THE INTERACTION BETWEEN GROUND WATER AND A LARGE TERMINAL LAKE DEVILS LAKE , NORTH DAKOTA: HYDROGEOLOGY OF THE DEVILS LAKE AREA

by

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North Dakota State Water Commission
Water Resources Investigation 13
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Prepared by the
North Dakota State Water Commission
In cooperation with the
U.S. Geological Survey

ND State Water Commission

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INTRODUCTION

General statement

For many years the level and quality of Devils Lake have been matters of concern in North Dakota. Historically this, "largest natural lake in North Dakota", has fluctuated between an expansive fresh water reservoir famous for its recreational opportunities to a shallow body of stagnant, brackish water. Recent high water levels of Devils Lake have posed a flood threat to highways, agricultural lands, utilities, recreational and residential cabins, the city of Devils Lake, and a National Guard camp. Conversely, low water levels have and will continue to have adverse impacts on all phases of life in the basin.

Purpose

Concerns over the level and quality of Devils Lake have prompted numerous hydrologic investigations dating back to the late 1800's. None of these studies, however, specifically investigated the complex relationship between Devils Lake and ground water in the area. The primary purpose of this study was to investigate the interaction between ground water and Devils Lake. Specific objectives were to:

1) Describe the geologic and hydrologic setting of the Devils Lake area.

2) Describe and interpret the quality of ground water in the area.

3) Develop a conceptual model of ground-water flow in the Devils Lake area.

Results from this ground-water investigation of Devils Lake will be used in the cooperative water budget investigation between the North Dakota State Water Commission (NDSWC) and the U. S. Geological Survey (USGS), (Wiche, 1992).

Description of Study Area

Location

The Devils Lake basin, located in northeastern North Dakota, is a 3,800 square mile closed basin which is a noncontributing part of the Red River of the North drainage (figs. 1 and 2). The northern, western, and eastern boundaries of the Devils Lake basin are poorly defined drainage divides. The southern boundary of the basin is a series of recessional moraines that lie between Devils Lake and the Sheyenne River.

Specifically, this ground-water investigation covers a 2124 square mile area including segments of Ramsey, Benson, Eddy and Nelson Counties (Plate 1 and fig. 3). The Sheyenne River is the southern boundary of the ground-water study area.

Topography and Drainage

Topographic relief of the study area is a result of glacial and alluvial processes (Paulson, 1964, Bluemle, 1965, and 1973, Carlson, 1975 and Hobbs, 1987). Numerous depressions, potholes, and small lakes occurring in the basin are connected by a poorly integrated drainage system (figs. 2 and 3). During prolonged wet cycles or extreme precipitation events, these areas can overflow and contribute water to Devils Lake. Conversely, during prolonged dry cycles, these areas essentially contribute no water to Devils Lake. Elevations range from 1,400 feet along the Sheyenne River to 1750 feet on top of Sully's Hill (fig. 3).

The Devils Lake basin consists of two large "chains of lakes"; the Sweetwater chain to the north (Sweetwater Lake, Morrison Lake, Cavanaugh Lake, Dry Lake, Mikes Lake, Chain Lake, Lake Alice and Lake Irvine) and the Devils Lake chain to the south (Devils Lake, East Devils Lake and Stump Lake) (figs. 1, 2 and 3). Runoff from the upper subbasins first goes to filling up the Sweetwater chain. When the Sweetwater chain is full, additional precipitation causes runoff into Devils Lake via Big Coulee (figs. 1 and 3). Since 1972, some water during high runoff periods is allowed to flow from Dry Lake into 6 Mile Bay (Devils Lake) via Channel A (figs. 1 and 3). As discussed by Wiche, 1986B, runoff processes in the Devils Lake basin are complex and transient.

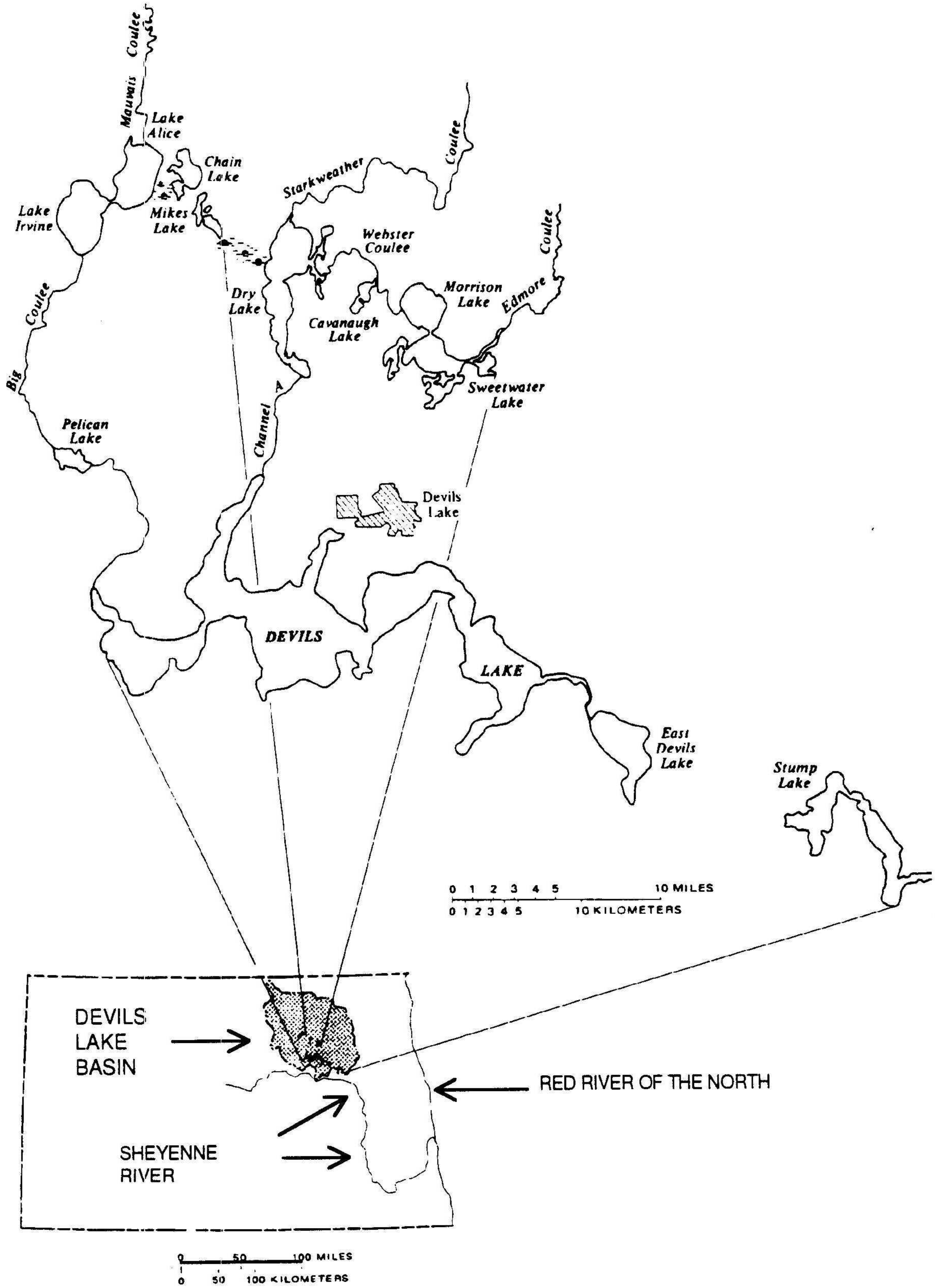


FIGURE 1. Location of the Devils Lake Basin, North Dakota (modified from Ryan and Wiche, 1988)

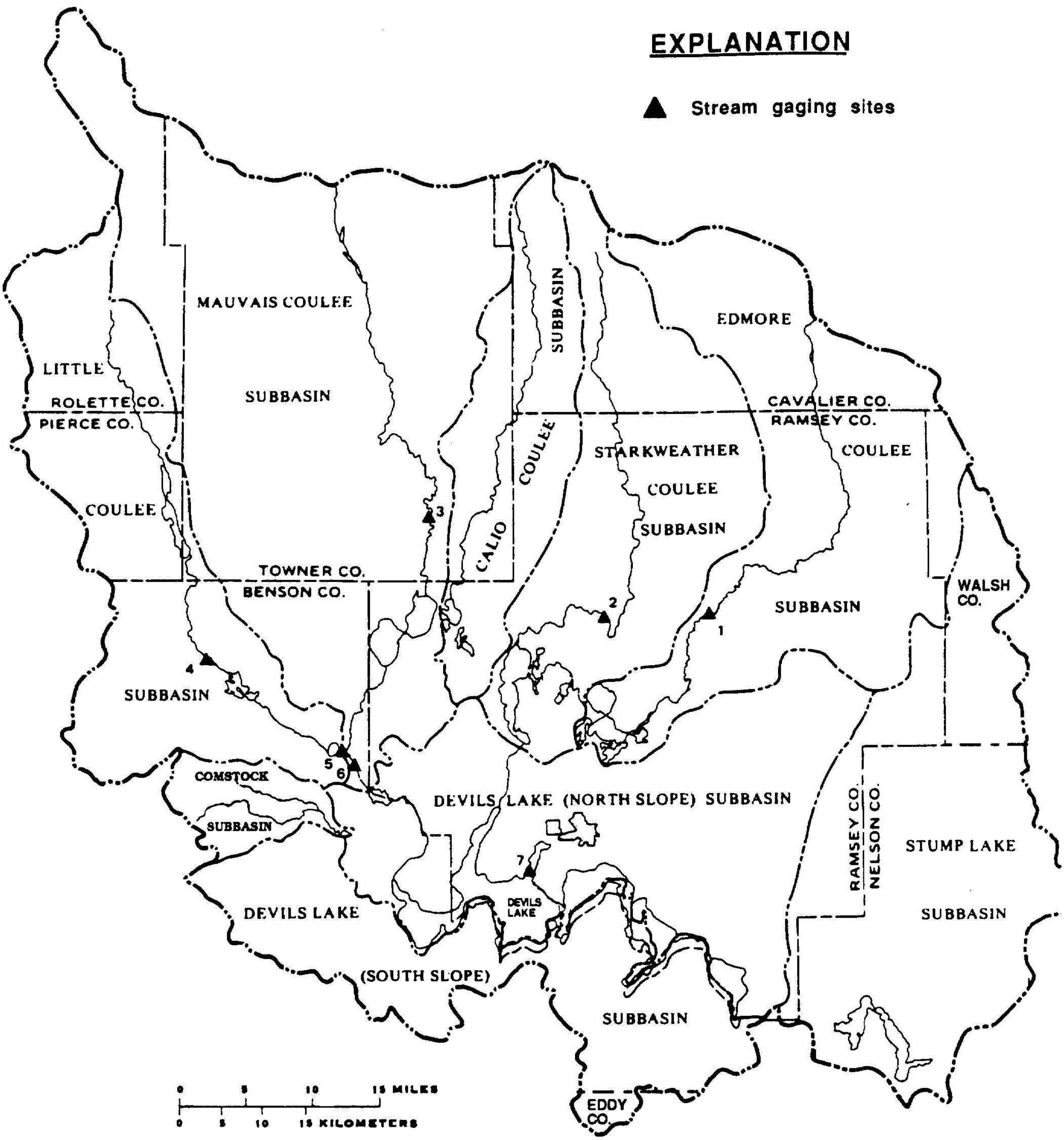


Figure 2. Major subasins and drainage in the Devils Lake Basin (Modified from Wiche and Hoetzer, 1986)

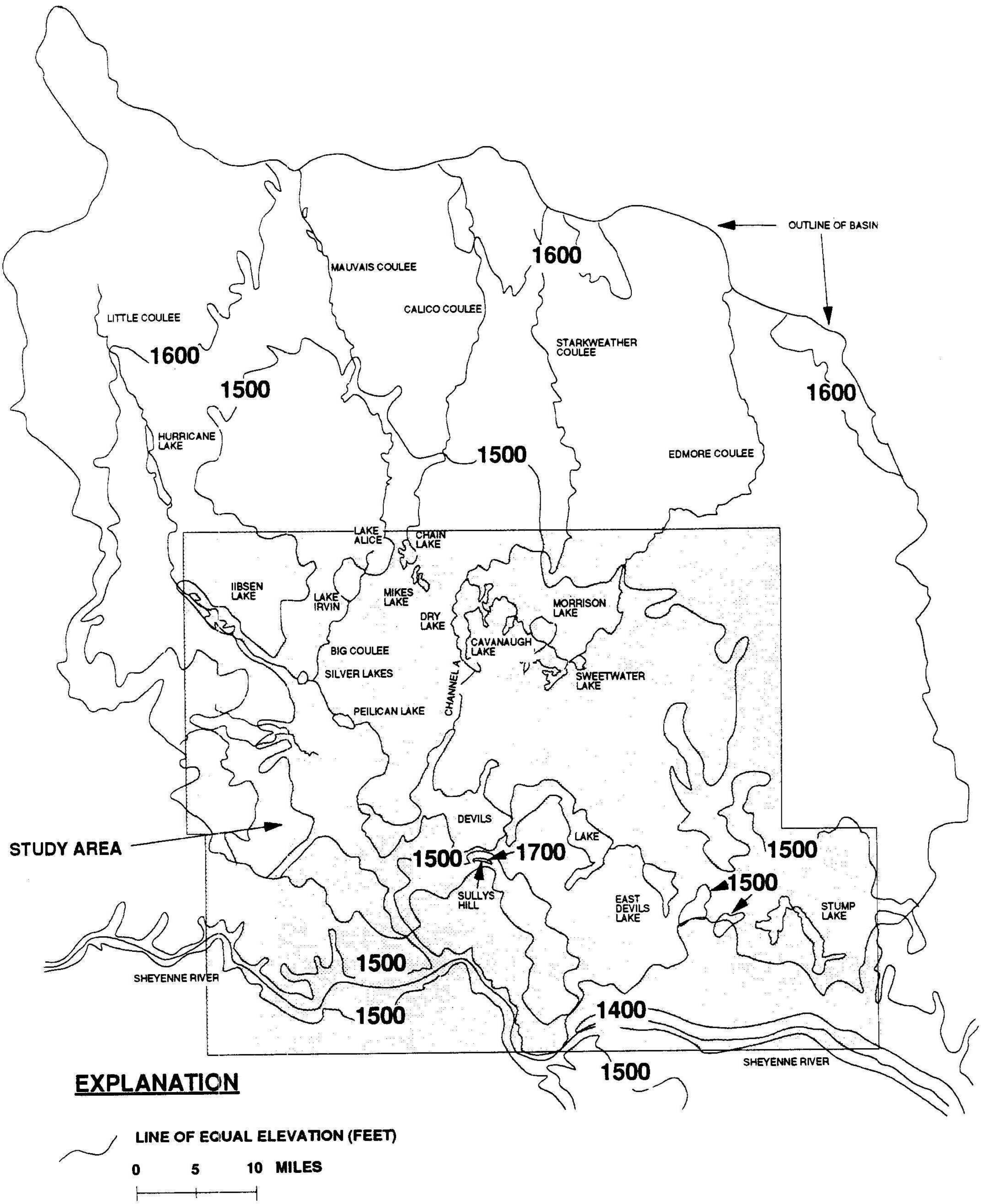


Figure 3. Topographic map of the Devils Lake Basin

Hydrology of Devils Lake

Prehistoric Water Level Fluctuations

Before recorded history, the level of Devils Lake fluctuated within a wide range. Aronow (1955 and 1957) after analyzing abandoned shorelines, lacustrine sand and gravel containing buried soils, vertebrate remains and rooted stumps, concluded that the water level of Devils Lake has fluctuated between the spill elevation of 1453 feet to a low of about 1400 feet. Bluemle (1981) concluded that Devils Lake was 1400 feet above sea level about 8,500 years ago. Callender (1968), after analyzing sediment samples from Devils Lake stated that:

> "The lake was dry during the latter part of the Hypsithermal interval. The level rose and then declined several times between 6,000 and 2,500 years, after which a peat was deposited in Creel Bay approximately 1,340 years ago. Several more lake-level fluctuations culminated in a very saline, low-water stage at 500 years before present, when oak trees grew on the dry surface sediment of East Stump Lake. The level subsequently rose until 1800 A.D., declined to a low-water state in 1940 A.D., rose again until 1951 A.D., and steadily declined from that time to the present. Comparison of the Devils Lake chronology with those from other regions indicates that major climatic changes which caused significant fluctuations in the lake level may have extended beyond the northern Great Plains region."

Thus, Callender (1968) concluded that the water level of Devils Lake fluctuated mainly in response to changing climatic conditions.

Historic Water Level Fluctuations

Upham (1895), using tree ring data, concluded that the level of Devils Lake was 1441 feet in 1830. Water levels were not recorded from 1830 to 1867. Sporadic water-level data are available from 1867 to 1901. In 1867, Devils Lake reached an elevation of 1438 feet and covered an area of about 140 square miles (Wiche, 1986).

The U.S. Geological Survey established a gage on Devils Lake in 1901. From 1867 to 1940, the level of Devils Lake generally declined (fig. 4). In 1940, the lake reached a low of 1400.9 feet and covered only about 10.2 square miles (N.D. State Eng. 1944). The level of Devils Lake generally increased from 1940 to 1956. From 1956 to 1968, the level of Devils Lake receded. Between 1968 and 1987, the level of Devils Lake steadily increased. In the spring of 1987, Devils Lake rose to the highest water level of

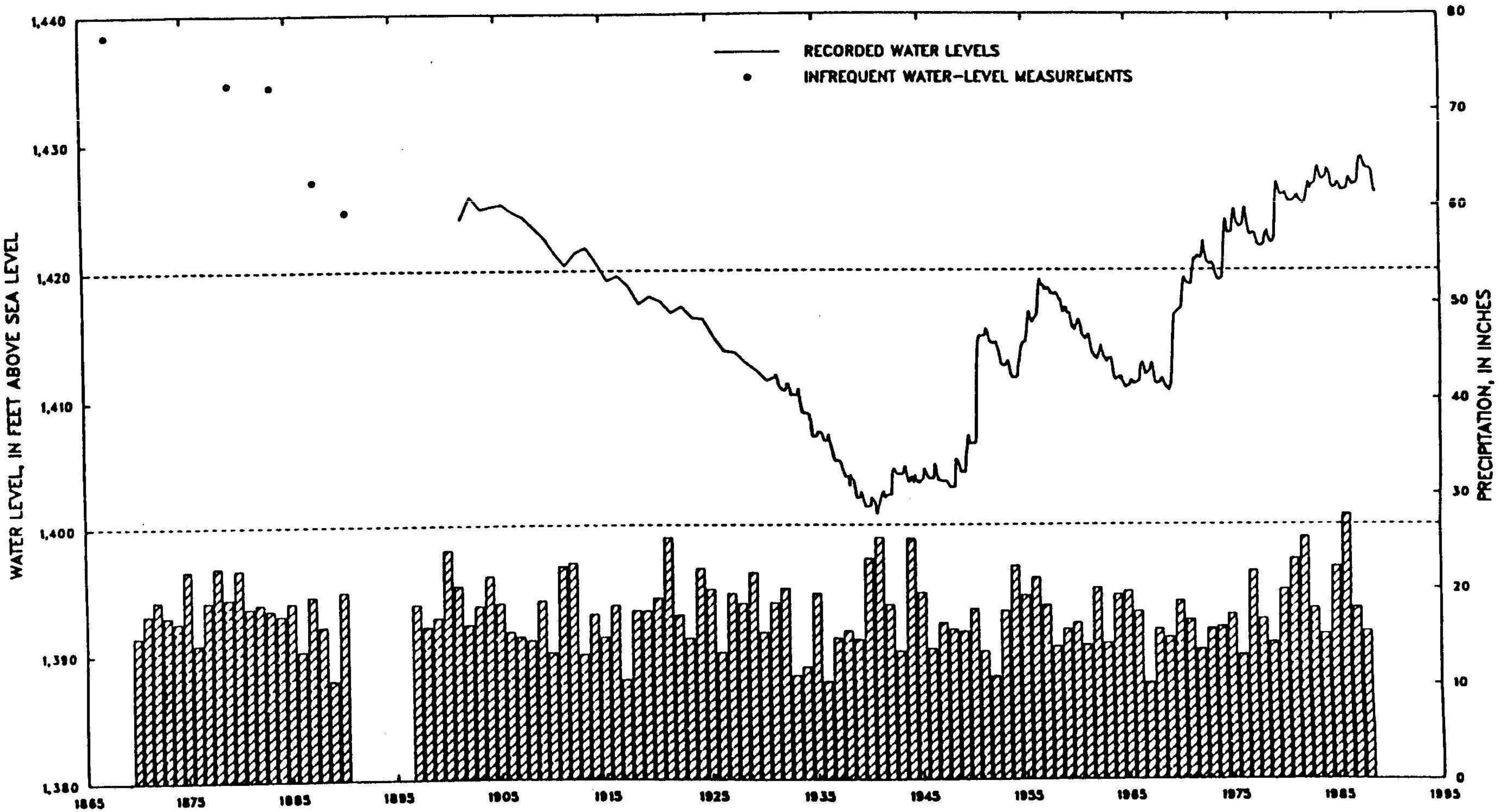


Figure 4.--Historic water levels of Devils Lake, 1867-1988, and annual precipitation, 1870-90 (Fort Totten) and 1897-1988 (city of Devils Lake). (Precipitation data from U.S. Department of Agriculture, Weather Bureau, 1932; 1932-40; U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1941-89.) (Modified from Wiche, 1986B)

this century (1,428.9 feet). Between the spring of 1987 and the fall of 1989, the water level of Devils Lake declined 3.83 feet to a stage of 1,425.07 feet (fig. 4).

Seasonal Water Level Fluctuations

A complex sequence of events cause seasonal fluctuations in the level of Devils Lake. Wiche (1986B) outlined a generalized annual hydrologic model for Devils Lake as follows:

> "1) During late fall, the water level in Devils Lake declines to a minimum and remains relatively constant from freeze-up until spring thaw.
>
> 2) Snowmelt and rain in March through May produce runoff from the basin into Devils Lake. The maximum water level occurs in April or May in drier years and June or July in wetter years.
>
> 3) Sometime in April through July, outflow (primarily evaporation) exceeds the inflow, and the water level starts to decline to a minimum in late fall or early winter. Then the cycle is repeated."

Previous Investigations

There are no previous studies that specifically investigated the complex relationship between Devils Lake and ground water in the region. Numerous investigations have, however, discussed ground water as part of basin or county-wide water resources studies.

The first report to discuss the geology of the Devils Lake area was the classic work on glacial Lake Agassiz by W. Upham (1895). Upham (1895) concluded that the level of Devils Lake was controlled mainly by fluctuations in climate. He stated:

> "...Devils Lake may many times have been raised to this beach by the periodic variations in rainfall during the many centuries since the ice age....the high stage of Devils Lake before mentioned was near the time of the highest known flood of the Red River, in 1826, when its water rose 5 feet above the surface where Winnipeg is now built."

In reference to very low lake levels, Upham (1895) stated:

> "...this prolonged epoch of comparative desiccation may have coincided with the yet more arid conditions in the great Basin..."

E. J. Babcock (1902) discussed the water resources of the Devils Lake area. Babcock reported that shale underlying the area is impermeable and thus prevents subterranean drainage. Refuting Upham's climate theory, Babcock (1902) concluded that the water level decline in Devils Lake:

"...is caused by the breaking of the prairie sod which in turn exposed the more permeable soil."

Thus, Babcock made the assumption that runoff prior to the late 1800's was greater than runoff after the sod was broken. He inferred that recharge to the soil increased because of the farming practices. Because of the lower runoff, evaporation dominated the system, and lake levels declined.

Horton (1910) reiterated what Babcock reported:

"...that the breaking of the prairie sod and soil cultivation had reduced surface runoff."

Simpson (1912) in his bench mark work on the physiography of Devils Lake-Stump Lake region stated that:

"The present sources of water of Devils Lake are, therefore, three: 1) the rainfall upon the surface of the lake, 2) the runoff from the small, uncertain and very irregular area sloping toward and immediately surrounding the lake and, 3) the ground water coming into the bed of the lake, chiefly in the form of seepage. No considerable springs are known to feed the lake."

Simpson (1912) observed that:

"No surface streams flow into either Devils Lake or Stump Lake except very minor spring thaws and after extensive rains."

Because of no significant stream flows and no visible outlet, Simpson (1912) concluded that:

"...the chief source of the water of Devils Lake is undoubtedly to be found in the ground water. Water passes from the lake by 1) evaporation into the air, and 2) by underground outflow in the form of ground water. The ground water level is in general higher than the lake level and the lake is the lowest part of the great inland drainage basin, so it is improbable the water actually flows out from the lake underneath any part of the surrounding country...the escape of water from Devils Lake is almost entirely by evaporation."

Later, Simpson (1929), reiterated that ground water is the chief source of water to Devils Lake while discharge is primarily from evaporation.

E. F. Chandler (written commun. 1931, from Wiche, 1986A), Dean of the College of Engineering, University of North Dakota, after observing Devils Lake from 1903 to 1934 concluded that:

"Devils Lake has no surface outlet, and apparently its losses by seepage are inappreciable or nothing. It rises or falls until its surface is large enough to dissipate by surface evaporation the total inflow. At an elevation of 50 feet or thereabouts above the present lake surface elevation it would have a surface outlet eastward to Stump Lake and thence southward into the Sheyenne River, and the character of the forests near the lake and the mineral content of the water seem to indicate that in very recent geologic times, within a few hundred years, the lake had such an outlet. The changes in soil conditions of the tributary drainage area within the past 50 years, consequent upon the settlement of the region and cultivation of the soil,...by increasing the ability of the soil to receive water and retain it for plant transpiration...have presumably increased the local transpiration and evaporation by the very slight amount necessary to diminish by a very large percentage the small remainder that constitutes the runoff. The inflow into the lake having thus suffered so large a percentage decrease, the area of the lake surface has tended to the same decrease."

Aronow and Dennis (1953A) described the geology and ground-water resources of the Minnewaukan area. They documented that ground-water movement in the shallow water table near Minnewaukan was very slow and generally towards Devils Lake.

Swenson and Colby (1955) described the quality of surface water in the Devils Lake Basin. They refute earlier claims that agricultural practices caused the lake level to decline, but rather they state that climatic changes are more likely the cause. Concerning ground water, Swenson and Colby (1955) concluded:

"Ground-water inflow and changes in ground-water storage have generally been disregarded, partly because ground-water movement is slow in much of Devils Lake Basin and partly because information on ground-water movements at the shores of Devils Lake does not seem to be available. In the computation of inflow to Devils Lake by years, the assumption was made that changes in bank storage would amount to 5 percent of the changes in capacity of the lake."

Paulson and Akin (1964) described the ground-water resources of the Devils Lake area. The primary purpose of their investigation was to determine whether or not an adequate supply of potable water could be obtained from ground water in the region to serve the city of Devils Lake. Concerning ground-water interaction with Devils Lake, they made the brief statement:

"There is probably some movement (ground water) northward from the northern parts of the Tokio and Warwick outwash plains into the Devils Lake drainage basin."

Mitten and others (1968) continued the water quality work of Swenson and Colby(1955) by describing the hydrology and chemistry of Devils Lake from 1952 to 1960. They stated that:

"The lakes of the Devils Lake chain probably receive ground water...Because lake deposits and lake-modified glacial drift composed of laminated clay and silt underlie the lakes in the chain and because these deposits are in turn underlain by boulder clay and glacial till, ground-water movement is slow; therefore, no allowance is made for ground-water movement or bank storage in the water budget calculations."

In 1976, the Devils Lake Advisory Committee developed a basin wide water plan. A very brief summary of the known geology and ground-water resources were included. They stated that:

"The Lake chain also receives ground-water flows."

No attempt was made, however, to quantify the relationship between ground water and Devils Lake.

The North Dakota State Water Commission (NDSWC), in cooperation with the United States Geological Survey (USGS), the North Dakota Geological Survey (NDGS), and various County Water Management Districts conducted ground-water surveys of Benson and Pierce Counties, Ramsey County, Eddy and Foster County and Nelson and Walsh Counties. The Part I's, Geology, are comprehensive investigations of the surficial geology and general discussions of the subsurface geology (Bluemle, 1965, Bluemle, 1973, Carlson, 1975 and Hobbs, 1987). The Part II's, Basic Data, include inventories of test holes, well logs, water level measurements and chemical analyses (Downey, 1971, Hutchinson, 1977, Randich, 1971 and Trapp, 1966). The Part III's, Ground-Water Resources, present general evaluations of the water yielding potential and chemical quality of major bedrock, glacial drift and alluvial aquifers in the various counties (Downey, 1973, Hutchinson, 1980, Randich, 1977 and Trapp, 1968).

Concerning water levels in the Spiritwood aquifer in Benson county, Randich (1977) stated:

"The gradual rise in water levels (Spiritwood aquifer) during the period of record indicates an increase in storage, which can be attributed to seepage from East Devils Lake. East Devils Lake was dry in 1968. Overflow from Devils Lake and high runoff during 1969 partly filled East Devils Lake, and lake levels continued to rise during the period 1969-74."

Hutchinson, 1980, in his discussion of the Spiritwood aquifer in Ramsey county stated:

"Discharge from the aquifer system (Spiritwood) southeast of the divide is by pumping, evapotranspiration and movement (ground water) into the lakes that form the Devils Lake chain. However, large extended ground-water withdrawals from the aquifer system could reverse the hydraulic gradient and the lakes would become a source of recharge to the aquifer system." .

Parekh (1977) developed a watershed model for the Devils Lake Basin. Ground water was accounted for by specifying soil infiltration capacities for the various types of soils in the region. Parekh (1977) varied the soil infiltration in his model from 1.9 inches to 3.3 inches. No estimates were made, however, concerning ground-water interaction with Devils Lake.

R. L. Whartman (1986) completed a draft report discussing the impact of proposed discharge channels on ground-water levels in the Devils lake area. Whartman (1986) stated:

"The lakes occupy the low points in the ground-water system and are, therefore, ground-water discharge areas. Regionally, the lakes are not efficient discharge areas and impose little impact on the water table over most of the basin."

Wiche (1986A and B) described in detail the hydrology of Devils Lake with special emphasis on factors affecting lake level fluctuations. Based on the work of Paulson and Akin (1964), Wiche (1986A and B) assumed that ground-water contributions to Devils Lake were negligible. Wiche (1986 A) concluded:

"In general, the water level of Devils Lake fluctuates in response to climate variability, but the hydrologic characteristics of the Devils Lake basin distort the hydrologic response. Potholes and lakes that eventually drain into Devils Lake have the ability to retain a significant proportion of the runoff, especially in the drier years. The upstream chain of lakes has enough storage capacity that they significantly decrease the discharge that reaches Devils Lake. For example, 112,000 acre-feet of water was stored in the upstream lakes during 1965-67. The timing and rate of snowmelt also affect the relationship between winter precipitation and water-level fluctuations of Devils Lake."

Wiche (1986A) also substantiated his claim that climate dominates the water level of Devils Lake by showing that water levels of other terminal lakes in North America (eg. The Great Salt Lake) have fluctuated in a manner similar to Devils Lake.

Methods of Study

Hydrogeologic investigation of the Devils Lake study area was accomplished by test drilling at 100 sites, installing 152 observation wells and measuring and recording depth to water in 289 observation wells. Additional data collected included: (1) measuring the level of Devils Lake, and (2) collecting surface water and ground-water samples for chemical analyses.

Test holes were drilled with a Failing model 1250 forward hydraulic mud rotary drill rig owned by the NDSWC. Observation wells were constructed using either 1 and 1/4-inch or 2-inch polyvinyl chloride (PVC) casing with 5 or 10 foot long PVC screens.

Nests of observation wells were constructed specifically for this investigation to determine vertical hydraulic gradients in the area. Construction of the observation well nests involved the drilling of an initial deep test hole to determine the number of observation wells to be installed at a particular site. The initial deep test hole also served as a hole for the deep observation wells. After drilling was completed, the desired length of casing and screen were inserted into the test hole. Silica sand was then placed around the screen using a tremie pipe. After sand packing, the tremie pipe was lifted so that the bottom of the tremie pipe was above the top of the sand pack. Neat cement grout was then injected down the tremie pipe and upward in the annular space. This process continued until the grout overflowed around the casing at land surface. After the grout settled, additional grout was poured down the hole until the annular space was filled to land surface. The grout was allowed to "set" and then the observation wells were slugged with a small quantity of fresh water and pumped with air for development. Observation wells screened in glacial till and/or lake clay were not, however, slugged with fresh water. Instead, these observation wells were bailed immediately after well construction. Subsequent observation wells were completed at each nest site by moving the drilling rig ahead 15 to 20 feet and drilling the next hole. As many as five observation wells were installed at various depths, at the same site, using this technique. Numerous shallow water table wells were also constructed in the area using the aforementioned techniques.

