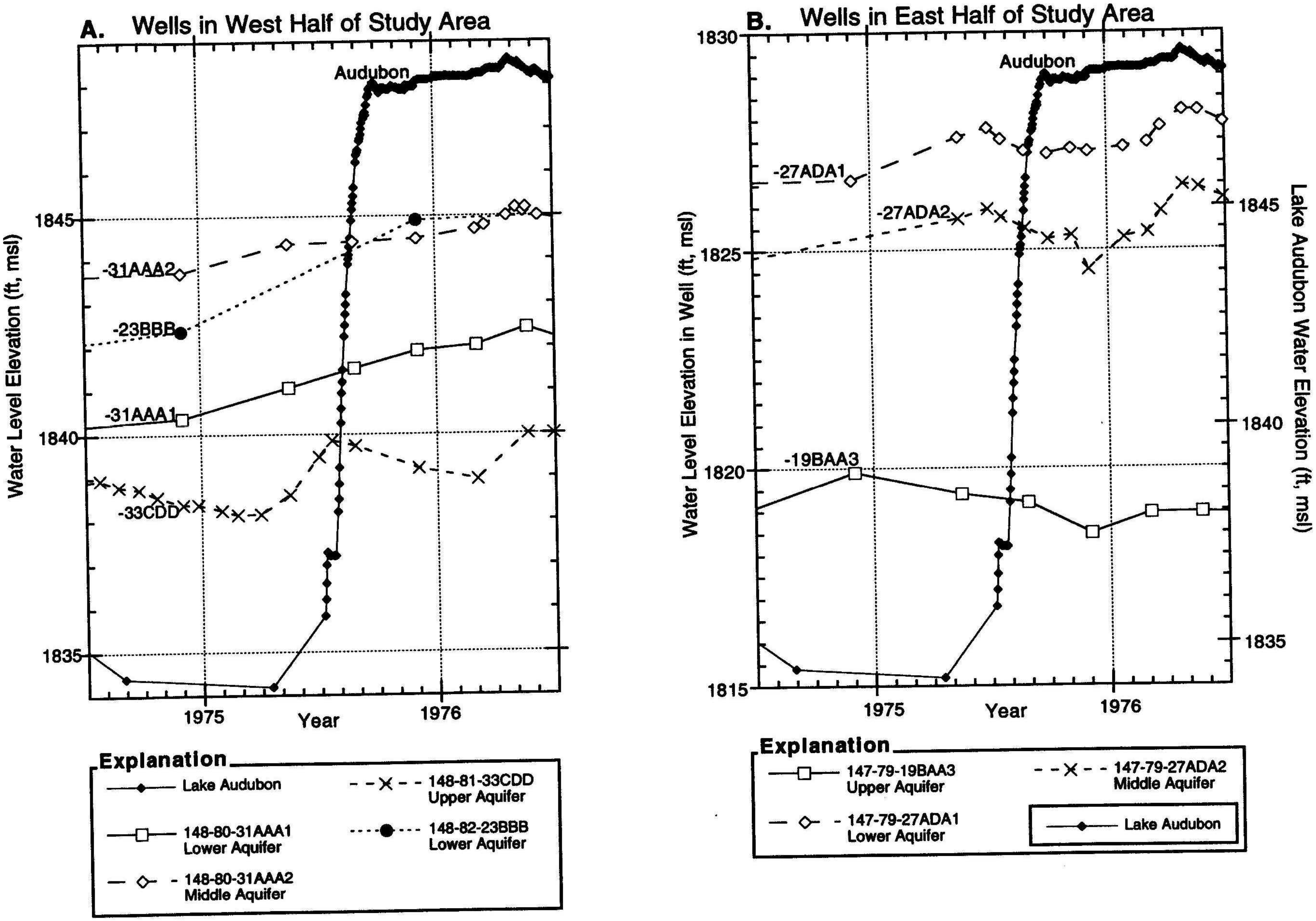


Figure 35. Water level elevations in selected observation wells and in Lake Audubon, July 1974 to July 1976.

agreement between predicted and measured water level response in the lower aquifer unit supports the extrapolation of the 1985 Lake Audubon response test data to reliably estimate the magnitude of groundwater change in response to changes in reservoir stage.

Water level trends shown in Figure 35B for the east half of the study area show no indication of water level rise in response to Lake Audubon. The wells plotted in Figure 9B are 18 to 21 miles east of Lake Audubon. The relationship between predicted water level rise and distance from Audubon (Fig. 32) suggests that the predicted groundwater level rise extinguishes to zero at about 15 miles from the lake. Practically speaking, water level increases of less than about 1 foot would be very difficult to distinguish from seasonal climatic variations.

CONCLUSIONS FROM LAKE AUDUBON RESPONSE TEST

It is clear from the Lake Audubon response test that groundwater levels in the middle and lower units of the Lake Nettie aquifer, and the confined units of the Turtle Lake aquifer, did rise in response to the increase in the level of Lake Audubon from 1835 to 1848 feet in 1975. The rise in water levels was a result of increased fluid pressure in the aquifer caused by the weight of the lake water column in the area overlying the aquifer. Because the increased load is applied only beneath the column of lake water, increased pressure dissipated away from the reservoir and the amount of induced groundwater rise decreases with increasing distance form the reservoir. The estimated increase in groundwater levels ranged from greater than 5 feet in the middle aquifer unit within a quarter of a mile of the reservoir, between 2 and 3 feet from 1 to 3 miles, between 1 and 2 feet from 3 to 10 miles and less than one foot at distances greater than 10 miles from the reservoir.

Groundwater levels in the confined lower and middle aquifer units responded quickly to the partial drawdown and refilling of Lake Audubon, equilibrating with the changed reservoir stage within a few days to a few weeks. The rapid equilibration of groundwater levels observed during the response test contradicts Armstrong's (1983) conclusion, which was based on groundwater level trends from 1967 to 1982, that water levels east of Lake Nettie were still rising in 1982. Equilibration of groundwater levels in the confined aquifer units with the 13 foot increase in Lake Audubon elevation (July through September 1975) would have occurred by the end of 1975. Groundwater levels in the upper aquifer unit near Lake Nettie showed no measurable response to changes in Lake Audubon elevation during the 1985 response test.

LAKE NETTIE WATER LEVEL CONTROL PROJECT

During the summer of 1987 water was pumped from Lake Nettie into Mud Lake in order to temporarily alleviate high surface water levels at the Lake Nettie National Wildlife Refuge. Water was pumped using two diesel powered pumps, rated at 6.25 and 11.55 cubic feet per second, from the east side of Lake Nettie and discharged through pipes into the northwest bay of Mud Lake. Pumping operations were performed by the USBR, commencing on June 29, 1987 and ending on September 20, 1987. The pumps were operated for a total of 3,139 hours with a total pumped water volume of 2,240 acre-feet.

Groundwater levels were monitored to evaluate the interaction between groundwater and surface water in the Lake Nettie area. Beginning in June and continuing through October, water levels in 34 observation wells at 27 sites were measured weekly and 40 observation wells at 34 sites were measured three times per week. The wells are located in the Lake Audubon - Lake Nettie - Turtle Creek portion of the study area.

Staff gages were maintained on Lake Nettie, Crooked Lake and Mud Lake and read weekly for the duration of the pumpdown. A National Weather Service standard storage type rain gage was set out on the east side of Lake Nettie and was monitored daily by the USBR. In order to provide a measure of the amount of evaporative loss from surface water bodies in the area, a 42-inch diameter stock tank was set out on July 1 near the pump site on Lake Nettie. Water level in the tank was read daily from a surveyors rod calibrated to 0.01 foot that was clamped to the side of the tank. Measured amounts of water were added to the tank as needed to keep the water level near the top of the tank to facilitate evaporation, but low enough to minimize spilling out of the tank due to wave action caused by wind. The tank was covered with a one inch mesh chicken wire to discourage animals from imbibing from the tank. Water samples were collected from 16 observation wells around Lake Nettie and from Crooked Lake, Lake Nettie and Mud Lake in June, August, September and October 1987 in order to evaluate any potential changes in water chemistry resulting from the lake pumpdown.

Water level and water quality data associated with the Lake Nettie pumpdown are included in the basic data portion of this report (Part I). Precipitation and evaporation tank data at Lake Nettie are summarized in the Table 5.

Because precipitation will also fall in the evaporation tank, the cumulative net evaporative loss represents the total evaporation minus offsetting rainfall to yield net evaporative loss. Because the lakes of interest are shallow (less than 4 or 5 feet deep with many areas less than 3 feet) it will be assumed in this analysis that the measurements of net evaporation from the stock tank provides a reasonably accurate approximation of net evaporative loss (total evaporation minus direct precipitation) from the adjacent lakes.

Total evaporation measured from the tank (net evaporation loss plus rainfall) was 23.3 inches for the period 6/29/87 to 9/21/87. Average total July through November evaporation for the

Table 5. Precipitation and Evaporation Data at Lake Nettie, July - November 1987

date	precipitation (inches)	*cumulative precipitation (inches)	*cumulative net evaporative loss (inches)	*cumulative net evaporative loss (feet)
7/6/87	0.03	0.03	1.44	0.12
7/9/87	0.37	0.40	2.16	0.18
7/10/87	0.35	0.75	1.80	0.15
7/11/87	0.13	0.88	1.80	0.15
7/12/87	0.85	1.73	0.84	0.07
7/14/87	0.03	1.76	1.32	0.11
7/19/87	1.66	3.42	0.96	0.08
7/20/87	0.13	3.55	0.96	0.08
7/22/87	1.35	4.90	0.60	0.05
7/29/87	0.31	5.21	2.04	0.17
7/30/87	0.15	5.36	1.92	0.16
8/1/87	0.15	5.51	2.16	0.18
8/2/87	0.02	5.53	2.40	0.20
8/14/87	0.20	5.73	5.52	0.46
8/15/87	1.12	6.85	4.68	0.39
8/16/87	0.12	6.97	4.80	0.40
8/18/87	0.31	7.28	4.68	0.39
8/19/87	0.05	7.33	4.80	0.40
8/21/87	0.03	7.36	5.04	0.42
8/25/87	0.42	7.78	5.64	0.47
8/26/87	0.92	8.70	4.80	0.40
9/11/87	0.21	8.91	7.44	0.62
9/17/87	0.03	8.94	8.28	0.69
9/21/87	---	8.94	8.64	0.72
9/29/87	0.18	9.12	9.72	0.81
11/3/87	0.05	9.17	13.56	1.13
11/13/87	---	9.17	14.16	1.18
TOTAL	9.17	9.17	14.16	1.18

* = cumulative since 6/29/87.

area is 22 inches (U.S.W.B.; TP-37). Total evaporation measured at Lake Nettie for July through September 29 was 18.84 inches (9.72 inches of measured net loss from the tank plus 9.12 inches to offset rain falling in the tank). July through September precipitation recorded at Lake Nettie was 9.12 inches, about three inches greater than average for the area. The NOAA station in Turtle Lake reported 7.81 inches of precipitation for July through September versus an average of 6.02 inches. Above normal precipitation was experienced in July and August, while September and October precipitation was below normal.

Estimated area and capacity data for Lake Nettie and Crooked Lake is tabulated below. In the analyses of water volumes gained or lost by the lakes, necessary elevation - area/capacity relations were determined by interpolating between the data points.

	Lake Nettie		Crooked Lake		Combined Lakes	
Elevation	Area	Capacity	Area	Capacity	Area	Capacity
1837	355		215		570	
1838	400	375	295	255	695	630
1839	451	901	375	490	826	1391
1840	505	1379	455	905	960	2284
1841	561	1912	535	1400	1096	3312
1842	615	2501	615	1975	1230	4476

Area in acres; Capacity in Acre-feet

RESPONSE OF SURFACE WATER BODIES

Figure 36 shows the water surface elevations for the Lake Nettie, Crooked Lake and Mud Lake together with precipitation data. The water surface elevation of Lake Nettie dropped 2.6 feet from an elevation of 1841.49 feet on 6/29/87 to an elevation of 1838.89 feet on 9/21/87 when pumping had stopped, then rebounded about 0.4 feet total through mid November. Crooked Lake dropped 1.01 feet from 6/29/87 to 9/21/87 and then continued to decline about an additional 0.3 feet total through mid November. Pumping from Lake Nettie also affected Crooked Lake as the east bay of Crooked Lake is connected to the north bay of Lake Nettie via a road culvert with an invert elevation of 1839.3 feet. Mud Lake rose about 0.7 feet to elevation 1840.1 after pumping started and stayed fairly consistently near that elevation until pumping discharge into the lake ceased, at which time it declined in elevation due to outflow to Turtle Creek. Water elevations in other lakes and sloughs between Lake Audubon and Highway 41 typically had seasonal water level declines of 0.1 to 0.3 feet and in some cases increases of about 0.1 feet between 6/29/87 and 9/21/87.

Water elevations in Lake Nettie and Crooked Lake increased between July 19 and 22 due to intense rainfall events. The response of the lakes during this and similar short time periods allows a partial evaluation of the amount of runoff into the lake. Rainfall totaling 1.66 inches was recorded on 7/19. Between 7/18 and 7/19, Lake Nettie rose 1.6 inches (0.13 feet). Had there been no water input other than direct precipitation, Lake Nettie would have declined due to evaporation and the removal by pumping of approximately 35 acre-feet between 7/18 and 7/19. The 35 acre-feet pumped from the lake corresponds to about 0.76 inches of water with a lake area of about 554 acres at elevation 1840.9. The estimated evaporative loss betwen 7/18 and 7/19 was about 0.34 inches (1.66 inches of rainfall minus 1.32 inches of measured water level gain in the evaporation tank). Thus, the one day amount of surface runoff plus groundwater inflow was equal to about 1.1 inches of water (about 51 acre-feet).

Between 7/21 and 7/22 the lake rose 1.3 inches (0.11 feet) in response to 1.35 inches of precipitation recorded on 7/22. Approximately 32 acre-feet (corresponding to 0.7 inches of water) was pumped from the lake during the one day period. The estimated evaporative loss between 7/21 and 7/22 was about 0.51 inches (1.35 inches of rainfall minus 0.84 inches of measured water level gain in the evaporation tank). Thus, the one day amount of surface runoff plus groundwater inflow was equal to about 1.2 inches of water (about 55 acre-feet).

Between 7/22 and 7/25 the lake dropped only 0.01 feet (0.12 inches) No rainfall fell in this three day period which followed the 7/19 and 7/22 storms. Net evaporation during this period was about 0.02 feet per day (or about 0.72 inches for the three days). The amount of water pumped from the lake between the 7/22 and 7/25 staff gage readings was about 80 acre-feet (or 1.75-inches of water). If no runoff or inflow occurred to the lake, then the lake water

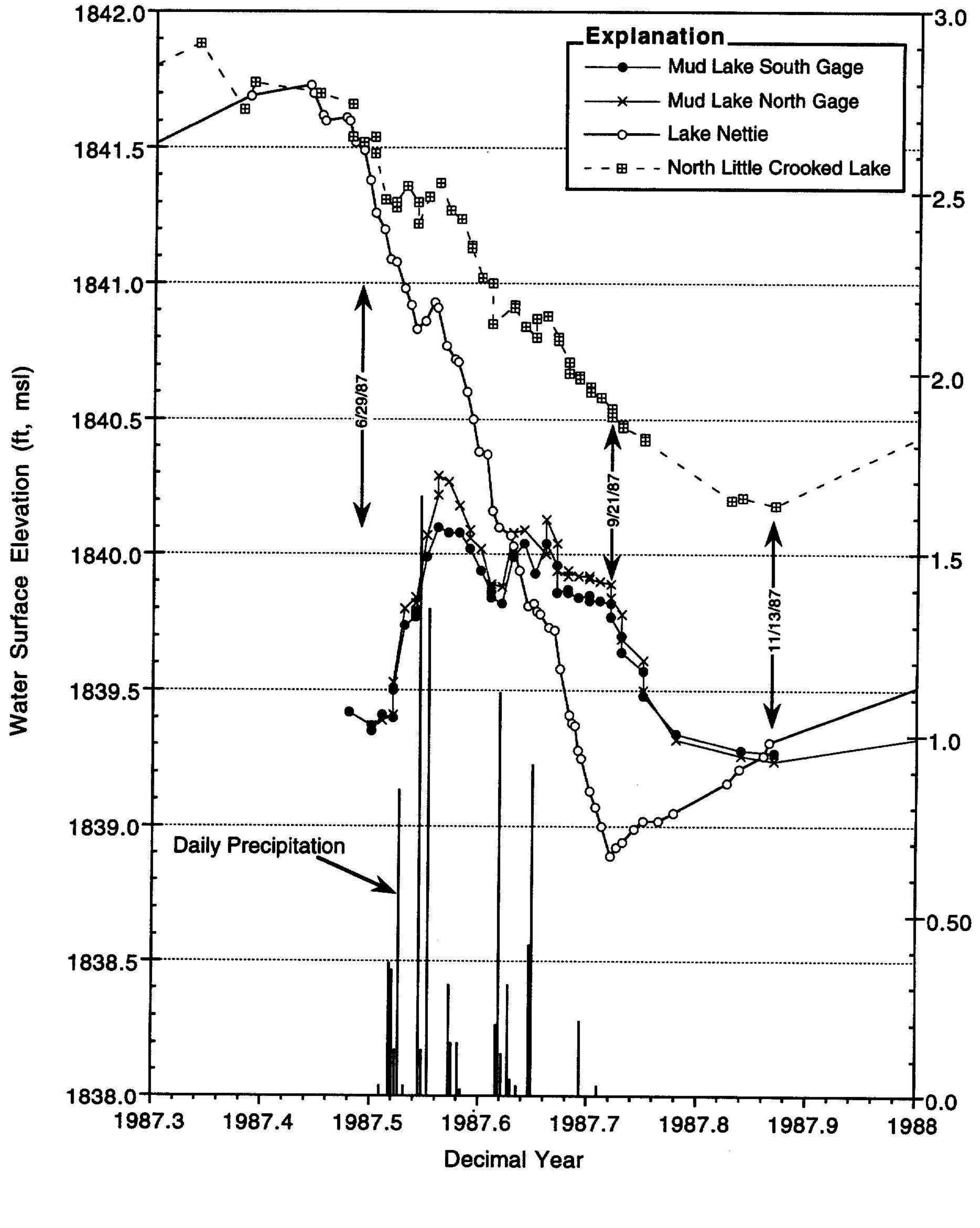


Figure 36. Lake stage elevations and July through September precipitation during Lake Nettie pumpdown, 1987.

level should have dropped 0.20 feet (2.47 inches) due to the combined effect of pumping and evaporation, but the measured drop was only 0.01 feet (0.12 inches). Thus surface runoff or inflow plus groundwater inflow made up for 0.19 feet (2.28 inches) of water or 104 acre-feet, equivalent to about 35 acre-feet per day for the three day period.

It is not possible to directly separate this calculated estimate of inflow into its surface water runoff and groundwater inflow components, as the rate of flow through the culvert from Crooked Lake to Lake Nettie was not measured. However, the estimates show the relatively small amount of surface runoff contribution to the lake's water budget over the course of the pumpdown. Estimates of daily groundwater inflow rates during periods when there had been no precipitation, suggests that about 1/3 of the 35 acre-feet per day rate is due to groundwater inflow. The total amount of runoff inflow to the lakes for the 7/19 to 7/25 period was thus about 3 inches, approximately equal to the amount of direct precipitation falling on the lakes on 7/19 and 7/22. The only other periods with a potential to have produced surface runoff into the lakes were 8/15 with 1.12 inches and 8/25 to 8/26 with a total of 1.34 inches of rainfall. Thus, the upper limit on the estimated total amount of surface runoff or surface inflow into Lake Nettie and Crooked Lake during the course of the pumpdown was about 5 inches, or a total volume of less than 500 acre-feet. The remaining amount of water contributed to the lakes to replace the water removed was contributed by groundwater discharge.

RESPONSE OF GROUNDWATER SYSTEM

Groundwater elevations in the upper aquifer responded in varying degrees to the pumpdown of Lake Nettie. Water levels in observation well 148-81-29CAA (800 feet west of Lake Nettie with screened interval 38-48 feet) declined largely in concert with water levels in Lake Nettie. Water levels in the upper aquifer as much as 1/2 mile from Lake Nettie or Crooked Lake showed measurable decreases in response to the pumpdown. Water level trends in three of the responding wells are shown on Figure 37 along with Lake Nettie water elevations and those of well 148-81-22DDD3, which shows the upper aquifer "background" signal during the time period of the pumpdown. In areas away from Lake Nettie water levels in the upper aquifer generally showed no measurable net decrease in water levels between the beginning of July and the end of September, due to recharge by the above average July and August precipitation. The areal distribution of the response of water levels in the upper aquifer is shown on Figure 38. The area delineated as having a measurable response to the pumpdown of Lake Nettie encompasses about 3.5 square miles when the area of the lakes is subtracted. The groundwater drawdown boundary shown in Figure 38 is approximate and would be physically indistinct because the amount of drawdown in the shallow "drawdown cone" radiating out from the lake would decrease asymptotically toward zero with distance from the lake.

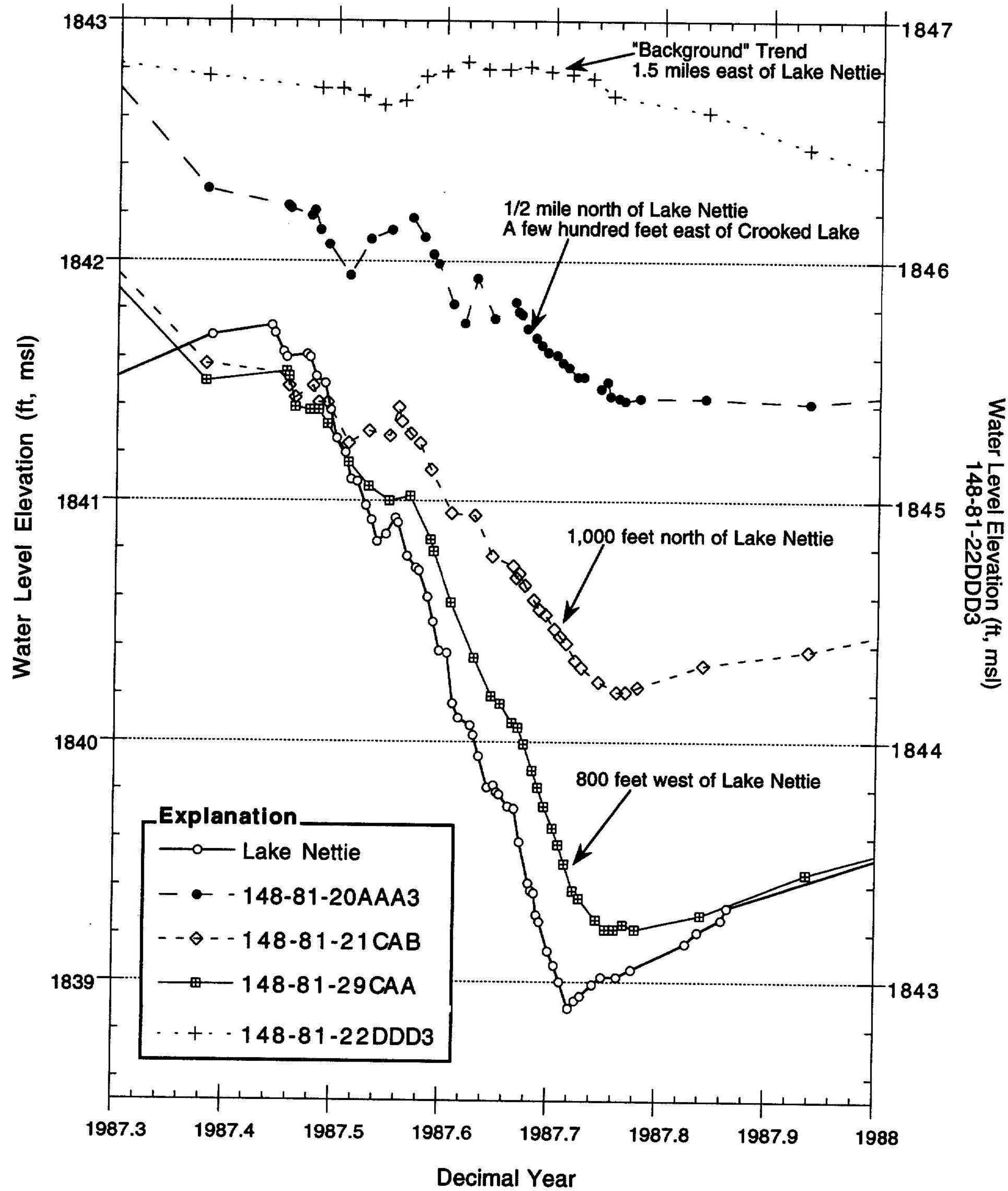


Figure 37. Representative water level changes in the upper aquifer unit near Lake Nettie during the Lake Nettie pumpdown, 1987.

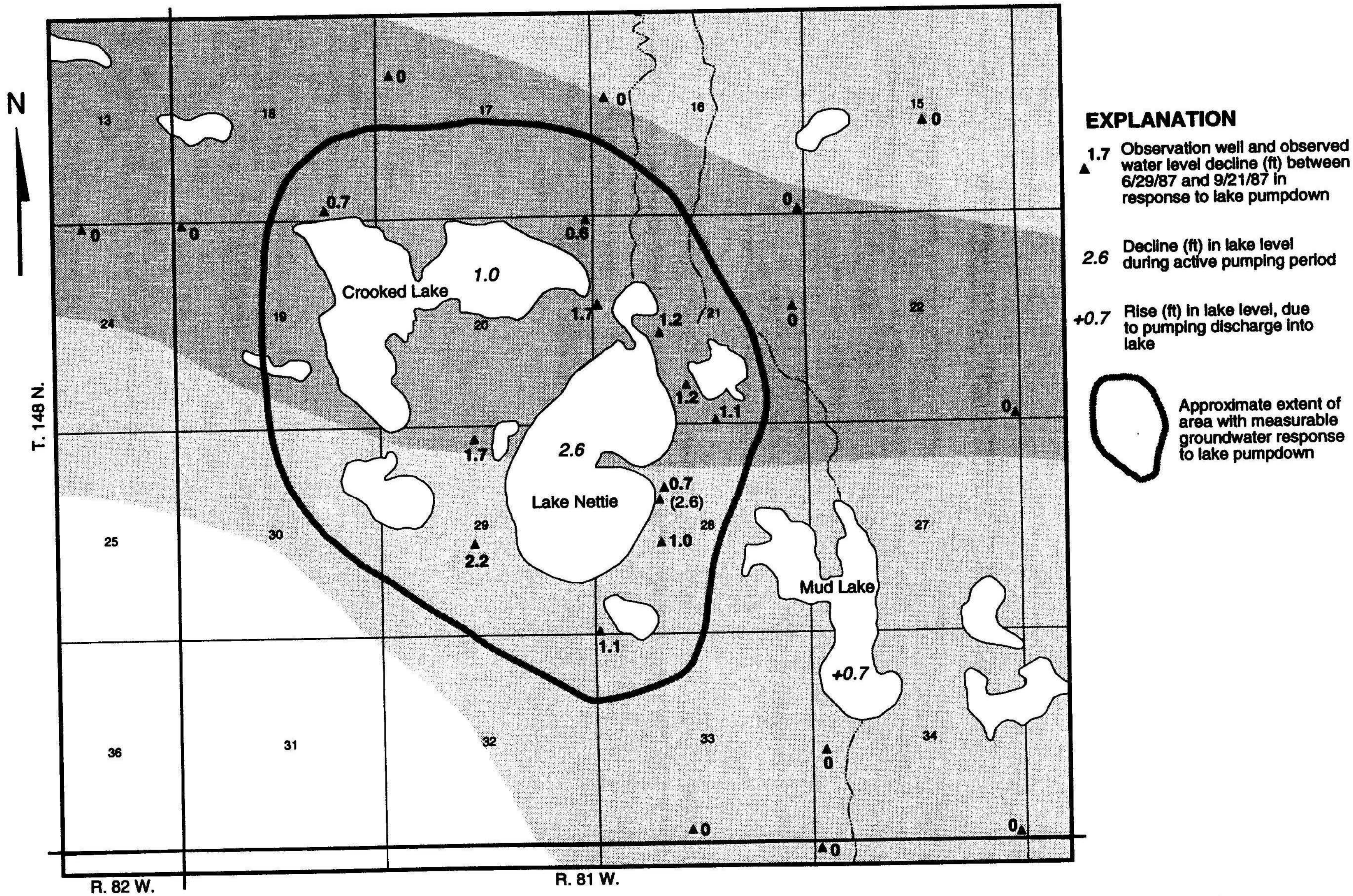


Figure 38. Decline in upper aquifer unit groundwater levels in response to Lake Nettie pumpdown, July through September 1987.

