HYDROLOGIC AND CLIMATOLOGIC FACTORS AFFECTING WATER LEVELS OF DEVILS LAKE, NORTH DAKOTA

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SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC UNITS

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

Multiply inch-pound unit	By	To obtain metric unit
Acre	0.4047	hectare
Acre-foot	1,233	cubic meter
	0.001233	cubic hectometer
Cubic foot per second	0.02832	cubic meter per second
Foot	0.3048	meter
Gallon per minute	0.06309	liter per second
Inch	25.40	millimeter
Mile	1.609	kilometer
Square mile	2.590	square kilometer

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

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ABSTRACT

High water levels of Devils Lake, North Dakota, and other terminal lakes, have, in recent years, threatened highways, agricultural land, recreational cabins, and communities located near these lakes. This study was undertaken to describe the hydrology of the Devils Lake basin and to determine how to estimate future water-level probabilities.

Analysis of the available hydrologic and climatologic data indicates the water level of Devils Lake fluctuates largely in response to climatic variability. Average annual net storage gain has varied from 70,000 acre-feet for 1969-83 to as little as 4,530 acre-feet for 1931-40. In addition to the influence of climatic variability on the inflow to Devils Lake, an interconnected chain of lakes upstream of Devils Lake retains runoff and acts as an evaporation basin for runoff from the Devils Lake basin. During 1965-67, at least 112,000 acre-feet of water was stored in this upstream chain of lakes.

A review of research conducted on other terminal lakes indicates that water levels in these lakes fluctuate primarily in response to climate variability unless the basin hydrology has undergone significant human modification. There is agreement between water-level fluctuations of terminal lakes in western North America and the water-level fluctuations of Devils Lake during times of climatic extremes. Notable examples of climatic extremes are the relatively wet years during 1860 to 1885 when most terminal lakes in western North America were at or near historic maximum water levels and the drought of the 1930's when most terminal lakes were at or near historic minimum water levels.

No standardized methods are available for computing water-level probabilities of terminal lakes. Most of the development of a method for determining future water-level probabilities has been focused on Great Salt Lake, Utah. A number of techniques have been used to estimate the future water-level probabilities for Great Salt Lake; however, they provide a wide range in probability of occurrence for any given water level.

INTRODUCTION

About 5 percent of the landmass of North America drains into terminal lakes, which are lakes that are located at the lowest point within a closed drainage basin (de Martonne, 1927). Closed drainage basins have no outlet to the oceans of the world. High water levels of many of these terminal lakes have, in recent years, threatened highways, agricultural land, recreational cabins, and communities located near these lakes. The current high water levels of Devils Lake, N. Dak., pose a flood threat to the city of Devils Lake, a National Guard camp, roads, and sewer and lagoon systems of several other communities. Rising ground-water levels have caused problems in basements and with septic tanks in and near the city of Devils Lake.

The U.S. Army Corps of Engineers (1984) is conducting a feasibility study of possible flood-control projects to protect the cities, roads, and other properties around Devils Lake. An understanding of the hydrology of Devils Lake and some knowledge of the probability of future lake levels is needed as a basis for implementation of the flood-control project. For data collected at streamflow stations, the standard procedure most often used to compute probabilities is to fit the annual series of discharge data to a log-Pearson Type III distribution. However, fitting an annual series of lake levels to a frequency distribution, such as the log-Pearson Type III, violates the primary assumption of independence of events. Future lake levels of all terminal lakes are dependent to varying degrees on the previous years' lake level.

This report describes the results of a study to: (1) Analyze discharge and climate data to determine how hydrologic and climatologic factors affect the water-level fluctuations of Devils Lake, (2) compare water-level fluctuations of other terminal lakes and the variability of long-term discharge records to the water-level fluctuations of Devils Lake, and (3) conduct a literature search to determine what approaches have been used to estimate probabilities of future water levels of terminal lakes. The description of the hydrology of the Devils Lake basin is limited to currently available data (1983).

DESCRIPTION OF THE STUDY AREA

Devils Lake basin, in northeastern North Dakota, is a 3,810-square-mile closed basin in the drainage of the Red River of the North (fig. 1). About 3,320 square miles of the total 3,810 square miles is tributary to Devils Lake; the remainder is tributary to Stump Lake. The topographic relief and surficial landforms are of glacial origin. A large number of shallow depressions and potholes occur throughout the basin. Many of these depressions are connected by poorly defined channels and swales.

The eastern, western, and northern boundaries of the Devils Lake basin are poorly defined low divides. The southern boundary is a series of recessional moraines that lie between Devils Lake and the Sheyenne River. The major subbasins within the Devils Lake basin and the principal tributaries draining them are shown in figure 2, and the drainage areas are listed in table 1. Edmore, Starkweather, and Calio Coulees originate in southern Cavalier County and flow in a south-southwesterly direction. Mauvais Coulee originates along the southern flanks of the Turtle Mountains 300 to 400 feet above the elevation of Devils Lake.

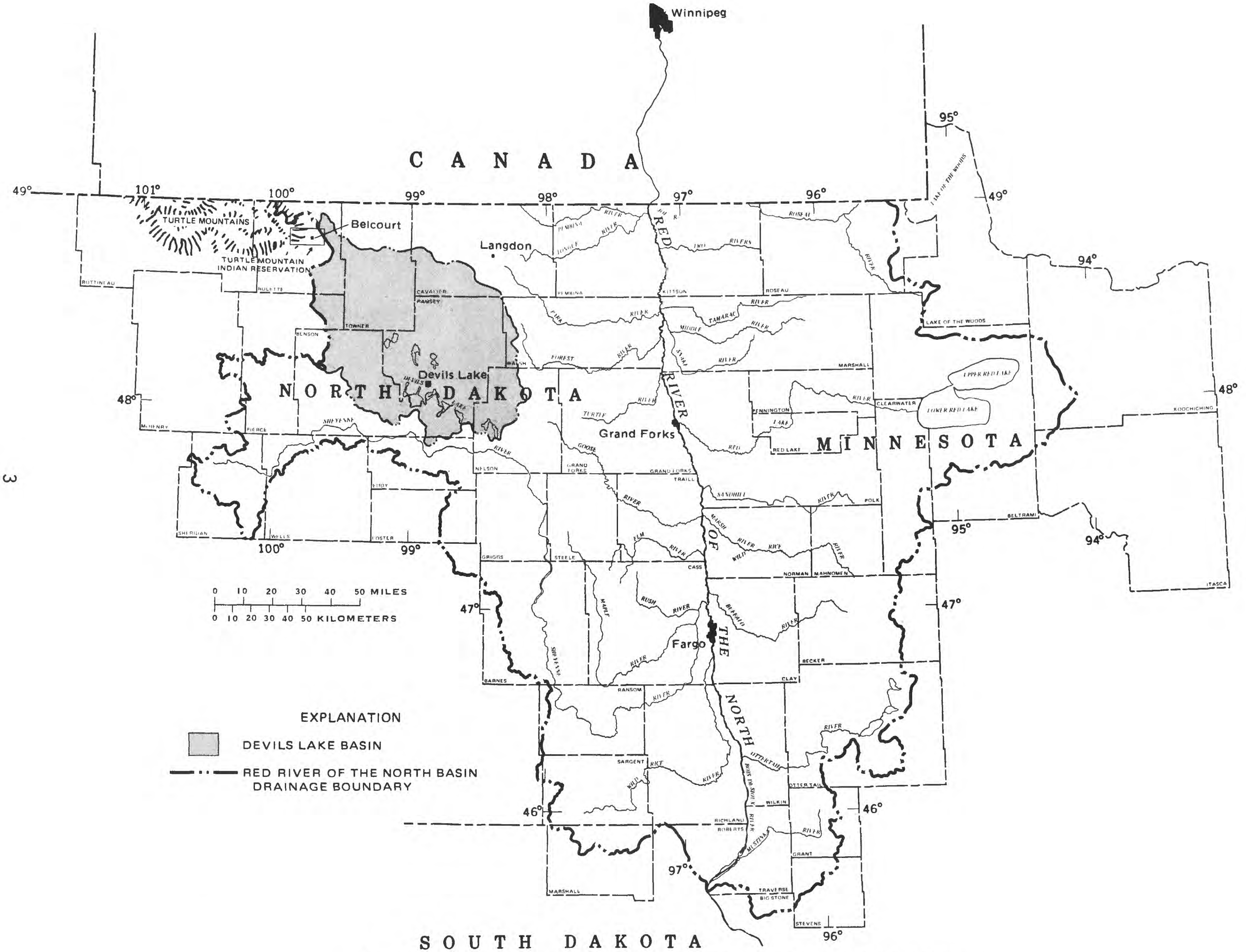


Figure 1.–Location of the Devils Lake basin. (Modified from Miller and Frink, 1984.)

Figure 2.—Major subbasins and location of gaging stations.

Table 1.--Drainage areas of subbasins

[Modified from Devils Lake Basin Advisory Committee, 1976]

Subbasin	Drainage area (square miles)		
	Contributing[1]	Noncontributing[1]	Total
Edmore Coulee	389	112	501
Starkweather Coulee	291	[2]100	[3]391
Calio Coulee	233	--	[3]233
Mauvais Coulee	872	10	882
Little Coulee	263	158	421
Comstock	58	--	[3]58
Devils Lake (north slope)	512	--	[3]512
Devils Lake (south slope)	328	--	[3]328
Stump Lake	488	--	[3]488

[1] Contributing and noncontributing drainage areas are based on current conditions. Unusually large quantities of precipitation or runoff could cause some noncontributing areas to contribute runoff temporarily; similarly, unusually dry conditions may decrease the drainage area that would contribute runoff during normal conditions.

[2] The noncontributing drainage area within the subbasin of Starkweather Coulee was not determined by the Devils Lake Basin Advisory Committee (1976). The noncontributing area indicated was estimated for this investigation.

[3] The contributing and noncontributing drainage areas have not been determined for the subbasin.

Prior to 1979, discharge from the tributaries flowed into the interconnected chain of lakes through Sweetwater Lake, Morrison Lake, Dry Lake, Chain Lake, Lake Alice (Lac aux Mortes), Lake Irvine, and then into Big Coulee. Most of the discharge entering Devils Lake flowed through Big Coulee, which is the only principal stream discharging directly to Devils Lake. A small quantity of runoff entered Devils Lake by overland flow from drainage areas adjacent to the lake. Then, in 1979, the Ramsey County and Cavalier County Water Management Boards completed the construction of channel A, which connects Dry Lake to Sixmile Bay on Devils Lake. Channel A modified the drainage pattern in the basin; drainage into Sweetwater, Morrison, and Dry Lakes is conveyed to Devils Lake by channel A, and the remaining discharge follows the natural watercourse.

The geology and ground-water resources of the Devils Lake basin have been discussed on a county-by-county basis in reports by Downey (1973), Hutchinson (1977), Randich (1977), Hutchinson and Klausing (1980), and Randich and Kuzniar (1984). Cretaceous and Paleocene bedrock is covered by several hundred feet of Pleistocene glacial deposits throughout most of the basin. However, Randich (1977) indicated that bedrock ridges crop out beneath Devils Lake along its northern shore. A pronounced bedrock trench corresponds to the central axis of the lake, suggesting the lake may have developed as a result of tectonic controls.

The principal bedrock aquifers in the area are the Dakota aquifer and the overlying Pierre aquifer. Paulson and Akin (1964) believed that hydraulic connections between these aquifers and Devils Lake were minimal. The Dakota aquifer underlies the entire Devils Lake basin and includes undifferentiated sand and sandstone beds in the Cretaceous Dakota Sandstone. Depth to the top of the Dakota aquifer ranges from 1,150 feet in northeastern Ramsey County north of Devils Lake to 2,000 feet in southwestern Benson County south of Devils Lake. The city of Devils Lake has the only known wells withdrawing water from the Dakota aquifer within the Devils Lake basin.

The Pierre aquifer yields small quantities of water from fractures and silty layers in the upper part of the Cretaceous Pierre Shale. Although the formation has a maximum thickness of about 600 feet within the basin, only the upper 50 to 200 feet is sufficiently fractured or permeable to serve as an aquifer.

Aquifers in the glacial drift occur principally as buried-valley deposits and undifferentiated sand and gravel deposits associated with glacial till. The most significant of these aquifers within the basin is the Spiritwood aquifer system. This buried-valley aquifer system generally follows a trend from north of Lake Irvine along Devils Lake and beneath the Sheyenne River. The aquifer ranges from 1 to 11 miles in width and has potential yields to wells of 200 to 1,500 gallons per minute. The Spiritwood aquifer system is recharged by precipitation infiltrating through the overlying and adjacent glacial till. Discharge from the aquifer system is by pumping of wells, evapotranspiration, and leakage to surface-water bodies. Although Lake Irvine, Lake Alice, Devils Lake, and East Devils Lake overlie the aquifer system, the availability of hydraulic connections between these lakes and the aquifer system is uncertain. Paulson and Akin (1964) indicated that interaction between Devils Lake and glacial aquifers probably was very small, as the lake was believed to be lined with relatively impermeable fine-grained bottom sediments. However, Hutchinson and Klausing (1980) believed that the Spiritwood aquifer system discharged to several lakes of the Devils Lake chain. They suggested that extensive ground-water withdrawals from the Spiritwood aquifer system could reverse the hydraulic gradient, permitting Devils Lake to recharge the aquifer system.

HYDROLOGY OF THE DEVILS LAKE BASIN

Prehistoric Water-Level Fluctuations

Since the retreat of the Pleistocene glaciation, the water level of Devils Lake has fluctuated between about 1,453 feet above sea level, the spill elevation, to less than 1,400 feet above sea level. According to Bluemle (1981), Devils Lake stood at an elevation higher than 1,440 feet above sea level prior to 8,500 years before present. Callender (1968) analyzed sediment samples from Devils Lake for their physical, chemical, and mineralogical properties and concluded that water levels in Devils Lake have fluctuated in response to shifting climate and hydrologic conditions. He also concluded that: (1) Sometime during the period 8,500 years before present to 6,000 years before present Devils Lake was dry; (2) from 6,000 years before present to 2,500 years before present the water level rose and declined several times; (3) from 2,500 years before present to 500 years before present there were minor lake-level fluctuations that culminated in low lake levels; and (4) from 500 years before present until the year 1800 the water level rose, and then from 1800 until 1940 the water level declined.

Aronow (1955, 1957) analyzed abandoned strand lines, lacustrine sand and gravel deposits containing buried soils and vertebrate remains, and rooted stumps uncovered by receding water around Stump Lake. In general, Aronow's (1955, 1957) research is in agreement with most of Callender's (1968) work, but there are some differences. Aronow (1955, 1957) indicated that a lowering of water levels of lakes in the Devils Lake basin occurred during a dry period in the 15th and 16th centuries, as evidenced by the growth of burr oak in Stump Lake. According to Brooks (1951), this dry period occurred throughout most of western North America. Following this dry period, there was a general rise in water levels from the mid-1500's until the mid- to late 1800's. This period of rising water levels commonly is referred to as the Little Ice Age (Wahl, 1968).

Historic Water-Level Fluctuations

Upham (1895, p. 595) indicated that the water level of Devils Lake was 1,441 feet above sea level in 1830. He based this water level on a large and dense stand of timber that grew at and above 1,441 feet above sea level. Below 1,441 feet above sea level scattered trees and brush existed. Captain H.H. Heerman informed Upham that, based on tree-ring chronology, the largest tree cut below 1,441 feet above sea level was 57 years old in 1887. Thus, Upham (1895, p. 595) concluded that 57 years prior to 1887 (1830) the water level of Devils Lake was 1,441 feet above sea level. No water-levels were recorded from 1830 to 1867.

