HYDROLOGY OF THE DEVILS LAKE BASIN, NORTHEASTERN NORTH DAKOTA

By

Gregg J. Wiche,
U.S. Geological Survey,

Steve M. Hoetzer,
Garrison Conservancy District,

and

James G. Rankl,
U.S. Geological Survey

Prepared by the U.S. Geological Survey
In Cooperation With The
North Dakota State Water Commission And The
U.S. Bureau Of Reclamation

Water-Resources Investigation 3
North Dakota State Water Commission
Vernon Fahy, State Engineer

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

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

Multiply inch-pound unit	By	To obtain SI unit
Acre	0.4047	hectare
Acre-foot	1,233	cubic meter
	0.001233	cubic hectometer
Cubic foot per second	0.02832	cubic meter per second
Foot	0.3048	meter
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

Since 1867, the water level of Devils Lake has fluctuated from 1,438 feet above sea level in 1867 to 1,400.9 feet above sea level in 1940. The greatest annual maximum 30-day water-level rise was 3.82 feet, and this rise occurred in 1979. The greatest 1-day water-level rise was 0.40 foot, and this rise occurred in 1950.

Analysis of the available hydrologic and climatologic data indicates the water level of Devils Lake fluctuates largely in response to climatic variability. Computed average annual inflow 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 effects of climatic variability on the inflow to Devils Lake, an interconnected chain of lakes upstream of Devils Lake retains runoff and is 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.

The higher the water level of Devils Lake, the greater the inflow required to raise the water level a given increment. As an example, an inflow to Devils Lake of 72,200 acre-feet has an exceedance probability of 10 percent. This inflow results in a 4.20-foot water-level rise if Devils Lake is at a starting water level of 1,410 feet above sea level; but, if the starting water level is 1,430 feet above sea level, the water-level rise is only 1.41 feet. Based on a starting water level of 1,426.1 feet above sea level and an inflow of 72,200 acre-feet, the lateral change in shoreline location ranges from 16.8 feet along the south shore of Devils Lake and along the shore of Creel Bay to 148 feet along the West Bay of Devils Lake near Minnewaukan Flats.

Based on previously recorded hydrologic and climatologic data, a "high-runoff" and a "low-runoff" condition were simulated from 1985 through 1990, assuming the current (1985) water level for the initial lake stand. The "high-runoff" simulation indicates that Devils Lake would have a maximum water level of 1,431.43 feet above sea level. The "low-runoff" simulation indicates that Devils Lake would have a minimum water level of 1,420.69 feet above sea 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 utilities.

The rising water levels of Devils Lake in recent years have led to a lawsuit between 101 Ranch and the United States of America, Civil No. A2-81-89. This lawsuit concerns the issue of ownership of the bed of Devils Lake. The litigation required to settle this suit will involve the hydrology of the Devils Lake basin.

The purpose of this study is to describe the hydrology of the Devils Lake basin. The objectives of this study are to: (1) Describe the general climate and hydrology of the Devils Lake basin, (2) analyze specific hydrologic and climatologic factors that affect water-level fluctuations of Devils Lake, (3) compare water-level fluctuations of other terminal lakes to water-level fluctuations of Devils Lake, and (4) estimate future water levels of Devils Lake. The description of the hydrology of the Devils Lake basin is limited to the currently (1983) available data.

DESCRIPTION OF THE STUDY AREA

Devils Lake basin, in northeastern North Dakota, is a 3,800-square-mile closed basin in the drainage of the Red River of the North (fig. 1). About 3,310 square miles of the total 3,800 square miles is tributary to Devils Lake; the remaining 490 square miles 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 and may be noncontributing to Devils Lake or Stump Lake during some hydrologic conditions and contributing during other hydrologic conditions.

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 streams draining them are shown in figure 2, and the drainage areas of these subbasins 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 and flows in a generally southerly direction. Little Coulee originates in southern Rolette County and flows in a south-southeasterly direction.

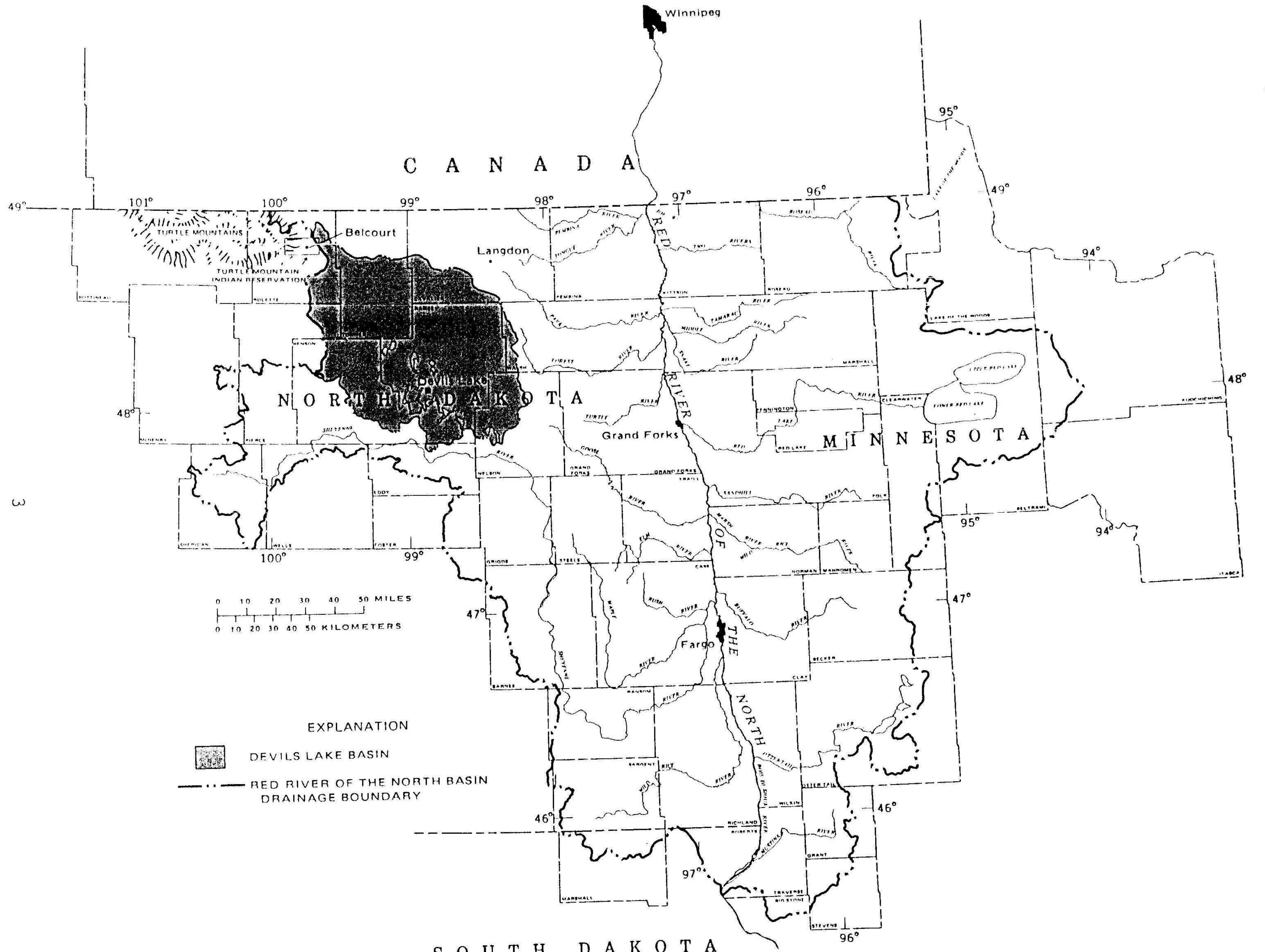

Figure 1.—Location of the Devils Lake basin. (Modified from Miller and Frink, 1984.)

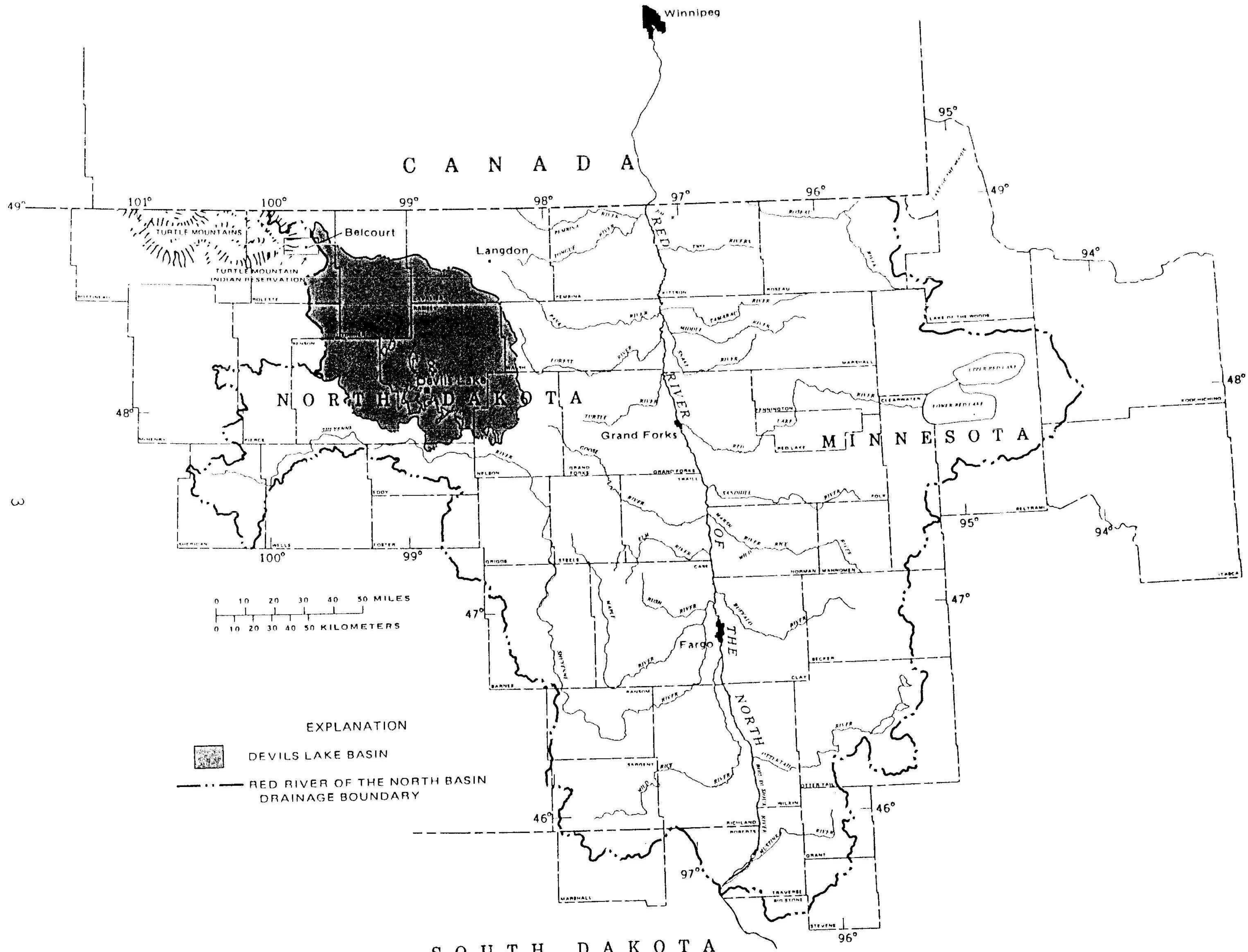

Figure 1.—Location of the Devils Lake basin. (Modified from Miller and Frink, 1984.)

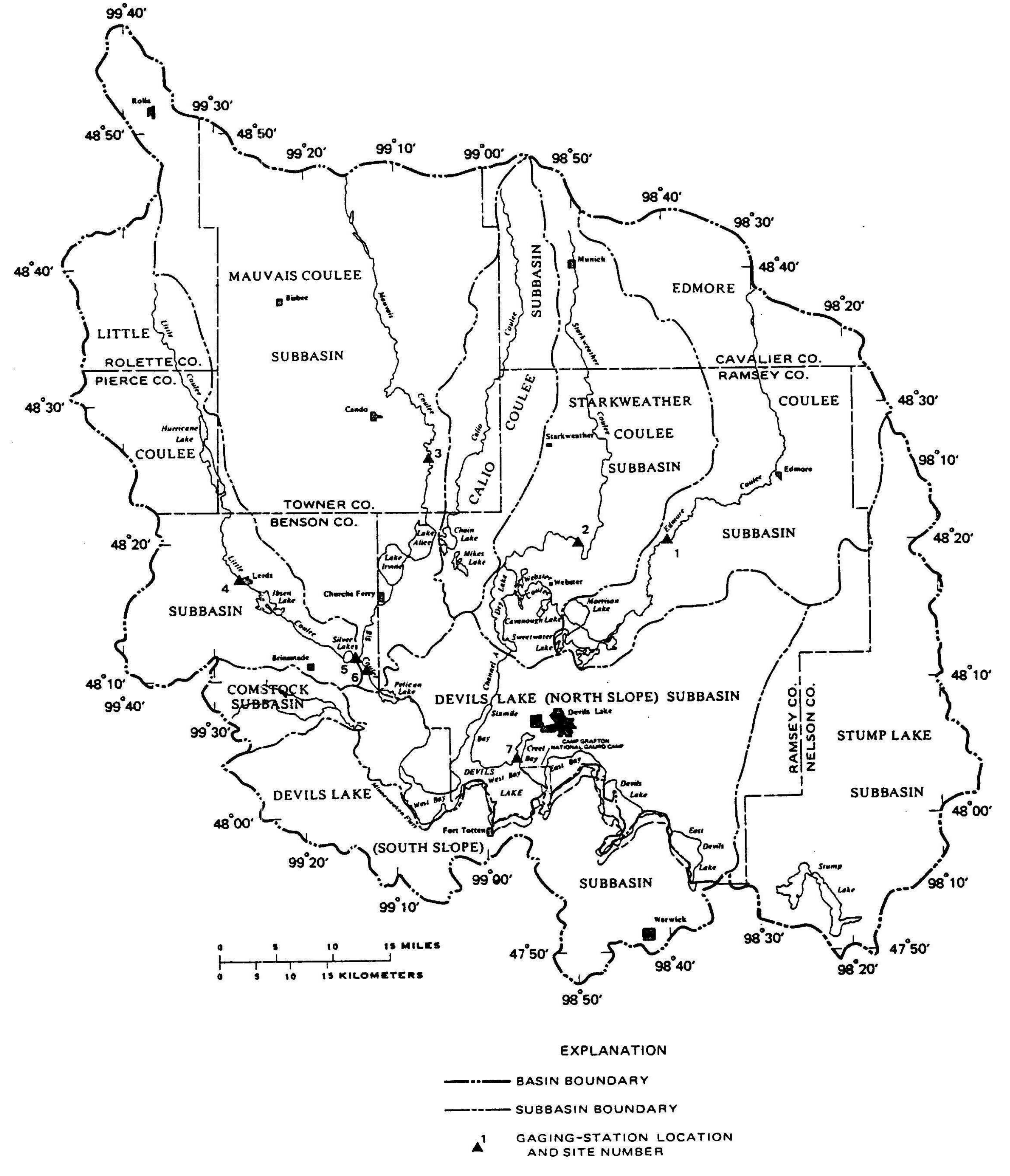

Figure 2.—Major subbasins and location of gaging stations.

Table 1.--*Drainage areas of subbasins*

[Devils Lake Basin Advisory Committee, 1976]

Subbasin	Drainage area, in square miles		
	Contributing1/	Noncontributing1/	Total
Edmore Coulee	389	112	501
Starkweather Coulee	--	--	2/391
Calio Coulee	--	--	2/233
Mauvais Coulee	872	10	882
Little Coulee	263	158	421
Comstock	--	--	2/58
Devils Lake (north slope)	--	--	2/512
Devils Lake (south slope)	--	--	2/328
Stump Lake	--	--	2/488

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 a normal event.

2/The contributing and noncontributing drainage areas have not been determined for the subbasin.

Prior to 1979, discharge from the coulees flowed into the interconnected chain of lakes shown in figure 2 and then, starting with the upstream lake in downstream order, flowed through Sweetwater Lake, Morrison Lake, Dry Lake, Mikes Lake, Chain Lake, Lake Alice (Lac aux Mortes), Lake Irvine, and into Big Coulee. Prior to 1979, most of the discharge entering Devils Lake flowed through Big Coulee, which is the only principal stream discharging directly to Devils Lake. Some runoff entered Devils Lake by overland flow from drainage areas adjacent to the lake. In 1979, the Ramsey County and Cavalier County Water Management Boards completed construction of channel A, which connects Dry Lake to Sixmile Bay of Devils Lake. Channel A divides the Devils Lake basin into two subbasins; drainage into Sweetwater, Morrison, and Dry Lakes is conveyed to Devils Lake by channel A, and the remaining discharge follows the natural watercourse.

CLIMATE OF THE DEVILS LAKE BASIN

The Devils Lake basin has a continental climate characterized by relatively short, warm summers and long, cold winters. Maximum summer temperatures greater than 100°F and minimum winter temperatures less than -35°F are not uncommon. The average annual temperature from 1905 to 1984 has varied from 34°F during 1950 to 43.3°F during 1931 (U.S. Department of Agriculture, Weather Bureau, 1932b, and U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1941-85). The Rocky Mountains located west of the Devils Lake basin are a barrier to the prevailing westerly flow of air across North America. The temperature and moisture characteristics of air masses that originate over the Pacific Ocean are modified as air rises over the Rocky Mountains. The cold, dry air masses that originate in the Arctic and the tropical air masses originating over the Gulf of Mexico often reach the Devils Lake basin with only minor modification. Rapid progression of these air masses over the Devils Lake basin results in frequent and rapid changes in weather.