Water levels in the lower aquifer did not noticeably respond to the pumpdown of Nettie. Water levels in well 148-81-29BAA1 (screened from 158 - 178 feet) located 800 feet west of Lake Nettie exhibited the same seasonal trend observed in other lower aquifer unit wells (Fig. 39). Lower aquifer unit water levels showed a net decline of about 0.5 feet from the beginning of July to the beginning of November. The affect of the 2 foot decrease in Lake Nettie on the lower aquifer was indiscernible. An unloading effect on the lower aquifer unit, similar to but of lower magnitude than that observed during the Lake Audubon Response Test), was anticipated at wells located near Lake Nettie (e.g. 148-81-29BAA1). Apparently the size of Lake Nettie is insufficient to propagate an unloading signal to the deeper confined aquifer.

QUANTIFICATION OF GROUNDWATER INFLOW

It is obvious from the measured response in wells screened in the upper aquifer unit between depths of 18 and 60 feet that the pumpdown of Lake Nettie significantly affected water levels in the upper aquifer unit, well beyond a bank storage affect. The amount of surface runoff and groundwater inflow to the lakes during the test can be estimated as follows:

Runoff
+ Groundwater Inflow = Volume Pumped
+ Evaporation Volume Loss
- Measured Lake Volume Decrease

The volumetric changes for Crooked Lake and Lake Nettie for the periods 6/29/87 (when pumping started) to 9/21/87 (after pumping stopped) and 9/21/87 to 11/13/87 (the last date of data collection) are tabulated below.

Lake Nettie Volumetric Change					
Date	Stage (ft)	Capacity (acre-ft)	Vol. Change (acre-ft)	Net Evap (ft)	Evap Vol Loss (acre-ft)
6/29/87	1841.49	2197			
			-1352	0.72	374
9/21/87	1838.89	845			
			+208	0.46	210
11/13/87	1839.31	1053			
Total			-1144	1.18	584

Crooked LakeVolumetric Change					
Date	Stage (ft)	Capacity (acre-ft)	Vol. Change (acre-ft)	Net Evap (ft)	Evap Vol Loss (acre-ft)
6/29/87	1841.52	1684			
			-534	0.72	385
9/21/87	1840.51	1150			
			-152	0.46	223
11/13/87	1840.18	998			
Total			-686	1.18	608

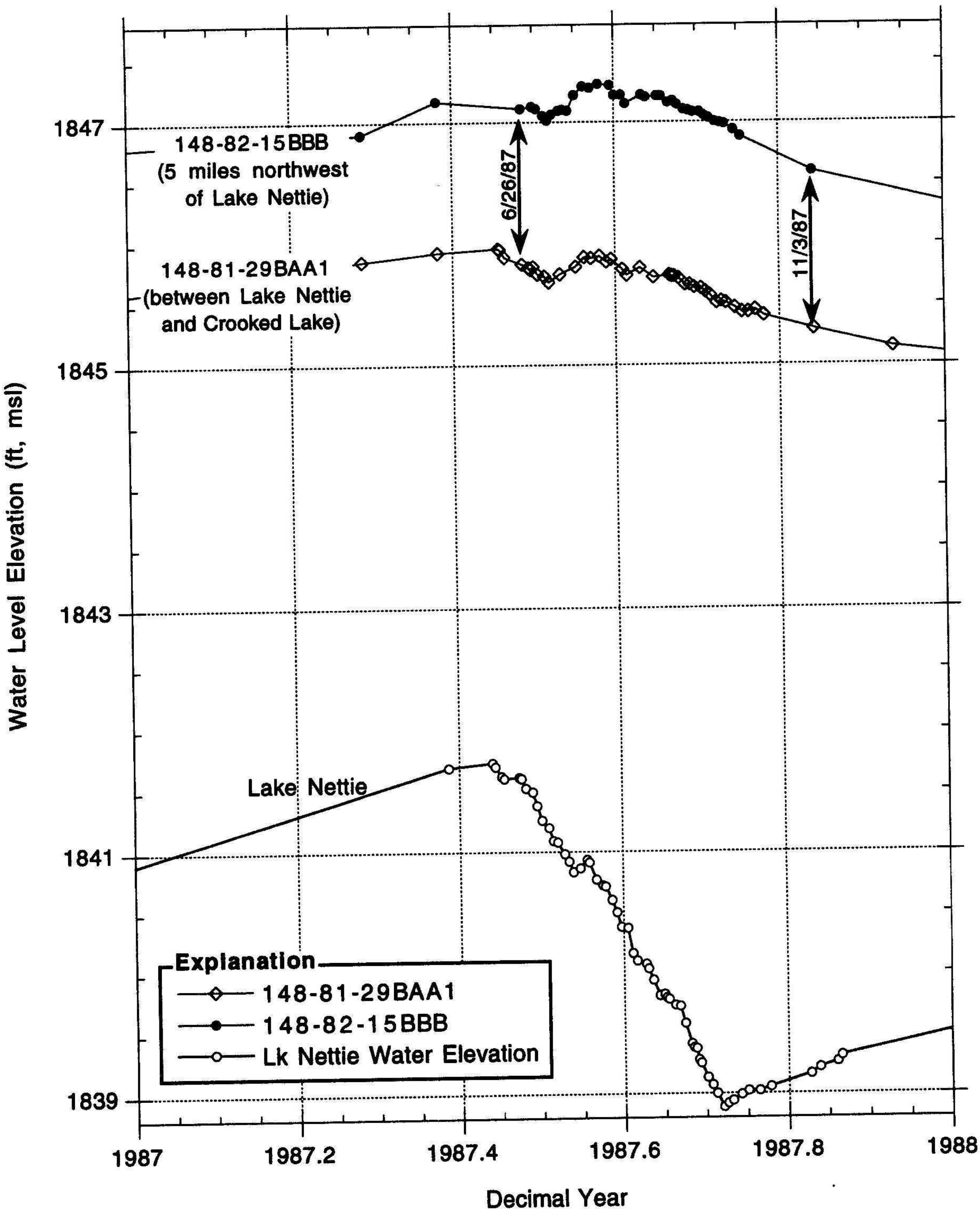


Figure 39. Water level trends in lower aquifer unit during Lake Nettie pumpdown, 1987.

The combined lake volume decrease indicated by measured lake stage changes for both Lake Nettie and Crooked Lake is 1,830 acre-feet (1144 + 686). A total of 2,240 acre-feet was pumped from Lake Nettie into Mud Lake between 6/29/87 and 9/21/87. The total estimated volume of inflow (excluding direct precipitation) into Lake Nettie and Crooked Lake from 6/29/87 to 11/13/87 is about 1,600 acre-feet, calculated as follows:

2,240	volume pumped from Lake Nettie into Mud Lake
+1,192	volume removed from lakes by net evaporation loss
- 1,830	volume decrease calculated from lake stage measurements
1,602 acre-ft	net influx of groundwater and surface runoff

Since the amount of surface runoff was estimated to be less than 500 acre-feet, the data suggest that 1,100 acre-feet or more of groundwater discharged into Lake Nettie and Crooked Lake to replace a portion of the water removed by pumping and evaporation. The estimates are approximate. However, it is clear from the response of groundwater levels in upper aquifer observation wells that there is a strong connection between the upper aquifer unit and surface water bodies in the Lake Nettie area.

WATER CHEMISTRY CHANGES DURING LAKE PUMPDOWN

Total dissolved solids (TDS) concentrations in Lake Nettie, Crooked Lake and Mud Lake are summarized on Figure 40. Dissolved concentrations in Lake Nettie remained between 1,500 and 1,800 mg/L throughout the lake pumpdown. There was a slight concentration decrease in the early August and September samples relative to the late June samples due to the influence of July and August precipitation and the discharge of fresher groundwater into the lakes. The increase in concentration between the 9/1/87 and 10/7/87 samplings is attributable to the concentrating effects of evaporation.

Salinity in the somewhat restricted northwest bay of Mud Lake decreased initially from about 2,500 to 1950 mg/L because of the diluting effect of the Lake Nettie water which was less saline than that in the northwest bay. Salinity in the Mud Lake northwest bay then increased again to about 2,300 mg/L between the 9/01/87 sampling and the 10/07/87 sampling after the pumping operations had ceased. Total dissolved solids increased from about 1,000 mg/L to 1,600 mg/L in the main bay of Mud Lake because the discharge of Lake Nettie water caused the movement of the more saline water from the northwest bay into the main bay of Mud Lake. The increase in salinity in Mud Lake was likely a temporary phenomenon as normal periods of winter snowmelt and spring rainfall would flush water through Mud Lake and into Turtle Creek.

Distinct perturbations in groundwater chemistry during the lake pumpdown were detectable in only two of the monitoring wells that were sampled, wells 148-81-29BAA2 (screened interval 54 - 59 feet) and 148-81-29CAA (screened interval 38 - 48 feet). These wells are both located between Crooked Lake and Lake Nettie, about 800 to 1000 feet west of Lake Nettie. Well

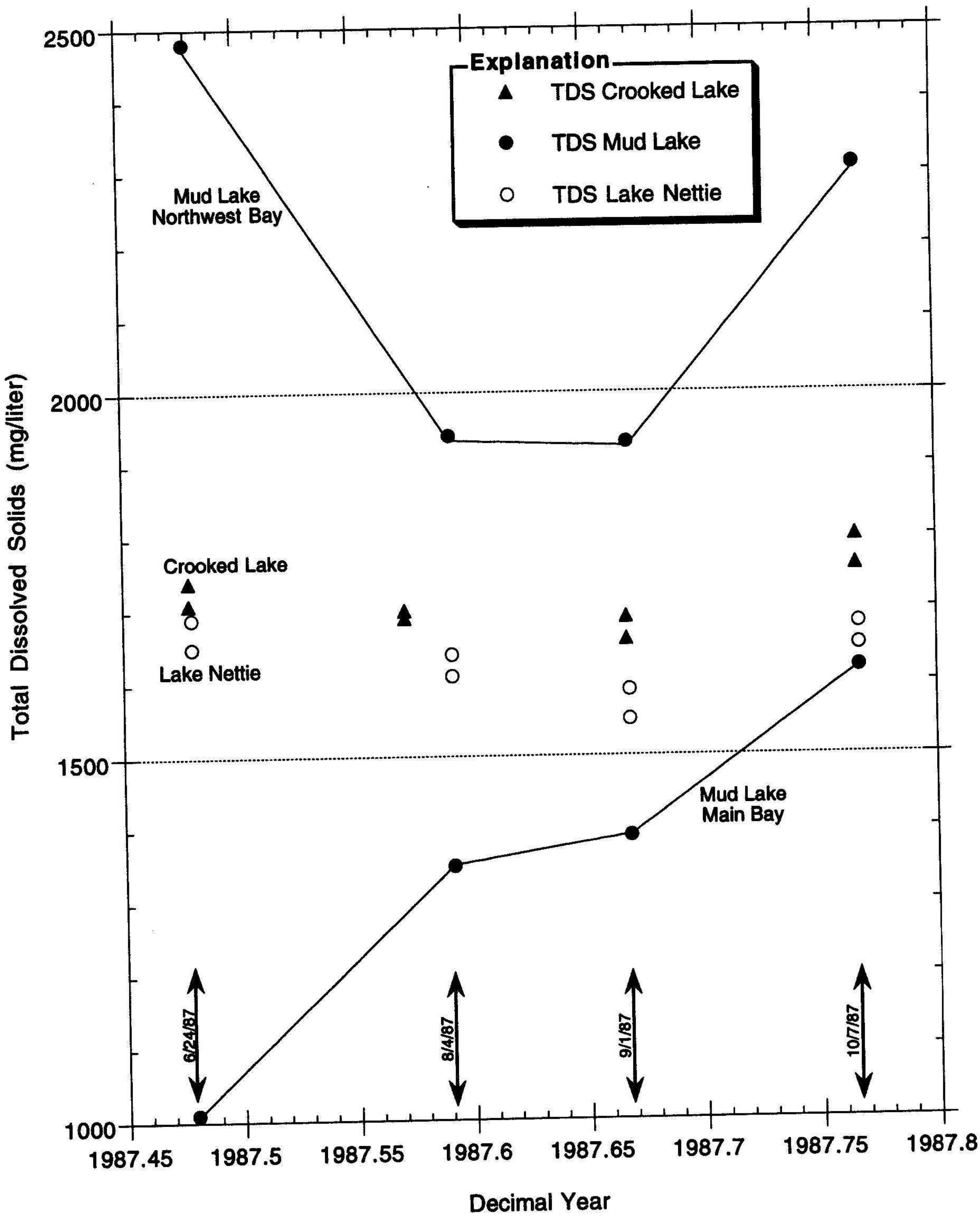


Figure 40. Trends in total dissolved solids concentrations in surface water bodies during Lake Nettie pumpdown, 1987.

148-81-29BAA2 is about 1/2 mile north of well 148-81-29CAA. Water levels in both wells responded strongly to the lake pumpdown. Water level in well 148-81-29BAA2 declined a total of 1.7 feet while water level in well 148-81-29CAA declined a total of 2.2 feet.

The major ion chemistry for these wells is summarized on Figures 41 and 42. Total dissolved solids at well 148-81-29CAA initially increased from about 2,900 to 3,200 mg/L between the mid June and early August samplings then fell to about 2,350 mg/L by the early October sampling. Individual major ion concentrations showed similar relative changes (Fig. 41). Total dissolved solids at well 148-81-29BAA2 showed a consistent downward trend from about 2,500 mg/L at the mid June sampling to about 2,050 mg/L at the early October sampling. Individual major ion concentrations showed similar relative changes (Fig. 42).

The chemical signature of the groundwater at wells 148-81-29BAA2 and 148-81-29CAA, with TDS concentrations of 2,000 to 3,000 mg/L and elevated amounts of sodium, bicarbonate and chloride is similar to water sampled from Crooked Lake and Lake Nettie. The groundwater chemistry at these two wells, located between Crooked Lake and Lake Nettie, indicates an evaporative effect suggesting that a percentage of the groundwater in the upper aquifer unit at these locations was recharged by seepage from the lakes and sloughs in the area. The groundwater chemistry between Crooked Lake and Lake Nettie is consistent with the potentiometric analysis of the upper aquifer unit which suggested that groundwater discharges into the west sides of Crooked Lake and Lake Nettie and that lake water recharges the upper aquifer unit by seepage from the east sides of the lakes (e.g. Figs. 12 and 13).

In contrast to the more saline lake water influence observed in the groundwater chemistry at wells 148-81-29BAA2 and -29CAA, groundwater in the upper aquifer unit in the area typically has TDS concentrations of less than 500 mg/L to about 800 mg/L with much lower percentages of sodium and chloride. The freshening of the groundwater at these two wells during the Lake Nettie pumpdown indicates that lowering the lake level caused a perturbation of the flow system in the upper aquifer unit which resulted in flow of less saline groundwater toward the well screens. The perturbation of the flow system indicates a good hydraulic connection between surface water bodies and the upper aquifer unit in the Lake Nettie area.

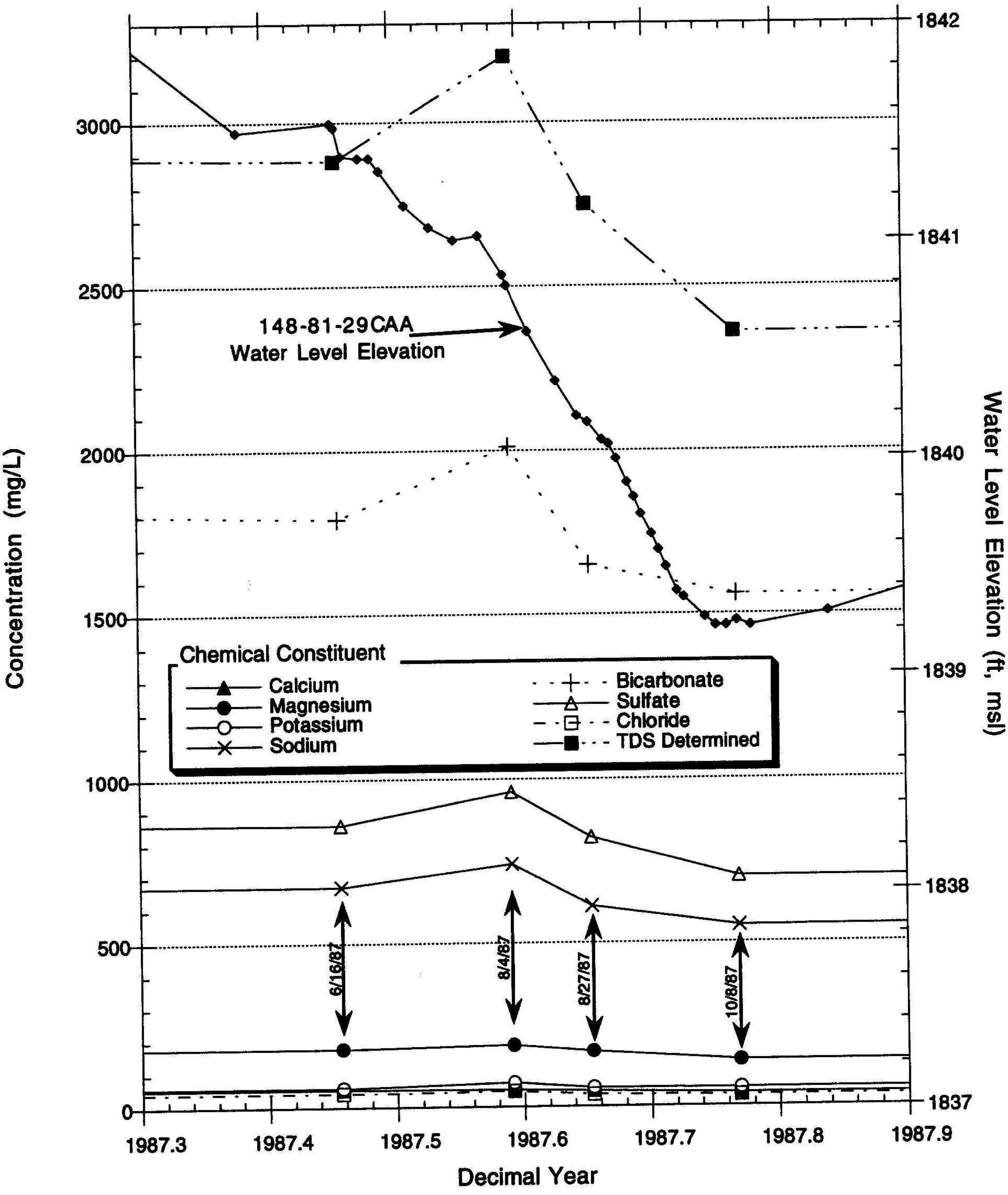


Figure 41. Groundwater chemistry changes and groundwater level elevations at well 148-81-29CAA during Lake Nettie pumpdown, 1987.

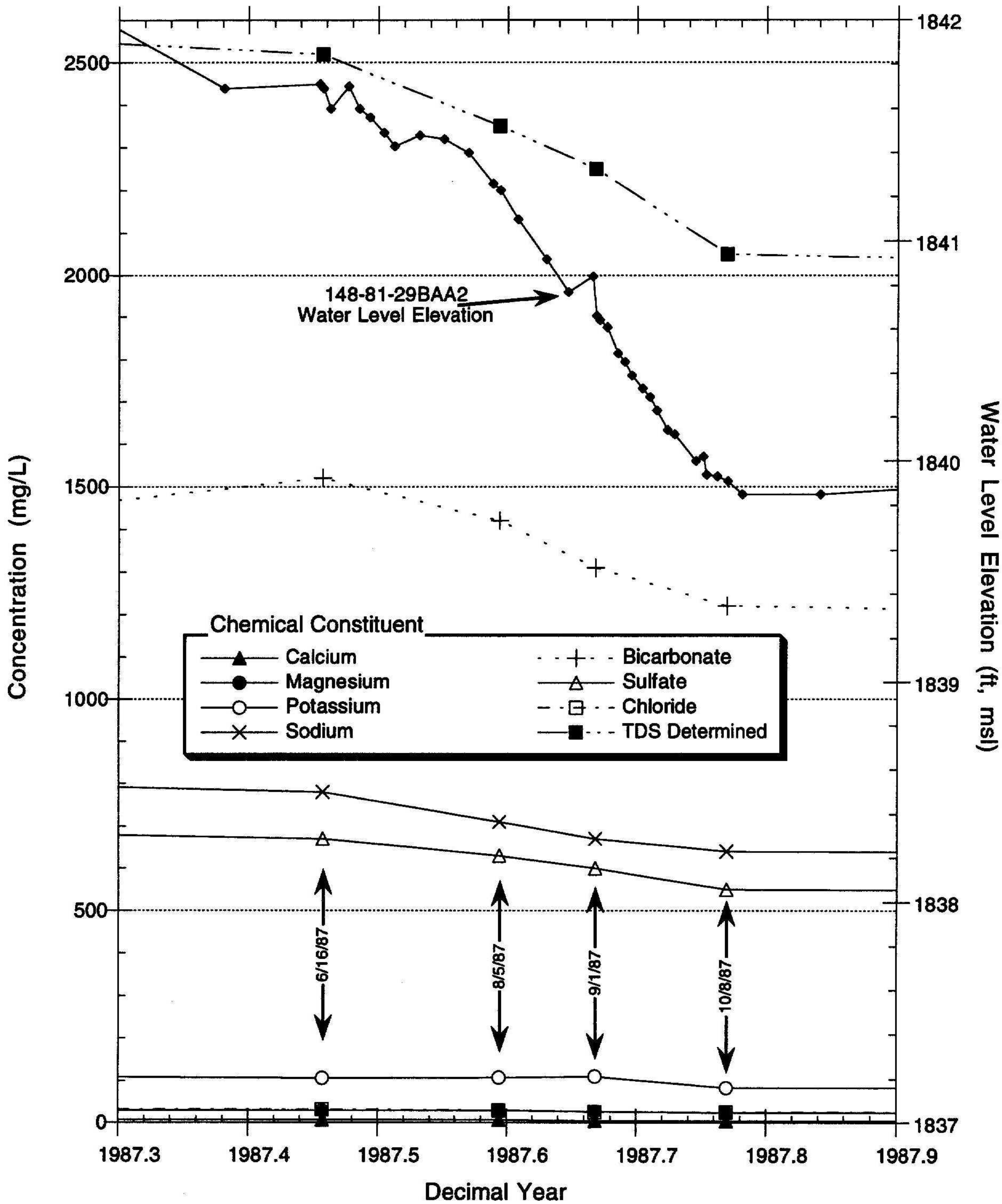


Figure 42. Groundwater chemistry changes and groundwater level elevations at well 148-81-29BAA2 during Lake Nettie pumpdown, 1987.

ANALYSIS OF GROUNDWATER LEVEL CHANGES SINCE THE 1960's

Presentation of an analysis of water level trends through time in the aquifer units that honors a sufficient sampling of the data set collected for this study would require publication of a tedious number of individual well or well nest hydrographs. To facilitate the analysis and presentation of water level changes in the study area, "averaged" hydrographs of groundwater levels in observation wells are generated to evaluate relative groundwater level trends that have occurred in various zones of the aquifer system since groundwater data collection was initiated in the late 1960's. In addition to the averaged water level trend hydrographs, hydrographs showing actual measured water level elevations for 28 observation well or well nest sites are presented on Plate 2.

WATER LEVEL TRENDS ANALYSIS METHOD

With the relative groundwater level trends method, the difference in water levels measured at an individual well on successive measurement dates is divided by the number of days in between the measurements to yield an average daily change between the two measurement dates. For example, if the water level at Well A during one measurement was 1840.0 feet and was 1841.0 feet (1 foot increase) when measured again 100 days later, the daily change calculated for the intervening 100 day period would show water levels rising at a rate of 0.01 feet per day, and a hydrograph generated from the data would show a total relative increase of 1.0 feet across the 100 day period.

Water levels in groups of wells in similar areas of the aquifer can be averaged together. When water levels for a number of wells is grouped, the total cumulative daily change (positive or negative) for the group is divided by the number of wells in the group to yield the average daily water level change for the group. For instance, if the water level in Well B measured during the same 100 day period as Well A increased from 1847.0 to 1849.0 (2 foot increase), the relative average daily water level change for Well A plus Well B during the 100 day period would be a rise of 0.015 feet per day. The hydrograph for the group Well A + Well B would show a total relative increase of 1.5 feet (the average increase of Well A and Well B) across the 100 day period. If the water level in Well A increased by 1.0 feet and in Well B decreased by 1.0 feet across the same period, then the relative water level trend hydrograph would show no change in water level for the Well A plus Well B group during that time period.

This relative water level trend method facilitates the incorporation of a large volume of groundwater level data into the time-trend analysis. By grouping wells in related parts of the aquifer together, the method also reduces the likelihood of potentially misleading conclusions that could be drawn from anomalous water level changes measured at a single well site that may be associated with unrecognized local factors. The initial relative water level on a hydrograph generated using this method is arbitrary. However, the magnitude and direction of the relative average change in water levels is physically meaningful and the method provides a tool for examining prevalent groundwater level trends in an area of interest. The averaged trends show whether groundwater levels have generally increased or decreased in a selected well grouping area across a given time period.

Several groupings of wells were selected for the analysis and presentation of relative water level trend hydrographs. The wells are grouped first by whether they are screened in the upper unconfined aquifer unit (designated as "upper") or in the confined middle and lower aquifer units (designated as "lower" for the remainder of this discussion). The distinction between upper aquifer and lower aquifer well groupings is maintained across other subsequent groupings. A second grouping consists of distinguishing wells that are located east of Highway 41 from those located west of Highway 41. The observation well groups were further disaggregated based on proximity to Lake Audubon into the Far East group in the southeast portion of the area and into groups 148-81 (T. 148 N., R. 81 W.) and 148-82 (T. 148 N., R. 82 W.) in the west part of the study area nearest to Lake Audubon. The well groupings used in the following discussion and accompanying figures are:

Group Name	Location	No. of Wells
All Upper	entire study area, upper aquifer	82
All Lower	entire study area, lower aquifer	79
East Upper	east of highway 41	31
West Upper	west of highway 41	51
East Lower	east of highway 41	41
West Lower	west of highway 41	38
Far East Upper	Twps 146-79, 147-78, 147-79	8
Far East Lower	Twps 146-79, 147-78, 147-79	15
148-81 Upper	Twp 148-81	30
148-81 Lower	Twp 148-81	13
148-82 Lower	Twp 148-82	8

Upper refers to wells screened in the upper unconfined aquifer units;
Lower refers to wells screened in the lower and middle confined aquifer units.

The number of wells shown for each group represents the total number of wells at the height of the data collection effort, and was less for most of the groupings prior to 1984.

