HYDROLOGY OF THE CHAIN OF LAKES TRIBUTARY TO DEVILS LAKE AND WATER-LEVEL SIMULATIONS OF DEVILS LAKE, NORTHEASTERN NORTH DAKOTA

By Gerald L. Ryan and Gregg J. Wiche

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TO METRIC UNITS

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

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

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

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ABSTRACT

High water levels of the chain of lakes tributary to Devils Lake, North Dakota have, in recent years, caused flooding of cropland and county roads, thus disrupting agricultural interests. High water levels of Devils Lake pose a flood threat to the city of Devils Lake, Camp Grafton National Guard Camp, and road, sewer, and lagoon systems of several communities. The chain of lakes acts as an evaporation and storage basin. During the spring and summer of 1985, about 25,980 acre-feet of runoff flowed into the chain of lakes from upstream tributaries. About 10,180 acre-feet (about 39 percent) of that runoff flowed out of the chain of lakes. By September 30, 1985, about 440 acre-feet (less than 2 percent of the runoff that flowed into the chain of lakes) remained in storage in the chain of lakes upstream of Devils Lake. The other 15,360 acre-feet (about 59 percent of the runoff that flowed into the chain of lakes) was removed from the chain of lakes, mainly by evaporation.

High-runoff conditions for Devils Lake were simulated on the basis of records of hydrologic and climatologic data for the years 1985-2032, and a low-runoff condition for Devils Lake was simulated for the years 1985-1990. The January 1985 water level of 1,426.12 feet above sea level was used for the initial lake level. A combination of storage conditions in the upstream chain of lakes and different hydrologic and climatologic variables were used for the high-runoff-condition simulations. For existing storage conditions in the chain of lakes, Devils Lake would have a maximum water level ranging from 1,432.0 to 1,442.6 feet above sea level. For midlevel storage conditions, maximum water levels of Devils Lake would range from 1,432.4 to 1,441.4 feet above sea level. For high-level storage conditions, maximum water levels of Devils Lake would range from 1,431.3 to 1,439.9 feet above sea level. The low-runoff condition simulation indicates that Devils Lake would have a minimum water level of 1,420.7 feet above sea level.

INTRODUCTION

Sweetwater Lake, Morrison Lake, Dry Lake, Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine are an interconnected chain of lakes that are tributary to Devils Lake in northeastern North Dakota (fig. 1). High water levels of the chain of lakes have, in recent years, caused flooding of cropland and county roads; thus disrupting agricultural interests. High water levels of Devils Lake pose a flood threat to the city of Devils Lake, Camp Grafton National Guard Camp, and to the road, sewer, and lagoon systems of several communities.

Figure 1.—Location of the chain of Lakes and Devils Lake in northeastern North Dakota.

The U.S. Army Corps of Engineers is conducting a feasibility study of possible flood-control projects to protect the cities, roads, and other properties around Devils Lake. The North Dakota State Water Commission is assisting the U.S. Army Corps of Engineers in the analysis of the hydrologic effects of different flood-control projects. Before a flood-control project can be implemented, an understanding of the hydrology of Devils Lake and some knowledge of the probability of future lake levels is needed.

In a report describing the hydrologic and climatologic factors controlling the water-level fluctuations of Devils Lake, Wiche and others (1986) concluded that, although the fluctuations are caused primarily by climatic variability, the chain of lakes upstream of Devils Lake can act as an evaporation and storage basin and can affect the water-level fluctuations of Devils Lake. An understanding of the hydrology of the chain of lakes is a prerequisite to gaining an improved understanding of the water-level fluctuations of Devils Lake. Therefore, the U.S. Geological Survey, in cooperation with the North Dakota State Water Commission and the U.S. Army Corps of Engineers, has undertaken a study to identify the effects of the chain of lakes on Devils Lake water levels.

This report describes the hydrology of the chain of lakes upstream of Devils Lake and their effect on the water-level fluctuations of Devils Lake. The specific objectives are to: (1) Document the runoff from the major tributaries to the chain of lakes for March 1 through September 30, 1985; (2) document the maximum and minimum water levels of selected lakes in the chain of lakes for March 1 through September 30, 1985; and (3) to present multilake management situations by simulating water levels of Devils Lake for different storage conditions in the chain of lakes, for different runoff conditions in the Devils Lake basin, and for different outlet options for Devils Lake.

DESCRIPTION OF THE STUDY AREA

Devils Lake basin is a 3,810-square-mile closed drainage basin in northeastern North Dakota. Closed drainage basins have no outlet to the oceans of the world. About 3,320 square miles of the drainage basin is tributary to Devils Lake; the remaining 490 square miles is tributary to Stump Lake, which lies to the east of Devils Lake. About 2,010 square miles of the 3,320 square miles that is tributary to Devils Lake drains into the chain of lakes.

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. The topographic relief and surficial landforms are of glacial origin. A large number of shallow depressions and potholes occur throughout the basin. Many of these depressions are connected by poorly defined channels and swales.

The major subbasins within the Devils Lake basin and the principal tributaries draining them are shown in figure 2, and the drainage areas of these subbasins are listed in table 1. Edmore Coulee, Starkweather

EXPLANATION

- BASIN BOUNDARY
- SUBBASIN BOUNDARY
- ▲1 GAGING-STATION LOCATION AND SITE NUMBER

Figure 2.—Major subbasins and location of gaging stations in the Devils Lake basin.

Table 1.--Drainage areas of subbasins

[Modified from Devils Lake Basin Advisory Committee, 1976]

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

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

Coulee, and Calio Coulee originate in the northeastern part of the basin and flow in a south-southwesterly direction. Mauvais Coulee originates in the northwestern corner of the basin and flows in a south-southeasterly direction.

The tributaries and the chain of lakes referred to in this report are: Edmore Coulee, which is tributary to Sweetwater and Morrison Lakes; Starkweather Coulee and Webster Coulee, which are tributary to Dry Lake; channel A, which is tributary to Devils Lake; Calio Coulee, which is tributary to Chain Lake; Mauvais Coulee, which is tributary to Lake Alice-Lake Irvine; and Big Coulee, which is tributary to Devils Lake.

Sweetwater and Morrison Lakes are connected by a channel that is about 150 feet wide and 500 feet long. This natural channel between the two lakes has been dredged at least once. For the purposes of this study, Sweetwater and Morrision Lakes were treated as one lake.

In 1968, the U.S. Fish and Wildlife Service constructed a control structure between Lake Alice and Lake Irvine. The control structure normally is used by the U.S. Fish and Wildlife Service during the summer and fall months to maintain water levels on Lake Alice, which is part of the Lake Alice National Wildlife Refuge.