Water levels of Devils Lake have been recorded, albeit somewhat sporadically, from 1867 to 1901 (fig. 3), and these records have been authenticated by the U.S. Geological Survey. In 1901, the U.S. Geological Survey established a gage at Devils Lake. The water levels of Devils Lake (1901-83) and the annual precipitation recorded at Fort Totten (1870-90) and at the city of Devils Lake (1897-1983) are shown in figure 3. A discussion of the interaction between precipitation and the recorded water levels of Devils Lake is included in the "Hydrologic and Climatologic Analysis" section. For the period of record at Devils Lake, the maximum water-level occurred in 1867; the water level was 1,438 feet above sea level and the lake had a surface area of about 140 square miles. From

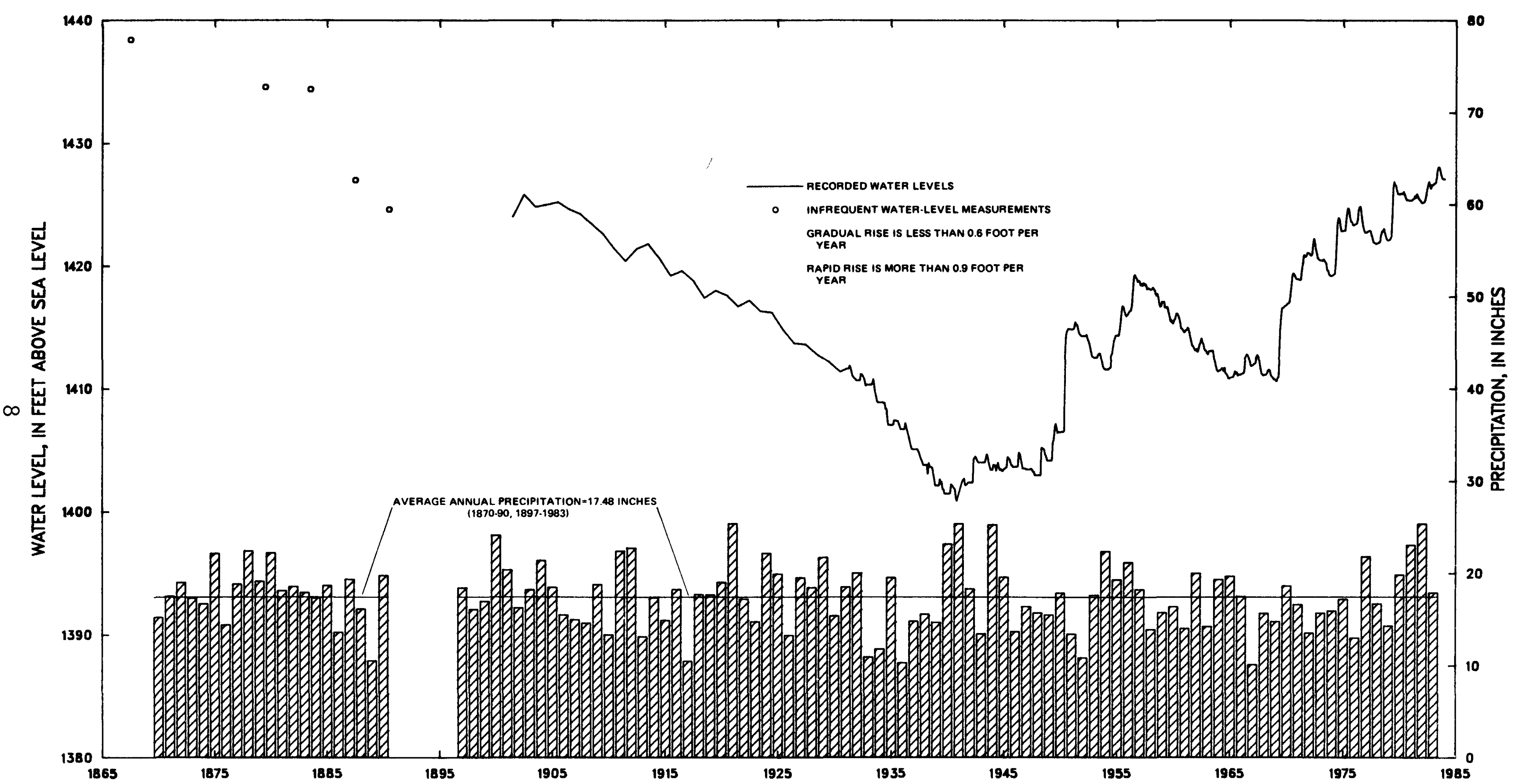


Figure 3.—Historic water levels for Devils Lake, 1867-1983, and average annual precipitation, 1870-90 (Fort Totten) and 1897-1983 (city of Devils Lake).

1867, the water level of Devils Lake declined almost continuously until 1940, when it reached a recorded low of 1,400.9 feet above sea level and the lake was a shallow brackish body of water covering 10.2 square miles (North Dakota State Engineer, 1944). From 1940 to 1956 the water level generally rose; from 1956 to 1968 the water level generally declined. From 1968, the water level generally rose until 1983 when it reached a peak of 1,428.1 feet above sea level, which is the highest water level in about 100 years.

Previous Investigations

Numerous investigators in the past 90 years have studied the factors controlling the water-level fluctuations of Devils Lake. Upham (1895, p. 595), in reference to a study by Whittlesey (1860), mentioned that during 1760-1860 the water-levels of the great Laurentian lakes alternated in cycles of about 12 years. Upham (1895) made two important observations: (1) Much less than average precipitation for several years was followed by much more than average precipitation; and (2) "* * *besides such short cycles, important secular changes of the mean annual precipitation in North Dakota, occupying considerably longer periods, have caused remarkable changes in the levels of numerous lakes which have no outlet."

Based on his study of shoreline, gravel, and other deposits around Lake Irvine and to the southeast in the Devils Lake basin, E.J. Babcock (1903) concluded that the small lakes north of Devils Lake also were larger at some time in their history. In summary, Babcock (1903, p. 228) wrote

> There is little doubt that Lake Irvine, at no very remote period, extended from one mile to three miles farther east, and stretching toward the south, widened out irregularly three or four miles more towards the southeast. At this time Lac aux Mortes (Lake Alice), Twin Lakes, and Dry Lake were probably connected and formed one sheet of water, which may have been continuous with Cavanaugh and Sweetwater Lakes, thus forming a large body of water which stretched out with irregular shore line toward the southeast, nearly parallel to the present Devils Lake, presenting an appearance similar to the Devils Lake of today. This old lake and Devils Lake were doubtless connected by a long, narrow bay, filling all the low land of the coulee bed between Lake Irvine and Devils Lake.

Regarding the water-level fluctuations of Devils Lake, Babcock (1903) indicated that the shale underlying the glacial drift is impermeable and prevents "subterranean" drainage. His theory was that lake-level decline "* * *is caused by the breaking of the prairie sod which in turn exposed the more permeable soil." Thus, the inference is made that surface runoff prior to the late 1800's was greater than the runoff after the late 1800's. Apparently Babcock (1903) believed that the increased volume of water that infiltrated the soil never reached the streams that are tributary to Devils Lake.

Horton and others (1910, p. 52) maintained that the breaking of prairie sod and soil cultivation had retarded surface runoff and the lake level was continuously lowered by evaporation. They indicated that Devils Lake had reached equilibrium in 1910 and should remain that way unless a change in the extent or method of agriculture took place.

Simpson (1912, p. 116) stated that the chief source of water to Devils Lake was ground water. According to Simpson (1912), the water-level of Devils Lake is controlled by the ground-water elevation and by evaporation. He further indicated that the two factors were dependent on climatic control. In a ground-water report, Simpson (1929, p. 189) reiterated that ground-water elevation and evaporation control the water level of Devils Lake.

E.F. Chandler, Dean of the College of Engineering, University of North Dakota, in the early 1900's, developed his theory regarding the water-level fluctuations by visiting Devils Lake at least once a year and often several times a year from 1903 through 1934. Chandler (written commun., 1931) stated:

> 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 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.

Swenson and Colby (1955) indicated that climatic change is more likely the cause of water-level fluctuations of Devils Lake than agricultural practices. Swenson and Colby (1955) stated that the drainage area upstream from the gaging station of the Sheyenne River near Sheyenne, N. Dak., is similar in topography, vegetation, soils, and climate to the drainage area that contributes runoff to Devils Lake, so that the runoff from the two areas should be comparable. Swenson and Colby (1955) estimated that the average annual runoff of the Sheyenne River at Sheyenne was 0.23 inches for the 22-year period ending September 30, 1951. Runoff was below this average during 66 percent of the 22-year period. They also indicated that the variability of inflow to Devils Lake probably is greater than the variability of discharge on the Sheyenne River at

Sheyenne because a larger percentage of runoff is stored in upstream lakes during years of minimal runoff than during years of substantial runoff. Thus, there is a trend toward clustering of many years of minimal runoff interspersed with a few years of substantial runoff.

Swenson and Colby (1955) developed a multiple linear regression equation using annual runoff of the Sheyenne River at Sheyenne as the dependent variable and annual precipitation and annual temperature as the independent variables. The coefficient of determination was 0.50. They concluded that runoff in the Sheyenne River basin, and presumably Devils Lake basin, is poorly related to annual temperature and precipitation. Swenson and Colby (1955, p. 15) stated:

> Although the available records are short and the relationships are affected predominately by the cold, wet year of 1950, the data indicate that a 1-degree rise in average annual temperature may be associated with a decrease of 0.08 or 0.09 inch of runoff per year, whereas a 1-inch decrease in annual precipitation may be associated with a decrease of about 0.03 or 0.04 inch of runoff per year. These relationships, even though poorly defined and perhaps distorted by the data for 1950, emphasize the possible effect of annual average temperatures on runoff. The higher than normal temperatures since 1930, particularly from 1930 to 1940, probably considerably decreased the inflow to Devils Lake as well as increased the evaporation from it.

Langbein (1961) described the factors controlling the water level of terminal lakes. He developed and simplified a mass-balance equation that explains the water-level fluctuations of terminal lakes. The response-time coefficient, k, used in Langbein's (1961) equation is the ratio of a change in lake volume to the corresponding change in rate of discharge (lake loss). Langbein (1961) stated that the response-time coefficient explains a great deal about the nature of fluctuations of terminal lakes. A lake with a value of k of about 1 year responds to the present year's precipitation and then dries up in the same year. The terminal lakes investigated by Langbein (1961) have response times varying from less than 1 year in some lakes to 300 years for the Caspian Sea. Devils Lake has a response time of 14 years. Langbein (1961) stated "* * *a lake with high level of k reacts slowly and may be at a high stand during a period of low rainfall and vice versa."

Langbein (1961) further indicated that the decline in water levels on some terminal lakes seemed to be greater than can be explained by climate variability and measured diversions of water. In reference to this apparent anomaly, Langbein (1961) mentioned that Devils Lake was a noted example. He indicated that the 35-foot decline in water level from 1867 to 1940 was greater than could be accounted for on the basis of a decrease in precipitation and some negligible irrigation.

Mitten and others (1968) continued the water-quality work of Swenson and Colby (1955) and they discussed the surface-water hydrology of Devils Lake for 1952-60. They indicated that the water-level rise during 1952-60 was caused by greater-than-normal precipitation in 1954, 1956, and 1957. Mitten and others (1968) mentioned that the flow that passes the Big Coulee gage near Churchs Ferry may not represent the flow that enters Devils Lake, even though there is little inflow between the gage and the lake. At the time of their study, a large marshy area capable of storing a large volume of water existed between the gage and Devils Lake. Presently, this large marshy area is part of Devils Lake; therefore, all of the discharge passing the Big Coulee gage enters Devils Lake.

Paulson and Akin (1964) completed a study of the ground-water resources of the Devils Lake area. They indicated that some ground water moves northward into the Devils Lake basin. Q.F. Paulson (U.S. Geological Survey, oral commun., 1984) indicated that material that has relatively little hydraulic conductivity is a barrier between the bottom of Devils Lake and the aquifers below the lake.

No studies were conducted from the early 1960's to the late 1970's that had the objective of either directly or indirectly determining the factors that control the water-level fluctuations of Devils Lake. In response to the rapid rise in water levels of Devils Lake in the 1970's and the flood threat to the city of Devils Lake, a number of studies were begun in the late 1970's. In 1976, the North Dakota State Legislature passed House Bill 1587, an act to create the Devils Lake Basin Advisory Committee to study solutions to water-resources problems in the basin, primarily flood-related problems. As a result of this legislation, the Devils Lake Basin Advisory Committee (1976) completed a study to address the water-resource problems of Devils Lake.

Parekh (1977) attempted to develop a hydrologic model for the Devils Lake basin. His primary objective was to develop the capability to predict the downstream effects of proposed land-use changes throughout the Devils Lake basin. Model validation was made for 4 years--October 1966 to September 1970. Parekh's best model validation occurred when a snowfall correction factor of between 1.8 and 2.0 was used.

The U.S. Army Corps of Engineers (1983) completed a detailed project report that recommended flood-control measures for the city of Devils Lake based on the great potential damage that would occur if the level of Devils Lake continued to rise. The U.S. Army Corps of Engineers (1984) indicated that additional flood-control structures to protect areas around the lake also were potentially economically justified if the level of Devils Lake would continue to rise. Ideally, the justification of these structures should be based on statistical probabilities of future water levels of Devils Lake. However, many of the statistical methods do not provide reasonable results because of the dependence of water levels from month to month and year to year.

HYDROLOGIC AND CLIMATOLOGIC ANALYSIS

It is necessary to determine the major cause or causes of past water-level fluctuations of Devils Lake before techniques that could be used to estimate future water-level probabilities may be evaluated. Therefore, an analysis of the hydrologic and climatologic data collected in the Devils Lake basin was made to determine if water-level fluctuations respond primarily to hydrologic and climatologic factors. This analysis is especially necessary in light of the fact that many conflicting theories for water-level fluctuations of Devils Lake have been proposed.

Statistical Analysis of the Discharge Record

Discharge data collected at three long-term gaging stations (fig. 4 and table 2) were used to describe the temporal variability in discharge of the major tributaries to Devils Lake. Monthly streamflow statistics computed for these long-term gaging stations (table 3) indicate a large variability in discharge from month to month (fig. 4). Most of the runoff occurs during April and May in Edmore and Mauvais Coulees and during May and June in Big Coulee. The maximum monthly mean and median flows occur during April in Edmore and Mauvais Coulees and during May in Big Coulee. The later peak in Big Coulee is caused by the relatively long travel time of the flow passing through the interconnected chain of lakes upstream from Big Coulee near the Churchs Ferry gage.

The large differences between the median and mean monthly discharges (table 3) indicate that the monthly discharge distribution is markedly skewed. The mean discharge is significantly influenced by a relatively few high flows. The mean and median discharges for October through February at the Edmore and Mauvais Coulee gages indicate that little discharge ever occurs during the winter months. Apparently there is little ground-water contribution in the Edmore and Mauvais Coulee drainages.

The monthly flow statistics (table 3) indicate that lakes upstream of Devils Lake affect the timing and quantity of discharge that passes the Big Coulee gage. A mass-balance approach was used to estimate the quantity of discharge passing the Big Coulee gage. The annual discharge for the period of record for five gaging stations is listed in table 4. The annual discharge at the Starkweather Coulee gage from 1957 through 1979 was estimated by adding the average annual runoff per square mile at the Edmore Coulee gage and the Mauvais Coulee gage, dividing the sum by 2, and then multiplying the quotient by the contributing drainage area at the Starkweather Coulee near Webster gage.

Based on the values listed in table 2, the contributing drainage area of the Big Coulee near Churchs Ferry gage, about 36 percent (659 square miles) is from Edmore Coulee near Edmore and Mauvais Coulee near Cando; 12 percent is from Starkweather Coulee near Webster; and 10 percent is from Little Coulee near Brinsmade. Thus, 58 percent of the contributing drainage area upstream of the Big Coulee gage is gaged.

A conservative estimate of the losses in lakes upstream of the Big Coulee gage was made by subtracting the sum of the annual discharge recorded at the four gages upstream of the Big Coulee gage from the annual

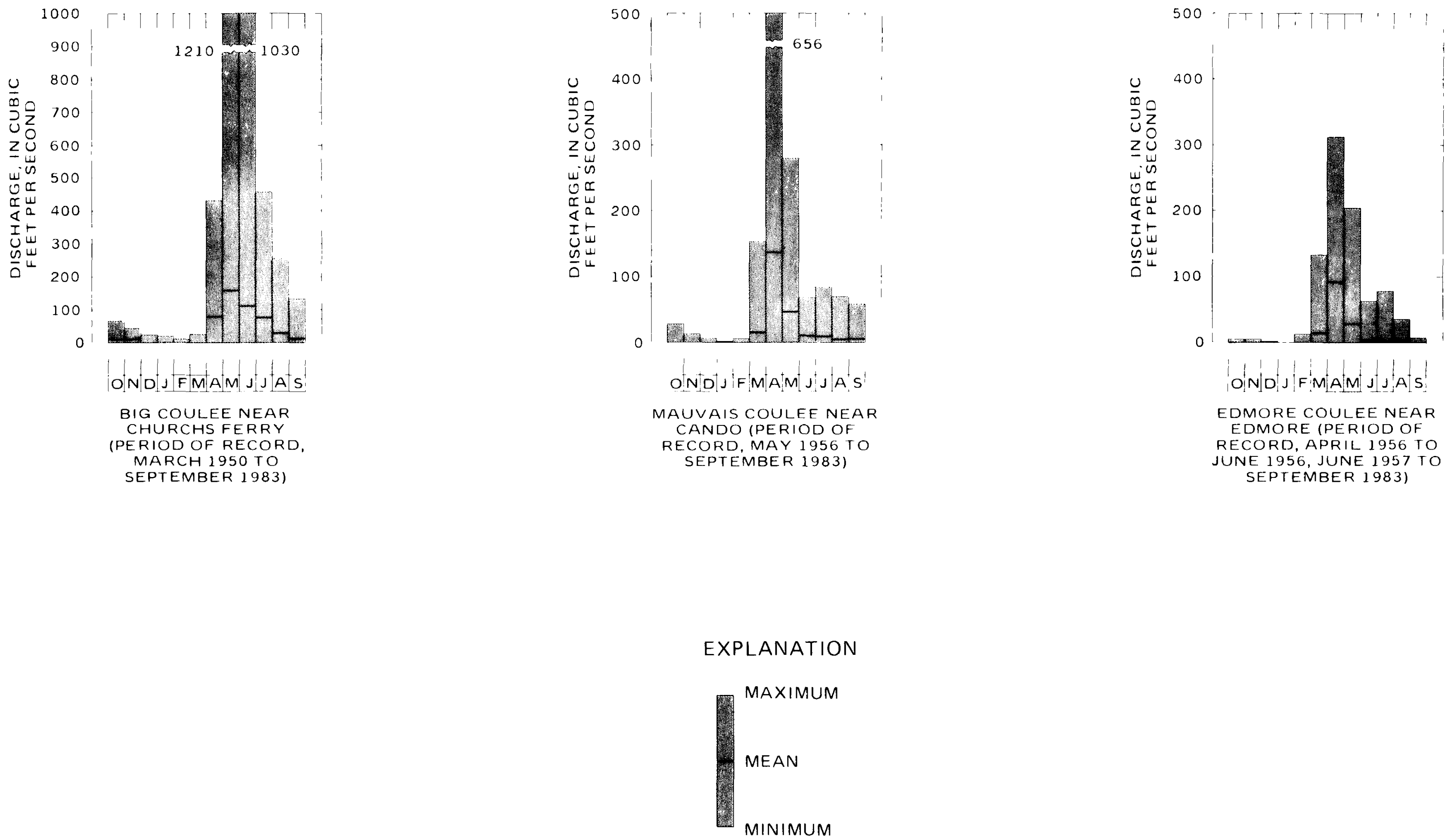


Figure 4.—Monthly discharge for period of record at three long-term gaging stations.