Collection of precipitation data in the Devils Lake basin began in 1870 at Fort Totten, located about 10 miles southwest of the city of Devils Lake (U.S. Department of Agriculture, Weather Bureau, 1932b). Monthly precipitation data are available for Churchs Ferry from 1891 through 1905 and at the city of Devils Lake from 1897 through the present. Currently (1984), monthly precipitation data are published for five locations in the Devils Lake basin--city of Devils Lake, Edmore, Leeds, Munich, and Rolla (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1985).

Precipitation in the Devils Lake basin varies substantially on an annual as well as a monthly basis. The normal precipitation (fig. 3) ranges from 16.52 inches at the city of Devils Lake to 18.15 inches at Rolla (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1951-82). The U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service (1982a) defines the term normal, as used in this report, as:

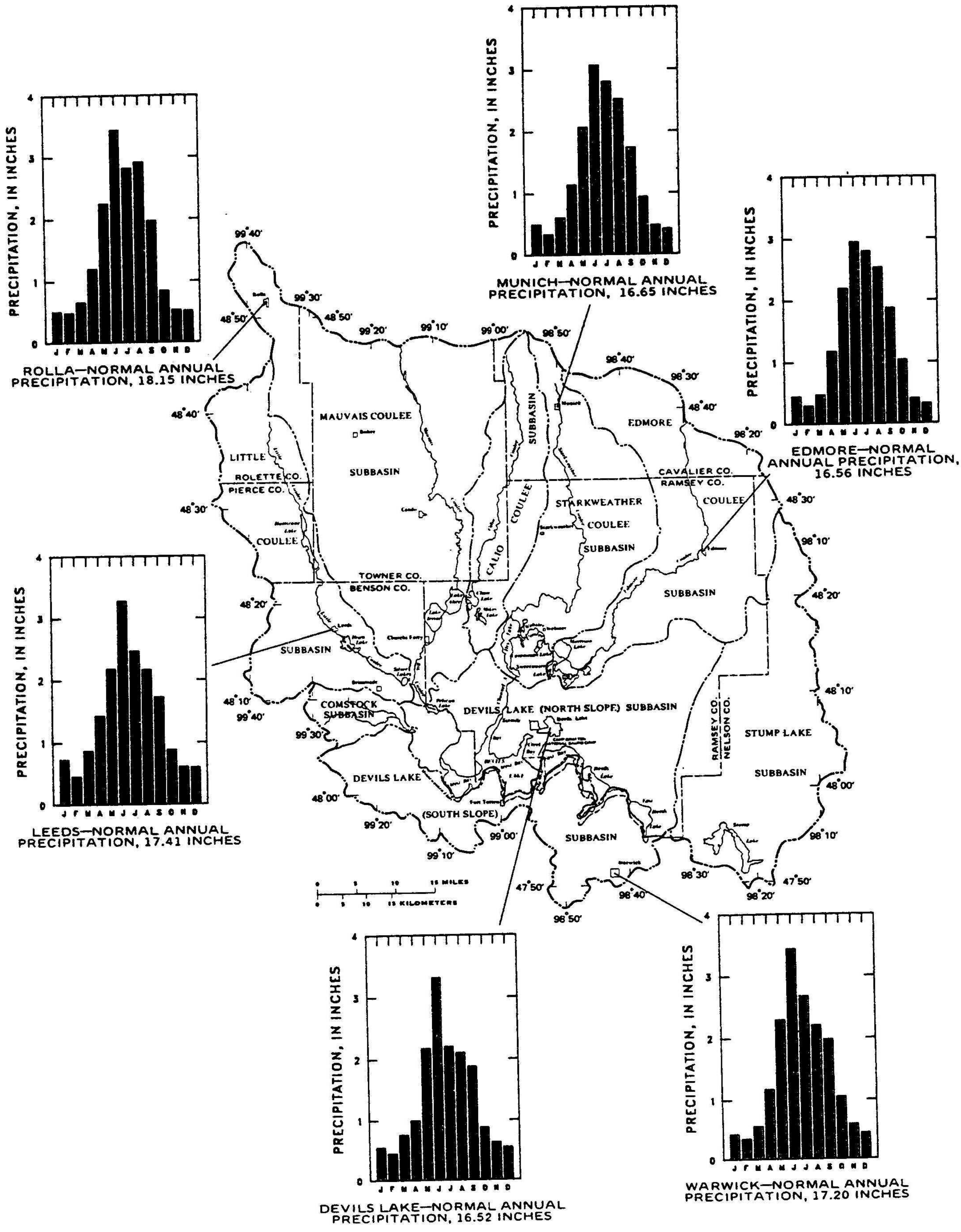

Figure 3.—Normal monthly and annual precipitation at six locations.

"A normal of a climatological element is the arithmetic mean computed over a time period spanning three consecutive decades. Homogeneity of instrument exposure and station location is assumed. If no exposure changes have occurred at a station, the normal is estimated by simply averaging the 30 values from the 1950-80 record. Since it is next to impossible to maintain a multiple purpose network of meteorological stations without having exposure changes, it is first necessary to identify and evaluate these changes and then make adjustments for them if necessary. After the periods of heterogeneity have been determined, adjustments are applied to remove the heterogeneities introduced into the mean. This is done by comparing the record at the base station, for which the normal is desired, to the records at supplementary stations with homogeneous periods which covers the heterogeneous period at the base station. The difference method is applied to the monthly average maximum and minimum temperature and the ratio method to the monthly total precipitation. A weighted average of the various partial means of the adjusted and unadjusted record is then prepared to give the normal."

At the city of Devils Lake, the annual precipitation from 1897 through 1984 has varied from a minimum of 10.08 inches in 1967 to a maximum of 25.39 inches in 1921 (U.S. Department of Agriculture, Weather Bureau, 1932b, and U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1968). The average annual precipitation at Devils Lake for 108 years (1870-90 at Fort Totten and 1897-1983 at the city of Devils Lake) is 17.48 inches.

The normal monthly precipitation at the city of Devils Lake ranges from 0.45 inch in February to 3.32 inches in June (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982a). Monthly precipitation averages 1.00 inch or less from October through April. Typical of the northern plains, 71 percent of the normal annual precipitation occurs from May through September.

Collection of temperature data in the Devils Lake basin began at Devils Lake in 1905 (U.S. Department of Agriculture, Weather Bureau, 1932b). Currently, daily maximum and minimum temperatures are published for four locations in the Devils Lake basin (city of Devils Lake, Edmore, Leeds, and Rolla). The normal annual temperature in the Devils Lake basin ranges from 37.1°F at Edmore to 38.8°F at the city of Devils Lake (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982). The average annual temperature at the city of Devils Lake for 74 years (1905-75 and 1981-83) is 38.9°F.

The continental climate, typical of the Devils Lake basin, is characterized by large variation in average monthly temperatures throughout the year. At the city of Devils Lake, the normal monthly temperature ranges from 2.3°F in January to 69.1°F in July (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982a).

The average monthly temperature has ranged from -15°F in February 1936 to 79°F in July 1936.

Pan-evaporation data were collected from April through September at the city of Devils Lake from 1951 through 1970 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1952-71). Pan-evaporation data were not collected during April and May in most years from 1964 through 1970. From 1951 through 1963, the April-September pan evaporation ranged from 27.57 inches in 1954 to 39.40 inches in 1952 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1953-72). Monthly pan evaporation during the period of record has ranged from 1.52 inches in April 1951 to 9.08 inches in June 1961 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1953-72).

Kennedy (1931) computed monthly evaporation from Devils Lake from July 1905 through September 1930. Annual lake evaporation ranged from 21.7 inches in 1928 to 46.7 inches in 1910.

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 from about 1,453 feet above sea level, the spill elevation, to about 1,400 feet above sea level (Aronow, 1957). According to Bluemle (1981), Devils Lake stood at an elevation above 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 the water level of Devils Lake has fluctuated in response to changing climatic and hydrologic conditions (fig. 4). Callender (1968) reached the following conclusions:

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

Aronow (1955 and 1957) analyzed abandoned shorelines, lacustrine (water-deposited) sand and gravel deposits containing buried soils and vertebrate remains, and rooted stumps uncovered by receding water around Stump Lake.

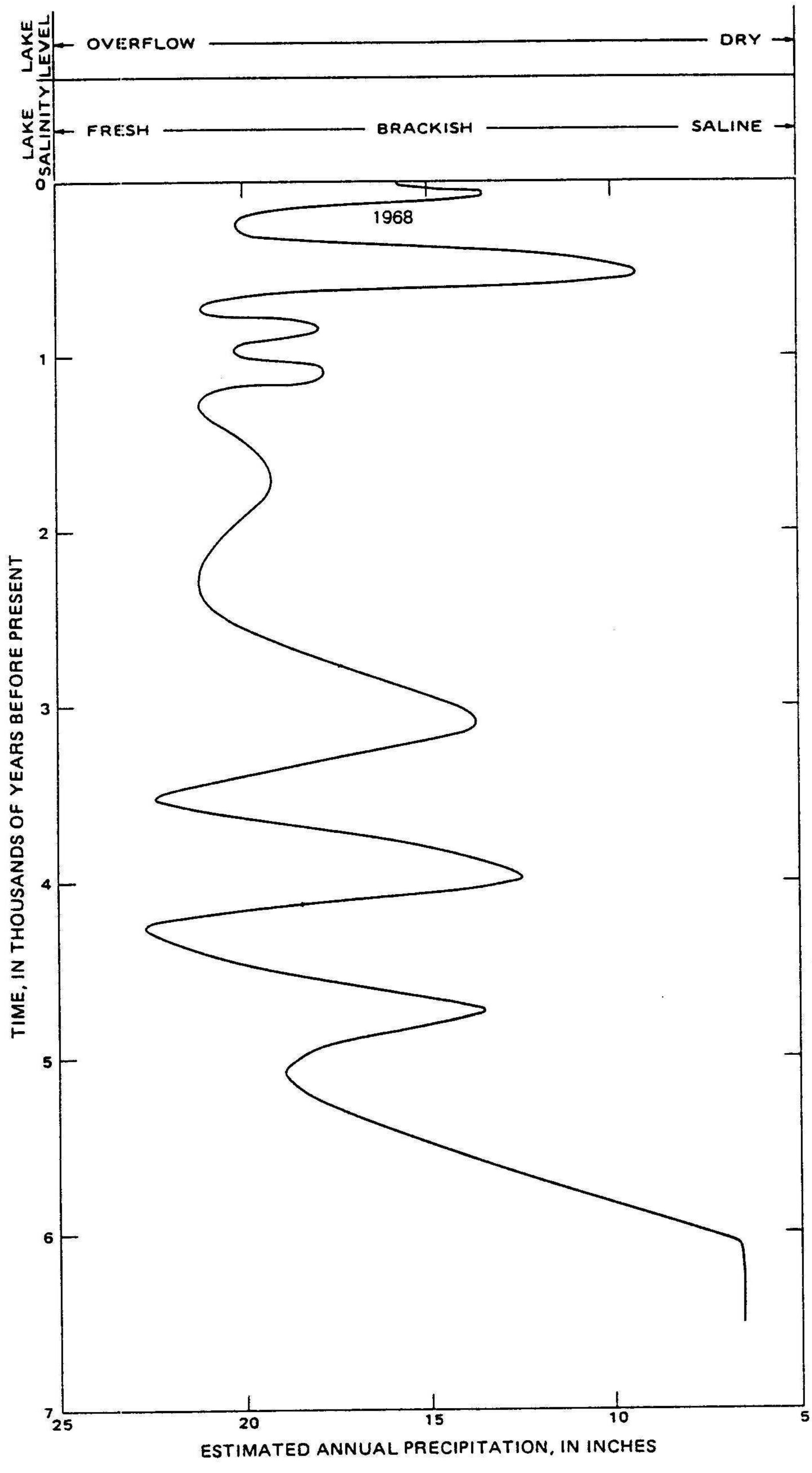

Figure 4.—Estimated prehistoric annual precipitation. (Modified from Callender, 1968.)

In general, Aronow's (1955 and 1957) research is in agreement with most of Callender's (1968) work, but there are some differences. Aronow (1955 and 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, or 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. 5), and these records have been authenticated by the U.S. Geological Survey (E. F. Chandler, written commun., 1931). 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 5. 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 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, and 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 almost 100 years.

Short Duration Water-Level Fluctuations

The data in figure 5 indicate how the water level of Devils Lake has fluctuated since 1867, but these data do not indicate how the water level has fluctuated during shorter periods of a month or less. Maximum 30-day water-level rises for Devils Lake during each year since 1949 are listed in table 2 and the four most rapid rises are plotted in figure 6. The maximum 30-day water-level rise during each year could not be determined with confidence prior to 1949 because water levels were recorded too infrequently. The maximum 30-day water-level rise has ranged from no rise during 1958 when the water

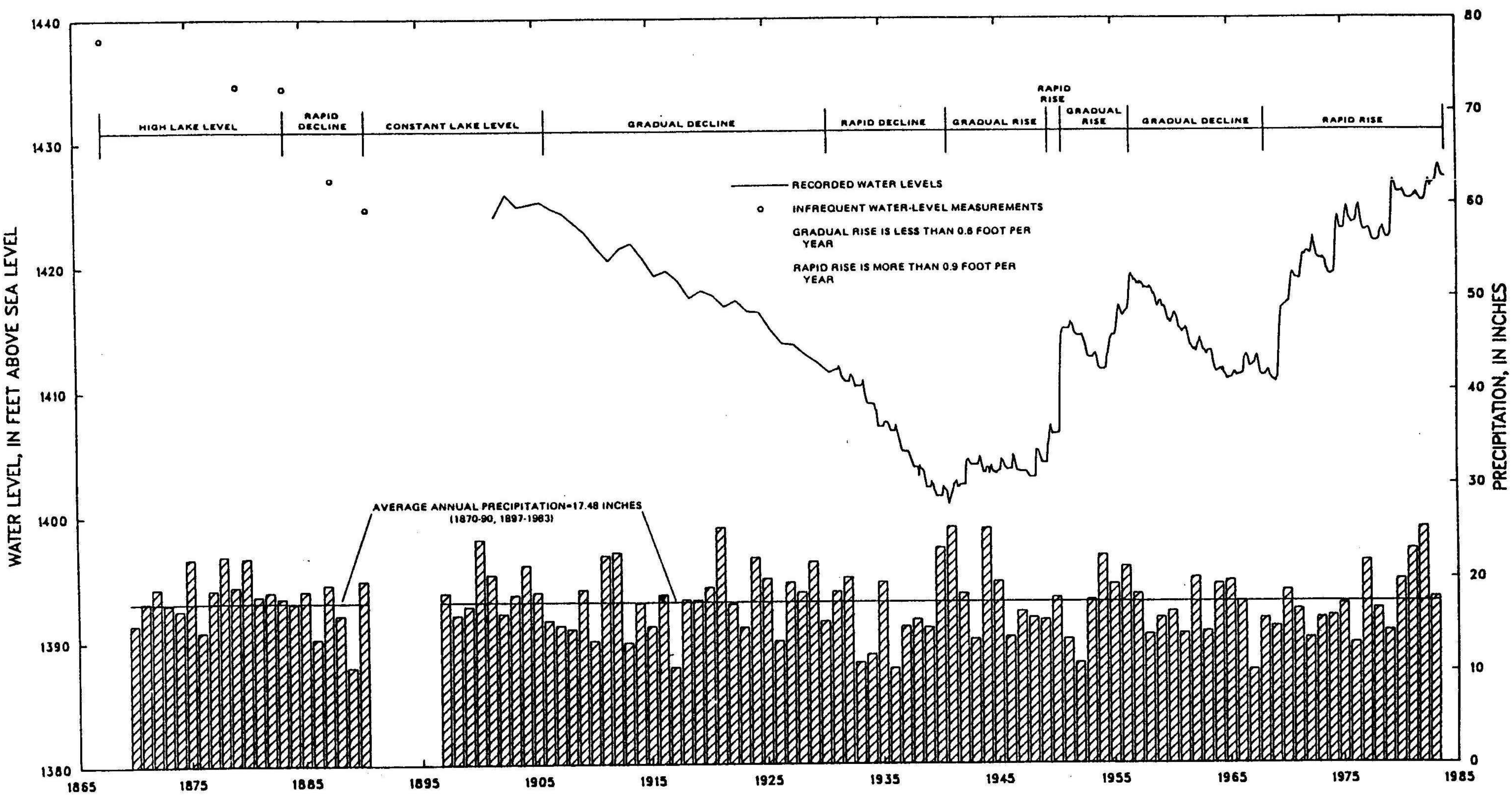

Figure 5.—Historic water levels for Devils Lake, 1867-1983, and average annual precipitation, 1870-90 (Fort Totten) and 1897-1983 (city of Devils Lake).

Table 2.--*Maximum 30-day water-level rise of Devils Lake during each year, 1949-83*

Year	Starting date	Starting water level	Ending date	Ending water level	Change in water level
1949	5/10	1,405.58	6/09	1,406.55	0.97
1950	5/05	1,409.20	6/04	1,412.97	3.77
1951	4/03	1,415.18	5/03	1,415.47	.29
1952	3/28	1,414.35	4/27	1,414.44	.09
1953	2/28	1,412.48	3/30	1,412.80	.32
1954	6/01	1,411.73	7/01	1,412.80	1.07
1955	5/16	1,415.91	6/15	1,416.71	.80
1956	5/12	1,417.42	5/11	1,418.91	1.49
1957	3/24	1,418.41	4/23	1,418.60	.19
1/1958	--	--	--	--	--
1959	3/15	1,416.60	4/14	1,416.73	.13
1960	3/30	1,415.70	4/29	1,416.10	.40
1961	3/15	1,414.82	4/14	1,414.93	.11
1962	5/14	1,413.68	6/13	1,414.30	.62
1963	4/03	1,413.06	5/03	1,413.18	.12
1964	6/05	1,411.40	7/05	1,411.67	.27
1965	5/05	1,411.23	6/04	1,411.60	.37
1966	4/03	1,411.96	5/03	1,412.63	.67
1967	4/12	1,412.24	5/12	1,412.81	.57
1968	3/26	1,411.33	4/25	1,411.57	.24
1969	5/03	1,412.35	6/02	1,414.74	2.39
1970	5/24	1,418.23	6/23	1,419.24	1.01
1971	4/05	1,418.89	5/05	1,419.70	.81
1972	4/09	1,421.05	5/09	1,421.87	.82
1973	3/01	1,420.41	3/31	1,420.59	.18
1974	5/18	1,420.61	6/17	1,423.23	2.62
1975	4/17	1,423.06	5/17	1,424.36	1.30
1976	3/30	1,423.70	4/29	1,424.53	.83
1977	4/05	1,422.89	5/05	1,422.98	.09
1978	3/26	1,421.94	4/25	1,422.56	.62
1979	4/17	1,422.62	5/17	1,426.44	3.82
1980	4/21	1,425.88	5/21	1,426.05	.17
1981	5/25	1,425.57	6/24	1,425.91	.34
1982	4/29	1,425.76	5/29	1,426.36	.60
1983	3/27	1,427.10	4/26	1,427.83	.73

1/Water level declined throughout the year.