Downstream of Lake Irvine, Big Coulee flows into and out of a relatively shallow body of water called Pelican Lake (fig. 1). Pelican Lake has little effect on the timing and magnitude of discharge in Big Coulee.

Prior to 1979, runoff from the tributaries flowed into the interconnected chain of lakes and all of the discharge from the chain of lakes flowed downstream through Big Coulee and into Devils Lake. A small amount of runoff also entered Devils Lake by overland flow from drainage areas adjacent to the lake. In 1979, the Ramsey County and Cavalier County Water Management Boards constructed channel A, which connects Dry Lake to Sixmile Bay on Devils Lake. A levee also was constructed across the natural outlet of Dry Lake in 1979. Discharge from Dry Lake to channel A is regulated by an adjustable gate control at the south shore of the lake. The construction of channel A and the levee on Dry Lake modified the drainage pattern in the basin, runoff into Sweetwater, Morrison, and Dry Lakes discharges through channel A, and the remaining runoff discharges along the natural watercourse down Big Coulee into Devils Lake.

Water levels of Devils Lake have fluctuated from 1,438 feet above sea level in 1867 to 1,400.9 feet above sea level 1940. Surface areas of the lake have varied from about 140 square miles in 1867 to about 10 square miles in 1940. The maximum water level for Devils Lake during 1985 was 1,426.9 feet above sea level and the lake had a surface area of about 84 square miles.

HYDROLOGY OF THE CHAIN OF LAKES

The hydrology of the chain of lakes that drain into Devils Lake can be characterized by four processes: Runoff, storage, outflow, and evaporation.

Runoff is the water that flows downslope on the surface of the land into the tributaries and lakes. Runoff occurs as a result of precipitation. Precipitation in the Devils Lake basin (fig. 3) can occur as ice, snow, or rain. Precipitation that occurs from the beginning of November through mid-March generally is in the form of snow and is released as runoff during snowmelt. Snowmelt generally begins to occur in the basin in mid-March and lasts, on the average, for 2 to 3 weeks. Precipitation that occurs during the rest of the year either is immediately available for runoff (rainfall) or, in the case of an early fall or late spring snow, is released as runoff when temperatures rise above freezing.

The topography of the basin previously has been described as having large numbers of shallow depressions and potholes, many of which are connected by poorly defined channels and swales. As runoff begins, overland flow occurs until it enters one of these depressions. If the water level in the depression is lower than the outlet elevation, storage will occur in the depression. As the water level in the depression rises, the outlet elevation is reached and outflow begins. At times, depending on the amount of runoff and the size of the depression, runoff does not raise the water level in the depression above its outlet elevation and all of the runoff goes into storage. The process is repeated many times as runoff

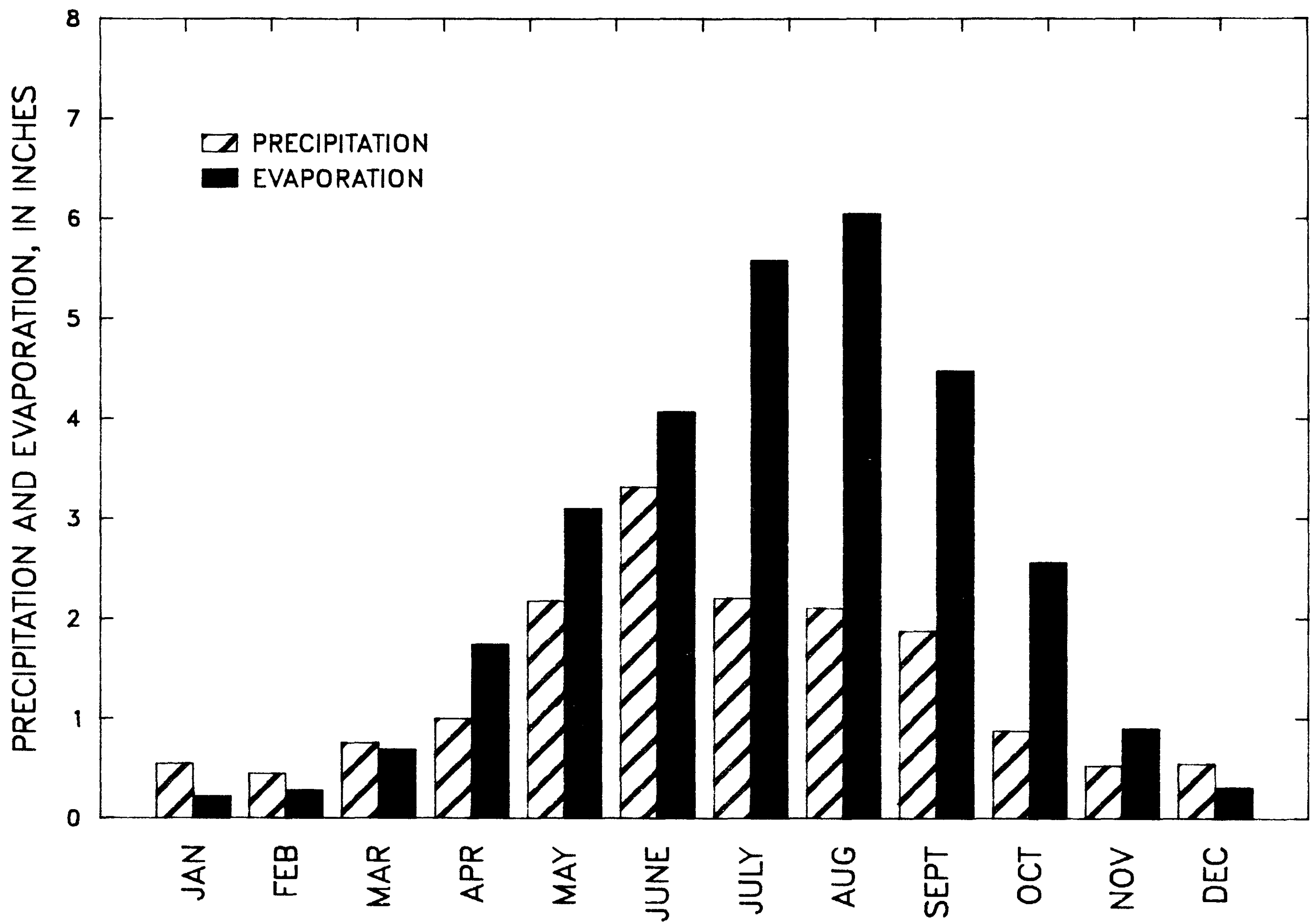

Figure 3.—Average monthly precipitation (1951-80) and evaporation for Devils Lake. Sources: Precipitation data from U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982; evaporation data from U.S. Department of Agriculture and U.S. Soil Conservation Service, no date and U.S. Department of Commerce, 1959.

travels through depressions, potholes, sloughs, and lakes on its way to Devils Lake at the downstream end of the basin.