Samples of drill cuttings were collected and visually analyzed on a continuous basis throughout the drilling process. Resistivity and spontaneous potential logs were run in most of the NDSWC test holes. Copies of the geophysical logs are available for inspection in the office of the NDSWC. Locations of all test holes and observation wells are presented on plate 1. Pertinent data at each test hole site are published in Pusc, 1992.

Water level measurements were recorded on a bimonthly or monthly basis in 289 observation wells throughout the study area (Pusc, 1992). Inclement weather, poor road conditions and freezing up of observation wells prevented readings during most of the winter months. Water levels were measured with steel tapes, electronic well sounders, and one continuous recorder.

A continuous float type water level recorder was installed in October of 1976 on a 4-inch diameter well (Spiritwood aquifer) located just north of Camp Grafton (plate 1). Plugging of the well screen, however, resulted in a loss of most of these data. The well was successfully redeveloped in 1987, and the continuous recorder reinstalled.

Water level data collected for this study were coupled with the existing data to evaluate: (1) the horizontal and/or vertical direction of ground-water movement, (2) ground-water level response to natural recharge and/or discharge events, (3) ground-water level response to height of Devils Lake, and (4) ground-water level response to man-induced ground-water withdrawals.

Water samples for chemical analysis were collected from a majority of the observation wells in the study area. The water sampling procedure involved the collection of 500 milliliters (ml) of raw water, 500 ml of filtered water and 500 ml of filtered and acidified (nitric acid) water. Selected wells were also sampled for trace metals and nutrients. Field measurements of specific conductance and water temperature were also made. Water temperature was, however, measured at land surface and does not represent an in situ temperature. The pH was measured in the lab.

State Water Commission observation wells were sampled using two methods: airlift and bailing. Airlift sampling was accomplished with a small diameter rubber hose attached to a portable air compressor. Airlift sampling was used on a few of the older county study wells because frequently a bailer would not go down the smaller diameter wells. Water samples were obtained from domestic and city supply wells by using the existing pumps.

Sampling with a bailer involved the removal of at least three casing volumes of water by airlift and/or bailing techniques to introduce formation water into the well. After evacuating at least three casing volumes of water, a variable capacity PVC point source bailer was lowered to just above the bottom of the well screen. Bailing continued until enough water was secured for the sample. Water chemistry data are presented in Pusc (1992).

Location Numbering System

Wells and test holes presented on plate 1 are numbered according to a system based on the location in the public land classification of the United States Bureau of Land Management (fig. 5). The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. Letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10 acre tract). For example, well 153-64-04ADD is in the SE1/4 SE1/4 NE1/4 Section 4, Township 153 North, Range 64 West (fig. 5). Consecutive terminal numerals are added if more than one well is located in a 10-acre tract.

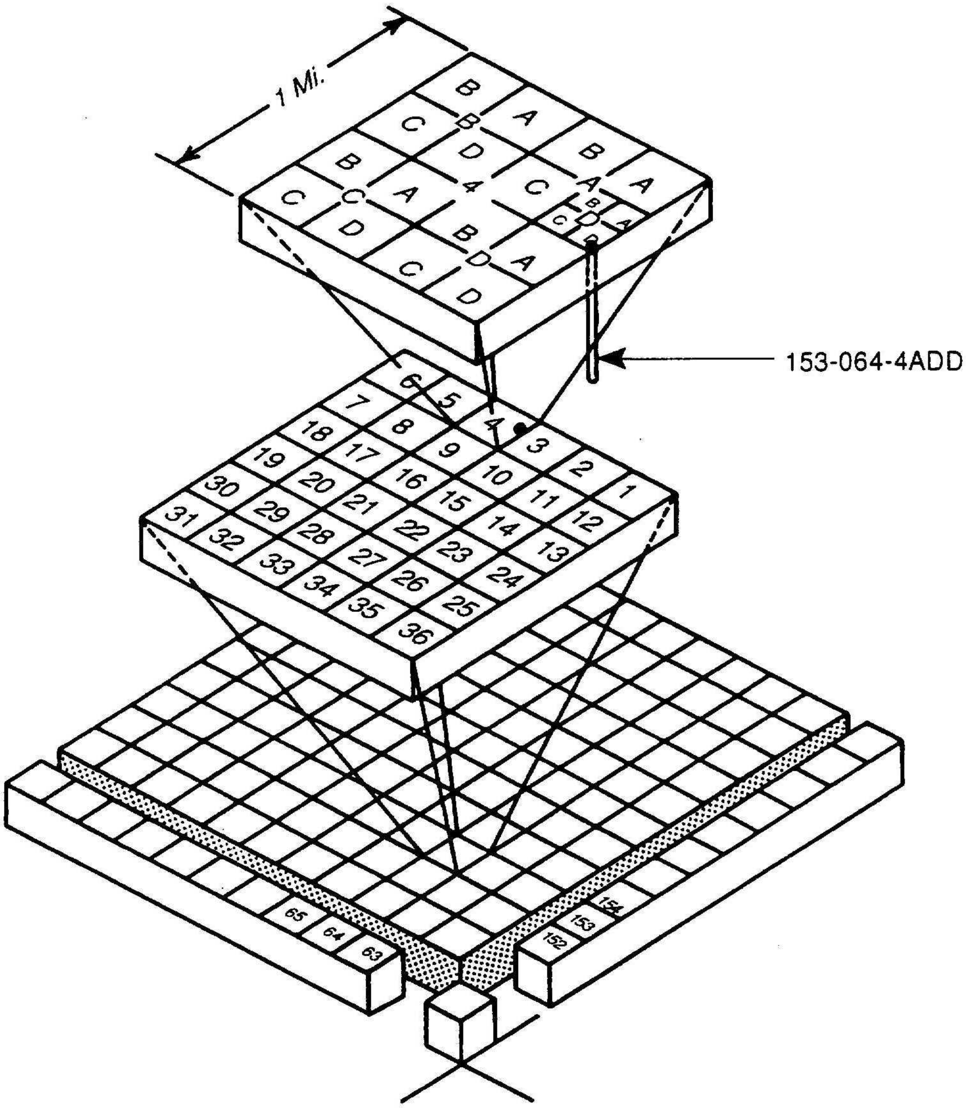


FIGURE 5. Location Numbering System

Acknowledgements

The collection of data for this report was made possible by the cooperation of residents and officials of Ramsey, Benson, Eddy and Nelson Counties and the Fort Totten Indian Reservation who furnished essential information on wells, allowed the drilling of test holes on their property and permitted water level measurements and the collection of water samples. Particular recognition is due the following personnel of the North Dakota State Water Commission: C. E. Naplin, L. L. Froelich, D. P. Ripley, M. O. Lindvig, R. W. Schmid, G. L. Sunderland, L. M. Knutson, L. D. Smith, and G. J. Calheim for drilling and logging test holes and contributions to the understanding of the stratigraphy; G. O. Muri for chemical analyses of water samples and to M. H. Hove, K. K. Kunz, and M. B. Osborn for compiling the water level and quality files. Special thanks to Chris Bader for developing the data base programs used for this report. Appreciation is also expressed to M. O. Lindvig, R. B. Shaver, D. P. Ripley, and R. L. Cline of the NDSWC and Tom Winter of the USGS for their critical review of the report. Special thanks to the private drilling companies that furnished well logs and other information used in this report. I am also indebted to Tom Winter of the USGS in Denver, Colorado for contributing to the understanding of lake/ground-water interaction and for assisting in site selection for test drilling and observation well installation. And, to my wife Collette for her support and encouragement throughout the duration of this project.

GEOLOGIC SETTING

General Geology

Sediments occurring in the Devils Lake area are primarily a result of alluvial, glaciofluvial and lacustrine processes (figs. 6, 7 and 8). Deposits of glacial origin are classified under the broad term, glacial drift (fig. 6). Glacial drift mantles most of the Devils Lake area and ranges in size from clay to boulder. Glacial drift composed of an unsorted mixture of clay, silt, sand, gravel, and boulders is termed glacial till. Lenses of sand and gravel of unknown lateral extent commonly occur within the glacial till (figs. 9-15).

Glacial drift in the area ranges in thickness from a few feet to over 400 feet (figs. 9-15). Thickest deposits of glacial drift occur in the area underlying the Devils Lake chain of lakes. In this area, the drift commonly consists of 100 to 200 feet of till and lake clays overlying 100 to 200 feet of sand and gravel(figs. 9-15). North and south of Devils Lake, the glacial drift thins. Near the Sweetwater chain of lakes, the glacial drift is less than 50 feet thick. In some areas along the Sheyenne River, the glacial drift has been eroded away and outcrops of Pierre Shale occur (Paulson , 1964).

Major landforms occurring in the area include ground moraine, end moraine, outwash deposits, eskers, kames, and lake deposits(fig. 6). Ground moraine deposits, as shown in figure 6, are composed mainly of low permeability glacial till. Topographically, the areas covered by ground moraine have rolling to low relief with numerous potholes and a nonintegrated drainage. Ground moraine mantles a large portion of the area north of Devils Lake. South of Devils Lake, ground moraine occurs in scattered areas (fig. 6).

End moraine deposits, also composed mainly of glacial till, occur throughout the area (fig. 6). Major end moraines in the study area include the North Viking moraine, the Heimdal moraine, and the Sweetwater moraine. Topographically, end moraines are areas of high relief with hummocky tops (knob and kettle). Bluemle (1984) and Hobbs (1987) speculate that some of the isolated hills or hilly areas were formed by glacial shear blocks.

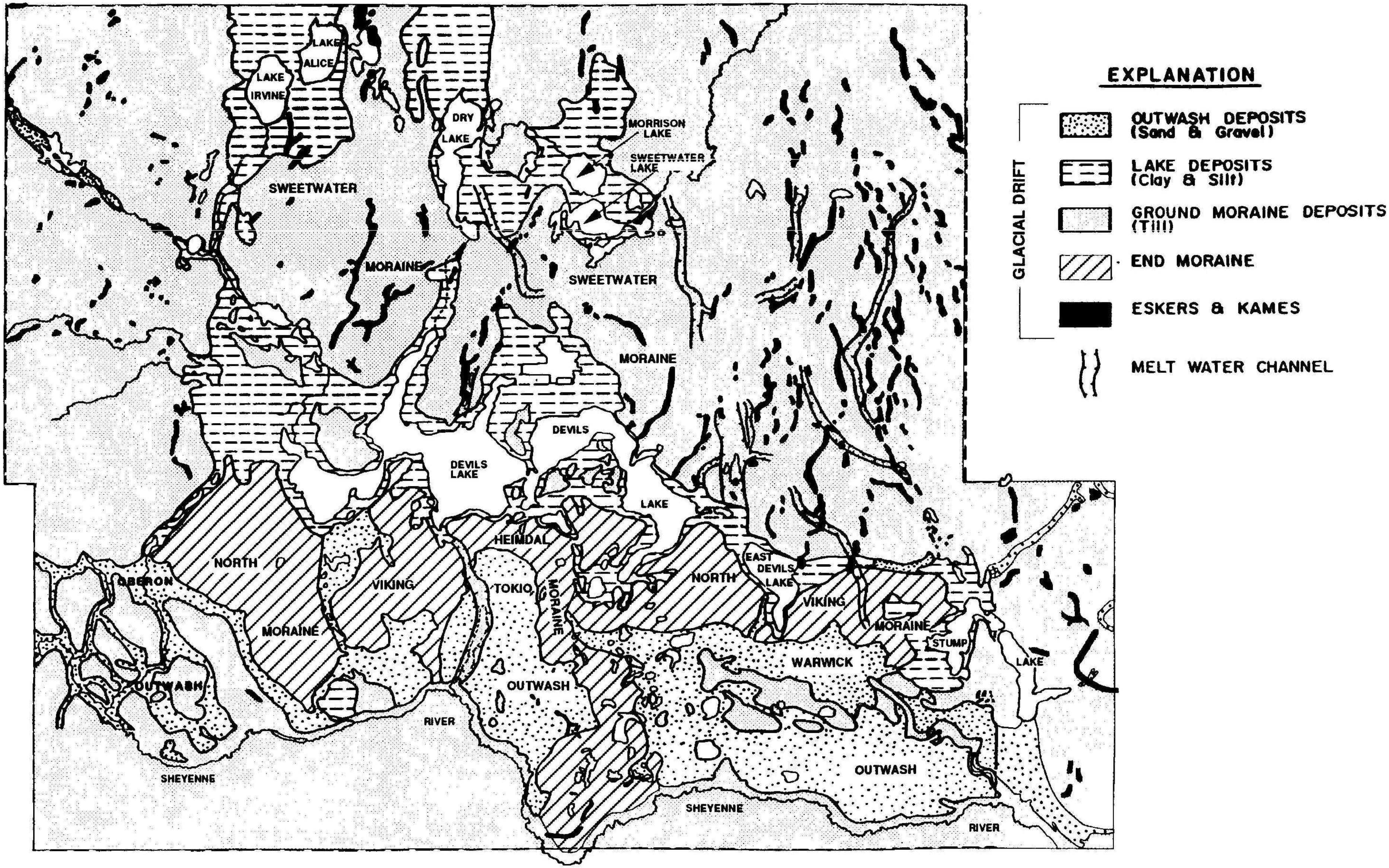


FIGURE 6. Generalized surficial geologic map of the Devils Lake area, Portions of Benson, Ramsey, Nelson and Eddy Counties (Modified from Paulson, 1964, Bluemle, 1965, Bluemle, 1973, Carlson, 1975, Clayton, 1980A & B, and Hobbs, 1987

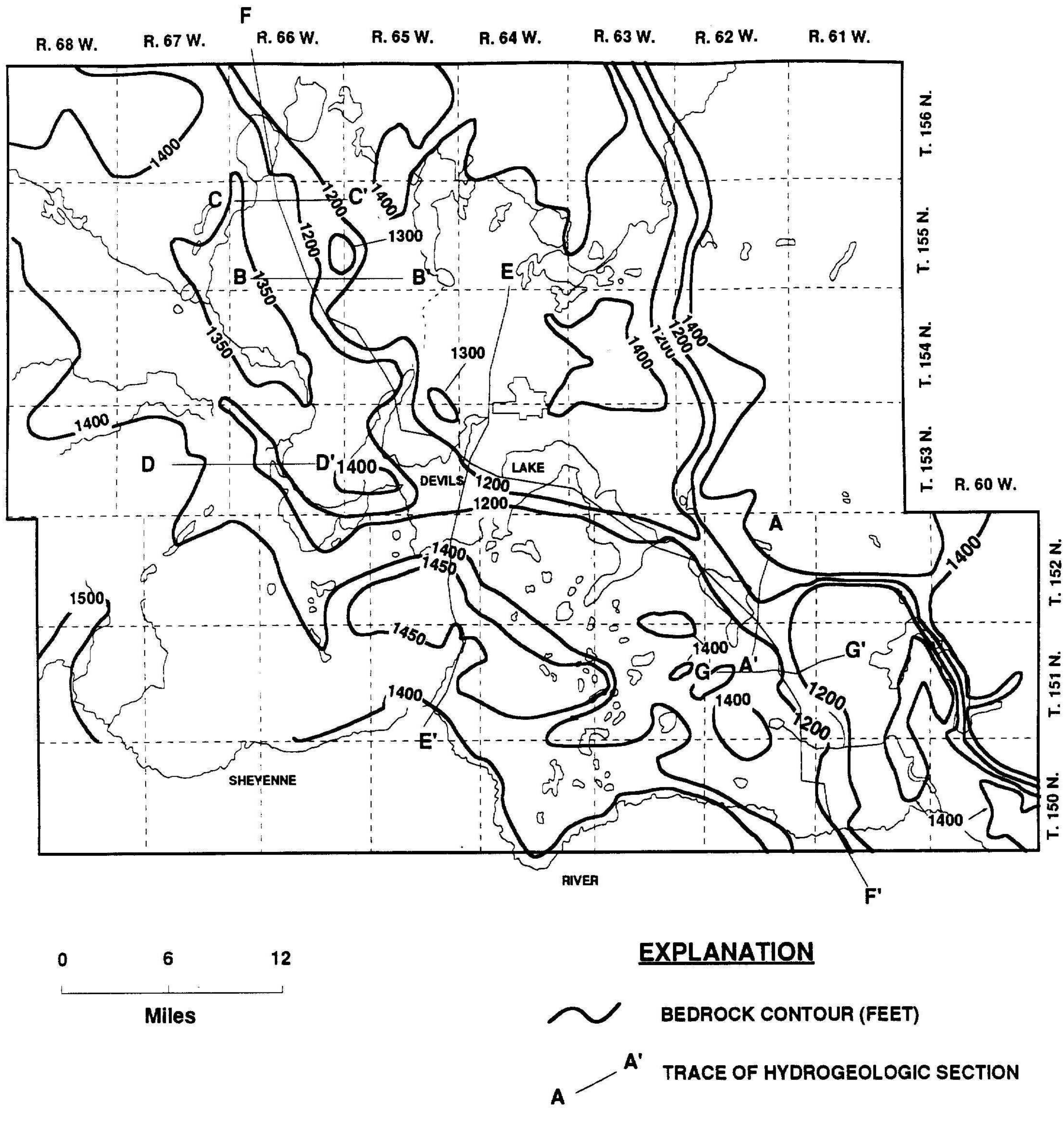


Figure 7. Structure contours of the top to the Pierre Shale, Devils Lake Area

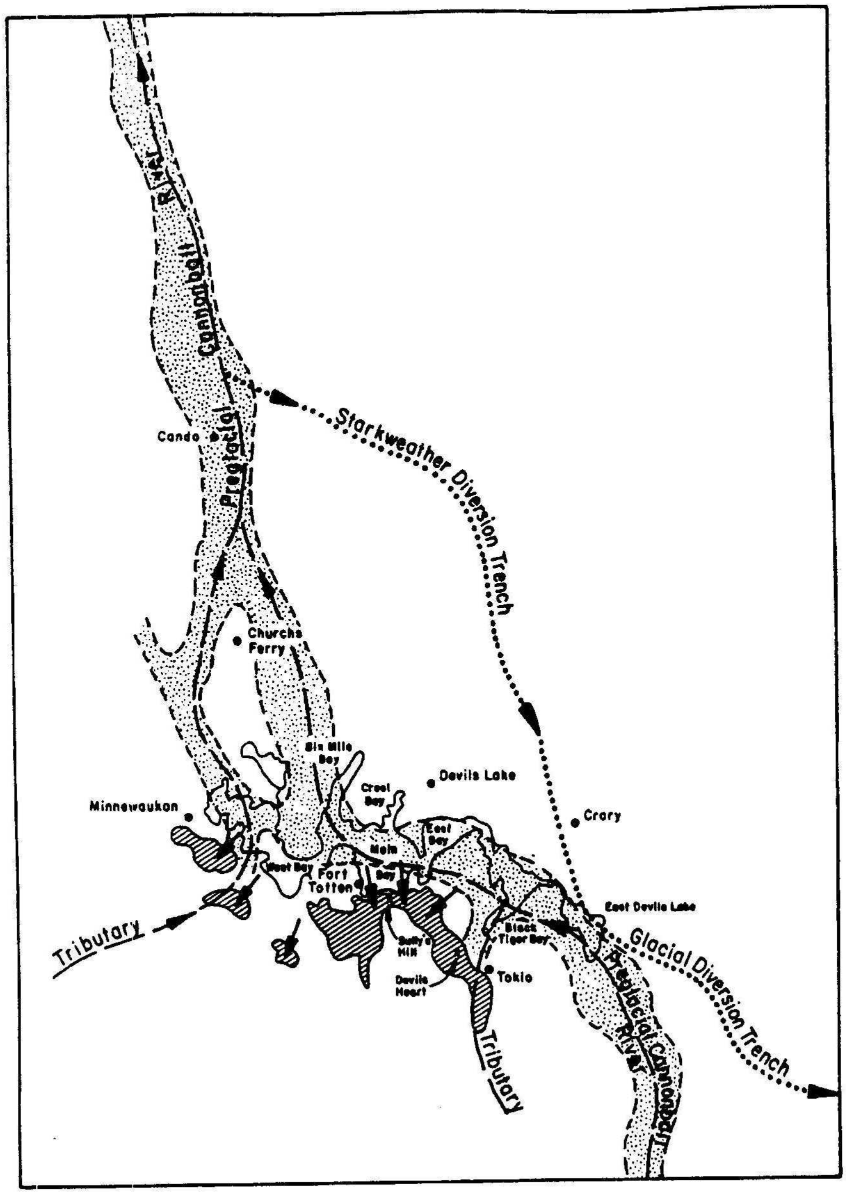


Figure 8. Generalized map of the Devils Lake area showing the main geologic relationships. The preglacial routes of the Cannonball River and some of its tributaries are shown along with the extent of the Spiritwood Aquifer in the area (stippled pattern) and the route of the Starkweather Diversion Trench. Areas of ice-thrust topography are shown (lined pattern), all immediately south of (downglacier from) the Spiritwood Aquifer. (From Hobbs, 1987)

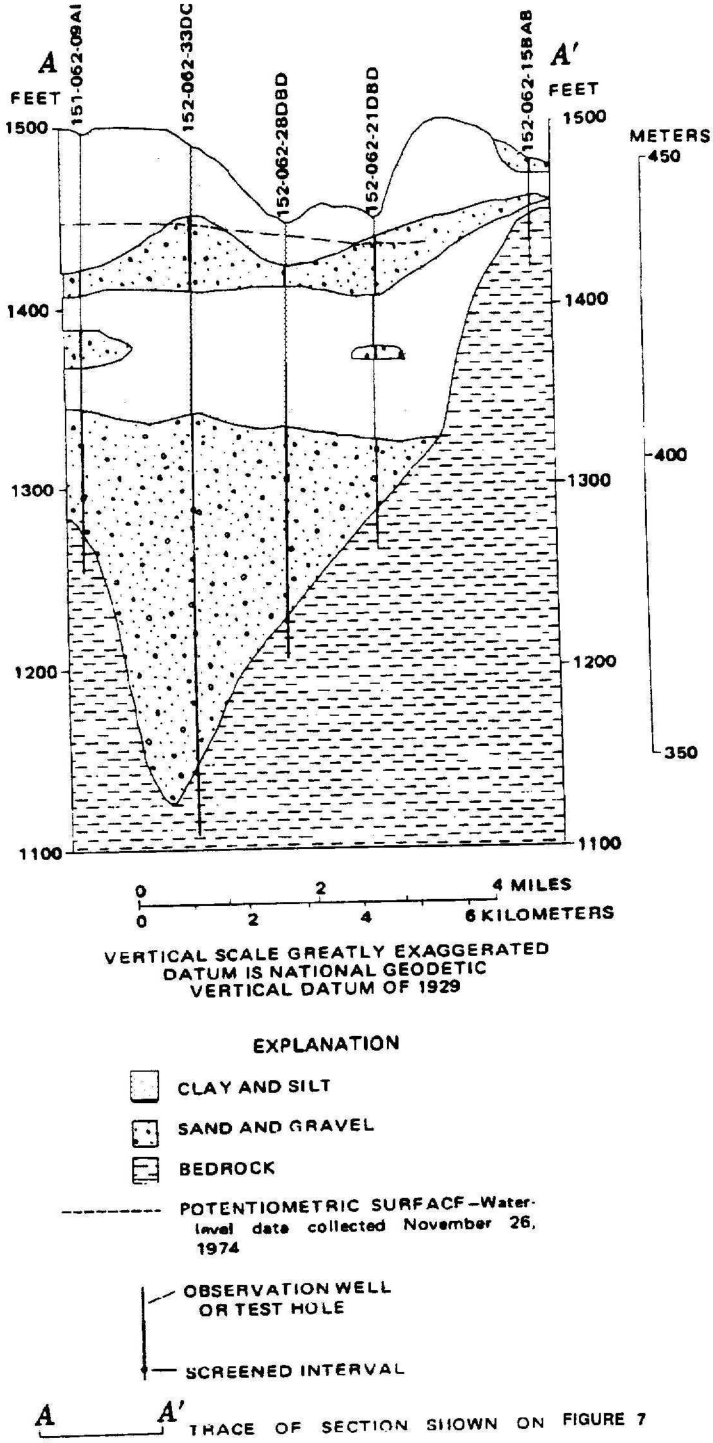


FIGURE 9. HYDROGEOLOGIC SECTON A-A' SHOWING THE SPIRITWOOD AQUIFER (FROM HUTCHINSON AND KLAUSING, 1980)

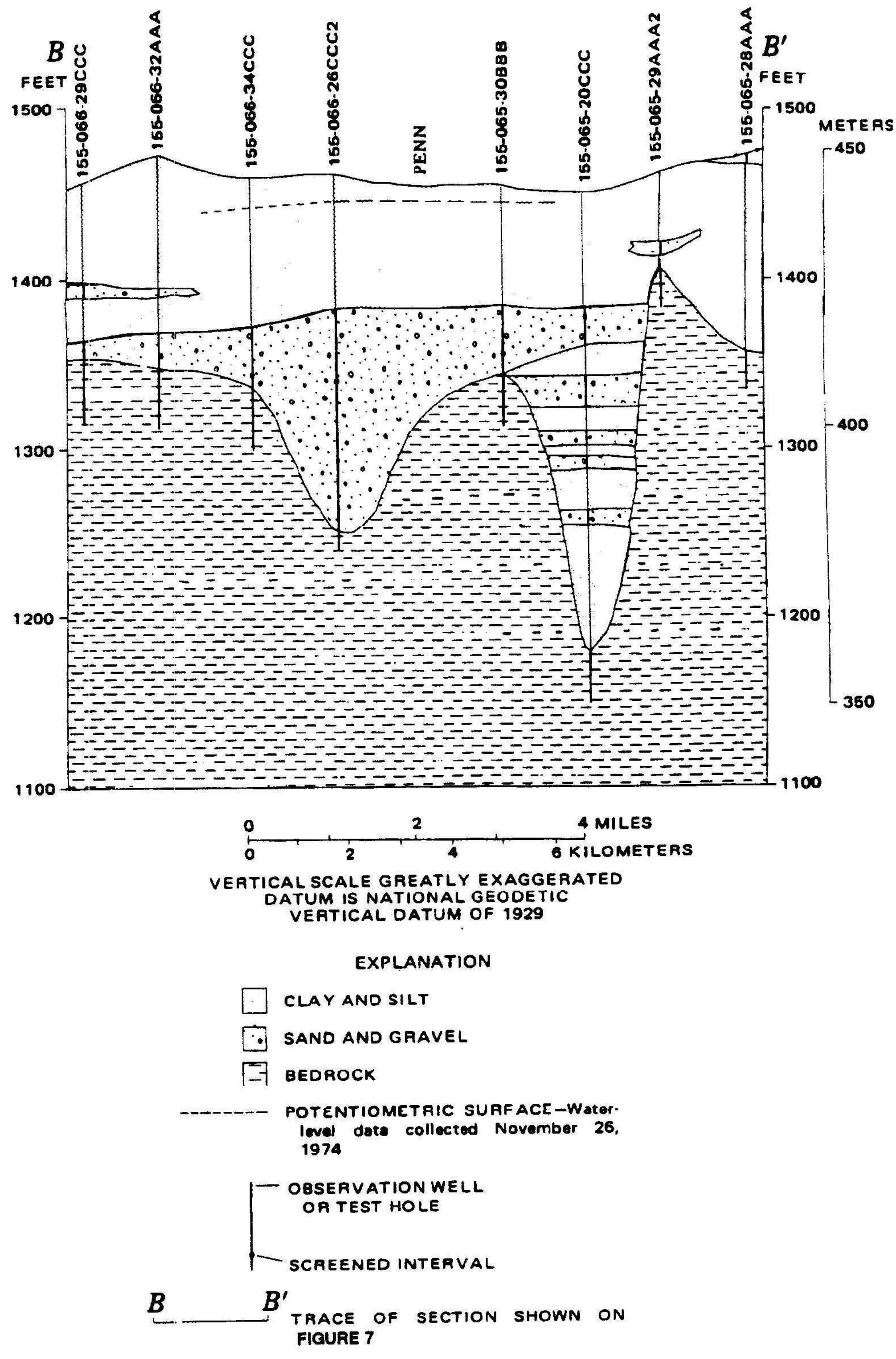


FIGURE 10. HYDROGEOLOGIC SECTION B-B' SHOWING THE SPIRITWOOD AQUIFER SYSTEM (FROM HUTCHINSON AND KLAUSING, 1980)

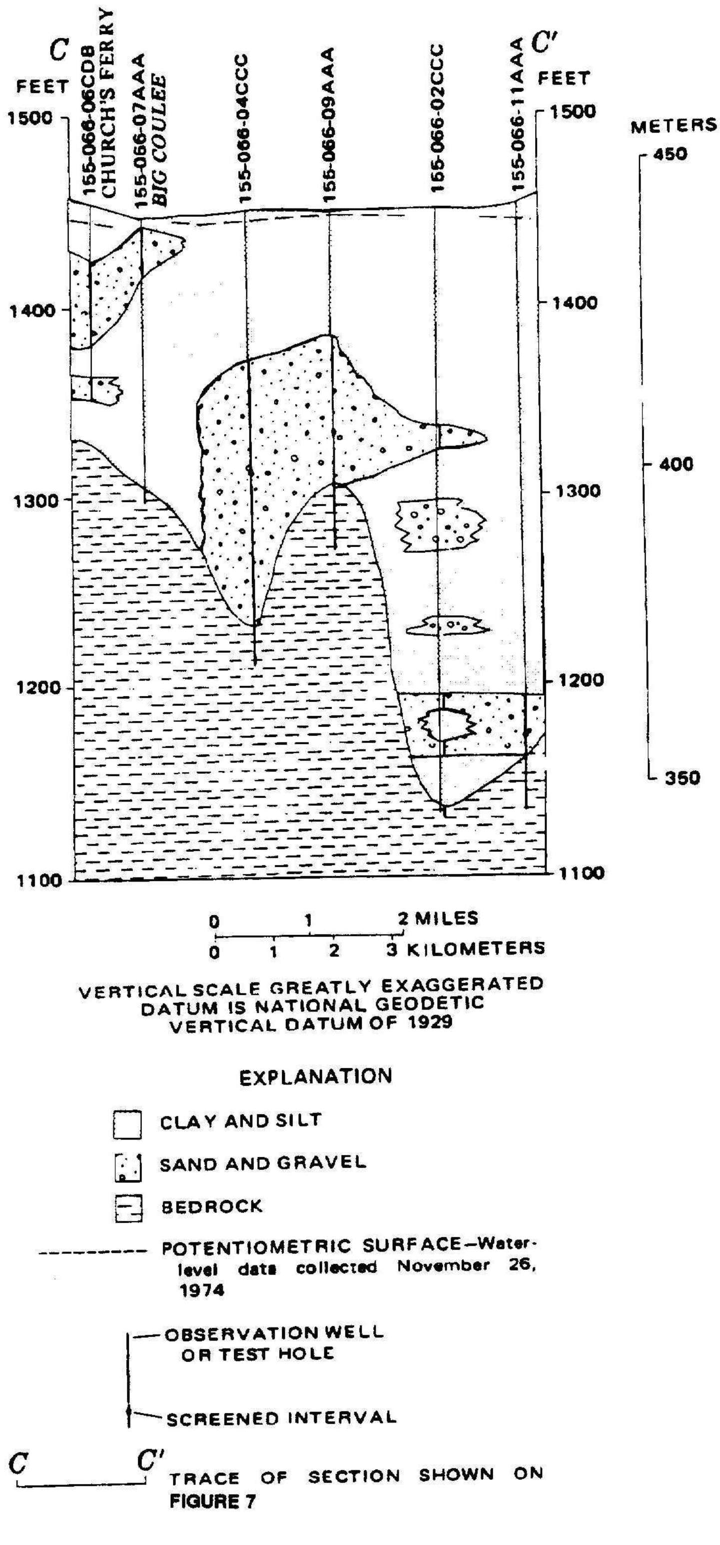
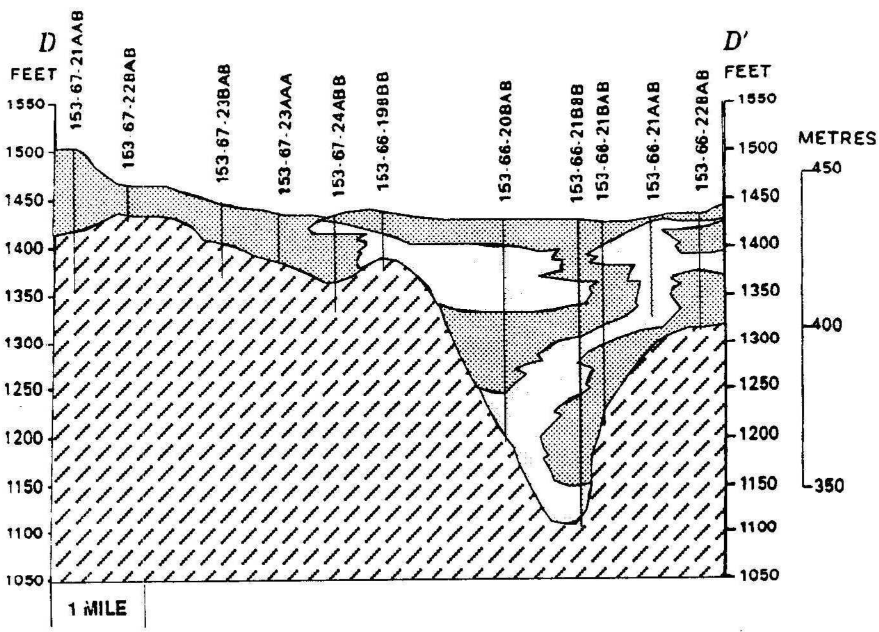