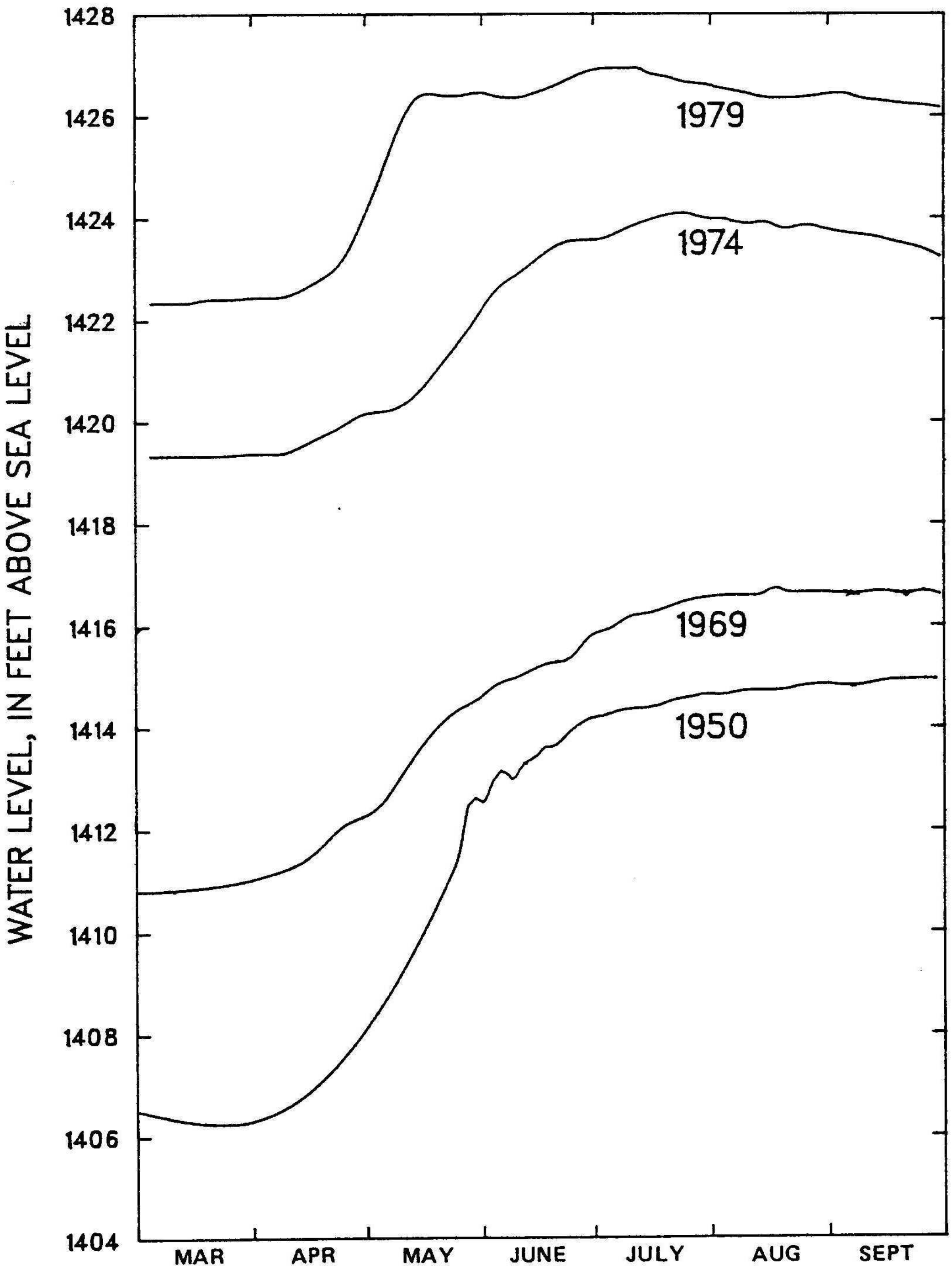

Figure 6.—The four most rapid water-level rises of Devils Lake, 1949-83.

level declined throughout the year to 3.82 feet in 1979. The maximum 30-day water-level rise was 1.00 foot or greater in 5 out of the 11 years during 1969-79.

The four most rapid 1-day, 2-day, and 8-day water-level rises that have been recorded during 1949-83 are listed in table 3. The maximum 1-day rise of 0.40 foot occurred in 1950, but the water-level rise could have been greater because it was interpolated from a 2-day rise. Any of the water-level rises listed in table 3 may have been wind affected, but an attempt was made to eliminate periods that were wind affected. The most rapid 8-day (table 3) and 30-day water-level rises (fig. 6) occurred in 1979. The rate of the water-level rise is a function of many variables including the water content of the soil at freezeup, the water content of the snowpack, distribution of the snowpack, temperature during the snowmelt period, the starting water level, and changes in the hydraulic characteristics of the drainage basin. The relatively rapid water-level rise in 1979 was at least partially a result of the construction of channel A because channel A facilitated the flow from Morrison, Sweetwater, and Dry Lakes to Devils Lake.

Shoreline Slopes Around Devils Lake

In order to make an evaluation of the progression and regression of the water along the shoreline of Devils Lake, the slope of the bank around the four main bays of Devils Lake needs to be known. Using the 1,435-foot contour (feet above sea level) as a control, topographic quadrangle maps may be used to determine these shoreline slopes at representative locations along the lakeshore. Based on 190 cross sections developed normal to the lakeshore (fig. 7), the shoreline slopes were calculated between the bottom of the lake or the lowest topographic contour shown and the 1,450-foot contour (feet above sea level). The average shoreline slopes for specific shoreline areas around Devils Lake are listed in table 4. The slopes varied from 0.75 percent (0.43°) in the Minnewaukan Flats area to 14.46 percent (8.23°) at several locations along the shore of Devils Lake. The average shoreline slope representing the lakeshore as defined by the cross sections is about 3.7 percent (2.1°). The approximate horizontal movement of water up the beach for a given rise in lake elevation is listed in table 5. For example, a 0.5-foot rise in the lake would cause the water to move 50 feet up a beach with a 1-percent slope.

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), indicated 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."

Table 3.--*Maximum 1-day, 2-day, and 8-day water-level rises of Devils Lake, 1949-83*

Year	Starting date	Starting water level	Ending date	Ending water level	Change in water level
		1-day rise in water level			
1950	5/26	--	--	--	1/0.40
1969	6/25	1,415.38	6/26	1,415.59	.21
1974	5/19	1,420.76	5/20	1,421.02	.26
1979	5/10	1,425.79	5/11	1,426.03	.24
		2-day rise in water level			
1950	5/26	1,411.67	5/28	1,412.47	.80
1969	6/25	1,415.38	6/27	1,415.66	.28
1974	5/18	1,420.61	5/20	1,421.02	.41
1979	5/09	1,425.59	5/11	1,426.03	.44
		8-day rise in water level			
1950	5/24	1,411.21	6/01	1,412.52	1.31
1969	5/08	1,412.78	5/16	1,413.66	.88
1974	5/18	1,420.61	5/26	1,421.61	1.00
1979	5/04	1,424.61	5/12	1,426.22	1.61

1/1-day water-level rise was interpolated using the 2-day water-level rise.

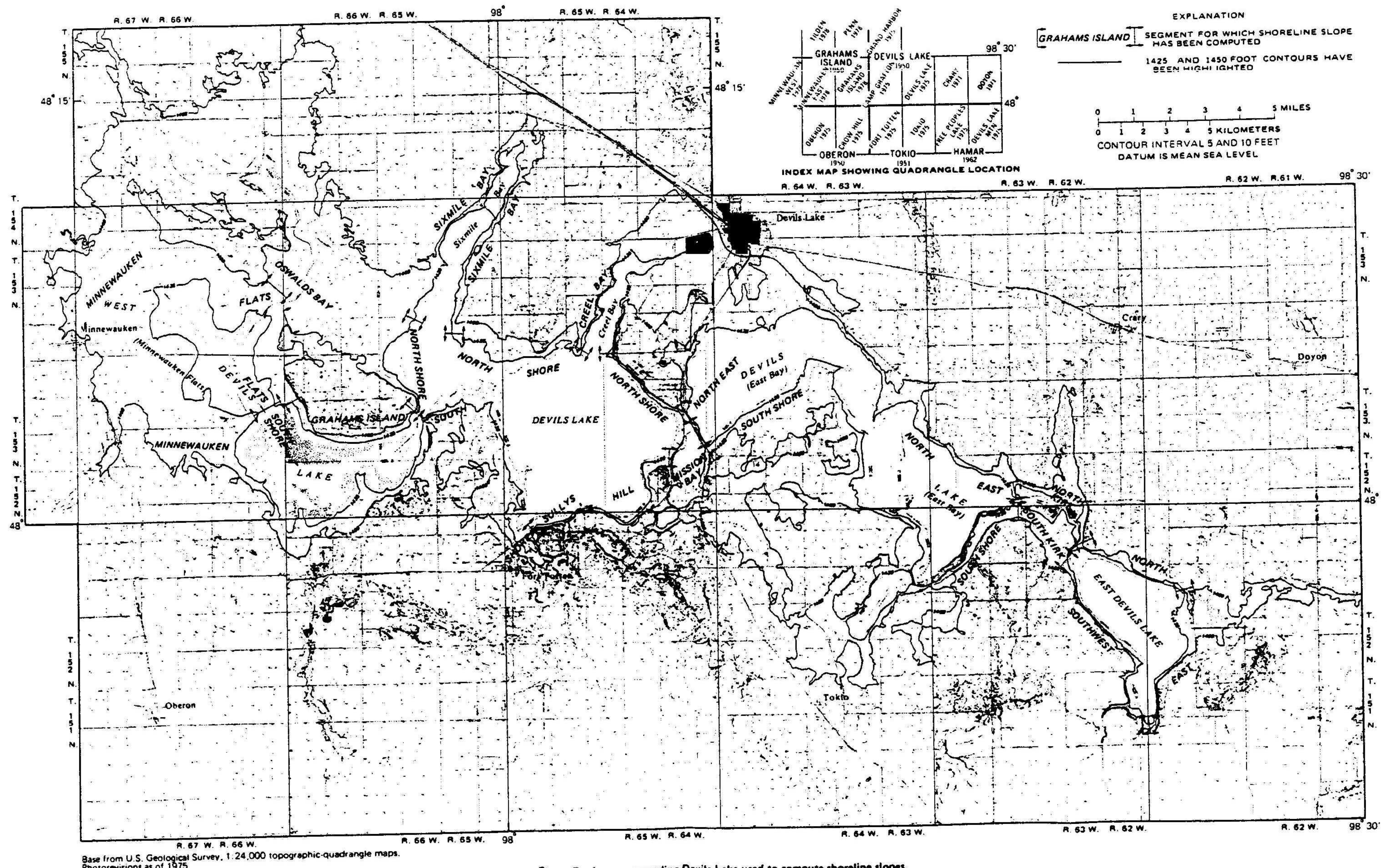

Figure 7.—Areas surrounding Devils Lake used to compute shoreline slopes.

Table 4.--*Relationship of water level to shoreline slope of Devils Lake*

Water-level intervals, in feet above sea level	Shoreline slope, in percent	Shoreline slope, in degrees
	West Bay Devils Lake	
	Minnewaukan Flats	
1,420-1,425	0.75	0.43
1,425-1,430	1.08	.62
1,430-1,435	1.29	.74
1,435-1,440	1.90	1.09
1,440-1,445	3.82	2.19
1,445-1,450	5.12	2.93
	Oswalds Bay	
1,430-1,435	.99	.57
1,435-1,440	1.11	.64
1,440-1,445	1.92	1.10
1,445-1,450	2.44	1.40
	Grahams Island	
1,420-1,425	1.20	.69
1,425-1,430	3.10	1.78
1,430-1,435	4.78	2.74
1,435-1,440	2.25	1.29
1,440-1,445	3.05	1.75
1,445-1,450	5.20	2.98
	Sixmile Bay	
1,415-1,420	2.09	1.20
1,420-1,425	3.95	2.26
1,425-1,430	6.58	3.76
1,430-1,435	5.53	3.16
1,435-1,440	6.44	3.68
1,440-1,445	5.45	3.12
1,445-1,450	4.69	2.68

Table 4.--*Relationship of water level to shoreline slope of Devils Lake*--Continued

Water-level intervals, in feet above sea level	Shoreline slope, in percent	Shoreline slope, in degrees
	North shore Devils Lake	
1,415-1,420	1.33	0.76
1,420-1,425	1.53	.88
1,425-1,430	3.38	1.94
1,430-1,435	3.63	2.08
1,435-1,440	4.30	2.46
1,440-1,445	7.26	4.15
1,445-1,450	10.83	6.18
	Creel Bay	
1,415-1,420	4.36	2.50
1,420-1,425	4.34	2.48
1,425-1,430	9.53	5.44
1,430-1,435	8.66	4.95
1,435-1,440	8.42	4.81
1,440-1,445	5.94	3.40
1,445-1,450	5.32	3.04
	South shore Devils Lake	
1,415-1,420	4.36	2.50
1,420-1,425	4.34	2.48
1,425-1,430	9.53	5.44
1,430-1,435	8.66	4.95
1,435-1,440	8.42	4.81
1,440-1,445	5.94	3.40
1,445-1,450	5.32	3.04

Table 4.--*Relationship of water level to shoreline slope of Devils Lake*--Continued

Water-level intervals, in feet above sea level	Shoreline slope, in percent	Shoreline slope, in degrees
	Sullys Hill	
1,415-1,420	4.60	2.63
1,420-1,425	4.55	2.60
1,425-1,430	5.50	3.15
1,430-1,435	11.00	6.28
1,435-1,440	11.00	6.28
1,440-1,445	14.46	8.23
1,445-1,450	14.46	8.23
	East Bay Devils Lake	
	North shore	
1,415-1,420	1.95	1.12
1,420-1,425	1.85	1.06
1,425-1,430	3.60	2.06
1,430-1,435	3.94	2.26
1,435-1,440	4.28	2.45
1,440-1,445	4.54	2.60
1,445-1,450	5.56	3.18
	South shore	
1,415-1,420	2.55	1.46
1,420-1,425	3.07	1.76
1,425-1,430	3.97	2.27
1,430-1,435	4.37	2.50
1,435-1,440	4.68	2.68
1,440-1,445	7.40	4.23
1,445-1,450	7.88	4.51

Table 4.--*Relationship of water level to shoreline slope of Devils Lake*--Continued

Water-level intervals, in feet above sea level	Shoreline slope, in percent	Shoreline slope, in degrees
	Mission Bay	
1,410-1,415	7.38	4.22
1,415-1,420	5.07	2.90
1,420-1,425	5.67	3.24
1,425-1,430	6.24	3.57
1,430-1,435	5.00	2.86
1,435-1,440	5.00	2.86
1,440-1,445	6.86	3.92
1,445-1,450	9.29	5.31
	Kirk	
	North shore	
1,425-1,430	2.51	1.44
1,430-1,435	3.57	2.04
1,435-1,440	3.32	1.90
1,440-1,445	6.30	3.60
1,445-1,450	9.00	5.14
	South shore	
1,425-1,430	2.72	1.56
1,430-1,435	2.71	1.55
1,435-1,440	1.70	.97
1,440-1,445	3.30	1.89
1,445-1,450	1.30	.74

Table 4.--*Relationship of water level to shoreline slope of Devils Lake*--Continued

Water-level intervals, in feet above sea level	Shoreline slope, in percent	Shoreline slope, in degrees
	East Devils Lake	
	North shore	
1,405-1,410	4.85	2.78
1,410-1,415	3.20	1.83
1,415-1,420	3.48	1.99
1,420-1,425	3.48	1.99
1,425-1,430	6.52	3.73
1,430-1,435	6.52	3.73
1,435-1,440	10.42	5.95
1,440-1,445	8.45	4.83
1,445-1,450	8.45	4.83
	Southwest shore	
1,405-1,410	4.83	2.76
1,410-1,415	5.24	3.00
1,415-1,420	6.49	3.71
1,420-1,425	6.54	3.74
1,425-1,430	7.72	4.41
1,430-1,435	9.20	5.26
1,435-1,440	8.48	4.85
1,440-1,445	10.16	5.80
1,445-1,450	10.62	6.06
	East shore	
1,405-1,410	2.25	1.29
1,410-1,415	2.00	1.15
1,415-1,420	1.48	.85
1,420-1,425	1.48	.85
1,425-1,430	2.52	1.44
1,430-1,435	3.25	1.86
1,435-1,440	3.55	2.03
1,440-1,445	3.05	1.75
1,445-1,450	1.40	.80

Table 5.--*Relationship of lateral change in shoreline location to shoreline slope and water-level rise of Devils Lake*

Shoreline slope, in percent	Lateral change in shoreline location, in feet, for indicated rise in lake level				
	0.1 foot	0.25 foot	0.50 foot	0.75 foot	1.0 foot
0.20	50	150	250	375	500
.50	20	50	100	150	200
1.00	10	25	50	75	100
2.00	5.0	12.5	25	37.5	50
3.00	3.3	8.3	16.7	25	33.3
3.77	2.6	6.6	13.3	19.9	26.5
4.00	2.5	6.3	12.5	18.5	25
5.00	2	5	10	15	20
8.00	1.2	3.1	6.2	9.4	12.5
10.00	1.0	2.5	5	7.5	10.0
14.00	.71	1.8	3.6	5.4	7.1

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, p. 228) said that the small lakes north of Devils Lake also were larger at some time in their history. In summary, Babcock (1903) 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) developed a multiple linear-regression equation using annual precipitation and annual temperature as the dependent variables and annual runoff as the independent variable. They applied this equation to data collected in the Sheyenne River basin and concluded that runoff in the Sheyenne River basin, and presumably the Devils Lake basin, has little relation to annual precipitation. 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 relatively substantial runoff.