OBSERVED RELATIVE GROUNDWATER LEVEL TRENDS

Hydrographs of the relative water level trends between November 1967 and mid-1994 for the various well groupings are shown in Figures 43, 44 and 45. A starting point of November 1967 was selected because by this point a sufficient number of water level data points had been collected during the McLean County groundwater study to produce multiple data points within each of the various well groupings. The relative groundwater elevation was set to zero at November 1967 for all well groupings so that changes in the relative groundwater elevations could be compared across groupings.

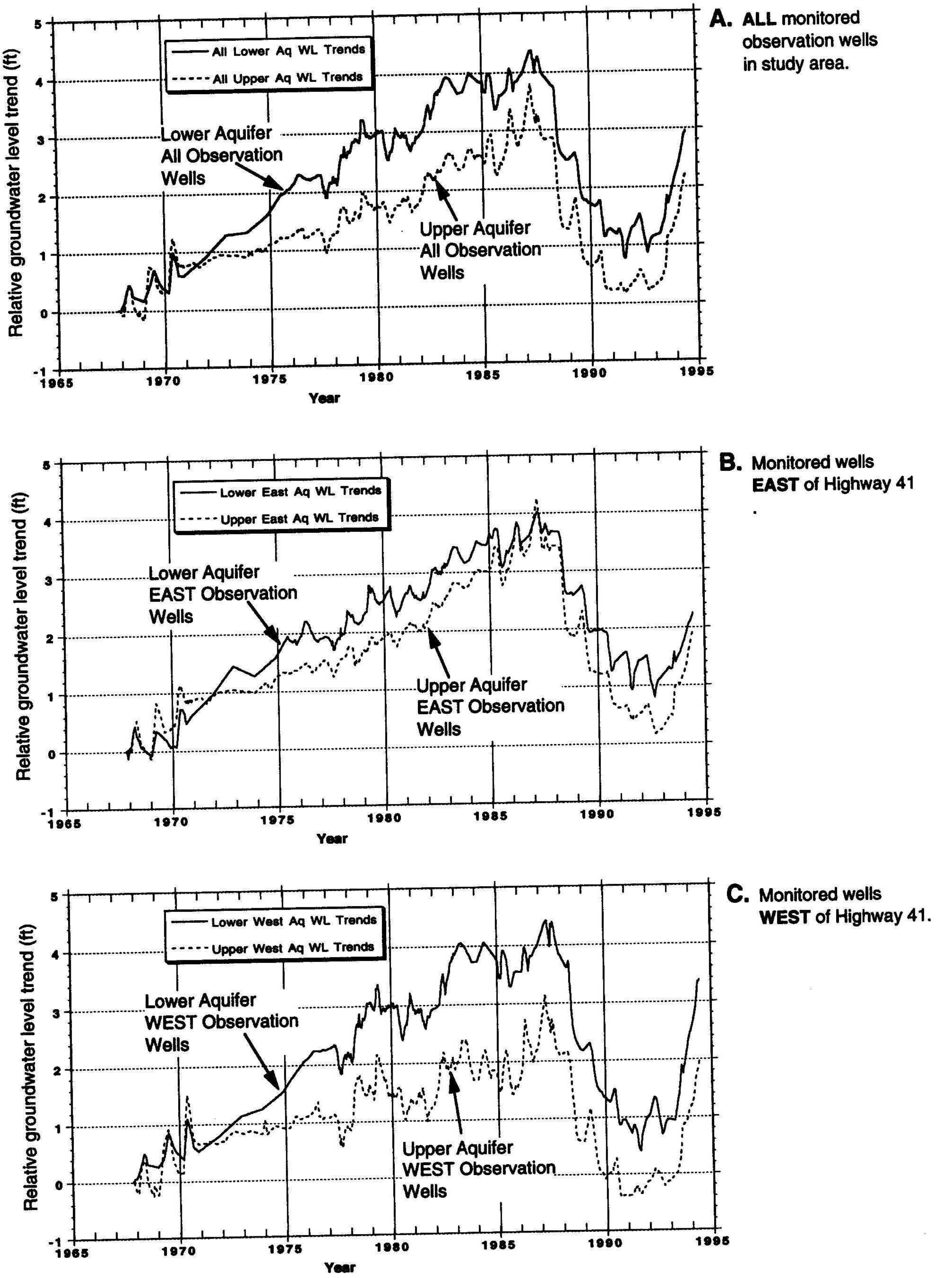
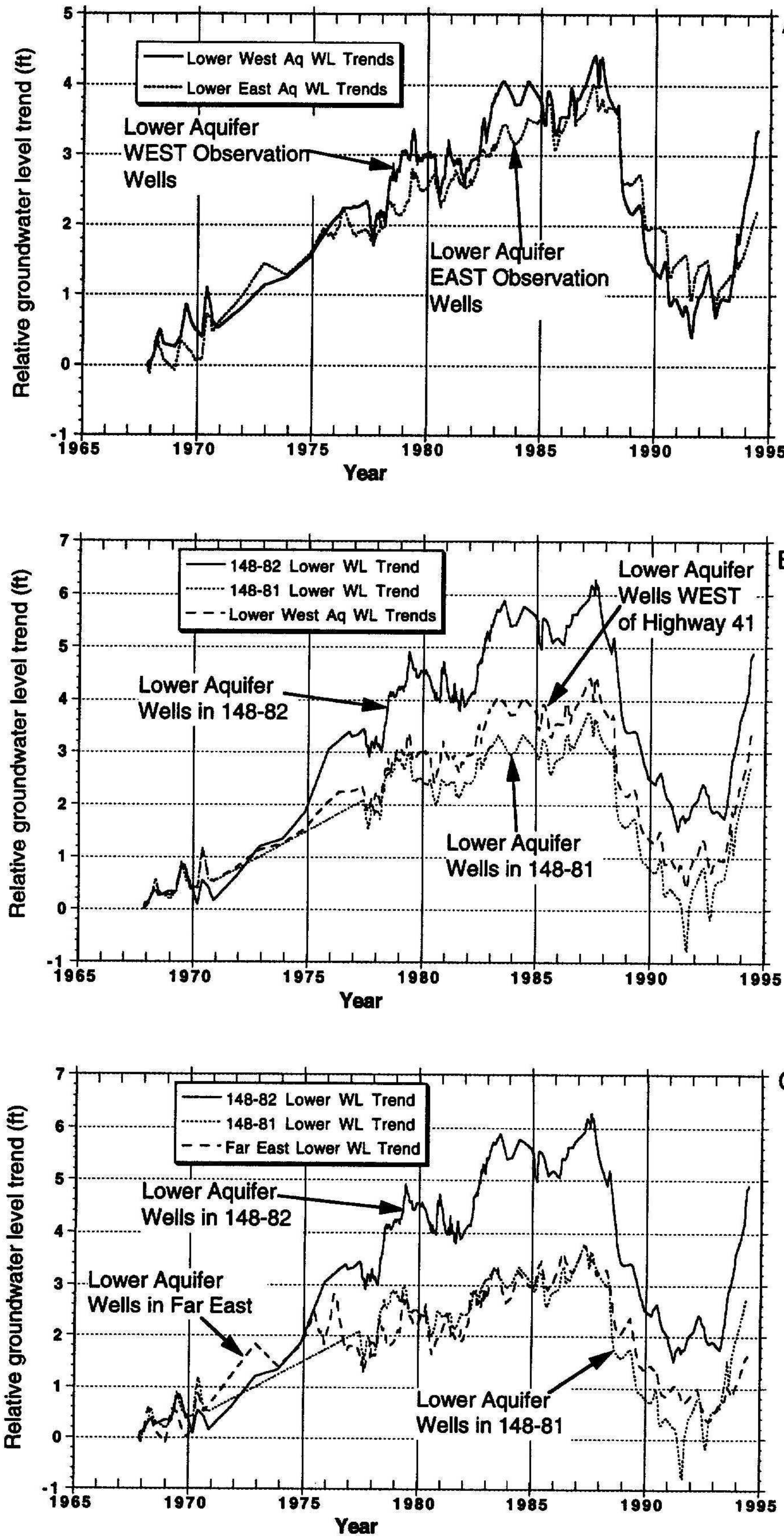


Figure 43. Relative groundwater level trends since November 1967, upper and lower aquifer units.

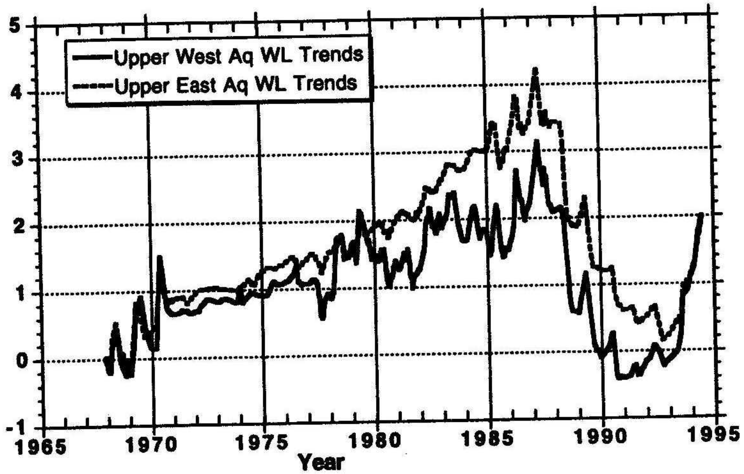


A. Lower aquifer unit; observation wells west of Highway 41 compared to observation wells east of Highway 41.

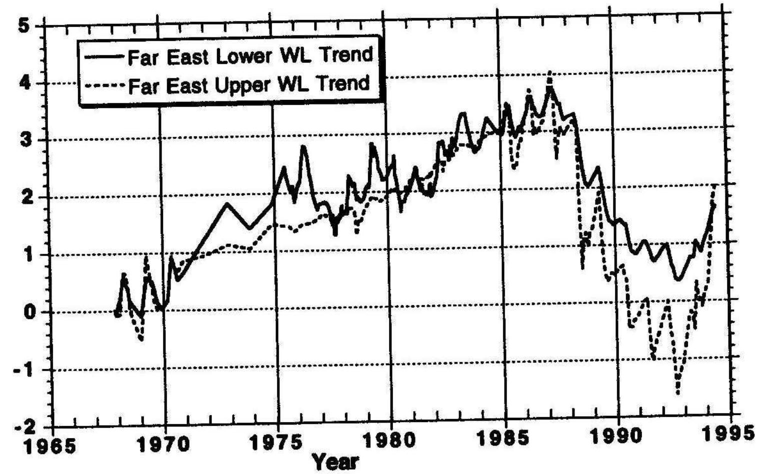
B. Lower aquifer unit; observation wells west of Highway 41 compared to observation wells in Twp. 148-81 and Twp. 148-82 (far west portion of study area).

C. Lower aquifer units; observation wells in Twp. 148-81 and Twp. 148-82 (far west portion of study area) compared to observation wells in far east portion of study area.

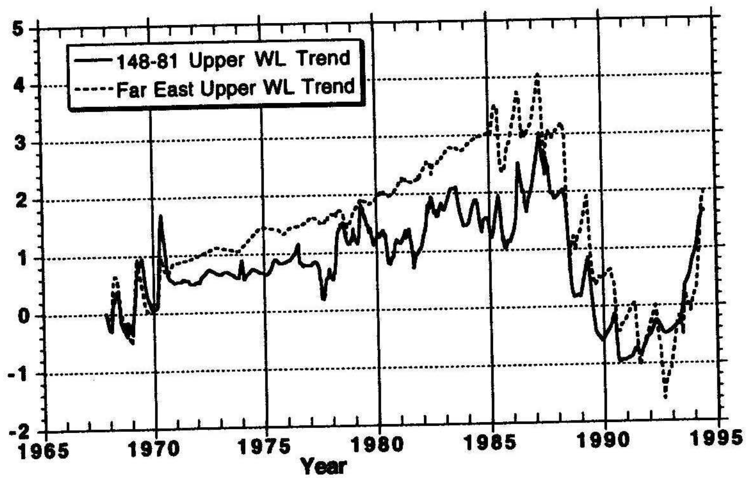
Figure 44. Relative groundwater level trends since November 1967 - lower aquifer unit, east and west well locations.



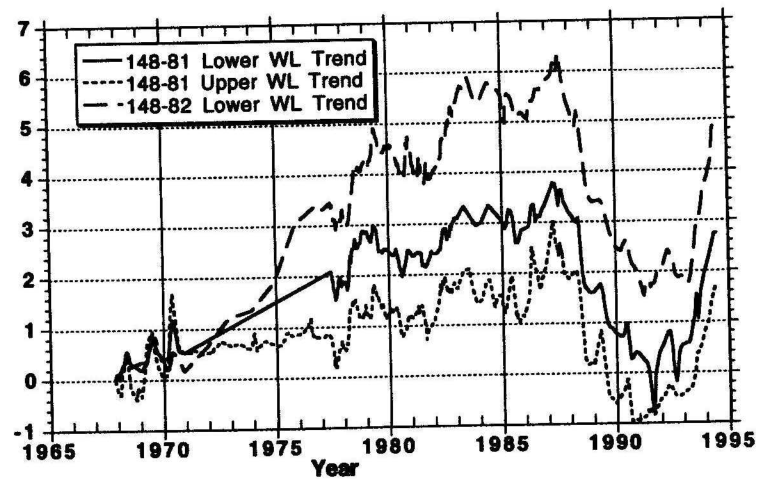
A. UPPER aquifer unit - EAST versus WEST well groupings.



C. UPPER versus LOWER aquifer units - FAR EAST well grouping.



B. UPPER aquifer unit - FAR EAST versus FAR WEST (Twp. 148-81) well groupings.



D. UPPER versus LOWER aquifer units - FAR WEST well groupings (Twps. 148-81 and 148-82).

Figure 45. Comparison of groundwater level trends since November 1967: upper aquifer unit in the east versus west and far east versus far west well groupings; and upper versus lower aquifer units in the far east and far west well groupings.

Groundwater levels exhibited a generally increasing trend from 1967 through 1987, declined significantly between 1987 and 1991, then began a marked upward trend in mid 1993. Comparison of the relative water level hydrographs to those of actual measurements at the individual wells presented on Plate 2 shows that the shape of the relative water level trends curve mimics the shape of the individual well hydrographs. Note that very few water level measurements were obtained between 1971 and the late 1970's, hence the relatively smooth nature of the curves between 1971 and 1976.

TRENDS IN UPPER AND LOWER UNITS, ENTIRE STUDY AREA

Figure 43A presents the relative water level trends in the upper and lower aquifer units for all monitored observation wells in the study area. A distinctive feature of the hydrograph is the one foot increase in the water levels in the lower aquifer relative to those of the upper aquifer between 1971 and 1976, coincident with the period when Lake Audubon was raised 13 feet. The relative water level trends then roughly parallel each other from the late 1970's through mid-1994. The graph indicates that groundwater levels, on average, increased fairly steadily from 1971 to a peak in 1987. The 1987 peak was approximately 3 to 3.5 feet higher in early 1987 than in 1970 for the lower unit and about 2 to 2.5 feet higher for the upper unit. Note that a general upward trend is also discernible between 1967 and 1971, before Lake Audubon was raised. Relative water levels in both the upper and lower units were approximately 0.5 to 1 foot higher in 1971 than they had been in 1967.

Water levels declined steeply from the 1987 peak by a total of about 3 feet through late 1987 to 1990. Water levels remained relatively steady through 1991, 1992 and early 1993, then increased abruptly by a total of about 2 feet from July 1993 to July 1994. Note that, overall, water levels in the lower aquifer unit were about 1/2 feet higher in 1991 to mid-1993 than they had been in 1970, while water levels in the upper unit were about 1/2 feet lower in 1991 through mid 1993 than they had been in 1970.

TRENDS IN EAST VERSUS WEST PARTS OF THE STUDY AREA

Figures 43B and 43C presents the relative water level trends in the upper and lower aquifer units with the data disaggregated into groupings of wells east of Highway 41 and west of Highway 41.

EAST PART OF THE STUDY AREA

Figure 43B shows that the divergence in lower versus upper aquifer unit water level trends between 1971 and 1976 was less pronounced in the area east of Highway 41 than it was for the aquifer as a whole (0.5 feet versus 1 foot). The trends in the East upper and lower unit water levels remain fairly parallel from 1975 through early 1985. However, in 1985 through 1987, the relative water elevations increase more rapidly in the upper unit than in the lower unit so that the 1987 peak is actually higher in the upper unit than in the lower unit. Water levels then decline more rapidly in the upper unit across the drought of 1988-1989 through 1991-1992 than in the lower unit. At the low point in 1992 to early 1993, water levels in the East upper unit are about 0.5 feet lower than they had been in 1971 while those of the East lower unit are about 0.5 feet higher. The July 1993 through 1994 period produced an increase of about 1 foot in elevation for water levels in the lower aquifer unit and about 1.5 feet in the upper unit. The greater magnitude of changes in the East upper unit water levels relative to those of the East lower unit in 1985 through 1994 is possibly due to more direct communication of the upper unconfined unit with precipitation cycles.

WEST PART OF THE STUDY AREA

Figure 43C shows the relative water level trends in the lower and upper aquifer units in the study area west of Highway 41. Water levels in the West lower unit increased about 1 foot more than the increase in the West upper aquifer from 1971 to 1976, similar to the averaged trend for the entire study area (Fig. 43A). From the late 70's through 1987, the relative water levels in the West lower aquifer unit rose at a faster rate than those in the West upper unit. As a result, relative water levels in 1987 were about 1.5 feet higher in the West lower unit than in the West upper unit (in comparison to the relation in 1967-1970, when the West upper and West lower groups showed approximately equal relative water levels).

The 3 to 3.5 foot decrease in the lower unit water levels through the drought of 1988-89 resulted in late 1990 to early 1993 water levels in the West lower unit being about equal to what they had been in 1970, before the 13 foot increase in Lake Audubon elevation occurred in 1975. The 3 foot decrease from the 1987 peak in water levels in the West upper unit through the drought of 1988-89 resulted in late 1990 to early 1993 water levels that were about 1 foot lower than they had been in 1970. Water levels in both the West upper and West lower units increased about 2 feet from July 1993 to July 1994.

TRENDS IN LOWER AQUIFER WEST, EAST, FAR WEST, FAR EAST GROUPINGS

Figure 44 shows a comparison of the water level trends in the lower confined aquifer unit for the west and east location groupings. Figure 44A shows that the relative water level trends in the lower aquifer averaged over the study area west of Highway 41 were quite similar to those averaged over the area east of Highway 41, except for a much sharper rise in water levels from early 1993 through 1994 in the west part of the study area. The reason for this rise is apparently a response in the far west part of the study area to a rise in Lake Sakakawea, which will be illustrated later with individual well hydrographs.

Figure 44B presents the water level trends in the lower aquifer west of Highway 41 with those of the lower aquifer in Twps. 148-81 and 148-82. The Twp. 148-81 and Twp. 148-82 groupings are both subsets of the West of Highway 41 grouping. Wells in Twp. 148-82 represent the area of the Lake Nettie aquifer that are closest to Lakes Audubon and Sakakawea.

Relative water levels in the lower unit in Twp. 148-82 exhibited an increase between 1970 and 1976 that was about 1 foot greater than that of the lower aquifer unit in Twp. 148-81 (a 3 foot increase versus a 2 foot increase). Relative water levels in the lower unit in Twp. 148-82 were about 2 feet higher than those of Twp. 148-81 for the period 1982 through 1987. In addition, the water level rise between early 1993 and mid-1994 totaled about 3 feet for the lower unit in Twp. 148-82 versus about 2 feet in Twp. 148-81 and also in the entire study area west of Highway 41. The greater amplitude of lower aquifer water level changes in Twp. 148-82 compared to that of Twp. 148-81 is due to the closer proximity of wells in Twp. 148-82 to Lakes Sakakawea and Audubon and the greater influence of major surface water stage changes on wells located in Twp. 148-82.

Water levels trends in the lower aquifer unit in the Far East part of the study area are similar to those of Twp. 148-81, except for a less pronounced rise in water levels from early 1993 to 1994 (Fig. 44C). The lower aquifer in the Far East grouping is not influenced by the presence of Lake Audubon. The similarity of the water level trends in the lower aquifer Far East grouping and the lower aquifer Twp. 148-81 grouping, coupled with the offset in the Twp. 148-82 lower aquifer grouping indicates that effect of the reservoirs is largely limited to the lower aquifer within 3 to 5 miles of Lake Audubon.

UPPER AQUIFER TRENDS IN THE WEST VERSUS EAST GROUPINGS

Water levels in the upper aquifer in the area east of Highway 41 exhibited about a 1 foot greater increase between 1967 and 1985 than those of the upper aquifer in the area west of Highway 41 (Fig. 45A). The 1 foot higher average water level of the east relative to that of the west was maintained from 1985 through 1991. Upper aquifer water levels in the east half of the study area increased by 3 to 4 feet by 1985 through 1987 relative to 1967 - 1968 levels, while upper aquifer water levels in the west half the study area gained 2 to 3 feet for the same time period. The average water levels in the east fell 3 to 4 feet from the 1987 peak to a low in 1991 - 1992 which was about 0.5 feet lower than the relative water levels had been in 1970. The average water levels in the west fell 3 to 3.5 feet from the 1987 peak to a low in 1990 - 1991 which was about 1 foot lower than the relative water levels had been in 1970. A sharper rise of water levels in 1993 -1994 in the west part of the study area eliminated the 1 foot greater relative water level that had existed between 1985 and 1991 in the upper aquifer in the east compared to the west.

Figure 45B presents a comparison of relative water level trends in the upper aquifer in the far east part of the study area (mostly wells in Twp. 147-79) with those in Twp. 148-81, which encompasses the Lake Nettie area in the western part of the study area. Relative water level trends relations between the far east part of the study area and Twp. 148-81 were similar to those between the entire east and entire west parts of the study area. Water levels in the far east upper aquifer grouping (removed from any potential influence by Lake Audubon) rose slightly more between 1980 and 1985 than those in Twp. 148-81, where rising water levels during this period had been ascribed to the presence of Lake Audubon. It is notable that the decline in water levels in 1988 and 1989 resulted in upper aquifer relative water levels in 1990 - 1992 that were 1 to 2 feet lower in the far east, and 1 to 1.5 feet lower in Twp. 148-81, than they had been in 1970.

UPPER VERSUS LOWER AQUIFER TRENDS IN THE FAR EAST

In the far east part of the aquifer relative water level trends in the lower aquifer were similar to those in the upper aquifer from 1967 through 1987 (Fig. 45C). A greater decline in the upper aquifer from the 1987 peak resulted in water levels in 1991 - 1992 that were 1 to 2 feet lower than in 1970, while lower aquifer water levels in 1991 - 1992 were at about the same relative elevation as in 1970.

UPPER VERSUS LOWER AQUIFER TRENDS IN TWP. 148-81 AND TWP. 148-82

The relative water level trends in the upper and lower units of the Lake Nettie aquifer in Twp. 148-81 and Twp. 148-82 are compared in Figure 45D. There is an insufficient water level data set prior to 1984 for the upper aquifer in Twp. 148-82 to allow generation of the relative water level trends. The relation between the water level trends in the lower aquifer in Twp. 148-81 versus the lower aquifer in Twp. 148-82 have been discussed above. Although all three hydrographs show the same general trend, the magnitude of the changes is significantly greater in the lower aquifer than in the upper aquifer due to the influences of Lakes Sakakawea and Audubon which are superimposed on climatic factors which affect both the upper and lower aquifers.

Water levels in the upper aquifer in Twp. 148-81 were about 2 feet higher in 1987 than they had been in 1970. A subsequent water level decline of almost 4 feet from 1987 through 1990 resulted in 1990 - 1991 water levels in the upper aquifer in Twp. 148-81 being, on average, about 1.5 feet **below** what they were in 1970. In contrast to the upper aquifer unit, water levels in 1990-1991 in the lower aquifer in Twp. 148-81 were about the same as they had been in 1970, and were about 1.5 feet above what they had been in 1970 in Twp. 148-82. The fact that groundwater levels in 1990-1991 in the upper aquifer in Twp. 148-81 were below what they had been in 1970, demonstrates that the 13 foot increase in Lake Audubon elevation in 1975 is not the controlling factor on upper aquifer unit groundwater levels in Twp. 148-81, an area where high water levels in the early to mid 1980's had been attributed to the increased elevation of the reservoir.

RELATIVE WATER LEVEL TRENDS SUMMARY

The magnitude of the relative water level changes for various benchmark periods is summarized in Table 6. Net relative groundwater elevation changes for the periods 1970 to 1984, 1970 to

Table 6. Summary of Relative Water Level Changes by Well Grouping

	1. Rel. Water Elev Change 1970 - 84	2. Rel. Water Elev Change 1968 - 87	3. Rel. Water Elev Change 1970 - 87	4. Rel. Water Elev Change 1987 - 91/92	5. Rel. Water Elev Change 1968 - 91/92	6. Rel. Water Elev Change 1970 - 91/92	7. Rel. Water Elev Change 6/93 to 6/94	8. Lower Aq vs Upper Aq 1967 - 70	9. Lower Aq vs Upper Aq 1985 - 87	10. Lower Aq vs Upper Aq 1991 - 92
All Upper	2.3 ft	3.2	2.6	-3.1	0.1	-0.5	1.8	0	0.8	0.8
All Lower	3	4	3.4	-3	1	0.4	1.6			
West Upper	1	2.4	1.6	-2.8	-0.4	-1.2	1.9	0	1.5	1
West Lower	3	4	3.4	-3.3	0.7	0.1	2.2			
East Upper	2.2	3.6	3	-3.3	0.3	-0.3	1.5	0	0	0.8
East Lower	2.9	3.6	3.3	-2.4	1.2	0.9	1			
148-81 Upper	0.7	2.5	1.6	-3.1	-0.6	-1.5	1.8	0	1	1.1
148-81 Lower	2.4	3.1	2.5	-2.8	0.3	-0.3	1.9			
148-82 Lower	5.4	5.8	5.8	-4.0	1.8	1.8	2.5			
Far East Upper	2.4	3.2	2.9	-3.9	-0.7	-1	2.2	0	0	1.3
Far East Lower	2.5	3.2	2.9	-2.6	0.6	0.3	0.9			

1. Average relative water level change in feet from 1970 to 1984 for the well grouping.
2. Average relative water level change in feet from 1968 to 1987 for the well grouping.
3. Average relative water level change in feet from 1970 to 1987 for the well grouping.
4. Average relative water level change in feet from 1987 to 1991/92 for the well grouping.
5. Average relative water level change in feet from 1968 to 1991/92 for the well grouping.
6. Average relative water level change in feet from 1970 to 1991/92 for the well grouping.
7. Average relative water level change in feet from June 1993 to July 1994 for the well grouping.
8. The approximate difference in feet between the relative average water elevation in the lower aquifer and that in the upper aquifer in the well grouping for the period 1967 through 1970.
9. The approximate difference in feet between the relative average water elevation in the lower aquifer and that in the upper aquifer in the well grouping for the period 1985 through 1987.
10. The approximate difference in feet between the relative average water elevation in the lower aquifer and that in the upper aquifer in the well grouping for the period 1991 through 1992.

1987, 1987 to 1991/92 and 1970 to 1991/92 are presented graphically in Figure 46. The 1970 data is used as a reference point as it represents the last year prior to 1975 where an abundant amount of groundwater level data was collected. The year 1984 approximates relative water levels in 1983 to 1985 prior to the wet cycle of 1986 to mid 1987 which produced the period of record water level peak in mid-1987. The 1991/92 period approximates the lowest water levels after the drought of 1988 - 1989 which followed the 1987 peak.