Evaporation is the process by which water becomes vapor at a temperature below the boiling point. Throughout the year, but mainly during summer months (fig. 3), evaporation can have a significant effect in reducing water levels in the chain of lakes. Lower water levels, in turn, increase the capacity available for future storage of flows originating upstream. Runoff from a summer rainfall may occur in part of the basin and never reach Devils Lake. All of the runoff may be contained in the chain of lakes where evaporation has lowered water levels well below outlet elevations. Runoff that enters a downstream lake is reduced by the amount lost to storage in upstream lakes. If the number of lakes that the runoff flows through is reduced or if the storage capacity of the lakes is reduced, the potential for additional flows into Devils Lake is increased. Conversely, if storage capacity in the chain of lakes is increased, the potential for reducing flows into Devils Lake is increased.

Other processes that could affect the hydrology of the chain of lakes include ground-water inflow and outflow and soil-moisture gains and losses. However, determination and documentation of these processes was beyond the scope of this study.

RUNOFF DURING THE SPRING AND SUMMER OF 1985

During 1985, the U.S. Geological Survey operated 11 gaging stations in the Devils Lake basin. The site number, name, period of record, type of record, and drainage area for each gage is shown in table 2.

During the spring and summer of 1985, inflow into Sweetwater and Morrison Lakes was recorded by the Edmore Coulee near Edmore gage. Inflow into Dry Lake was recorded by the Starkweather Coulee near Webster gage. Together these two gages recorded discharge from about 74 percent of the area drained by channel A. Recorded inflow at the two gages exceeded recorded outflow from Dry lake by 4,790 acre-feet in 1985 (table 3). This 4,790 acre-feet was lost to storage, evaporation, or ground water. Assuming that the whole area drained by channel A contributed runoff at the same rate as the area recorded by the two gages, about 15,880 acre-feet of inflow entered the lakes in the area drained by channel A, of which about 8,920 acre-feet was lost.

During the spring and summer of 1985, inflows into Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine were recorded by the Mauvais Coulee near Cando gage. This gage recorded discharge from about 30.5 percent of the area drained by these lakes. Recorded inflow at the Mauvais Coulee near Cando gage was about 3,080 acre-feet (table 3). The Big Coulee near Churchs Ferry gage recorded an outflow from the lakes of about 3,220 acre-feet. (Inflow into Big Coulee from Little Coulee was subtracted from the total flow passing the Big Coulee near Churchs Ferry gage to get the flow from the lakes). Assuming that the whole area contributed runoff at the same rate as the area recorded by the Mauvais Coulee near Cando gage,

Table 2.--Gaging stations operated in the Devils Lake basin during 1985

Site number	Gaging-station name	Period of record	Type of record	Drainage area (square miles)	Noncontributing drainage area (square miles)
1	Mauvais Coulee near Cando	May 1956 to present[1]	Discharge	387	10
2	Edmore Coulee near Edmore	April to June 1956, June 1957 to present[1]	Discharge	382	100
3	Morrison Lake near Webster	March to September 1985	Stage	501	([2])
4	Webster Coulee at Webster	October 1979 to present	Stage	670	([2])
5	Starkweather Coulee near Webster	October 1979 to present	Discharge	310	([2])
6	Dry Lake near Penn	October 1983 to present	Stage	920	([2])
7	Lake Alice-Irvine channel near Churchs Ferry	March to September 1985	Stage	999	([2])
8	Little Coulee near Brinsmade	October 1975 to present[3]	Discharge	350	158
9	Big Coulee near Churchs Ferry	March 1950 to present	Discharge	[4]1,620	([2])
10	Channel A near Penn	October 1983 to present	Discharge	930	([2])
11	Devils Lake near Devils Lake	January 1964 to present[6]	Stage	[5]3,320	([2])

[1] Seasonal, March through September, since 1982.
[2] Contributing and noncontributing drainage areas have not been determined.
[3] Seasonal, March through September, since 1983.
[4] Drainage area was revised after the completion of channel A; drainage area previously published as 2,510 square miles.
[5] Contributing and noncontributing drainage areas are unknown, but total drainage area is about 3,320 square miles.
[6] Single stage reading for 1867, 1879, 1883, 1887, 1890, and 1896. Fragmentary for 1901-63.

Table 3.--Discharge, in acre-feet, recorded by six gaging stations in the Devils Lake basin, March 1 through September 30, 1985

Month	Inflow into Sweetwater and Morrison Lakes	Inflow into Dry Lake	Outflow from Dry Lake	Inflow into Lake Alice-Lake Irvine	Inflow into Big Coulee	Outflow from Lake Alice-Lake Irvine and Little Coulee
	Edmore Coulee near Edmore	Starkweather Coulee near Webster	Channel A	Mauvais Coulee near Cando	Little Coulee near Brinsmade	Big Coulee near Churchs Ferry
March	4,750	5,000	1,050	1,740	53	407
April	637	1,090	5,600	765	309	1,430
May	8.4	.8	296	227	108	1,110
June	1.4	0	14	55	0	559
July	0	0	.6	3.3	1.9	133
August	107	0	2.6	286	.9	40
September	157	0	.6	3.6	0	12
Totals (rounded)	5,660	6,090	6,960	3,080	473	3,690

about 10,100 acre-feet of inflow entered the lakes and about 6,880 acre-feet was lost. Inflow into Hurricane, Ibsen, and Silver Lakes was not measured, but the outflow from those lakes was measured by the Little Coulee near Brinsmade gage.

Maximum and minimum water levels of selected lakes in the Devils Lake basin for March 1 through September 30, 1985, are listed in table 4. On September 30, Lake Alice-Lake Irvine had a net storage gain of about 440 acre-feet (less than 2 percent of the total inflow to the chain of lakes); all other lakes were at or below their respective March 1 water levels.

The total inflow of water into the chain of lakes was about 25,980 acre-feet. The total outflow from the chain of lakes into Devils Lake was about 10,180 acre-feet (about 39 percent of the total inflow into the chain of lakes). Net storage gain in the chain of lakes totaled 440 acre-feet (less than 2 percent of the total inflow into the chain of lakes). The remaining 15,360 acre-feet (about 59 percent of the total inflow into the chain of lakes) was removed from the chain of lakes, mainly by evaporation.

Runoff into the chain of lakes began during the second week of March. The maximum water level on Sweetwater and Morrison Lakes occurred April 4; the maximum water level on Dry Lake occurred April 13; and the maximum water level on Lake Alice-Lake Irvine occurred April 15. Devils Lake reached its maximum water level on April 20.

On April 20, Devils Lake had a surface area of about 54,000 acres and a storage capacity of about 779,000 acre-feet. On the same day, Sweetwater Lake, Morrison Lake, Dry Lake, Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine had a combined surface area of about 16,500 acres and a combined storage capacity of about 47,900 acre-feet.