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 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 climatic 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 has been inundated and 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.

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.

HYDROLOGIC AND CLIMATOLOGIC ANALYSIS

Most recent investigators (such as Swenson and Colby, 1955, and Mitten and others, 1968) have concluded that climate is a major factor in determining the water level of Devils Lake. However, previous attempts to directly relate climatic data and water levels in Devils Lake (such as Swenson and

Colby, 1955) have been only marginally successful. A variety of conditions, some unique to the Devils Lake basin, may contribute to the limited direct correlation between climate and water levels in Devils Lake. Among these conditions are:

(1) Upbasin storage in a number of lakes and potholes that eventually drain to Devils Lake. Until the storage capacities of these lakes are exceeded and they overflow into coulees draining to Devils Lake, increased precipitation will have minimal effect on water levels in Devils Lake. Similarly, decreased precipitation may be compensated for by continued flow from upbasin lakes and maintain water levels in Devils lake for some time. Accordingly, changes in upbasin storage and contributing area is expected to have a dampening effect on the hydrologic response of Devils Lake to climatic change that might be reflected in a lag response time. Accordingly, protracted periods of climatic extremes may be necessary to produce corresponding effects on water levels in Devils Lake.

(2) Even if climatic conditions are extreme, the conditions of snowmelt that contribute most of the runoff to drainages leading to Devils Lake may mitigate the effects of those climatic conditions on water levels in the lake. If, during an unusually wet climatic period, snowmelt is slow and initial prewinter soil moisture is minimal, much of the snowmelt may infiltrate to the ground-water system and not contribute to runoff reaching the lake. Similarly, if, during an unusually dry climatic period, snowmelt is fast and the soil frozen because of substantial prewinter soil-moisture content, much of the snowmelt may run off and help maintain higher water levels in the lake than general climatic conditions might predict.

(3) Land-use changes also may affect the relative magnitude of runoff within the basin. Particularly significant might be draining of previously noncontributing potholes and thus increasing the contributing area of the basin. Babcock (1903) and Horton and others (1910) also discussed how cultivation could increase infiltration and decrease runoff.

Improved methods of statistical and hydrologic analysis may provide an opportunity to determine the significance of such conditions relative to climatic factors. Thus, a new analysis of the hydrologic and climatologic data available for the Devils Lake basin was undertaken to determine if water-level fluctuations respond primarily to climatologic and hydrologic factors or to mitigating conditions.

Statistical Analysis of Discharge Record

Discharge records from six gaging stations (fig. 2) have been used to describe the major tributary inflows to Devils Lake (table 6). Discharge data collected at three long-term gaging stations (fig. 8) were used to describe the temporal variability in discharge of the principal tributaries to Devils Lake. Monthly streamflow statistics computed for these long-term gaging stations indicate a large variability in discharge from month to month (fig. 8). Most of the runoff occurs during April and May in Edmore and

Table 6.--*Drainage areas and period of record for gaging stations*

Site number (figure 2)	Gaging-station name	Drainage area, in square miles: Contributing	Drainage area, in square miles: Noncontributing	Period of record
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

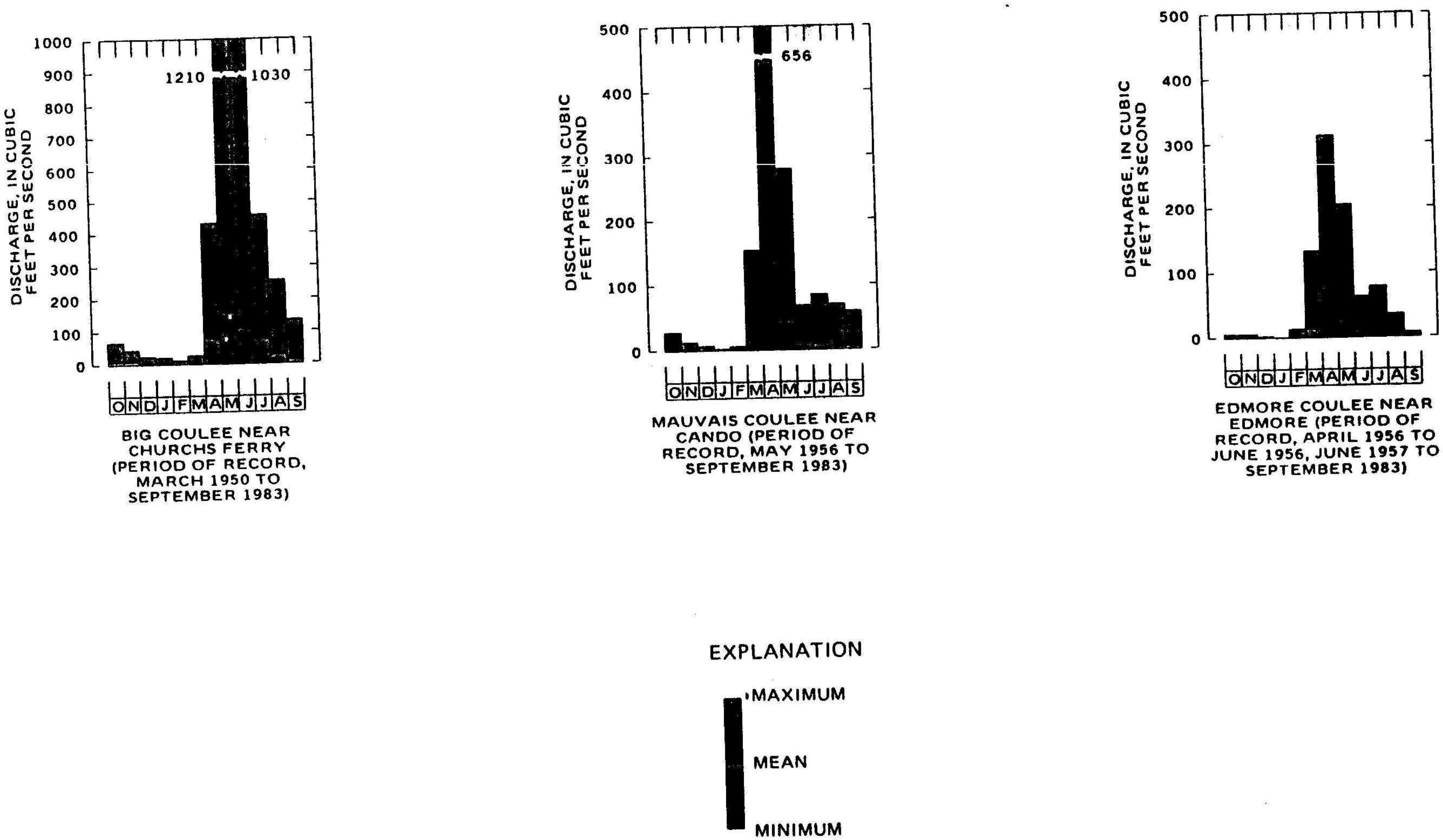

Figure 8.—Monthly discharge for period of record at three long-term gaging stations.

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 traveltime 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 7) indicate that the monthly discharge distribution is markedly skewed. The mean discharge is significantly influenced by 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 7) 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 8. 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.

Of 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 (210 square miles) is from Starkweather Coulee near Webster; and 10 percent (190 square miles) 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 discharge recorded at the Big Coulee near Churchs Ferry gage (table 8). 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 storage in many years. During 1965-67, the upstream lakes provided at least 112,000 acre-feet of storage. 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 feet 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

Table 7.--*Monthly flow statistics, in cubic feet per second, for three long-term gaging stations*

Month	Gaging-station name					
	Edmore Coulee near Edmore		Mauvais Coulee near Cando		Big Coulee near Churchs Ferry	
	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

Table 8.--*Annual discharge at gaging stations*

[The gain or loss (-) is equal to the discharge of Big Coulee minus the sum of the discharge of Mauvais Coulee, Little Coulee, Edmore Coulee, and Starkweather Coulee. 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]

Calendar year	Discharge, in acre-feet: Edmore Coulee	Starkweather Coulee	Mauvais Coulee	Little Coulee	Big Coulee	Gain or loss (acre-feet)
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	46,700
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.

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).

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, and some areal factors. Conger (1971) assumed all lake and marsh area not directly connected to the stream to be noncontributing. In the Devils Lake basin, there are many potholes and lakes that have significant depressional storage but contribute runoff only after the storage has been filled. 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 Geological Survey stated (H. M. Erskine, written commun., 1954):

> "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) studied the water-storage capacity of natural wetland depressions in the Devils Lake basin and concluded that they provide a maximum storage capacity of 657,000 acre-feet. They also concluded that these depressions retain 72 percent of the total runoff of a 2-year flood and 41 percent of the total runoff of a 100-year flood. The percentage of runoff retained for the two floods was based on dry depressions at the beginning of runoff. According to the Devils Lake Basin 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, 1980). Miller and Frink (1984) studied the flood-response changes in the Red River of the North basin and concluded that large variations in hydrologic characteristics of depressional storage in the basin cause effects on flood peaks that are not well understood.

Temporal Variability of Inflow to and Outflow from Devils Lake

A water-balance model was used to estimate the variability of inflow to Devils Lake for periods ranging from 1 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 is composed of numerous small closed drainage basins. These closed drainage basins have no defined drainage network and thus contribute no significant runoff to Devils Lake. In this study, inflow from Devils Lake (south slope) subbasin to Devils Lake was assumed to be zero.

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, an 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 freezeup 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.

Deviations from the annual hydrologic model undoubtedly occur.

The terms "inflow" and "outflow" have a specific meaning in this report. Inflow 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 outflow 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 inflow (gain) to Devils Lake and the annual outflow (loss) from Devils Lake (table 9) using equation 1. Annual inflow is equal to the capacity of the lake at maximum water level minus the capacity of the lake at minimum water level. Thus, the inflow is equal to the storage change (S_C) in equation 1. 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

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for 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, inflow was computed by subtracting the capacity of the lake at minimum water level from the capacity of the lake at maximum water level. After examining the water-level records to obtain the maximum water level after spring breakup and the minimum water level at winter freezeup, outflow was computed by subtracting the capacity of the lake at minimum water level from the capacity of the lake at maximum water level]

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
11/04/30	1,411.7	0.2	2,500	05/17/31	1,411.9	-1.2	14,700
05/17/31	1,411.9			11/08/31	1,410.7		
11/17/31	1,410.7	.7	8,500	06/12/32	1,411.4	-1.5	18,300
06/12/32	1,411.4			10/19/32	1,409.9		
10/19/32	1,409.9	.5	5,000				
11/03/32	1,410.4						
02/25/33	1,410.3	.5	6,100	05/31/33	1,410.8	-1.9	22,200
05/31/33	1,410.8			10/02/33	1,408.9		
04/25/34	1,408.8	--	--	04/25/34	1,408.8	-1.7	18,000
09/13/34	1,407.1			09/13/34	1,407.1		
09/13/34	1,407.1	--	--	05/23/35	1,407.4	-.7	7,000
10/19/35	1,406.7			10/19/35	1,406.7		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
10/19/35	1,406.7	0.5	5,000	05/02/36	1,407.2	-2.1	21,000
05/02/36	1,407.2			10/24/36	1,405.1		
10/24/36	1,405.1	--	--	10/24/36	1,405.1	-1.3	12,600
05/29/37	1,404.9			10/26/37	1,403.8		
03/21/38	1,403.1	.9	7,200	04/15/38	1,404.0	-1.9	15,200
04/15/38	1,404.0			11/21/38	1,402.1		
11/21/38	1,402.1	.6	4,800	04/25/39	1,402.7	-1.2	9,350
04/25/39	1,402.7			03/22/40	1,401.5		
03/22/40	1,401.5	.8	6,200	04/29/40	1,402.3	-1.4	10,600
04/29/40	1,402.3			10/24/40	1,400.9		
10/24/40	1,400.9	2.0	15,400	06/06/41	1,402.9	-.6	4,800
06/06/41	1,402.9			09/20/41	1,402.3		
10/11/41	1,402.4	2.1	17,800	06/08/42	1,404.5	-.5	5,000
06/08/42	1,404.5			09/30/42	1,404.0		
09/30/42	1,404.0	.7	7,000	06/30/43	1,404.7	-1.3	11,800
06/30/43	1,404.7			11/06/43	1,403.4		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, n feet above sea level	Change in water level, in feet	Outflow, in acre-feet
04/24/44	1,403.0	1.0	8,000	06/30/44	1,404.0	-0.8	6,400
06/30/44	1,404.0			10/19/44	1,403.2		
01/10/45	1,403.5	.9	8,000	06/04/45	1,404.4	-.9	8,000
06/04/45	1,404.4			11/01/45	1,403.5		
12/11/45	1,403.7	1.3	12,400	04/20/46	1,405.0	-1.6	14,800
04/20/46	1,405.0			12/10/46	1,403.4		
01/07/47	1,403.5	.1	800	05/10/47	1,403.6	-.6	4,800
05/10/47	1,403.6			10/13/47	1,403.0		
10/13/47	1,403.0	2.2	20,000	06/11/48	1,405.2	-1.0	10,000
06/11/48	1,405.2			10/28/48	1,404.2		
10/28/48	1,404.2	3.0	30,000	07/16/49	1,407.2	-.8	8,000
07/16/49	1,407.2			10/01/49	1,406.4		
04/11/50	1,406.6	8.4	110,000	12/01/49	1,406.5	--	--
09/24/50	1,415.0			10/02/50	1,415.0		
12/09/50	1,414.9	.6	7,000	05/03/51	1,415.5	-1.2	13,500
05/03/51	1,415.5			11/20/51	1,414.3		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
02/29/52	1,414.3	0.2	2,200	04/11/52	1,414.5	-2.0	33,700
04/11/52	1,414.5			01/30/53	1,412.5		
01/30/53	1,412.5	.5	9,100	06/26/53	1,413.0	-1.4	23,800
06/26/53	1,413.0			12/01/53	1,411.6		
06/04/54	1,411.7	2.7	46,100	05/06/54	1,411.7	--	--
11/29/54	1,414.4			11/29/54	1,414.4		
03/01/55	1,414.4	2.4	28,100	06/20/55	1,416.8	-.9	14,300
06/20/55	1,416.8			11/17/55	1,415.9		
01/31/56	1,416.2	3.2	63,400	07/14/56	1,419.4	-.7	18,000
07/14/56	1,419.4			10/21/56	1,418.7		
01/28/57	1,418.4	.3	6,600	10/05/57	1,418.7	-.6	11,900
05/05/57	1,418.7			08/31/57	1,418.1		
01/01/58	1,418.1	--	--	02/26/58	1,418.3	-1.7	28,600
10/08/58	1,416.6			10/08/58	1,416.6		
01/16/59	1,417.0	--	--	02/17/59	1,417.1	-1.8	26,000
12/22/59	1,415.3			11/24/59	1,415.3		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
01/01/60	1,415.6	0.6	8,200	06/12/60	1,416.2	-1.6	19,100
06/12/60	1,416.2			12/07/60	1,414.6		
02/14/61	1,414.8	.1	1,100	04/19/61	1,414.9	-1.8	27,000
04/19/61	1,414.9			12/12/61	1,413.1		
03/01/62	1,413.2	1.1	18,500	06/13/62	1,414.3	-1.5	25,900
06/13/62	1,414.3			12/04/62	1,412.8		
03/19/63	1,413.1	.1	1,900	05/03/63	1,413.2	-1.8	30,000
05/03/63	1,413.2			12/03/63	1,411.4		
01/01/64	1,411.5	.3	3,600	06/19/64	1,411.8	-1.0	12,500
06/19/64	1,411.8			11/22/64	1,410.8		
01/01/65	1,411.0	.6	7,300	06/04/65	1,411.6	-.6	7,500
06/04/65	1,411.6			09/12/65	1,411.0		
01/14/66	1,411.2	1.7	26,900	07/08/66	1,412.9	-1.0	18,200
07/08/66	1,412.9			12/01/66	1,411.9		
01/01/67	1,411.9	.9	16,400	05/15/67	1,412.8	-1.7	26,300
05/15/67	1,412.8			12/08/67	1,411.1		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
12/08/67	1,411.1	0.6	7,300	06/13/68	1,411.7	-1.0	12,500
06/13/68	1,411.7			11/05/68	1,410.7		
01/22/69	1,410.5	6.3	88,900	01/22/69	1,410.5	--	--
12/31/69	1,416.8			12/31/69	1,416.8		
01/01/70	1,416.8	2.7	55,500	07/31/70	1,419.5	-.6	21,700
07/31/70	1,419.5			11/12/70	1,418.9		
03/03/71	1,418.8	2.2	54,900	07/12/71	1,421.0	-.3	18,100
07/12/71	1,421.0			08/31/71	1,420.7		
08/31/71	1,420.7	.4	8,900				
11/31/71	1,421.1						
02/20/72	1,420.8	1.5	36,000	06/03/72	1,422.3	-1.9	72,700
06/03/72	1,422.3			12/23/72	1,420.4		
02/26/73	1,420.4	.2	1,300	04/01/73	1,420.6	-1.5	53,800
04/01/73	1,420.6			11/18/73	1,419.1		
01/11/74	1,419.2	4.9	152,000	07/25/74	1,424.1	-1.3	57,500
07/25/74	1,424.1			10/30/74	1,422.8		

Table 9.--*Computed annual inflow (gain) and annual outflow (loss) for Devils Lake*--Continued

Inflow				Outflow			
Date	Water level, in feet above sea level	Change in water level, in feet	Inflow, in acre-feet	Date	Water level, in feet above sea level	Change in water level, in feet	Outflow, in acre-feet
12/13/74	1,422.8	2.0	65,000	07/05/75	1,424.8	-1.4	63,300
07/05/75	1,424.8			11/23/75	1,423.4		
01/22/76	1,423.4	1.7	59,400	06/13/76	1,425.1	-2.4	108,000
06/13/76	1,425.1			11/30/76	1,422.7		
01/12/77	1,422.7	.3	6,000	05/05/77	1,423.0	-1.4	59,100
05/05/77	1,423.0			11/20/77	1,421.6		
01/01/78	1,421.9	1.3	26,900	07/20/78	1,423.2	-1.2	48,000
07/20/78	1,423.2			11/10/78	1,422.0		
01/10/79	1,422.1	4.9	248,100	07/12/79	1,427.0	-1.2	65,100
07/12/79	1,427.0			12/16/79	1,425.8		
01/03/80	1,425.8	.3	15,800	04/21/80	1,426.1	-1.0	51,900
04/21/80	1,426.1			10/13/80	1,425.1		
01/02/81	1,425.3	.6	30,900	06/24/81	1,425.9	-.8	41,200
06/24/81	1,425.9			12/30/81	1,425.1		
01/01/82	1,425.1	1.8	95,700	07/24/82	1,426.9	-.7	38,300
07/24/82	1,426.9			09/27/82	1,426.2		
09/27/82	1,426.2	1.9	104,100	05/27/83	1,428.1	-1.0	54,900
05/27/83	1,428.1			09/30/83	1,427.1		

level were recorded. Based on a study by Paulson and Akin (1964), the ground-water contribution (G) was assumed to be negligible for the computation of inflow and outflow. No inflow or outflow 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 9 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 inflow to Devils Lake. 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.