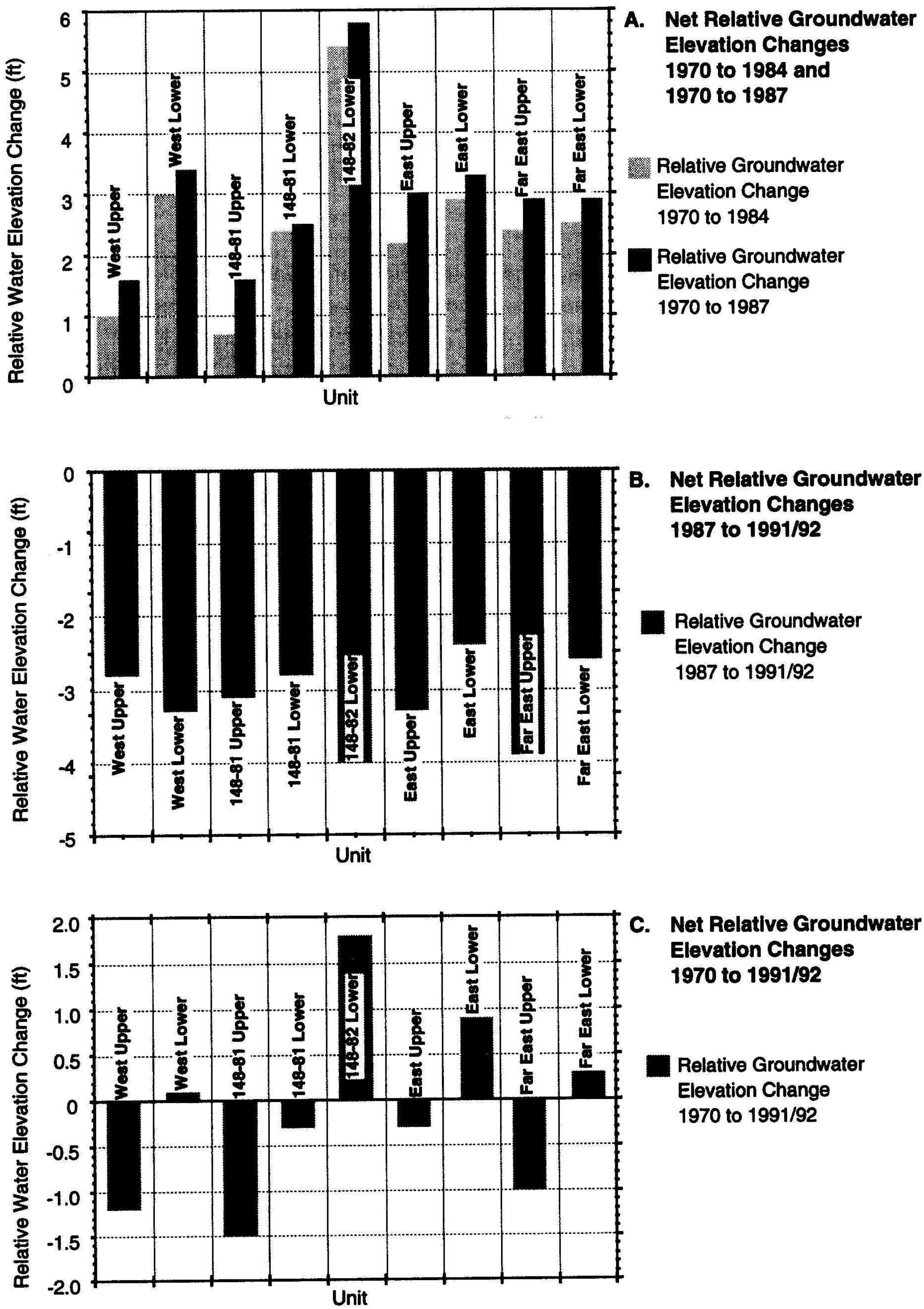


Figure 46. Bar graph summary of net relative groundwater elevation changes for well groupings in the lower and upper aquifer units.

The greatest relative water level changes between the 1970 reference point and 1984 and the peak in 1987 occurred in the Twp. 148-82 lower aquifer grouping (Fig. 46A), which showed relative increases about 2.5 feet greater than most of the remaining groups. It is important to note that this 2.5 foot difference is consistent with the amount of groundwater level rise, based on the 1985 Lake Audubon response test, that was estimated to have occurred in the lower aquifer in Twp. 148-82 in response to the 13 foot increase in 1975 in Lake Audubon elevation (Fig. 31).

It is instructive to note that the smallest average increases in relative water elevation between 1970 and 1984 and between 1970 and 1987 occurred in the upper aquifer unit in the west part of the study area and in Twp. 148-81 (Fig. 46A). The relatively small increase in the upper aquifer in Twp. 148-81 is significant as this well grouping encompasses the Lake Nettie and McLean County Slough No. 1 area, where high surface water levels in the early and mid 1980's had been attributed high upper aquifer groundwater levels caused by the presence of Lake Audubon and specifically to raising its level by 13 feet in 1975. Substantially greater increases in groundwater levels in the upper aquifer occurred between 1970 and 1984 to 1987 in areas further removed from Lake Audubon than the Twp. 148-81 grouping, which indicates that the raising of Lake Audubon did not contribute to the high surface water levels.

The change in water levels between the 1987 peak and the 1991/92 low is presented on Figure 46B. The greatest decreases were observed in the Twp. 148-82 lower aquifer grouping and the far east upper aquifer grouping. In groupings in the west part of the study area, slightly larger decreases occurred in the lower aquifer than in the upper aquifer. The converse was observed in groupings in the east part of the study area, where water level decreases in the upper aquifer were greater than in the lower aquifer. The greater decrease in the lower aquifer relative to the upper in the western part of the study area is due, at least in part, to the 20 - 25 foot decrease in Lake Sakakawea elevation across the same time period. The greater decrease in the upper aquifer water levels relative to the lower aquifer in the eastern part of the study area may be due to a more direct communication of the upper aquifer with precipitation patterns.

Relative groundwater levels during the 1991 - 1992 low compared to those of 1970 are summarized in Figure 46C. Water levels in the upper aquifer unit within all the groupings were lower in 1991 to 1992 than they had been in 1970, due to the influence of climatic cycles. Water levels in the lower aquifer unit were higher in Twp. 148-82 and the east part of the study area in 1991 to 1992 than they had been in 1970. The higher levels in the lower aquifer unit in Twp. 148-82 can be attributed to the 13-ft increase in Lake Audubon, but the large separation distance from Lake Audubon suggests that the higher water levels in the lower aquifer in the east part of the study are due to other factors.

WATER LEVELS TRENDS AND PRECIPITATION

Total monthly, average monthly, total annual and average annual precipitation data from the NOAA observer station in the city of Turtle Lake for the period 1961 through 1993 are summarized graphically on Figure 47. Total annual, 5-year trailing moving average and average annual precipitation for 1940 through 1993 are summarized on Figure 48A. The cumulative departure from average annual precipitation is shown on Figure 48B together with the Total Annual and 5-year Trailing Moving Average precipitation. The cumulative departure from average precipitation is determined by incrementing the difference between the year's total precipitation and the average annual precipitation. The year 1940 was selected as an arbitrary starting point for calculating the cumulative departure. As with the averaged water level trends, the absolute value of the cumulative departure is arbitrary, but the directional trend of the cumulative departure is meaningful. A prolonged rising trend indicates an extended period of generally above normal precipitation, whereas a prolonged downward trend indicates an extended period of generally below normal precipitation.

As can be seen in Figure 48B, the late 1950's to early 1960's represent a prolonged period of below normal precipitation. Then beginning in 1962 there is a generally rising trend in cumulative departure from average precipitation that continues until 1987, with periodic intervening declines in the mid to late 1970's. The 1962 to 1987 rising trend corresponds to a period when the trailing moving average precipitation was generally above average annual precipitation (Fig. 48B). The 1988 -1989 drought is indicated by the sharp downturn in the cumulative departure after the 1987 peak. The cumulative departure curve is then relatively stable in 1990 through 1993 as annual precipitation was within +/- 3 inches of average.

The average water level trends for the upper unconfined and lower confined aquifer units for the entire study area groupings are presented in Figure 49 together with the cumulative departure from average precipitation. The parallel nature of the precipitation and groundwater level trend curves demonstrates the dominant role of precipitation and recharge in determining groundwater levels. The continued increase in groundwater levels from the late 1960s through the peak in 1987 follows the rising trend in the cumulative departure from normal precipitation curve. As a whole, 1962 through 1987 was a period of above average precipitation. During this 26 year period total annual precipitation at the city of Turtle Lake was within 1 inch of normal in 8 of the years, more than 1 inch below normal in 4 of the years, and greater that 1 inch above normal in 14 of the years. The prolonged period of overall above normal precipitation resulted in above average infiltration and groundwater recharge creating the increasing trend in groundwater levels.

The drop in water levels after the 1987 peak resulted from the drought of 1988 and 1989 marked by a sharp downward swing in the cumulative departure from normal precipitation curve. Annual precipitation at Turtle Lake was 8.45 inches in 1988, about 50% of normal and 11.40 inches in 1989, 5.6 inches below normal. In addition, the summers of 1988 and 1989 were hot with above normal evaporation. Totals of 51.5 inches in 1988 and 44.5 inches in

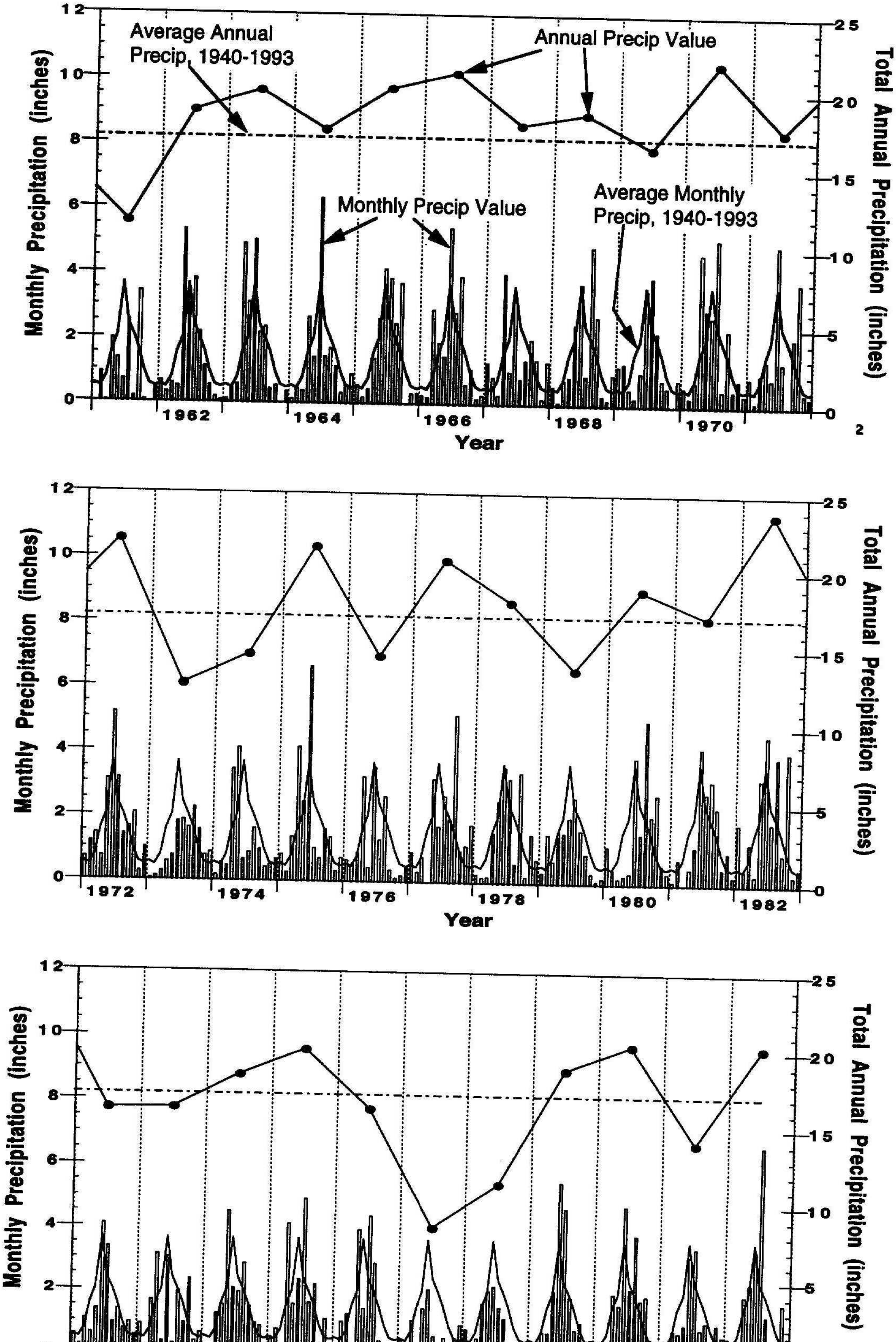
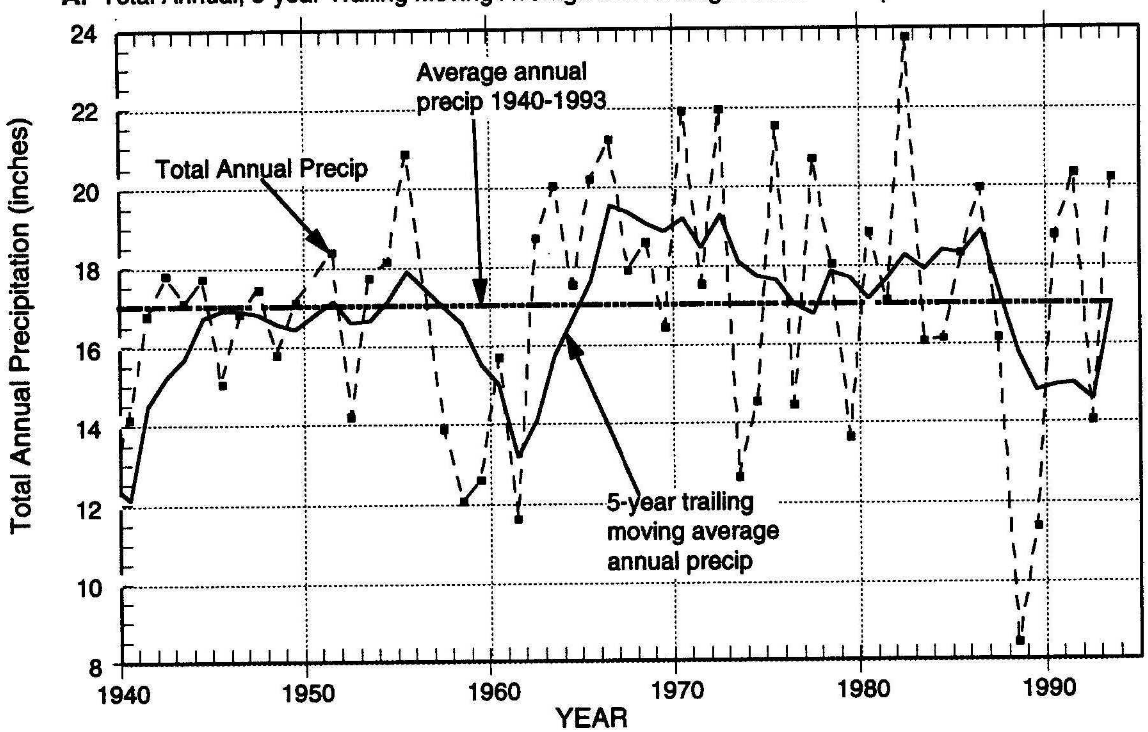


Figure 47. Summary of NOAA Precipitation Data Recorded at the city of Turtle Lake, 1961 - 1993.

A. Total Annual, 5-year Trailing Moving Average and Average Annual Precipitation 1940-1993.



B. Total Annual, 5-year Trailing Moving Average and Cumulative Departure from Average Annual Precipitation 1940-1993.

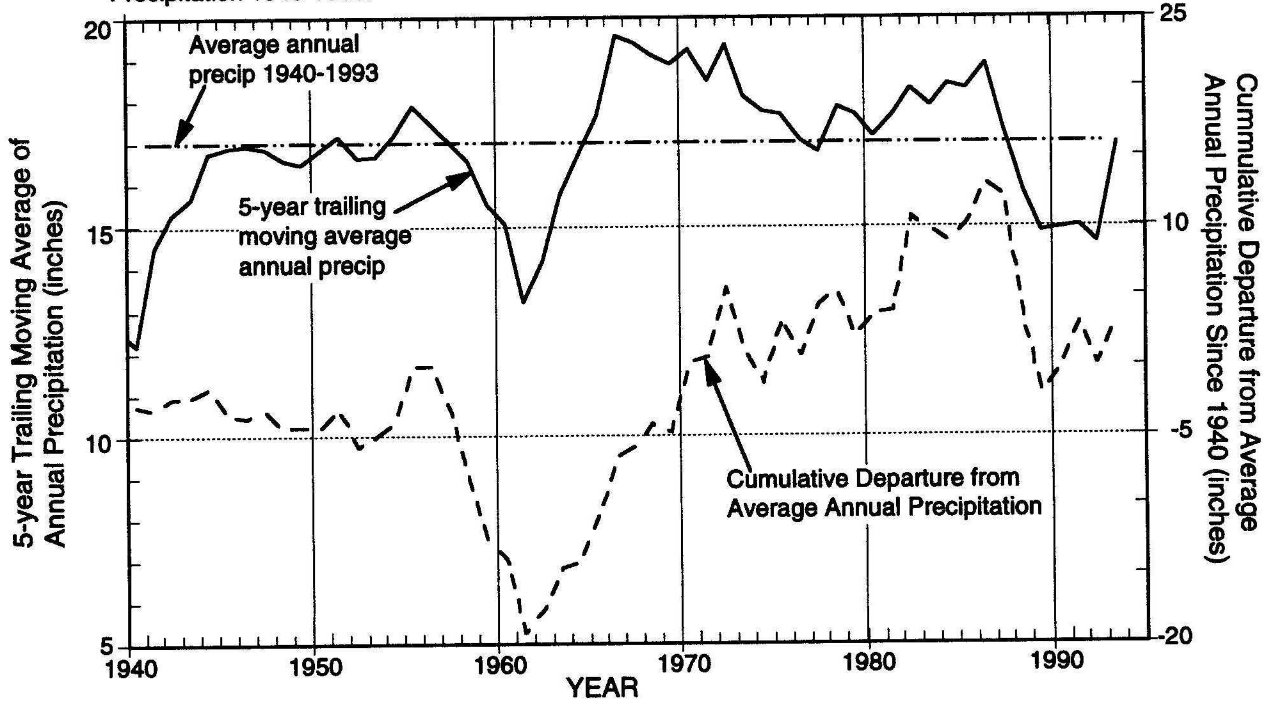


Figure 48. Trends in NOAA Precipitation Data Recorded at the city of Turtle Lake.

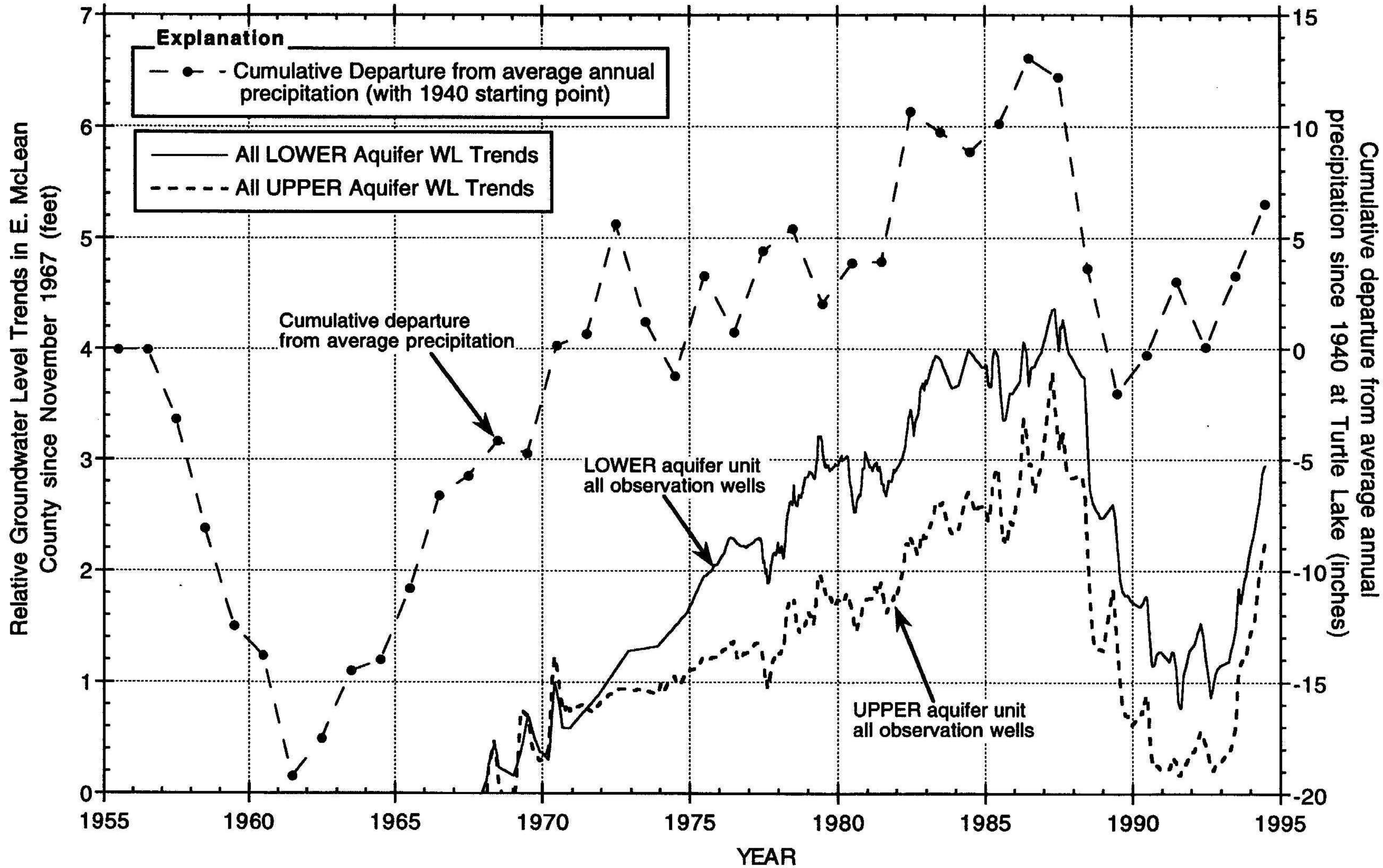


Figure 49. Groundwater level trends in the upper and lower units of the Lake Nettie aquifer system and cumulative departure from average annual precipitation at the city of Turtle Lake (NOAA Data).

1989 of evaporation were recorded between April and September at the Mandan Experiment Station, located 50 miles south of the study area. Thus, evaporation exceeded precipitation by over 40 inches in 1988 and over 30 inches in 1989, compared to a regional average of 17 to 20 inches of evaporation in excess of precipitation.

Water levels continued to drop through 1990 and remained relatively stable through 1991 even though annual precipitation in the area was above normal (1.7 and 3.3 inches above normal at Turtle Lake, for 1990 and 1991, respectively). The above normal annual precipitation in 1990 and 1991 was insufficient to overcome the soil moisture deficit created by the severity of the 1988 and 1989 drought. With extremely low antecedent soil moisture conditions, a larger percentage of the precipitation would be retained in the vadose zone resulting in less recharge to the groundwater system.

Water levels generally remained near their 1991 levels through 1992 and early 1993. Then in mid 1993 water levels began a upward trend in response to unusually high precipitation in July 1993. The trend continued through early 1995 due to above normal precipitation in 1993 and 1994. Figure 50 illustrates that the upward trend resulted in relative water levels in the upper aquifer unit in mid 1995 that approached those of the previous period of record high in 1987. The well grouping in Figure 50 includes 21 upper aquifer wells in sections 13 through 36 of Twp. 148-81, which focuses the grouping on the Lake Nettie area and eliminates wells screened in the Horseshoe Valley aquifer in the northern part Twp. 148-81. The well grouping considered in Figure 50 encompasses the area where high surface water levels in the 1980's had been ascribed to the effect of Lake Audubon on groundwater levels in the upper unconfined aquifer unit. The 4 foot groundwater level decline from 1987 to 1991 followed by the 4 ft rise between 1991 and 1995 in this well grouping, a time period when Lake Audubon was operated at its normal post-1975 elevation, indicates that the reservoir is not a controlling factor with regard to upper aquifer groundwater levels or surface water levels in the Lake Nettie area.

When the analysis and development of the relative water level trends hydrographs presented in Figures 43 - 49 was performed for this study, data were available only through July 1994. Time constraints prohibit the regeneration of relative water levels trends hydrographs with data through 1995 for all the well groupings. However, examination of data for individual wells indicates that groundwater levels in early 1995 approached, and in some cases exceeded, the previous period of record water level highs of early 1987.