FIGURE 11. HYDRGEOLOGIC SECTION C-C' SHOWING THE SPIRITWOOD AQUIFER SYSTEM (FROM HUTCHINSON AND KLAUSING, 1980)



EXPLANATION

CLAY AND SILT

SAND AND GRAVEL

BEDROCK

OBSERVATION WELL OR TEST HOLE

D D'

TRACE OF SECTION SHOWN ON FIGURE 7

FIGURE 12. HYDROGEOLOGIC SECTION D-D' SHOWING THE SPIRITWOOD AQUIFER SYSTEM (FROM RANDICH, 1977)

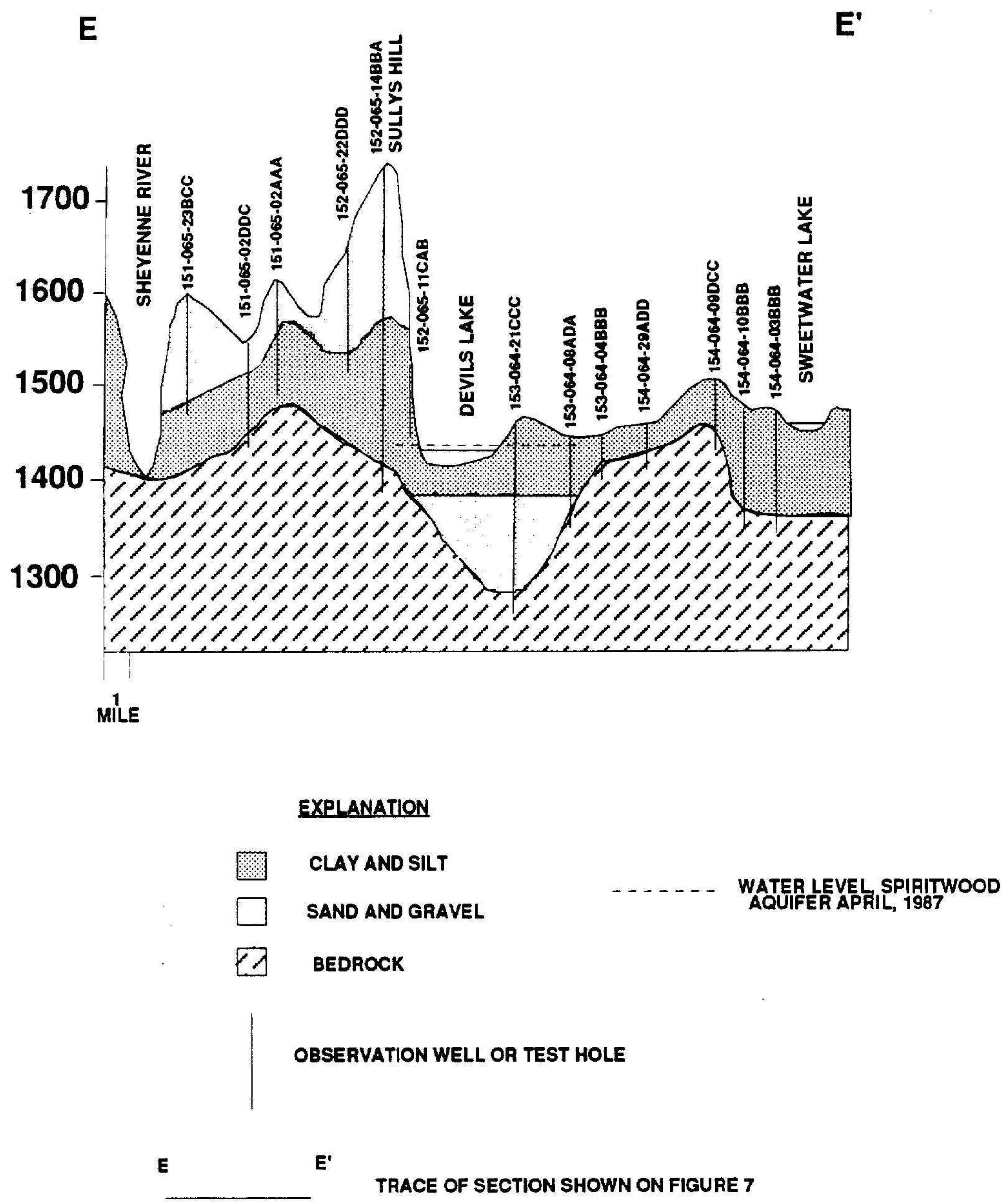


FIGURE 13. HYDROGEOLOGIC SECTION E-E' SHOWING THE SPIRITWOOD AQUIFER SYSTEM

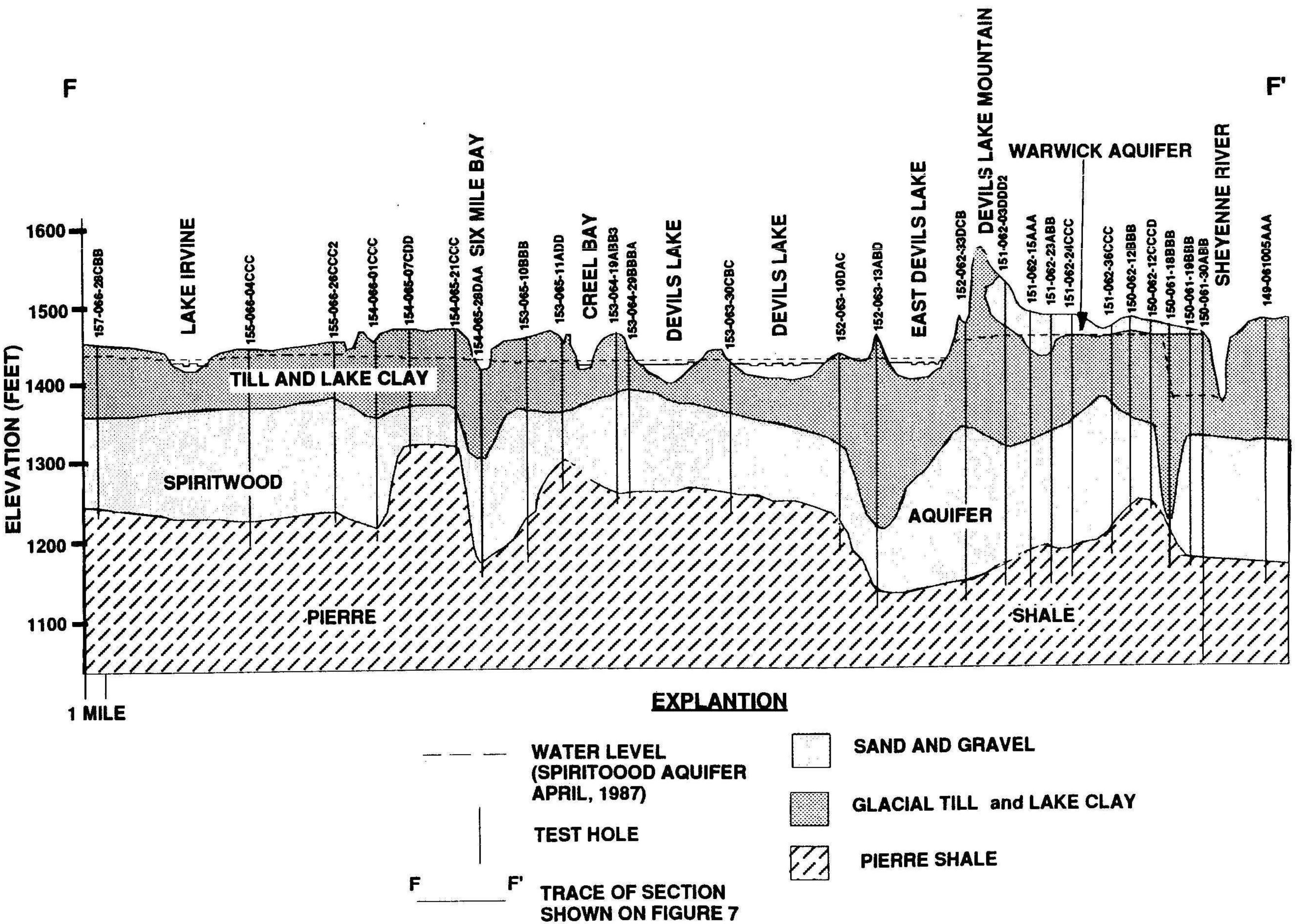


FIGURE 14. HYDROGEOLOGIC SECTION F-F' ALONG THE APPROXIMATE AXIS OF THE SPIRITWOOD AQUIFER SYSTEM

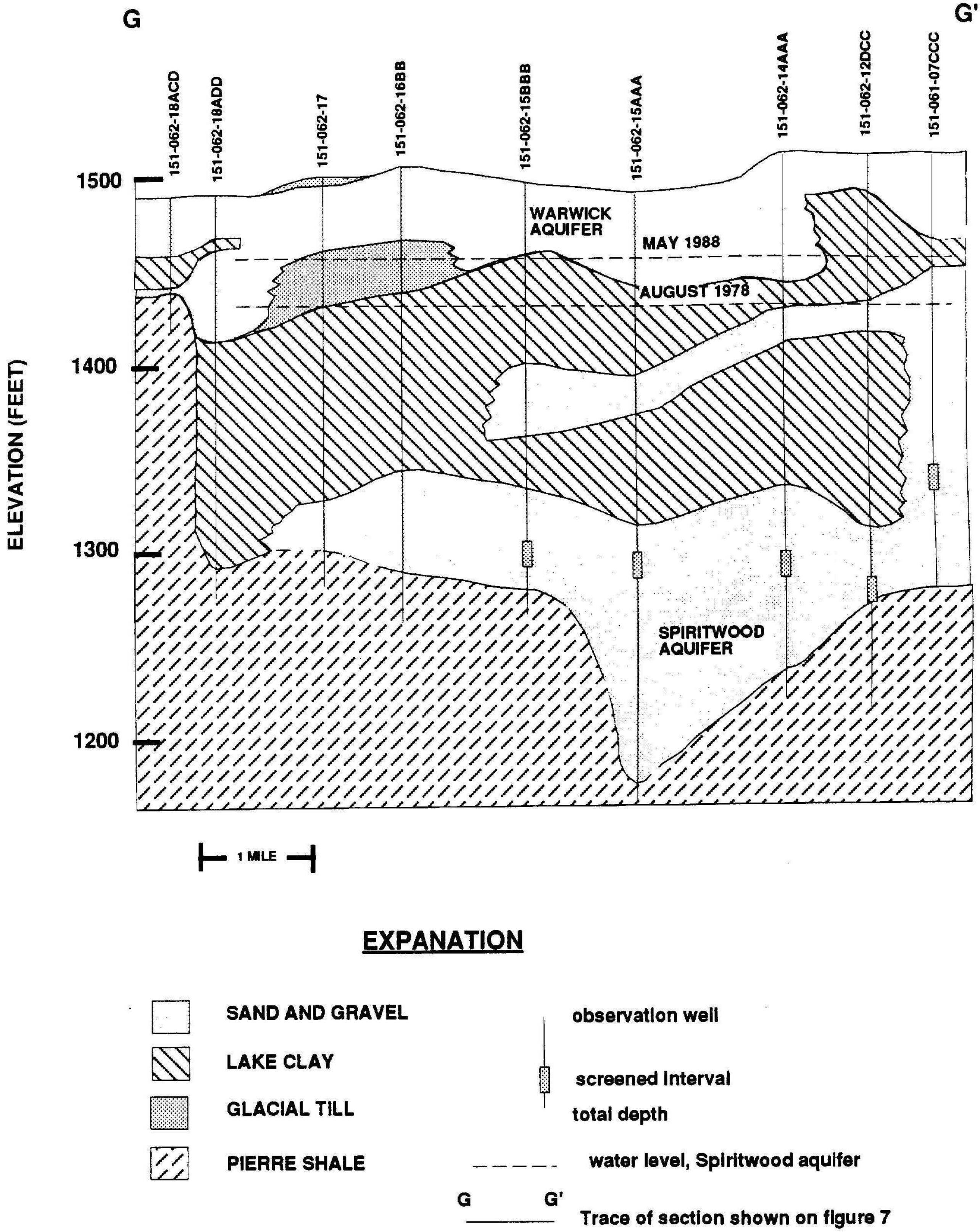


FIGURE 15. Hydrogeologic section G-G' showing the Warwick and Spiritwood aquifers, northeastern Benson County

Glacial outwash deposits in the area consist primarily of sand and gravel. South of Devils Lake, several flat to gently rolling plains of sand and gravel constitute the Tokio and Warwick outwash deposits (fig. 6). In contrast, the Oberon outwash results from sand and gravel being deposited in distinct channels. In most of the area, outwash deposits are separated from Devils Lake by glacial till of the North Viking and Heimdal moraines (figs. 6 and 9-15). The Tokio and Warwick outwash deposits extend southward to the Sheyenne River.

Lake deposits, composed mainly of laminated clay and silt, occur all around Devils Lake (fig. 6). Occasionally, small isolated beaches of sand and gravel occur along old shorelines of Devils Lake (Hobbs, 1987).

Several scattered, lenticular, ridge-like features of sand and gravel overlie portions of the study area (fig. 6). These deposits are described in the literature as kames and eskers. Ground water moving in these features probably contributes very little water to Devils Lake. As such, the kame and esker features are not discussed in any detail.

Bedrock Geology

Shale of the Pierre Formation directly underlies glacial drift over most of the study area. The surface of the bedrock immediately underlying the glacial drift is a result of a complex sequence of geologic events. Ancient rivers (Cannonball) and glacial diversion channels (Starkweather) carved deep valleys into the Pierre Shale (figs. 7-15). These valleys were formed at different times and cross one another in a complicated manner making the subsurface geology very complex (Hobbs, 1987). Sand and gravel deposited within these ancient drainage networks comprise the major buried valley aquifers in the area (fig. 8). Later, glaciers, moving across the area deposited successive sequences of glacial drift and lacustrine deposits on top of the ancient river valley sediments (figs. 9-15).

Glacial thrusting is also believed to have helped shape the bedrock surface. In some areas, the glaciers appear to have gouged out depressions in the bedrock surface while in others, huge blocks of Pierre Shale have been displaced into the glacial drift. As stated by Hobbs (1987):

"The subglacial and glacial geology in the area is extremely complex because extensive glacial thrusting by the glacial ice has greatly disrupted the materials; it is difficult to determine which buried low areas formed as river valleys and which depressions were excavated by the glacier."

GROUND-WATER FLOW SYSTEMS

Introduction

Prior to the 1960's, the interaction of lakes and ground water had received little attention. Subsequent investigations by Meyboom (1966), Williams (1968), Lissey (1968) , Sloan (1972), Winter (1976), (1978), (1980), (1981), (1983), (1984 A and B), (1986) and (1988), LaBaugh and others(1987) and Anderson (1981) greatly advanced the understanding of lake/ground-water interaction. Winter (1976) using computer simulation concluded that factors which influence the interaction of lakes and ground water are:

"1) height of adjacent water table mounds relative to the lake level,
2) position and relative hydraulic conductivity of aquifers within the ground-water system,
3) ratio of horizontal to vertical hydraulic conductivity of the ground-water system,
4) regional slope,
5) lake depth,
6) ground-water reservoir thickness,
7) presence of lake bottom sediments and
8) strength and position of the stagnation point."

To assess the ground-water-lake interaction in the Devils Lake area, it was necessary to define the geology and three-dimensional ground-water flow regime that exists within the sediments. To accomplish this, numerous shallow wells were installed throughout the basin to determine the nature of the sediments near Devils Lake and the position of the water table in relation to the lake level. Also, several observation well nests were constructed to determine the vertical hydraulic gradients in the area. With this data, a conceptual model of ground-water flow was developed.

Shallow Water Table

Introduction

As discussed earlier, glacial till and lacustrine clay covers most of the study area. Depth to the shallow water table in these low permeability sediments is a direct result of land surface elevation, topographic setting, and climate. Near Devils Lake, water levels in shallow water table wells ranged from less than one foot below land surface during the spring of 1987 to as much as six feet below land surface in the late fall and winter of 1989. In upland areas within the Devils Lake Basin, depth to the shallow water table ranged from 25 to 35 feet below land surface.

Factors which control water level fluctuations and direction of ground-water movement are both complex and transient. As stated by LaBaugh and others (1987):

> "The process changes annually and seasonally depending on quantity of snow before snowmelt, timing of snowmelt and quantity, and timing of rainfall. Results show that it would be misleading to assume general processes exist, particularly if data are collected for one or two years."

Therefore, because each year of the Devils Lake study had its own unique hydrologic conditions, ground water in the shallow water table is discussed on a year by year basis.

1987

Above normal precipitation and high runoff in the Devils Lake Basin during 1986 caused the Sweetwater chain to be near spill elevation. This, coupled with heavy snowfall (40-50 inches) over the winter of 1986-1987, resulted in high runoff in the spring of 1987. Due to this surge of inflow, Devils Lake rose from 1426.87 feet on March 23, 1987 to 1428.77 feet on May 30, 1987 (fig. 16). After the spring runoff event, water levels in Devils Lake declined throughout the summer of 1987.

Presented in figure 16 are hydrographs constructed from water levels measured in several shallow observation wells located near the shores of Devils Lake. The pattern of ground-water and lake levels response is similar. Snowmelt and rain in the spring of 1987 caused a substantial rise in both the level of the shallow water table and Devils Lake. In the summer and early fall of 1987, water levels in both Devils Lake and the shallow water table declined in response to evapotranspiration. During the late fall and winter of 1987, water levels of both Devils Lake and the shallow water table near the lake remained relatively constant.

Shallow ground water in the moraine surrounding Devils Lake appears, however, to respond more to local precipitation, snowmelt and evapotranspiration than to the level of Devils Lake (fig. 17). Snowmelt and infiltration in the spring of

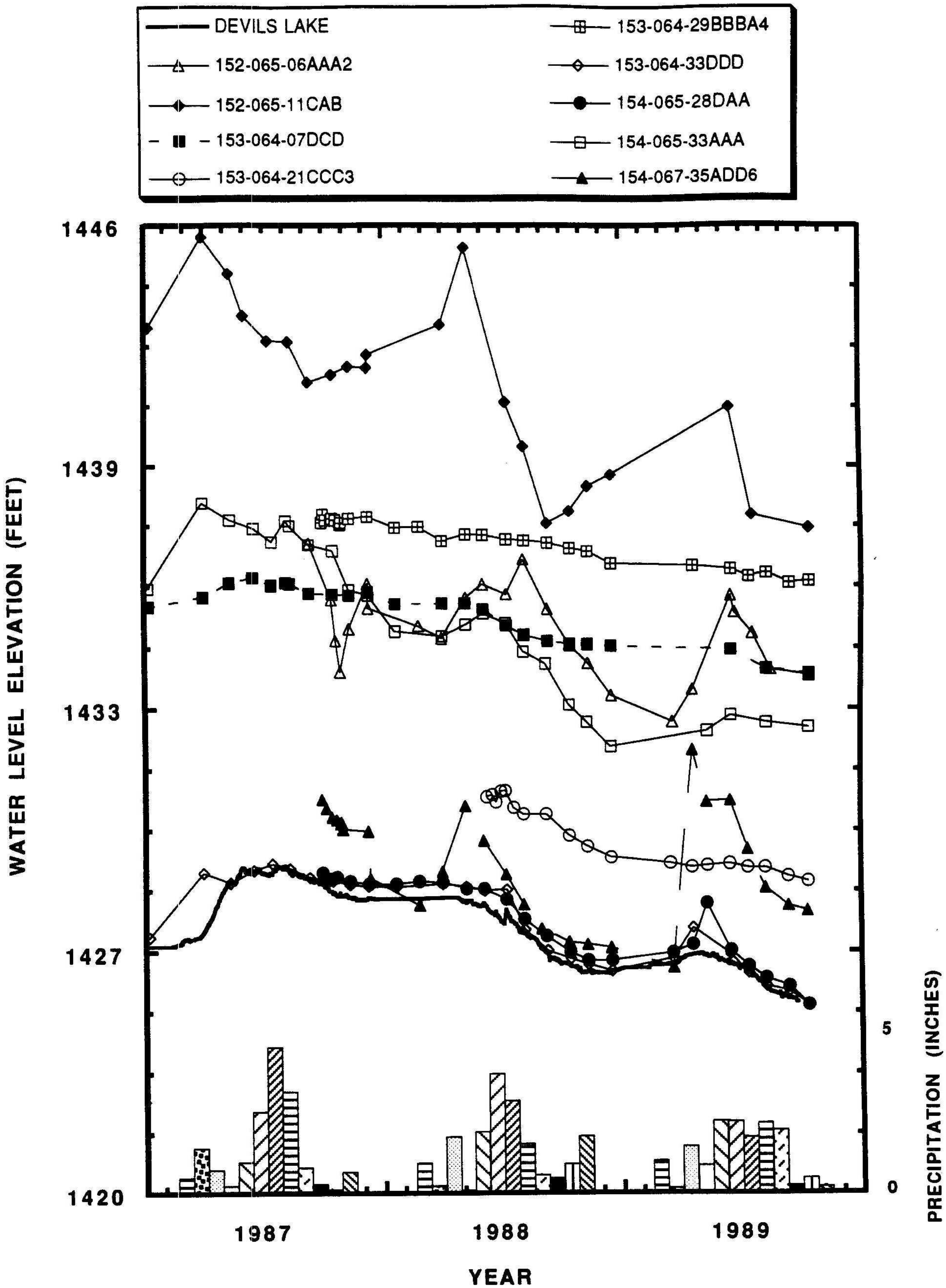


Figure 16. Water levels in wells completed in the shallow water table near Devils Lake versus water levels in Devils Lake

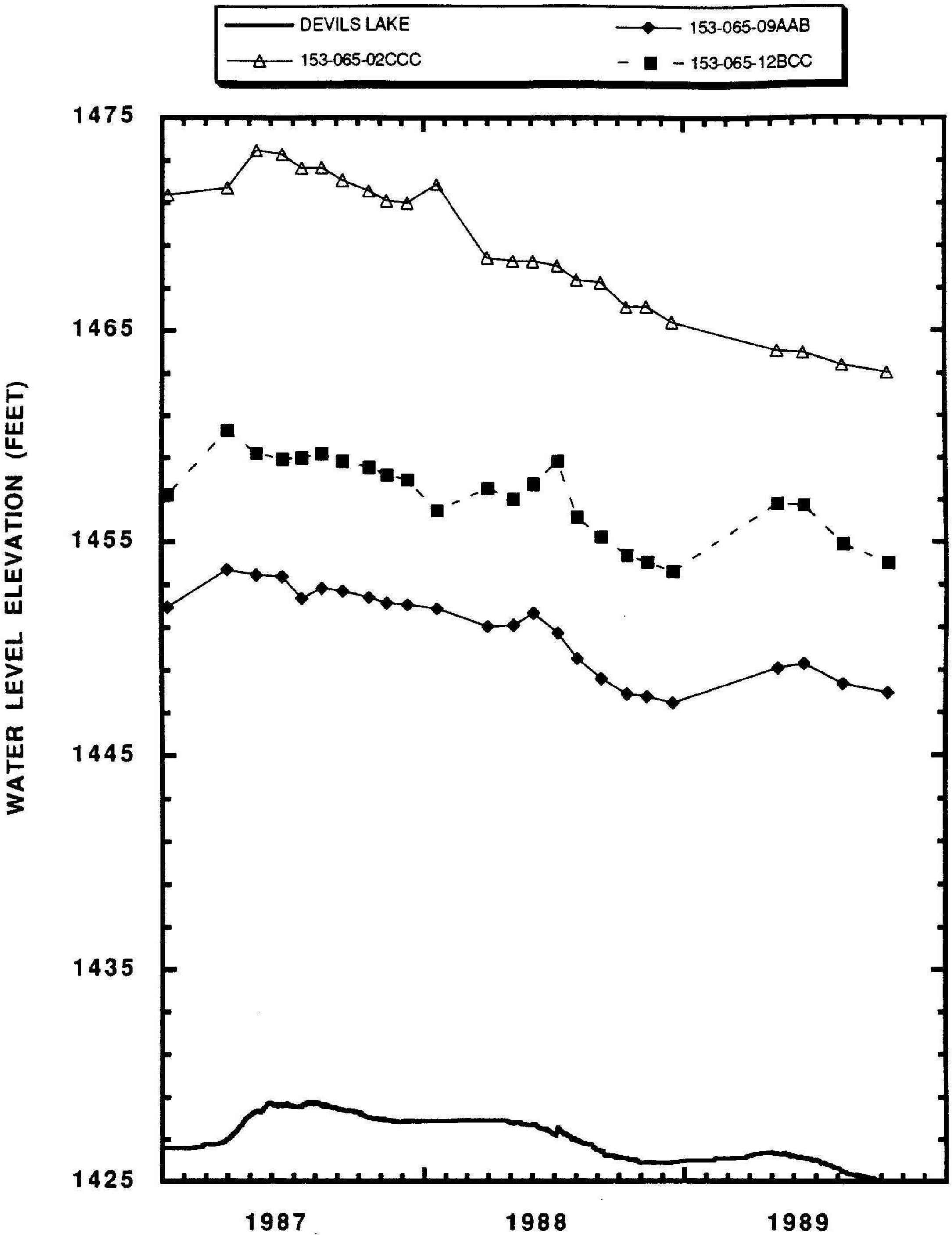


Figure 17. Water levels in shallow water table wells.Wells are located on the moraine surrounding Devils Lake

1987 resulted in a two to six foot rise in portions of the shallow water table. Precipitation events in May, June and July of 1987 caused a slight water level rise in many of the shallow wells in the basin. Evapotranspiration caused a general decline in water levels throughout the summer of 1987. As expected, wells with water levels near land surface or wells located near trees respond the most to precipitation and evapotranspiration events (fig. 16).

A water level contour map for May of 1987 was constructed for the area using wells which tap the shallow water table (fig. 18). At all the sites, water levels in the shallow water table wells were generally higher than and sloping towards Devils Lake. Basically, the shallow water table in May of 1987 was a subdued replica of the land surface topography. Regionally, ground-water movement was towards the large depressions occupied by the Devils Lake chain of lakes. Gradients varied from 1 foot/mile to as much as 22 feet/mile. Ground-water velocities based on the Darcy relationship ($V = KI/a$, Fetter, 1988) with $K =$ to 1.3×10^{-7} feet/day, a of .3 and $I = 1$ to 22 feet/mile are low, ranging from 7×10^{-7} to 3×10^{-8} feet/year. Thus, the low hydraulic conductivity of the clay and till surrounding Devils Lake restrict ground-water movement and limit the amount of shallow ground water contributing to the Devils Lake water budget.

1988

1988 will be remembered in North Dakota as one of the driest and hottest years on record. In the Devils Lake Basin, only 2.76 inches of precipitation occurred during the winter and spring of 1987-1988. As a result of the light snowpack, stream flow into Devils Lake was minimal. In fact, no appreciable rise in lake level was recorded in the spring of 1988 (fig. 16), despite a recorded inflow of 2,000 acre-feet (Wiche personal comm. 1989). High evaporation rates, and little precipitation during the summer and fall of 1988 resulted in approximately two feet of decline in the level of Devils Lake. Between the spring of 1987 and November of 1988, the water level of Devils Lake declined almost three feet (fig. 16).

During the winter of 1987-1988, water levels in several of the shallow water table wells declined at a faster rate than they had in the late fall (figs. 9 and 19-22). In the spring of 1988, water levels had recovered back to pre-winter levels. This water level fluctuation may be due in part to the formation of the frost zone during the winter. According to Schneider (1961):

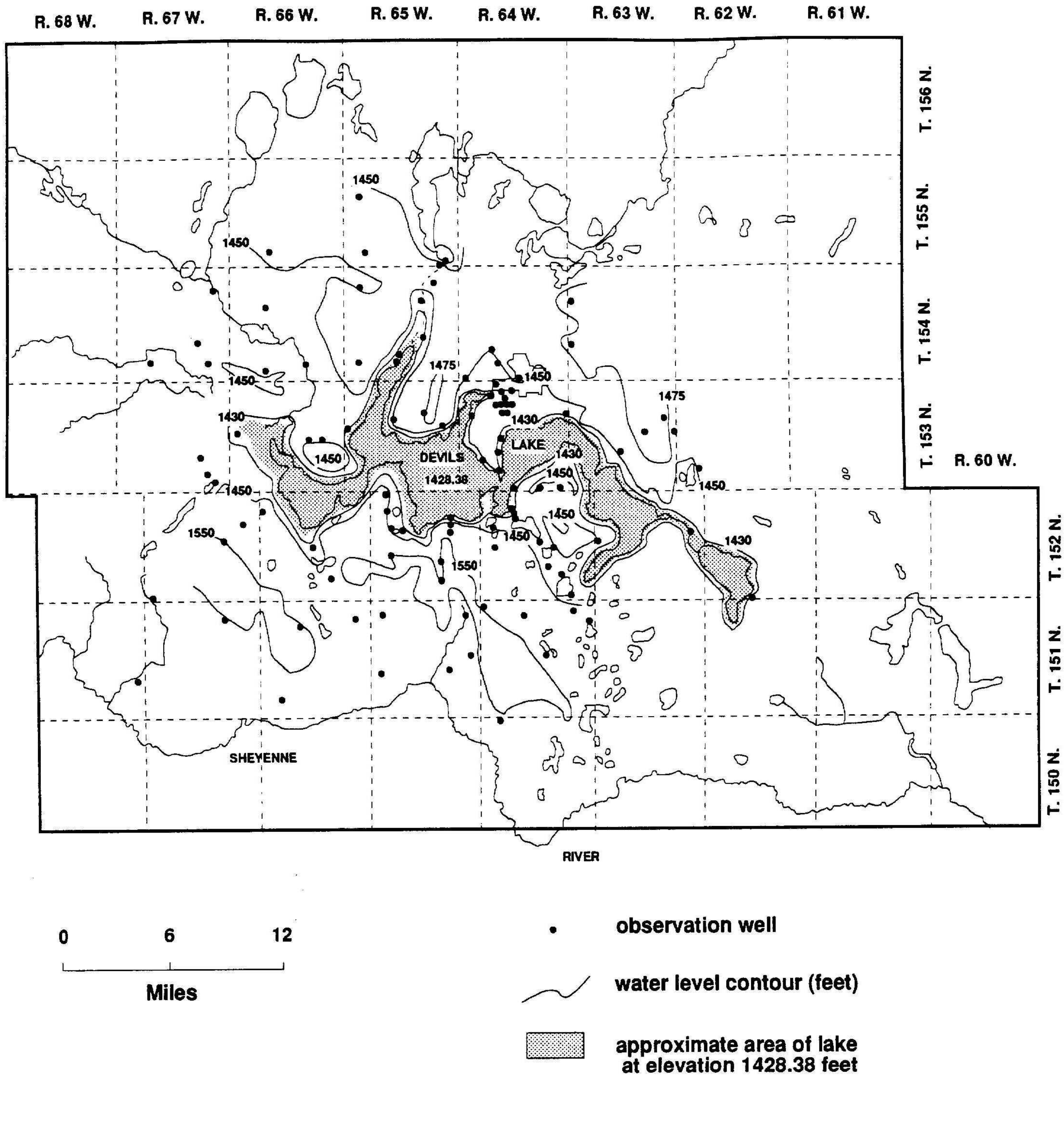


Figure 18. Water level contour map for the shallow water table in the Devils Lake area, May, 1987

"It has been shown in the laboratory that capillary water and water vapor move in the direction of the thermal gradient. The winter decline of the water table probably is caused in part by the upward movement of moisture below the frozen soil by capillary action, resulting in accretion to the frost layer from below. When the air temperature rises above freezing, the water table begins to rise as a result of downward percolation of melt water from the bottom of the frost layer.