The hydrographs shown in figure 4 are typical of the runoff regimen that occurred in the chain of lakes for March 1 through September 30, 1985. Lake Alice-Lake Irvine was ice covered during early March, therefore no water-level fluctuations occurred because there was no inflow or outflow. When the spring thaw began during the second week of March, water levels of Lake Alice-Lake Irvine began to rise and continued to rise until the middle of April when the maximum water level for the year occurred. Then, water levels in the lakes began to decline as outflows from the lakes exceeded inflows.

Mauvais Coulee, which flows into Lake Alice-Lake Irvine, and Big Coulee, which originates at the outlet of Lake Alice-Lake Irvine, had initial increases in discharge during the second week of March. These increases in discharge were caused by local runoff, which originated from snowmelt. Discharge from Mauvais Coulee increased significantly during the third and fourth week of March, and then decreased just as significantly as runoff from upstream areas of the basin passed the Mauvais Coulee near Cando gage before entering Lake Alice-Lake Irvine. Discharge from Big Coulee decreased to less than 1 cubic foot per second during the

Table 4.--Recorded water levels, in feet above sea level, of five lakes in the Devils Lake basin, March 1 through September 30, 1985

Lake	Water level on March 1	Water level on September 30	Maximum water level and date of occurrence	Minimum water level after spring maximum and date of occurrence	Outlet elevation
Ibsen Lake	1,489.0	1,488.5	1,489.8 March 29	1,488.4 September 17	1,489.5
Sweetwater and Morrison Lakes	1,457.5	1,457.5	1,459.1 April 4	1,457.4 August 13	1,458.5
Dry Lake	1,445.5	1,445.5	1,446.5 April 13	1,445.4 September 15	1,445.0
Lake Alice-Lake Irvine	1,439.3	1,439.6	1,440.8 April 15	1,439.6 September 28-30	1,439.6
Devils Lake	1,426.4	1,425.9	1,426.9 April 20	1,425.9 August 11 September 28-30	[1]1,445.0

[1]Approximate natural outlet to Stump Lake (Aronow, 1955).

same period. Discharge from Big Coulee started to increase during the first week of April; however, discharge upstream on Mauvais Coulee continued to decrease. Although the Big Coulee near Churchs Ferry gage is only 27 miles downstream of the Mauvais Coulee near Cando gage, a significant lag occurs in the two hydrographs because of the time needed to fill Lake Alice-Lake Irvine to the outlet elevation. The hydrograph for the Big Coulee near Churchs Ferry gage has a much longer recession limb than the hydrograph for the Mauvais Coulee near Cando gage because the outlet from Lake Alice-Lake Irvine controls and retards the discharge that enters Big Coulee. Discharge from Mauvais Coulee generally decreases during the the spring and summer, but there are occasional rises caused by rain. Because Lake Alice-Lake Irvine has a greater inflow than outflow during snowmelt runoff, the maximum discharge from Big Coulee is less than might

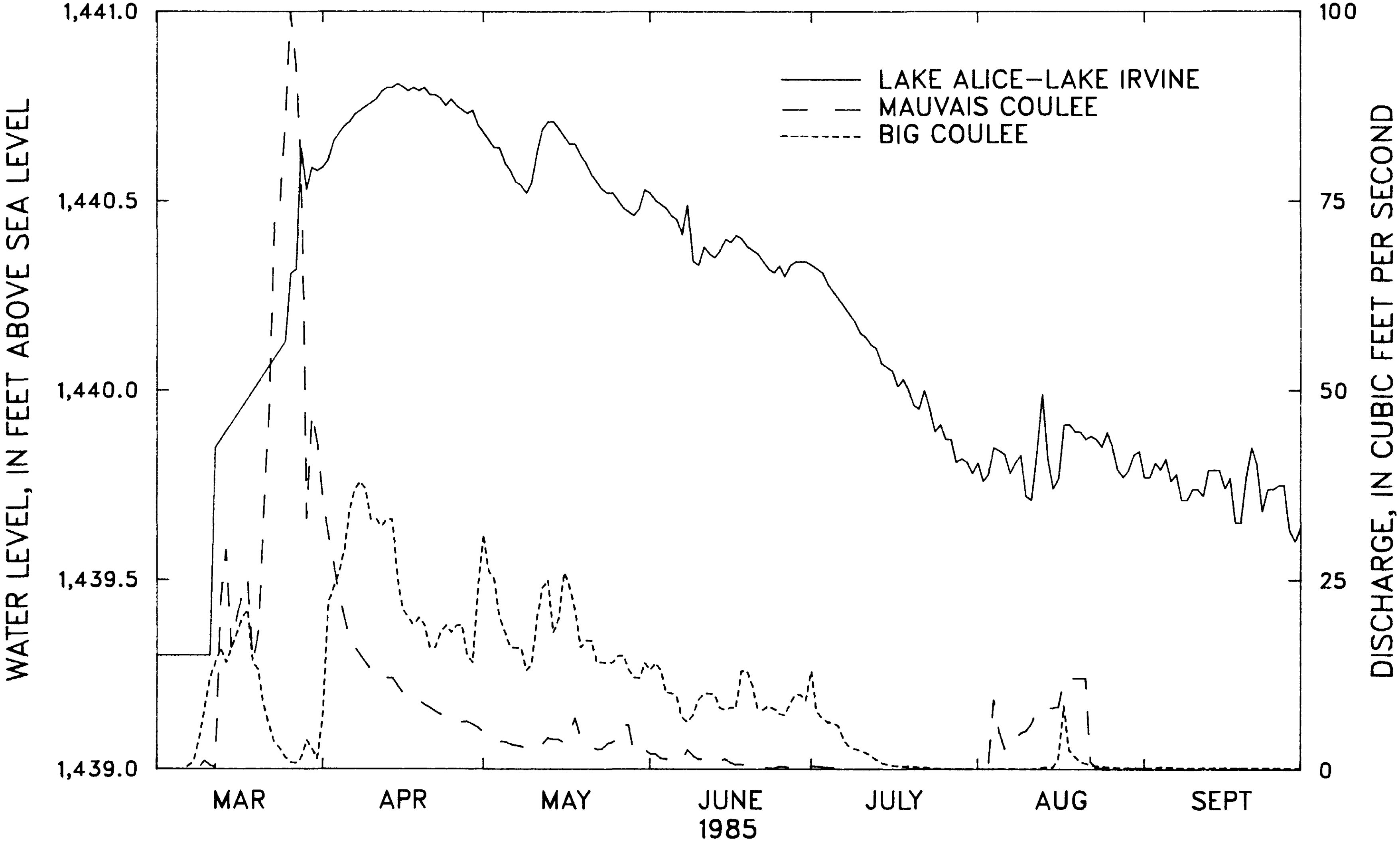

Figure 4.—Water level of Lake Alice-Lake Irvine and discharges of Mauvais Coulee and Big Coulee for March 1 through September 30, 1985.

otherwise be expected, and discharge is sustained longer and at a greater rate than the discharge from Mauvais Coulee. Sharp increases in water levels on Lake Alice-Lake Irvine, especially during August and September, are caused by wind (fig. 4).