Elevations of water levels measured in upper unconfined aquifer unit wells 148-80-33CCC and 148-81-33CCD (which represent the observation wells with the most continuous long-term water level records in the study area) are shown together with the cumulative departure from average precipitation in Figure 51. As with the average relative water level trends hydrographs the parallel nature of the trends in the cumulative precipitation departure curve and the actual water level elevations demonstrates the dominant role of climate in controlling groundwater levels. The relation between climatic patterns and groundwater level changes is

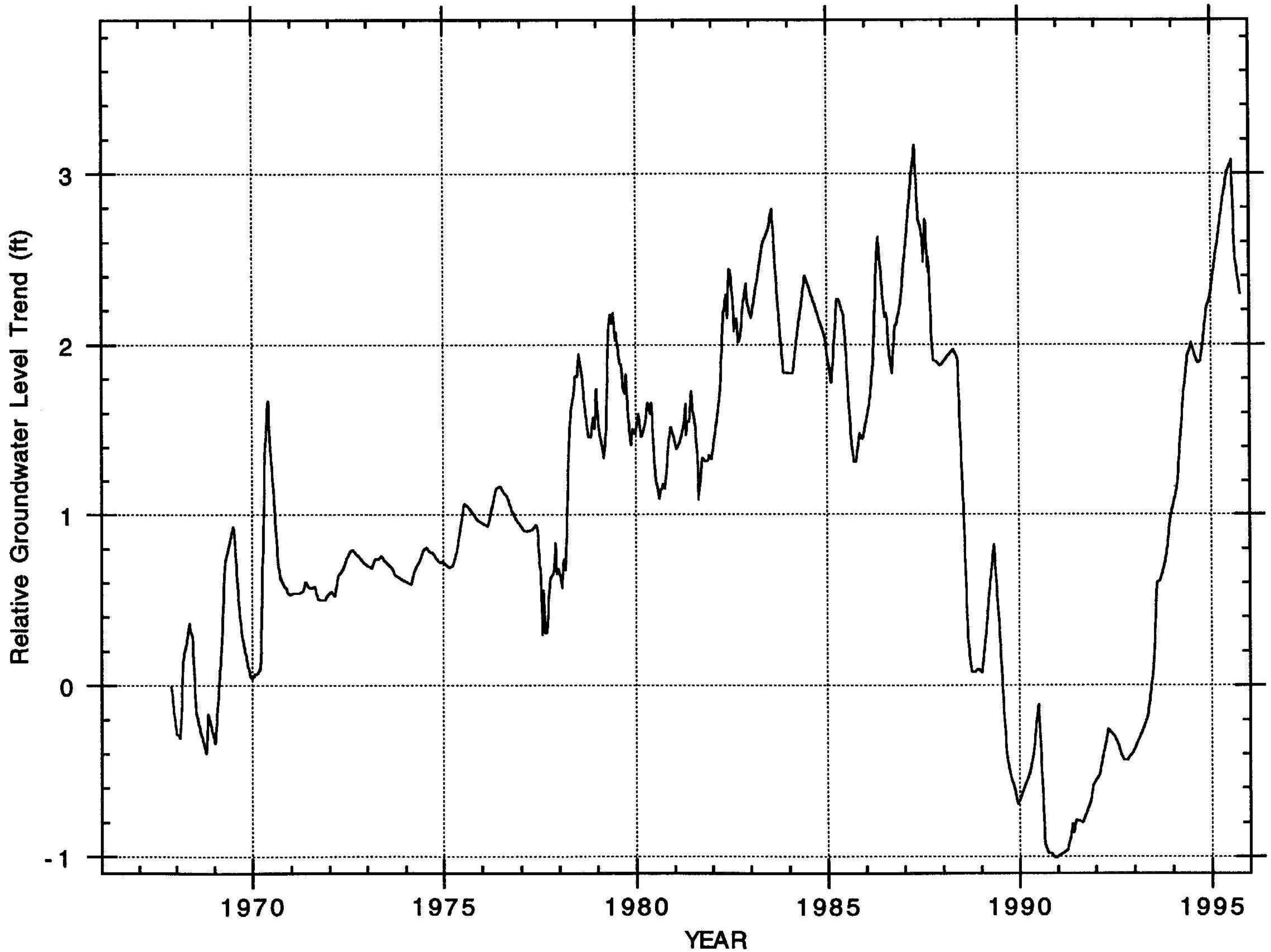
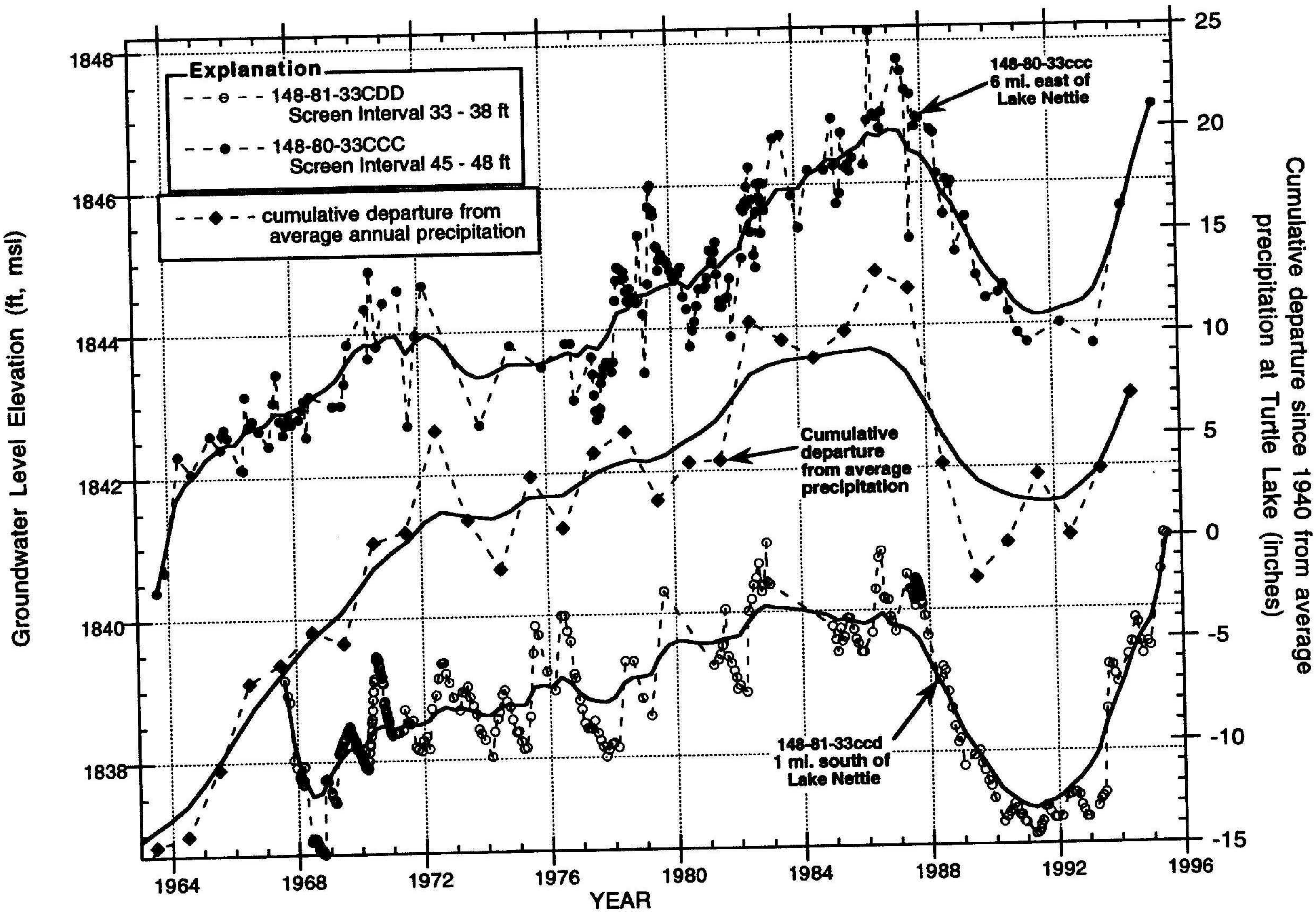


Figure 50. Relative groundwater level trends in the Lake Nettie aquifer upper unit November 1967 through September 1995; all upper aquifer unit observation wells in Sections 13 to 36, Township 148-81.



Solid lines through data points represent the smoothed curved generated by a Stineman Function, which applies a geometric weight to the current point and plus or minus 10% of the data.

Figure 51. Groundwater level elevations in upper aquifer wells 148-81-33CDD and 148-80-33CCC compared to cumulative departure from average annual precipitation at the city of Turtle Lake.

emphasized by the statistically smoothed curves (Stineman function) that are included Figure 51. Of particular significance in the figure is the upward trend in groundwater levels prior to the raising of Lake Audubon in 1975.

Water levels in well 148-81-33CCD, located about 1 mile south of Lake Nettie, were about 1.5 feet lower in 1990 to 1992 than they had been in 1970 through 1974. Water levels in well 148-80-33CCC, located about 6 miles east of Lake Nettie, were about the same in 1990 to 1992 as they had been in 1970 to 1972 and about 1.5 feet higher than in 1965 to 1968. The higher water levels at well 148-80-33CCC in 1990 to 1992 relative to 1965 through 1968 must be attributed to long term climatic patterns, because there could be no effect from Lake Audubon on water levels in this upper aquifer well due to the large separation distance from the reservoir.

RESPONSE OF WATER LEVELS TO TIMING OF PRECIPITATION

The total amount of annual rainfall is an incomplete predictor of short term groundwater level response. Total annual rainfall in Turtle Lake was 18.77 inches in 1990 and 20.33 inches in 1991, both above the 17.03 inch 1940 to 1992 average. In general, groundwater levels in 1990 and 1991 either continued the decline which began in 1988 or remained stable near the levels to which they had declined through 1988 and 1989. In contrast to 1990 and 1991, groundwater levels rose significantly in 1993 (e.g. Figs. 49 and 51) even though the total annual rainfall at Turtle Lake was 20.23 inches, similar to 1990 and 1991. The difference between the large groundwater response to the 20 inches of rainfall in 1993 and the general lack of response to 20 inches of 1990 was the timing and intensity of the precipitation, coupled with antecedent soil moisture conditions.

Most of the above average July and August 1990 rainfall, which was not lost to runoff, went to replacing moisture in the unsaturated zone that had been severely depleted in 1988 and 1989, with little deeper percolation to provide groundwater recharge. In 1993, July was an unusually wet month. Total July precipitation recorded at the Turtle Lake NOAA station was 6.73 inches compared to a monthly average of 2.42 for July. An SWC recording rain gage located in 148-82-26BBB (4 miles west of Lake Nettie and 1 mile east of Lake Audubon) recorded 9.35 inches for July 1993. July 1993 rainfall reported by 10 North Dakota Atmospheric Resource Board (ARB) observers within the study area ranged from a low of 7.41 inches to a high of 11.2 inches, with an average of 8.8 inches. July 1993 was also extremely wet for most counties in North Dakota.

The effect of the above normal July precipitation on groundwater recharge is shown by the mid-1993 sharp water level rise of about 1.5 feet in well 148-81-33CDD, and between the early 1993 and early 1994 measurements at well 148-80-33CCC (Fig. 51). Water levels in wells similarly screened in the upper aquifer in the west part of the study area also showed abrupt water level rises in 1993 between the late June and early August measurements in response to the July rain (Fig. 52). The rise continues through early 1995 with water levels approaching

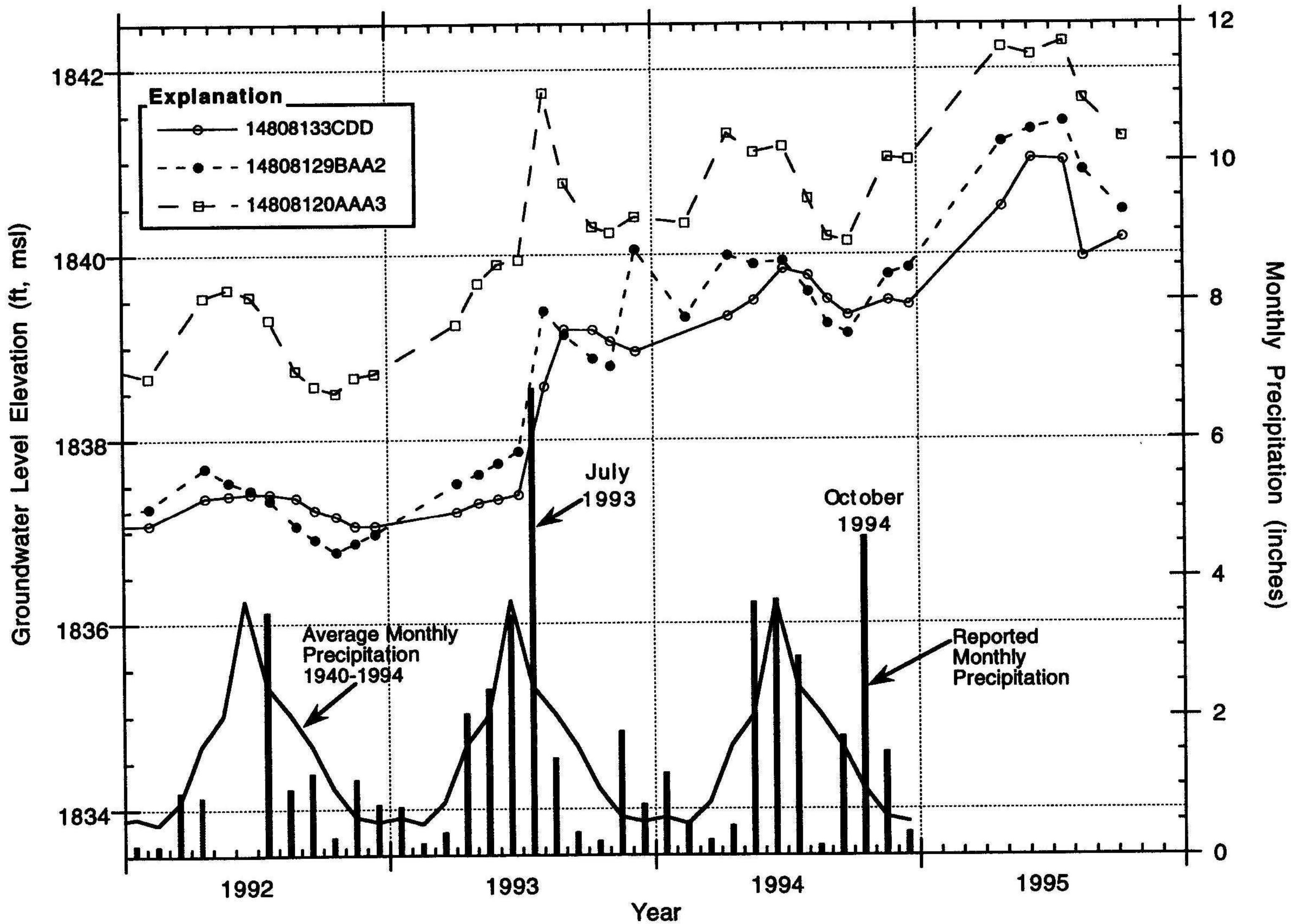


Figure 52. Groundwater level elevations in upper aquifer wells in the Lake Nettie area and monthly precipitation at the city of Turtle Lake (NOAA station), 1992 - 1994.

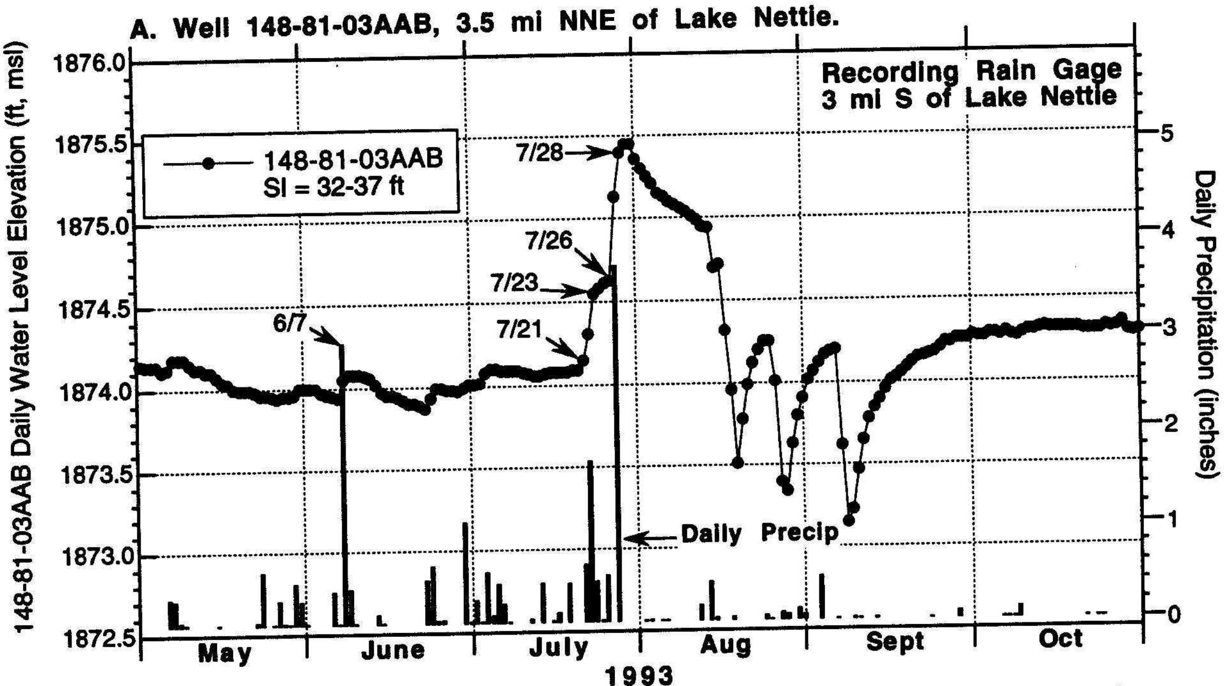
or exceeding the 1987 high in many wells. A wet fall season in 1994 increased the amount of water stored in the unsaturated zone, contributing to groundwater recharge and rising groundwater levels in spring 1995 (Fig. 52).

The role of the timing and intensity of precipitation events in determining the amount groundwater recharge is illustrated in Figure 53, which present the daily maximum water level elevations for continuous recorder wells 148-81-03AAB and 150-80-08BBB together with daily precipitation data measured at the SWC recording rain gage in 148-82-26BBB. Well 148-81-03AAB is located in the upper unconfined aquifer unit near the confluence of the Lake Nettie and Horseshoe Valley aquifers and is about 7 miles northeast of the recording rain gage. Well 150-80-08BBB is in the northern part of the Horseshoe Valley aquifer about 16 miles north-northeast of the recording rain gage.

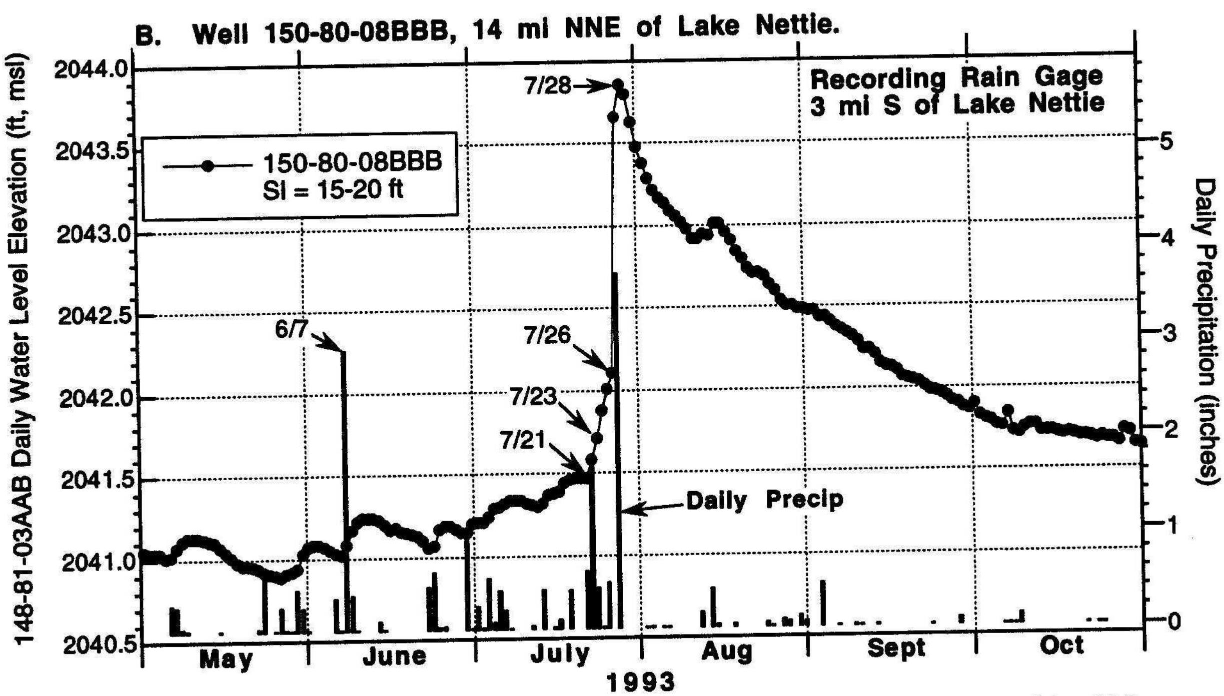
The water level in well 148-81-03AAB rose 0.8 feet between 7/26/93 and 7/28/93, in response to precipitation events that included 3.7 inches on 7/27/93 at the recording rain gage location (Fig. 53A). The water level had also risen about 0.5 feet in the well in response to rainfall between 7/21/93 and 7/25/93 which measured a total of 3 inches at the recording rain gage station. It is interesting to note that a rainfall event of similar intensity to the 7/27/93 event was recorded on 6/7/93. However, water level response to the 6/7/93 precipitation event was barely perceptible. The abundant rainfall throughout July (6.7 inches between 6/29 and 7/25 at the recording gage station) created such wet soil moisture conditions that the July 27 deluge resulted in an exceptionally large groundwater recharge event. The heavy precipitation event of 6/7/93 did not generate groundwater recharge near the magnitude of the 7/27/93 event because the wet antecedent soil moisture conditions were absent, and most of the precipitation that was not lost to runoff was retained in the vadose zone.

The water level at well 150-80-08BBB reacted to the late July precipitation in a manner similar to that of 148-81-03AAB (Fig. 53B). The water level rose approximately 1.5 feet between 7/26/93 and 7/28/93 and 0.5 feet in the few days prior to that. Water levels in well 150-80-08BBB also showed little response to the 6/7/93 precipitation event that was measured at the recording rain gage station. In addition to the hypothesis of lower antecedent soil moisture conditions, it is possible that the 6/7/93 precipitation event was not as wide spread as those of late July. However, North Dakota Atmospheric Resource Board observers' reports indicate widespread rainfall events in the study area between 6/6/93 and 6/8/93, ranging from 1 to 2.5 inches in magnitude, similar to the range reported around the 7/27/93 event.

Following the sharp recharge rise at the end of July 1993, water levels in both wells 148-81-03AAB and 150-80-08BBB declined through October to near the level they were earlier in the summer (Fig. 53). This decline is not representative of water levels in the aquifer system as a whole, which were 1 to 2 feet higher in late 1993 to early 1994 than they had been in early 1993. Rather the late 1993 decay of water levels in the two recorder wells is attributable to local conditions at the recorder well locations. The water level decline at well 150-80-08BBB



Well 148-81-03AAB is completed in a sand and gravel layer that exists from a depth of 1 to 45 ft and is underlain by shale. The well is located in the Horseshoe Valley aquifer near its confluence with the Lake Nettie Aquifer.



Well 150-80-08BBB is completed in a sand and gravel layer that exists from a depth of 1 to 20 ft and is underlain by clayey till. The well is located in the Horseshoe Valley aquifer near the northern border of McLean County.

Figure 53. May through October 1993 daily precipitation at Lake Nettie area recording rain gage and daily maximum groundwater level elevation in surficial unconfined aquifer recorder wells.

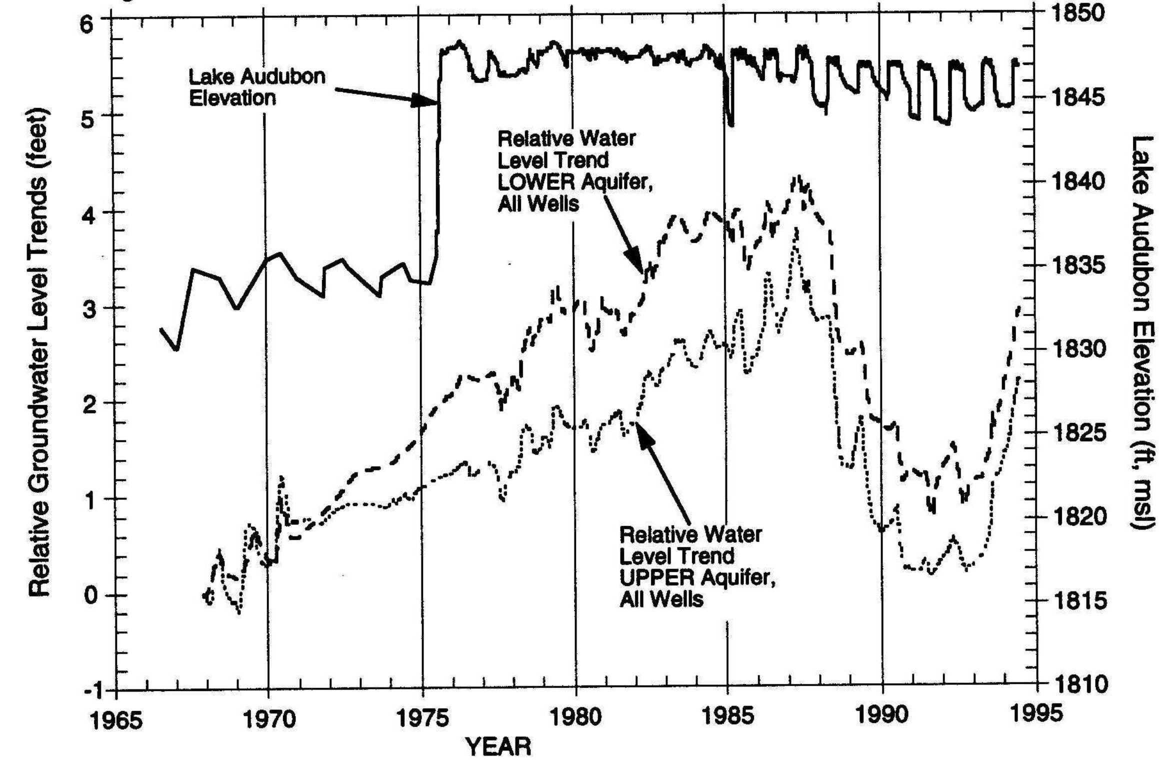
was largely due to evapotranspiration loss as depth to water in the well was only 3 to 5 feet below land surface in mid to late 1993. Well 148-81-03AAB is located a few hundred feet east of the northern reach of Turtle Creek. The water level decline measured at this well is likely due to the groundwater discharging into the ephemeral creek, which fixes the base level elevation which the local water table will seek. The return of the water table to the local base level would be expected to be relatively rapid, given the coarse, gravelly nature of the upper aquifer unit in this area. The effect of the ephemeral stream on maintaining a consistent groundwater base level is shown in the water level record of monthly to quarterly measurements for the well. Since 1975, the non-irrigation pumping season water level elevation in well 148-81-03AAB has fluctuated less than 1 foot, remaining between 1874 and 1875 feet (major storm and recharge events will temporarily raise the water level before an ensuing decay as shown in Figure 53A). By contrast, water levels in most other wells have fluctuated a total of 3 to 5 feet over the same time period. The water level decline toward the base level at well 148-81-03AAB in late 1993 is assisted by irrigation pumping which is evident in the temporary drawdown cones in mid August to early September (Fig. 53A).

EFFECT OF LAKE SAKAKAWEA ON GROUNDWATER LEVELS

Although evaluation of the data indicates that climatic patterns are the dominant factor in determining groundwater level changes in the study area, Lakes Sakakawea and Audubon have also affected water levels in the confined units of the aquifer. Surface water elevations of Lake Audubon and Lake Sakakawea are shown together with relative water level trends in Figure 54. The effect of raising Lake Audubon on water levels in the lower confined aquifer units has been discussed in previous chapters. Since Lake Audubon was raised by 13 feet in 1975, the average groundwater level elevations in both the confined and unconfined aquifer units have fluctuated by 3 to 4 feet (Fig. 54A), which is greater than the amount of groundwater level increase predicted in the lower unit for the 13 foot change in Lake Audubon elevation at distances greater than 3 miles from the lake.

Large changes in Lake Sakakawea stage can also have an affect on the water levels in the confined parts of the aquifer, although the water level change in the aquifer is a small percentage of the change in Lake Sakakawea. The trough in water level elevation trends in 1990 through 1992 between the peak in 1987 and the rebound in 1993 -1995 is exaggerated in the lower aquifer unit in Twp. 148-82 relative to that in the far east part of the study area (Fig. 54B). Lake Sakakawea also experienced a large dip in groundwater elevation that parallels the aquifer water levels. There are also noticeable groundwater level rises in 1978 and 1982 in the lower aquifer in Twp. 148-82 that correspond to significant increases in Lake Sakakawea stage. Separating groundwater rises that may be a response to the reservoir from climatic cycles is problematic as large changes in reservoir level (responding to regional climate cycles) have tended to correspond to wet and dry cycles in the study area.

A. Relative groundwater level trends in the UPPER and LOWER aquifer units and elevation of Lake Audubon.



B. Lake Sakakawea elevation and relative groundwater level trends in the LOWER aquifer unit in the FAR EAST and FAR WEST (Twp. 148-82) well groupings.