Analysis of the water-level fluctuations indicates that there are three 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 relatively small rise was the result of an inflow of 5,000 acre-feet 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 water-level rise was the result of an inflow of 8,900 acre-feet caused by generally intense rainfall over the Devils Lake basin in October. Rainfall 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. 9) differs markedly from the conceptual model. Snowmelt runoff and spring rains produced no detectable change in the water level of Devils Lake. 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 an inflow 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, 1982a). 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). The normal September rainfall is 1.60 inches at Bisbee and 1.97 inches at Langdon (U.S. Department of Commerce,

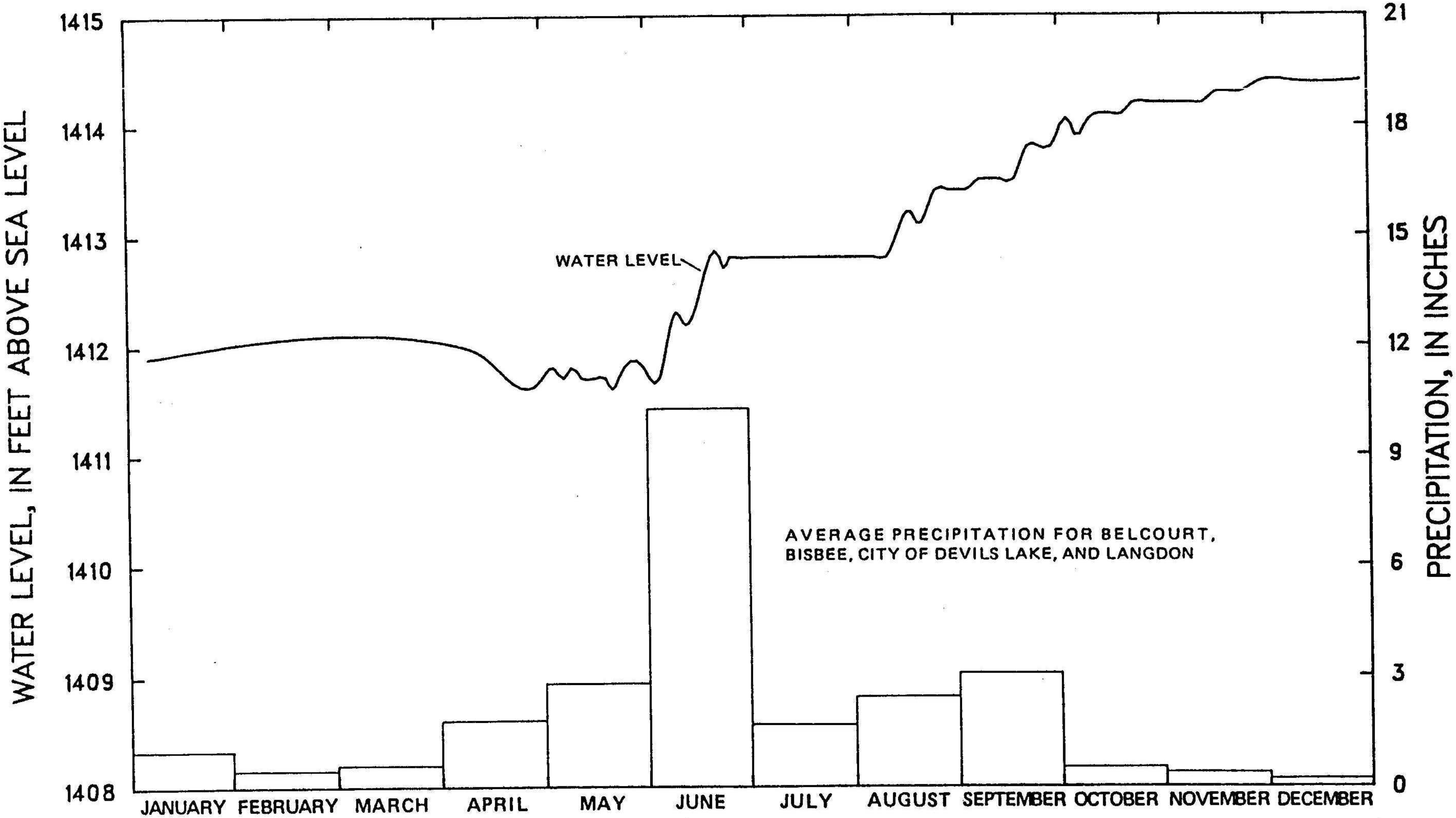

Figure 9.—Water levels of Devils Lake, January-December 1954, and average precipitation at four locations, January-December 1954.

National Oceanic and Atmospheric Administration, Environmental Data Service, 1973a and 1982a). The water-level rises caused by the two rainstorms are evident (fig. 9). Thus, even though the inflow usually decreases from late July through early September, in 1954 inflow was greater than outflow and the water level continued to rise throughout the summer and fall.

Outflow (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 outflow was computed by subtracting the capacity of the lake at minimum water level from the capacity of the lake at maximum water level. The precipitation (PR) falling on the lake surface and the evaporation (EV) 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 was assumed to be negligible. Outflow from Devils Lake has not been as variable as the inflow to the lake. From 1931 through 1969 outflow ranged from zero in 1950, 1954, and 1969 to 33,700 acre-feet in 1952 (table 9). Since 1969 the outflow has averaged about 53,800 acre-feet per year. The large increase in outflow 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- 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. While the assumptions used in conjunction with equation 1 may be valid "on the average," they probably will be poor during periods of climatic extremes. As an example, during wet years, precipitation is greater than normal and the cool humid weather reduces evaporation. During droughts, precipitation is minimal and hot dry weather causes increased 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 were computed using equation 1. The 18 years (1867-84) represent a "wet" period that had the highest sustained lake levels for the period of record (1867-1983), and the 10 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 10. It is interesting to note that

Table 10.--*Computed water-balance equations for Devils Lake for 1867-84 and 1931-40*

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

the 58,300 acre-feet of inflow to Devils Lake from 1867 to 1884 occurred during a period of declining water levels.

The computed inflow to Devils Lake for the more recent period of rising water levels (1969-83) can be compared to the relatively "wet" and "dry" periods listed in table 11 and shown in figure 10. The terms "gradual" and "rapid" have been used in table 11, in figure 5, 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 computed annual inflow to Devils Lake averaged 70,000 acre-feet per year during 1969-83 as compared to an average annual inflow of 58,300 acre-feet during 1867-84 (table 10) and a total computed inflow of 45,200 acre-feet for the drought years of 1931-40.

Hydrologic and Climatologic Interaction

Unless major changes in the factors affecting runoff have occurred, there should be a general relationship between major changes in water-level fluctuations and the climatic indices of temperature, precipitation, and evaporation. If a probability analysis is applied to the water-level fluctuations of Devils Lake, it is essential to know if these fluctuations are caused by human changes in the runoff processes in the Devils Lake basin or are the result of climatic variability.

To evaluate the relationship between water-level fluctuations and climatic indices, an attempt was made to compare runoff to winter (October through April) precipitation. Winter precipitation was selected as the climatic variable that has the greatest effect on annual runoff in the northern Great Plains and, in turn, on water-level fluctuations. 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. The Mauvais Coulee gage was chosen because it only has 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 provided 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 snowmelt, and wind velocity affect the 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. 11 and 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 regression coefficient of 0.91. In order to achieve the accuracy reported by Miller and Frink (1984), the independent variables needed were: (1) Winter precipitation south of Grand Forks, (2) an 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.

Table 11.--*Major lake-level fluctuations of Devils Lake*

Years	Comparative water-level fluctuations	Water level, in 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

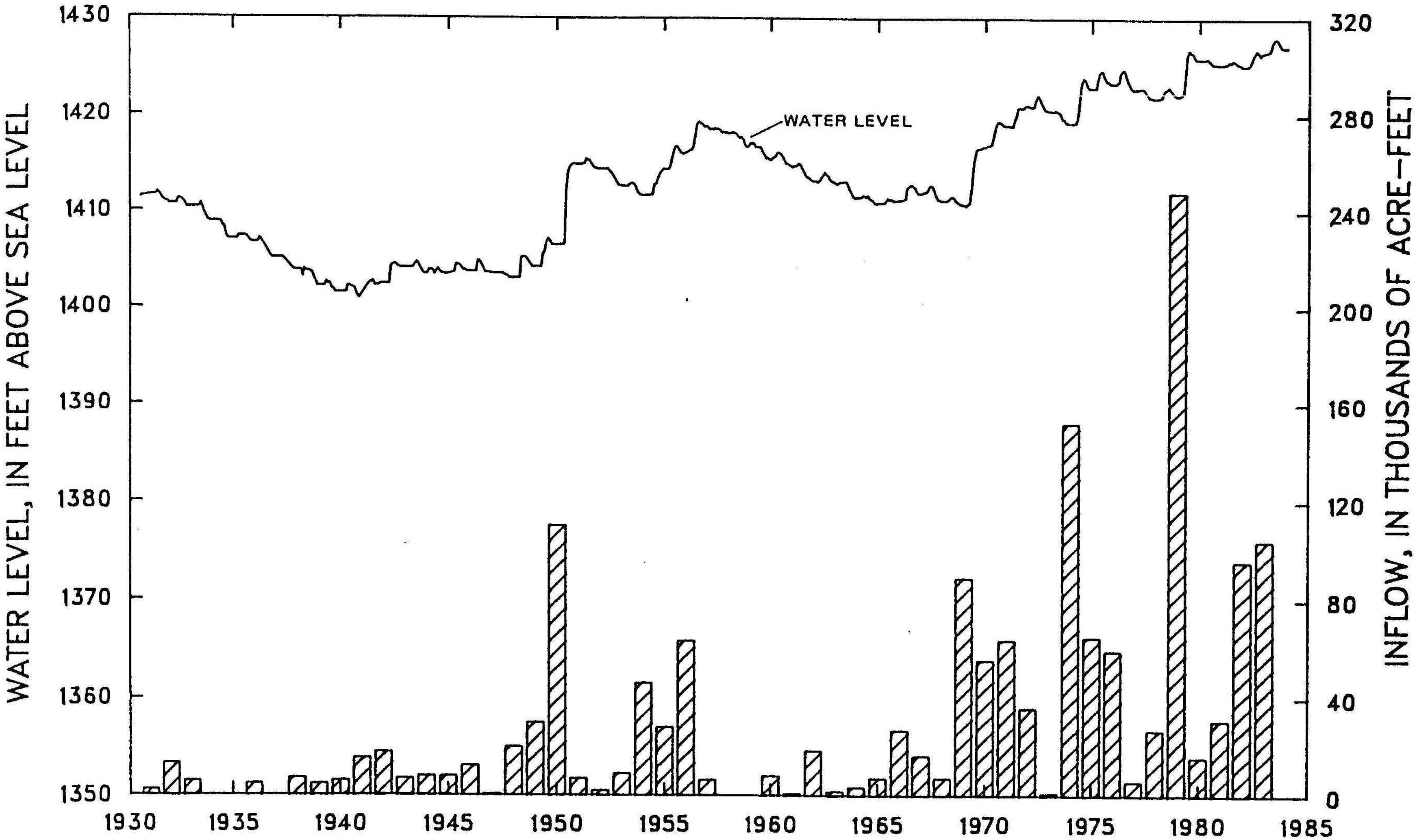

Figure 10.—Recorded water levels and computed annual inflow (gain) of Devils Lake, 1931-83.

Based on their work, an improvement in the regression coefficient 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 water-level fluctuations of Devils Lake on a yearly basis and climatologic variables. Thus, a more general, less quantitative approach was attempted by dividing the water-level fluctuations into major lake stands. The major lake-level fluctuations are listed in table 11 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 (fig. 11a) of 6.78 inches from 1870 through 1884 (U.S. Department of Agriculture, Weather Bureau, 1932b). In addition to the relatively greater-than-average winter precipitation, 1871-80 is characterized as having relatively wet summers (fig. 11b). 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 levels prior to 1880 were caused by greater-than-average precipitation and less-than-average temperatures. Wahl and Lawson (1970) indicated that November and December precipitation from 1850 through 1869 was 10 to 20 percent greater than normal (1931-60) across North Dakota; January through March precipitation was 30 to 40 percent greater than normal (1931-60). This period of greater-than-average winter precipitation correlates with the evidence provided by Upham (1895) that indicated that the high water-level stand 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. Average annual precipitation at Fort Totten, which is located 10 miles southwest of the city of Devils Lake, was greater than the normal (1951-80) precipitation at Devils Lake for 13 of the 15 years during 1870-84. At Bismarck, where the normal (1951-80) precipitation is 15.36 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982a), 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, 1982a). Thus, compared to the normal (1951-80) precipitation, 1885-90 was not extremely dry.

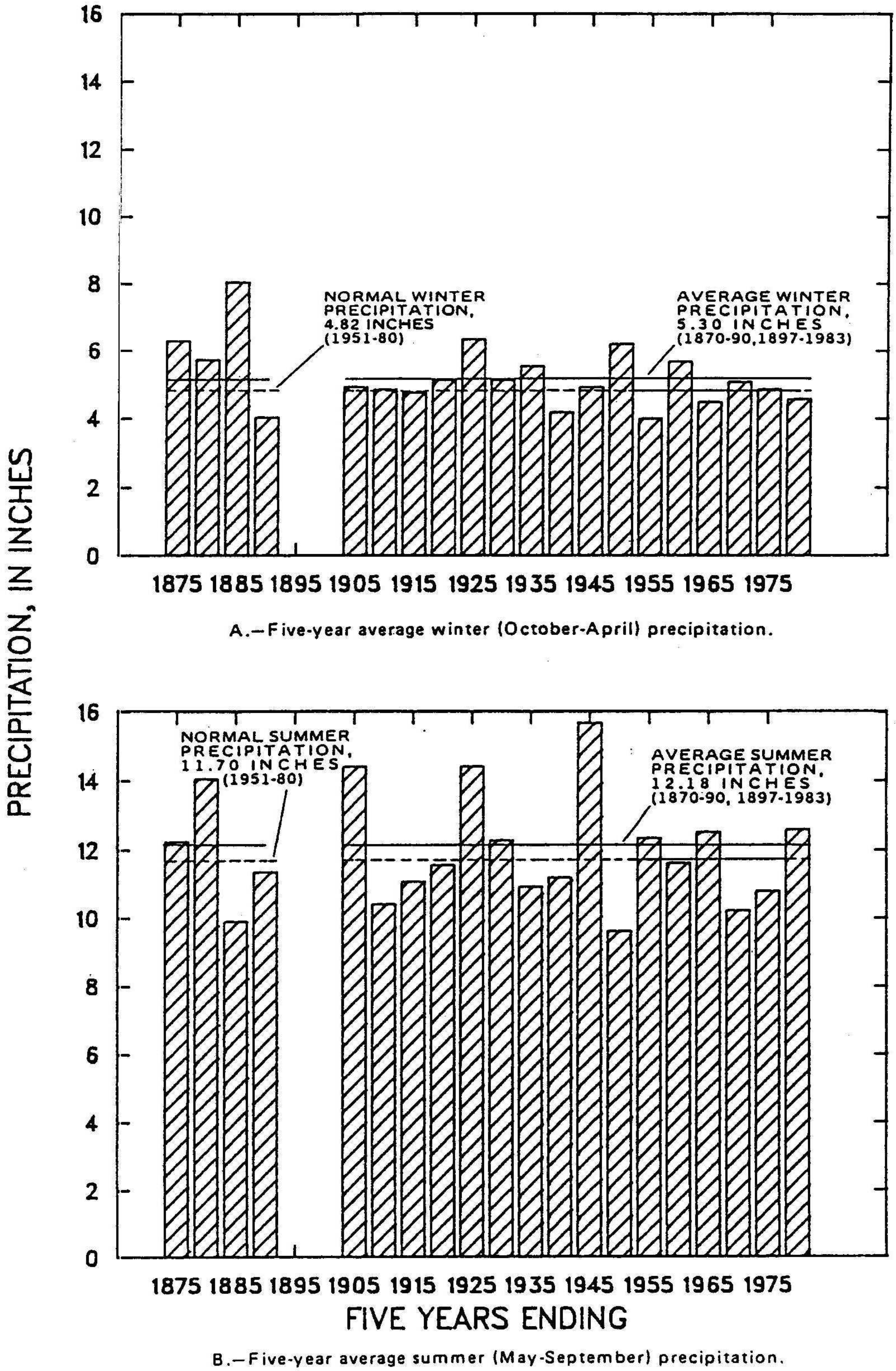

Figure 11.—Five-year average precipitation at Fort Totten (1870-90) and at the city of Devils Lake (1897-1983).