WATER-BALANCE MODEL

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. The water-balance model was used to simulate water-level fluctuations for two conditions--a high-runoff or wet condition and a low-runoff or dry condition. Three levels of storage in the upstream chain of lakes were used in the high-runoff simulations. The following water-balance-model equation was used to simulate water levels in the chain of lakes and Devils Lake:

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

where

Q_I = inflow to the 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 or outflow from the lake, in acre-feet.

Model Description

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.

Sweetwater and Morrison Lakes are treated as one lake in the water-balance model. Discharge from Edmore Coulee and precipitation falling on the lake surface are added to the capacity of the lake. Evaporation from the lake surface is subtracted from the capacity of the lake. The outlet elevation of Sweetwater and Morrison Lakes 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 greater than the outlet-elevation capacity, the difference is treated as outflow from Sweetwater and Morrison Lakes to Webster Coulee.

Dry Lake receives inflow from Webster and Starkweather Coulees and from precipitation falling on the lake surface. Evaporation from the lake surface is subtracted from the capacity of the lake. If the capacity of Dry Lake at the end of the month is greater than the capacity of Dry Lake at the outlet 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--the outlet elevation of Dry Lake in the model is set at 1,445.0 feet above sea level for October through April and is set at 1,447.5 feet above sea level for May through September (table 5).

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 greater than the outlet elevation of 1,440.8 feet above sea level (table 5) is released to Lake Alice.

Lake Alice receives inflow from Chain Lake and Mauvais Coulee and from precipitation falling on the lake surface. Water is removed from Lake Alice-Lake Irvine by evaporation. The sill elevation of the control structure in the channel between Lake Alice and Lake Irvine is 1,436.0 feet above sea level and the outlet elevation from Lake Irvine to Big Coulee is 1,439.6 feet above sea level (table 5). For November through April, the gates at the control structure are open and Lake Alice and Lake Irvine essentially are one lake. The operating level of Lake Alice is maintained at 1,439.0 feet above sea level if there is sufficient discharge into the lake and if Lake Irvine is equal to or less than 1,439.0 feet. For November through April the water-balance model treats the lakes as a combined lake with a uniform water level. Outflow occurs when the computed water level is greater than 1,439.6 feet above sea level. For May through October, the gates of the control structure are closed and the water level for Lake Alice is held at 1,442.0 feet above sea level. Therefore, separate lake levels are computed for May through October in the water-balance model and flow from Lake Alice to Lake Irvine occurs only when the computed water level of Lake Alice is greater than 1,442.0 feet above sea level. During 1985, the U.S. Fish and Wildlife Service left the gates open throughout the year.

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 adjacent Devils Lake subbasin (north and south slopes, fig. 2), but this inflow was assumed to be zero. Precipitation falling on the lake surface is treated as inflow in the water-balance model. Ground-water inflow was assumed to be zero for this study, based on a discussion with Q.F. Paulson (U.S. Geological Survey, oral commun., 1984). Paulson indicated that material that has relatively little hydraulic conductivity is a barrier between the bottom of Devils Lake and the aquifers beneath the lake. Evaporation is the only process that removes water from Devils Lake. Therefore, a declining lake level can occur only when evaporation from Devils Lake exceeds inflow into Devils Lake plus precipitation falling on the lake surface.

Table 5.--Outlet elevations of several lakes in the chain of lakes upstream of Devils Lake for the validation, high-runoff-condition, and low-runoff-condition simulations

	Outlet elevation (feet above sea level)				
		High-runoff-condition simulations			
Outlet	Validation simulation	Existing storage 1a-1e and 4a	Midlevel storage 2a-2d and 5a	High-level storage 3a-3d	Low-runoff-condition simulation
Sweetwater and Morrison Lakes to Webster Coulee	1,458.5	1,458.5	1,462.0	1,465.0	1,458.5
Dry Lake to channel A					
October-April	1,445.0	1,445.0	1,450.0	1,455.0	1,445.0
May-September	1,447.5	1,447.5	1,450.0	1,455.0	1,447.5
Mikes Lake to Chain Lake	1,444.0	1,444.0	1,444.0	1,444.0	1,444.0
Chain Lake to Lake Alice	1,440.8	1,440.8	1,440.8	1,444.0	1,440.8
Lake Alice to Lake Irvine					
November-April	1,439.0	1,439.0	[1]1,439.0	[1]1,439.0	1,439.0
May-October	1,442.0	1,442.0	[1]1,439.0	[1]1,439.0	1,442.0
Lake Irvine to Big Coulee	1,439.6	1,439.6	1,442.0	1,442.0	1,439.6

[1]Water levels of Lake Alice from 1,439.0 to 1,442.0 feet above sea level are controlled by the outlet from Lake Irvine to Big Coulee.

Computation of Water-Balance-Model Inputs

The water-balance model requires, as input, monthly discharge from the coulees draining subbasins in the Devils Lake basin and precipitation and evaporation values. Discharge from the coulees was computed by applying drainage-area ratio techniques to recorded discharge in the Devils Lake basin. A monthly series of input data was developed for 1968-83. Discharge recorded by the Edmore Coulee near Edmore gage (fig. 2, site 2) was multiplied by a factor of 1.42 (402 square miles/282 square miles) to account for the intervening contributing drainage area between the gage and Sweetwater Lake. The total contributing drainage area of Edmore Coulee (401 square miles) was obtained by subtracting the noncontributing drainage area (table 2) of Edmore Coulee near Edmore from the total drainage area of Edmore Coulee (table 1). Prior to 1980, discharge of Starkweather Coulee, which is tributary to Dry Lake, was computed by multiplying discharge recorded by the Edmore Coulee near Edmore gage by a factor of 1.39 (391 square miles/282 square miles). The drainage area of Starkweather Coulee at its confluence with Dry Lake is 391 square miles (table 1) and the contributing drainage area of Edmore Coulee near Edmore is 282 square miles. For 1980-83, discharge of Starkweather Coulee at the mouth of Dry Lake was computed by multiplying discharge recorded by the Starkweather Coulee near Webster gage (fig. 2, site 5) by a factor of 1.26 (391 square miles/310 square miles).