This water level fluctuation does not, however, represent a loss or gain of water, but rather a seasonal redistribution.

Because of the light snowpack, the shallow water table exhibited very little rise in the spring of 1988 (figs. 16 , and 30-35). Precipitation events in May and July of 1988 caused minor increases in the height of the water table. High evapotranspiration rates in the summer and fall of 1988 caused water levels in the shallow water table to decline two to three feet. In the late fall and winter of 1988, water levels in both Devils Lake and the shallow water table remained relatively constant (figs. 16 , and 30-35).

1989

1989 was almost a repeat of 1988, with very little precipitation in either the summer, fall or winter. Because of the light snowpack, and depleted upstream storage, stream flow into Devils Lake was once again minimal. Because of the low stream flow, very little rise in the level of Devils Lake was recorded (fig. 16). High evaporation rates, and little precipitation during the summer and fall of 1989 resulted in approximately one and one half feet of decline in the level of Devils Lake. Between the spring of 1987 and October of 1989, the water level of Devils Lake declined almost four feet (fig. 16).

Ground-water movement in December of 1989 was similar to the movement observed 2 years earlier however depth to water had dropped 5 to 10 feet (fig. 19).

In reality, ground water in the shallow water table (lake clays and tills) probably moves very slowly towards the many localized closed depressions (potholes, small lakes etc.) throughout the basin. Because of this, a large percentage of the ground water in the shallow water table never reaches Devils Lake. Instead, ground water in the shallow water table circulates locally from the effects of precipitation, infiltration and evapotranspiration. It appears that only the relatively small area of the shallow water table immediately adjacent to Devils Lake interacts with the lake.

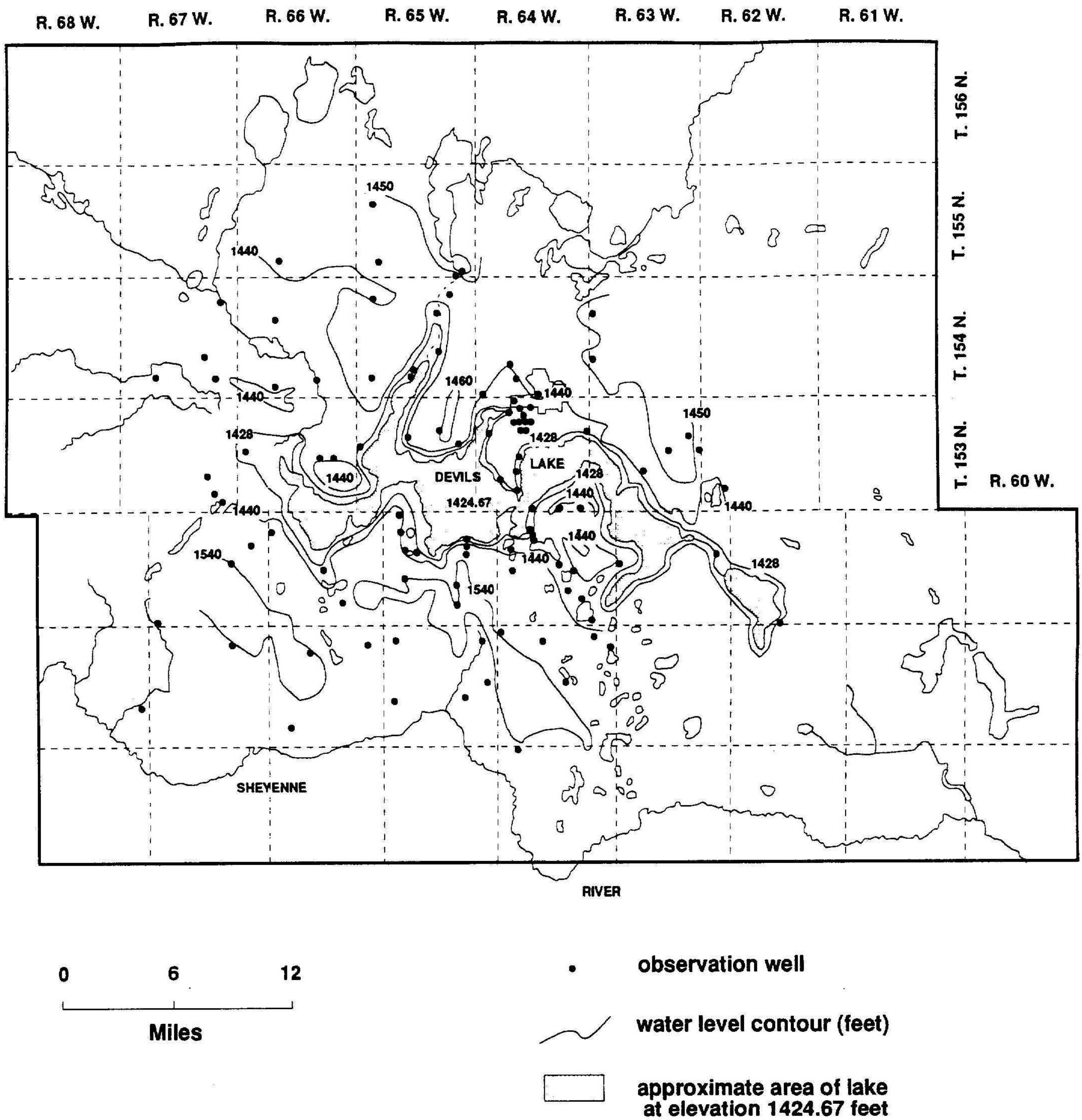


Figure 19. Water level contour map for the shallow water table in the Devils Lake area, December, 1989

Spiritwood Aquifer System

Physical characteristics

The Spiritwood aquifer system, in the Devils Lake study area, is part of an extensive buried valley aquifer complex that extends from the Canadian border in Towner County, southeastward to the South Dakota border (fig. 20, NDSWC, 1986). The Spiritwood aquifer was named for its discovery near the town of Spiritwood, N.D., in Stutsman County (Huxel , 1961).

The Spiritwood aquifer system occurring in the area has been divided into segments based on geographic location within the basin. In Benson County, the aquifer was divided into, the Spiritwood aquifer near Minnewaukan and the Spiritwood aquifer near Warwick (Randich, 1977). In Ramsey County, the authors classified all sand and gravel within and overlying the bedrock valley complex as the Spiritwood aquifer (Hutchinson, 1980). In Eddy County, the Hamar aquifer appears to be a tributary channel to the Spiritwood aquifer system (Trapp, 1968). In this report, any saturated sand and gravel occurring within the valley network of the preglacial Cannonball River will be classified as the Spiritwood aquifer system (figs. 8-15, and 21). This classification suggests that sand and gravel within the ancient Cannonball River Valley is one extensive, well connected body of aquifer material. Test drilling and water level measurements reveal, however, that sand and gravel deposits of the Spiritwood aquifer system occur as pockets and/or cells of aquifer material, separated by bedrock ridges, glacial till and lake clay(figs. 9-15).

Length of the main valley complex of the Spiritwood aquifer system, in the Devils Lake study area, is approximately 55 miles (fig. 21). Thickness of individual sand and gravel unites ranges from less than a foot on the bedrock valley flanks to 300 feet thick along the axis of the valley (figs. 9-15). Width of the aquifer ranges from less than one mile to six miles. In general, 100 to 200 feet of glacial till and lake clay overlies and confines the Spiritwood aquifer system(figs. 9-15). A major portion of the Spiritwood aquifer system appears to directly underlie the Devils Lake chain of lakes (figs. 13, 14, and 21). To the southeast, the Spiritwood aquifer system crosses beneath the Sheyenne River Valley (figs. 14 and 21).

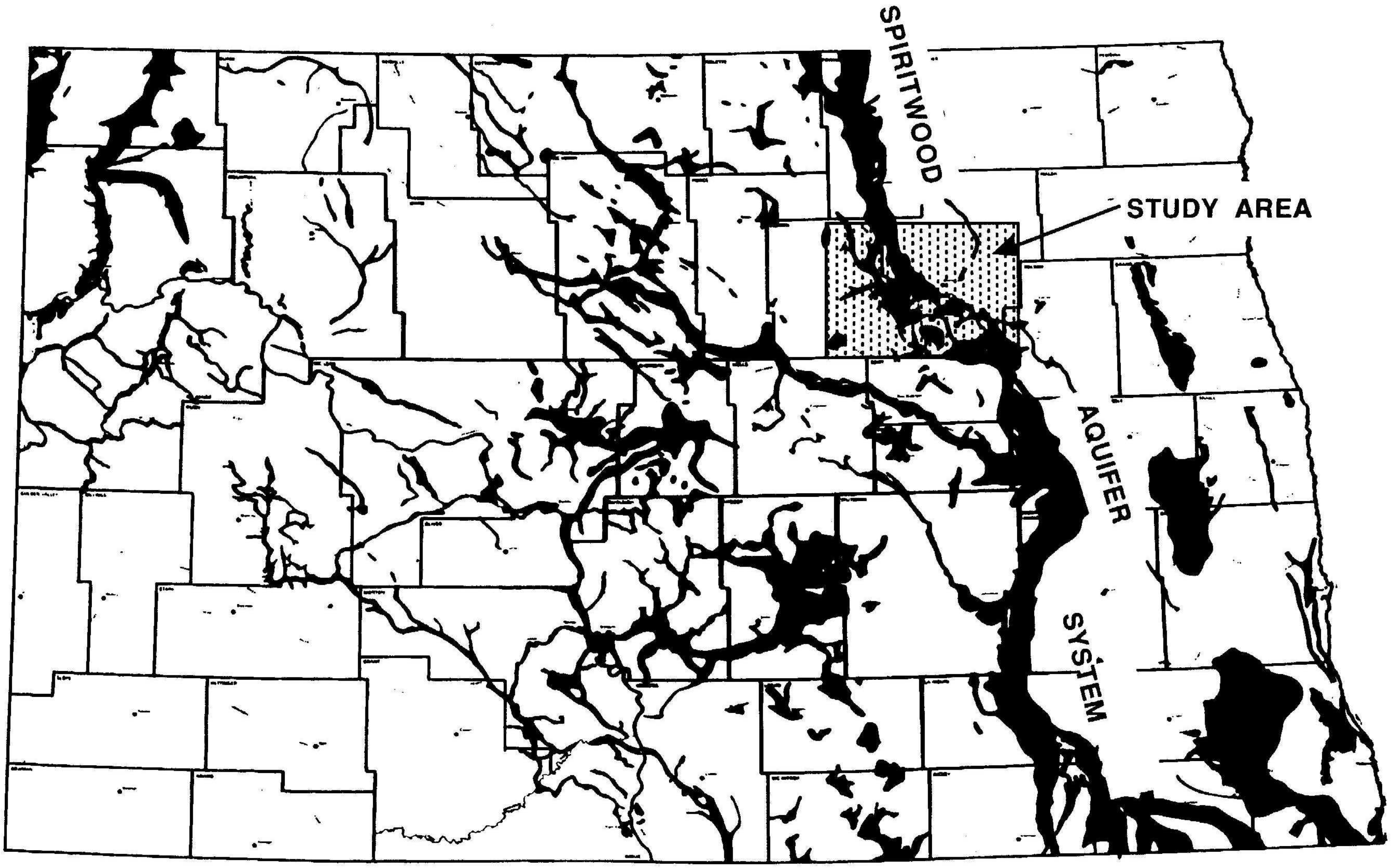


Figure 20. Location of major glacial drift aquifers in North Dakota (from North Dakota State Water Commission 1986)

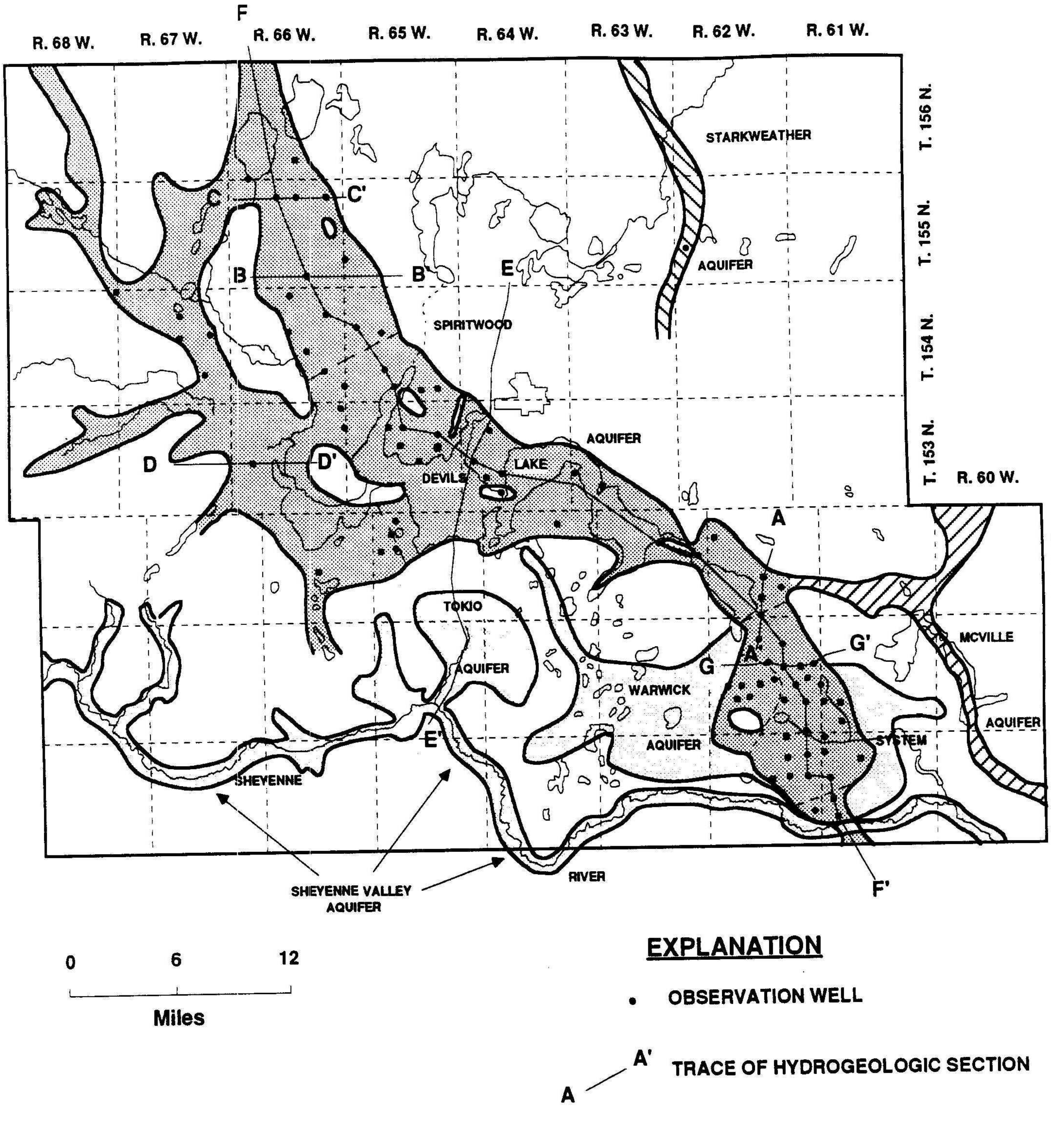


Figure 21. Major aquifers in the Devils Lake area (modified from Trapp, 1968, Downey, 1973, Randich, 1977 and Hutchinson and Klausing, 1980)

According to Bluemle (1981), the depression containing Devils Lake may have been excavated by glaciers and the quarried material deposited to form Sully's Hill (fig. 13). Bluemle (1981), speculates that the existence of the Spiritwood aquifer under the moving ice sheet caused a build up of pore pressure, forcing geologic material upward into the advancing glacier. Interestingly, Sully's Hill may be in part composed of sand and gravel from the Spiritwood aquifer. If Bluemle's theory is correct, ground water's major role in the history of Devils Lake may be in the formation of the depression that contains the lake.

Transmissivities of the Spiritwood aquifer, estimated from lithologic logs and analyses of aquifer tests in Benson and Ramsey Counties, range from 4,000 ft^2/day to 20,000 ft^2/day (Randich, 1977, Hutchinson, 1980 and Johnson, 1979). Depending on local aquifer thickness and hydraulic conductivity, properly constructed wells completed in the Spiritwood aquifer should yield 50 to 1500 gpm. Storage coefficients calculated from aquifer tests range from 2×10^{-4} to 4×10^{-4}, indicating confined conditions (Randich, 1977, Hutchinson, 1980 and Johnson, 1979).

Recharge to the Spiritwood aquifer is primarily from infiltration of precipitation through overlying and adjacent glacial drift deposits, underflow from connecting tributary buried valleys and from adjacent bedrock formations (Randich, 1977 and Hutchinson, 1980). Discharge from the aquifer system is by pumping, evapotranspiration, and movement into the lakes that form the Devils Lake chain (Hutchinson, 1980). Estimates made by Randich, (1977) and Hutchinson (1980) place the total amount of water available from storage in Benson and Ramsey Counties at around 1.5 million acre-feet. In contrast, Devils Lake contains 836,410 acre-feet at elevation 1428 feet.

Long term water level trends

Approximately 20 years of Spiritwood aquifer water level data are available for several NDSWC observation wells in the Devils Lake area (fig. 22). Throughout that period, the level of Devils Lake generally rose from a low of 1417 feet in 1970 to a high of 1428 feet in 1987. Over that same period, water levels in the Spiritwood aquifer fluctuated in a manner similar to the lake level fluctuations(fig. 22). In addition, water levels in wells tapping the Spiritwood aquifer were consistently higher than the level of Devils Lake indicating that the potential for ground-water movement was from the aquifer to the lake. As distance increases away from the lake, the similarity between lake and ground-water levels is still evident however the magnitude of the response is less (figs. 22 and 23). It is difficult to determine from the long term water level record if local climatic events are causing these water level fluctuations or if the lake has an influence on the ground-water levels far away from the lake.

Short term water level fluctuations

Water levels in observation wells near Devils Lake respond in a manner similar to a rise or decline in lake level (fig. 24). Nine miles northwest of Devils Lake, water levels in the Spiritwood aquifer respond in a manner similar to the lake however the magnitude is less (fig. 25). This rather quick response nine miles away from the lake confirms the confined nature of the Spiritwood aquifer. In these areas, the rise in ground water-levels may also be due also to infiltration from precipitation/snowmelt. In addition, the annual fluctuations of ground-water levels may be due in part to loading effects caused by changes in surface moisture (van der Kamp and Maathuis, 1991).

Note also that while water levels in the Spiritwood aquifer decline throughout the fall and winter months, the level of Devils Lake rises slightly (figs. 22, 24, and 25). The decline of water levels in the Spiritwood aquifer is a natural response to discharge from the system. The slight increase in water levels in Devils Lake is a reflection of the water input into the lake from the ground-water sources.

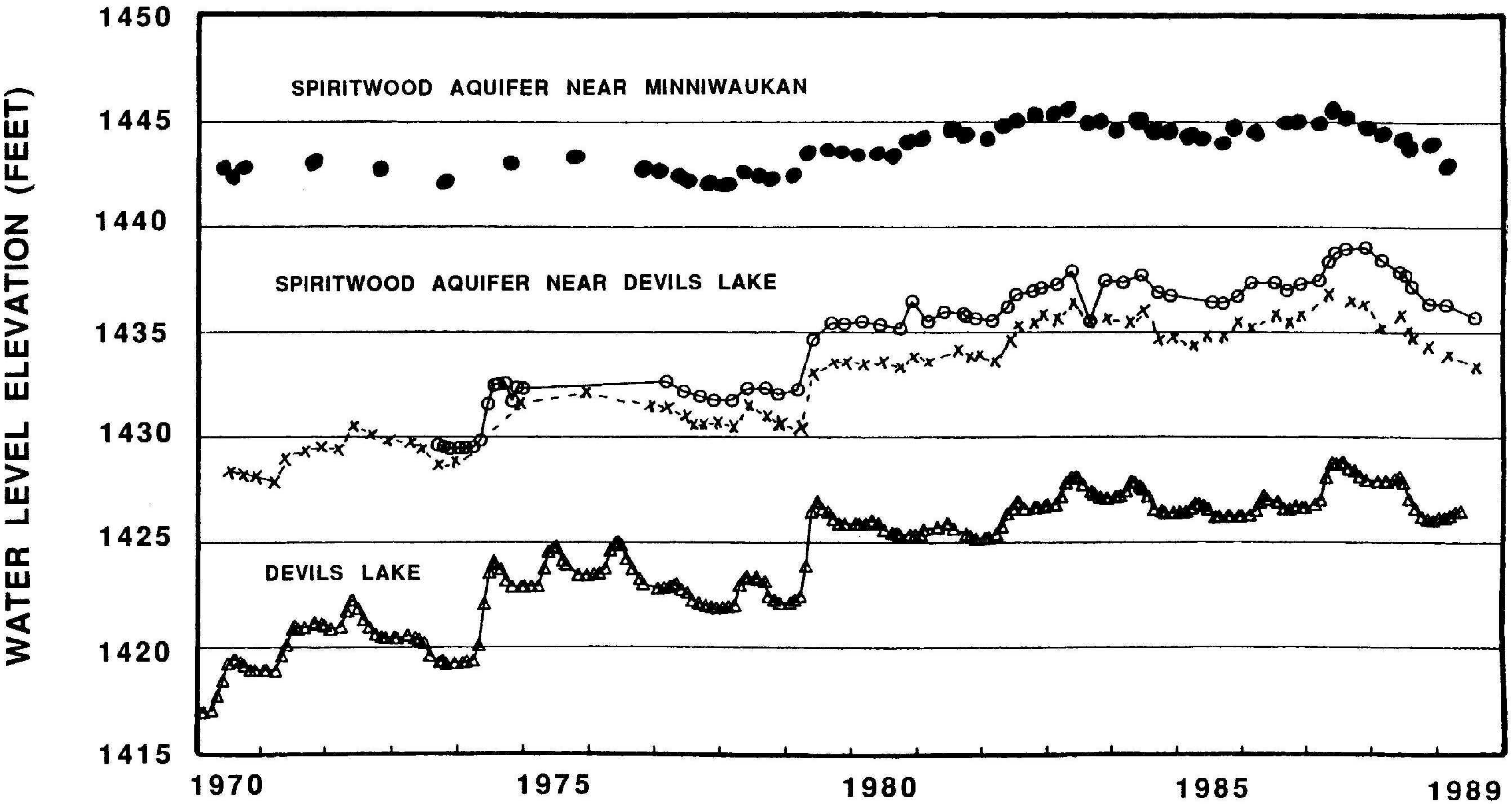


Figure 22. Water levels in wells completed in the Spiritwood aquifer system versus water levels in Devils Lake (1970-1989)

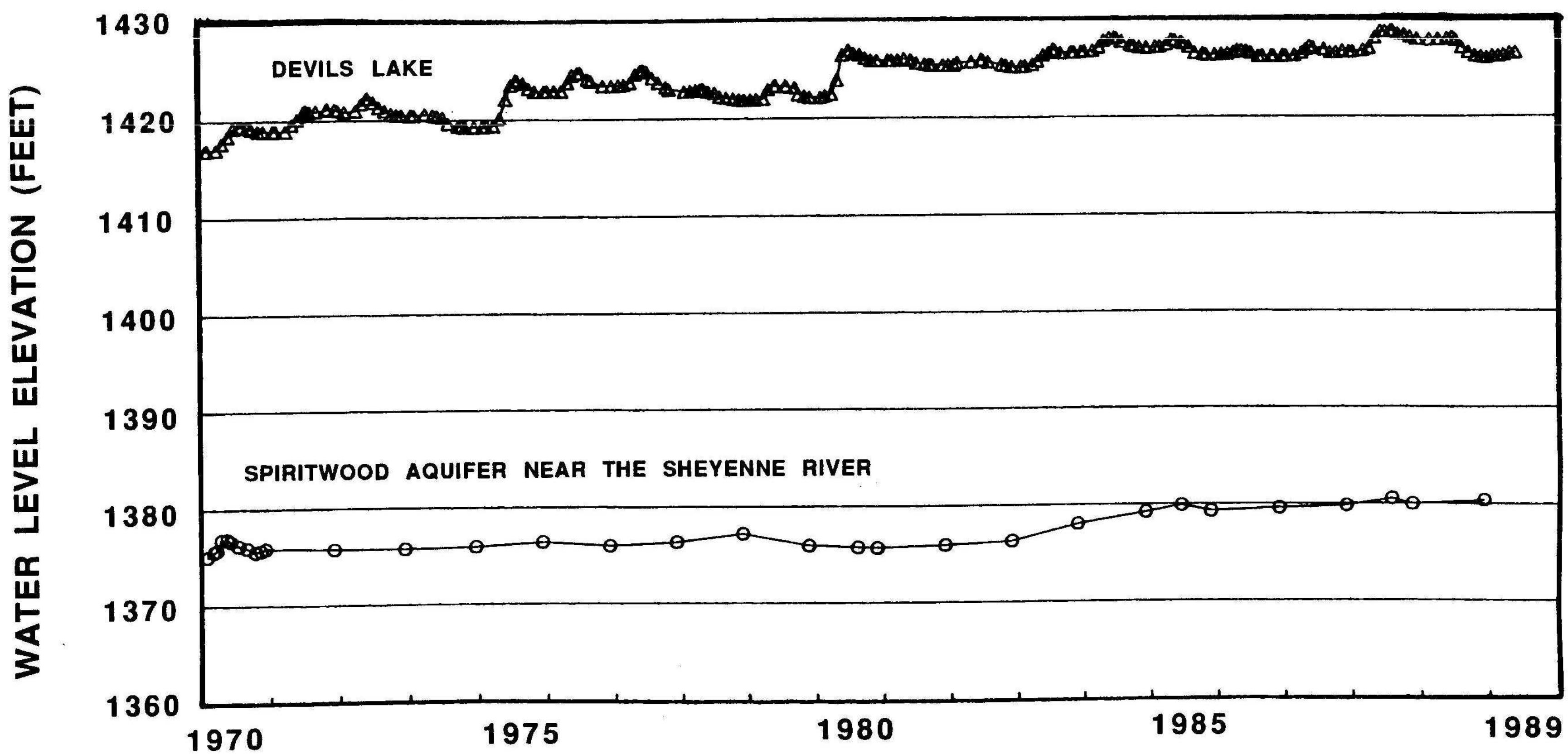


Figure 23. Water levels in a well completed in the Spiritwood aquifer near the Sheyenne River versus water levels of Devils Lake (1970-1989)

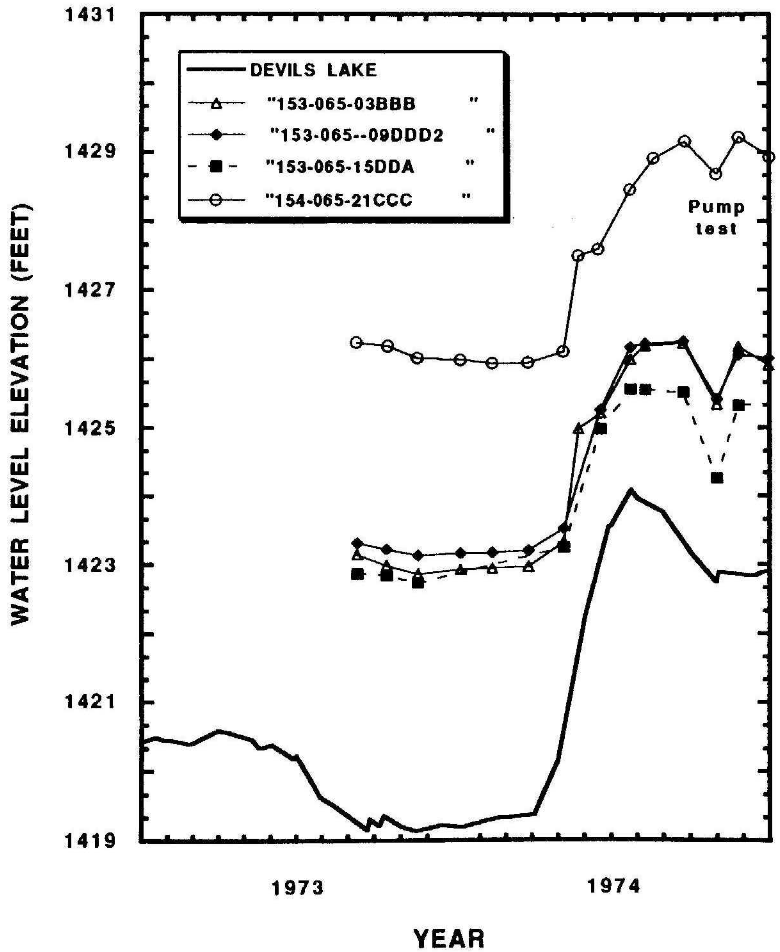


Figure 24A. Water levels in wells completed in the Spiritwood Aquifer near Devils Lake vrs. water levels in Devils Lake (1973-1974)

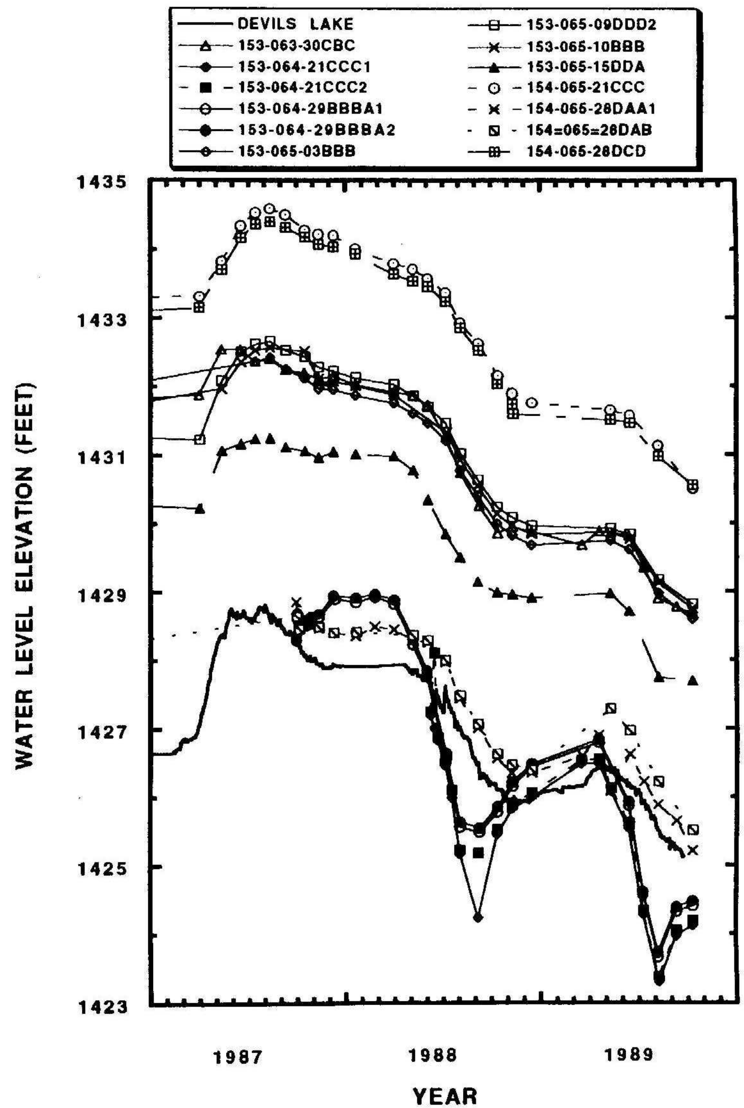


Figure 24B. Water levels in wells completed in the Spiritwood Aquifer near Devils Lake vrs. water levels in Devils Lake (1987-1989)