Table 2.--Drainage areas and period of record for gaging stations

[Drainage area values listed in tables 1 and 2 were computed by different agencies. Inconsistancies may occur when comparisons are made between the values listed in tables 1 and 2. As an example, the drainage area of Big Coulee (2,428 square miles) can be obtained from table 1 by summing the drainage areas of Edmore, Starkweather, Calio, Mauvais, and Little Coulees; but the drainage area of Big Coulee listed in table 2 is 2,510 square miles]

Site number (figure 2)	Gaging-station name	Drainage area (square miles)		Period of record
		Contributing	Noncontributing	
1	Edmore Coulee near Edmore	282	100	April 1956 to June 1956. June 1957 through December 1983.
2	Starkweather Coulee near Webster	210	100	October 1979 through December 1983.
3	Mauvais Coulee near Cando	377	10	May 1956 through December 1983.
4	Little Coulee at Leeds	140	140	October 1955 through December 1973.
5	Little Coulee near Brinsmade	190	160	October 1975 through December 1983.
6	Big Coulee near Churchs Ferry	1,820	690	March 1950 through December 1983.
7	Devils Lake near Devils Lake	([1])	([1])	See text.

[1] Contributing and noncontributing drainage areas are unknown, but total drainage area is about 3,320 square miles.

Table 3.--Monthly flow statistics, in cubic feet per second, for three long-term gaging stations

	Gaging-station name					
	Edmore Coulee near Edmore		Mauvais Coulee near Cando		Big Coulee near Churchs Ferry	
Month	Mean	Median	Mean	Median	Mean	Median
January	0	0	0.02	0	1.1	0
February	.47	0	.19	0	.56	0
March	13.3	.01	15.7	.01	4	.55
April	97.7	81.5	136	63.7	79.6	25.6
May	29.7	8.8	47.8	13.3	162	36.5
June	6.4	1.4	9.8	3	117	26.2
July	5.2	.14	7.4	.64	71.1	5.7
August	4.9	0	3.9	.22	31.5	.35
September	.52	0	4.2	.11	13.2	.39
October	.41	0	1.81	.07	8.7	.19
November	.31	0	.96	.06	6.6	.41
December	.06	0	.25	.02	2.9	0

discharge recorded at the Big Coulee near Churchs Ferry gage (table 4). A negative number in the gain or loss column indicates more discharge flowed past the upstream gages than arrived at the Big Coulee gage. A positive number indicates an increase in discharge at the Big Coulee gage.

The chain of lakes upstream of Devils Lake provides significant space to store water in many years. During 1965-67, the upstream lakes stored at least 112,000 acre-feet of water. The water going into storage eventually is removed from the upstream lakes by evaporation and any ground-water seepage that might occur. To illustrate the effect of this upstream storage, the maximum water level of Devils Lake in 1967 would have been 1,419.7 feet above sea level instead of 1,412.9 if the upstream storage had not been available from 1965 through 1967. Therefore, the computed water level without upstream storage would have been 6.8 feet higher than the recorded water level of Devils Lake. For illustrative purposes, the assumption was made that the increase in net evaporation from Devils Lake would be equal to the inflow from the 42 percent of the ungaged drainage area not included in the storage estimate. If discharge records were available from all contributing drainage areas upstream of Big Coulee near Churchs Ferry, the losses, or storage, in the upstream lakes probably would be larger in most years (larger negative values and smaller positive values).

Table 4.--Annual discharge at gaging stations

[The gain or loss (-) is equal to the discharge of Big Coulee minus the sum of the discharge of Edmore Coulee, Starkweather Coulee, Mauvais Coulee, and Little Coulee. Discharge data for Little Coulee at Leeds were used from 1956 through 1966 and for Little Coulee near Brinsmade from 1976 through 1983. The annual discharge at the Starkweather Coulee gage from 1957 through 1979 was estimated by adding the average annual runoff per square mile at the Edmore Coulee gage and the Mauvais Coulee gage, dividing the sum by 2, and then multiplying the quotient by the contributing drainage area at the Starkweather Coulee near Webster gage]

	Discharge (acre-feet)					Gain or loss (acre-feet)
Calendar year	Edmore Coulee	Starkweather Coulee	Mauvais Coulee	Little Coulee	Big Coulee	
1956	--	--	7,610	7,610	56,600	--
1957	28.8	102	326	--	556	99.2
1958	3.6	11.3	35.8	0	48.4	-2.3
1959	1,000	423	181	0	73.6	-1,530
1960	9,070	6,010	11,600	562	282	-27,000
1961	150	56.7	2.9	0	1.59	-208
1962	7,770	3,850	3,440	646	590	-15,100
1963	6,470	2,420	22.2	0	115	-8,800
1964	2,620	1,520	1,940	286	104	-6,260
1965	6,560	8,930	23,300	911	1,310	-38,400
1966	24,400	12,600	12,500	2,130	14,600	-37,000
1967	28,800	13,300	9,280	--	14,800	-36,600
1968	837	1,670	4,880	--	386	-7,000
1969	13,800	17,200	43,300	--	100,000	25,700
1970	3,660	8,330	25,000	--	59,200	22,200
1971	14,200	13,100	28,100	--	77,400	22,000
1972	13,200	10,200	19,000	--	47,100	4,700
1973	603	359	483	--	2,090	645
1974	34,500	27,300	51,900	--	160,400	46,500
1975	7,450	7,340	16,400	--	55,200	24,000
1976	6,720	10,600	29,100	6,370	52,900	110
1977	209	92.5	52.8	4.2	2,140	1,780
1978	11,200	5,690	5,440	28.6	24,900	2,540
1979[1]	26,400	22,400	45,200	25,900	[2] 227,900	108,000
1980	1,340	1,120	2,240	134	[3] 2,160	--
1981	4,800	4,300	9,020	1,240	[3] 226	--
1982	15,200	10,600	17,800	1,920	[3] 34,600	--
1983	11,400	7,730	12,500	4,010	[3] 28,900	--

[1] Construction of channel A completed and channel A put into operation.
[2] Discharge conveyed in channel A was 56,000 acre-feet.
[3] Discharge of channel A is unknown; therefore, gain or loss is not given.

Knowledge about the hydrologic significance of these upstream lakes is limited. Many studies reference a report by Conger (1971) when citing the significance of depressional storages on flood peaks. The variables determined by Conger (1971) to be significant are drainage area, main channel slope, lake and marsh area directly interrupting the stream channel, and some areal factors. Conger (1971) assumed that all lake and marsh areas not directly connected to the stream are noncontributing. In reference to storage in the upstream lakes at the time of intense rainfall over the Devils Lake basin in June 1954, the North Dakota District Engineer for the U.S. Geological Survey (H.M. Erskine, written commun., 1954) stated:

> Although the small tributaries have contributed moderate amounts of runoff to Devils Lake, Mauvais Coulee, the only large tributary, has contributed very little flow to Devils Lake because most of the runoff from its basin so far has been retained in Lac aux Mortes (Lake Alice), Lake Irvine, and other lakes on the tributaries, all of which were several feet below their outlets when the heavy rainfall began.

In addition to the hydrologic significance of storage in these upstream lakes, other depressional storage in the Devils Lake basin also affects the inflow to Devils Lake. Ludden and others (1983) used photogrammetric methods to estimate the depressional storage in 212 quarter sections of land in the Devils Lake basin. A majority of the depressions were dry or nearly dry at the time of the study. Ludden and others (1983) concluded that the wetland depressions provide a maximum water-storage capacity of 657,000 acre-feet in the Devils Lake basin. They also concluded that these depressions retain 72 percent of the total runoff of a 2-year flood and 41 percent of a 100-year flood. According to the Devils Lake Advisory Committee (1976), human modification of the drainage network has contributed to flooding in the Devils Lake basin. Many of the residents believe that drainage of wetland depressions has contributed to flood problems in the Devils Lake basin (U.S. Army Corps of Engineers, 1984).

Temporal Variability of Inflow To and Outflow From Devils Lake

A water-balance model was used to estimate the variability of inflow and net storage gain to Devils Lake for time periods ranging from a month to 10 years or more. The following water-balance model was used:

$$Q_I = S_C + (E_{LS}A_{LS}) - (P_{LS}A_{LS}) - G \qquad (1)$$

where

Q_I = surface-water inflow to Devils Lake, in acre-feet;
S_C = storage change, in acre-feet.
E_{LS} = evaporation from the lake surface; in feet;
A_{LS} = lake-surface area, in acres;
P_{LS} = precipitation falling on the lake surface, in feet; and
G = ground-water inflow to the lake, in acre-feet.

The inflow (Q_I) enters Devils Lake in three ways: (1) Inflow through Big Coulee (the major tributary to Devils Lake), (2) inflow through channel A, and (3) inflow from the 512-square-mile Devils Lake (north slope) subbasin. The 328-square-mile Devils Lake (south slope) subbasin consists of numerous small closed drainage basins. These closed drainage basins have no defined drainage network and thus contribute no significant runoff to Devils Lake.

The combination of the dynamic processes described in equation 1 results in fluctuations in water levels from month to month and year to year. Based on the recorded water levels (fig. 5), a generalized annual hydrologic model can be outlined 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.

The terms net storage gain and net storage loss have a specific meaning in this report. Net storage gain is used to denote the change in storage volume between the fall or winter minimum water level and the following spring or summer maximum water level; this storage change represents the excess of inflow compared to other subtractions. Conversely, the net storage loss is defined as the change in storage volume between the seasonal maximum water level and the succeeding seasonal minimum.

An attempt was made to compute the annual net storage gain to and the annual net storage loss from Devils Lake (tables 5 and 6) using equation 1. Net storage gain was substituted for inflow (Q_I) in equation 1. Annual net storage gain is equal to the capacity of the lake at maximum water level minus the capacity of the lake at minimum water level. The precipitation (P_{LS}) falling on the lake surface and the evaporation (E_{LS}) from the lake surface are assumed to be equal between the time that the minimum water level and the maximum water level were recorded. Based on a study by Paulson and Akin (1964), the ground-water contribution (G) was assumed to be negligible. Thus, the net storage gain is equal to the storage change (S_C) in equation 1. No net storage gain or loss was computed for the years prior to 1931 because water-level measurements were too infrequent to determine the minimum water level prior to spring breakup.

An examination of table 5 indicates that the conceptual model does not fit in some years. As an example, in the dry years of 1934, 1935, and 1937, there is no net storage gain to Devils Lake, and there probably was extremely minimal inflow. In these years, the water level either remained unchanged or actually declined. Thus, in these dry years of the 1930's, the inflow to Devils Lake plus the precipitation falling on the lake apparently always was less than the evaporation from the lake surface.

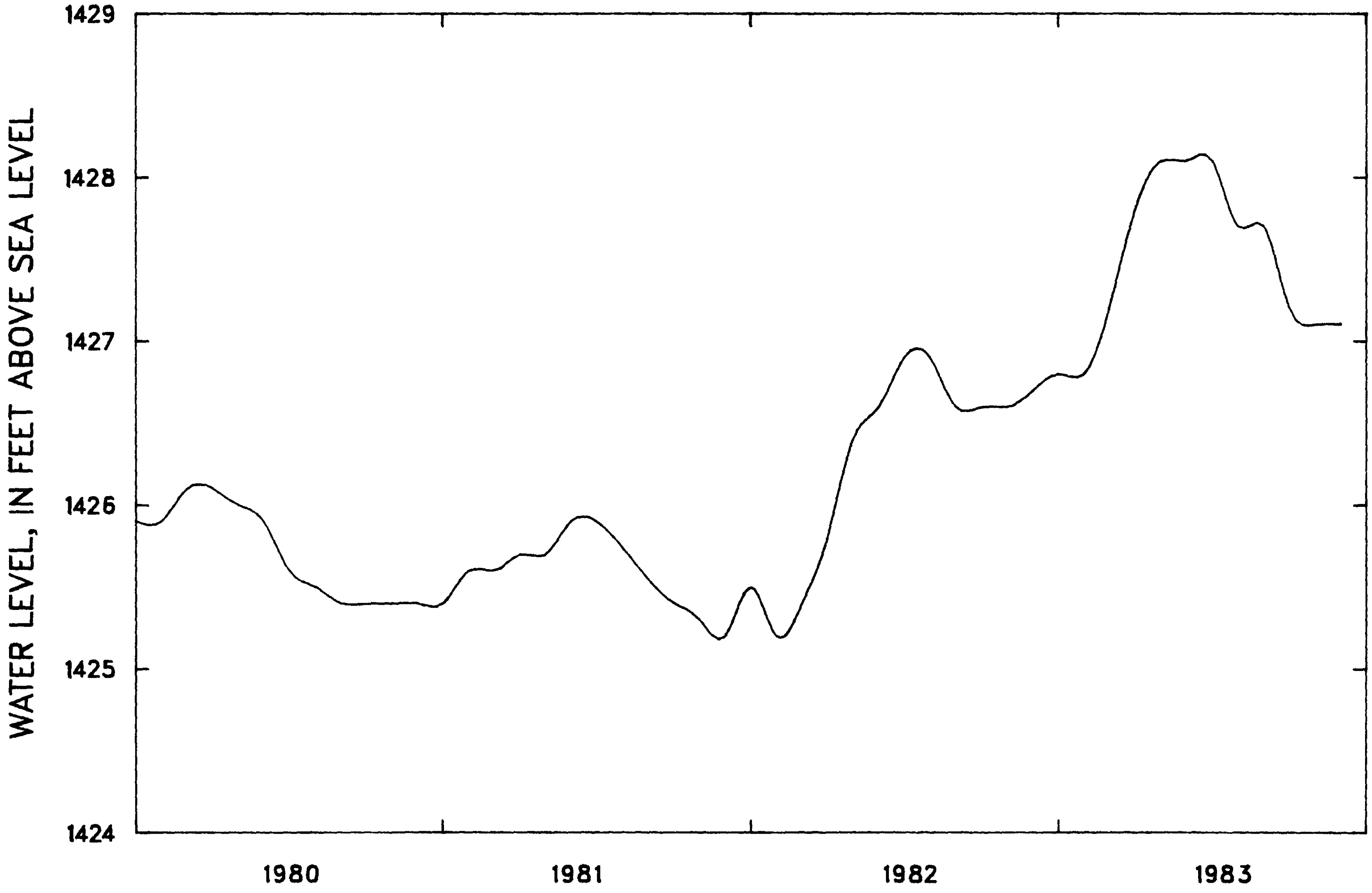


Figure 5.—Water-level fluctuations of Devils Lake, 1980-83.