Discharge from Calio Coulee at its mouth at Chain Lake was computed by multiplying discharge recorded by the Mauvais Coulee near Cando gage by a factor of 0.62 (233 square miles/377 square miles). The drainage area of Calio Coulee at its mouth at Chain Lake is 233 square miles (table 1) and the contributing drainage area of Mauvais Coulee near Cando is 377 square miles (table 2). Discharge from Mauvais Coulee at the mouth was computed by multiplying discharge recorded by the Mauvais Coulee near Cando gage by a factor of 2.31 (872 square miles/377 square miles).

For 1976-83, discharge from Little Coulee at its confluence with Big Coulee was computed by multiplying discharge recorded by the Little Coulee near Brinsmade gage (fig. 2, site 8) by a factor of 1.37 (263 square miles/192 square miles) to account for the intervening drainage area. The contributing drainage area of Little Coulee at its confluence with Big Coulee is 263 square miles (table 1) and contributing drainage area of Little Coulee near Brinsmade is 192 square miles (table 2). Concurrent discharge records of two gaging stations on Little Coulee and of the Mauvais Coulee near Cando gage (fig. 2, site 1) are listed in table 6. Average discharge in acre-feet per square mile during 1958-67 and 1976-82 was used to develop the weighted discharge of Little Coulee and Mauvais Coulee (table 6). The weighted average discharge of Little Coulee, in acre-feet per square mile, is about 54 percent of the weighted average discharge of Mauvais Coulee. The drainage area of Little Coulee at its confluence with Big Coulee is 70 percent of the drainage area of Mauvais Coulee near Cando. Therefore, discharge from Little Coulee at its confluence with Big Coulee for 1968-75 was computed by multiplying discharge recorded by the Mauvais Coulee near Cando gage by a factor of 0.38 (0.54x0.70).

Table 6.--Concurrent annual discharge recorded by gages located on Little Coulee and Mauvais Coulee, 1958-67 and 1976-82, and computation of ratio of runoff between Little Coulee and Mauvais Coulee

[Contributing drainage area for Little Coulee at Leeds is 140 square miles, contributing drainage area for Little Coulee near Brinsmade is 192 square miles, and contributing drainage area for Mauvais Coulee near Cando is 377 square miles]

	Discharge (acre-feet per year)			Discharge (acre-feet per year)	
Year	Little Coulee at Leeds	Mauvais Coulee near Cando	Year	Little Coulee near Brinsmade	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	45,180
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	5,510	49,300		35,620	108,900
	Average (acre-feet per square mile per year)				
	3.93	13.1		26.8	41.3

Weighted discharges:

Little Coulee- $\frac{[(3.93x10)+(26.8x7)]}{17}$ = 13.3 acre-feet per square mile

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

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

Monthly precipitation data are required by the water-balance model in order to compute the amount of water falling on the surface of all lakes modeled. Monthly precipitation data for 1968-83 were developed using an average monthly precipitation at Leeds, Devils Lake, and Warwick, N. Dak. (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1969-84).

Pan-evaporation data were collected at the city of Devils Lake for April through September during 1951-70 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1952-71). Pan-evaporation data are not available for some years, especially for April and May. Lake evaporation differs from pan evaporation but can be empirically derived from pan-evaporation data. Three techniques were used to derive monthly lake evaporation for 1968-83. For months when pan-evaporation data were collected (U.S. Department of Commerce, 1959), monthly values of pan evaporation were multiplied by a factor of 0.75 to convert the values to an equivalent lake evaporation.

When pan-evaporation data were not collected, a linear-regression equation was developed to compute monthly pan-evaporation values for April through September 1968-83. The 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. Seventy-seven pairs of monthly pan-evaporation and temperature data were log-transformed and used to develop the regression equation:

$$E = 0.023T^{1.34}, \qquad (2)$$

where

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

Equation 2 has a coefficient of determination of 0.58. Monthly pan-evaporation values computed using equation 2 were multiplied by a factor of 0.75 to convert the pan-evaporation values to equivalent lake evaporation.

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 values for October through March were obtained by: (1) Computing the monthly pan evaporation for April through September using equation 2; (2) dividing the total April through September pan evaporation for each year by 0.83; (3) multiplying the annual pan evaporation by 0.75 to convert to lake evaporation; and (4) multiplying the annual lake evaporation for a given year by the proportion associated for the months October through March.

Validation Simulation

Monthly discharge, precipitation, and lake-evaporation values for 1968-83 were used as inputs to the water-balance model to simulate monthly water levels of Devils Lake. The water-balance model was validated by comparing the simulated water levels to the recorded water levels. The initial water level for Devils Lake was 1,411.25 feet above sea level, which is the recorded water level for January 1968. Initial water levels for the upstream chain of lakes were based on the water levels at freezeup in 1984. Monthly water levels were not simulated prior to 1968 because hydraulic changes in the upstream chain of lakes cannot be determined with any degree of certainty. As an example, prior to 1968, no control structure existed between Lake Alice and Lake Irvine, and the natural outlet elevation was about 1,443 feet above sea level (Dale Frink, Engineer, North Dakota State Water Commission, written commun., 1985).

Comparison of simulated and recorded water levels is shown in figure 5. In general, there is good agreement between the water levels. The maximum difference between the simulated and the recorded water levels occurs in April 1969, when the simulated water level is 5.18 feet greater than the recorded water level. This relatively large difference occurs because of a 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 because the model assumes that all water above the outlet elevation discharges instantaneously; whereas, the recorded water levels reflect the traveltime through the interconnected chain of lakes. Thus, the model does not lag the outflows as would reservoir routing. By August 1969, the recorded water level is 0.50 foot greater than the simulated water level. The annual maximum deviation between the simulated and the recorded water level usually occurs during April-June, when the simulated water level is greater than the recorded water level. The maximum simulated water level of 1,428.1 feet above sea level occurred in April 1983, and the maximum recorded water level of 1,428.1 feet above sea level occurred in June 1983.

Although many assumptions were made regarding model inputs, based on comparison of the simulated and recorded water levels, the water-balance model seems to provide reasonable results and no further model validation was considered necessary.