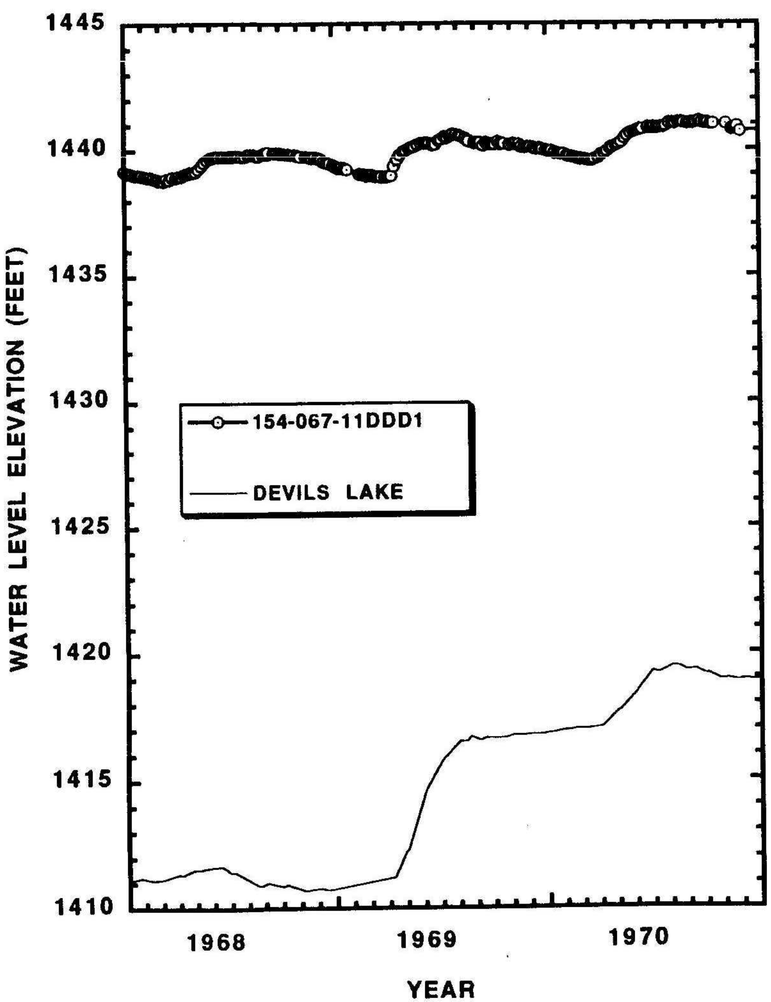


Figure 25A. Water levels in wells in the Spiritwood aquifer near Minnewaukan versus water in Devils Lake (1968-1970)

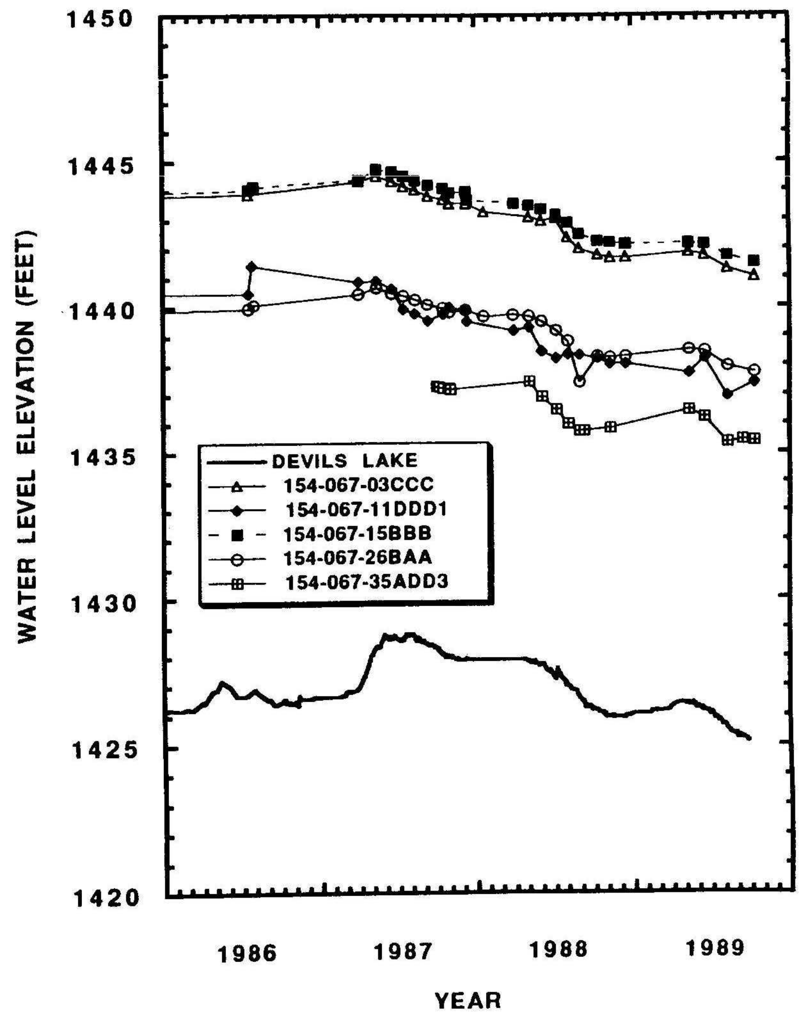


Figure 25B . Water levels in wells completed in the Spiritwood Aquifer near Minnewaukan vrs. water levels in Devils Lake (1986-1989)

Water levels in the main channel of the Spiritwood aquifer near Camp Grafton and Lakewood, however, dropped slightly below the level of Devils Lake in the summers of 1988 and 1989 (fig. 24B). It appears that, in this area, the combined effects of pumping of several hundred domestic wells cause water levels to seasonally decline 2 to 3 feet. Water levels recover during the late fall and winter (less domestic water use), and eventually rise above the level of Devils Lake. Thus, in this area, the potential would be for movement of water from Devils Lake through the intervening clays and into the Spiritwood aquifer during summer pumping. The potential reverts back to natural conditions after the summer pumping cycle is completed and the Spiritwood Aquifer once again becomes a possible source of water for Devils Lake.

Water levels in the Spiritwood aquifer near Warwick have fluctuated in response to changing climate patterns and variations in irrigation pumping (fig. 26). During the summer months, water levels in the area decline as a result of the irrigation pumping. Water levels recover during the fall, winter and early spring months. Maximum drawdown has been about 20 feet during a typical irrigation season(fig. 26). The recorded low water level was approximately 1430 feet above mean sea level in August of 1978 (drawdown due to irrigation). Currently there is over 100 feet of available drawdown (drawdown to top of aquifer) in the Spiritwood aquifer near Warwick (fig. 15).

Since 1977, two distinct water level trends have been recorded in the Spiritwood aquifer near Warwick. From 1977 through 1988 water levels generally rose at a rate of 1/2 foot per year(fig. 26). Since 1988 water levels have decreased at a rate of 1/2 foot per year. This response is due to changing water use patterns (brought on by changing climatic conditions) in the area. Also, water levels in the Spiritwood aquifer near Warwick may be adjusting slightly to fluctuations in the height of the regional discharge area (Devils Lake, fig. 26).

Loading effects

Another factor that may cause water levels in the Spiritwood aquifer to fluctuate is loading effects imposed by a rise or fall in the level of Devils Lake. The increased or decreased weight imposed on the underlying confined aquifer (Spiritwood aquifer) would change the pressure on the aquifer thereby increasing or decreasing the

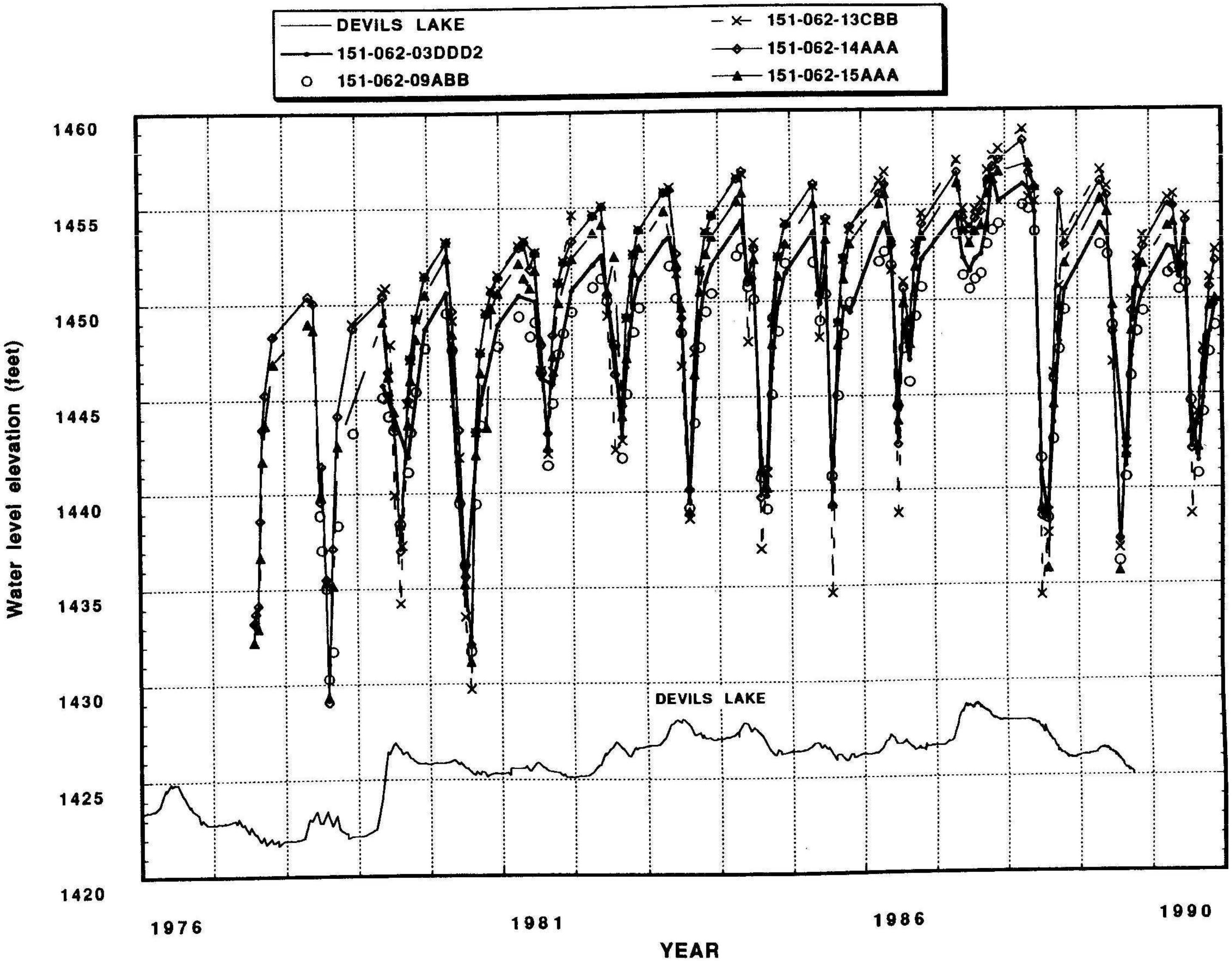


Figure 26. Water levels in the Spiritwood aquifer near Warwick, northeastern Benson county and southwestern Ramsey county, North Dakota (1976-1990)

pressure on the water in the pore space. This increase or decrease in pressure on the pore water would in turn cause ground-water levels to rise or fall depending on: 1) the magnitude of the rise or fall in lake level, 2) the elasticity of the aquifer skeleton and 3) porosity of the aquifer. The more rigid the aquifer the less transfer of weight to the pore water and water levels would fluctuate very little. The more elastic the aquifer, the greater the transfer of pressure to the pore water and water levels would fluctuate significantly.

Water levels recorded in the spring of 1974 were used to analyze this phenomenon (fig. 24A). Note that approximately a 5 foot rise in lake level was recorded from April to August of 1974. This rise represents an increase of 122,000 acre-feet or 165 million tons of water into Devils Lake. Over that same time period, water levels in the Spiritwood aquifer near Devils Lake rose approximately 3 feet.

According to DeWeist (1965) the effect of an increase or decrease in weight on an underlying confined aquifer can be calculated with the equation:

$$dh = \frac{\alpha dH}{\alpha + n\beta}$$

where:

dh = change in ground-water level

dH= change in lake level

α = vertical compressibility of the aquifer skeleton

n = porosity

β = compressibility of the fluid

For a 5 foot rise in lake level (fig. 24A) and assuming an aquifer compressibility of 10^{-8} m^2/N (for sand and gravel, Freeze and Cherry, 1979), a porosity of 0.3, the rise in aquifer water level caused by loading would be 4.9 feet. Thus, all the fluctuation in water levels in the Spiritwood aquifer in the Devils Lake area could be attributed to the effects of loading. This calculated response can, however, be varied by adjusting the value of the compressibility of the aquifer. If the compressibility is changed to 10^{-10} m^2/N, the aquifer response would be 2.1 feet or rather close to the observed 3 foot rise in ground-water levels.

In conclusion, water level fluctuations in the Spiritwood aquifer are a combined result of: (1) fluctuations in the height of the regional discharge area (Devils Lake), (2) recharge from precipitation, and (3) loading and unloading effects caused by fluctuating lake levels.

Ground-water movement

Presented in Figure 27 is a water level contour map for the Spiritwood aquifer during high Devils Lake stage of 1987. During this highest lake level of the century, water level elevations in the Spiritwood Aquifer were higher than and sloping towards Devils Lake. Based on the available data, ground water in the Spiritwood aquifer was generally moving from all directions towards the large depression occupied by Devils Lake (fig. 27). Water level gradients were rather small, 1 to 2 feet/mile. Ground water velocities, (Darcy) using K = 100 feet/day, ranged from 0.1 to 1 foot/year. Thus, even though the Spiritwood aquifer represents a significant source of stored water, the small gradients suggest that the movement of ground water towards Devils Lake was very slow.

Presented in Figure 28 is a water level contour map for the Spiritwood aquifer during low lake stage of 1989. Regionally, water levels in the Spiritwood were generally higher than and sloping towards Devils Lake. Just south of the city of Devils Lake, as discussed earlier, water levels were slightly lower than the lake level.

Several ground-water divides occur in the Spiritwood aquifer in the study area (figs. 27 and 28). The first occurs in Township 155 North, Range 66 West, where ground water moves both southeast towards Devils Lake and also northwest towards Lake Irvine. Two other ground-water divides occur in Townships 150 and 151, Range 61, where ground water in the Spiritwood aquifer moves both northwest towards East Devils Lake and southward towards the Sheyenne River and Tolna Coulee(figs. 27 and 28). Based on ground-water level response to the lake and the location of the ground-water divides, the Spiritwood aquifer system in the study area can be divided into the following (fig. 29):

1) Spiritwood aquifer near Devils Lake
2) Spiritwood aquifer near Minnewaukan
3) Spiritwood aquifer near Lake Irvine

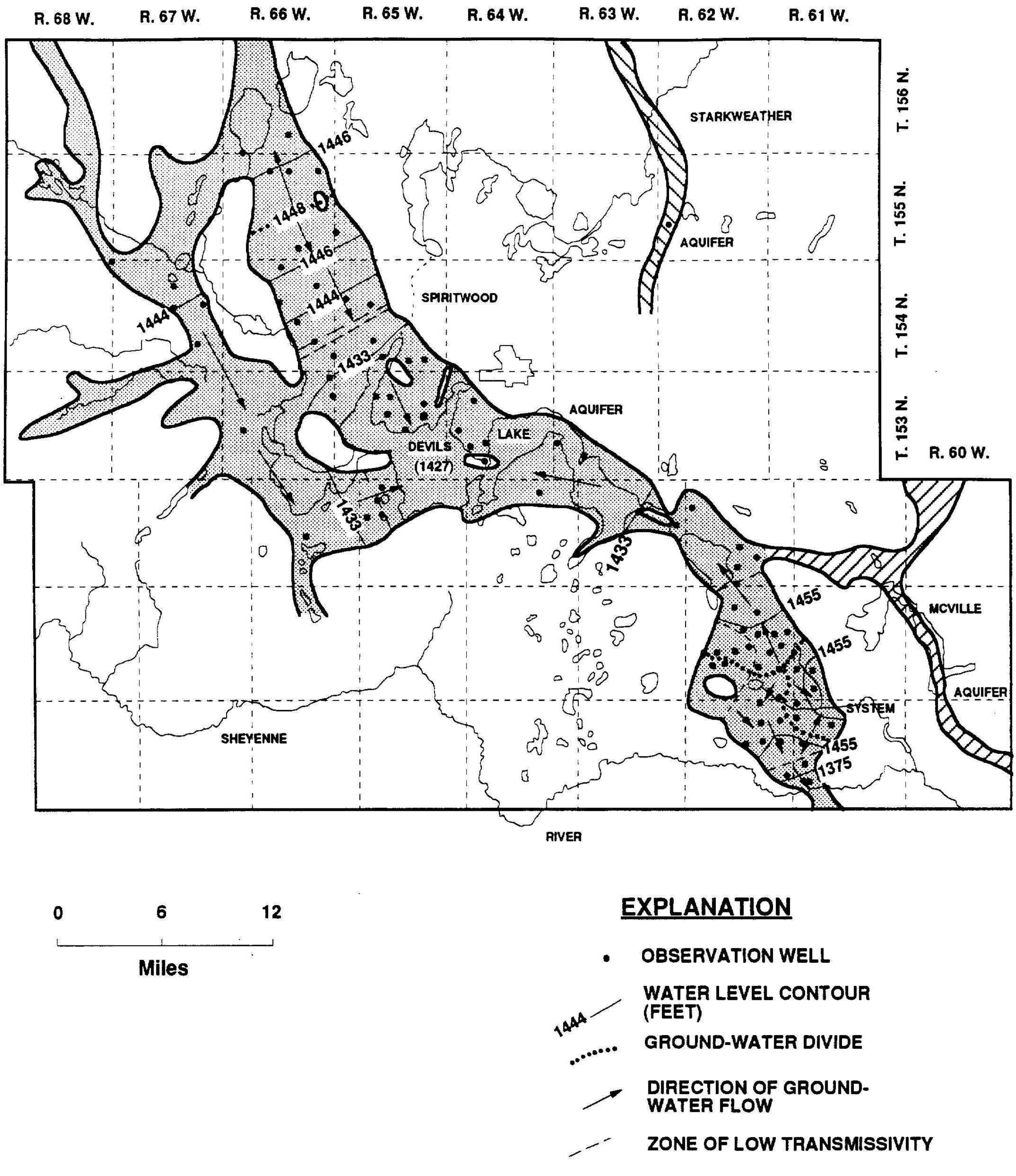


FIGURE 27. POTENTIOMETRIC SURFACE MAP OF THE SPIRITWOOD AQUIFER SYSTEM DURING HIGH DEVILS LAKE STAGE OF APRIL, 1987

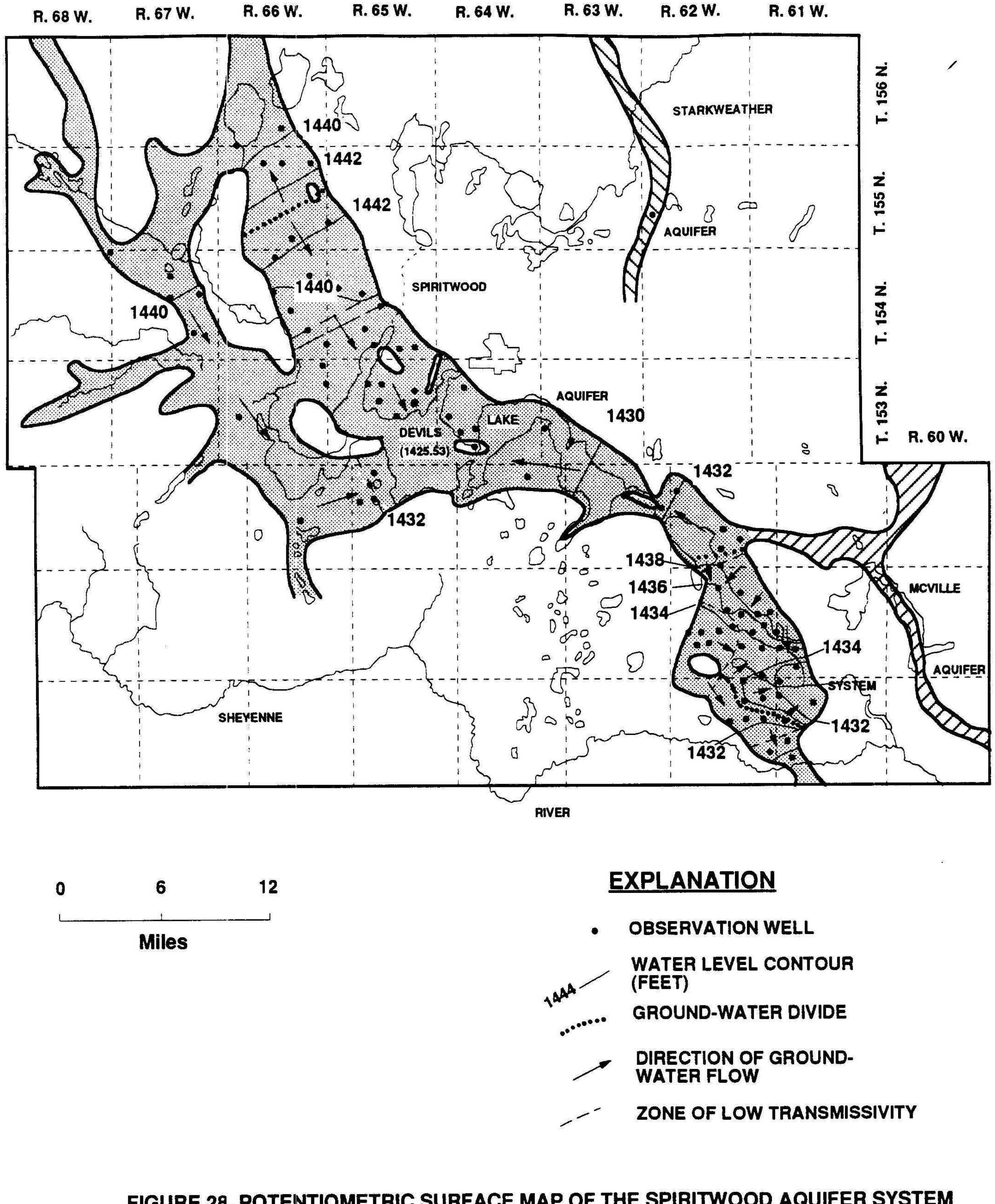


FIGURE 28. POTENTIOMETRIC SURFACE MAP OF THE SPIRITWOOD AQUIFER SYSTEM DURING LOW DEVILS LAKE STAGE OF JULY AND AUGUST, 1989

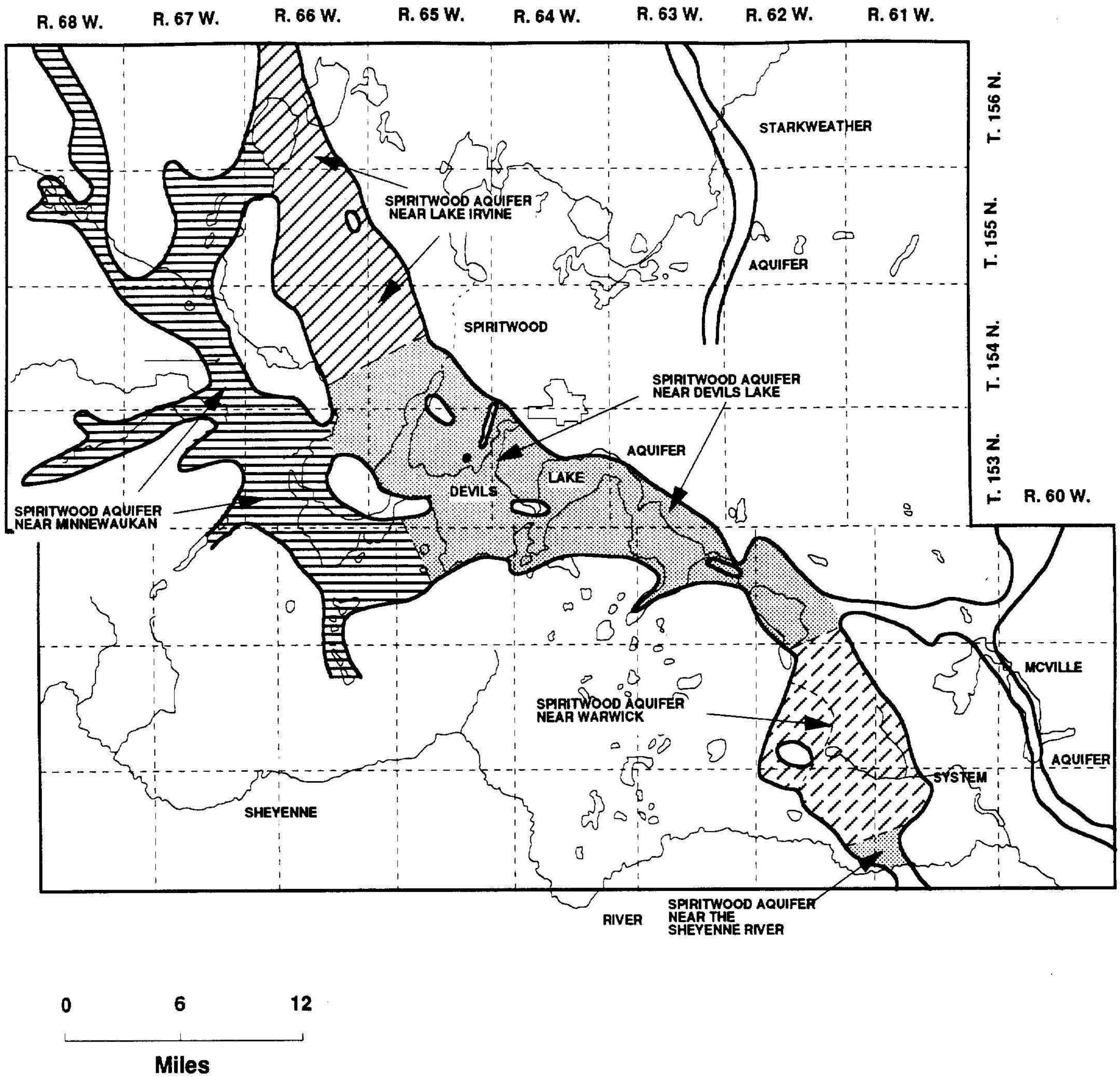


FIGURE 29. SUBDIVISIONS OF THE SPIRITWOOD AQUIFER SYSTEM IN THE DEVILS LAKE AREA (modified from Trapp, 1968, Downey, 1973, Randich, 1977 and Hutchinson and Klausing, 1980)

4) Spiritwood aquifer near Warwick

5) Spiritwood aquifer near the Sheyenne River

Vertical Distribution of Water Levels

Water levels were measured in the vertical at 20 nested observation well sites (figs. 30-35). The vertical distribution of water levels is important in determining recharge, flow through and discharge areas.

Presented in figure 30 are hydrographs of water levels obtained from observation wells located near the shores of Devils Lake. Note that at this site, water level elevations increase with depth, indicating upward ground-water flow from the Spiritwood aquifer, through the overlying till and clay, and finally discharge into Devils Lake (fig. 30).

Presented in figures 31 and 32 are hydrographs of water levels obtained from representative observation well nests located on high ground, but still near the lake shore. In these areas, water level elevations in the overlying till and clay decrease with depth until the Spiritwood aquifer is reached. Water level elevations in the Spiritwood aquifer are either the same or increase slightly with depth (fig. 31). This indicates that the potential for ground-water movement is slowly downward through the till and clay, and then laterally along the Spiritwood aquifer towards Devils Lake (fig. 31). The exception to this relationship is shown in figure 33, where pumping causes a seasonal lowering of water levels below the level of Devils Lake.

Several observation well nests were also placed along Big Coulee and Channel A to determine ground-water flow. The geology in these general areas consists of Pierre Shale overlain by 50 to 100 feet of low permeability lake clays and till. Observation well nest data indicates that along Big Coulee and Channel A, water level elevations increase with depth (figs. 34 and 35). In these areas, ground water moves upward to replace ground water being discharged into Big Coulee and Channel A. Big Coulee and Channel A dry up completely in the summer, indicating that base flow to these valleys is rather low.