Table 5.--Annual net storage gain to Devils Lake

[After examining the water-level records to obtain the minimum water level before spring breakup and the maximum water level after spring breakup, net storage gain was computed by subtracting the volume of the lake at minimum water level from the volume of the lake at maximum water level]

Year	Date	Water level (feet above sea level)	Net storage gain (acre-feet)
1931	Nov. 4, 1930	1,411.7	2,500
	May 17	1,411.9	
1932	Nov. 17, 1931	1,410.7	8,500
	June 12	1,411.4	
	Oct. 19	1,409.9	5,000
	Nov. 3	1,410.4	
1933	Feb. 25	1,410.3	6,100
	May 31	1,410.8	
1934	April 25	1,408.8	--
	Sept. 13	1,407.1	
1935	Sept. 13, 1934	1,407.1	--
	Oct. 19	1,406.7	
1936	Oct. 19, 1935	1,406.7	5,000
	May 2	1,407.2	
1937	Oct. 24, 1936	1,405.1	--
	May 29	1,404.9	
1938	Mar. 21	1,403.1	7,200
	Apr. 15	1,404.0	
1939	Nov. 21, 1938	1,402.1	4,800
	Apr. 25	1,402.7	
1940	Mar. 22	1,401.5	6,200
	Apr. 29	1,402.3	
1941	Oct. 24, 1940	1,400.9	15,400
	June 6	1,402.9	
1942	Oct. 11, 1941	1,402.4	17,800
	June 8	1,404.5	

Table 5.--Annual net storage gain to Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage gain (acre-feet)
1943	Sept. 30, 1942	1,404.0	7,000
	June 30	1,404.7	
1944	Apr. 24	1,403.0	8,000
	June 30	1,404.0	
1945	Jan. 10	1,403.5	8,000
	June 4	1,404.4	
1946	Dec. 11, 1945	1,403.7	12,400
	Apr. 20	1,405.0	
1947	Jan. 7	1,403.5	800
	May 10	1,403.6	
1948	Oct. 13, 1947	1,403.0	20,000
	June 11	1,405.2	
1949	Oct. 28, 1948	1,404.2	30,000
	July 16	1,407.2	
1950	Apr. 11	1,406.6	110,000
	Sept. 24	1,415.0	
1951	Dec. 9, 1950	1,414.9	7,000
	May 3	1,415.5	
1952	Feb. 29	1,414.3	2,200
	Apr. 11	1,414.5	
1953	Jan. 30	1,412.5	9,100
	June 26	1,413.0	
1954	June 4	1,411.7	46,100
	Nov. 29	1,414.4	
1955	Mar. 1	1,414.4	28,100
	June 20	1,416.8	
1956	Jan. 31	1,416.2	63,400
	July 14	1,419.4	

Table 5.--Annual net storage gain to Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage gain (acre-feet)
1957	Jan. 28	1,418.4	6,600
	May 5	1,418.7	
1958	Jan. 1	1,418.1	--
	Oct. 8	1,416.6	
1959	Jan. 16	1,417.0	--
	Dec. 22	1,415.3	
1960	Jan. 1	1,415.6	8,200
	June 12	1,416.2	
1961	Feb. 14	1,414.8	1,100
	Apr. 19	1,414.9	
1962	Mar. 1	1,413.2	18,500
	June 13	1,414.3	
1963	Mar. 19	1,413.1	1,900
	May 3	1,413.2	
1964	Jan. 1	1,411.5	3,600
	June 19	1,411.8	
1965	Jan. 1	1,411.0	7,300
	June 4	1,411.6	
1966	Jan. 14	1,411.2	26,900
	July 8	1,412.9	
1967	Jan. 1	1,411.9	16,400
	May 15	1,412.8	
1968	Dec. 8, 1967	1,411.1	7,300
	June 13	1,411.7	
1969	Jan. 22	1,410.5	88,900
	Dec. 31	1,416.8	
1970	Jan. 1	1,416.8	55,500
	July 31	1,419.5	

Table 5.--Annual net storage gain to Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage gain (acre-feet)
1971	Mar. 3	1,418.8	54,900
	July 12	1,421.0	
	Aug. 31	1,420.7	8,900
	Nov. 31	1,421.1	
1972	Feb. 20	1,420.8	36,000
	June 3	1,422.3	
1973	Feb. 26	1,420.4	1,300
	Apr. 1	1,420.6	
1974	Jan. 11	1,419.2	152,000
	July 25	1,424.1	
1975	Dec. 13, 1974	1,422.8	65,000
	July 5	1,424.8	
1976	Jan. 22	1,423.4	59,400
	June 13	1,425.1	
1977	Jan. 12	1,422.7	6,000
	May 5	1,423.0	
1978	Jan. 1	1,421.9	26,900
	July 20	1,423.2	
1979	Jan. 10	1,422.1	248,100
	July 12	1,427.0	
1980	Jan. 3	1,425.8	15,800
	Apr. 21	1,426.1	
1981	Jan. 2	1,425.3	30,900
	June 24	1,425.9	
1982	Jan. 1	1,425.1	95,700
	July 24	1,426.9	
1983	Sept 27, 1982	1,426.2	104,100
	May 27	1,428.1	

Table 6.--Annual net storage loss from Devils Lake

[After examining the water-level records to obtain the maximum water level after spring breakup and the minimum water level at winter freezeup, net storage loss was computed by subtracting the volume of the lake at minimum water level from the volume of the lake at maximum water level]

Year	Date	Water level (feet above sea level)	Net storage loss (acre-feet)
1931	May 17	1,411.9	14,700
	Nov. 8	1,410.7	
1932	June 12	1,411.4	18,300
	Oct. 19	1,409.9	
1933	May 31	1,410.8	22,200
	Oct. 2	1,408.9	
1934	Apr. 25	1,408.8	18,000
	Sept. 13	1,407.1	
1935	May 23	1,407.4	7,000
	Oct. 19	1,406.7	
1936	May 2	1,407.2	21,000
	Oct. 24	1,405.1	
1937	Oct. 24, 1936	1,405.1	12,600
	Oct. 26	1,403.8	
1938	Apr. 15	1,404.0	15,200
	Nov. 21	1,402.1	
1939	Apr. 25	1,402.7	9,350
	Mar. 22, 1940	1,401.5	
1940	Apr. 29	1,402.3	10,600
	Oct. 24	1,400.9	
1941	June 6	1,402.9	4,800
	Sept. 20	1,402.3	
1942	June 8	1,404.5	5,000
	Sept. 30	1,404.0	

Table 6.--Annual net storage loss from Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage loss (acre-feet)
1943	June 30	1,404.7	11,800
	Nov. 6	1,403.4	
1944	June 30	1,404.0	6,400
	Oct. 19	1,403.2	
1945	June 4	1,404.4	8,000
	Nov. 1	1,403.5	
1946	Apr. 20	1,405.0	14,800
	Dec. 10	1,403.4	
1947	May 10	1,403.6	4,800
	Oct. 13	1,403.0	
1948	June 11	1,405.2	10,000
	Oct. 28	1,404.2	
1949	July 16	1,407.2	8,000
	Oct. 1	1,406.4	
1950	Dec. 1, 1949	1,406.5	--
	Oct. 2	1,415.0	
1951	May 3	1,415.5	13,500
	Nov. 20	1,414.3	
1952	Apr. 11	1,414.5	33,700
	Jan. 30, 1953	1,412.5	
1953	June 26	1,413.0	23,800
	Dec. 1	1,411.6	
1954	May 6	1,411.7	--
	Nov. 29	1,414.4	
1955	June 20	1,416.8	14,300
	Nov. 17	1,415.9	
1956	July 14	1,419.4	18,000
	Oct. 21	1,418.7	

Table 6.--Annual net storage loss from Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage loss (acre-feet)
1957	May 5	1,418.7	11,900
	Aug. 31	1,418.1	
1958	Feb. 26	1,418.3	28,600
	Oct. 8	1,416.6	
1959	Feb. 17	1,417.1	26,000
	Nov. 24	1,415.3	
1960	June 12	1,416.2	19,100
	Dec. 7	1,414.6	
1961	Apr. 19	1,414.9	27,000
	Dec. 12	1,413.1	
1962	June 13	1,414.3	25,900
	Dec. 4	1,412.8	
1963	May 3	1,413.2	30,000
	Dec. 3	1,411.4	
1964	June 19	1,411.8	12,500
	Nov. 22	1,410.8	
1965	June 4	1,411.6	7,500
	Sept. 12	1,411.0	
1966	July 8	1,412.9	18,200
	Dec. 1	1,411.9	
1967	May 15	1,412.8	26,300
	Dec. 8	1,411.1	
1968	June 13	1,411.7	12,500
	Nov. 5	1,410.7	
1969	Jan. 22	1,410.5	--
	Dec. 31	1,416.8	
1970	July 31	1,419.5	21,700
	Nov. 12	1,418.9	

Table 6.--Annual net storage loss from Devils Lake--Continued

Year	Date	Water level (feet above sea level)	Net storage loss (acre-feet)
1971	July 12	1,421.0	18,100
	Aug. 31	1,420.7	
1972	June 3	1,422.3	72,700
	Dec. 23	1,420.4	
1973	Apr. 1	1,420.6	53,800
	Nov. 18	1,419.1	
1974	July 25	1,424.1	57,500
	Oct. 30	1,422.8	
1975	July 5	1,424.8	63,300
	Nov. 23	1,423.4	
1976	June 13	1,425.1	108,000
	Nov. 30	1,422.7	
1977	May 5	1,423.0	59,100
	Nov. 20	1,421.6	
1978	July 20	1,423.2	48,000
	Nov. 10	1,422.0	
1979	July 12	1,427.0	65,100
	Dec. 16	1,425.8	
1980	Apr. 21	1,426.1	51,900
	Oct. 13	1,425.1	
1981	June 24	1,425.9	41,200
	Dec. 30	1,425.1	
1982	July 24	1,426.9	38,300
	Sept. 27	1,426.2	
1983	May 27	1,428.1	54,900
	Sept. 30	1,427.1	

Analysis of the water-level fluctuations indicates that there are 3 years that differ significantly from the conceptual model. In 1932, a secondary peak occurred as the water level rose 0.5 foot between October 19 and November 3. This was a relatively small rise, and it was the result of a net storage gain of 5,000 acre-feet. This net storage gain was caused by rainfall of about 2.50 to 3.00 inches over the entire Devils Lake basin (U.S. Department of Agriculture, Weather Bureau, 1932c). In 1971, another secondary peak occurred as the water level rose 0.4 foot between August 31 and November 31. This secondary peak was the result of a net storage gain of 8,900 acre-feet. This water-level rise principally was caused by generally intense rainfall over the Devils Lake basin in October. Rainfall amounts ranged from 2.75 inches at the city of Devils Lake to 5.95 inches at Bisbee, N. Dak., which is located near the headwaters of Mauvais Coulee (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1971).

The water-level rise that occurred during the summer of 1954 (fig. 6) differs markedly from the conceptual model. No change in the water level of Devils Lake could be attributed to snowmelt runoff and spring rains. Then, in June, the water level began to rise from 1,411.7 feet above sea level and reached a maximum of 1,414.4 feet above sea level on November 29. This water-level rise of 2.7 feet was the result of a net storage gain of 46,100 acre-feet.

Two periods of intense rainfall contributed to the sustained runoff throughout the summer months of 1954. In June, rainfall totals ranged from 8.55 inches at the city of Devils Lake to 14.94 inches at Belcourt in the Turtle Mountain Indian Reservation, N. Dak. (U.S. Department of Commerce, Weather Bureau, 1954a). The normal June rainfall is 3.32 inches at the city of Devils Lake and 3.18 inches at Belcourt (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982). The rainfall in June of 1954 recharged the soil-moisture storage and filled the chain of lakes upstream of Devils Lake. The combined July and August rainfall ranged from 1.83 inches greater than normal at Langdon to 2.19 inches less than normal at the city of Devils Lake. The relatively normal precipitation of July and August was followed by generally intense rainfall over the entire Devils Lake basin in September. September rainfall totals ranged from 2.92 inches at Bisbee to 5.71 inches at Langdon (U.S. Department of Commerce, Weather Bureau, 1954b). Normal September rainfall is 1.60 inches at Bisbee and 1.97 inches at Langdon (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1973, 1982). Water-level fluctuations of Devils Lake for 1954 are shown in figure 6. The water-level rises caused by the two rainstorms are evident. Thus, even though the inflow usually decreases from late July through early September, in 1954 inflow and precipitation were greater than evaporation and the water level continued to rise throughout the summer and fall.

Net storage loss was computed by examining the water-level records to obtain the maximum water level after spring breakup and the minimum water level at winter freezeup. Annual net storage loss was computed by subtracting the capacity of the lake at minimum water level from the capacity

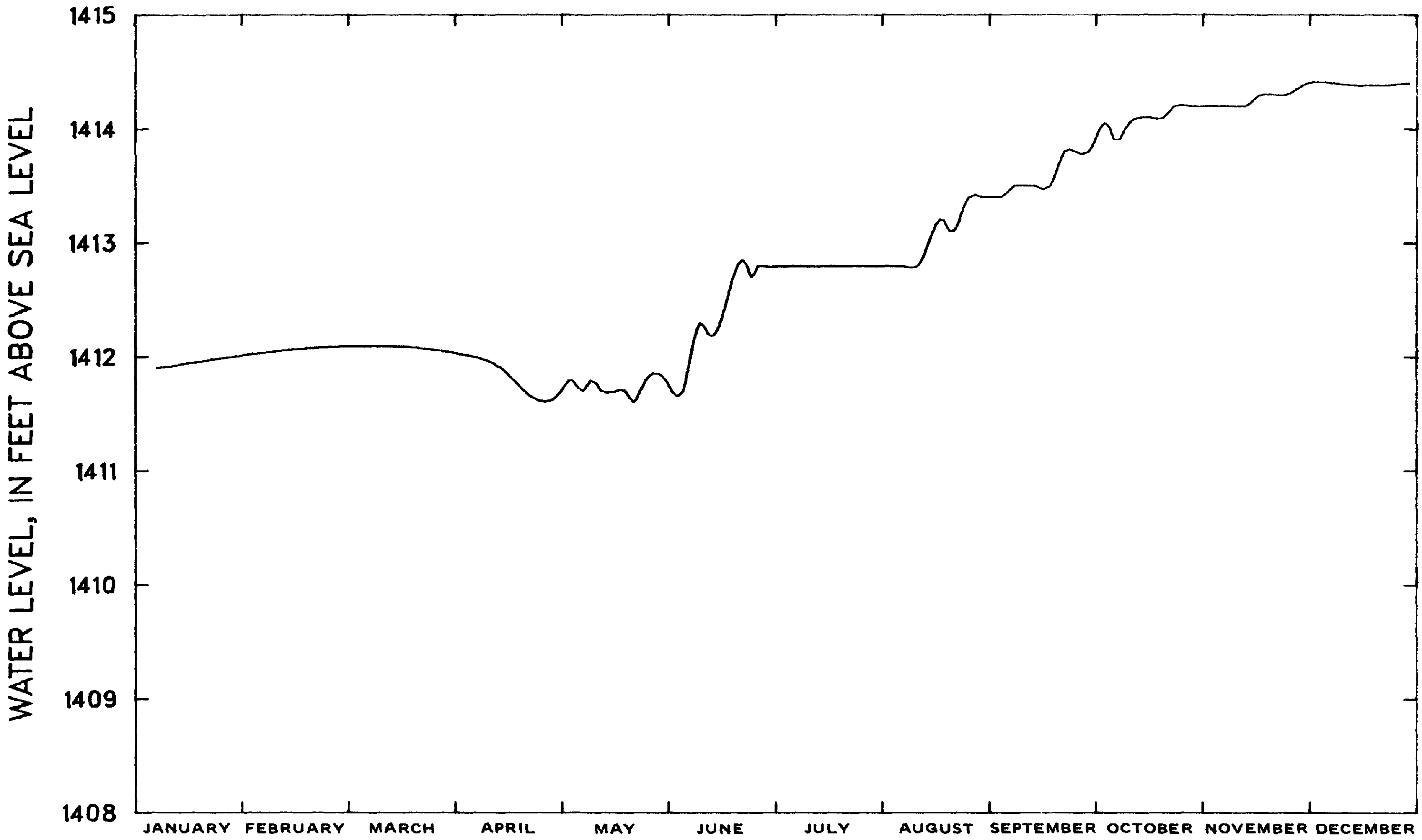


Figure 6.—Water levels of Devils Lake, January-December 1954.

of the lake at maximum water level. The precipitation (P_{LS}) falling on the lake surface and the evaporation (E_{LS}) from the lake surface are assumed to be equal between the time that the minimum water level and the maximum water level were recorded. The ground-water contribution (G) was assumed to be negligible. Net storage losses from Devils Lake have not been as variable as the net storage gains to the lake. From 1931 through 1969 the net storage loss ranged from zero in 1950, 1954, and 1969 to 33,700 acre-feet in 1952 (table 6). Since 1969 the net storage loss has averaged about 53,800 acre-feet per year. The large increase in net storage loss since 1969 primarily is the result of the large increase in the surface area of Devils Lake during the 1970's.

The water-balance model (equation 1) also was used to estimate the variability of inflow to Devils Lake that has occurred during 10-year to 20-year intervals. Equation 1 was used along with the following assumptions: (1) The average precipitation recorded at the city of Devils Lake is representative of the precipitation falling on Devils Lake, (2) the average evaporation from shallow ponds and lakes (U.S. Department of Commerce, 1959) is representative of the evaporation from the surface of Devils Lake, (3) the average surface area of Devils Lake for the period was computed using the average water level for the period, and (4) the total storage change that occurred during the period was assumed to occur in equal increments during the period.

Undoubtedly, there are uncertainties in these assumptions, but it was outside the scope of this study to complete an analysis of how errors in the assumptions would affect the water-balance variables. Although the assumptions used in conjunction with equation 1 may be valid "on average" they probably will be poor during periods of climatic extremes. As an example, during years when precipitation is greater than normal, the cool, humid weather reduces evaporation. During droughts, when precipitation is less than normal, the hot, dry weather increases evaporation. A comprehensive discussion of the errors associated with the variables used to estimate the water balance of lakes can be found in a report by Winter (1981).

Inflow for 1867-84 and 1931-40 was computed using equation 1. The years 1867-84 represent a "wet" period that had the highest sustained lake levels for the period of record (1867-1983). The years 1931-40 represent a "dry" period that had the lowest sustained lake levels. Although the selection of the "wet" and "dry" periods is subjective, the inflow computed for each period indicates the large differences in runoff that have occurred in the Devils Lake basin for 10 years or more. The water-balance equations for the two periods are listed in table 7. Although water levels generally declined during 1867-84, 58,300 acre-feet of inflow to Devils Lake occurred.