However, 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 33-percent decrease in average annual precipitation 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 to 1906 (fig. 5). No precipitation data are available from 1891 to 1896, but winter precipitation also was relatively constant from 1897 to 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 produced 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 is no record available (fig. 5).

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. 11a). Even though there was an increase in winter precipitation during 1921-25, the lake declined 1.9 feet. The climate during 1931-40 can be characterized as having less-than-normal summer precipitation, slightly greater-than-normal winter precipitation from 1931 to 1935 and less-than-normal winter precipitation from 1936 to 1940, and relatively substantial evaporation as indicated by the average summer temperature at Devils Lake (fig. 12). 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. This small volume caused the 5-foot water-level rise because, at that time, Devils Lake was a relatively small lake confined to the west bay (fig. 2). From 1941 through 1945, winter precipitation was about normal; but summer precipitation was the greatest for the period of record, and the summer temperature was less than normal. Thus, the evaporative losses from the lake surface probably were less than average. From 1945 through 1958, summer precipitation was less than normal; winter precipitation was greater than normal; and the summer temperature was about normal.

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. 11b) and temperatures (fig. 12) were about normal. The apparent discrepancy of rising water levels at a time of minimal winter precipitation is

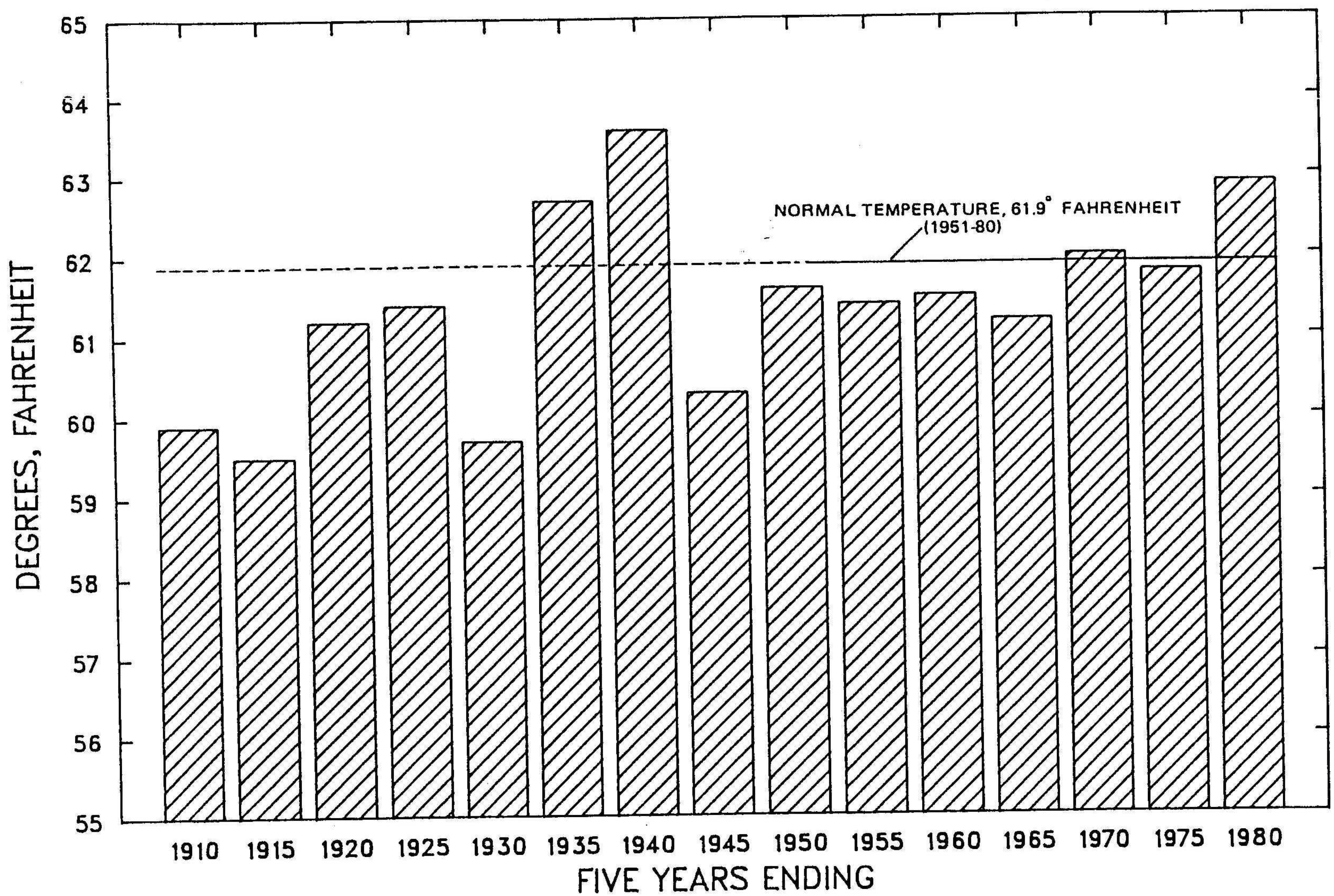

Figure 12.—Five-year average summer (May-September) temperature at the city of Devils Lake.

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 during 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 normal; and there is 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 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 normal for 1971-75 and slightly greater than normal for 1976-80.

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 13 for 1931-83. Relatively good agreement occurs between water-level fluctuations and changes in the 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.

WATER-LEVEL FLUCTUATIONS OF OTHER TERMINAL LAKES IN NORTH AMERICA

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 follows.

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., has had a general rise in water levels from 1965 to 1982. The original Government Land Office Survey plat made in 1847 shows the size of the lake to be about 2,300 acres. 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 rises in water levels of Big Marine Lake and associated aquifers can be detected a few days to a few weeks after precipitation has occurred. The rise in water levels of Big Marine Lake

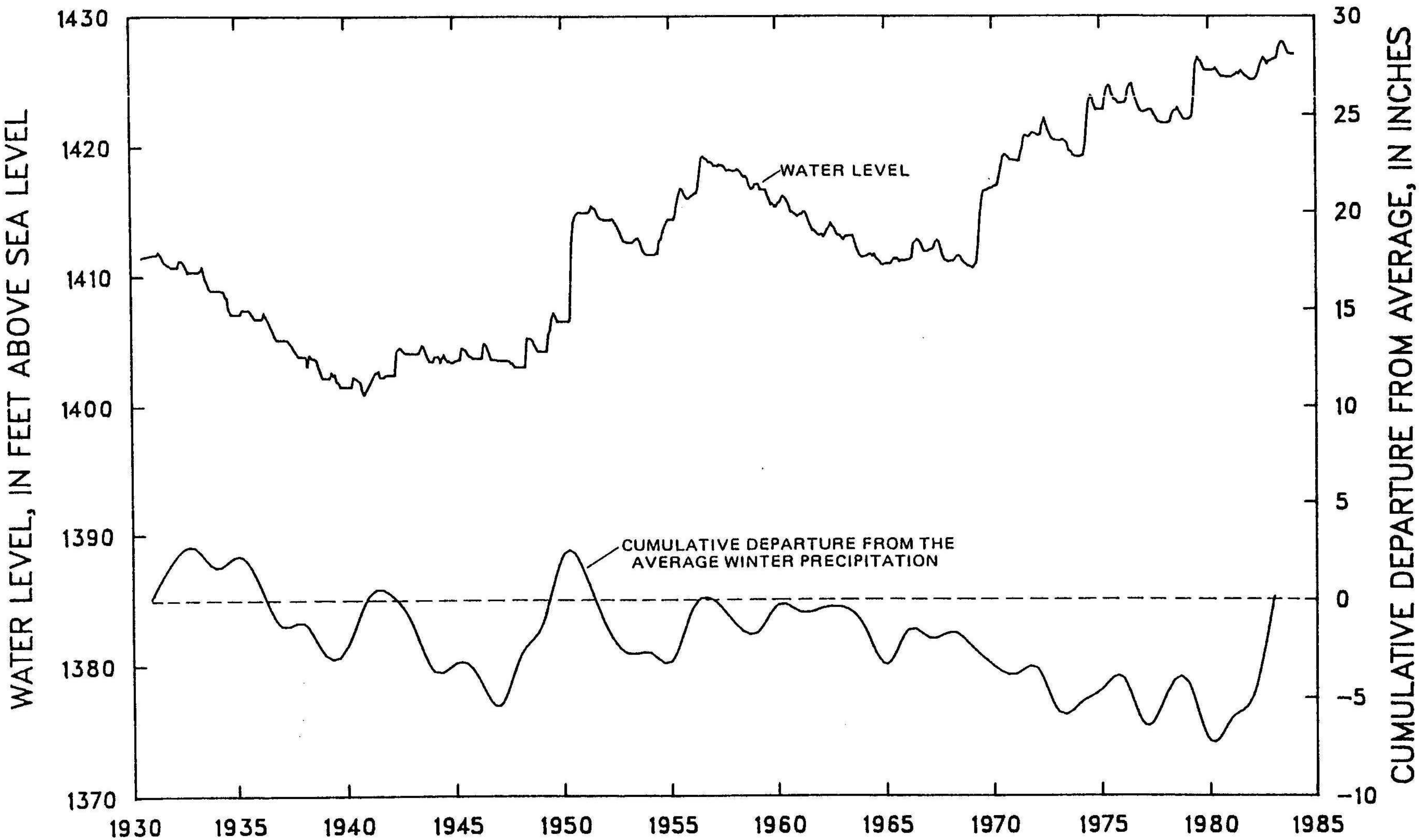

Figure 13.—Recorded water levels of Devils Lake and cumulative departure from the average winter precipitation, 1931-83.

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.

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) during 1934-40 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, 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 measured 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. Ngai (1981) stated 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." 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 1938-43 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 by 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 plagued by rising water levels in recent years. Water levels of Fishing Lake have risen about 7.2 feet from 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.

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 about 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 Francisco, 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 (1912-84) 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, 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 in comparison to those of Devils Lake are shown in figure 14.

Arnow (1984) indicated that Great Salt Lake has fluctuated primarily in response to climatic variation. Although there are differences in physiography and hydrology between Devils Lake basin and the Great Salt Lake basin, 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. 14). Great Salt Lake began to decline in 1953, whereas Devils Lake began to decline in 1958; Great Salt Lake began to rise in 1964, whereas 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.

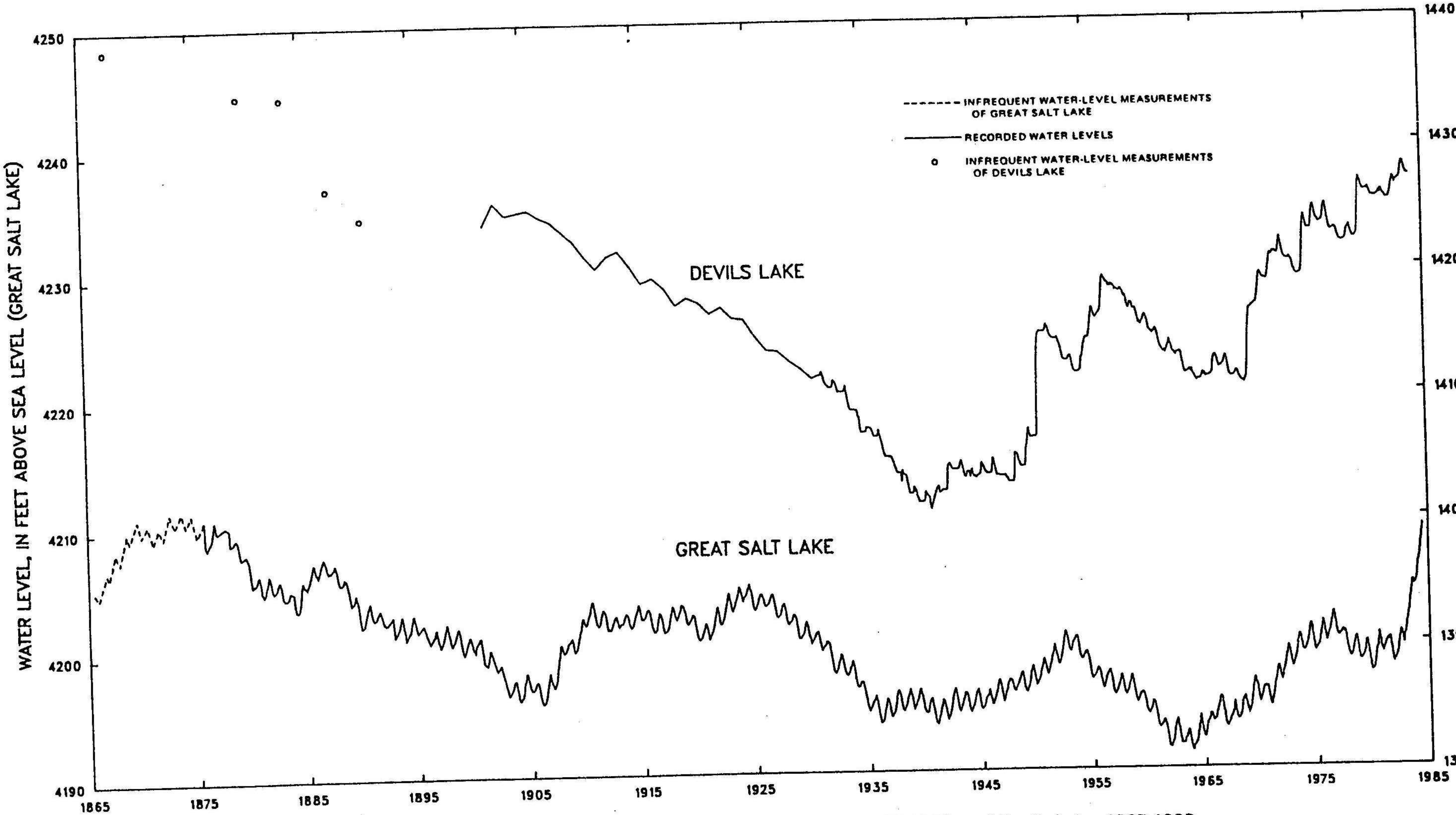

Figure 14.—Historic water levels for Great Salt Lake, Utah, 1865-1983, and Devils Lake, 1867-1983.

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 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.

ESTIMATES OF FUTURE LAKE LEVELS

Exceedance Probabilities of Inflows

No standardized methods are available for computing lake-level probabilities of terminal lakes. Most of the development of a method for determining future lake-level probabilities has been focused on Great Salt Lake, Utah. A number of methods have been used to estimate the future lake-level probabilities for Great Salt Lake (see Supplement 1); however, they provide a considerable range in probability for any given lake level.

Although problems are encountered when trying to predict the probability of a future lake level, it is possible to assign a probability to a given water-level rise if the starting water level has been determined. As an example, the annual exceedance probability is plotted against the water-level rise for three starting water levels in figure 15. The exceedance probability for a given water-level rise was computed by first developing the exceedance probability for the inflows listed in table 9 and then converting the inflow value to a water-level rise based on the selected starting water level.

The exceedance probability for a given inflow value to Devils Lake was computed using the procedures outlined by the U.S. Water Resources Council (1981). A log-Pearson type III distribution was fitted to the annual inflows by computing the base-10 logarithms of the inflow, Q, at the selected exceedance probability, P, by the equation:

$$\text{Log } Q = \overline{X}+KS, \tag{2}$$

where

$\overline{X}$ = mean logarithm,
K = a factor that is a function of the skew coefficient and the selected exceedance probability, and
S = standard deviation of logarithms.

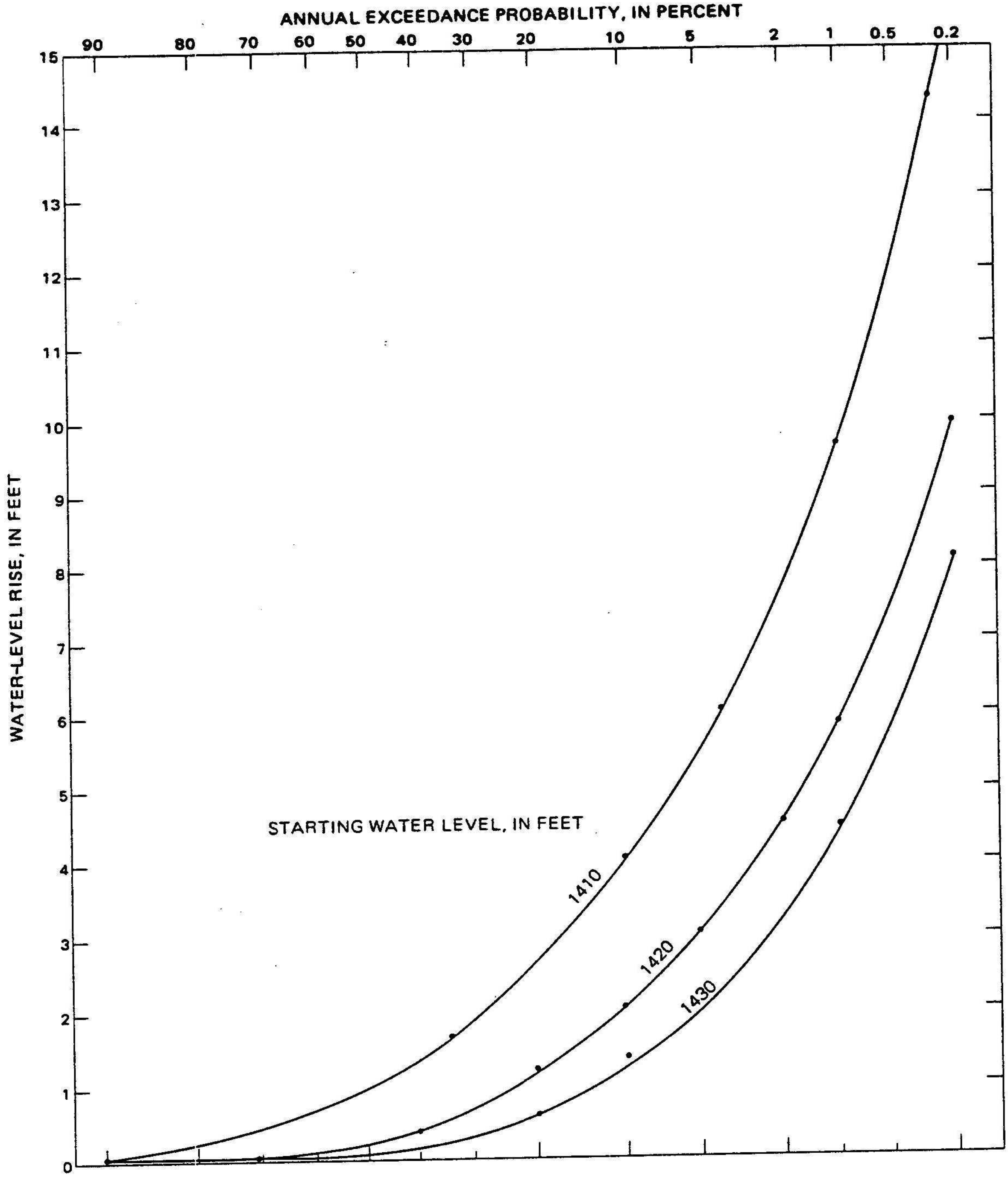

Figure 15.—Relationship between the magnitude and exceedance probability of annual water-level rises of Devils Lake.