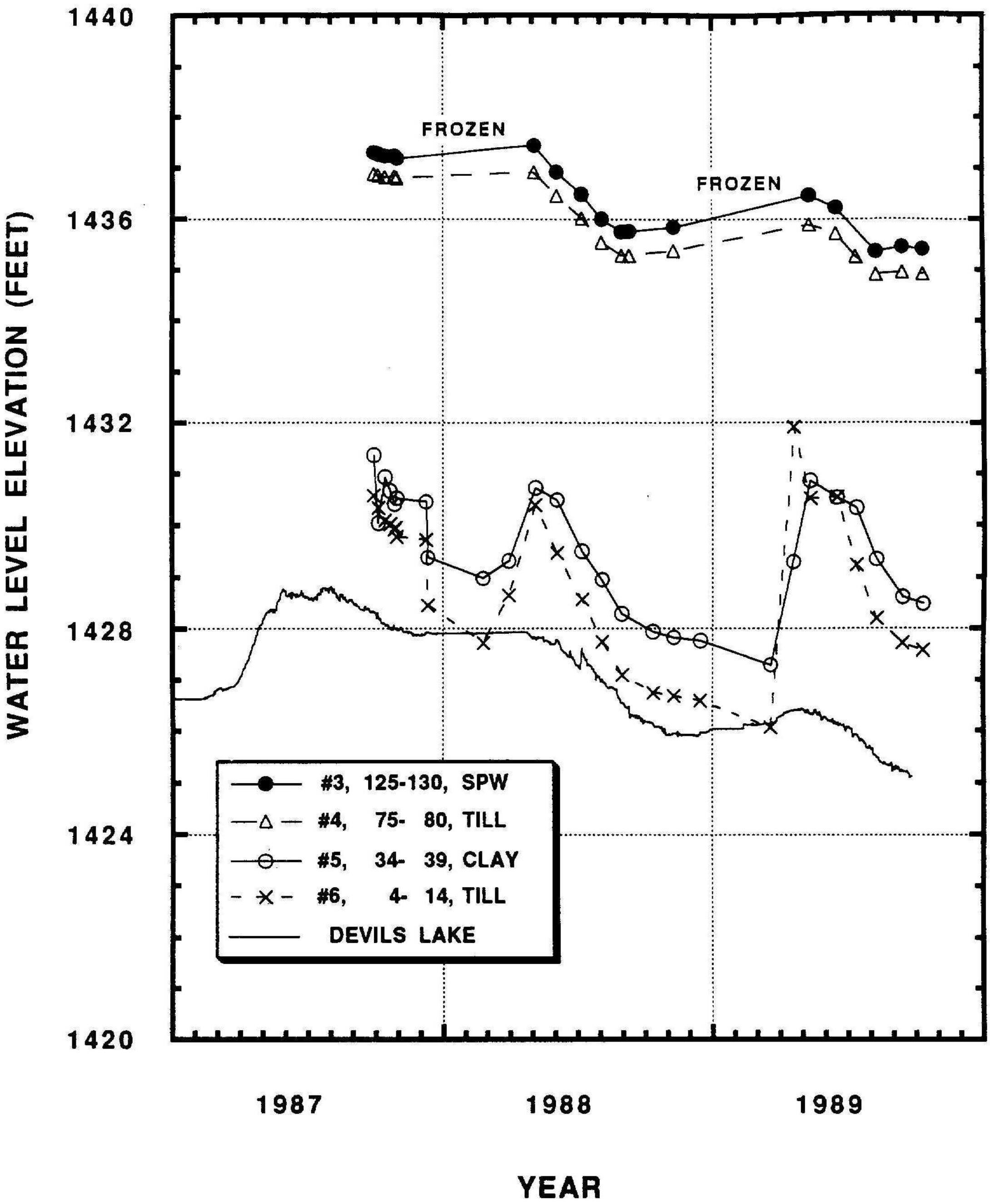


FIGURE 30. WATER LEVELS IN WELLS AT NEST SITE 154-067-35ADD VRS. WATER LEVELS IN DEVILS LAKE

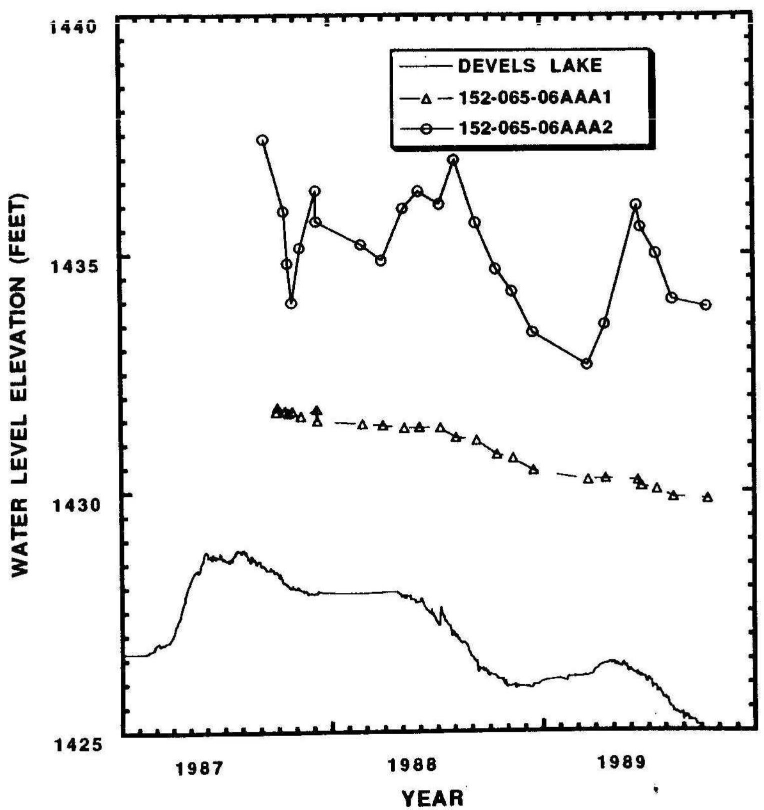


FIGURE 31A WATER LEVELS IN WELLS AT NEST SITE 152-065-06AAA VRS. WATER LEVELS IN DEVILS LAKE

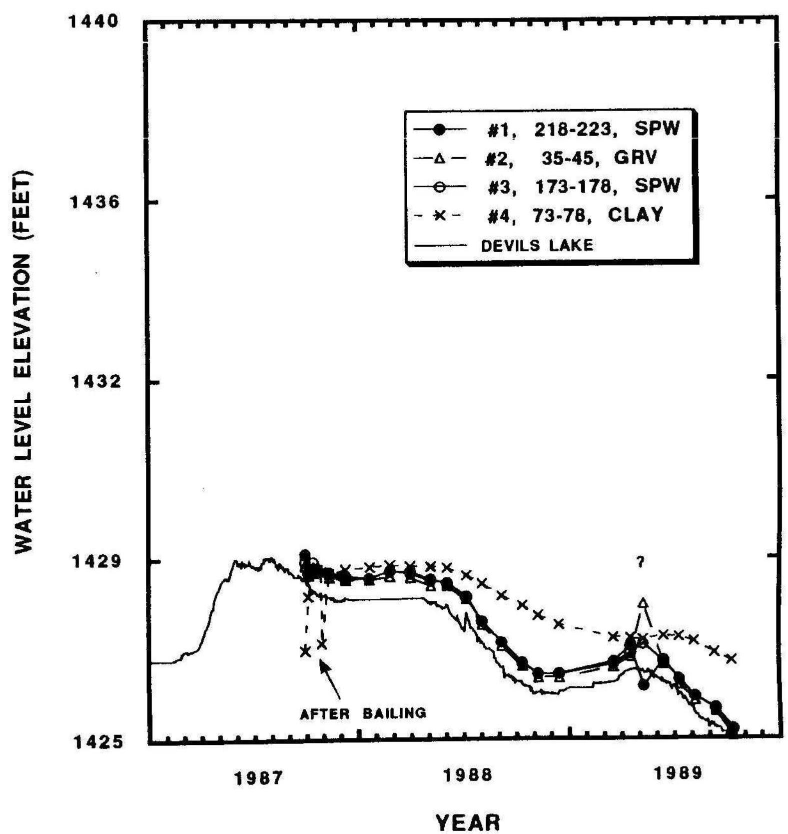


FIGURE 31B. WATER LEVELS IN WELLS AT NEST SITE 154-065-28DAA VRS. WATER LEVELS IN DEVILS LAKE

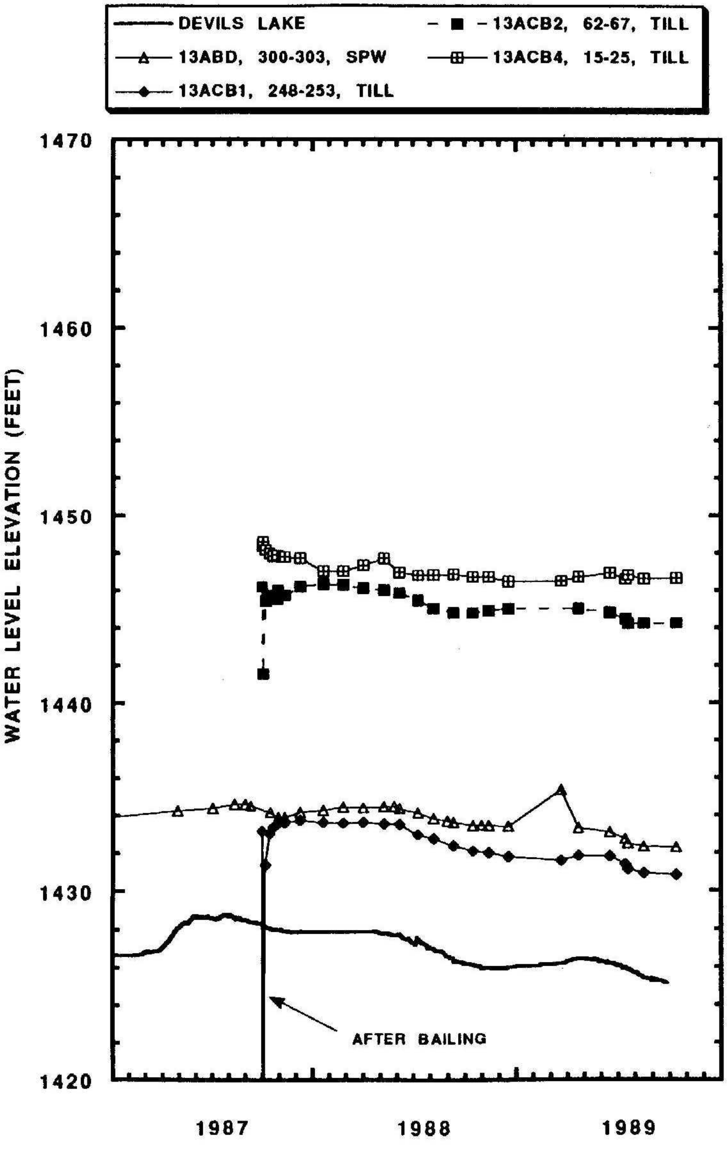


FIGURE 32A . WATER LEVELS IN WELLS AT NEST SITE 152-063-13ACD
VRS. WATER LEVELS IN DEVILS LAKE

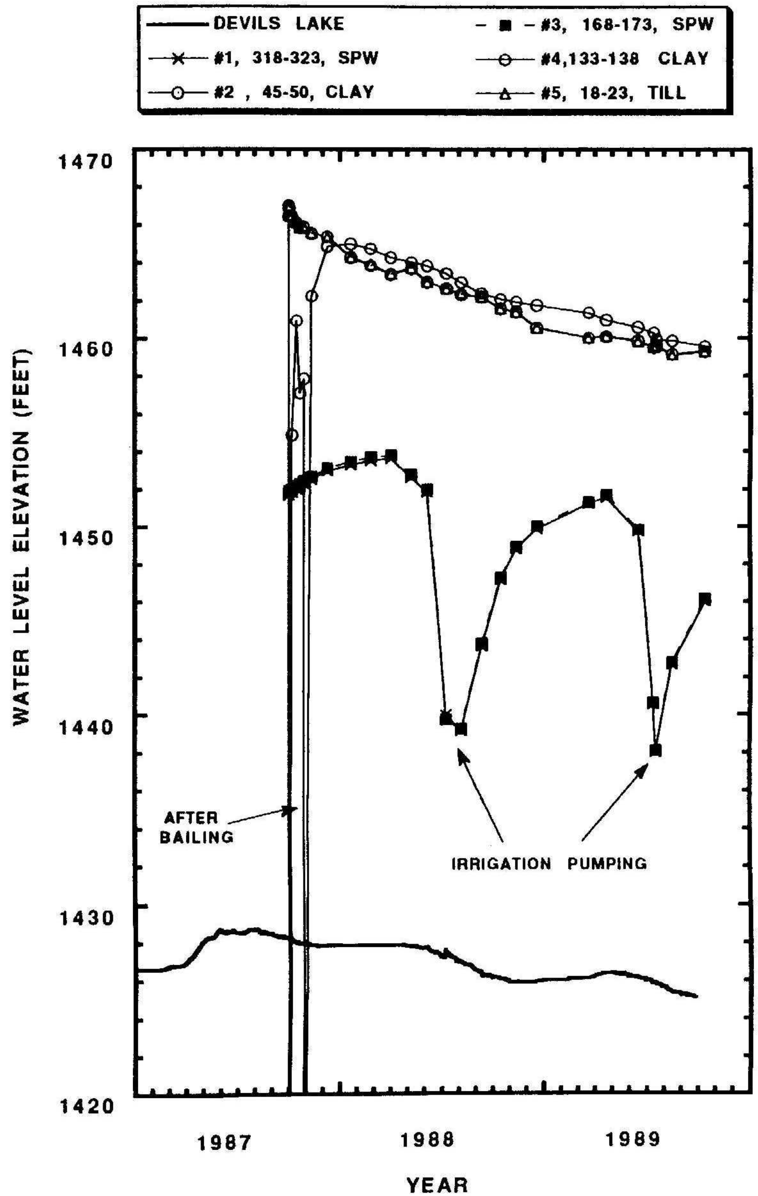


FIGURE 32B. WATER LEVELS IN WELLS AT NEST SITE 152-062-33CDA
VRS WATER LEVELS IN DEVILS LAKE

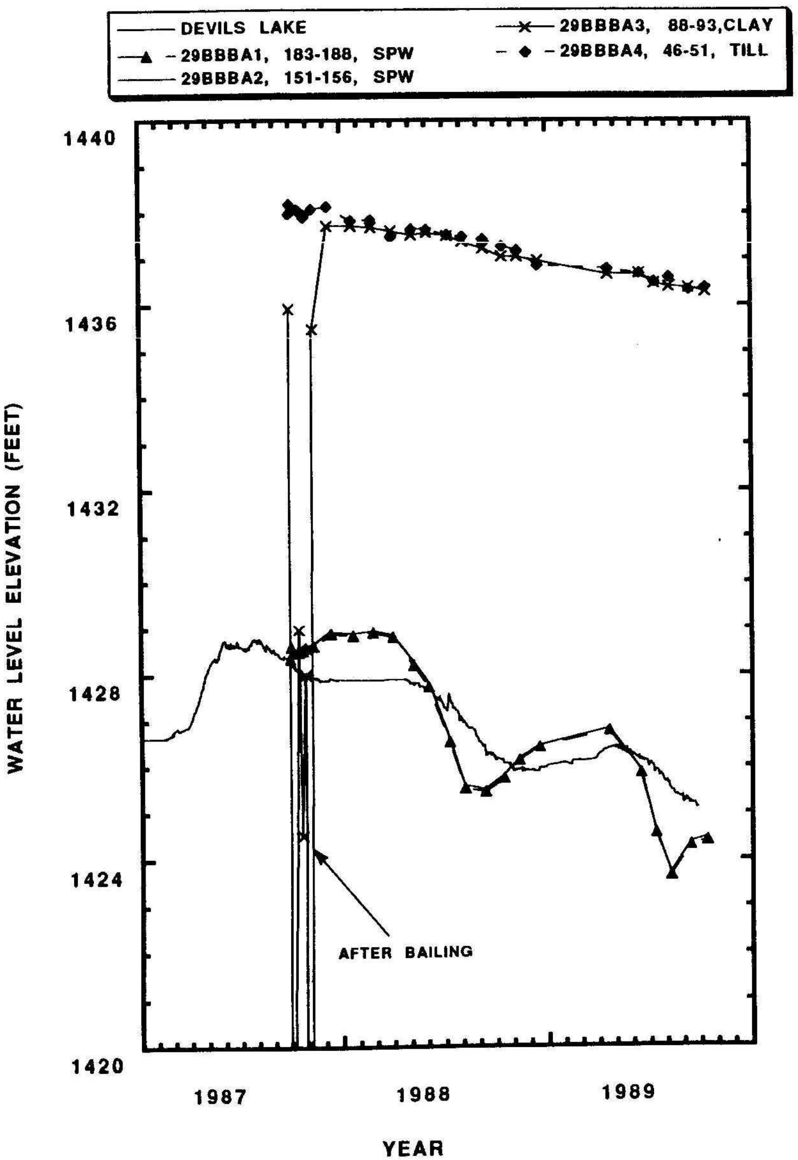


FIGURE 33A. WATER LEVELS IN WELLS AT NEST SITE 153-064-29BBBA VRS WATER LEVELS IN DEVILS LAKE

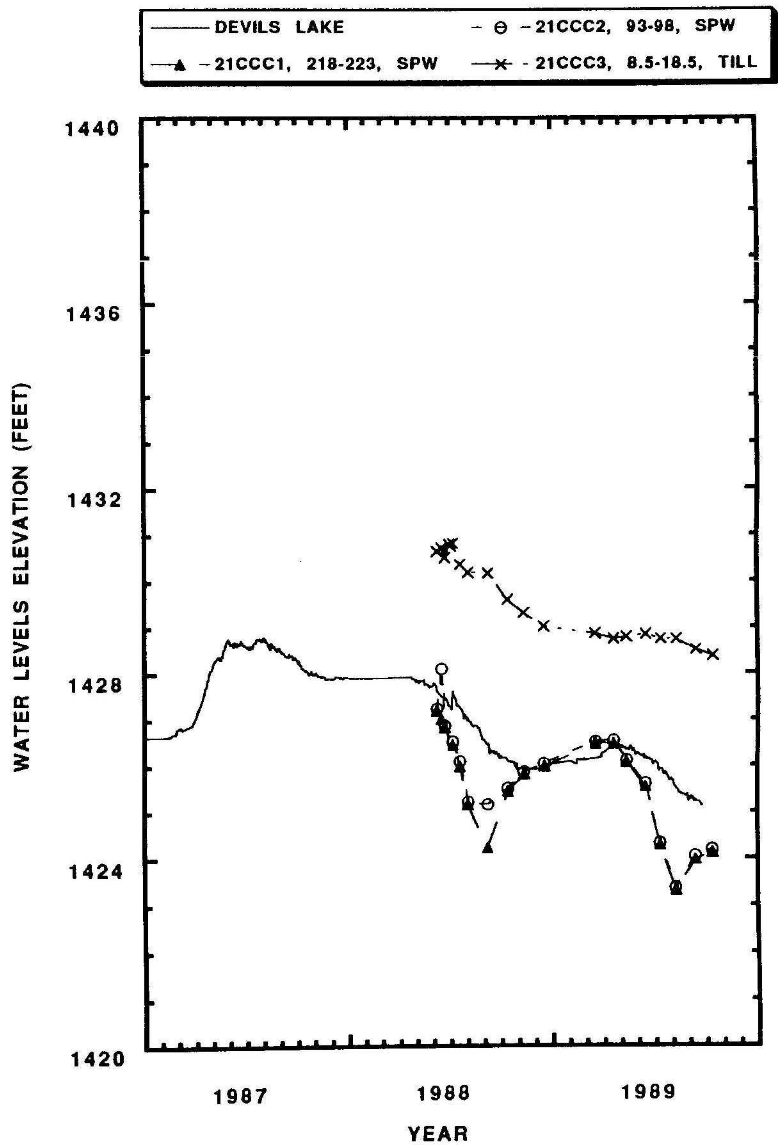


FIGURE 33B. WATER LEVELS IN WELLS AT NEST SITE 153-064-21CCC VRS WATER LEVELS IN DEVILS LAKE

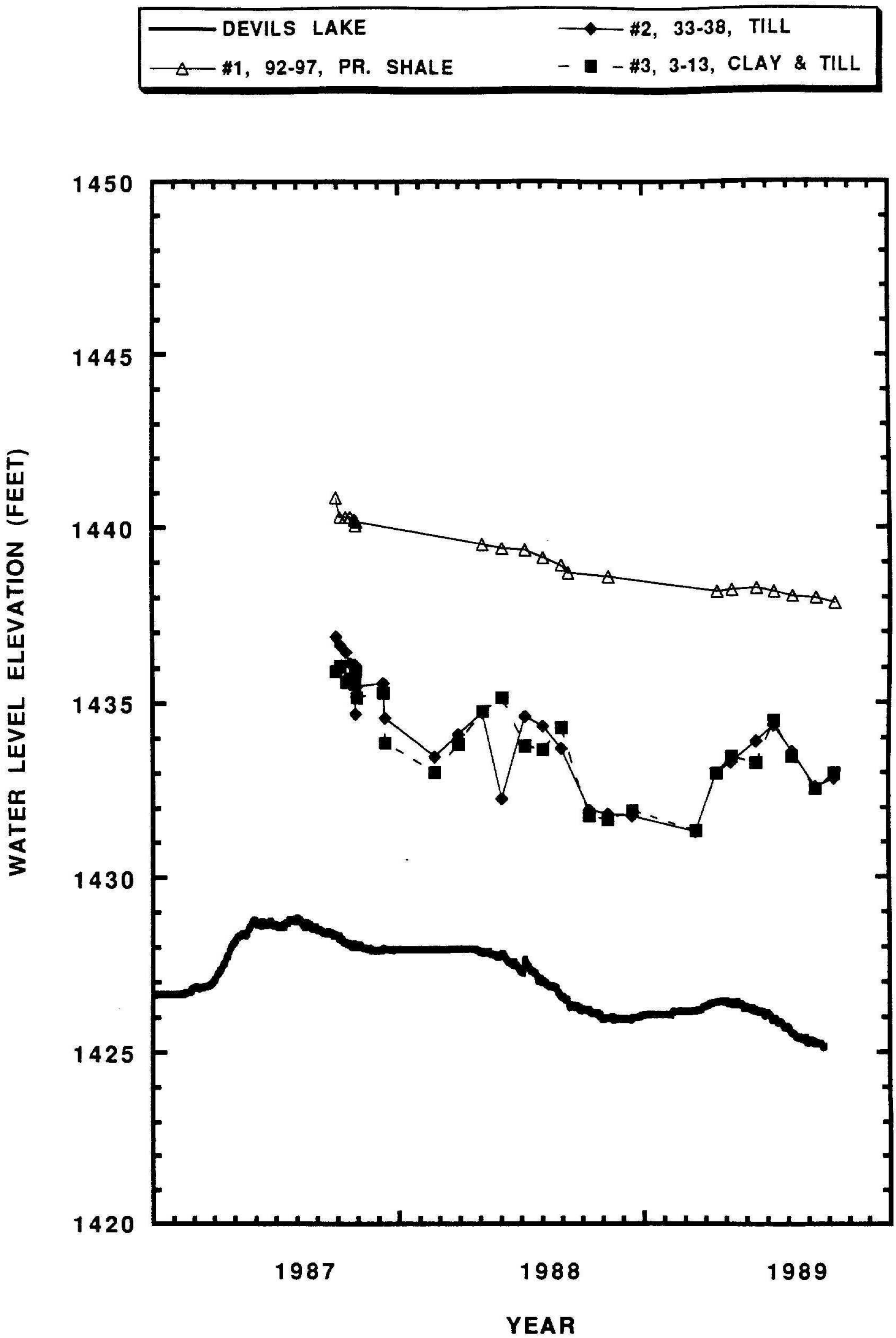


FIGURE 34. WATER LEVELS IN WELLS AT NEST SITE 154-067-12BBC (ALONG BIG COULEE) VRS. WATER LEVELS IN DEVILS LAKE

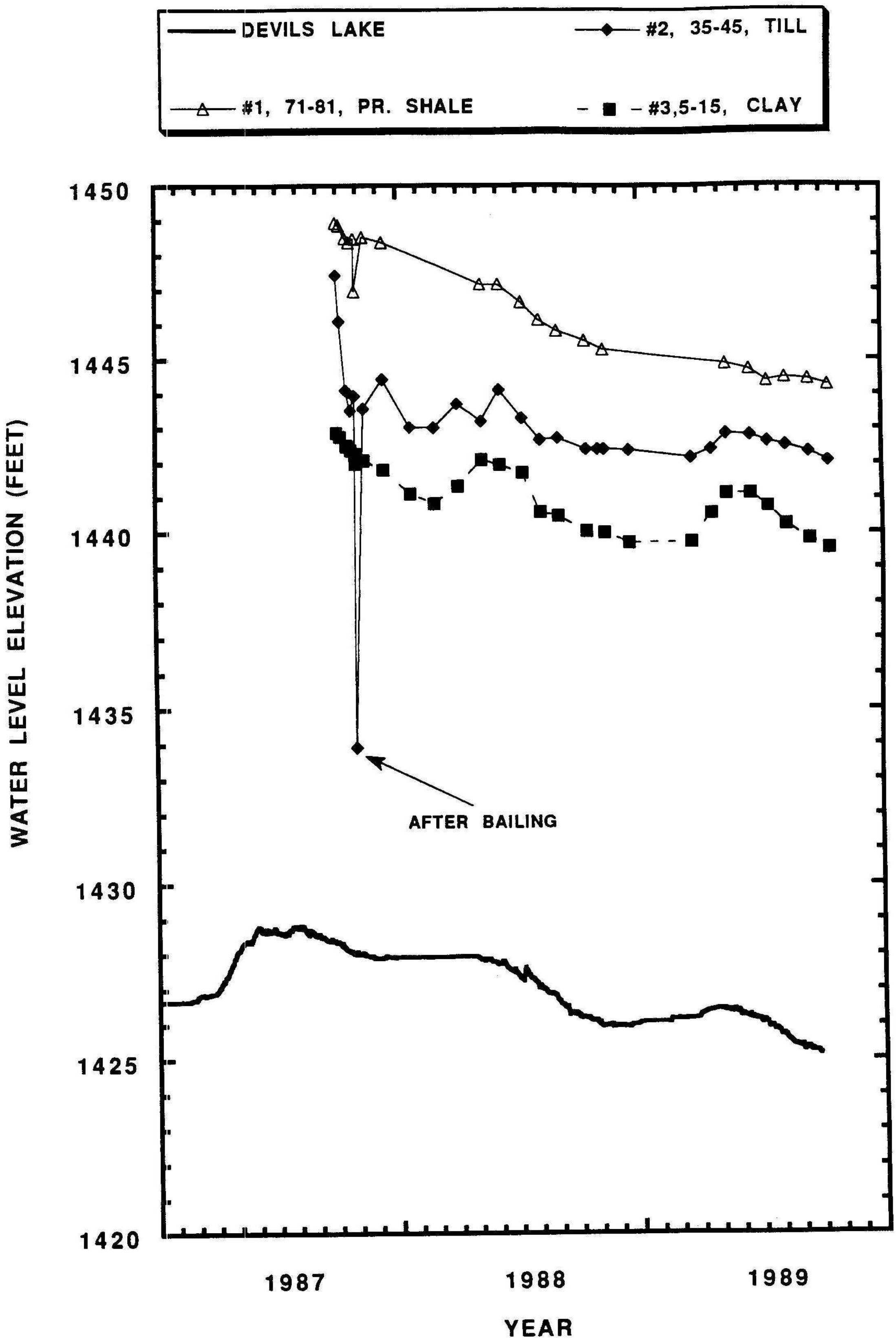


FIGURE 35. WATER LEVELS IN WELLS AT NEST SITE 154-065-11CCD (ALONG CHANNEL A) VRS. WATER LEVELS IN DEVILS LAKE

Other Aquifers

Other major aquifers occurring in the Devils Lake area include the Starkweather, McVille, Tokio, Warwick, and Sheyenne Valley aquifers (fig. 21). Ground-water flow in these aquifers is mainly towards nearby coulees, lakes, or the Sheyenne River Valley (Paulson, 1964 and Randich, 1977). As such, these aquifers interact very little with Devils Lake and were not considered when accessing the impact of ground water on Devils Lake.

GROUND-WATER QUALITY

Introduction

Several factors contribute to the quality of ground water: the type of soil in the recharge area, the soil and rock types the ground water encounters along its flow path, regional topography, length of flow path, velocity of ground-water flow, temperature and pressure. The temporal and spatial distribution of chemical constituents may be used to identify time and place of recharge, place of discharge and residence time within the aquifer (Back and Hanshaw, 1971).

The chemical analyses of ground water in the study area were separated into types with each type having a similar ionic distribution. Each type represents a distinct hydrochemical facies. To differentiate the hydrochemical facies, the major ionic distribution of each chemical analysis was plotted on Piper diagrams. The distribution of the hydrochemical facies was analyzed in relation to location within the flow system, transmissivity, and topography. The overall objective was to utilize water chemistry data to substantiate and/or further define the conceptual model of the ground-water flow system.

Shallow Water Table

Analyses of ground-water samples from wells screened in the shallow water table indicates that the quality of the water varies considerably throughout the study area (fig. 36). In areas with sand and gravel at the surface, such as the Tokio and Warwick aquifers, ground water is generally low in dissolved solids concentrations, and is a calcium-bicarbonate type water. In areas where the shallow water table fluctuates in low permeability clay and till, ground water ranges from a calcium-bicarbonate to a calcium - sodium - sulfate and finally to a magnesium sulfate type (fig. 36). Dissolved solids concentrations range from 400 to 600 mg/l in the shallow sand units to over 26,000 mg/l in the shallow till and lake clay water.

Magnesium-sulfate type ground water dominates in closed land surface depression areas. Closed land surface depression areas represent net discharge areas, where discharge primary is by evapotranspiration. In these areas the concentrating

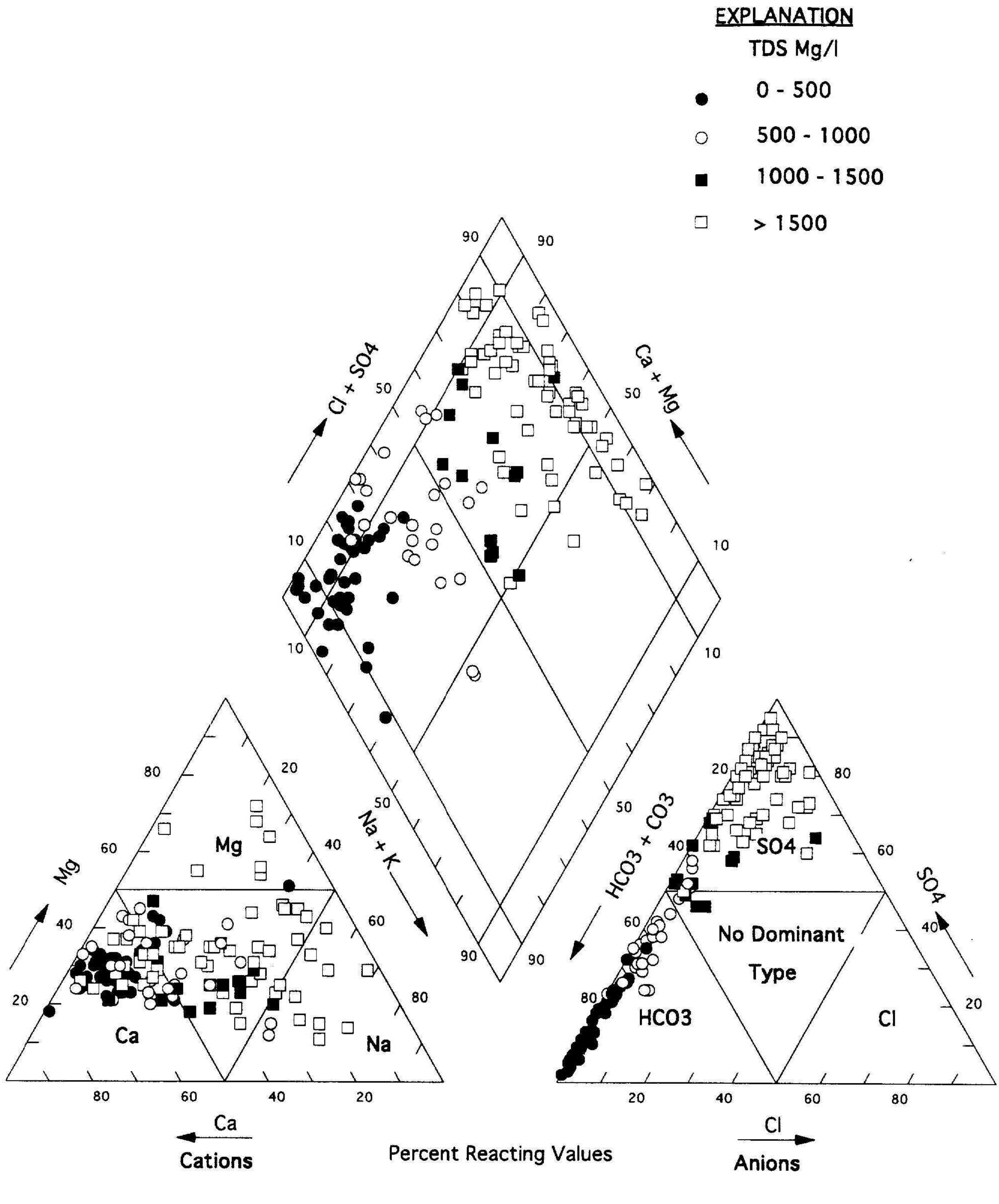


FIGURE 36. PIPER DIAGRAM SHOWING THE CHEMICAL DISTRIBUTION OF GROUND-WATER QUALITY IN THE SHALLOW WATER TABLE, DEVILS LAKE AREA

effects of evaporation, mineral precipitation and dissolution cause these waters to be highly saturated resulting in total dissolved solids concentrations of 10,000 to 20,000 mg/l.

Spiritwood Aquifer System

Analysis of ground-water samples from the Spiritwood aquifer system indicate that the quality of water varies considerably throughout the extent of the buried valley complex (fig. 37). Sodium and calcium are the predominant cations and bicarbonate and sulfate are the predominant anions (fig. 37).

Spiritwood aquifer near Warwick

Water analyzed from the Spiritwood aquifer system near Warwick has the lowest total dissolved solids concentrations of any of the Spiritwood samples (figs. 37 and 38). Ground water from this area of the aquifer system is generally a calcium-bicarbonate type near the central part of the aquifer, while the sodium-bicarbonate type predominates near the valley flanks. Dissolved solids concentrations range from 200 to 1,000 mg/l with the bulk of the samples in the 200 to 600 mg/l range. In general, ground water from the Spiritwood aquifer near Warwick is highest in dissolved solids concentrations near the discharge areas (East Devils Lake and the Sheyenne River). Dissolved solids concentrations are lowest near the central part of the buried valley, and in those areas where the Warwick aquifer overlies the Spiritwood aquifer. It appears that good quality, low total dissolved solids water is moving down from the Warwick aquifer and recharging the Spiritwood aquifer in this area.