The net storage gain to Devils Lake for the more recent period of rising water levels (1969-83; fig. 7) is greater than the net storage gain during any of the periods listed in table 8. The words "gradual" and "rapid" have been used in table 8 and in the text to modify rising or declining water levels of Devils Lake. Gradual refers to a water-level change of 0.6 foot or less per year and rapid refers to a water-level change of 0.9 foot or more per year. The annual net storage gain to Devils Lake averaged 70,000

Table 7.--Computed water-balance equations for Devils Lake for 1867 through 1884 and 1931 through 1940

Period	(Acre-feet) Storage change		Inflow		Precipitation	Evaporation
1867-84	-20,800	=	58,300	+	116,700	- 195,800
1931-40	-10,900	=	2,800	+	12,600	- 26,300

acre-feet per year during 1969-83 as compared to an average annual inflow of 58,300 acre-feet (based on water-balance computations) during 1867-84. The average annual net storage gain of 70,000 acre-feet during 1969-83 is greater than the total net storage gain of 45,300 acre-feet for the drought years of 1931-40.

Hydrologic and Climatologic Interaction

To evaluate the relationship between water-level fluctuations and climatic indices, an attempt was made to compare runoff to winter (October through April) precipitation. A linear regression model was developed that used annual discharge at the Mauvais Coulee near Cando gage as the dependent variable and winter precipitation at the city of Devils Lake as the independent variable. Winter precipitation was chosen as the independent variable because it represents the majority of precipitation available for runoff during the spring. The Mauvais Coulee gage was chosen because it has only 10 square miles of noncontributing drainage area out of a total drainage area of 387 square miles. Twenty-seven pairs of data were used in the linear regression equation. These provide a coefficient of determination (r^2) of 0.20, which indicates little relation between annual discharge and winter precipitation. Apparently, other climatologic variables such as antecedent moisture, temperature during the snowmelt, and wind velocity affect the amount of runoff derived from a given snowpack. In addition, the city of Devils Lake is not located in the Mauvais Coulee basin; therefore, the precipitation recorded at the city of Devils Lake only may provide a qualitative index of precipitation. A more complete discussion of the climatologic variables affecting runoff can be found in a study by Miller and Frink (1984, p. 41). Miller and Frink (1984) developed a regression equation to compute the 30-day snowmelt volume for the Red River of the North at Grand Forks, N. Dak., that had a coefficient of determination of 0.91. The independent variables Miller and Frink (1984) used were: (1) Winter precipitation south of Grand Forks, (2) an

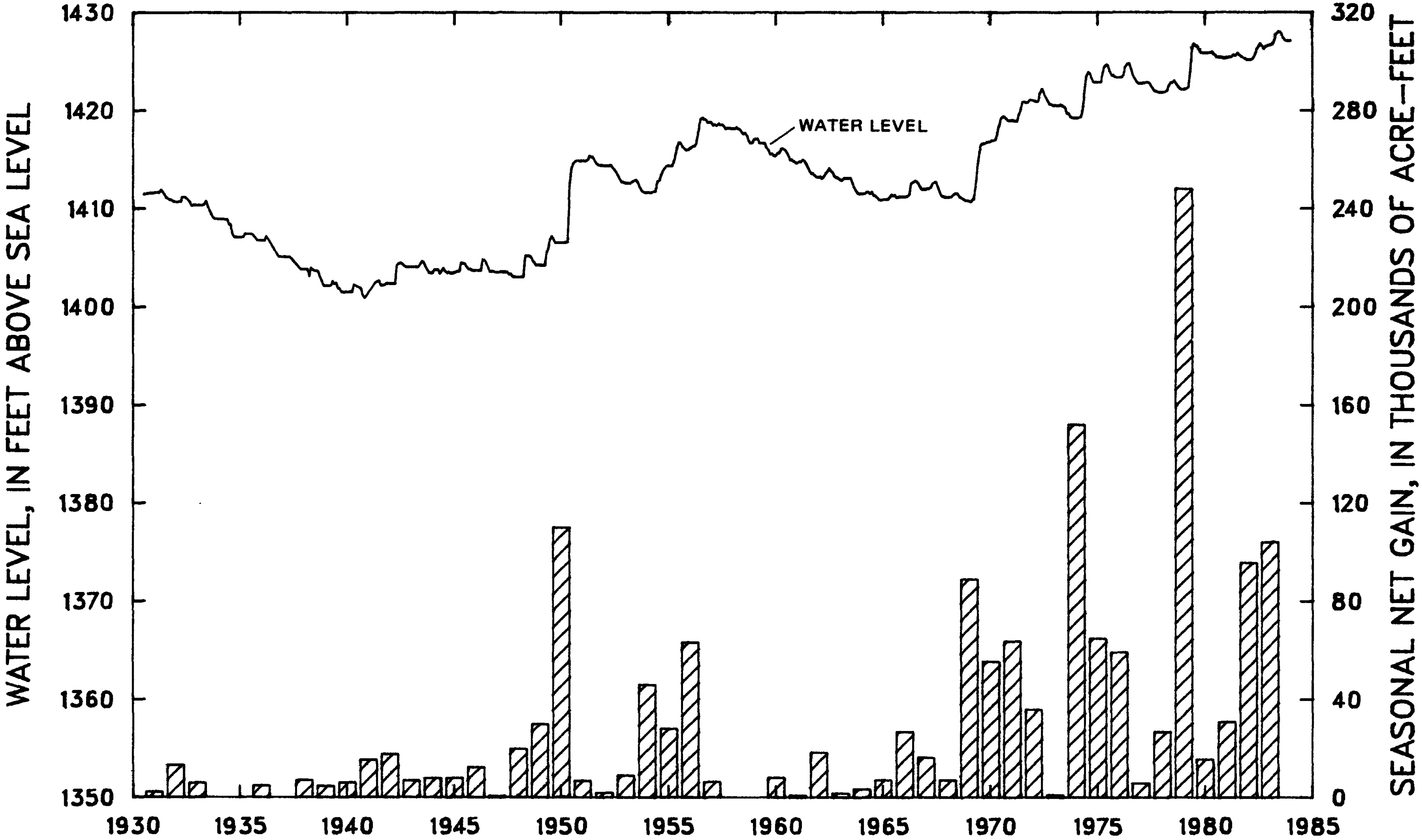


Figure 7.—Recorded water levels and annual net storage gain of Devils Lake, 1931-83.

Table 8.--Major lake-level fluctuations of Devils Lake

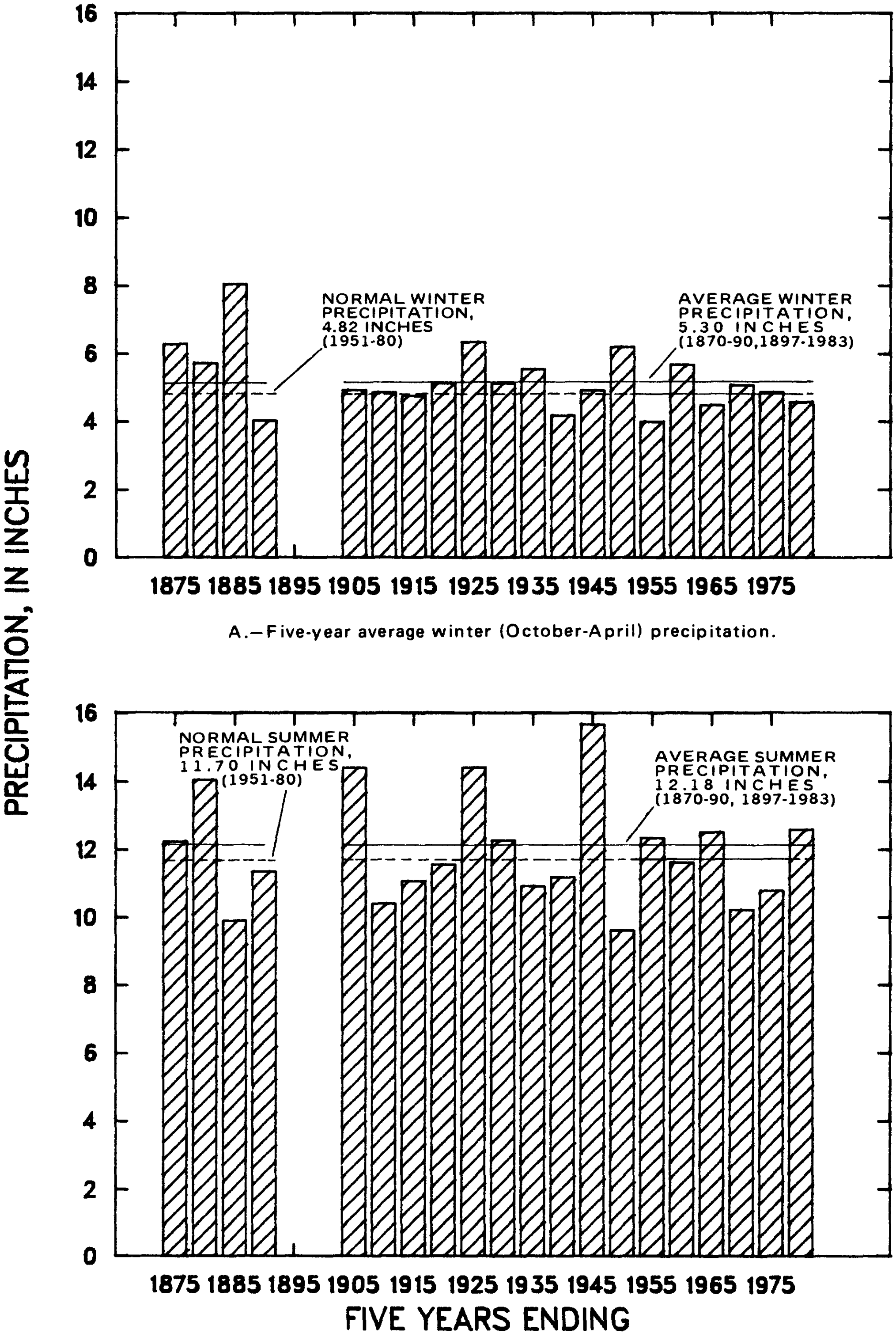
Years	Comparative water-level fluctuations	Water level (feet above sea level)
1867-84	High lake-level.	1,438.0-1,434.4
1885-90	Rapid decline.	1,434.4-1,424.6
1891-1906	Constant lake level.	1,425
1907-30	Gradual decline.	1,424.6-1,411.4
1931-40	Rapid decline.	1,411.4-1,402.3
1941-49	Gradual rise.	1,402.3-1,407.3
1950	Rapid rise.	1,407.3-1,414.9
1951-57	Gradual rise.	1,414.9-1,418.2
1958-68	Gradual decline.	1,418.2-1,411.7
1969-83	Rapid rise.	1,411.7-1,428.1

antecedent-moisture index south of Grand Forks, (3) a winter-temperature index, (4) a snowmelt index at Grand Forks, (5) 1-year lag volume, and (6) a land-use index factor. Based on their work, an improvement in the coefficient of determination could be made using a more complex multiple-regression model, but the development of a complex multiple-regression model was outside the scope of this study.

Because of the limited correlation between runoff from the tributaries in the Devils Lake basin and the winter precipitation and also because of the storage in the upstream chain of lakes, there is little likelihood of establishing good relationships between Devils Lake water-level fluctuations on a yearly basis and climatologic variables. Thus, a more general, less quantitative approach was attempted by grouping the water levels into major lake-level fluctuations. The major lake-level fluctuations are listed in table 8 along with their beginning and ending water levels.

The high water levels of Devils Lake from 1867 through 1884 were, in part, caused by the relatively greater-than-average winter precipitation of 6.78 inches from 1867 through 1884 (fig. 8A; U.S. Department of Agriculture, 1932b). In addition to the relatively greater-than-average winter precipitation, 1871-80 is characterized as having relatively wet summers (fig. 8B). No precipitation data were recorded in the Devils Lake basin prior to 1870.

Indirect evidence, based on climatic data for 1931-60 (Wahl and Lawson, 1970), indicates that the high water level prior to 1880 was caused by greater-than-average precipitation and less-than-average temperatures. Wahl and Lawson (1970) indicated that during 1850-69 the September through December precipitation was 10 to 20 percent greater than



B.—Five-year average summer (May-September) precipitation.

Figure 8.—Five-year average precipitation at Fort Totten (1870-90) and at the city of Devils Lake (1897-1983).

normal and the January through March precipitation was 30 to 40 percent greater than normal. This period of greater-than-average winter precipitation correlates with the evidence provided by Upham (1895) that indicated that the high water level probably began several years before 1867. Miller and Frink (1984) listed the major floods on the Red River of the North and they noted that large floods occurred in 1826, 1852, and 1861. Annual precipitation at Fort Totten, N. Dak., which is located 10 miles southwest of the city of Devils Lake, was greater than normal (1951-80) precipitation for 13 of the 15 years during 1870-84. At Bismarck, N. Dak., where the normal (1951-80) precipitation is 15.36 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982), the annual precipitation was greater than 20 inches in 6 of the 10 years during 1875-84 (U.S. Department of Agriculture, Weather Bureau, 1932a). Upham (1895) provided climatologic data at Winnipeg, Manitoba, that indicated a relatively wet period from 1875 through 1884. Thus, based on the climatologic record, a relatively wet period occurred in the Devils Lake basin and surrounding areas from at least 1875 through 1884.

A rapid water-level decline of about 10 feet occurred during 1885-90. The volume of Devils Lake decreased by about 584,000 acre-feet, or about 48 percent. The average annual precipitation during this period was 15.67 inches at Fort Totten, compared to the normal (1951-80) precipitation of 16.52 inches at the city of Devils Lake (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982). Thus, compared to the normal (1951-80) precipitation, 1885-90 was not extremely dry, but a significant decrease of 15.2 percent in average annual precipitation occurred from 1870-84 (18.47 inches) to 1885-90 (15.67 inches). At Bismarck, a marked decrease in average annual precipitation of 33 percent occurred from 1875-84 (21.48 inches) to 1885-90 (14.33 inches; U.S. Department of Agriculture, Weather Bureau, 1932a).

Based on limited data, the water level of Devils Lake remained relatively constant from 1891 through 1906 (fig. 3). No precipitation data are available from 1891 through 1896, but winter precipitation was relatively uniform from 1897 through 1906. The winter of 1896-97 was exceptionally severe, and it seems probable that precipitation in the Devils Lake basin was relatively great, although precipitation data are not available from October through December 1896. Melting of a great accumulation of snow in the Red River Valley caused the largest flood of record at Grand Forks (Miller and Frink, 1984). A significant water-level rise on Devils Lake might have occurred, but there are no recorded water levels from 1891 through 1895.

The water level of Devils Lake declined from 1907 through 1940; the most rapid decline was from 1930 through 1940. The winter precipitation was relatively uniform from 1901 through 1935 except for the greater winter precipitation during 1921-25 (fig. 8A). Even though there was an increase in winter precipitation during 1921-25, the lake declined 1.9 feet. The climate during 1931 to 1940 can be characterized as having less-than-average summer precipitation, slightly greater-than-average winter precipitation from 1931-35 and less-than-average winter precipitation from 1936 to 1940, and relatively substantial evaporation as indicated by the average summer temperature at Devils Lake (fig. 9). Thus, the decline in water levels from 1931 to 1940 was the result of: (1) Minimal inflow to Devils Lake, (2) hot summers (indicative of substantial evaporation), and (3) minimal summer precipitation. The hot summers and minimal summer precipitation caused large evaporative losses from the lake surface.

Water levels of Devils Lake rose 5.0 feet from 1941 through 1949, but this rise was caused by a relatively small increase in volume of 19,000 acre-feet. From 1941 through 1945, winter precipitation was about average, but summer precipitation was the greatest for the period of record and the summer temperature was less than average. Thus, the evaporative losses from the lake surface probably were less than average. From 1945 through 1958, summer precipitation was less than average, winter precipitation greater than average, and the summer temperature was about average.

The rapid water-level rise in 1950 was caused by the large accumulation of snow during the winter of 1949-50. The meteorologic factors that set the stage for this rise are discussed in an article by Nelson (1951).

A gradual rise in water levels occurred from 1951 through 1957, yet the average winter precipitation was only 4.64 inches. Summer precipitation (fig. 8A) and temperatures (fig. 9) were about average. The apparent discrepancy of rising water levels at a time of minimal winter precipitation is due to the fact that most of the rise in water levels occurred during 3 years (1954, 1956, and 1957) that had relatively substantial winter precipitation. Winter precipitation for the other 4 years during 1951-58 was minimal--thus, the less-than-average winter precipitation for a period of rising water levels.

Water levels declined from 1958 through 1968. During the period, winter and summer precipitation were about average, and there was no obvious climatologic variable that explains the decline in water levels.

Not all periods of water-level rise have good correspondence with winter precipitation. Devils Lake has risen approximately 16.4 feet from 1969 through 1983, yet the winter precipitation averaged only 5.22 inches during the period (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1970-84). The summer precipitation was less than average for 1971-75 and slightly greater than average for 1976 to 1980.