High-Runoff-Condition Simulations

Water levels for the high-runoff condition were simulated for January 1985 through December 2032. Monthly values of discharge, precipitation, and lake evaporation during 1968-83 were replicated three times to develop 48 years of input data. The period 1968-83 was selected because (1) Devils Lake rose rapidly during this period, and (2) there was a regional tendency for greater-than-normal runoff during this period (Miller and Frink, 1984). The high-runoff-condition simulations are based on the assumption that discharge, precipitation, and lake evaporation have the same timing and magnitude during 1985-2000, 2001-16, and 2017-32 as during

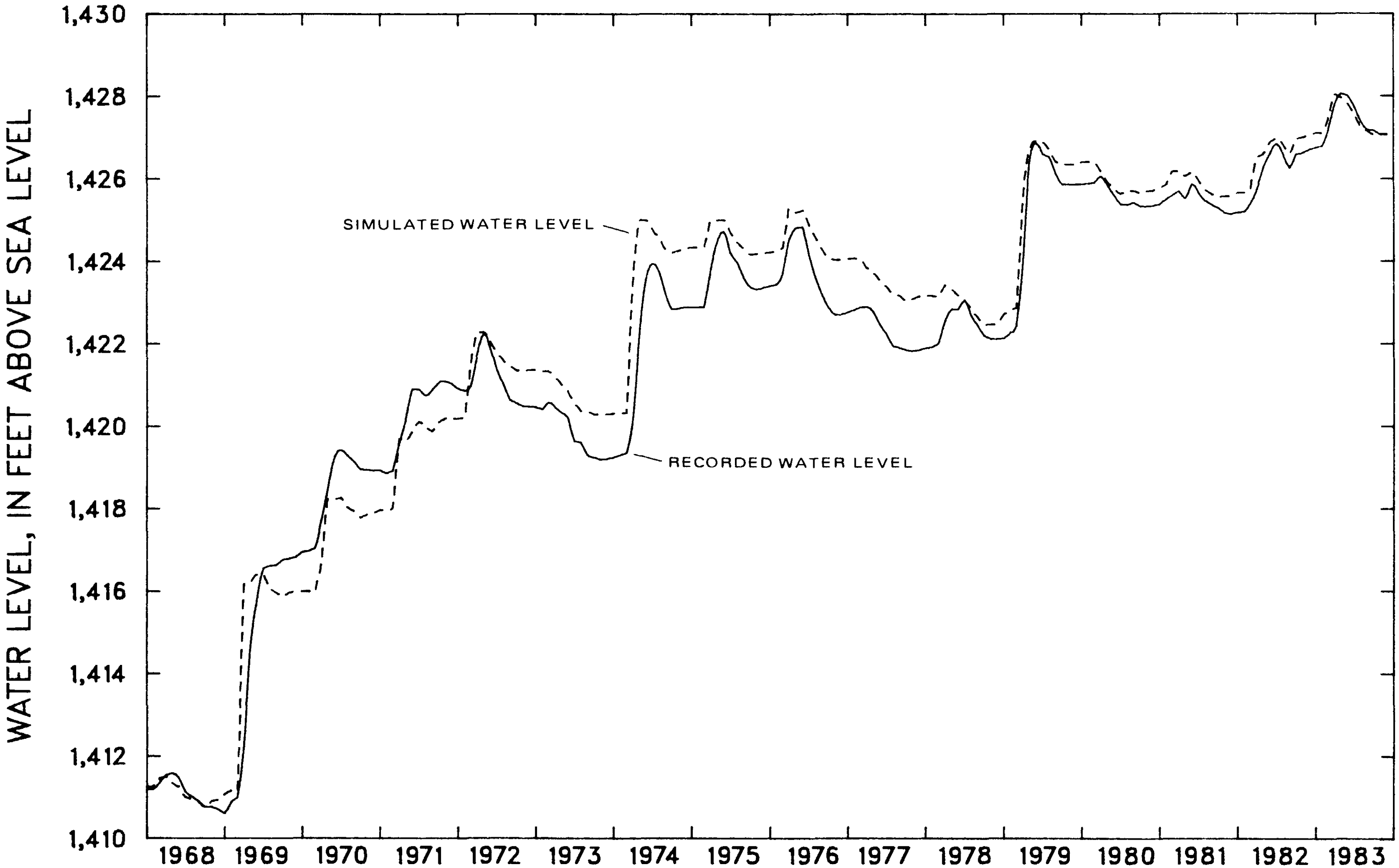

Figure 5.—Monthly simulated and recorded water levels in Devils Lake, 1968-83.

1968-83. It is not known if Devils Lake will continue to rise, but if the lake continues to rise the simulations should depict the water levels that can be expected given the observed timing and magnitude of hydrologic and climatologic data during 1968-83. The 48-year synthetic record provides no improved estimates of the flow regimen into the chain of lakes. The mean, variance, skew, and serial correlation of recorded hydrologic and climatologic data (1968-83) was maintained in the synthesized record (1985-2032).

Twenty-eight simulations were made for the high-runoff condition by using different precipitation values, lake-evaporation values, and storage conditions in the upstream chain of lakes. Outlets from Devils Lake to Stump Lake were incorporated in 13 of the simulations and outlets from Devils Lake to the Sheyenne River were incorporated in 12 of the simulations.

An outlet from Devils Lake to Stump Lake was incorporated in simulations 1b, 1c, 1e, 1j, 1k, 2b, 2d, 2e, 3b, 3d, 4a, 4d, and 5a (table 7). Stump Lake is comprised of west and east arms that currently are at different water levels. In these simulations, the initial water level for west Stump Lake was 1,400.0 feet above sea level and the initial water level for east Stump Lake was 1,385.0 feet above sea level.

Three different configurations of operating criteria were used in the model for west Stump Lake and east Stump Lake depending on the simulation. The first configuration is (1) fill east Stump Lake to a water level of 1,400.0 feet above sea level, (2) simultaneously fill west Stump Lake and east Stump Lake to a water level of 1,415.0 feet above sea level, and (3) continue to fill west Stump Lake to a water level of 1,425.0 feet above sea level. The maximum allowable simulated water levels for the first configuration are 1,425.0 feet above sea level for west Stump Lake and 1,415.0 feet above sea level for east Stump Lake.

The second configuration is to fill east Stump Lake to a water level of 1,400 feet above sea level and then simultaneously fill west Stump Lake and east Stump Lake to a water level of 1,405.0 feet above sea level. The maximum allowable simulated water levels for the second configuration is 1,405.0 feet above sea level for west Stump Lake and east Stump Lake.

The third configuration is to fill east Stump Lake to a water level of 1,400 feet above sea level and then simultaneously fill west Stump Lake and east Stump Lake to a water level of 1,425.0 feet above sea level. The maximum allowable simulated water level for the third configuration is 1,425.0 feet above sea level. When the maximum water level occurs in Stump Lake during a simulation using any of the configurations, all additional inflow into Devils Lake is either stored in Devils Lake or is discharged through the proposed outlet from Devils Lake to the Sheyenne River.