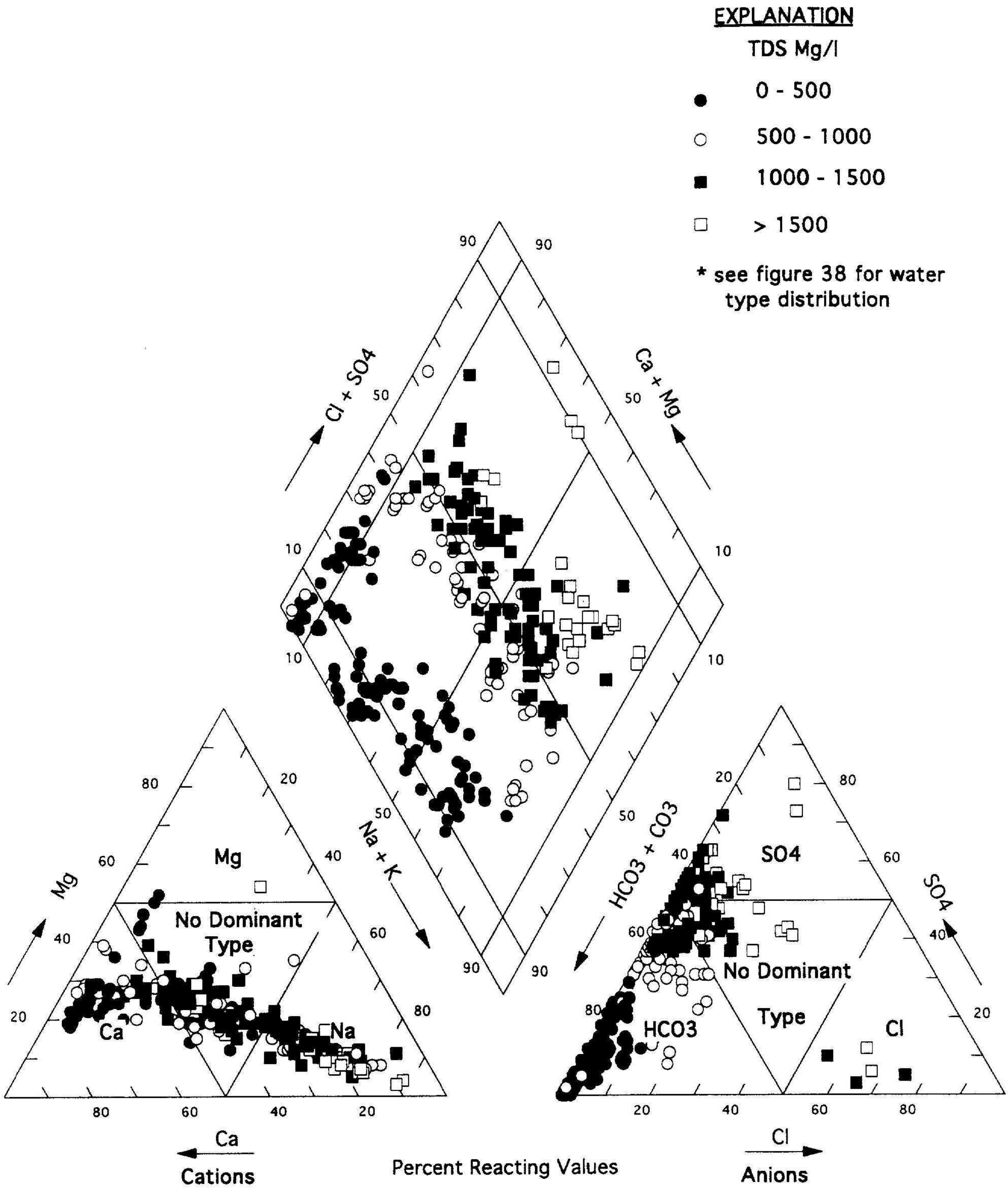


FIGURE 37. PIPER DIAGRAM SHOWING THE CHEMICAL DISTRIBUTION OF GROUND-WATER QUALITY IN THE SPIRITWOOD AQUIFER SYSTEM, DEVILS LAKE AREA

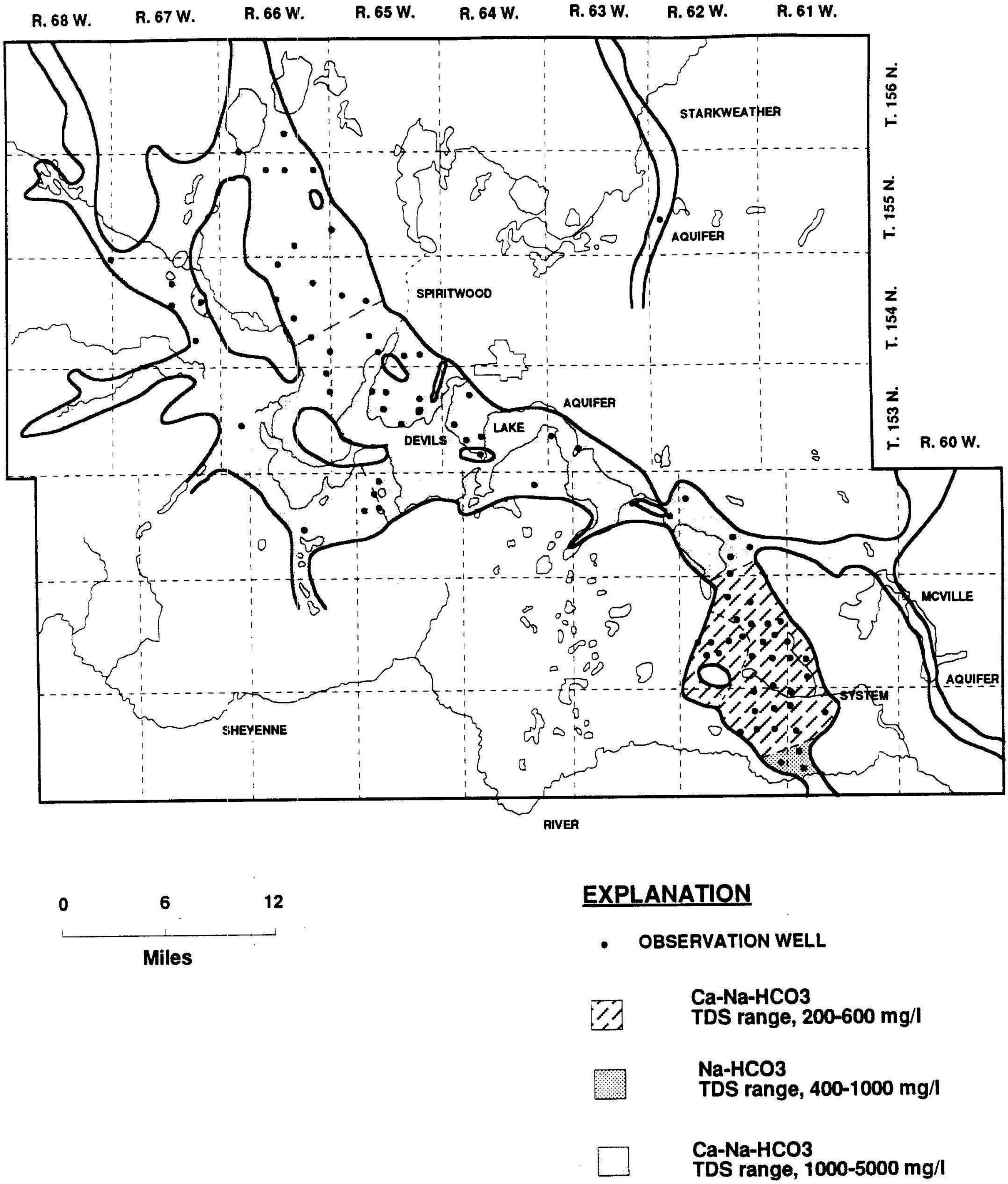


FIGURE 38. GENERALIZED DISTRIBUTION OF MAJOR CHEMICAL FACIES, SPIRITWOOD AQUIFER SYSTEM, DEVILS LAKE AREA

Spiritwood aquifer near the Sheyenne River

Ground-water in the Spiritwood aquifer near the Sheyenne River (discharge area) is very similar to ground water in the Spiritwood aquifer near Warwick except that the total dissolved concentrations are higher (fig. 38). The ground water also tends to be a sodium-bicarbonate type instead of a calcium-bicarbonate indicating that cation exchange from the overlying drift may be an important hydrogeochemical control (fig. 38).

Spiritwood aquifer near Minnewaukan

Water from the Spiritwood aquifer near Minnewaukan is generally a sodium-sulfate type with total dissolved solids concentrations ranging from 760 to 2310 mg/l (fig. 38). Sulfate concentrations ranged from 591 to 906 mg/l. Recommended drinking water limits for sodium, iron, sulfate, and hardness were exceeded in almost all samples analyzed from this portion of the aquifer. The one rare exception to the high total dissolved solids water is ground water in the vicinity of the city of Minnewaukan municipal well (fig. 38 , 154-67-11DDD). In this area, the water is much lower in dissolved solids, ranging from only 381 to 444 mg/l. Sulfate ranges from 71-140 mg/l while sodium is only 11-17 mg/l. Water from this area is a calcium-bicarbonate type rather than the sodium-sulfate type found in the surrounding aquifer.

Spiritwood aquifer near Lake Irvine

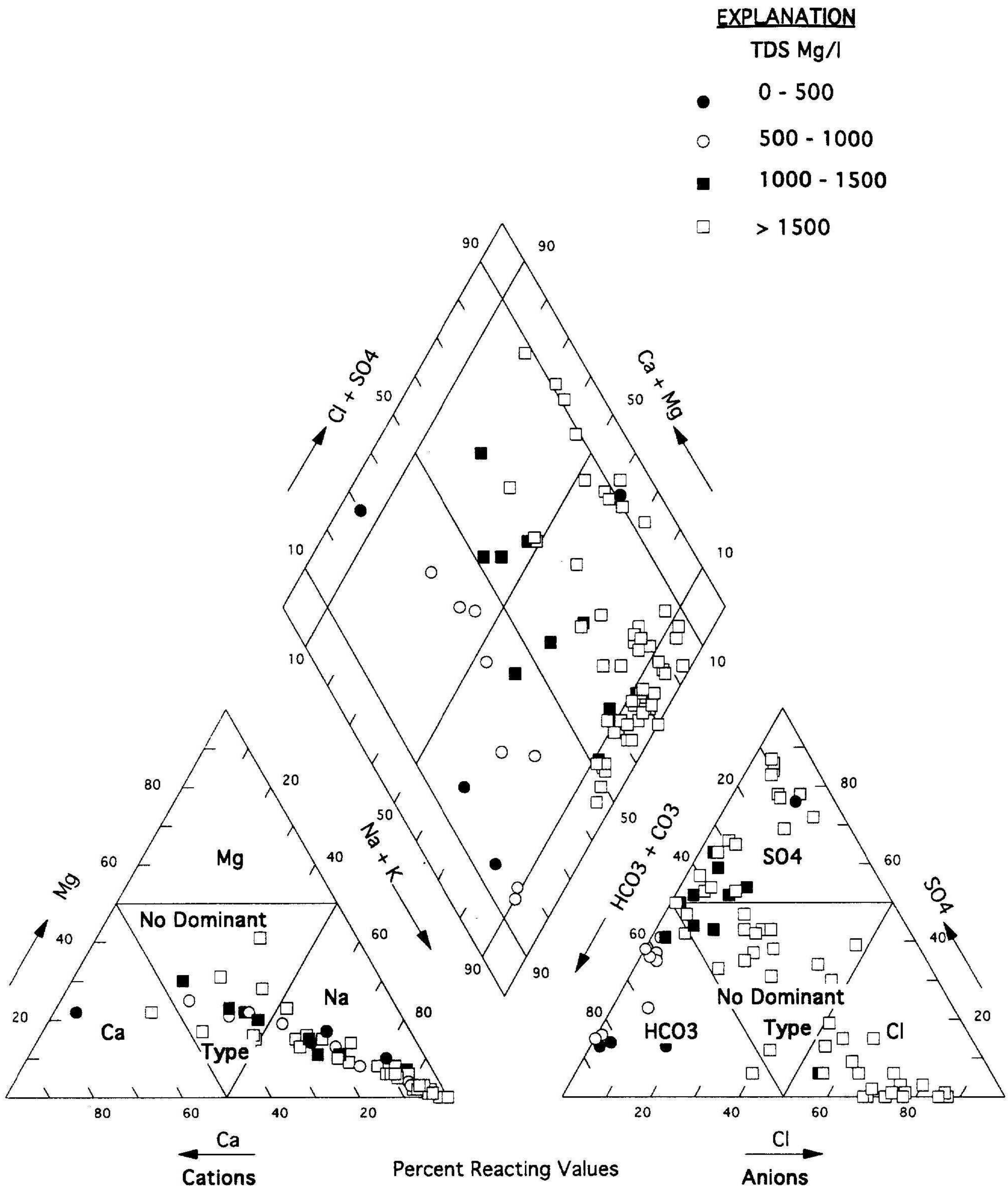
Water from the Spiritwood aquifer near Lake Irvine is predominantly a calcium - sodium - sulfate type with total dissolved solids concentrations ranging from 941 to 2430 mg/l, (figs. 37 and 38). Generally, the dissolved solids concentrations are highest near the discharge areas of Devils Lake and Lake Irvine. Increased flow path length and associated residence time coupled with upward flow from the underlying Pierre Formation probably cause increased dissolved solids in these areas.

Spiritwood aquifer near Devils Lake

Ground water in the Spiritwood aquifer near Devils Lake is generally a calcium-sodium-sulfate type with dissolved solids concentrations ranging from 616 to 5230 mg/l (fig. 38). Water with high total dissolved solids concentrations occurs in this area because Devils Lake is the regional ground water discharge area and as such, flow path length and travel time would tend to concentrate the chemicals in the discharge areas. Again, drinking water standards for sodium, sulfate, iron and hardness were exceeded in most of the samples.

Pierre Formation

Analyses of 23 samples of ground water from the Pierre Formation indicates that the water is predominantly a sodium-sulfate type with high chloride concentrations (fig. 39). Total dissolved solids range from 1090 mg/l to 9260 mg/l. The highest dissolved solids concentrations were generally found in areas where the shallow water table fluctuates within the Pierre Formation (153-64-04ADD 1 and 2). In these areas, concentration and mineral precipitation caused by evaporation appear to be responsible for increased solute concentrations. Inspection of figure 39 reveals that as calcium concentrations decrease, sodium concentrations increase, suggesting that cation exchange is an important hydrogeochemical control.



FIGRURE 39. PIPER DIAGRAM SHOWING THE CHEMICAL DISTRIBUTRION OF GROUND-WATER QUALITY IN THE PIERRE FORMATION, DEVILS LAKE AREA

Vertical Distribution of Ground-Water Quality

The vertical distribution of ground-water quality was determined at 20 nested observation well sites. Because of the unique hydrologic settings at the various sites, the vertical distribution of water quality will be discussed on an area by area basis.

Near Devils Lake, topographic low area

Ground-water quality in these areas varies from a calcium - sodium - sulfate to a sodium sulfate throughout the profile (fig. 40). Generally, solute concentrations increase in the direction of flow, or from bottom to top. Near Devils Lake, dissolved solids concentrations range from 1,570 mg/l in the Spiritwood aquifer to 10,600 mg/l in the shallow water table. Sulfate concentrations increase from 640 mg/l in the underlying Spiritwood aquifer to 6,900 mg/l in the shallow water table. The large increase in magnesium, from 26 to 630 mg/l probably reflects the concentrating effect by evapotranspiration within the shallow water table.

Near Devils Lake, topographic high area

Ground-water quality in these areas ranges from a sodium - bicarbonate - sulfate type in the underlying Spiritwood aquifer to a calcium-sulfate in the shallow water table (fig. 41). Generally, solute concentrations are highest in the shallow water table and decrease with depth, until the Spiritwood aquifer is encountered. In the Spiritwood aquifer, solute concentrations increase slightly with depth (fig. 41). Sulfate concentrations range from 460 mg/l in the Spiritwood aquifer to over 2,000 mg/l in the shallow water table. Significantly lower dissolved solids concentrations in the Spiritwood aquifer versus the overlying till and clay, suggests that in this area the movement of water downward from the till into the Spiritwood aquifer is very slow.

Southeast of East Devils Lake

Water level data from this area indicates that potential for ground-water flow is through clay and downward into the Spiritwood aquifer. Flow in the Spiritwood aquifer is slightly downward but predominantly lateral towards East Devils Lake. Ground-water samples analyzed from the observation well nest at 152-062-33CDA

Well#	6	5	4	3
Screened Interval(ft)	4-15	34-39	75-80	125-130
Geology	till	lake clay	Spiritwood	Spiritwood
TDS (mg/l)	10,600	5470	1570	1670
Na(mg/l)	1900	920	320	420
Ca(mg/l)	410	620	150	97
Cl(mg/l)	400	960	100	100
SO4(mg/l)	6900	2600	640	690
Mg (mg/l)	630	160	36	26

EXPLANATION

TDS Mg/l

- ● 0 - 500
- ○ 500 - 1000
- ■ 1000 - 1500
- □ > 1500

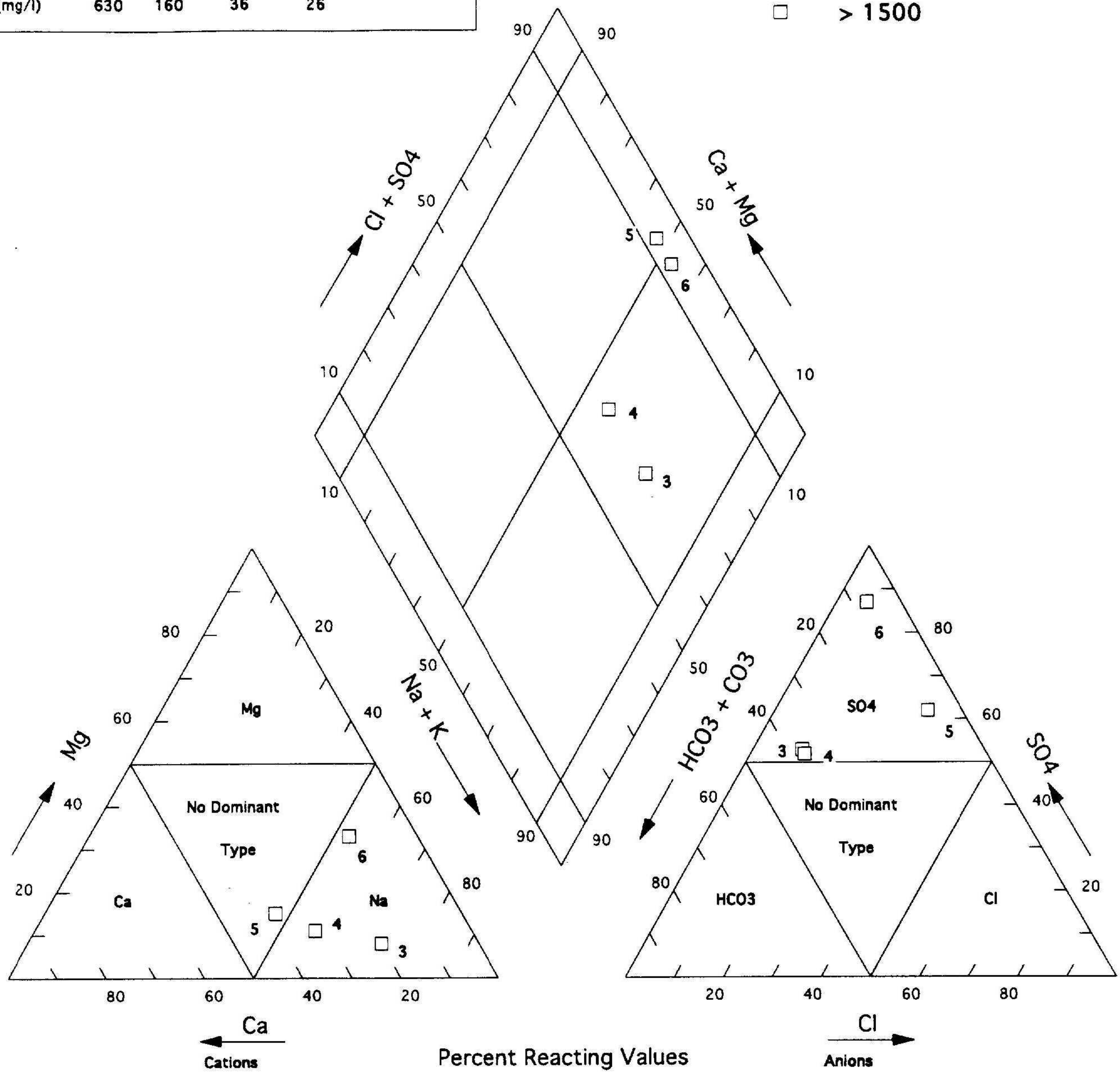


FIGURE 40. PIPER DIAGRAM SHOWING THE VERTICAL DISTRIBUTION OF GROUND-WATER QUALITY NEAR DEVILS LAKE, TOPOGRAPHIC LOW AREA (154-067-35ADD)

EXPLANATION

TDS Mg/l

● 0 - 500

○ 500 - 1000

■ 1000 - 1500

□ > 1500

Well #	4	3	2	1
Screened Interval(ft)	46-51	88-93	151-156	183-188
Geology	till	lake clay	Spiritwood	Spiritwood
TDS (mg/l)	3680	2320	1350	1550
Na (mg/l)	200	270	200	380
Ca (mg/l)	590	330	160	100
Cl (mg/l)	250	130	98	230
SO4 (mg/l)	2000	1100	500	460
Mg (mg/l)	240	110	56	38

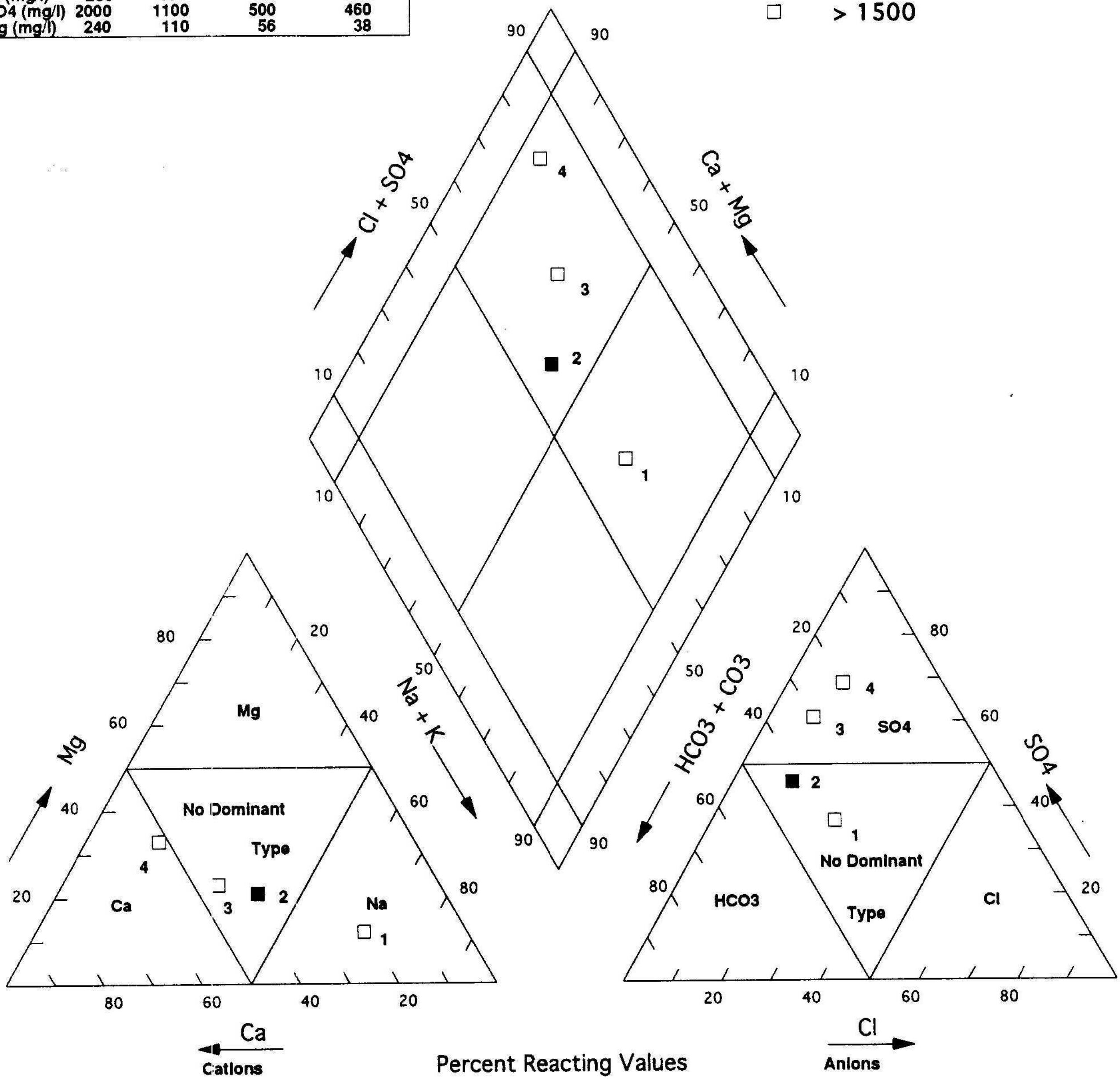


FIGURE 41. PIPER DIAGRAM SHOWING THE VERTICAL DISTRIBUTION OF GROUND-WATER QUALITY NEAR DEVILS LAKE, TOPOGRAPHIC HIGH AREA (153-064-29BBBA)

indicate that the water varies from a calcium-sulfate type water in the overlying till to a sodium-bicarbonate type in the Spiritwood aquifer (fig. 42). In general, solute concentrations decrease with depth, until the Spiritwood aquifer is encountered, then concentrations increase with depth. Sulfate, calcium and magnesium concentrations are largest in the shallow water table, again reflecting the concentrating effects of evapotranspiration. It appears that the low permeability till and lake clay above the Spiritwood aquifer restricts the downward movement of ground water.

Along Big Coulee

In areas of upward ground-water flow along Big Coulee, ground-water chemistry varies from a sodium-bicarbonate or sodium-chloride in the Pierre Formation to a sodium-sulfate in the shallow water table (fig. 43). At both observation well sites, most solute concentrations increase upward in the profile. Dissolved solids concentrations range from 1,090 to 1,460 mg/l at 154-066-34ADD and 1,490 to 4,160 mg/l at 154-067-12BBC. Again, the solute concentration appears to be occurring at the shallow water table. The fact that the high chloride concentrations in the Pierre Formation water did not migrate into the overlying till suggest that the upward ground-water flow rate is restricted.

Along Channel A

Along Channel A, ground-water flow is upward to replace a portion of the water being discharged by evapotranspiration and base flow to Channel A. In this area, ground-water chemistry varies from a sodium-sulfate type in the underlying Pierre Formation to a calcium-sulfate type at the surface (fig. 44). Generally, solute concentrations increase upward in the profile. Dissolved solids concentrations range from 1,860 mg/l in the Pierre Formation to a very high 20,800 mg/l in the shallow water table. Sodium levels increase from 660 mg/l in the Pierre to 4,000 mg/l in the shallow water table. Elevated concentrations of magnesium, sodium and sulfate in the shallow water table system indicates that concentration by evapotranspiration is an important hydrogeochemical control.

Well #	5	2	4	3	1
Screened Interval(ft)	18-23	45-50	133-138	168-173	318-323
Geology	Till	Lake Clay	Lake Clay	Spiritwood	Spiritwood
TDS (mg/l)	3460	2450	1130	327	855
Na (mg/l)	88	28	130	29	180
Ca (mg/l)	530	540	150	52	73
Cl (mg/l)	73	310	19	.9	8.9
SO4 (mg/l)	2200	1100	420	35	270
Mg (mg/l)	280	140	67	20	29

EXPLANATION

TDS Mg/l

- ● 0 - 500
- ○ 500 - 1000
- ■ 1000 - 1500
- □ > 1500

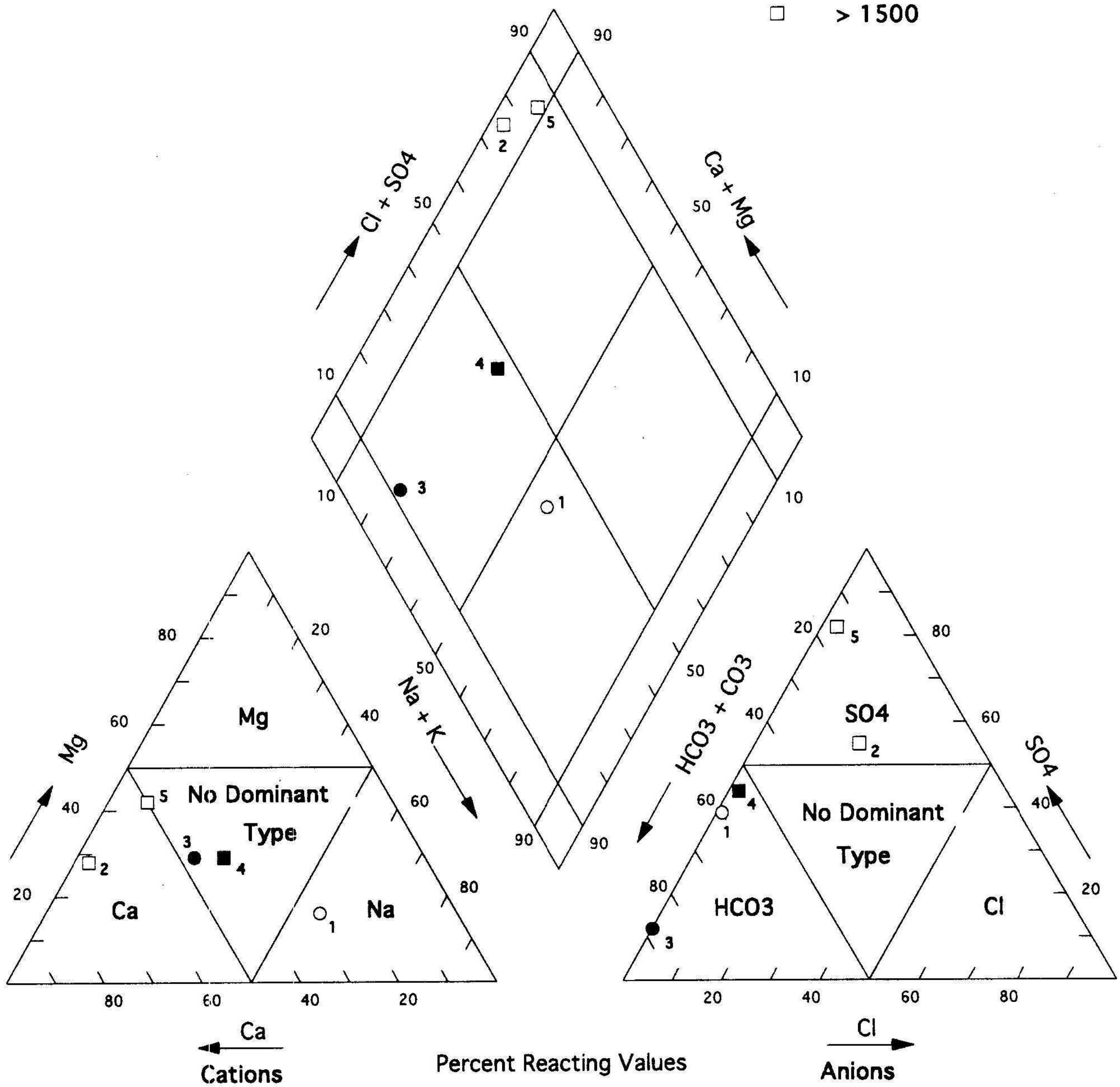


FIGURE 42. PIPER DIAGRAM SHOWING THE VERTICAL DISTRIBUTION OF GROUND-WATER QUALITY SOUTH EAST OF EAST DEVILS LAKE (152-062-33CDA)

Well #	3	2	1
Screened Interval(ft)	3-13	33-38	92-97
Geology	TIII	TIII	Pierre Shale
TDS (mg/l)	4160	1490	1490
Na (mg/l)	460	390	540
Ca (mg/l)	430	77	20
Cl (mg/l)	470	110	500
SO4 (mg/l)	2300	680	79
Mg (mg/l)	290	31	25