Although water-level fluctuations seem to show good correspondence to the climatologic variables of precipitation and temperature on time scales of 5 years and more, there are periods that do not show good correspondence. The best correspondence between water-level fluctuations and the climatic variables occurs during the abnormally wet periods (1870-84) and the abnormally dry periods (1931-40). Regression techniques, such as those used by Miller and Frink (1984), could be used to investigate some of the subtle combinations of climatologic variables and may better

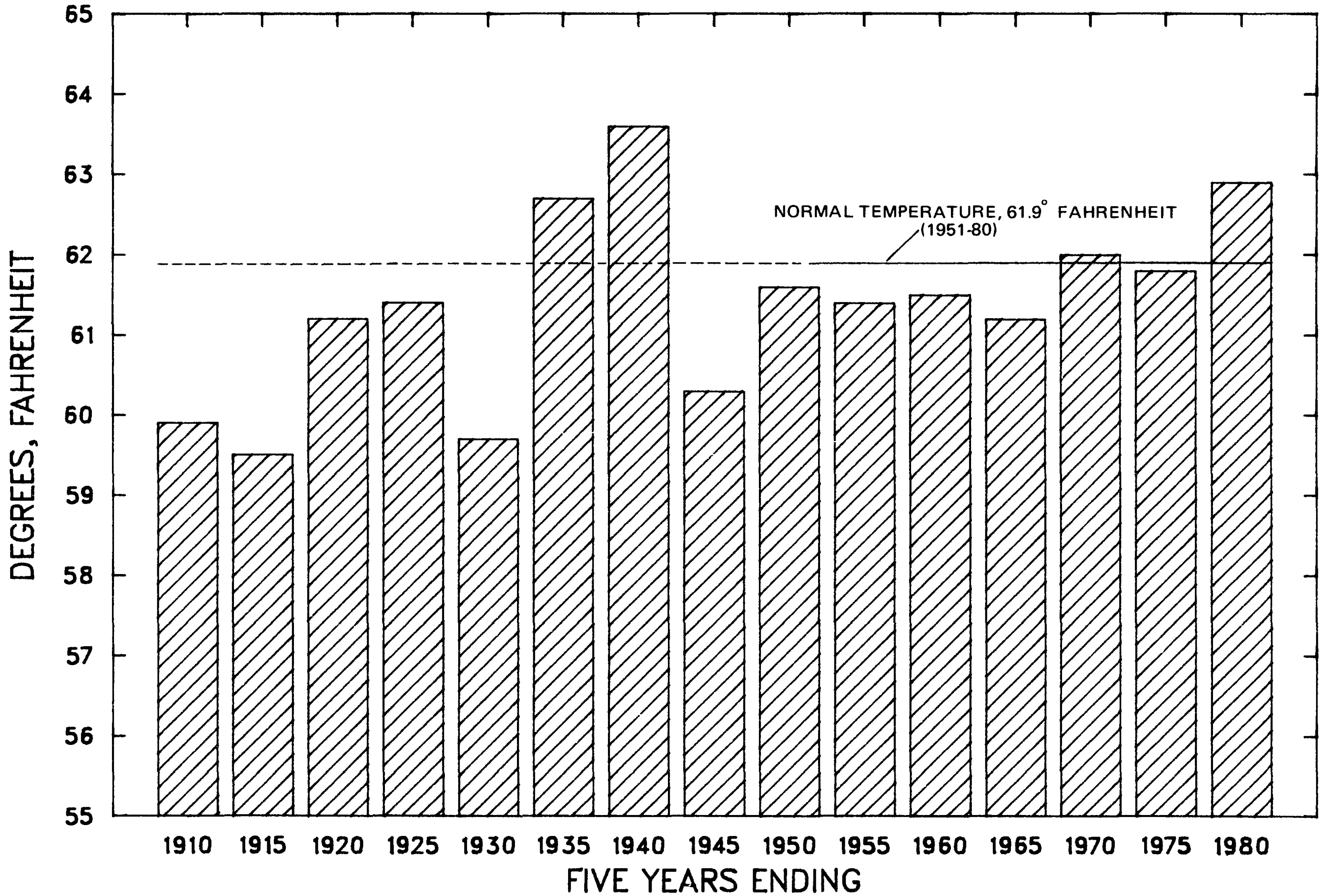


Figure 9.—Five-year average summer (May-September) temperature at the city of Devils Lake.

explain water-level fluctuations of Devils Lake. However, application of these regression techniques was outside the scope of the study.

As a general summary of the correspondence of climatic and hydrologic conditions to water levels of Devils Lake, cumulative departures from the average winter precipitation and water levels of Devils Lake are plotted in figure 10 for 1931-83. Relatively good agreement occurs between water-level fluctuations and changes in cumulative departure from average winter precipitation, except for 1969-80. Apparently other factors, such as changes in basin storage, changes in contributing and noncontributing drainage area, the timing and rate of snowmelt, and antecedent moisture conditions, caused an increase in water levels at a time when winter precipitation did not increase significantly.

RESEARCH CONDUCTED ON OTHER TERMINAL LAKES AND LONG-TERM DISCHARGE RECORDS

The general correspondence of water-level changes of terminal lakes throughout North America lends credence to the dominance of climatic factors in controlling lake levels. A literature search indicates such a general correspondence exists between water levels of Devils Lake and many other terminal lakes in North America. Discussion of known conditions affecting water-level fluctuations of these lakes in North America and terminal lakes located outside North America follows. Research conducted on long-term discharge records was reviewed to determine if there are relatively long periods of greater-than- or less-than-average discharge.

Water-Level Fluctuations of Terminal Lakes

Rising water levels of terminal lakes in Minnesota have caused serious flooding in recent years (R.G. Brown, U.S. Geological Survey, written commun., 1984). Big Marine Lake, a 1,900-acre lake located in northern Washington County, Minn., had experienced a general rise in water levels from 1965 to 1982. The original Government Land Office Survey plot made in 1847 shows the size of the lake to have been 2,300 acres in 1847. Big Marine Lake has a drainage area of about 6,010 acres. Unlike Devils Lake, water-level fluctuations of Big Marine Lake are controlled by surficial aquifers. Substantial interaction occurs between the aquifers and the lake, and a rise in water level of Big Marine Lake can be detected a few days to a few weeks after precipitation has occurred. The rise in water levels of Big Marine Lake from 1965 to 1982 correlates with the positive cumulative departure from average annual precipitation. A large negative cumulative departure from the average annual precipitation during 1930-40 occurred at a time when historical documents indicate low water levels of Big Marine Lake (R.G. Brown, written commun., 1984). R.G. Brown (written commun., 1984) concluded that future lake-level changes of Big Marine Lake will depend on long-term precipitation patterns. Therefore, based on the large negative departure from average annual precipitation for 1930-40, the inference can be made that water levels of Big Marine Lake were relatively low during this period.

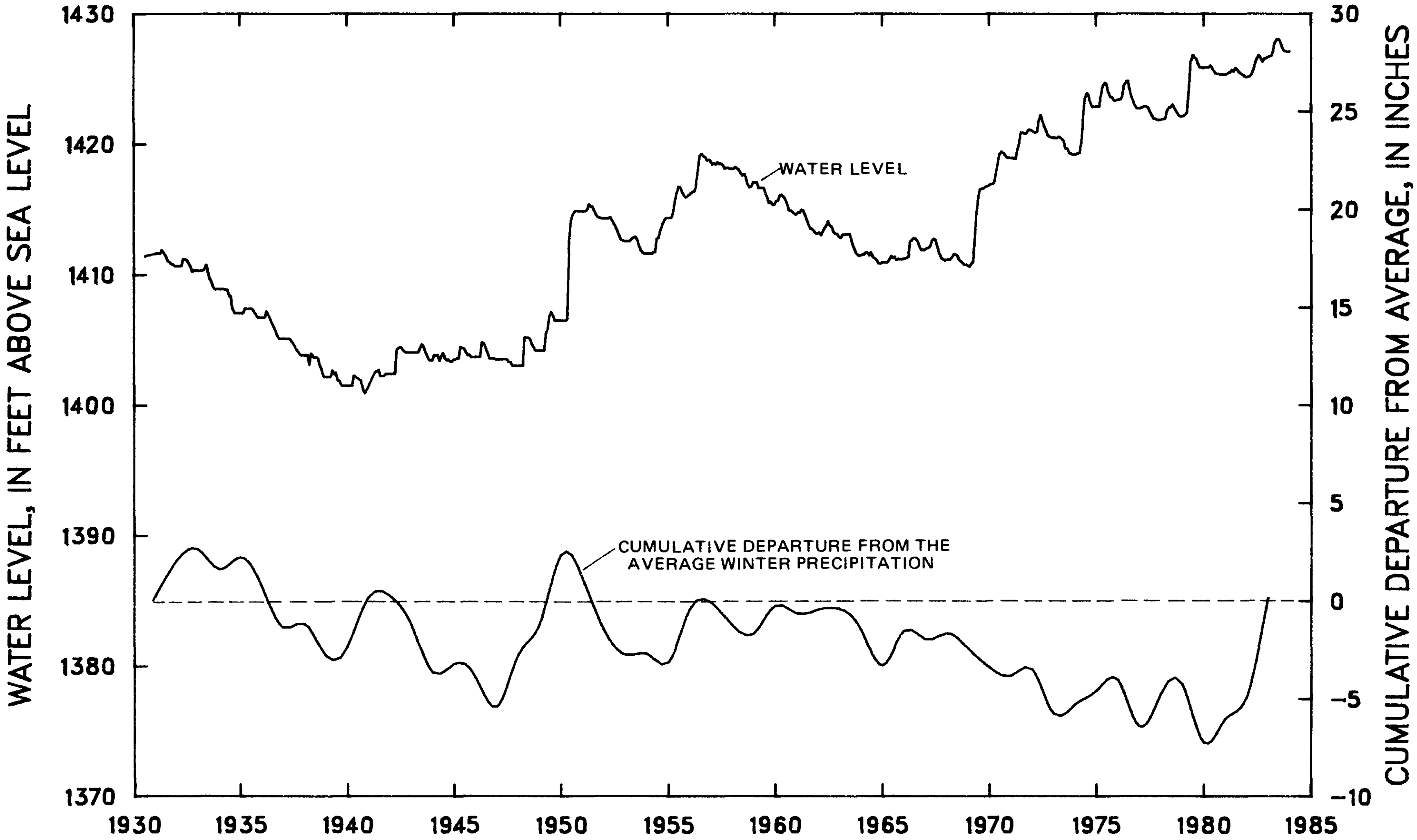


Figure 10.—Recorded water levels of Devils Lake and cumulative departure from the average winter precipitation, 1931-83.

Whitewater Lake, located 60 miles south of Brandon, Manitoba, has a drainage area of about 320 square miles. The lake has been subject to high water levels, especially from 1974 through 1976. During the period of record, 1921-76, Whitewater Lake has fluctuated from dry (1,625 feet above sea level) from 1934 through 1940 to a maximum water level of 1,632.3 feet above sea level in 1976 (MacKenzie, 1977).

Agricultural flooding has been a problem in recent years near Dennis Lake, located near Lake Winnipeg in Manitoba. Dennis Lake has a 150-square mile drainage area. As a result of high water levels, the Manitoba Department of Natural Resources completed a study that analyzed the hydrology of the Dennis Lake drainage basin and analyzed the preliminary design of different control structures and drains (Ngai, 1981).

Water levels of Dennis Lake were collected from 1966 through 1980. High water levels in Dennis Lake occurred from 1974 through 1980. These high water levels were caused primarily by the wet years of 1974 and 1979. A water-balance model was developed and calibrated using the period of record, 1966-80. Simulated water levels for the period of record were computed using the proposed regulation structures.

No probabilities were computed for future water levels of Dennis Lake. The statement was made that "* * *the period of record used in this study was considered representative of a typical hydrological cycle although the period may have been somewhat wetter than average." (Ngai, 1981). Therefore, the conclusion was reached that the simulated water levels should provide an assessment of how the regulation structures will affect the water levels of Dennis Lake.

Sixty lakes in central and southern Saskatchewan were investigated during 1938 to 1943 by Rawson and Moore (1944). The thrust of their investigation centered on identifying the seasonal, annual, and long-term variations in salinity. Many of the lakes studied were in closed basins. Rawson and Moore (1944) indicated that from available precipitation records it is evident that the maximum precipitation in Saskatchewan during the 1800's occurred during 1870-85. Although no water-level information is available, the terminal lakes in Saskatchewan probably had high water levels during 1870-85. The greater-than-average precipitation in Saskatchewan from 1870 to 1885 correlates well with the high water levels of Devils Lake during this period.

Water levels of lakes in closed drainage basins in Saskatchewan have had different trends in recent years. Kenosee Lake and White Bear Lake, located in Moose Mountain Provincial Park, have had low water levels in recent years (D.R. Richards, Saskatchewan Water Corporation, written commun., 1984). Water levels of these two lakes were high from 1928 to 1931, declined 15 feet from 1932 to 1954, rose 15 feet in 1955 and 1956, and slowly declined 12 feet to a low in 1982. The present low water levels on Kenosee Lake and White Bear Lake primarily have been caused by greater-than-average evaporation from 1964 through 1982 (D.R. Richards, written commun., 1984). The precipitation was less than average in the 1960's, greater than average in the 1970's, and less than average in the early 1980's. According to a study completed by the Saskatchewan Environment Hydrology Branch, the increase in precipitation in the 1970's was offset by the substantial evaporation, which resulted in declining water levels on Kenosee Lake and White Bear Lake in the 1970's (D.R. Richards, written commun., 1984).

Fishing Lake, located in a closed drainage basin in east-central Saskatchewan, has been affected by rising water levels in recent years. Water levels of Fishing Lake have risen about 7.2 feet during September 1964 to June 1979 (Inland Waters Directorate, Water Resources Branch, Water Survey of Canada, 1965-83). A water-balance model of the Fishing Lake basin was used in an attempt to simulate water levels of Fishing Lake under various degrees of development in the basin. The conclusion was reached that the period of record (1964-80) of hydrologic and climatologic data required for simulations was not long enough for statistical analysis of water levels (D.R. Richards, written commun., 1984).

In recent years, public concern has been voiced because of declining water levels of lakes in the Cooking Lake moraine, which is located 25 miles southeast of Edmonton, Alberta. The Cooking Lake moraine consists of an area of about 695 square miles and is comprised of several small closed lake basins. Written accounts of water levels in the Cooking Lake moraine begin in 1865 when travelers to the area mentioned that the lakes had low water levels (Nyland, 1969). Lake levels in the Cooking Lake moraine rose substantially in the 1870's due to greater-than-average precipitation. The timing of this rise in water levels corresponds to the high water levels recorded on Devils Lake (fig. 3).

Water levels of lakes in the Cooking Lake moraine declined during relatively dry years in the 1880's and 1890's, and then they rose during the wet years, 1899-1904 (Woodburn, 1977). The water levels of the lakes steadily declined from about 1904 until 1949, then they rose during the early 1950's. Unlike Devils Lake, the lakes in the Cooking Lake moraine had the lowest levels in approximately 100 years in the early 1970's. Woodburn (1977) concluded that climatic factors are the most probable cause for the decline in water levels of the lakes in the Cooking Lake moraine. Laycock (1973) documented the climatic factors in central Alberta and indicated that annual precipitation was less than average for many years from the mid-1930's through 1973. Two notable exceptions are 1950-56 and 1972-74 when precipitation was much greater than average. The lakes had significant water-level rises during these two periods.

Phillips and Van Denburgh (1971) conducted a study to determine the historic variations in water levels and chemical character of several terminal lakes in south-central Oregon including Lake Abert, Summer Lake, Goose Lake, Silver Lake, and Malhuer Lake. The longest period of record available for any of these terminal lakes was a computed water-level hydrograph for Lake Abert for 1915-64. This hydrograph was computed using an annual water-budget equation, infrequent water-level measurements prior to 1950, and frequent water-level measurements from 1950 through 1964.

There is agreement between the water-level fluctuations of Lake Abert and those of Devils Lake. The water level of Lake Abert declined 11 feet during 1915-24, when the lake went dry. During the same period, the water level in Devils Lake declined. From 1924 through 1937, Lake Abert was dry or nearly dry (Phillips and Van Denburgh, 1971); at the same time, the water level in Devils Lake was near a historic minimum. After the drought of the 1930's, the water level in Lake Abert rose about 4 feet and then remained relatively constant from 1938 through 1950; whereas, the water level in Devils Lake rose gradually from 1941 through 1949 and then rose rapidly in 1950. The water level in Lake Abert rose during a relatively wet period from 1951 through 1958, then declined slightly through 1964; whereas, the water level in Devils Lake rose from 1951 through 1957 and then declined from 1958 through 1968. Phillips and Van Denburgh (1971) indicated that water-level fluctuations of the terminal lakes in south-central Oregon are caused by climatic variability.

Rising water levels of Malhuer Lake have inundated about 70,000 acres and forced some ranchers to evacuate (Oregon Department of Agriculture, 1984). Malhuer Lake drains 2,100 square miles of the closed Harney basin and has a rapid response time, as it changed from a dry lake bed in 1977 to the highest water level in recorded weather history in 1983 (Oregon Department of Agriculture, 1984). Most of the discharge entering Malhuer Lake is derived from tributaries draining the mountains surrounding the Harney basin. A study by Hubbard (1975) includes a thorough discussion of the hydrology of Malhuer Lake.

A hydrologic model using water-balance techniques was developed to estimate water levels on Malhuer Lake for 1984-85. Because of the rapid response of Malhuer Lake to precipitation, short-term predictions are critical for planning purposes. The problems encountered in the Harney basin are similar to those encountered in many of the closed basins of North America. The need to develop a method or methods to estimate future water-level probabilities is evident based on the following conclusions in the Malhuer Lake study: (1) There are no firm predictions on how long it will take until the water levels recede naturally nor how long it will take to reclaim the land that presently is affected; and (2) water levels could stabilize at their current elevation, they could continue to rise to unpredictable levels, or they could recede until the lake is dry (Oregon Department of Agriculture, 1984).