The station skew coefficient was used because the map-skew and the weighted-skew options are based on peak discharge and not on annual inflow volume. The final exceedance probabilities plotted in figure 15 were adjusted for the 5 years out of the 55 years when the inflow was zero using the procedures described by the U.S. Water Resources Council (1981).

Analysis of figure 15 indicates that the lower the starting water level of Devils Lake the greater the water-level rise that will occur for any given exceedance probability. As an example, an inflow of 72,200 acre-feet has an exceedance probability of 10 percent (10-year return period) in any given year. This inflow would result in a 4.20-foot water-level rise if Devils Lake is at a starting water level of 1,410 feet above sea level, but, if the starting water level is 1,430 feet above sea level, the water-level rise is only 1.41 feet. The inflow of 248,100 acre-feet during 1979 was the largest inflow from 1931 through 1984 and had an exceedance probability of 1.8 percent (return period of about 56 years).

The water-level rise associated with an annual exceedance probability is expressed as a lateral change in shoreline location in table 12. The lateral shoreline change was computed using the following steps:

(1) Select a starting water level of Devils Lake.

(2) In table 4, for a given location, find the average shoreline slope, in percent, for the water-level interval containing the starting water level selected in step 1.

(3) In figure 15, find the water-level rise for a selected annual exceedance probability and the starting water level chosen in step 1.

(4) Divide the water-level rise computed in step 3 by the average shoreline slope, in percent, and multiply by 100.

As an example, based on a starting water level of 1,426.1 feet above sea level (water level in January 1985), the north shore of Devils Lake has an average shoreline slope of 3.38 percent (table 4). Based on figure 15, a starting water level of 1,426.1 feet above sea level and an annual exceedance probability of 20 percent yields a 0.90-foot water-level rise. The 0.90-foot water-level rise is divided by the average shoreline slope of 3.38 percent, and the sum is multiplied by 100 to obtain a lateral shoreline change of 26.6 feet.

Analysis of table 12 indicates that for an annual exceedance probability of 10 percent the lateral change in shoreline location ranges from 16.8 feet along the south shore of Devils Lake and along the shore of Creel Bay to 148 feet along the West Bay of Devils Lake near Minnewaukan Flats. Thus, at a starting water level in the range from 1,425 to 1,430 feet above sea level, a 1-foot lateral change in shoreline location along the south shore of Devils Lake corresponds to an 8.8-foot lateral change in shoreline location along the West Bay of Devils Lake near Minnewaukan Flats (148 feet/16.8 feet).

Table 12.--*Lateral change in shoreline location for selected locations at Devils Lake associated with annual exceedance probabilities of water-level rises*

Shoreline slope, in percent, at water level 1,426.1 feet above sea level	Annual exceedance probability, in percent	Water-level rise, in feet	Lateral change in shoreline location, in feet
	West Bay Devils Lake		
	Minnewaukan Flats		
1.08	20	0.90	83.3
	10	1.60	148
	2	3.92	363
	1	5.20	481
	Oswalds Bay		
--	20	0.90	--
	10	1.60	--
	2	3.92	--
	1	5.20	--
	Grahams Island		
3.10	20	0.90	29.0
	10	1.60	51.6
	2	3.92	126
	1	5.20	168
	Sixmile Bay		
6.58	20	0.90	13.7
	10	1.60	24.3
	2	3.92	59.6
	1	5.20	79.0
	North shore Devils Lake		
3.38	20	0.90	26.6
	10	1.60	47.3
	2	3.92	116
	1	5.20	154

Table 12.--*Lateral change in shoreline location for selected locations at Devils Lake associated with annual exceedance probabilities of water-level rises*--Continued

Shoreline slope, in percent, at water level 1,426.1 feet above sea level	Annual exceedance probability, in percent	Water-level rise, in feet	Lateral change in shoreline location, in feet
	Creel Bay		
9.53	20	0.90	9.4
	10	1.60	16.8
	2	3.92	41.1
	1	5.20	54.6
	South shore Devils Lake		
9.53	20	0.90	9.4
	10	1.60	16.8
	2	3.92	41.1
	1	5.20	54.6
	Sullys Hill		
5.50	20	0.90	16.4
	10	1.60	29.1
	2	3.92	71.3
	1	5.20	94.5
	East Bay Devils Lake		
	North shore		
3.60	20	0.90	25.0
	10	1.60	44.4
	2	3.92	109
	1	5.20	144
	South shore		
3.97	20	0.90	22.7
	10	1.60	40.3
	2	3.92	98.7
	1	5.20	131

Table 12.--*Lateral change in shoreline location for selected locations at Devils Lake associated with annual exceedance probabilities of water-level rises*--Continued

Shoreline slope, in percent, at water level 1,426.1 feet above sea level	Annual exceedance probability, in percent	Water-level rise, in feet	Lateral change in shoreline location, in feet
	Mission Bay		
6.24	20	0.90	14.4
	10	1.60	25.6
	2	3.92	62.8
	1	5.20	83.3
	Kirk		
	North shore		
2.51	20	0.90	35.9
	10	1.60	63.7
	2	3.92	156
	1	5.20	207
	South shore		
2.72	20	0.90	33.1
	10	1.60	58.8
	2	3.92	144
	1	5.20	191
	East Devils Lake		
	North shore		
6.52	20	0.90	13.8
	10	1.60	24.5
	2	3.92	60.1
	1	5.20	79.8

Table 12.--*Lateral change in shoreline location for selected locations at Devils Lake associated with annual exceedance probabilities of water-level rises*--Continued

Shoreline slope, in percent, at water level 1,426.1 feet above sea level	Annual exceedance probability, in percent	Water-level rise, in feet	Lateral change in shoreline location, in feet
	East Devils Lake--Continued		
	Southwest shore		
7.72	20	0.90	11.7
	10	1.60	20.7
	2	3.92	50.8
	1	5.20	67.4
	East shore		
2.52	20	0.90	35.7
	10	1.60	63.5
	2	3.92	156
	1	5.20	206

Water-Balance Model

Conceptual Design

A monthly water-balance model was developed, based on equation 1, that accounts for the gains and losses in streamflow that occur as water moves through the chain of lakes upstream from Devils Lake. The monthly water-balance model operates on monthly values of inflow, precipitation, and evaporation. Monthly values of inflow available at gaging stations in the different subbasins were adjusted using drainage-area ratio techniques to account for the intervening drainage area in a basin downstream from the gaging stations. Comparison of recorded and simulated monthly water levels indicates that the simulated monthly water levels may be distorted because excess water above the spill elevation is assumed to immediately discharge. Thus, the model does not lag the outflows as would reservoir routing.

Discharge from Edmore Coulee is added to the capacity of Sweetwater and Morrison Lakes. The precipitation falling on a lake surface is added and the evaporation from a lake surface is subtracted from the capacity of a lake. Sweetwater and Morrison Lakes are treated as a combined lake in the water-balance model. The spill elevation of Morrison Lake into Webster Coulee is about 1,458.5 feet above sea level. If the capacity of the lake at the end of the month is above the spill elevation capacity, the difference is treated as outflow from Sweetwater and Morrison Lakes to Webster Coulee.

Dry Lake receives inflow from Webster Coulee and Starkweather Coulee in addition to precipitation falling on the lake surface. Water is lost to the atmosphere through evaporation. If the capacity of Dry Lake at the end of the month is greater than the capacity of Dry Lake at the spill elevation, then all excess water is treated as outflow to channel A. The operating criteria for the control structure that regulates the water level of Dry Lake were incorporated into the water-balance model. From October through April the spill elevation of Dry Lake is set at 1,445 feet above sea level, and from May through September the spill elevation is set at 1,447.5 feet above sea level.

Chain Lake receives inflow from Mikes Lake and Calio Coulee and from precipitation falling on the lake surface. Water is removed from Chain Lake through evaporation. All water in Chain Lake above the spill elevation of 1,442 feet above sea level is released to Lake Alice.

Lake Alice receives inflow from Chain Lake, Mauvais Coulee, and precipitation falling on the lake surface. In 1968 the U.S. Fish and Wildlife Service constructed a control structure in the channel between Lake Alice and Lake Irvine that allows them to control the water level of Lake Alice. The low sill elevation between Lake Alice and Lake Irvine is about 1,436 feet above sea level, and the outlet elevation from Lake Irvine to Big Coulee is 1,439.6 feet above sea level. From November through April the gates at the control structure are open and Lake Alice and Lake Irvine virtually are one lake. Thus, when the gates are open, the water-balance model treats the lakes as a combined lake with a uniform water level. From May through October the gates are closed and the water level for Lake Alice is held at 1,442 feet above sea level. Thus, separate lake levels are computed from May through October in the water-balance model. In November the gates are again open, and Lake Alice and Lake Irvine operate as one lake. The capacities of the two lakes are combined and a new water level is determined by using a combined elevation-capacity table.

Inflow enters Lake Alice-Lake Irvine via Chain Lake and Mauvais Coulee. From May through October flow from Lake Alice to Lake Irvine occurs only during months when the computed water level is greater than 1,442 feet above sea level. From May through October flow out of Lake Irvine occurs when the computed water level is greater than 1,439.6 feet above sea level. From November through April outflow from Lake Alice-Lake Irvine occurs whenever the computed water level is greater than 1,439.6 feet above sea level.

Three tributaries, channel A, Big Coulee, and an unnamed tributary draining the Comstock subbasin, provide most of the inflow to Devils Lake. A small quantity of inflow probably enters Devils Lake from the Devils Lake subbasin adjacent to Devils Lake (fig. 2). Precipitation falling on the lake surface is treated as an inflow in the water-balance model. Evaporation from Devils Lake is the only way that water can be removed from Devils Lake. No accounting is made for ground-water inflow or outflow from Devils Lake in the water-balance model. Therefore, a declining lake level can occur only when evaporation from the lake exceeds inflow to Devils Lake plus precipitation falling on the lake surface.

Analysis of Simulations

Monthly lake-evaporation values, monthly precipitation values, and monthly discharge values from 1968 through 1983 were used as inputs to the water-balance model to simulate the monthly water levels of Devils Lake. A discussion of the methods used to develop the model inputs is included in Supplement 2. The water-balance model was validated by comparing the computed water levels to the recorded water levels. The simulation was made using an initial starting water level of 1,411.25 feet above sea level for Devils Lake, which is the recorded water level in January 1968. Estimates of initial water levels for the upstream chain of lakes were based on the water levels at freezeup in 1984. No monthly water levels were simulated prior to 1968 because hydraulic changes in the upstream chain of lakes cannot be determined with any degree of certainty. As an example of the changes, prior to 1968 no control structure existed between Lake Alice and Lake Irvine and the natural sill elevation was about 1,443 feet above sea level (Dale Frink, North Dakota State Water Commission, written commun., 1985).

Comparison of the simulated water levels and the recorded water levels is shown in figure 16, and, in general, there is agreement between the simulated and recorded water levels. The maximum deviation between the simulated and the recorded water level was for April 1969 when the simulated water level is 5.18 feet greater than the recorded water level. This relatively large difference between the computed and recorded water levels occurs because of a

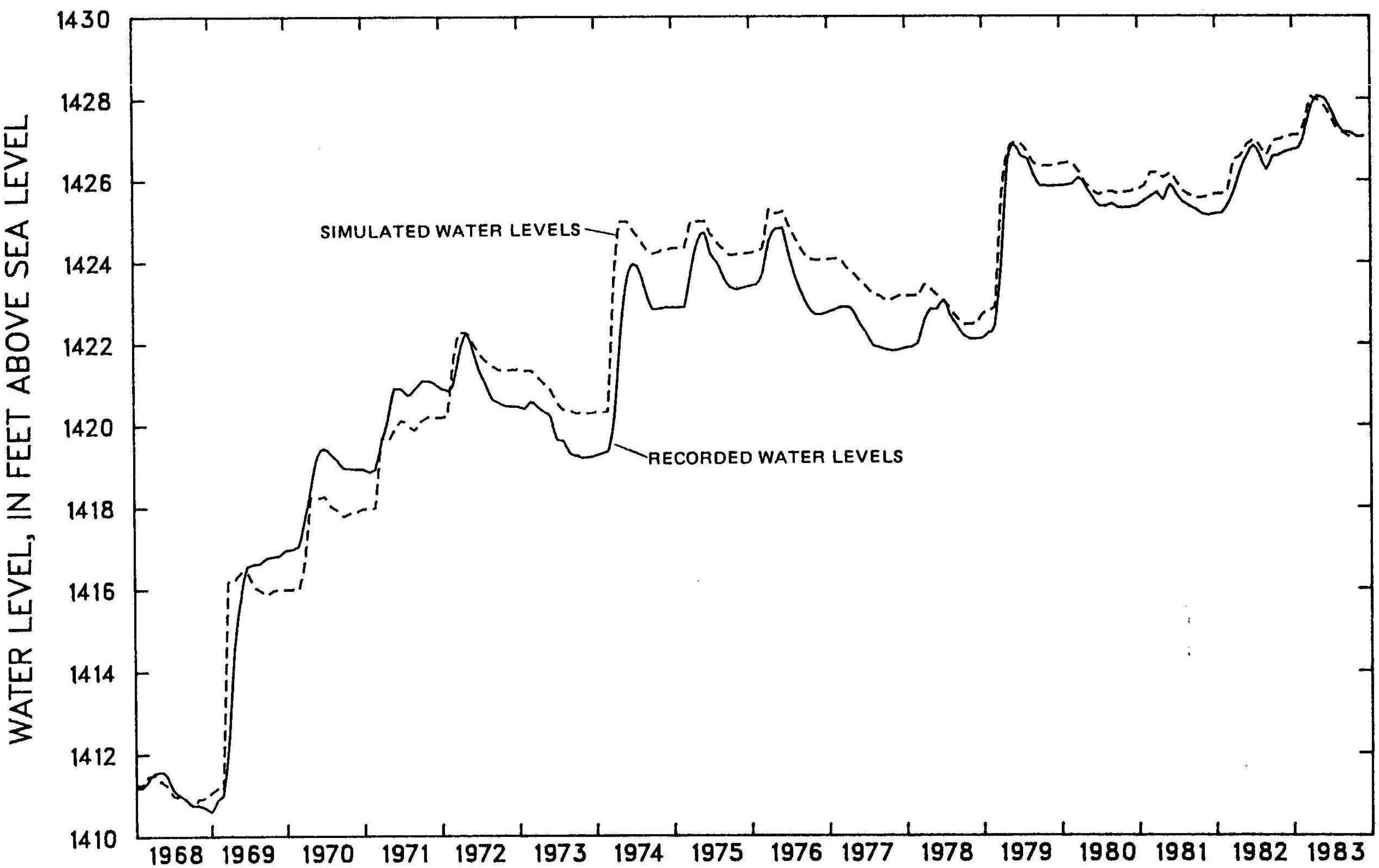

Figure 16.—Monthly simulated and recorded water levels of Devils Lake, 1968-83.

small bias in the timing of simulated water-level changes. The magnitudes of the simulated and recorded water-level changes are in agreement, but the changes occur in simulated water levels before they appear in recorded water levels. The reason for this timing error is that the model assumes that all water above the spill elevation discharges instantaneously, whereas the recorded water levels reflect the traveltime through the interconnected chain of lakes. The lag is caused by ignoring reservoir routing. By August 1969 the simulated water level is 0.50 foot greater than the recorded water level. The annual maximum deviation between the simulated and recorded water level occurs in April or May when the simulated water level usually is greater than the recorded water level. The maximum simulated water level of 1,428.1 feet above sea level was for April 1983 and the maximum recorded water level of 1,428.1 feet above sea level occurred in June 1983. Based on this comparison, no further model validation was considered necessary. Although many assumptions have been made regarding model inputs, the water-balance model seems to provide reasonable results.

The water-balance model was used to simulate possible water-level fluctuations for two different sets of input data--a "high-runoff or wet" condition and a "low-runoff or dry" condition. Water levels for the "high-runoff" condition were simulated from January 1985 through December 1990 by using the monthly values of precipitation, lake evaporation, and discharge from 1974 through 1979. A recorded water level of 1,426.12 feet above sea level in January 1985 was used as the initial water level for the "high-runoff" simulation. Thus, the simulated water levels of Devils Lake are based on the assumption that the lake evaporation, precipitation, and discharge will have the same timing and magnitude from 1985 through 1990 as occurred during 1974-79.