EXPLANATION

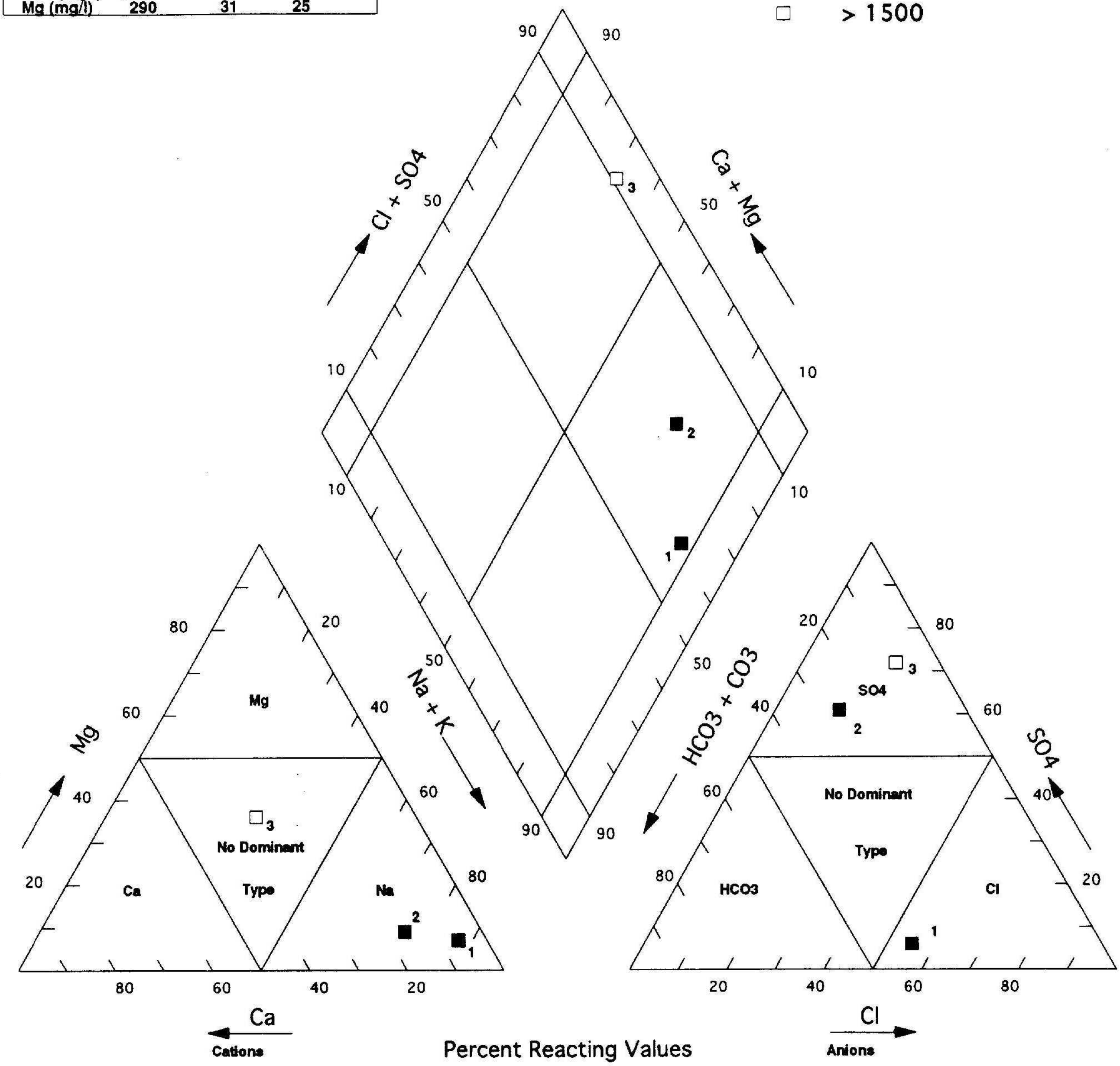
TDS Mg/l

● 0 - 500

○ 500 - 1000

■ 1000 - 1500

□ > 1500



FIGRUE 43. PIPER DIAGRAM SHOWING THE VERTICAL DISTRIBUTION OF GROUND-WATER QUALITY ALONG BIG COULEE (154-067-12BBC)

Well #	3	2	1
Screened Interval(ft)	5-15	35-45	70.5-80.5
Geology	Lake Clay	Till	Pierre Shale
TDS (mg/l)	20,800	2210	1860
Na (mg/l)	4000	600	660
Ca (mg/l)	380	140	22
Cl (mg/l)	410	660	470
SO4 (mg/l)	14,000	490	200
Mg (mg/l)	1600	38	9

EXPLANATION

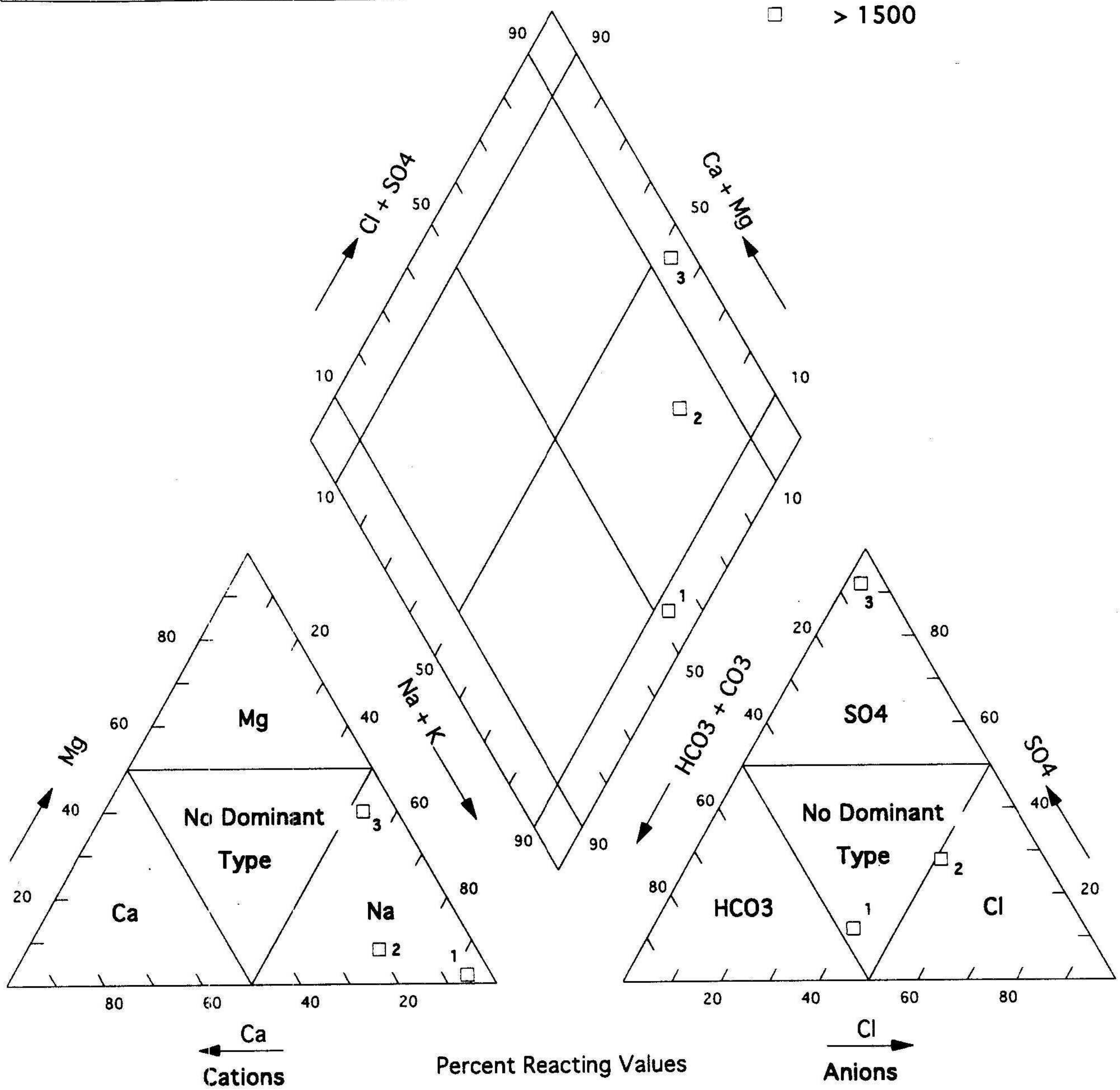
TDS Mg/l

● 0 - 500

○ 500 - 1000

■ 1000 - 1500

□ > 1500



FIGRUE 44. PIPER DIAGRAM SHOWING THE VERTICAL DISTRIBUTION OF GROUND-WATER QUALITY ALONG CHANNEL A (154-065-11CDD)

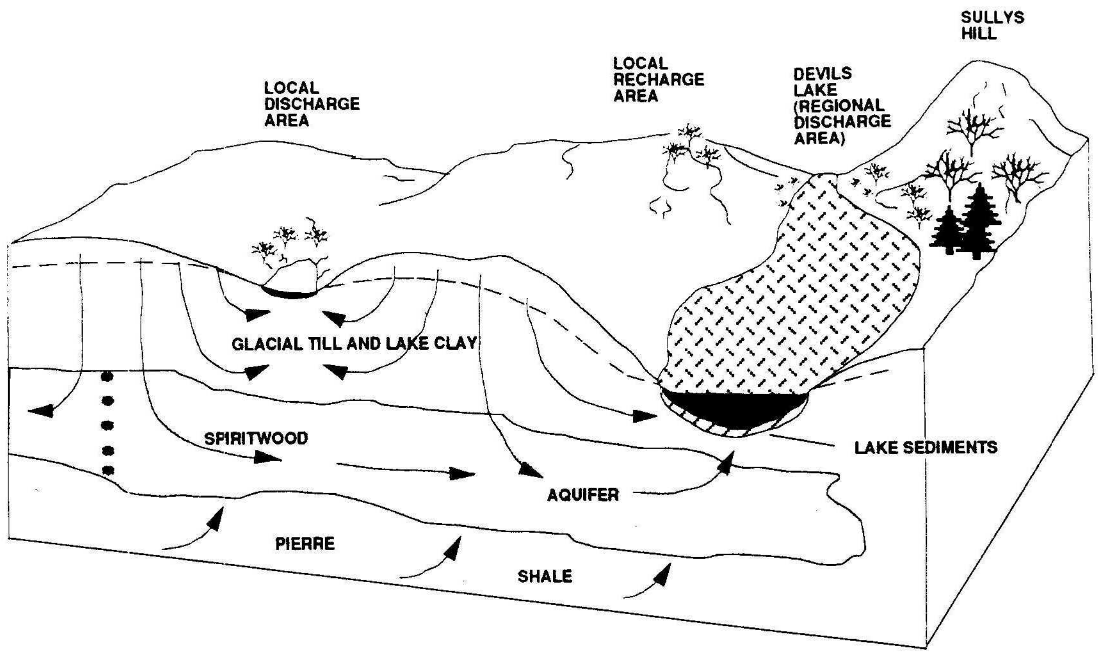
CONCEPTUAL MODEL OF GROUND-WATER FLOW

Devils Lake occupies the low points of a large inland basin. At present elevations, the lake has no outlet and evapotranspiration is the only discharge mechanism. Available data indicates that ground water in the area generally moves towards Devils Lake from all directions to replace a small portion of the water being removed from the lake by evaporation. Thus, Devils Lake can be classified as a regional ground-water discharge area (figs. 45 and 46).

An examination of the available hydrologic data however reveals that ground water moves and responds in a complex and transient fashion. In the shallow water table, ground-water levels fluctuate mainly up and down in response to precipitation and evapotranspiration (fig. 45). Some of the water in the shallow water table also moves very slowly towards the small (potholes) and large (Devils Lake) depressions throughout the basin (figs. 45 and 46).

In areas where the Spiritwood aquifer occurs, ground water that is able to escape the effects of evapotranspiration from the soil horizon moves very slowly downward through the glacial till and lake clays and into the Spiritwood aquifer (figs. 45 and 46). Ground water then moves slowly along the Spiritwood aquifer towards Devils Lake. Near Devils Lake, ground-water moves slowly upward in the Spiritwood aquifer through glacial till and lake clays and finally into Devils Lake (figs. 45 and 46). Water then leaves the system via evaporation and transpiration from the lake surface. During years of high runoff, when the level of Devils Lake rises, in effect, the level of the regional discharge area rises. Ground-water levels in the Spiritwood aquifer near Devils Lake rise in response to a combination of a higher discharge area elevation and loading effects. Conversely, when the lake recedes, ground-water levels decline in response to a combination of a lower discharge area elevation and unloading effects. In as much as the level of the discharge area (Devils Lake) is controlled by climate, so to ground-water levels in the Spiritwood aquifer near Devils Lake are controlled ultimately by climate.

Sediments immediately surrounding Devils Lake exhibit a very low hydraulic conductivity, restricting ground-water flow towards the lake. Thus, even though Devils Lake is the regional ground-water discharge area, ground-water flow to the lake appears



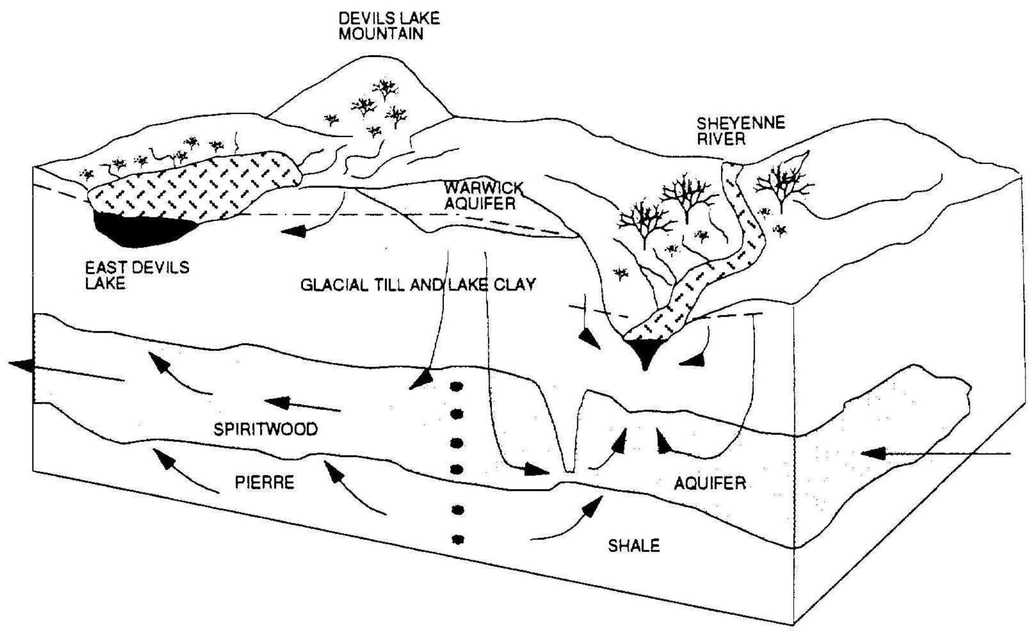
EXPLANATION

— — — — — WATER LEVEL, SPIRITWOOD AQUIFER SYSTEM

———► DIRECTION OF GROUND-WATER FLOW

⋮ GROUND-WATER DIVIDE, SPIRITWOOD AQUIFER SYSTEM

FIGURE 45. SCHEMATIC OF GROUND-WATER FLOW IN THE DEVILS LAKE AREA, FROM LAKE IRVINE TO DEVILS LAKE



EXPLANATION

WATER LEVEL, SPIRITWOOD AQUIFER SYSTEM

DIRECTION OF GROUND-WATER FLOW

GROUND-WATER DIVIDE, SPIRITWOOD AQUIFER SYSTEM

FIGURE 46. SCHEMATIC OF GROUND-WATER FLOW IN THE DEVILS LAKE AREA, FROM EAST DEVILS LAKE TO THE SHEYENNE RIVER

too be small. If the ground-water flow component were larger, the lake level would not decline so much in the summer and would recover substantially during the fall and winter.

Why then, if the ground-water component of the Devils Lake water budget appears to be so small, have scientists disagreed widely on its influence? The answer lies in the context of the time period in which the lake has been studied. From the late 1800's to 1940, Devils Lake was declining and no stream flows were observed to enter the lake. It is logical, and rightly so, that scientists such as Simpson (1912 and 1929) stated that ground water was the major input to the system. Later scientists observed major runoff events, such as 1950, and stated that stream flow was the major input. Thus, during very dry cycles, ground water is the major input to the system. However, the ground-water component alone is not large enough to keep up with evapotranspiration loses and the lake level recedes. During wet cycles or extreme precipitation events, stream flow and direct precipitation on the lake surface are the major components, with ground water still contributing, but in a relative sense at a much smaller rate than runoff and direct precipitation. In conclusion, climate (precipitation, runoff, and evaporation) dominates the level of Devils Lake with ground water having minor lagged dampening effects on lake levels (less than one-half foot).

GROUND-WATER FLOW TO DEVILS LAKE

Data collected and analyzed from the basin indicates that, under natural conditions, ground water moves slowly towards Devils Lake to replace a small portion of the water being removed from the lake by evaporation. Following are estimates of the amount of ground water contributing to the Devils Lake water budget.

Residual estimated from water budget

The water budget for Devils Lake as estimated by Wiche (1992), for the years 1986 through 1988 was as follows:

TABLE 1
DEVILS LAKE WATER BUDGET
1986-1988

YEAR	INFLOW	STORAGE CHANGE	PRECIP.	EVAP.	GROUND WATER NEEDED TO BALANCE BUDGET
1986	46,900 (34,500)	23,500	102,100	133,500	**20,400**
1987	166,600 (112,200)	69,100	77,900	183,400	**62,000**
1988	12,200 (2,180)	101,600	59,400	181,200	**18,020**

The residual needed from ground water to balance the water budget of Devils Lake was 20,400, 62,000 and 18,020 acre-feet respectively (table 1).

Base flow estimated from lake levels

Devils Lake can be compared to a large diameter, partially penetrating well. When the well (Devils Lake) is pumped (evaporation) water levels in the well (Devils Lake) will decline until the amount of water being pumped (evaporation) equals the amount of ground water moving towards the well (Devils Lake). If the amount of water being pumped (evaporation) exceeds the amount of ground water moving towards the well (Devils Lake), water levels will decline until the effects of evaporation are over or a new equilibrium is reached. When the effects of pumping are over, ground water moving towards the cone of depression, should cause the lake level to recover. The rate of recovery will depend on the rate of ground-water movement towards the well (lake). If the ground-water component is large, the lake level should recover (rise) substantially throughout the fall and winter months. If the ground-water component is small, the lake level should remain flat or recover ever so slightly. If the lake, following the pumping period (evaporation), loses water via the ground-water system, the lake level would continue to decline. If the lake level rises, or declines, an estimate of the volume of ground water moving into or out of the lake can be made by using the stage capacity curve for the lake. This procedure assumes, however, that: 1) no precipitation falls on the lake during the time periods in question, 2) no runoff into the lake occurs during the time period in question, 3) all ground-water flow is towards the lake, 4) the stage capacity curves are accurate, and the extrapolation between volume estimates is valid and 5) measurement of the lake level to the nearest .001 foot (especially during the winter months after freeze up) is not only possible but also accurate.

Presented in figure 47 is a plot of the volume of Devils Lake for the period, 1940-1989. Fall and winter recordings of the level of Devils Lake were not obtained prior to 1943, therefore, it is impossible to determine the effect that ground water may have had on Devils Lake for this time period. A hydrograph of the 1984 through 1989 water levels is presented in figure 48. Note that in most instances, the volume of Devils Lake gradually increases during the fall and winter months. Based on the available record, the volume increase for the fall through winter months ranges from 0 to 10,000 acre-feet, with an average of 4,500 acre-feet. This suggests that ground water is indeed moving towards the lake to fill in the "cone of depression." The impact of ground water on lake volume, however, appears to be very minor (less than 1/2 foot) when compared to the amount needed to overcome the yearly effects of evaporation.

The decline in lake volume during a few of the fall and winter periods indicates that the conceptual model of ground-water flow does not always hold (fig. 47). The decreases, as was the case with the increases, appear minor compared to the water needs of the lake.

It is impossible to determine the relationship between Devils Lake and ground water for the spring and summer months using the lake stage data because direct precipitation, runoff and evaporation dominate the system.

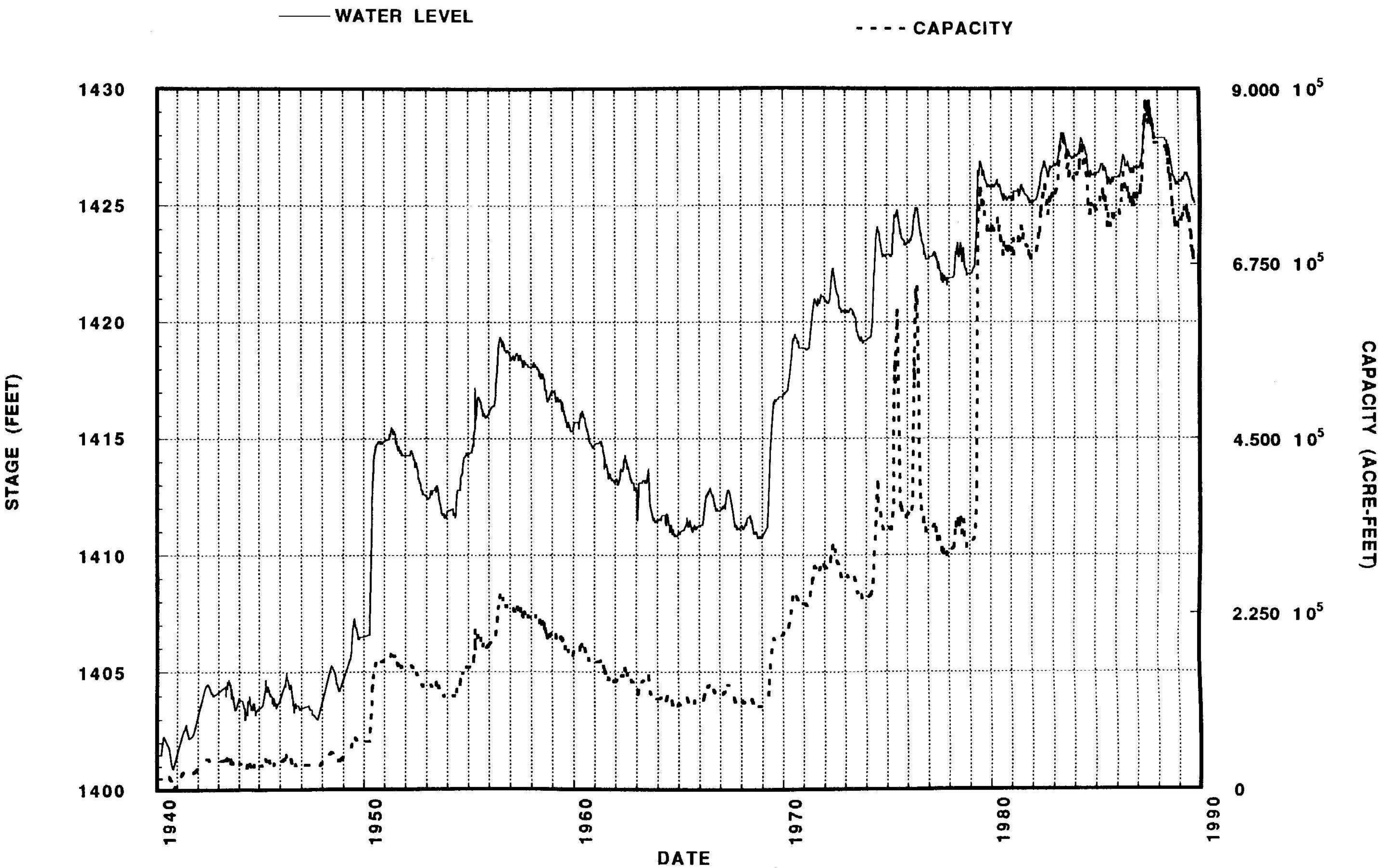


FIGURE 47. STAGE CAPACITY RELATIONSHIP, DEVILS LAKE, 1940-1989

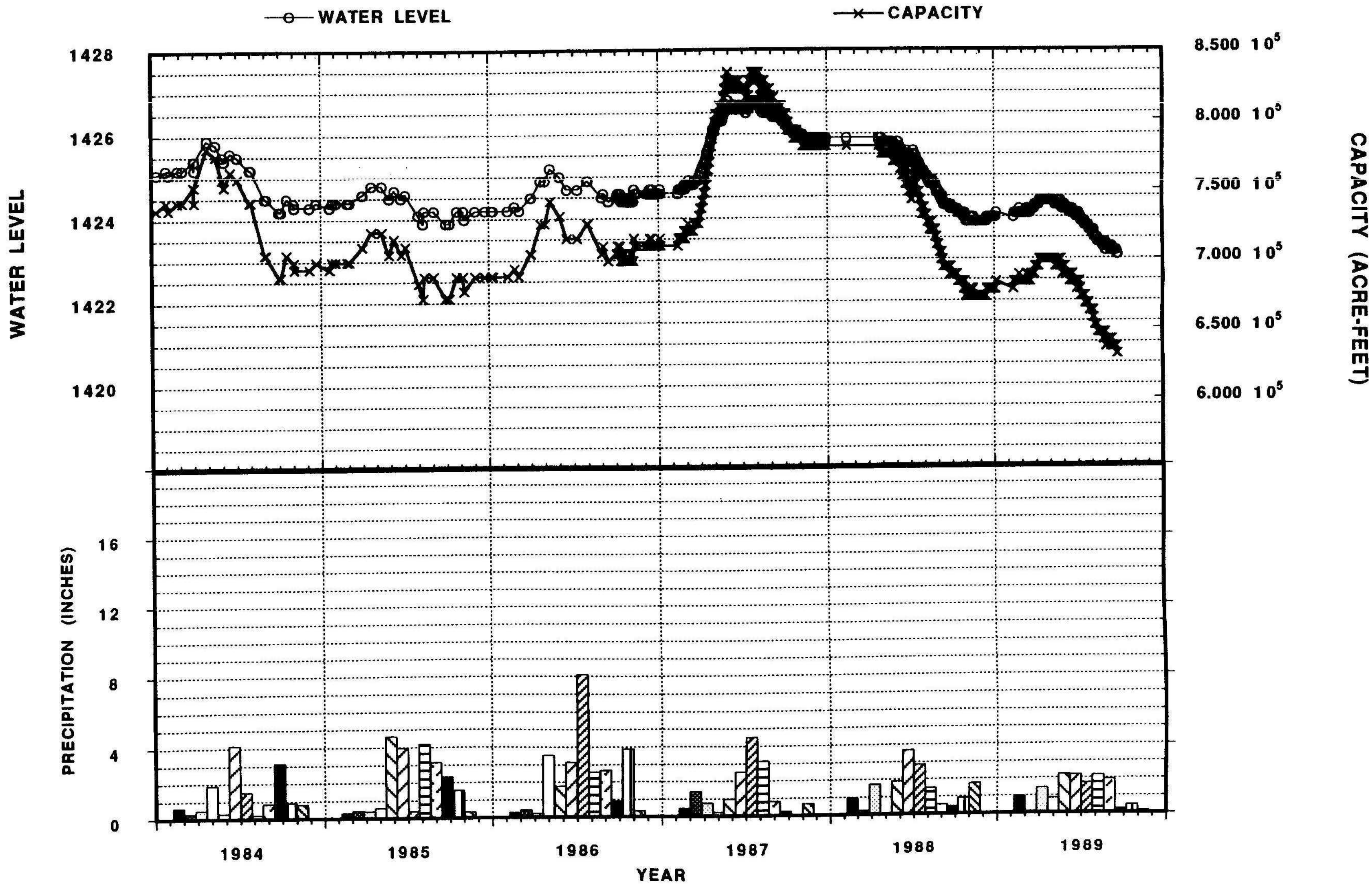


FIGURE 48. STAGE CAPCITY RELATIONSHIP, DEVILS LAKE, 1984-1989

Darcy Relationships

County study data and data collected as part of this study indicate that the Spiritwood aquifer system averages about 60 feet thick with transmissivities ranging from 5000 to 7500 feet^2/day. Assuming a width of 3 miles and a gradient of 1 foot/mile, the discharge to the lake using the Darcy equation would be 365 acre-feet/year. If the average hydraulic conductivity was 500 feet/day and the aquifer width was 6 miles, the discharge would be 3,000 acre-feet/year to the lake. This assumes flow from both the north and south into the lake. Ground-water divides in the Spiritwood aquifer may, however, restrict ground-water flow from the south. Using the Darcy equation, 3,000 acre-feet/year is probably an upper limit on discharge from the Spiritwood aquifer system, with discharge likely less than 500 acre-feet/year.

Another way to estimate the amount of ground water moving into Devils Lake is to calculate the flow based on the area of the lake bottom and the hydraulic conductivity of the lake bottom sediments. To discharge 20,000 acre-feet/year into Devils Lake would require a discharge rate of 0.00103 feet/day assuming a lake area of 53,000 acres. Average hydraulic conductivities of 0.001 feet/day for unweathered till are reported in the literature. The lake clays underlying the lake would have even lower conductivities. The assumed conductivity would require an upward gradient from the Spiritwood aquifer to the lake of about 1. Actual vertical gradients are more on the order of 0.1 to 0.08. Unless there is a high permeability zone connecting the aquifer to the lake, the aquifer cannot provide the quantity of water needed to balance the water budget of the lake. The observed gradient would indicate a discharge of 58 acre-feet/year. Even if the hydraulic conductivities are low by two orders of magnitude, the discharge to the lake would not approach the 18,000 to 60,000 acre-feet/year needed to balance the water budget.

Additional evidence that ground-water flow alone is not sufficient to balance the Devils Lake water budget is shown by the computational period for 1987 (Wiche, 1992). In that budget analyses, the computed shortfall was approximately 60,000 acre-feet. With the significant rise in lake level in the spring of 1987, regional ground-water discharge to the lake should be at a minimum. (the rise in lake level or regional discharge area would cause ground water to " back up" instead of contributing more) As the lake level declined, ground-water discharge to the lake should increase. However, the difference between computed and recorded inflow to Devils Lake declines through the May to September period (Wiche, 1992). Also, there should not be large oscillations in ground-water discharge from one period to the next. The difference between computed and measured surface inflow of 14,993 acre-feet in the period July 10-28, 1987 (Wiche, 1992) cannot be explained by the behavior of a regional ground-water system. Only a major sand and gravel aquifer near the shore of the lake could affect temporal changes in lake discharge of this magnitude. The area contributing to the lake would be too small to account for the volume of water the budget indicates occurred as surface inflow to the lake.

Ground-water discharge based on an estimate of recharge

Under natural conditions, ground-water flow systems are in a state of dynamic equilibrium. That is, "The amount of water recharging the aquifer is balanced by an equal amount of natural discharge ...", (Fetter, 1988). Thus, according to theory, an estimate of the amount of recharge to the Spiritwood aquifer would result in an estimate of the amount of discharge from the Spiritwood aquifer into Devils Lake.

Precipitation in the Devils Lake area for the past 100 years has ranged from 10 to 28 inches per year. Recharge to the Spiritwood aquifer will be some percentage of this precipitation range depending on antecedent soil moisture conditions, evapotranspiration and hydraulic conductivity of the overlying sediments.

The Spiritwood aquifer near Devils Lake has an areal extent of roughly 100 square miles (at present elevations). Based on a recharge rate of 1 inch per year, recharge to the Spiritwood aquifer near Devils Lake would be approximately 5000 acre-feet per year. Conversely, discharge to Devils Lake would be 5000 acre-feet. This technique, is however, rather flawed and should only be considered in a conceptual sense. That is , because of the low permeability of the overlying sediments in the area, recharge to the Spiritwood aquifer is rather low. If recharge to the Spiritwood aquifer is low, then discharge from the Spiritwood aquifer into Devils Lake is also rather low.

SUMMARY

Devils Lake occupies the low point of a large closed inland drainage basin and, as such, represents the regional discharge area. Major sources of water for the lake include: 1) runoff from snow melt and precipitation, 2) precipitation falling directly on the lake and 3) ground water. Because Devils Lake has not reached its spillway elevation in many years, evapotranspiration is the only way water leaves the basin. Results from this study show that ground-water flow within the region is very slow, and generally towards the low point of the basin (Devils Lake) to replace a small portion of the water being removed by evapotranspiration. Because of the small transmitting capacity of geologic materials surrounding and underlying Devils Lake, it appears that the amount of ground water reaching the lake is small when compared to the yearly evapotranspiration losses. Following is a brief summary of the role ground water plays in the Devils Lake water budget.

A) During wet cycles, with major spring runoff events, runoff is the major source of water for Devils Lake. In these years, ground water probably represents a very small percentage of the yearly water budget.

B) During dry cycles, with no runoff or direct precipitation, ground water is the major source of water to Devils Lake. However, even though ground water may be most of the yearly input to the lake, this amount is not adequate to make up for yearly evapotranspiration losses and the lake level declines.

C) If the area would go through a prolonged dry cycle, such as the early 1900's, the amount of ground water moving to the lake would slowly decline with time.

D) If significant precipitation follows a prolonged dry period, most of the water goes to filling the soil profile and the many depressions, potholes, soughs and lakes upstream of Devils Lake. As such, very little runoff reaches Devils Lake. In this scenario, ground water would again be a major input to the lake (along with direct precipitation on the lake surface), however, records show that ground-water flow is insufficient to keep up with the yearly evaporation losses and the lake level declines.

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