Mono Lake is a terminal lake draining a 750 square-mile closed basin 190 miles east of San Fransisco, Calif., along the California-Nevada border. Since 1940, the city of Los Angeles has been diverting a large percentage of the runoff that normally enters Mono Lake and the water level has declined 37 feet during 1940-84 (Todd, 1984). The U.S. Geological Survey began measuring water levels on Mono Lake in 1912. The maximum water level of 6,428.1 feet above sea level for the period of record (1912 to 1984) occurred in 1919. Todd (1984) indicated that "* * *during the past 3,500 years the water level of Mono Lake has fluctuated in irregular cycles over a vertical range of more than 130 feet in response to variations in climate, and more recently, human impacts." Although, in a hydrologic context, the large water withdrawals since 1940 limit any comparison of water levels between Mono Lake and Devils Lake, Mono Lake did have a 4-foot decline in water levels during the 1930's.

Todd (1984) mentioned that there is considerable interest in knowing what will happen to future water levels of Mono Lake. Although climate variations will have some affect on future water levels, diversions by the city of Los Angeles will be the major controlling factor.

Great Salt Lake, Utah, is the most well known and best documented terminal lake in North America. In fact, a recent publication by Gwynn (1980) includes papers discussing the scientific, historical, and economic aspects of the Great Salt Lake. The Great Salt Lake has a surface area of about 1,700 square miles (about one-half the drainage area of Devils Lake) at a water level of 4,200 feet above sea level, which is the average water level during historic times (Arnow, 1984). Most of the inflow into the Great Salt Lake is derived from snowmelt runoff from the Wasatch Mountains east of Salt Lake City.

A water-budget model for the Great Salt Lake was computed on a monthly basis for 1931-76 (Waddell and Barton, 1980). The model was developed so that the water and salt balances of Great Salt Lake could be analyzed for various combinations of diked bay areas. No estimates of future water-level probabilities were made.

Arnow (1984) conducted a study of the water-level changes in Great Salt Lake from 1847 to 1983. The primary purpose of Arnow's study was to describe the background and conditions that led to the 5.2-foot rise of water level in 1982 and 1983. The historic water levels of Great Salt Lake are shown in figure 11.

Arnow (1984) indicated that Great Salt Lake has fluctuated primarily in response to climatic variation. A quantitative comparison between major water-level changes of Great Salt Lake and Devils Lake is listed in table 9. Apparently, the climatic extremes are the same for the two lakes. The extremes in water levels are similar. The high water levels of Great Salt Lake and Devils Lake occurred during 1860-85. In contrast, the drought from 1930 to 1940 caused major water-level declines in both lakes. Water-level changes of Great Salt Lake and Devils Lake are similar from 1953 to 1983; however, water levels in Devils Lake appear to change about 5 years later than the change is evidenced in Great Salt Lake (fig. 11). Great Salt Lake began to decline in 1953, whereas Devils Lake began to decline in 1958; Great Salt Lake began to rise in 1964, and Devils Lake began to rise in 1969.

Despite the correspondence of water levels in the past 30 years, historic water-level fluctuations of the two lakes have not been always in concert. As an example, water levels of Great Salt Lake rose from 1906 through 1924, but water levels of Devils Lake declined during the period.

Many other water-budget studies of Great Salt Lake have been developed primarily to assist industries in analyzing the salinity differences between the north and south parts of the lake, which were created by the

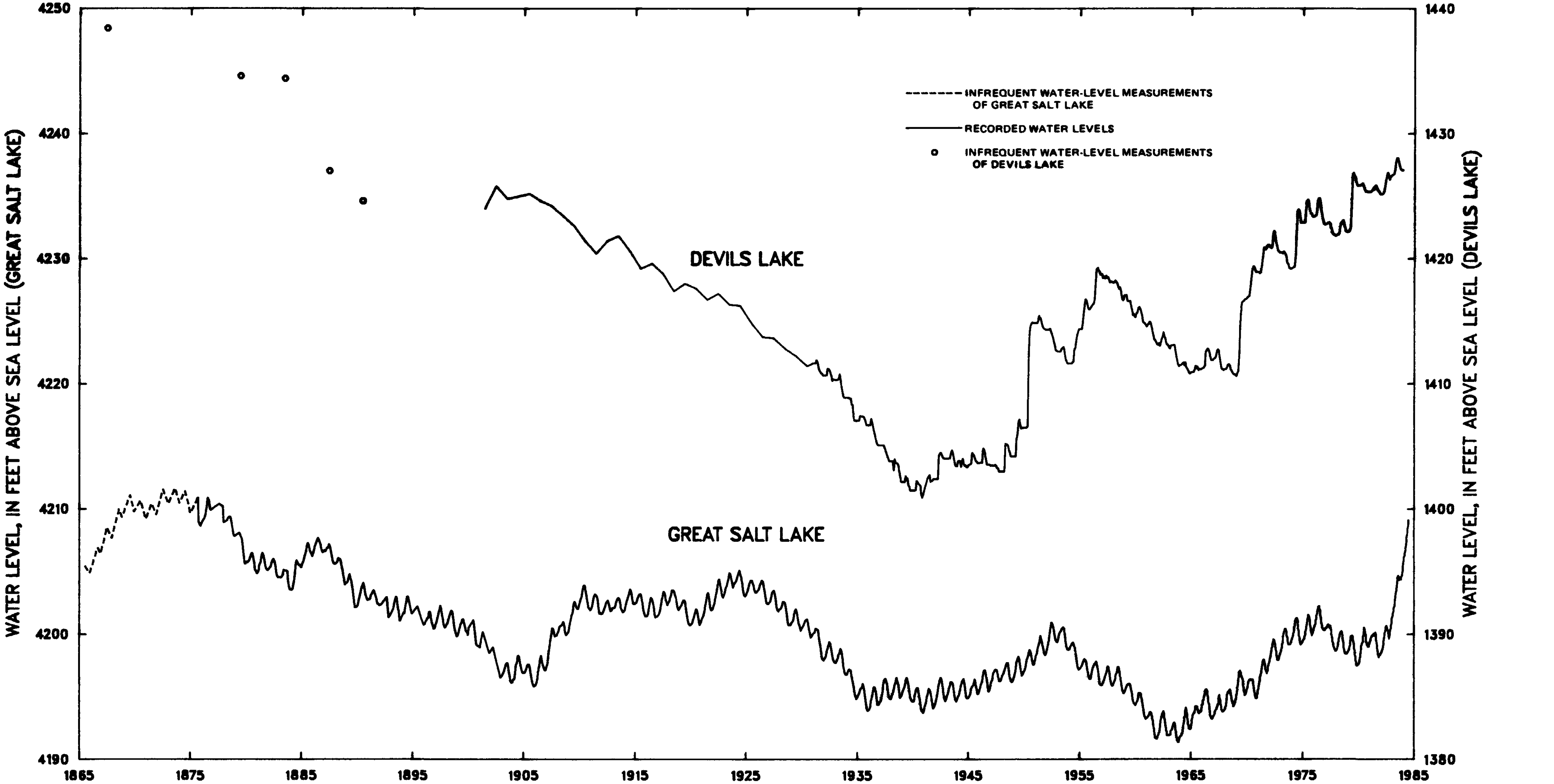


Figure 11.—Historic water levels for Great Salt Lake, Utah, 1865-1983, and Devils Lake, 1867-1983.

Table 9.--Comparison of water-level trends between Great Salt Lake, Utah, and Devils Lake

Years	Great Salt Lake, Utah	Devils Lake
1860-85	Constant highest stand of water level during the historic record.	Constant highest stand of water level during the historic record.
1885-90	Decline.	Major decline.
1890-1906	Decline.	No major change.
1906-30	Rapid rise early in period followed by gradual rise later in this period until 1924, then a decline.	Gradual decline 1907-30.
1930-40	Rapid decline.	Rapid decline 1931-40.
1940-53	Gradual rise ending in 1953.	Gradual rise 1941-49. Rapid rise 1950. Gradual rise 1951-53.
1953-63	Gradual decline.	Gradual rise 1953-57. Gradual decline 1958-63.
1964-83	Rapid rise.	Gradual decline 1964-68. Rapid rise 1969-83.

Southern Pacific Railroad embankment. A chronological review of the water-budget studies conducted on Great Salt Lake from 1970 through 1978 can be found in a report by Stauffer (1980).

Based on historic lake-level information and climatic data presented by Upham (1895), Rawson and Moore (1944), Brooks (1951), Wahl (1968), and Nyland (1969), many terminal lakes in western North America reached historic maximum water levels during 1860-85. Based on historic lake-level information and climatic data, many historic minimum water levels were recorded on terminal lakes in western North America during 1930-40. Many terminal lakes have risen substantially during the 1970's and early 1980's. Big Marine Lake, Whitewater Lake, Dennis Lake, Devils Lake, and Great Salt Lake are examples of terminal lakes that have had substantial water-level rises since 1970.

Many other terminal lakes outside of North America have been studied. In general, there is poor agreement between water-level changes of these lakes and Devils Lake. This poor agreement may be caused by many factors: (1) The controlling climatologic variables are different; (2) basin hydrology is significantly different than that in the Devils Lake basin; and (3) human changes such as large-scale development of reservoirs for hydroelectric power, transportation, and irrigation have altered the hydrology of some of these terminal lakes. With these factors in mind, other studies of terminal lakes were reviewed to determine (1) what is known about the factors that control the water levels and (2) if any studies have been completed to estimate the probabilities for future water levels.

The Caspian Sea in the U.S.S.R. is the world's largest terminal lake and has a surface area of approximately 150,000 square miles. In the last 30 years, the surface area of the Caspian Sea has decreased by approximately 30,000 square miles. The decrease in water levels in the last 30 years has been caused primarily by construction and large-scale development of reservoirs on the Volga River (Greer, 1977).

Chappell (1977) reviewed the two major astronomical theories of climatic change and compared these theories to water-level fluctuations of terminal lakes. Chappell (1977), based on research of Russian scientists, indicated that the water level of the Caspian Sea is high when sea ice in the Arctic is abundant. The high water levels and the abundant sea ice occurred when meridional circulation decreased and sunspot activity decreased, especially prevalant during the Little Ice Age when sunspot activity was at a minimum. Chappell (1977) pointed out that East African terminal lakes fluctuated out of phase compared to the Caspian Sea and other mid- and high-latitutde terminal lakes in the U.S.S.R.

The Aral Sea in the U.S.S.R. is the world's second largest terminal lake and has a surface area of 26,000 square miles. As in the case of the Caspian Sea, water levels of the Aral Sea have been declining in recent years because major water withdrawals for irrigation projects along the Amu Darya and Syr Darya Rivers have reduced discharge into the Aral Sea. Apparently the large water withdrawals that caused a decline in water levels of the Caspian Sea and Aral Sea have masked any climatologic effect that may have occurred.

Lamb (1966) discussed the problems associated with rising water levels of Lake Victoria and other lakes in eastern equatorial Africa. Lake Victoria has an outlet to the Nile River and sometimes is not classed as a terminal lake. Lake Victoria (approximately 26,000-square mile surface area) was discovered in 1858, but nothing is known about water levels of the lake until 1876. Lake Victoria had high water levels from 1876 through 1880, and then, after a decline in water levels in the 1880's, the water level did not attain the maximum observed in the 1880's until a rapid rise of approximately 7 feet from 1961 through 1964. Lamb (1966) indicated that all the major water-level fluctuations observed on the lakes he studied are "* * *ultimately traceable to runs of wetter or drier years."

Dalhunty (1977) discussed the hydrology of Lake Eyre, Australia. Runoff from monsoonal rains that occur on the north coast of Australia flows south approximately 600 miles to Lake Eyre. Runoff from these monsoons reaches the lake every 2 to 5 years, and then the lake is dry within a year. Thus, there is no long period of record, and no studies have been completed to estimate future water-level probabilities.

Kamau (1977) studied beach gravels around Lake Naivasha, Kenya, and indicated a high water-level stand has occurred in the last 10,000 years. Historic record for Lake Naivasha begins in the early 1900's.

Neev and Hall (1977) documented cyclic fluctuations of the regional climatic conditions since 20,000 years before present by analyzing lateral and vertical facies changes along the shores of the Dead Sea. Neev and Hall (1977) indicated that the Dead Sea rose 40 meters from approximately 1000 A.D. to the beginning of the 20th century. They stated that "* * *although a climatic factor cannot be ruled out, it seems that the cultural change from an agricultural to a grazing regimen, which occurred after the Moslem conquest of Palestine during the 7th century A.D., was the dominant factor in increasing the runoff to the Dead Sea."

The water level of the Dead Sea has been falling since the 1930's as a result of climatic variability and human modification, but the human modification is the dominant cause for the decline in water levels. Inflow to the Dead Sea since 1930 is 33 percent less than pre-1930 inflow because of diversion of water for irrigation (Neev and Hall, 1977).

Sauer (1978) analyzed the available information to determine the rate and magnitude of recent changes of the water level of the Dead Sea and to relate these changes to changes in inflow. The Dead Sea has a surface area of 351 square miles, and about 15,400 square miles drain into the Dead Sea. A 183-year historic record is available for the Dead Sea. The period 1800 to 1964 was compiled by Klein (1965) using information such as photographs, travelogues, and measurements. Sauer (1978) compared water levels of the Dead Sea to accumulated rainfall departure and found close correlation except for the period since 1964. Accumulated rainfall departure was computed by calculating the average precipitation for the period of record, computing the difference between the average value and the recorded precipitation for each year, and summing the differences for the time period used to compute the average value. The water levels of the Dead Sea have declined since 1964, yet the precipitation has been near average.

Comparison of the water levels of the Dead Sea (fig. 12) to the water levels of Devils Lake (fig. 3) indicates somewhat of an inverse correspondence. Water levels of the Dead Sea were relatively low from 1860 to 1880 when water levels of Devils Lake were high, and the water level of the Dead Sea was near a historic high in the 1930's when water levels of Devils Lake and other terminal lakes in North America were at or near historic minimums.

Methods Used to Estimate Future Water-Level Probabilities

Sauer (1978) used a water-balance model to project changes in water levels of the Dead Sea for a 50-year period. Assumptions used in the

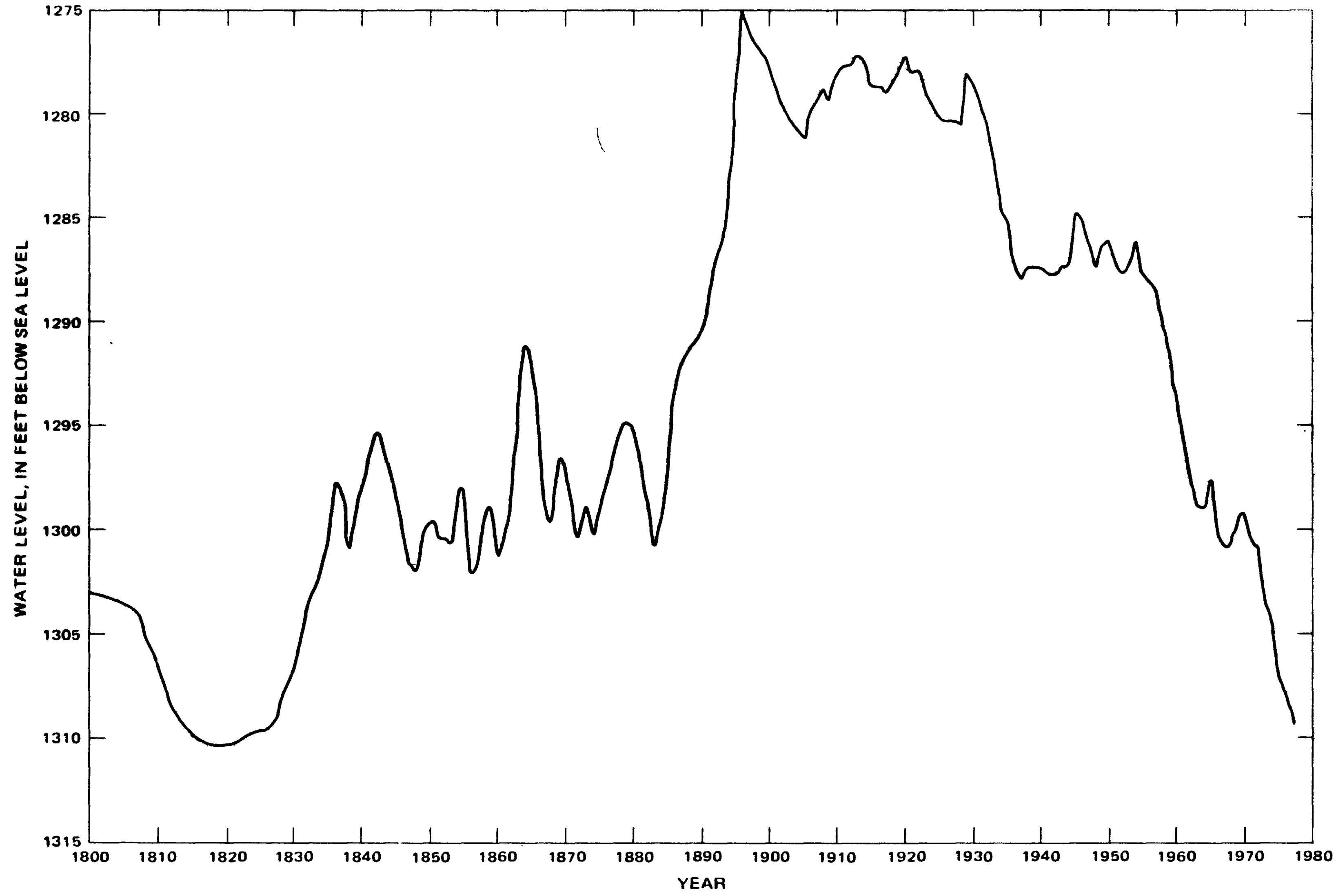


Figure 12.—Historic water levels for the Dead Sea, 1800-1977. (Modified from Sauer, 1978.)

water-balance model are as follow: (1) Average annual rainfall is constant; (2) average annual inflow from surface-water and ground-water sources, other than the Jordan River, is constant; (3) starting elevation is 1,216 feet below sea level; (4) initial dissolved-solids concentration is 322,000 milligrams per liter; and (5) evaporation from the water surface is 51.6 inches per year at the starting elevation of 1,216 feet below sea level, and the evaporation decreased below this elevation as the salinity increased. Based on these assumptions, six water balances were computed by selecting a constant inflow for the Jordan River ranging from 0 to 600,000 acre-feet per year, then changes in water levels of the Dead Sea at the end of a 50-year period were determined. No probabilities for the different Jordan River inflows were computed.