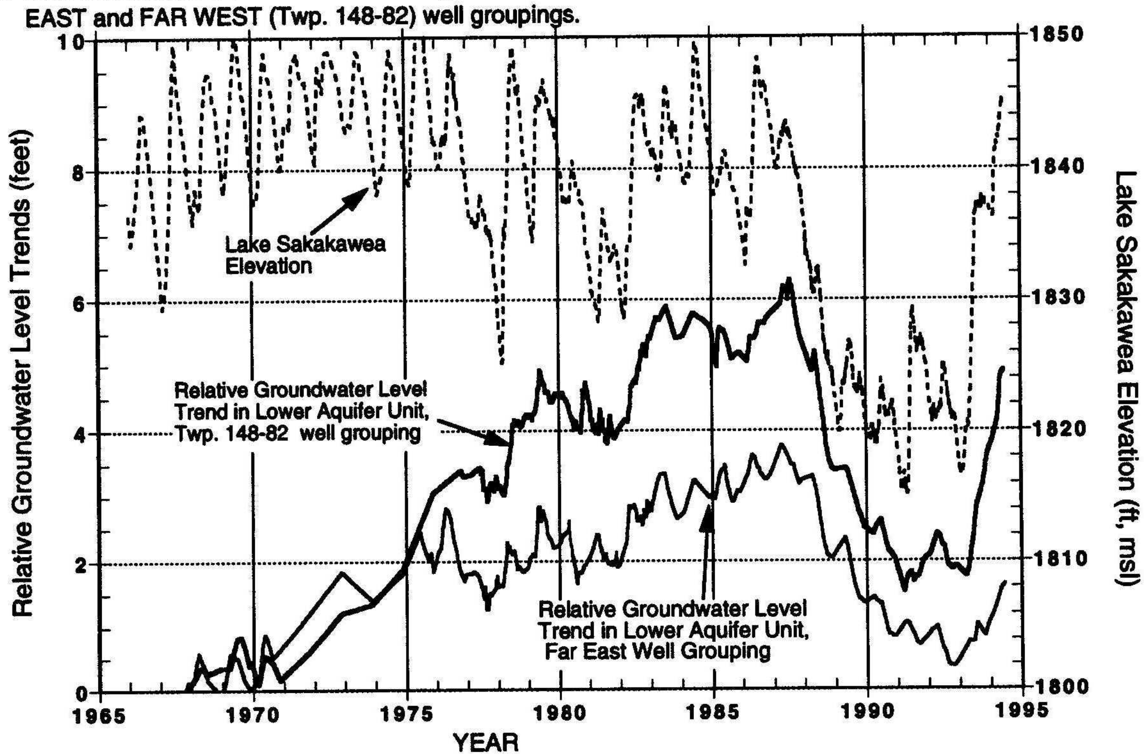


Figure 54. Comparison of relative groundwater elevation trends in the Lake Nettie aquifer upper and lower units with Lake Audubon and Lake Sakakawea water surface elevations.

Water levels in the confined aquifer layers in the west part of the study area began rising in response to Sakakawea in May 1993 (Fig. 55) prior to the heavy July precipitation which caused the pronounced increase in groundwater elevations in the upper unconfined aquifer unit between the June 29 and August 4 water level measurements. Comparison of Figures 55A and 55B shows differences in the timing, consistency and magnitude of groundwater elevation increases between wells screened in the lower confined aquifer unit and upper unconfined unit. A significant and consistent rise in groundwater elevations is evident between 4/5/93 and 6/30/93 in the lower confined aquifer unit in the west part of the study area. This rise in groundwater elevations, consistent across the western part of the study area, was initiated prior to the heavy precipitation which occurred in the area in July 1993. The rising trend in lower aquifer unit water elevations throughout 1993 is attributed in part to aquifer response to rising Lake Sakakawea stage which gained approximately 17 feet (1820 to 1837 feet, msl) between 4/93 and 8/93. Water levels in Lake Sakakawea began rising in March with an increase in refilling rate beginning in late May.

The early to mid 1993 lower aquifer water level rise in the western part of the study area was not apparent in observation wells in the eastern part of the study area (Fig. 56). At least a portion of this rise is likely a result of the rising Sakakawea reservoir stage. However Lake Audubon was also raised 3 feet from its winter level to its normal operating level in late April to early May and would have contributed up to 0.5 feet to the lower aquifer unit groundwater level rise in the west part of the study area.

With multiple factors that can affect water levels operating simultaneously, it is impossible to precisely quantify the magnitude of groundwater response to Lake Sakakawea. However, across the time period when Sakakawea rose 17 feet the water level in well 148-82-08CDC1 (well closest to Sakakawea) rose about 1.2 feet, in response to the Sakakawea increase plus other potential contributing factors. Thus the increase in water levels in the lower aquifer at the observation point closest to Lake Sakakawea was less than 7% of the associated rise in Lake Sakakawea. Figure 54 shows that the relative water levels in the Twp. 148-82 well grouping rose 1 foot in from April to July 1978 when Lake Sakakawea rose 24 feet (from 1825 to 1849 feet elevation). Water levels in wells 148-82-15BBB and 148-82-23BBB rose 1 foot during this same time period (hydrograph 3, Plate 2). It is apparent that Lake Sakakawea stage elevation affects the groundwater levels in the lower confined aquifer units in the western part of the study area, but that the magnitude of the groundwater level change is on the order of 5% of that of the associated change in Lake Sakakawea stage, and is much smaller than changes induced by climatic cycles.

EFFECT OF LAKE AUDUBON ON GROUNDWATER LEVELS

The magnitude of the effect that raising Lake Audubon water elevation 13 feet in 1975 had on groundwater levels in the lower confined aquifer has been discussed in preceding sections of this report. Generally, raising the reservoir had little substantive effect on the aquifer system

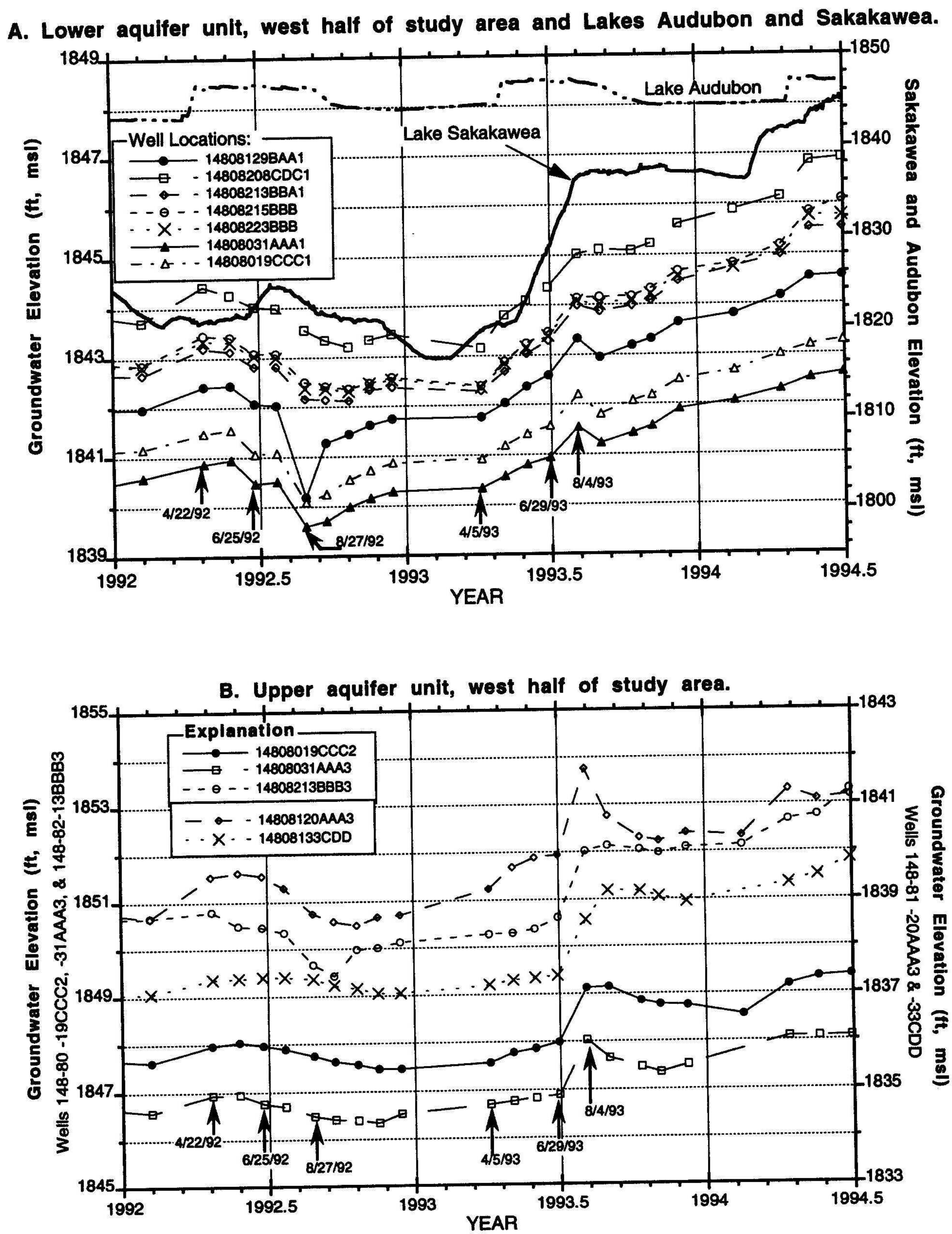
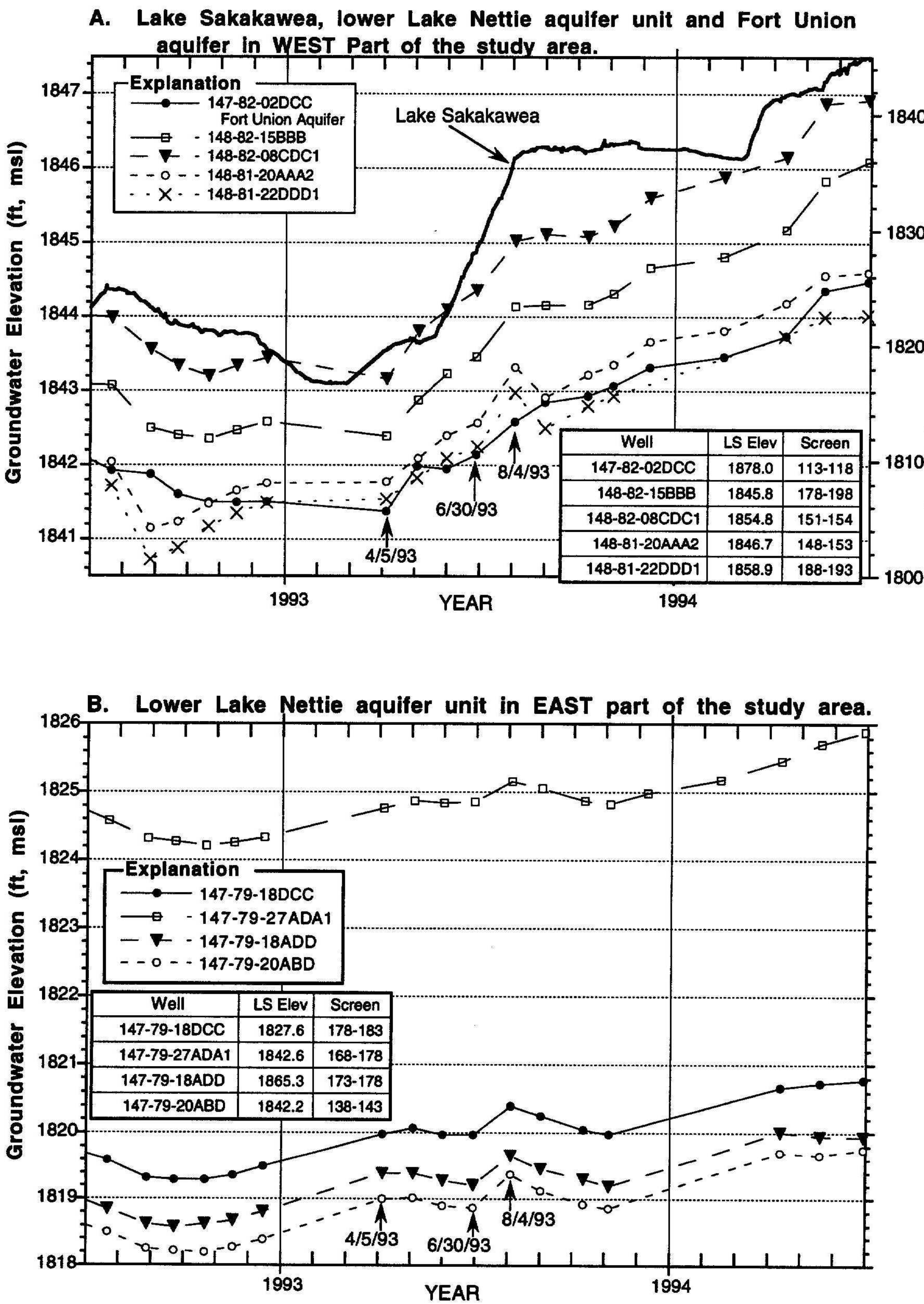


Figure 55. Groundwater elevations in selected observation wells in west half of study area and water surface elevations of Lakes Audubon and Sakakawea, 1992 through 1994.



Well	LS Elev	Screen
147-82-02DCC	1878.0	113-118
148-82-15BBB	1845.8	178-198
148-82-08CDC1	1854.8	151-154
148-81-20AAA2	1846.7	148-153
148-81-22DDD1	1858.9	188-193

Well	LS Elev	Screen
147-79-18DCC	1827.6	178-183
147-79-27ADA1	1842.6	168-178
147-79-18ADD	1865.3	173-178
147-79-20ABD	1842.2	138-143

Figure 56. Mid-1992 through mid-1994 Lake Sakakawea elevations and comparison of groundwater level changes in the Fort Union and lower Lake Nettie aquifer unit in the west and east parts of the study area.

beyond a few miles from the shore. As shown in Figure 57, water levels in 2 observation wells in the data collection network, wells 148-82-07AAD3 and 148-82-08CDC2, are controlled predominantly by Lake Audubon. These wells are both screened in the upper part of the middle unit of the Lake Nettie aquifer. Well 148-82-07AAD3 is located a few hundred feet west of the Snake Creek arm of Lake Audubon, while well 148-82-08CDC2 is located about 1/4 mile east of the reservoir. Water levels in these wells are affected by Lake Audubon because of their lateral and vertical proximity to the lake. Based on the January 1985 Lake Audubon response test, a one foot change in Lake Audubon level produces changes of about 0.6 and 0.4 feet in 148-82-07AAD3 and 148-82-08CDC2, respectively. Even with the dominant role of Lake Audubon in setting water levels in the upper portion of the middle aquifer unit at these two well locations, a climatic signature (a 1 foot decline and rebound between 1987 and 1995) is evident in the hydrograph, though it is less prominent than the 4 to 5 foot decline and rebound observed in the lower aquifer well 148-82-08CDC1 (Fig. 57).

It is apparent from the water level elevation fluctuations of 4 to 5 feet between 1987 and 1995 at well 148-82-08CDC1 (Fig. 57) that factors other than the stage level of Lake Audubon are dominant in determining groundwater levels in the lower Lake Nettie aquifer. Representative hydrographs of wells located within two miles of Lake Audubon and screened in confined layers of the Wolf Creek, Lake Nettie and Turtle Lake aquifers are shown on Figure 58. Although the 13 foot increase in Lake Audubon in 1975 raised groundwater levels on the order of 2 feet in these wells, climatic patterns after 1975 have generated groundwater level fluctuations of 5 to 6 feet.

COMPARISON OF WATER LEVEL CHANGES WITH ARMSTRONG (1983) DATA

Armstrong (1983) concluded that water levels in the lower and upper aquifer units had risen in response to the 13 foot increase in Lake Audubon. Armstrong's conclusions regarding water level increases in the lower unit is consistent with data collected for this study, except that the 4 foot increase attributed at well 148-82-15BBB (Armstrong, 1983, Figure 10) appears to be about 1 foot high. Although Armstrong's conclusion regarding the 1 to 2 foot increase in the upper aquifer water levels appeared to have been supported by the smaller data set available in 1983, the additional data collected for this study contradict Armstrong's conclusion attributing 1 to 2 foot water level increases in the upper unconfined unit of the Lake Nettie aquifer to the increase in Lake Audubon operating level. Water level fluctuations for three wells for which hydrographs were included in Armstrong's 1983 report are shown on Figure 59. Also shown in the hydrograph is a line marking the end of the data record available to Armstrong.

With the benefit of the longer water level record collected through varying climatic cycles, and the measurement of water levels during the January 1985 pumpdown of Lake Audubon, it is apparent that the water levels in the upper aquifer were not raised by the increase in Lake Audubon operating level. Armstrong concluded that the 13 foot increase in Audubon stage level

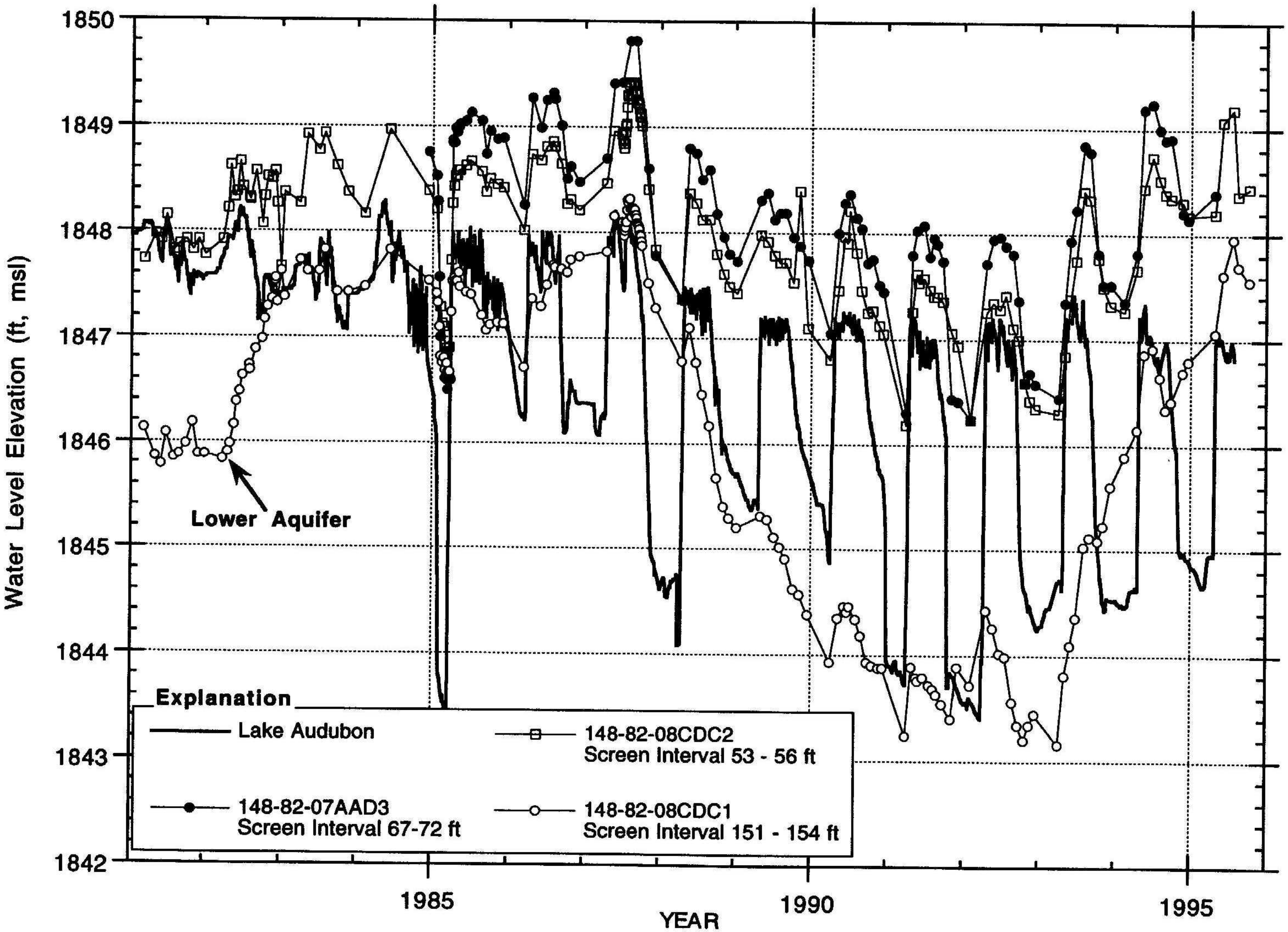


Figure 57. Comparison of Lake Audubon water level elevations and water level elevations in observation wells nearest Lake Audubon in the upper portion of the middle unit and the lower unit of the Lake Nettie aquifer.

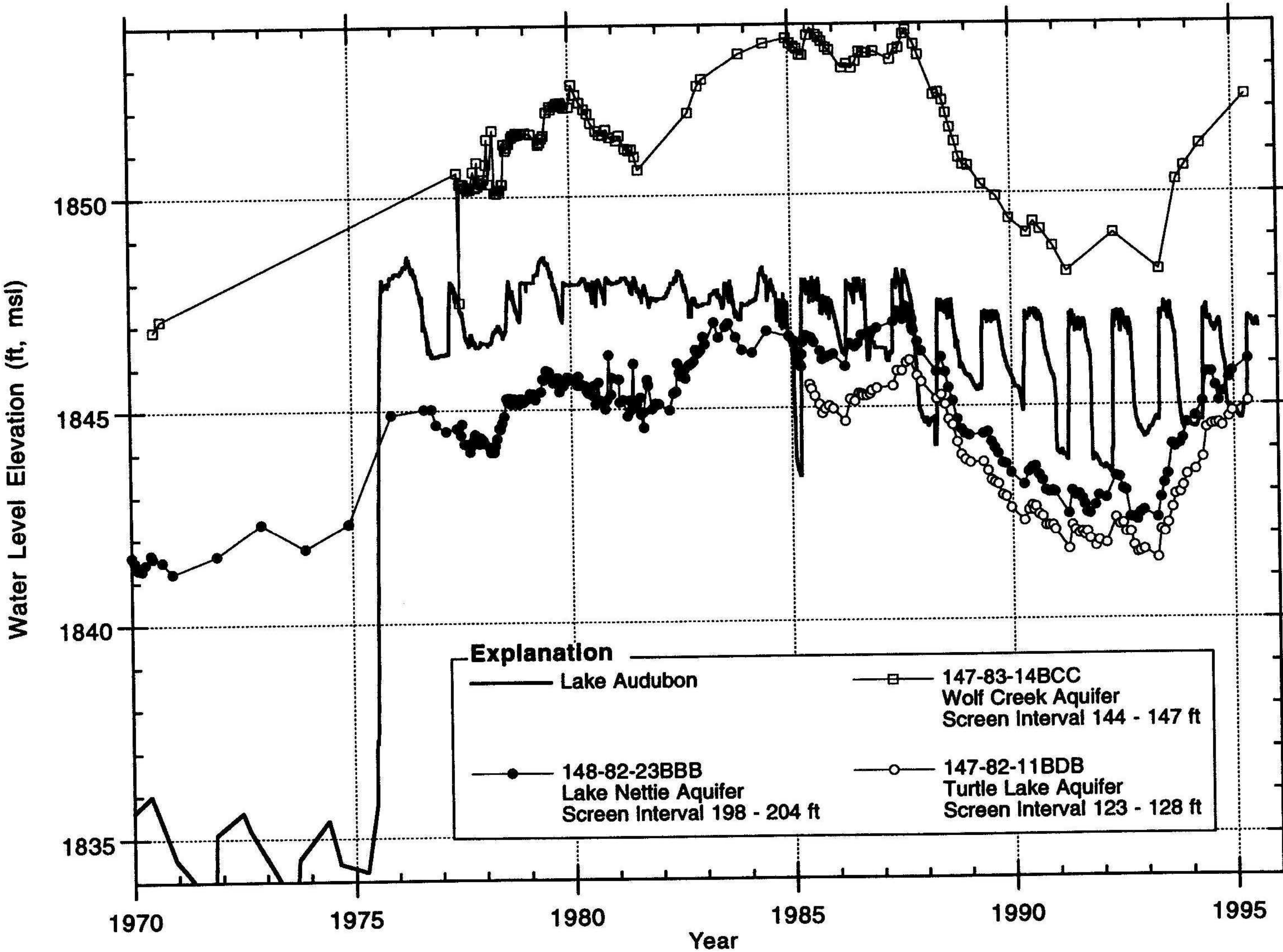


Figure 58. Comparison of Lake Audubon water level elevation with water level elevations in observation wells near Lake Audubon in the lower and middle units of the Lake Nettie, Turtle Lake and Wolf Creek aquifers.

had resulted in a one foot rise in the water level in the upper aquifer at well 148-81-18DCD2 (Figure 10, Armstrong, 1983). Although water levels at well 148-81-18DCD2 were generally 1 to 2 feet higher in 1978 through 1982 than they had been in 1976 through 1973, the water levels dropped 5.5 feet from the 1987 peak so that they were 1 to 2 feet lower in 1991 and 1992 than they had been in 1970 to 1973 (Fig. 59).

Water levels in the lower aquifer at 148-81-18DCD1 (nested with -18DCD2), were approximately the same elevation in 1991 and 1992 as they had been in 1968 through 1971 (Fig. 59) even though the 1975 increase in Lake Audubon resulted in an approximate 2 foot water increase in the lower aquifer unit at this location. Water levels in well 148-82-15BBB, which likely rose approximately 3 feet in response to the 1975 increase in lake Audubon remained 1.5 to 2 feet higher in 1991 through 1992 than they had been in 1970. It is apparent from Figure 59 that although raising Lake Audubon slightly reset the base elevation in the lower aquifer in the western part of the study area, in areas greater than 1/2 mile from the reservoir groundwater level fluctuations due to climatic cycles have been greater in magnitude than the amount of change induced by the increase in Audubon elevation. Figure 59 also illustrates that the length of time required to establish a representative "baseline" water level elevation is dependent upon the length and nature of climatic cycles.

Figure 60 presents hydrographs of wells located 18 to 19 miles east of Lake Audubon. Because of their distance from Lake Audubon and location in the flow system, changes in the reservoir stage have had absolutely no influence on groundwater levels in the vicinity of the wells. Well 147-78-06BBB is screened in the upper unconfined unit of the Lake Nettie aquifer, at a location where the bottom of the aquifer is about 16 feet higher in elevation than the normal operating level of Lake Audubon. Well 146-79-15ADD is located in the surficial Mercer aquifer, which is physically separated from the Lake Nettie aquifer system by intervening till deposits (see for example cross-section I-I', Plate I).

The water level fluctuations shown in Figure 60 are fundamentally similar to those in areas of the aquifer where changes in Lake Audubon have had an effect on the lower and middle aquifer units. Water levels in the early 1980's through 1987 were 2 to 4 feet higher than they had been in 1968 through 1970. The water levels then declined 2 to 6 feet from the 1987 peak through 1991/1992 and then increased again in late 1993 through 1995. No portion of the water level fluctuations measured in these wells could be reasonably ascribed to changes in the stage elevations of Lake Audubon or Lake Sakakawea, but rather must be attributed to changing climatic patterns which operate over the entire study area and constitute the dominant influence on groundwater and surface water levels.