Based on the computed net inflow to Devils Lake (table 9), this period has the greatest 6-year inflow for the period of record, 1931-83. Total inflow for the period was 557,400 acre-feet or 92,900 acre-feet per year. The annual precipitation at the city of Devils Lake was 15.92 inches in 1974, 17.20 inches in 1975, 13.00 inches in 1976, 21.80 inches in 1977, and 14.30 inches in 1979 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1975-80). The computed lake evaporation was 28.31 inches per year for the period.

The maximum simulated water level of 1,431.43 feet above sea level would occur in April of 1987; and after a decline in water levels in 1988 and 1989, a secondary peak of 1,430.9 feet above sea level would occur in June of 1990 (fig. 17). There would be about a 5.3-foot difference between the initial water level of Devils Lake used in the "high-runoff" simulation and the maximum water level for this simulation. The maximum difference of the recorded water levels between 1974 and 1979 is 7.8 feet. The recorded water level in January of 1974 is about 5.0 feet lower than the initial water level for January of 1985 used for the "high-runoff" simulation. Therefore, the volume of water needed to increase the water level of Devils Lake a given increment is greater for the "high-runoff" simulation than for the recorded water levels of 1974 through 1979.

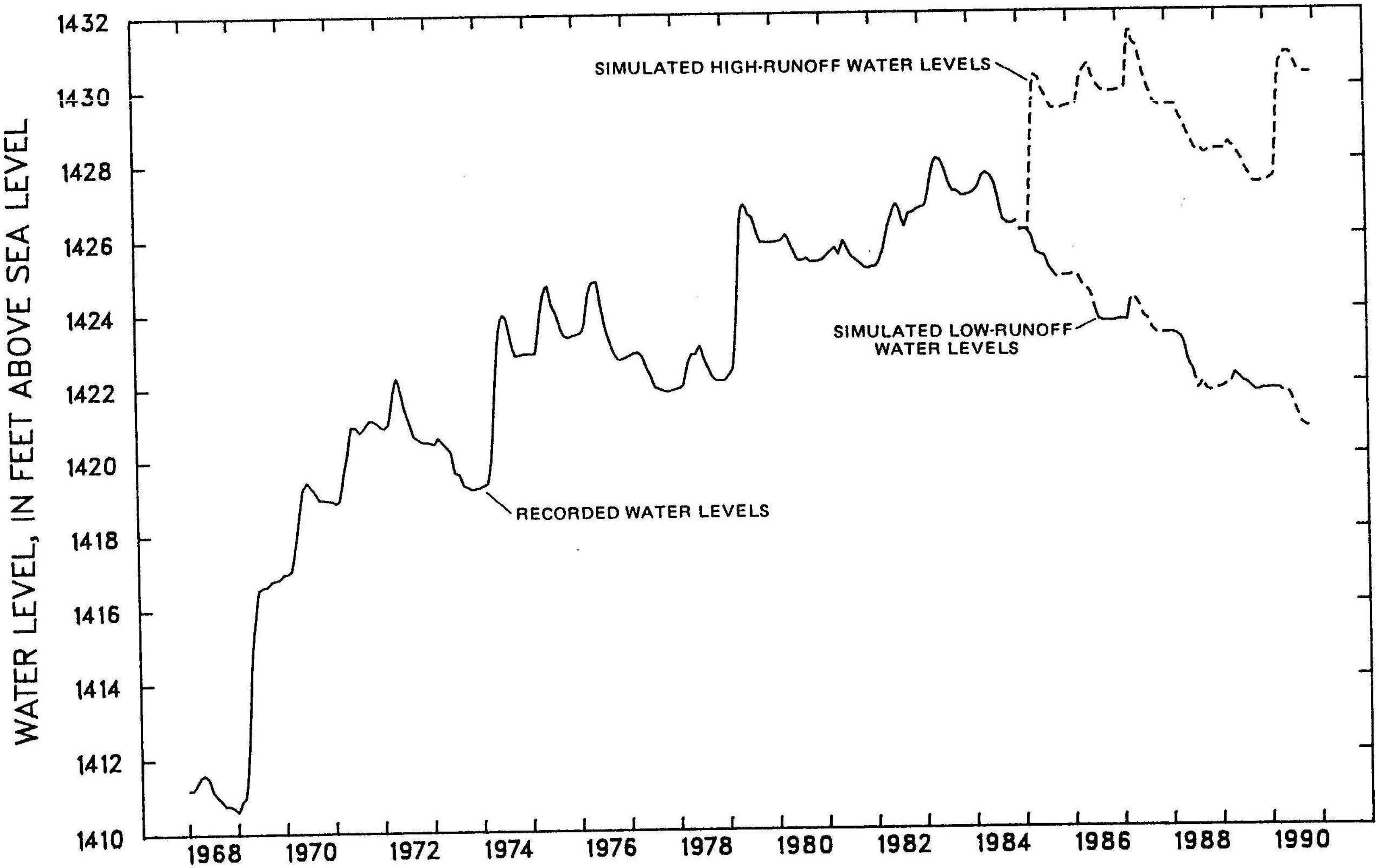

Figure 17.—Recorded water levels, 1968-84, and simulated water levels of Devils Lake, 1985-90.

The "low-runoff" condition was simulated using the monthly values of lake evaporation, precipitation, and discharge for 1958-63. The "low-runoff" condition was chosen based on the extremely minimal inflow of 29,700 acre-feet for this period. The annual precipitation at the city of Devils Lake averaged 15.71 inches during this period as compared to normal (1951-80) precipitation of 16.52 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1959-64 and 1983). The computed annual lake evaporation for this period was 28.75 inches.

Total inflow from 1933 through 1938 was 18,300 acre-feet. The annual precipitation at the city of Devils Lake averaged 13.82 inches during this period (U.S. Department of Agriculture, 1934-39). Although 1933-38 probably represents a more extreme "low-runoff" condition than does 1958-63, no gaging stations were in operation in the Devils Lake basin; thus, all discharges needed as input for the water-balance model would have to be synthesized. Therefore, data limitations associated with 1933-38 eliminated this period from consideration as the "low-runoff" condition.

The simulated water levels for the "low-runoff" conditions are plotted in figure 17. There would be a steady decline in water levels from 1985 through 1990 although a minor increase in water levels would occur in the spring of 1987 and 1989. The simulated water level would decline about 5.4 feet from 1,426.12 feet above sea level in January of 1985 to 1,420.69 feet above sea level in December of 1990. Based on recorded water levels from January 1958 through December 1963, Devils Lake declined 6.6 feet.

CONCLUSIONS

The Devils Lake basin has a continental climate characterized by relatively warm, short summers and long, cold winters. Typical of a continental climate, the Devils Lake basin has large monthly and annual variations in temperature and precipitation. At the city of Devils Lake, the average annual temperature has varied from 34°F during 1950 to 43.3°F during 1931. The average monthly temperature has ranged from -15°F during February 1936 to 79°F during July 1936. At Fort Totten (1870-90) and at the city of Devils Lake (1897-1984), the annual precipitation from 1870 through 1984 (excluding 1891-96) has varied from 10.08 inches in 1967 to 25.39 inches in 1921.

Based on indirect evidence and recorded water levels in the last 155 years, Devils Lake has fluctuated about 40 feet from a maximum water level of 1,441 feet above sea level in 1830 to a minimum of 1,400.9 feet above sea level in 1940. The maximum annual water-level rise was 8.4 feet in 1950. The maximum annual water-level decline from 1931 through 1983 was 2.4 feet in 1976.

The maximum 30-day water-level rise of Devils Lake during 1949-83 has ranged from no rise in 1958 when the water level declined throughout the year to 3.82 feet in 1979. The maximum 2-day rise during 1949-83 was 0.80 foot in 1950 and the maximum 8-day rise was 1.61 feet in 1979.

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

Discharge 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 computed average annual inflow to Devils Lake from 1931 through 1940 was 4,530 acre-feet and from 1969 through 1983 was 70,000 acre-feet; however, based on water-balance computations, average annual inflow from 1867 through 1884 was 58,300 acre-feet. The variations in inflow from period to period have been accompanied by corresponding variations in climate. The average annual precipitation (15.14 inches) at the city of Devils Lake from 1930 through 1939 was 18 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.

Based on the review of investigations conducted on terminal lakes in North America, 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 1860-85. 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 protracted climatic extremes such as 1860-85 and the 1930's. 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 other than during these protracted climatic extremes.

The exceedance probability for a given water-level rise was computed by first developing the exceedance probability for the inflows and then converting the inflow value to a water-level rise based on the starting water level of Devils Lake. The analysis indicates that the higher the starting water level the lower the associated water-level rise for a given inflow. As an example, an inflow of 72,200 acre-feet has an exceedance probability of 10 percent; and this inflow results in a 4.20-foot water-level rise if Devils Lake is at a starting water level of 1,410 feet above sea level. However, if the starting water level is 1,430 feet above sea level, the water-level rise is only 1.41 feet.

The lateral change in shoreline location at Devils Lake associated with annual exceedance probabilities of water-level rises was computed. Based on a starting water level of 1,426.1 feet above sea level and an annual exceedance probability of 10 percent, the lateral change in shoreline location ranges from 16.8 feet along the south shore of Devils Lake and along the shore of Creel Bay to 148 feet along the West Bay of Devils Lake near Minnewaukan Flats. The lateral change in shoreline location for a given annual exceedance probability and any starting water level is greatest at Minnewaukan Flats because of the slight shoreline slopes.

A water-balance model was developed that accounts for the gains and losses in discharge that occur as water moves through the chain of lakes upstream of Devils Lake. Monthly values of lake evaporation, precipitation, and discharge were used to simulate a "high-runoff" and a "low-runoff" condition from 1985 through 1990. Inputs to the water-balance model for the "high-runoff" simulation were based on hydrologic and climatologic data recorded from 1974 through 1979. Under the "high-runoff" conditions, the maximum water level of 1,431.43 feet above sea level would occur in April 1987. The "low-runoff" simulation was based on hydrologic and climatologic data recorded from 1958 through 1963. Under the "low-runoff" simulation, the water level of Devils Lake would decline steadily from 1,426.12 feet above sea level in January 1985 to 1,420.69 feet above sea level in December 1990.

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Supplement 1.--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 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. Thus, the future water levels are based on past water levels as well as the assumption that the annual water levels are independent events. The problems associated with this method are discussed by James and others (1984).

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:

$$(I_s+I_g+I_p-O_e-O_t)\Delta t = \Delta S \tag{3}$$

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 and 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

$$(I_s+I_p-O_e)\Delta t = \Delta S. \tag{4}$$

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

$$I_s = 6,376(P_2)+2,187(P_2)^{-2}-7,555 \qquad (5)$$

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:

$$O_e = 3.48-0.963(P_1) \qquad (6)$$

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 5) and net evaporation (equation 6). 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:

$$P_1 = 1.071-0.064P_{L1}+0.081P_{L2}+0.162P_{L3}+t_i\delta\sqrt{1-\rho^2} \qquad (7)$$

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;
$t_i\delta\sqrt{1-\rho^2}$ = random term,
t_i = random number,
δ = standard deviation, and
ρ = multiple regression coefficient.

The random part of the equation used the standard deviation and multiple-regression coefficient 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 average precipitation equal to 16.2 inches). Exceedance probabilities for the two cases were computed for water levels ranging from 4,190 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 then can 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 events that were used as input in the water-balance model to provide 1,000 possible water levels for each year 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. Great Salt Lake had a maximum water level of 4,200 feet above sea level in 1982, but, by July 1983, Great Salt Lake had a maximum water level of 4,205 feet above sea level, 2 years after Willett's (1977) prediction. Willett (1977) 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), indicate 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 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.

Supplement 2.--Model inputs

Supplement 2A.--Discharge

The water-balance model requires, as input, monthly precipitation, evaporation, and discharge from the coulees draining subbasins in the Devils Lake basin. The discharge of the coulees was computed by applying drainage-area ratio techniques to discharge records in the Devils Lake basin. A monthly series of input data was developed from 1968 through 1983 for: (1) Edmore Coulee at its mouth (Sweetwater Lake), (2) Starkweather Coulee at its mouth (Dry Lake), (3) Calio Coulee at its mouth (Chain Lake), (4) Mauvais-Big Coulee at its mouth (Devils Lake), (5) Little Coulee at its mouth (Big Coulee), and (6) an unnamed tributary from the Comstock subbasin at its mouth (Devils Lake).

Monthly discharge for the Edmore Coulee near Edmore gage is available from 1968 through 1983. The discharge of the Edmore Coulee gage was multiplied by 1.42 to account for the intervening drainage area between the gage and Sweetwater Lake.

No gage record was collected on Starkweather Coulee prior to 1980. Thus, from 1968 through 1979, the discharge of Starkweather Coulee, which is tributary to Dry Lake, was computed by multiplying the discharge of the Edmore Coulee near Edmore gage by a factor of 1.39 (391 square miles/282 square miles). From 1980 through 1983 the discharge of Starkweather Coulee at its mouth (Dry Lake) was computed by multiplying the discharge of the Starkweather Coulee near Starkweather gage by a factor of 1.26 (391 square miles/310 square miles).

No discharge record has been collected on Calio Coulee. Discharge of Calio Coulee at its mouth (Chain Lake) was computed by multiplying the discharge of the Mauvais Coulee near Cando gage by a factor of 0.62 (233 square miles/377 square miles).

Discharge for the Mauvais Coulee near Cando gage is available from 1968 through 1983. Thus, the discharge of Mauvais Coulee at its mouth (Lake Alice) was computed by multiplying the discharge of Mauvais Coulee near Cando by a factor of 2.31 (872 square miles/377 square miles).

No discharge record is available for Little Coulee from 1968 through 1975. Gaging stations were operated at Little Coulee near Brinsmade from 1958 through 1967 and at Little Coulee near Leeds from 1976 through 1982. The concurrent discharge record of Mauvais Coulee near Cando and the two gaging stations on Little Coulee are listed in table 13. The average discharge, in acre-feet per square mile, during 1958-67 and 1976-82 was used to develop the weighted discharge of Mauvais Coulee and Little Coulee (see table 13). The average discharge of Little Coulee, in acre-feet per square mile, is about 54 percent of the average discharge of Mauvais Coulee. The drainage area of Little Coulee at its junction with Big Coulee is 69 percent of the drainage area of Mauvais Coulee near Cando. Therefore, the discharge of Little Coulee at its junction with Big Coulee from 1968 through 1975 was computed by multiplying the discharge by a factor of 0.37 (0.54x0.69).

Table 13.--*Concurrent annual discharge of gages located on Little Coulee and Mauvais Coulee, 1958-82, and computation of ratio of runoff between Little Coulee and Mauvais Coulee*

Year	Discharge, in acre-feet per year: Little Coulee near Brinsmade	Discharge, in acre-feet per year: Mauvais Coulee near Cando	Year	Discharge, in acre-feet per year: Little Coulee at Leeds	Discharge, in acre-feet per year: Mauvais Coulee near Cando
1958	0	83.4	1976	6,370	29,200
1959	0	185	1977	4.2	54
1960	562	11,650	1978	28.6	5,440
1961	0	3	1979	25,920	45,175
1962	646	3,440	1980	133	1,140
1963	0	22	1981	1,240	10,110
1964	286	1,920	1982	1,920	17,790
1965	910	21,260			
1966	2,130	1,450			
1967	972	9,290			
Total	5,506	49,300		35,620	108,900
Acre-feet per square mile	3.93	13.1		26.7	41.3

Weighted discharges:

Little Coulee--$\frac{[(26.7x7)+(3.93x10)]}{17}$ = 13.3 acre-feet per square mile

Mauvais Coulee--$\frac{[(41.3x7)+(13.1x10)]}{17}$ = 24.7 acre-feet per square mile

$\frac{\text{13.3 acre-feet per square mile}}{\text{24.7 acre-feet per square mile}}$ = 0.54

From 1976 through 1983 the discharge of Little Coulee at its junction with Big Coulee was computed by multiplying the discharge recorded at the Little Coulee near Brinsmade gage by a factor of 1.37 (261 square miles/190 square miles) to account for the intervening drainage area.

Supplement 2B.--Precipitation

The monthly precipitation data are required for operation of the water-balance model to compute the quantity of water falling on the surface of all lakes modeled. The monthly precipitation data from 1968 through 1983 were developed using a three-station average of Leeds, Devils Lake, and Warwick.

Supplement 2C.--Evaporation

No lake-evaporation data are collected at Devils Lake; thus, pan-evaporation data were converted to lake evaporation. Pan-evaporation data were collected at the city of Devils Lake during April through September from 1951 through 1970. A linear-regression equation was developed using monthly pan evaporation at the city of Devils Lake as the dependent variable and monthly temperature at the city of Devils Lake as the independent variable. The regression equation was developed as follows:

$$E = 0.023T^{1.34} \tag{8}$$

where

E = the monthly pan evaporation, in inches, at the city of Devils Lake, and
T = the average monthly temperature, in degrees Fahrenheit, at the city of Devils Lake.

Equation 8 has a regression coefficient of 0.76. This equation was used to compute the monthly pan evaporation during April through September from 1968 through 1983. The monthly pan-evaporation data were multiplied by a factor of 0.75 to convert the pan-evaporation data to an equivalent lake evaporation (U.S. Department of Commerce, 1959).

Lake evaporation from April through September is equal to 83.4 percent of the annual lake evaporation (U.S. Department of Commerce, 1959). The remaining 16.6 percent is distributed as follows: October, 8.5 percent; November, 3.0 percent; December, 1.0 percent; January, 0.8 percent; February, 1.0 percent; and March, 2.3 percent. Monthly lake evaporation for October through March was computed by: (1) Dividing pan evaporation for a given year computed using equation 8 by 0.83, (2) multiplying the annual pan evaporation by 0.75 to convert to annual lake evaporation, and (3) multiplying the annual lake evaporation for a given year by the percentage associated for the months October through March.