Great Salt Lake, Utah, has been the subject of many of the studies to determine methods for estimating the probabilities of future water levels of terminal lakes. Austin and Stauffer (1977) and Austin (1980) plotted historic water levels of Great Salt Lake, adjusted for depletions, on log-normal paper. The computed water-level probabilities are based on the assumption that the annual water levels are independent events. The problems associated with this method are discussed by James and others (1984). They indicate that even though there is a long series of annual maximum water levels, these water levels could not be fit to a standard statistical distribution. A large serial correlation in annual maximum water levels violates the assumption of independence in the annual events; for example, James and others (1984) computed a lag-one correlation coefficient of 0.98 for annual maximum water levels of the Great Salt Lake.

Glenne and others (1977) used a water-balance model and a Markov random function term to generate future water-level probabilities for Great Salt Lake. Their water balance was approximated by the equation:

$$(I_s+I_g+I_p-O_e-O_t)\Delta t = \Delta S \quad (2)$$

where

I_s = net surface inflow rate, length^3/time;
I_g = net ground-water inflow rate, length^3/time;
I_p = precipitation inflow rate, length^3/time;
O_e = net evaporation outflow rate, length^3/time;
O_t = transpiration outflow rate, length^3/time;
Δt = time interval, month or year; and
ΔS = change in lake storage, length^3.

They indicated that the ground-water inflows (I_g) and transpiration outflows (O_t) are relatively small and nearly equal. Thus, the equation can be rewritten as

$$(I_s+I_p-O_e)\Delta t = \Delta S. \quad (3)$$

The inflows (I_s) to Great Salt Lake were estimated using a nonlinear equation:

$$I_s = 6,376(P_2)+2,187(P_2)^{-2}-7,555 \quad (4)$$

where

I_s = annual surface inflow to Great Salt Lake, in thousands of acre-feet, and

P_2 = 2-year average precipitation, in inches, at the Salt Lake City airport.

The net evaporation (O_e) was computed using a linear regression equation:

$$O_e = 3.48-0.963\ (P_1) \quad (5)$$

where

P_1 = annual precipitation, in inches, at the Salt Lake City airport.

After net evaporation was computed, it was multiplied by the lake surface area to obtain the total loss from the lake.

Glenne and others (1977) used a 3-year lag Markov model to generate precipitation sequences used to compute inflow (equation 4) and net evaporation (equation 5). Precipitation data from 1875 through 1972 were used to develop the statistical terms in the model. The equation used by Glenne and others (1977) is:

$$P_1 = 1.071-0.064P_{L1}+0.081P_{L2}+0.162P_{L3}+t_i\sigma\sqrt{1-\rho^2} \quad (6)$$

where

P_1 = present-year precipitation, length;

P_{L1} = 1-year lagged precipitation, length;

P_{L2} = 2-year lagged precipitation, length;

P_{L3} = 3-year lagged precipitation, length;

$t_i\sigma\sqrt{1-\rho^2}$ = random term;

t_i = random number;

σ = standard deviation of the lagged precipitation; and

ρ = multiple coefficient of determination.

The random part of the equation used the standard deviation and coefficient of determination of the lagged precipitation. Lake levels were simulated for a 1,000-year period for two cases (average precipitation equal to 15.6 inches and an average precipitation equal to 16.2 inches). Exceedance probabilities for the two cases were computed for water levels from 4,190 feet above sea level to 4,212 feet above sea level.

James and others (1977) were critical of the types of analysis used by Austin and Stauffer (1977) and Glenne and others (1977) because their methods for computing water-level probabilities violated one or more of the three criteria that James and others (1977) believed must be considered. These criteria are: (1) Long-term persistence and short-term persistence in the annual series of water levels should be included, (2) stage-frequency distributions should be conditional on previous water levels, and (3) the sensitivity of stage-frequency distributions to changes in hydrology within the basin should be determined.

Based on these criteria, James and others (1977) developed an approach that links a stochastic model for generating long sequences of sets of inflow and outflow data to a water-balance model used to compute water levels. This sequence of computed water levels can then be used to compute stage-frequency distributions. The inflow sequences generated are precipitation falling on the lake, surface-water inflows, and ground-water inflows; the outflow sequence is evaporation.

A lag-one autoregressive multivariate model was chosen to provide the inflow and outflow data sets. The primary objective selected for calibrating this model was to preserve the mean, standard deviation, and the cross-correlation matrices among the input data. This model was used to generate 1,000 possible samples that were used as input in the water-balance model to provide 1,000 possible water levels for each year in a 68-year period starting October 1, 1983, and ending September 30, 2050. All 1,000 samples are considered equally probable and the water-level probability distribution is computed by treating the simulated water levels as a random sample.

Willett (1977) computed probabilities for future water levels of Great Salt Lake based on sunspot cycles. He indicated that 1795 and 1975 mark the end of 100-year cycles that are separated by an 80-year cycle. Willet (1977) indicated that the 80-year cycle has climate characteristics that differ from the 100-year cycles. Based on Willet's (1977) analysis, 1975 to 2055 should be cooler and wetter than the past 100 years. Willet (1977) compared water-level fluctuations of Devils Lake, Great Salt Lake, and the Caspian Sea to sunspot cycles. Based on these comparisons water-level predictions for Great Salt Lake were made through 2040.

Comparison of the probabilities for future water levels of the Great Salt Lake computed by different researchers provides a considerable range of probabilities for any given water level. In 1977, Willet (1977) predicted that there was a 90 percent chance that Great Salt Lake would have a water level of 4,205 to 4,206 feet above sea level by 1981. However, Great Salt Lake had a maximum water level of only 4,200 feet above sea level in 1982. It was not until July 1983, approximately 2 years after the year Willett (1977) predicted that water levels would have a maximum water level of 4,205 feet, that this water level actually was attained. Willett (1977) also indicated that there is an 80 percent chance that the water level in Great Salt Lake will cease to rise and then decline to 4,202 feet above sea level by 1988. Personnel at the Utah Water Research Laboratory (1984), using the methods outlined by James and others (1984), indicated that there is less than a 1-percent chance of the lake level declining below 4,204.5 feet above sea level by 1988. According to the log-probability plot of Great Salt Lake stage data (Austin, 1980), a water level of 4,202 feet above sea level would be equaled or exceeded 20 percent of the time.

There is no general agreement for water-level probabilities extending to 2000 and beyond. Willett (1977) indicated that there is an 80 percent chance that the water level in Great Salt Lake will have an elevation of 4,216 to 4,218 feet above sea level by 2002. Personnel at the Utah Water

Research Laboratory (1984) indicate that there is an 8.6 percent chance of the Great Salt Lake having a water level of 4,216 feet above sea level by the year 2000. Based on the work of Austin (1980), a probability cannot be assigned to a water level of 4,216 feet above sea level, but the probability of the water level in Great Salt Lake equaling or exceeding 4,210 feet above sea level in any given year is 0.5 percent. Based on the work of Glenne and others (1977), there is a 0.1 percent chance that the water level in Great Salt Lake will equal or exceed 4,209 feet above sea level, assuming that the average annual precipitation equals 15.6 inches at Salt Lake City.

In summary, no standardized methods to compute future water-level probabilities of terminal lakes similar to those outlined by the U.S. Water Resources Council (1981) and used to compute discharge-frequency statistics at stream-gaging stations are available. In fact, the techniques developed and used by Austin and Stauffer (1977), James and others (1984), and Willett (1977) to compute future water-level probabilities on Great Salt Lake provide a wide range of probability for any given water level. The procedure used by James and others (1984) provides a more statistically valid approach for computing future water-level probabilities. However, if their approach were used to compute future water-level probabilities of Devils Lake, several climatologic and hydrologic data limitations would affect the accuracy of the results. First, the city of Devils Lake has the only long-term precipitation station in the Devils Lake basin. Thus, it would be necessary to assume that the Devils Lake precipitation data are representative of the precipitation falling on the basin. Second, long-term pan evaporation data are not readily available from any climatologic stations in the Devils Lake basin. Only fragmentary pan evaporation data collected at the city of Devils Lake from 1951 through 1970 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1970) are available. Therefore, record extension techniques would have to be used to develop a long-term evaporation record. Third, monthly discharge data required as input in the water-balance computations are available for much of the basin, but some estimates would have to be made for the drainage area surrounding Devils Lake. Fourth, the hydrologic interaction between the upstream chain of lakes and Devils Lake would have to be incorporated in the water-balance computations.

Long-Term Discharge Records

Jarvis (1936) presented a brief summary of the long-term discharge records worldwide to determine if a continuous record of stages of a river for 500 to 1,000 years might indicate more definitely trends or cyclic patterns of stage through time. Jarvis (1936) indicated that flood records exist intermittently for about 200 years for the Ohio River at Pittsburgh, Penn., and on other rivers along the east coast of the United States. Closer to the Devils Lake basin, Miller and Frink (1984) used a variety of sources and listed the major floods along the Red River of the North since 1776.

Liebscher (1983) used long-term records at six gaging stations on the Rhine River in an effort to study climatic variations in Germany. Discharge measurements on the Rhine River began in the late 18th century, and, despite errors affecting the early measurements, Liebscher (1983) stated that they have been combined with more recent discharge measurements in stable-bed river sections to construct a discharge record at some gages back to the mid-19th century, or approximately the same period of record that is available for Devils Lake.

Jarvis (1936) discussed the availability of flood information for the Thames, Seine, Rhine, Rhone, Loire, Po, and Danube Rivers. On the Rhone, Loire, and Seine Rivers, floods that occurred in the 4th century have been documented, but for the next 1,000 years, only fragmentary qualitative data are available. Jarvis (1936) indicated that within the last 300 years quantitative relations of flood magnitudes have been recorded for some European rivers, but no annual stage or discharge records are available prior to the mid-18th century for European rivers.

Jarvis (1936) presented annual maximum flood elevations for the Nile River at Cairo, Egypt, for a 1,300-year period. No attempt was made to evaluate the data, but many of the problems associated with the record are outlined: (1) Changes in the vegetative cover of a drainage area, (2) erosion, (3) increase or decrease of natural or artificial storage either in basins or on flood plains, (4) diversion to other drainage basins by either natural or artificial means, (5) restriction of the river channel by levees, (6) facilitation of flow by dredging and removal of obstructions, or (7) formation or abandonment of auxiliary channels and bypass areas.

Riehl and others (1979) used the annual maximum stage data analyzed and compiled by Jarvis (1936) to search for reliable evidence of climatic variations by using a long series of annual maximum stage record. Riehl and others (1979) computed the deviation from the average annual discharge of the Nile River for each year from 1830 to 1976 and plotted the cummulative deviations from the average. Based on their computations, the Nile River discharge was greater than average from 1870 through 1900 and generally less than average from 1901 through 1970; however, a period of near average discharge occurred from 1945 through 1965. Riehl and others (1979) used annual maximum stage data compiled by Jarvis (1936) to develop the annual discharge on the Nile River near Cairo, Egypt for a 300-year period. Based on this 300-year period, they found that except for short periods of 10 to 20 years the discharge was never constant. Periods of above or below average discharge occurred with durations of 50 to 100 years.

Riehl and others (1979) stated that for the 300-year period of Nile discharge studied, two "cycles" occurred and the discharge deviated by 10 to 20 percent from the average discharge. Thus, in terms of water supply, deviations of at least 25 percent occur from maximum to minimum.

Riehl and others' (1979) findings are in agreement with those of Jarvis (1936), who, in reference to annual maximum stages of the Nile River from 641 A.D. to 1450 A.D., stated that "* * *over considerable periods, sometimes as long as 50 years, floods are above average, while over other periods they are below average."

Similar conclusions have been reached by other researchers. Cook and Jacoby (1983) reconstructed the flow on the Potomac River for a 248-year period using dendrochronologic methods, and they state that "* * *there appear to have been several long periods of about 50 years in length when the flow was generally above or below the long-term median flow." Riehl and Meitin (1979) developed a regression equation using annual discharge of the Nile River as the dependent variable and annual maximum stage as the independent variable. They used this equation to compute an annual discharge beginning in the year 622. Riehl and Meitin (1979) concluded that there have been eight episodes of at least 50 years duration where:

$$\sum \frac{(\text{annual discharge} - \text{mean annual discharge})}{\text{mean annual discharge}}$$

has exceeded ± 1 at the extreme value.

CONCLUSIONS

Discharge and climate data collected in the Devils Lake basin were analyzed using statistical and graphical techniques in order to gain a better understanding of the hydrologic and climatologic factors affecting the water-level fluctuations of Devils Lake. Large variations in inflow to Devils Lake have occurred during 10 consecutive years or more. For example, the average annual net storage gain to Devils Lake was 4,530 acre-feet from 1931 through 1940, and average annual net storage gain was 70,000 acre-feet from 1969 through 1983. Based on water-balance computations, average annual inflow from 1867 through 1884 was 58,300 acre-feet. The variations in climate from period to period have been accompanied by corresponding variations in inflow. The average annual precipitation (15.14 inches) at the city of Devils Lake from 1930 through 1939 was 23 percent less than the average annual precipitation (18.47 inches) at Fort Totten from 1870 through 1884. No precipitation data are available prior to 1870.

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 the rate of snowmelt also affect the relation between winter precipitation and water-level fluctuations of Devils Lake.

Based on the review of investigations conducted on terminal lakes in North America and other areas of the world, a number of observations can be made. In general, the extremes in water levels of terminal lakes in western North America fluctuate primarily in response to climatic variability. The evidence presented by Rawson and Moore (1944) in Saskatchewan, Laycock (1973) and Woodburn (1977) in Alberta, Arnow (1984) in Utah, and the climatic analysis presented by Wahl and Lawson (1970) indicates that many terminal lakes in western North America reached historic maximum water levels during 1860 to 1885. Similar evidence exists that indicates many terminal lakes in western North America reached historic minimum water levels during the 1930's. Therefore, agreement among lake levels in western North America, including Devils Lake, has occurred during periods of climatic extremes. The 1870's and the 1930's are two notable examples of these climatic extremes. The upstream storage in the Devils Lake basin probably contributes to the lack of agreement between Devils Lake and other terminal lakes in North America during "average" climatic periods.

Many factors limit the potential for developing regression equations between water-level fluctuations of Devils Lake and long-term streamflow records. As with water-level data, only limited continuous-stage data are available prior to 1850, and the records that exist are from areas far removed geographically. In addition, the stage data that are available prior to 1850 often are subject to unknown or questionable datum corrections. The research conducted on long-term streamflow records by Jarvis (1936), Riehl and Meitin (1979), Riehl and others (1979), and Cook and Jacoby (1983) indicates that periods of greater-than-average discharge and less-than-average discharge of 50 years or more duration are common.

Only a few terminal lakes in other areas of the world have a reliable period of record longer than that of Devils Lake. Terminal lakes that have a longer period of record than Devils Lake, namely the Caspian Sea and the Dead Sea, have declining water levels primarily due to construction of major reservoirs for hydroelectric power generation and diversions for large-scale irrigation projects. Thus, comparision of Devils Lake to other terminal lakes, as stated in objective 2, is limited to qualitative discussion of different periods. Little chance of developing statistically significant regression equations between Devils Lake and other terminal lakes exists because: (1) Water levels of many of these terminal lakes have been affected by major withdrawals of water from rivers feeding the lakes; (2) many of these terminal lakes have differing hydrologic and climatologic regimes that control their water levels; (3) none of the terminal lakes discussed have similar storage in upstream lakes, which has a major effect on the volume of water reaching Devils Lake in any given year; and (4) as Langbein (1961) mentioned, the response time of the terminal lakes differs considerably.

No standardized methods to compute future water-level probabilities of terminal lakes are available. In fact, the techniques developed and used by Austin and Stauffer (1977), James and others (1984), and Willett (1977) to compute future water-level probabilities on Great Salt Lake provide a wide range of probability for any given water level. The procedure developed by James and others (1984) provides a sound scientific approach for computing future water-level probabilities.

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