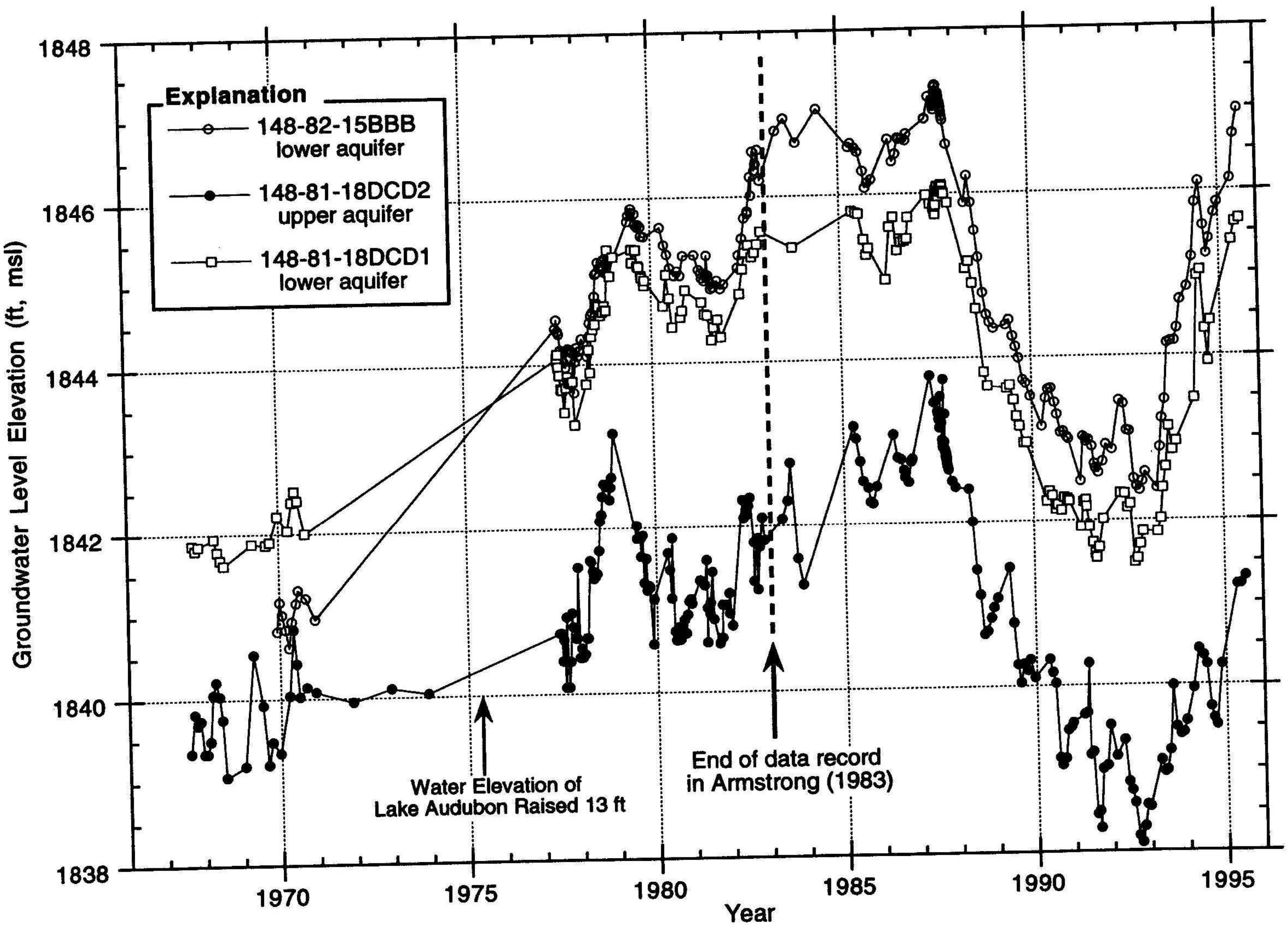
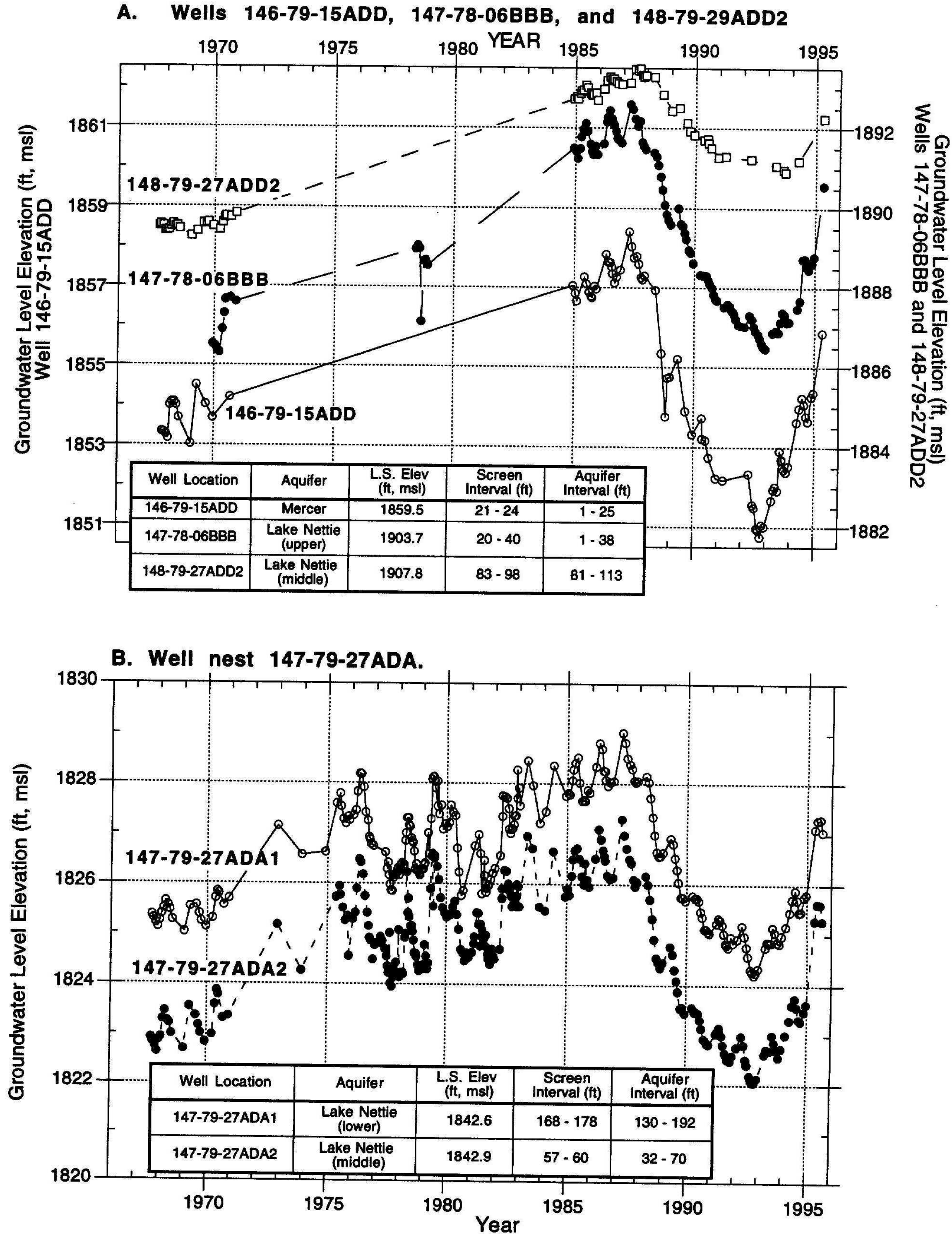


Figure 59. Groundwater level elevation changes in observation wells 148-82-15BBB, 148-82-18DCD1 and 148-82-18DCD2, wells considered by Armstrong (1983).



Well Location	Aquifer	L.S. Elev (ft, msl)	Screen Interval (ft)	Aquifer Interval (ft)
146-79-15ADD	Mercer	1859.5	21 - 24	1 - 25
147-78-06BBB	Lake Nettie (upper)	1903.7	20 - 40	1 - 38
148-79-27ADD2	Lake Nettie (middle)	1907.8	83 - 98	81 - 113

Well Location	Aquifer	L.S. Elev (ft, msl)	Screen Interval (ft)	Aquifer Interval (ft)
147-79-27ADA1	Lake Nettie (lower)	1842.6	168 - 178	130 - 192
147-79-27ADA2	Lake Nettie (middle)	1842.9	57 - 60	32 - 70

Figure 60. Groundwater level elevation changes in study area observation wells located 18 to 19 miles east of Lake Audubon, in areas with no groundwater response to changes in Lake Audubon.

SURFACE WATER ELEVATION CHANGES

Water surface elevations of lakes and sloughs within the study are have varied in a manner similar to groundwater levels. In cases where lakes and sloughs overlie and intersect the surficial aquifer deposits, the surface water body represents a "window" into the water table of the surficial aquifer. In relation to the groundwater system, a surface water body will either function as a recharge area (water seeps out of the lake/slough into the surficial aquifer), as a discharge area (groundwater seeps into the lake/slough) or as a flow through area (groundwater discharges into the lake/slough along one side or sides and water seeps out of the slough to recharge groundwater along another side or sides).

The hydrologic function can be ascertained by water level relations between the surface water body and in observation wells adjacent to the slough or lake. The nature of the hydraulic connection and actual amount of water exchange between the surface water body and the groundwater system will depend on the permeability of the adjacent sediments and the bottom sediments of the surface water body. In areas where local data control is insufficient to characterize the surface water - groundwater relations, general inferences can be made from water chemistry of the surface water body.

This section of the report presents hydrographs of lakes and sloughs in the study area for which multiple years of water level elevation data were collected from staff gages. Groundwater data is included in the graphical presentation where appropriate. Water level elevations in lakes or sloughs for which only one year of data is available were also included in the basic data report. The areal distribution of surface water level elevations was presented above in the discussion of flow systems.

CHAIN OF LAKES AREA

The chain of lakes consists of (from east to west) Brush Lake, Blue Lake, south Pelican Lake, Peterson Lake, Lake Williams, Lake Holmes and Lake Brekken. There are no significant surface water inlets or outlets from the chain of lakes. Thus the main components of water to the lakes are direct precipitation, contributing runoff and groundwater discharge. Water surface elevations for Brush Lake, Blue Lake, Pelican Lake and Peterson Lake are shown on Figure 61. Water elevations decrease from east to west from Brush Lake to Lake Williams. Prior to the filling of Lake Brekken-Holmes to about 1827 to 1828 feet, Lake Holmes constituted the lowest water elevation in the chain of lakes area. As was discussed above in the Groundwater Flow Systems section, the chain of lakes represents the terminal discharge areas for the east half of the study area. With the exception of Brush Lake, the lakes act largely as evaporation pans producing high total dissolved solids (TDS) concentrations. Although temporal variability occurs, TDS generally increases with decreasing water surface elevation. The TDS range of the available water quality data for the lakes is tabulated below in order of decreasing lake elevation:

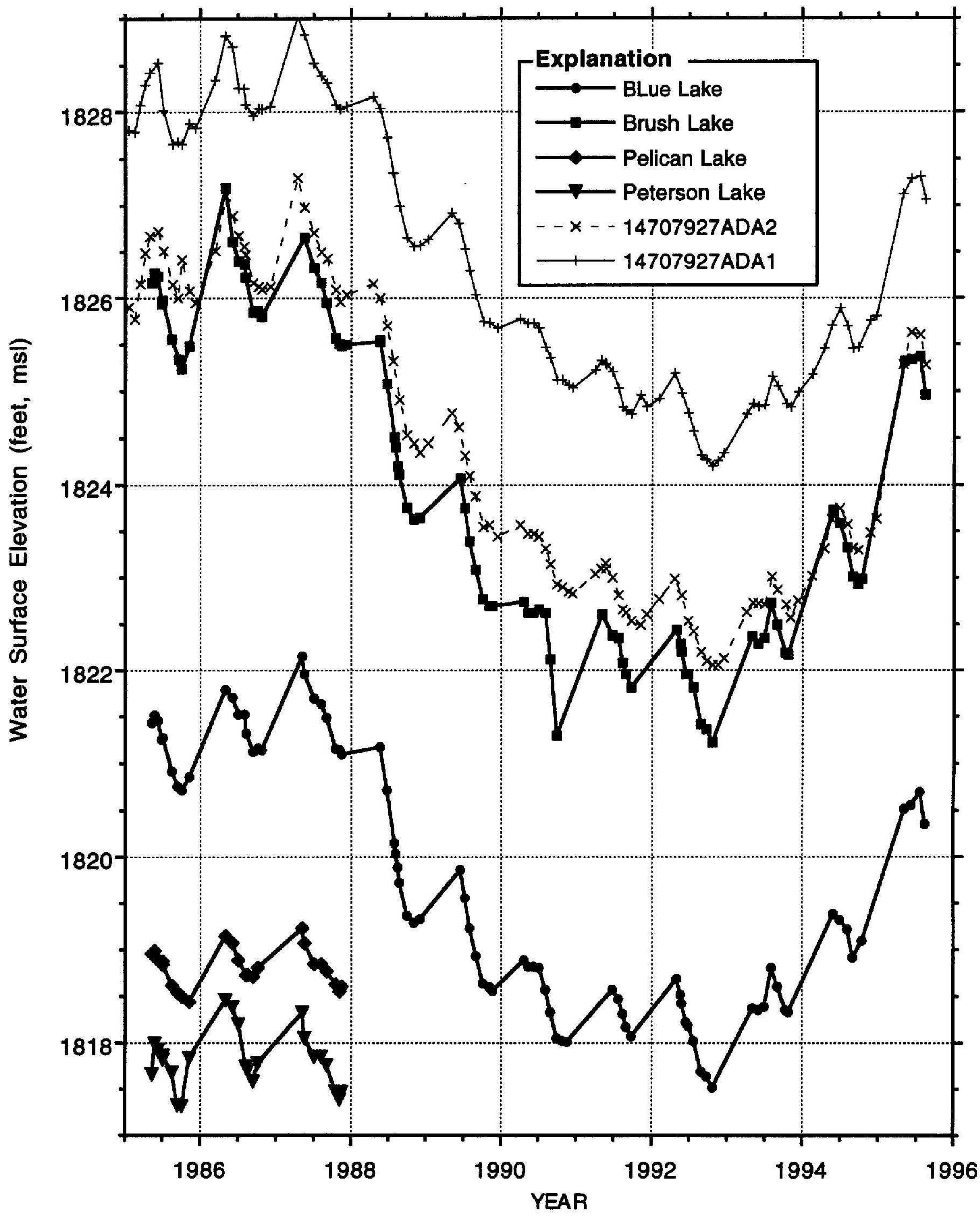


Figure 61. Chain of Lakes area surface water elevation fluctuations and groundwater level fluctuations in nearby observation wells.

Lake	TDS Range (mg/L)
Brush Lake	600 - 1,000
Blue Lake	5,000 - 8,000
Pelican Lake	9,500 - 24,000
Peterson Lake	12,500
Lake Williams	45,000
Lake Brekken	85,000 (1968 sample)

Brush Lake remains low in dissolved solids concentrations because of its good communication with the shallow groundwater system. In addition to water received by direct precipitation and runoff, Brush Lake intersects a surficial sand and gravel outwash channel that forms an arm of the Lake Nettie aquifer system in the northeast quadrant of Twp. 147-79 (see for example Figure 12). Groundwater discharges from this surficial aquifer channel into the northeast side of Brush Lake. Groundwater level data from well nest 147-79-27ADA1 and -27ADA2 near the east shore of Brush Lake also indicates groundwater discharge into the east side of Brush Lake (Fig. 61). Most important for the major ion chemistry of Brush Lake, however, is the continuance of the surficial sand and gravel channel out the west side of Brush Lake. Seepage of lake water into the groundwater system to the west removes dissolved constituents and helps keep the lake TDS relatively low. Without the seepage of water into the groundwater system, the only significant mechanism of water removal from the lake would be by evaporation, eventually resulting in high TDS concentrations similar to Blue Lake or Pelican Lake. Brush Lake would be considered a groundwater flow-through lake. Water chemistry indicates that the remaining lakes are predominantly groundwater discharge areas. The amount of seepage loss from Blue, Pelican and Peterson Lakes is small component of the lake budget in relation to the water residence time in the lake.

Water levels in the lakes typically decline about a foot across the summer with subsequent rebound the next spring (Fig. 61). The years 1988, 1989 and 1990 were exceptions with summer losses as great as 2 feet with only minor rebound the following spring. Total water level declines in Brush and Blue Lake between the 1987 peak and the lows in 1990 to 1992 were 4 to 5 feet and paralleled the changes in adjacent groundwater levels (Fig. 61).

CENTRAL PART OF STUDY AREA

Water levels in Nelson Lake, Kasper Slough, Lake Margaret and unnamed slough 147-80-23BDB (1 mi north of Lake Williams) showed about 1 foot increases between early 1985 and early 1987 (Fig. 62). Staff gage data were not obtained in these surface water bodies after 1987. There is insufficient local data control to precisely ascertain the relation between the lakes shown in Figure 62 and the groundwater system.

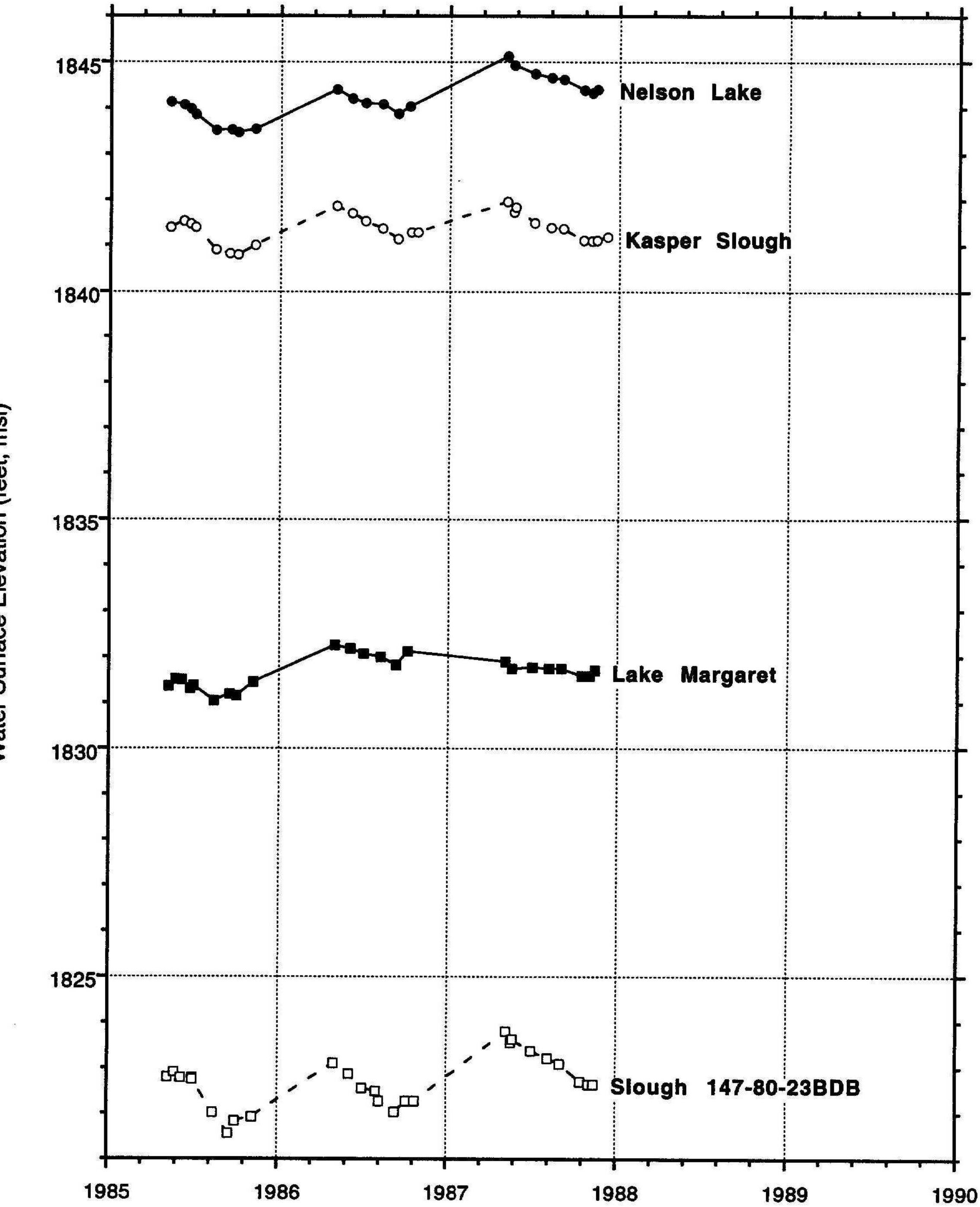


Figure 62. Surface water elevations in central part of study area: Nelson Lake, Kasper Slough, Lake Margaret and unnamed slough 147-80-23BDB.

Lake Margaret and Kasper Slough are relatively fresh with TDS ranges of 560-720 mg/L and 816 mg/L, respectively, suggesting a groundwater recharge or flow through character. However, water seeps through the dam on the south side of Lake Margaret into Billows Lake which would help to maintain the low TDS levels in Lake Margaret. Regional flow system information suggests Lake Margaret is more likely a groundwater flow through system than a recharge area. Kasper Slough has an intermittent surface water outlet and receives some inlet surface flow from poorly defined drainage to the northeast. The moderately low TDS value when sampled at a relatively high stage in 1986 may be a result of fresh water flushing through the system. Water chemistry in both Nelson Lake (4,000 - 5,000 mg/L TDS) and unnamed slough 147-80-23BDB (2,300 mg/L TDS), together with the regional flow system (Fig. 62) suggests they are groundwater discharge or flow-through type lakes.

LAKE NETTIE - LITTLE CROOKED LAKE AREA

Seasonal water level drops in Lake Nettie have typically been on the order of 1 foot, except for 2 foot declines in 1976 and 1988 (Fig. 63). The 3 foot decline seen in 1987 was due to pumping from Lake Nettie into Mud Lake. Between 1976 and 1990, Lake Nettie fluctuated from a low of 1837.4 feet to a high of 1841.7 feet.

Little Crooked Lake has shown water level fluctuations very similar to Lake Nettie. Water surface elevation in Little Crooked Lake is typically within a few tenths of a foot of Lake Nettie, except during the 1987 pumpdown (Fig. 63). Little Crooked Lake rose 2.6 feet to elevation 1839.9 feet between 6/29/93 and 8/04/93 due to the heavy July 1993 precipitation that was discussed above in the Analysis of Groundwater Level Changes section. Water levels remained within 1 foot of the August 1993 level through 1994. The Little Crooked Lake staff gage was not installed in 1995 because high water conditions made the historic staff gage location inaccessible.

Well 148-81-29BAA2 is located in the upper aquifer between Lake Nettie and Little Crooked Lake. Groundwater level elevations in this well are usually within a few tenths of a foot of Little Crooked Lake and Lake Nettie, except during the 1990 - 1992 water level low when they were about 3/4 feet higher than Little Crooked Lake. Groundwater level elevations in the well (Fig. 63) suggest that the water levels in Little Crooked Lake and Lake Nettie probably rose above 1841 feet in early 1995.

The magnitude of the surface water and groundwater level fluctuations in this area was on the order of 5 feet between 1976 and 1995, when the normal operating level of Lake Audubon was maintained between 1847 and 1848 feet elevation. The magnitude of the water level fluctuations when Lake Audubon was maintained underscores the dominant role of climatic patterns in determining relative water level changes in this region. In a manner similar to groundwater levels, surface water levels rose through the early and mid 1980's to a peak in 1987 due to prolonged periods of above average precipitation. The surface water levels then

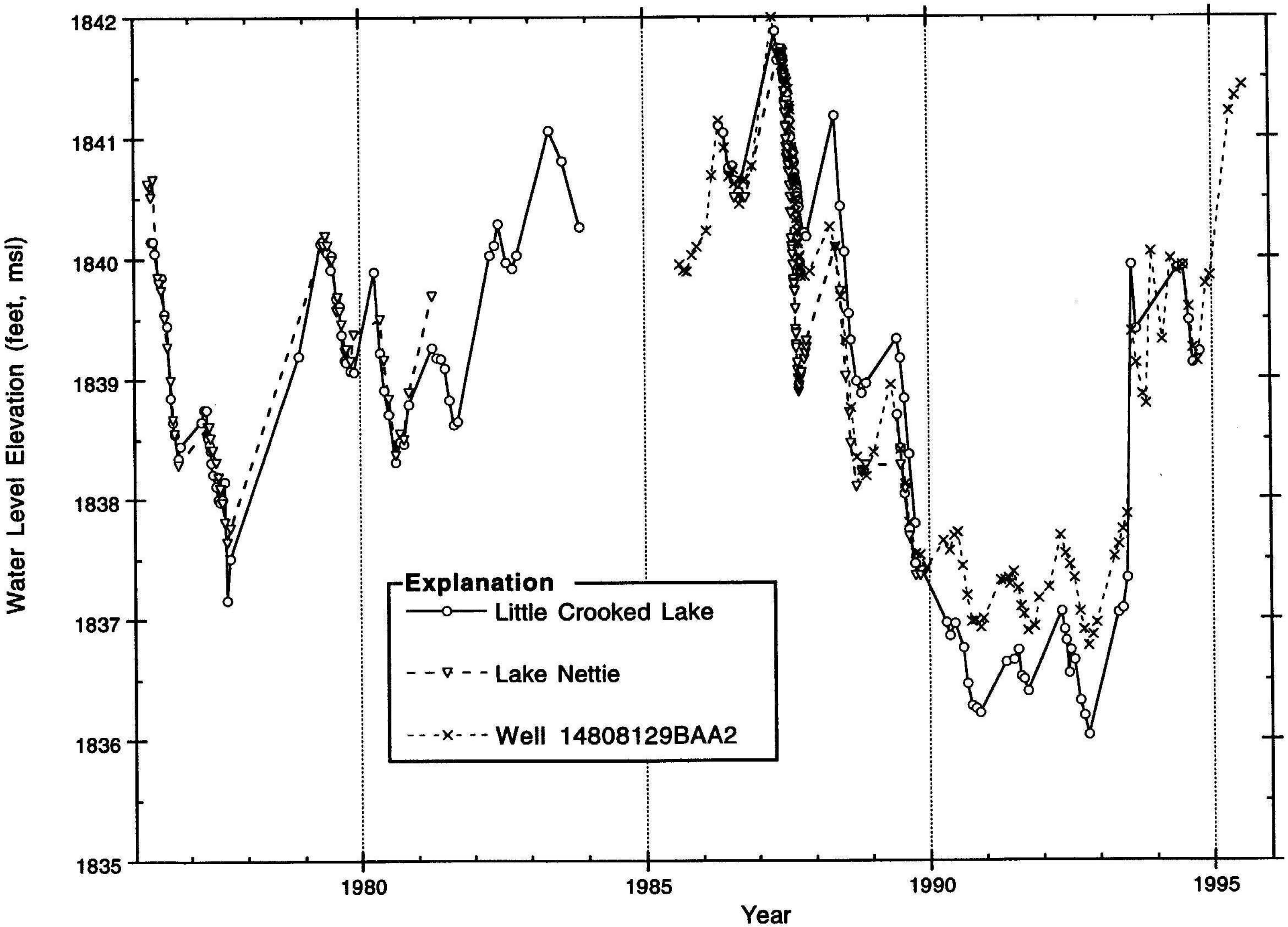


Figure 63. Water surface elevations of Lake Nettie and Little Crooked Lake and groundwater level elevations in upper aquifer unit observation well 148-81-29BAA2.

decreased dramatically through 1988, 1989 and 1990 due to drought conditions, but rose again from July 1993 into early 1995 in response to increased precipitation.

The parallel nature of the surface water and groundwater level changes results from the hydraulic continuum between the surficial sand and gravel aquifer and the surface water bodies in the Lake Nettie area, as has been discussed in previous sections. The moderate to moderately high TDS values for little Crooked Lake and Lake Nettie are consistent with the groundwater flow through nature of the lakes that was suggested by groundwater elevations in the upper aquifer (e.g. Fig. 13). TDS values in Little Crooked Lake ranged from 1,600 to 2,000 mg/L in 1986 and 1987. TDS values in Lake Nettie ranged from 1,500 to 2,000 mg/L from 1968 to 1987. In June 1992, TDS increased to 3,200 mg/L and 6,500 mg/L in Lake Nettie and Little Crooked Lake, respectively. The large increase in TDS was a result of increased net evaporation and decreased lake volume during the drought.

McLEAN SLOUGH #1

Rising water levels in McLean County Slough #1 (148-82-13B) were a source of concern in the late 1970's and early 1980's with some speculation that rising water levels were caused by Lake Audubon. Since 1977 water levels in McLean Slough #1 have fluctuated 5 feet, between 1849 and 1854 feet elevation (Fig. 64). The water level changes in Slough #1 have been in parallel with groundwater level changes in observation wells adjacent to the slough.

Well 148-82-13BBB1 was completed in the upper aquifer adjacent to the Slough #1. Armstrong (1983) attributed a 1 to 2 foot rise in water level in this well to the raising of Lake Audubon by 13 feet to 1848 feet elevation in 1975. Armstrong also postulated that the increased groundwater levels in the upper aquifer caused increased leakage into the slough, resulting in increased slough water levels. Armstrong (1983) assumed upward leakage from the lower aquifer to the upper aquifer, but suggested that it was small due to greater than 100 feet of till and clayey silt separating the upper and lower aquifer units in the area. The additional data collection points for this study and the benefit of data collection through climatic changes refute Armstrong's conclusions regarding the effect of the 1975 Lake Audubon stage increase on water levels in McLean Slough#1 and in the upper aquifer adjacent to Slough#1.

Unfortunately, well 148-82-13BBB1 which Armstrong used in his interpretation was destroyed after 1981. The well was screened from 18 to 38 feet in a sand and gravel layer that extended from the surface to a depth of 47 feet. The well was screened above, below and across a 5 foot thick layer of clay or till that was encountered from 26 to 31 feet in the well boring. Well 148-82-13BBB1 was replaced in 1986 by well nest 148-82-13BBB2 and -13BBB3, located about one hundred feet south of the original well -13BBB1. The clay till layer was encountered from about 22 to 29 feet at the replacement well nest site. Well 148-82-13BBB2 is screened from 28 to 33 feet, below the clay till layer and well 148-82-13BBB3 is screened from 17 to 23 feet, above the till layer. Water levels in wells 148-82-13BBB1, -2, and -3

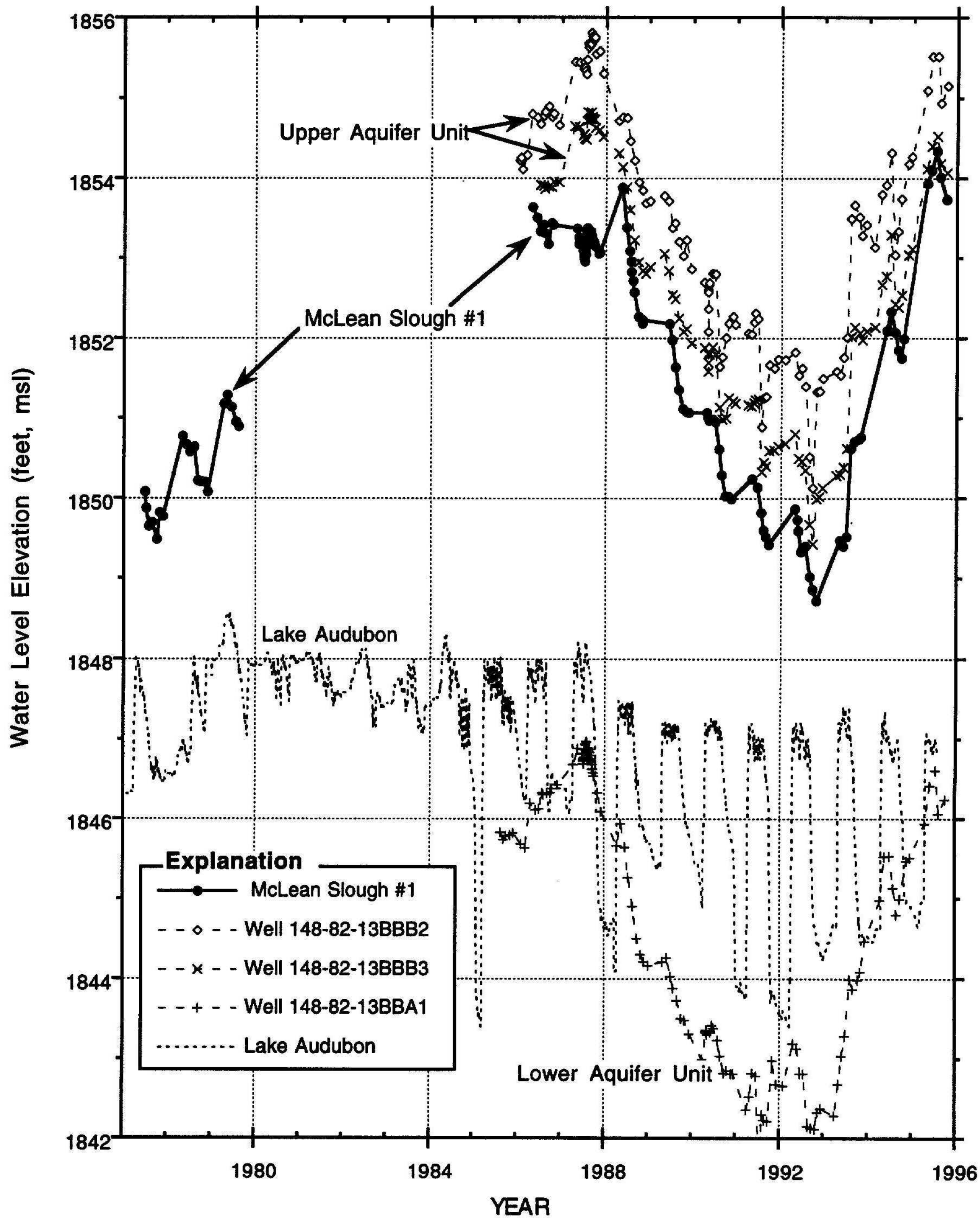


Figure 64. Water level elevations in Lake Audubon, McLean County Slough #1, and in observation wells adjacent to McLean County Slough #1.

are shown together on hydrograph 5 of Plate 2. Groundwater levels in original well 148-82-13BBB1 were between 1851 and 1853 feet from 1977 to 1980. Groundwater levels in the replacement well nest ranged between 1850 and 1855.5 feet from 1986 through 1995 (Fig. 64).

Figure 64 also illustrates the hydraulic relation between the upper aquifer, the lower aquifer and McLean Slough #1. Water level elevation in well 148-82-13BBB2 (screened below the clay layer) is always higher than in well 148-82-13BBB3 (screened above the clay layer), which is always higher than in the slough. Thus, water levels indicate discharge of groundwater from the upper aquifer into the western part of the slough. Water level in well 148-82-13BBA2, screened in the upper aquifer near the north shore of the slough about 1000 feet east of well nest 148-82-13BBB2,3, is always within a few hundredths of a foot of the slough elevation.

Even though the upward movement of groundwater with discharge into the slough occurs within the upper aquifer, the slough and upper aquifer water levels are consistently 7 to 9 feet higher in elevation than those of lower aquifer wells 148-82-13BBA1(Fig. 64) and 148-82-13BAB. These two lower aquifer wells are located along the north edge of Slough #1. The hydraulic head relations make it physically impossible for upward leakage to occur from the lower aquifer to the upper aquifer in the vicinity of Slough #1, as postulated by Armstrong (1983) without the benefit of the local water level data for the lower aquifer. Hydraulic head data indicate that the lower aquifer is well insulated from the upper aquifer in the area of Slough #1

It is not possible for Lake Audubon to exert any influence on water levels in the upper aquifer in the vicinity of Slough #1, or on Slough #1 itself. Water levels in the slough have fluctuated 5 feet since 1977 during a period when Lake Audubon has been maintained at its normal post-1975 operating level. The upper aquifer flow system is well connected to Slough #1 with groundwater discharge into the west end. Land surface topography suggests water seepage out the east end of the slough into a groundwater system that flows southeastward toward the northwest part of Little Crooked Lake (Fig. 13). Because there is no surface outlet, the fresh nature of Slough#1 (TDS of 400 - 650 mg/L when sampled in 1986 and 1992) suggests a significant amount of water and dissolved solids loss by way of seepage into the groundwater system.

The local upper aquifer flow system extends about one mile west of Slough #1. Beyond that point to the west, the surficial sand and gravel deposits that comprise the upper aquifer unit are generally absent and the upper aquifer near Slough #1 is separated from Lake Audubon by low permeability deposits (see for example cross-section J-J', Plate 1). Bluemle (1971) mapped an arm of surficial sand and gravel deposits extending northwest from Little Crooked Lake through to McLean Slough #1 area to the Snake Creek arm of Lake Audubon (Fig. 4). Test drilling suggests that these sand and gravel deposits are thin beyond 1 mile west of Slough #1. To hypothesize upper aquifer hydraulic continuity between Lake Audubon and Slough#1 would be highly tenuous. Even if there were some degree of sand and gravel continuity between Lake

Audubon and Slough #1, the upper aquifer groundwater flow divide located 1 to 1.5 miles west of Slough #1 (Figs. 12 and 13) hydraulically separates and prohibits groundwater flow between the two surface water bodies.

SIDLER SLOUGH

Sidler Slough is a surface water body of about 30 acres in size located mostly in 148-82-17A, about 0.5 miles east of Lake Audubon. Because of the slough's proximity of Lake Audubon, Sidler Slough is the most likely of the surface water bodies monitored during this study to be influenced by the reservoir. A staff gage has been maintained in Sidler Slough since 1988. Water levels in the slough have shown no indication of affect from Lake Audubon (Fig. 65). Water elevation in Sidler Slough declined about 3 feet from 1988 through 1992 then increased 6 feet between June 1993 and 1995, with 3.5 feet of increase occurring between June and August of 1993. The water level changes in the slough between 1988 and 1995 are attributable solely to variations in precipitation and runoff.

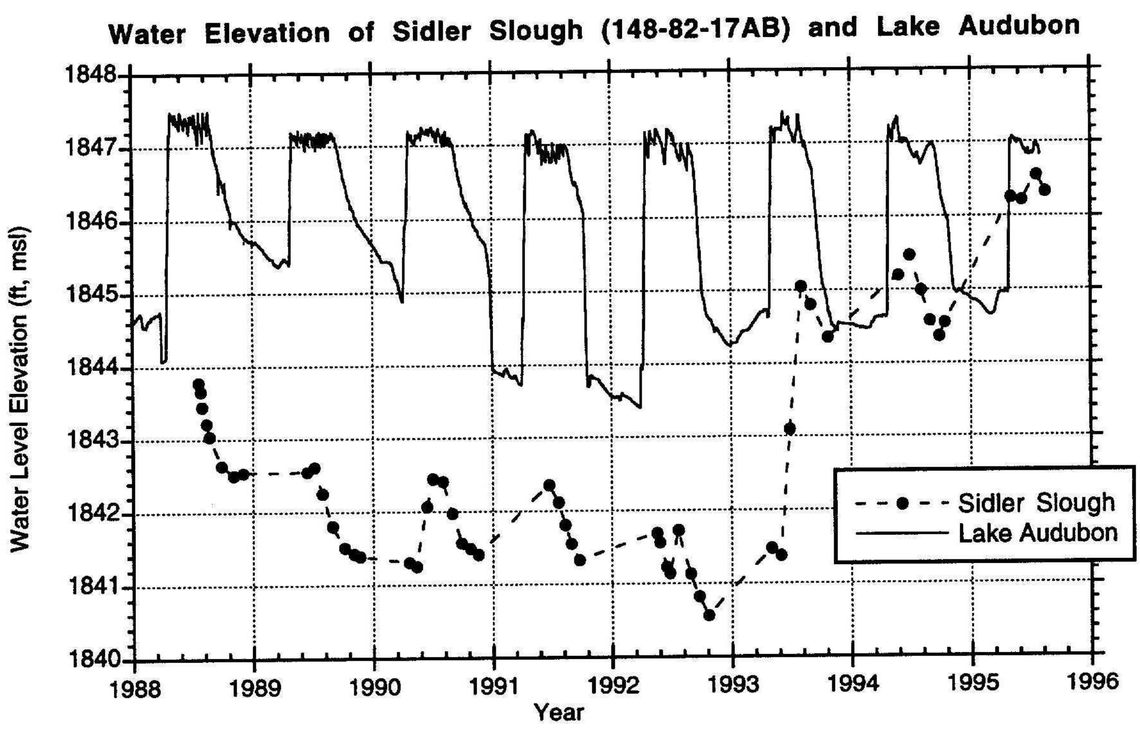


Figure 65. Water elevation fluctuations in Sidler Slough and Lake Audubon, 1988 - 1995.

PERCHED SURFACE WATER BODIES

Two surface water bodies in which staff gages had been installed appear to be perched. That is, there is an unsaturated zone between the floor of the water body and the local water table. Thus, the hydraulic connection between the lake or slough and the surface water body would be uncertain.

The water level in an unnamed slough about 20 acres in size in 148-82-23BC was about 20 feet higher in elevation than the water level in well 148-82-23BBB, which is screened in the lower aquifer about 1000 feet north of the slough (Fig. 66A). There is no shallower well nearer the slough to confirm whether the slough is actually perched. However, a 20 foot hydraulic head difference over the lateral distance between the wells corresponds to about 100 feet per mile, which is excessive given the land surface topography of the area. Water levels in slough 148-82-23BC fluctuated about 1 foot in 1986 and 1987 then declined over 4 feet through 1988 and 1989 before the staff gage went dry.

The south end of Big Crooked Lake also appears to be perched. Well 148-80-17CAB2 is located on the south shore of the lake and is screened from 118 to 138 feet in the Strawberry Lake aquifer. Groundwater levels in this well were about 1862 feet in elevation, about 55 feet below that of the 1916 to 1917 feet lake water elevation that was recorded between 1985 and 1987 (Fig. 66B). At the south shore the bottom of the lake and the top of the Strawberry Lake aquifer are separated by 60 to as much as 100 feet of till. The north end of Big Crooked Lake (about 4.5 miles north of the southern end) does not appear to be perched. Water level elevations in well 149-80-26ABA near the northern shore of the lake were within one foot of the lake elevation. The point between the north end and the south end of the lake where perched conditions are first encountered is not known.

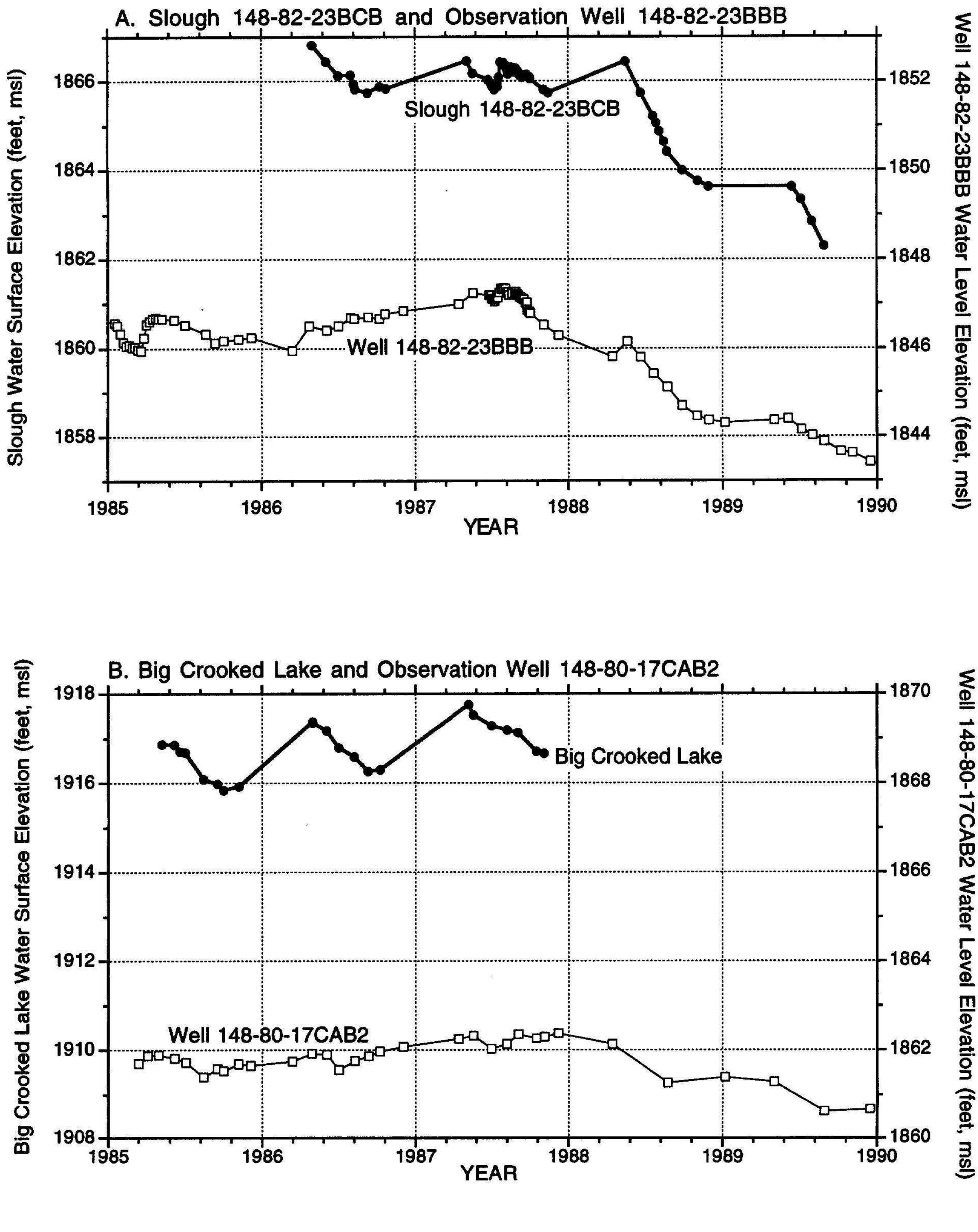


Figure 66. Water surface elevations of apparently perched surface water bodies and water level elevations in nearby observation wells.

SUMMARY AND CONCLUSIONS

Water logging of agricultural land, deterioration and flooding of county and township roads, and an increase in size of some lakes and sloughs in Eastern McLean County from Lake Audubon eastward to Brush Lake had been reported in the early and mid-1980's. A part of the high groundwater and surface water levels had earlier been attributed to raising Lake Audubon from an elevation of about 1835 feet to 1847 feet in 1975. Aquifer geometry, potentiometric relations, and groundwater level trends across wet and dry periods, as determined from the data collected and analyzed during this study, refute the earlier hypothesis that raising Lake Audubon by 13 feet in 1975 has had a substantive effect on surface water levels or upper aquifer groundwater levels beyond the immediate vicinity of the reservoir.

The study area is characterized by several confined glacial drift aquifers associated with buried pre-glacial bedrock valleys. The Lake Nettie aquifer system includes a generally unconfined upper aquifer unit, a confined middle aquifer unit and a confined lower aquifer unit. There is a degree of hydraulic connection between the lower and the middle and between the middle and the upper aquifer unit which varies with location. The Horseshoe Valley and Strawberry Lake aquifers are tributary to the Lake Nettie aquifer.

Regional groundwater flow within the glacial drift aquifers is generally from the edges of the aquifers toward the major discharge areas, which include surface water bodies in the Lake Nettie area, the Lake Williams to Brush Lake chain of lakes area, and the Turtle Lake/Lake Ordway area. Precipitation is the major source of water to the system. Except for intermittent flow to the south out of the study area through the Turtle Creek outlet from Lake Ordway, the study area is a closed system with evapotranspirative loss probably acting as the major sink for water within the study area. Vertical leakage between the lower and the upper aquifer units is restricted by the low hydraulic conductivity of till and clay which separate the aquifer units.

The McClusky Canal has had a local influence on water levels in certain areas adjacent to the canal. This local influence has been recognized by the Bureau of Reclamation and remedial action was taken on a case by case basis. No regional influence on groundwater levels has been observed, due to the line sink or line source nature of the canal.

Hydraulic head relations prohibit leakage loss from Lake Audubon to the Lake Nettie aquifer, and instead suggest the potential for discharge from the upper part of the middle aquifer unit by leakage across a till aquitard into Lake Audubon. Comparison of post-Lake Audubon groundwater flow patterns with those inferred from pre-reservoir topographic maps indicates that Lake Audubon has not altered the regional upper aquifer groundwater flow system beyond the immediate vicinity of the reservoir. The extremely flat potentiometric surface of the lower aquifer in the western part of the study area is due, at least in part, to the influence of operating Lake Audubon at an elevation of 1847 feet.

The 1985 Lake Audubon response test indicated that groundwater levels in the middle and lower units of the Lake Nettie aquifer, and the confined units of the Turtle Lake aquifer, would have risen in response to the 13 foot increase in Lake Audubon level in 1975. The rise in ground water levels resulted from the additional weight of the higher column of lake water in the area overlying the aquifer, and not from downward leakage of water from Lake Audubon. Groundwater levels in the confined lower and middle aquifer units responded quickly to the partial drawdown and refilling of Lake Audubon in early 1985, indicating that equilibration of groundwater levels in the confined aquifer units with the 13 foot increase in Lake Audubon elevation (July through September 1975) would have occurred by the end of 1975.

The calculated increase in groundwater levels in the confined aquifer units due to raising Lake Audubon in 1975 ranged from greater than 5 feet in the middle aquifer unit less than a quarter of a mile from the reservoir, between 2 and 3 feet from 1 to 3 miles from the reservoir, between 1 and 2 feet from 3 to 10 miles from the reservoir and less than one foot at distances greater than 10 miles from the reservoir. Groundwater levels in the upper aquifer unit near Lake Nettie showed no measurable response to changes in Lake Audubon elevation during the 1985 response test. The increase in lower aquifer unit hydraulic head due to raising Lake Audubon increased the vertical gradient between the lower aquifer unit and the upper aquifer unit near Lake Nettie. However, quantitative calculations indicate that the amount of increased potential upward leakage is negligible and would have no measurable effect on surface water levels.

The response of water levels and water chemistry in upper aquifer observation wells to the pumpdown of Lake Nettie in 1987 confirmed a direct hydraulic connection between the upper aquifer unit and surface water bodies in the Lake Nettie area, as had been suggested by contouring of water level elevations. Lake Nettie and Little Crooked Lake are groundwater flow through areas while Mud Lake is a groundwater discharge area.

Groundwater elevations in the study area aquifers were generally 3 to 5 feet higher in 1985 through 1987 than they had been in 1970. High water levels in 1985 to 1987 followed a prolonged period of above normal precipitation, and there is an indication of rising water level trends between the mid to late 1960's and the early 1970's, prior to the 1975 increase in Lake Audubon operating elevation. Following severe drought conditions in 1988 and 1989, groundwater levels fell several feet and in many cases were below the 1970 levels from 1990 through early 1993. Groundwater levels rose again between mid 1993 and 1995. Groundwater levels in early 1995 approached, and in some cases exceeded, the previous period of record water level highs of early 1987.

Multiple factors, including climatic variations (primarily precipitation and evapotranspiration rates) and stage changes in Lake Audubon and Lake Sakakawea, affect groundwater levels in the different aquifer units. At distances of greater than about 1/4 mile from Lake Audubon, climatic parameters are dominant in terms of determining rising and falling trends in groundwater levels in the study area. Prolonged changes in groundwater levels in the west part of the study area (in proximity to Lake Audubon) have been similar to those in the eastern part of the study area, where distance and aquifer geometry precludes Lake Audubon from influencing groundwater levels. Large changes in Lake Sakakawea elevation affect water levels in the lower confined aquifer unit in the far western part of the study area. However, the largest change in confined aquifer observation well water levels that can be attributed to Lake Sakakawea is about 5 per cent of the amount of change in the reservoir, much less than the changes caused by climatic variation.

Lake Audubon has not affected surface water levels or water levels in the upper aquifer near Lake Nettie or near McLean County Slough#1, areas where high water levels had been ascribed to possible influence of the reservoir. Upper aquifer discontinuity and potentiometric relations, including an intervening natural groundwater flow divide, prohibit any influence of the reservoir on water levels in McLean County Slough#1. Surface water levels in the Lake Nettie and McLean County Slough#1 areas have fluctuated up and down approximately five feet between 1985 and 1995, a time period when Lake Audubon has been maintained between 1844 and 1847 feet in elevation. No substantial future change in study area groundwater or surface water levels is expected with the reservoirs operated near their current levels. Because of the dominant role of climatic parameters, the ability to predict future changes in groundwater levels is dependent on the ability to predict future weather patterns.

REFERENCES

Anderson, M.P., and Woessner, W.W., 1992, Applied Groundwater Modeling, Simulation of Flow and Advective Transport, Academic Press, Inc., San Diego, CA., 381 p.

Armstrong, C.A., 1983, Evaluation of the effects of Lake Audubon on ground- and surface-water levels in the Lake Nettie area, eastern McLean County, North Dakota: U.S. Geological Survey Water-Resources Investigations Report 83-4242, 41 p.

Beaver, F.W., Jr., 1985, The hydrogeological effects of Lake Audubon and the McClusky Canal on the Chain of Lakes region, McLean County, North Dakota: North Dakota Mining and Mineral Resources Research Institute and the Institute for Ecological Studies, University of North Dakota, 34p.

Bluemle, J.P., 1971, Geology of McLean County, North Dakota: North Dakota Geological Survey, Bulletin 60, Part 1; and North Dakota State Water Commission, County Ground-Water Studies 19, Part 1, 65p.

Bredehoeft, J.D., and Hanshaw, B.B., 1968, On the maintenance of anomalous fluid pressures: I. Source layer at depth, Geological Society of America Bulletin, v. 69. pp. 1107-1122.

Clayton, L., Moran, S.R., and Bluemle, J.P., 1980b, Explanatory text to accompany the geologic map of North Dakota: North Dakota Geological Survey, Report of Investigation 69, 93p.

Clayton, L., Moran, S.R., Bluemle, J.P., and Carlson, C.G., 1980a, Geologic map of North Dakota: North Dakota Geological Survey map, 1:500,000.

Fenneman, N.M., 1946, Physiographic divisions of the United States: U.S. Geological Survey map prepared in cooperation with Physiographic Committee, U.S. Geological Survey, scale 1:7,000,000 (reprinted 1964).

Klausing, R.L., 1971, Ground-water basic data, McLean County, North Dakota: North Dakota Geological Survey Bulletin 60, Part II, and North Dakota State Water Commission County Groundwater Studies 19, Part II, 468 p.

Klausing, R.L., 1974, Ground-water resources of McLean County, North Dakota: North Dakota Geological Survey Bulletin 60, Part III, and North Dakota State Water Commission County Groundwater Studies 19, Part III, 73 p.

National Oceanic and Atmospheric Administration (NOAA), 1912-1994, Climatological Data for North Dakota.

Porter and O'Brian, Consulting Engineers, 1962, Subsurface site investigations, WS-133A Operational Facilities, Grand Forks and Minot Air Force Base Deployment Areas, Contract AF 04(647)-807 and AF 04(694)-160.

Simpson, H.E., 1929, Geology and ground-water resources of North Dakota: U.S. Geological Survey, Water-Supply Paper 595, p166-169.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1967-1987, Climatological data, North Dakota: Annual Summaries 1967-1995, v70-9.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration, Technical Report NWS33, 27p.

U.S. Department of Commerce, Weather Bureau, 1965, Climatic summary of the United States-supplement for 1951 through 1960, North Dakota, Decennial Census of the United States climate, Climatography of the United States 86-28, 75p.

U.S. Department of Commerce, Weather Bureau, no date, Climatic summary of the United States-supplement for 1931 through 1952, North Dakota: Climatography of the United States 11-28, 45p.

U.S. Department of Commerce, Bureau of the Census, 1991, TIGER/Line Census Files, 1990, Technical Documentation, Washington, D.C.