Table 7.--Hydrologic and climatologic variables used in the high-runoff-condition simulations

Simulation number	Storage condition in upstream chain of lakes (acre-feet)	Outlet elevation from Devils Lake to Stump Lake (feet above sea level)	Maximum monthly discharge allowed to Stump Lake (acre-feet)	Maximum monthly discharge from Devils Lake to the Sheyenne River (acre-feet)	Increase (+) or decrease (-) (percent)	
					Precipitation	Lake evaporation
1a	Existing storage.	No outlet.	0	0	0	0
1b	do.	1,430.0	[1]11,900	0	0	0
1c	do.	1,430.0	[1]35,700	0	0	0
1d	do.	No outlet.	0	0	+5.0	-5.0
1e	do.	1,430.0	[1]11,900	0	+5.0	-5.0
1f	do.	No outlet.	0	5,950	0	0
1g	do.	No outlet.	0	5,950	+5.0	-5.0
1h	do.	No outlet.	0	11,900	0	0
1i	do.	No outlet.	0	11,900	+5.0	-5.0
1j	do.	1,430.0	[2]11,900	11,900	0	0
1k	do.	1,430.0	[3]11,900	11,900	0	0
1l	do.	No outlet.	0	23,800	0	0
2a	Midlevel storage.	No outlet.	0	0	0	0
2b	do.	1,430.0	[1]11,900	0	0	0
2c	do.	No outlet.	0	0	+5.0	-5.0
2d	do.	1,430.0	[1]11,900	0	+5.0	-5.0
2e	do.	1,430.0	[2]11,900	0	0	0
2f	do.	No outlet.	0	5,950	0	0
3a	High-level storage.	No outlet.	0	0	0	0
3b	do.	1,430.0	[1]11,900	0	0	0
3c	do.	No outlet.	0	0	+5.0	-5.0
3d	do.	1,430.0	[1]11,900	0	+5.0	-5.0
4a	Existing storage.	1,435.0	[1]11,900	0	0	0
4b	do.	No outlet.	0	5,950	0	0
4c	do.	No outlet.	0	11,900	0	0
4d	do.	1,435.0	[2]11,900	11,900	0	0
4e	do.	No outlet.	0	23,800	0	0
5a	Midlevel storage.	1,435.0	[1]11,900	0	0	0

[1] Stump Lake operating configuration 1.
[2] Stump Lake operating configuration 2.
[3] Stump Lake operating configuration 3.

Simulations using Existing Storage Conditions in the Chain of Lakes

Seventeen simulations (1a-1l and 4a-4e, table 7) were run using existing storage conditions in the upstream chain of lakes. Outlet elevations for the chain of lakes at existing storage conditions are listed in table 5. Hydrologic and climatologic variables used in the 17 simulations are listed in table 7. Maximum water levels of Devils Lake range from 1,432.0 feet above sea level in simulation 1k to 1,442.6 feet above sea level in simulation 1d (table 8). No outlet from Devils Lake to Stump Lake was incorporated in simulation 1d, and precipitation was increased 5 percent and lake evaporation was decreased 5 percent (table 7). Comparison of simulations 1a and 1d (table 8) indicates that a 5-percent increase in precipitation and a 5-percent decrease in lake evaporation results in a 3.8-foot increase in the simulated maximum water level of Devils Lake during 1985-2032.

The maximum water levels in simulations 1b and 1c are 3.3 feet lower than the maximum water levels in simulation 1a and the maximum water level in simulation 4a is 2.6 feet lower than the maximum water level in simulation 1a (fig. 6). Thus, the outlet to Stump Lake in simulations 1b and 1c would cause a 3.3-foot decrease in the maximum simulated water level of Devils Lake compared to simulation 1a, and the outlet in simulation 4a would cause a 2.6-foot decrease in maximum simulated water level.

Stump Lake is filled to capacity in simulation 1b during 2004, in simulation 1c during 2003, and in simulation 4a during 2025. In simulation 1b, the maximum monthly discharge through the outlet into Stump Lake is 11,900 acre-feet and in simulation 1c the maximum discharge through the outlet is 35,700 acre-feet (table 6). Only minor differences exist between water-level fluctuations in simulations 1b and 1c and these differences are caused primarily by the different maximum discharge allowed to flow into Stump Lake. During years such as 1991, the maximum water level of Devils Lake in the spring is greater in simulation 1b than in simulation 1c. The annual maximum water level tends to peak earlier in the year in simulation 1c than it does in simulation 1b.

The maximum water level in simulation 4a is 0.7-foot greater than the maximum water level in simulations 1b and 1c. The only difference in the hydrologic and climatologic inputs (table 6) among these simulations is outlet elevation from Devils Lake to Stump Lake and the maximum discharge allowed to flow into Stump Lake. In simulations 1b and 1c, discharge from Devils Lake begins when the water level of Devils Lake exceeds 1,430.0 feet above sea level. In simulation 4a, discharge from Devils Lake begins when the water level exceeds 1,435.0 feet above sea level. The maximum monthly discharge to Stump Lake is 11,900 acre-feet in simulation 1b and 35,900 acre-feet in simulation 1c. In simulations 1b and 1c, discharge from Devils Lake into Stump Lake begins in April 1989 and Stump Lake is filled to capacity in simulation 1b in May 2004 and in simulation 1c in May 2003. In simulation 4a, discharge from Devils Lake into Stump Lake begins in April 2005 and Stump Lake is filled to capacity in June 2025. Raising the outlet elevation of Devils Lake from 1,430.0 feet above sea level (simulations 1b and 1c) to 1,435.0 feet above sea level (simulation

Table 8.--Simulated maximum water levels of Devils Lake during 1985-2032

Simulation number	Month	Year	Water level (feet above sea level)
1a	April	2025	1,438.8
1b	April	2025	1,435.5
1c	April	2025	1,435.5
1d	April	2025	1,442.6
1e	April	2025	1,440.5
1f	May	2023	1,432.5
1g	May	2023	1,432.9
1h	May	2023	1,432.4
1i	May	2023	1,432.7
1j	May	2023	1,432.2
1k	May	2023	1,432.0
1l	May	2023	1,432.2
2a	April	2025	1,436.7
2b	April	2025	1,432.8
2c	April	2025	1,441.4
2d	April	2025	1,438.9
2e	April	2025	1,434.4
2f	May	2025	1,432.4
3a	April	2025	1,434.6
3b	May	2023	1,431.3
3c	April	2025	1,439.9
3d	April	2025	1,436.8
4a	May	2023	1,436.2
4b	May	2023	1,436.8
4c	May	2023	1,436.6
4d	May	2023	1,436.4
4e	May	2023	1,436.5
5a	May	2023	1,436.0

4a) would have minor effect on the simulated maximum water level but timing of the water-level fluctuations, especially during 1989-2021, would be affected.

Simulations 1f, 1h, and 1l (fig. 7) used identical hydrologic and climatologic inputs (table 7) except that varying maximum discharge rates for the outlet to the Sheyenne River were specified. The monthly maximum discharge to the Sheyenne River was 5,950 acre-feet in simulation 1f, 11,900 acre-feet in simulation 1h, and 23,800 acre-feet in simulation 1l.

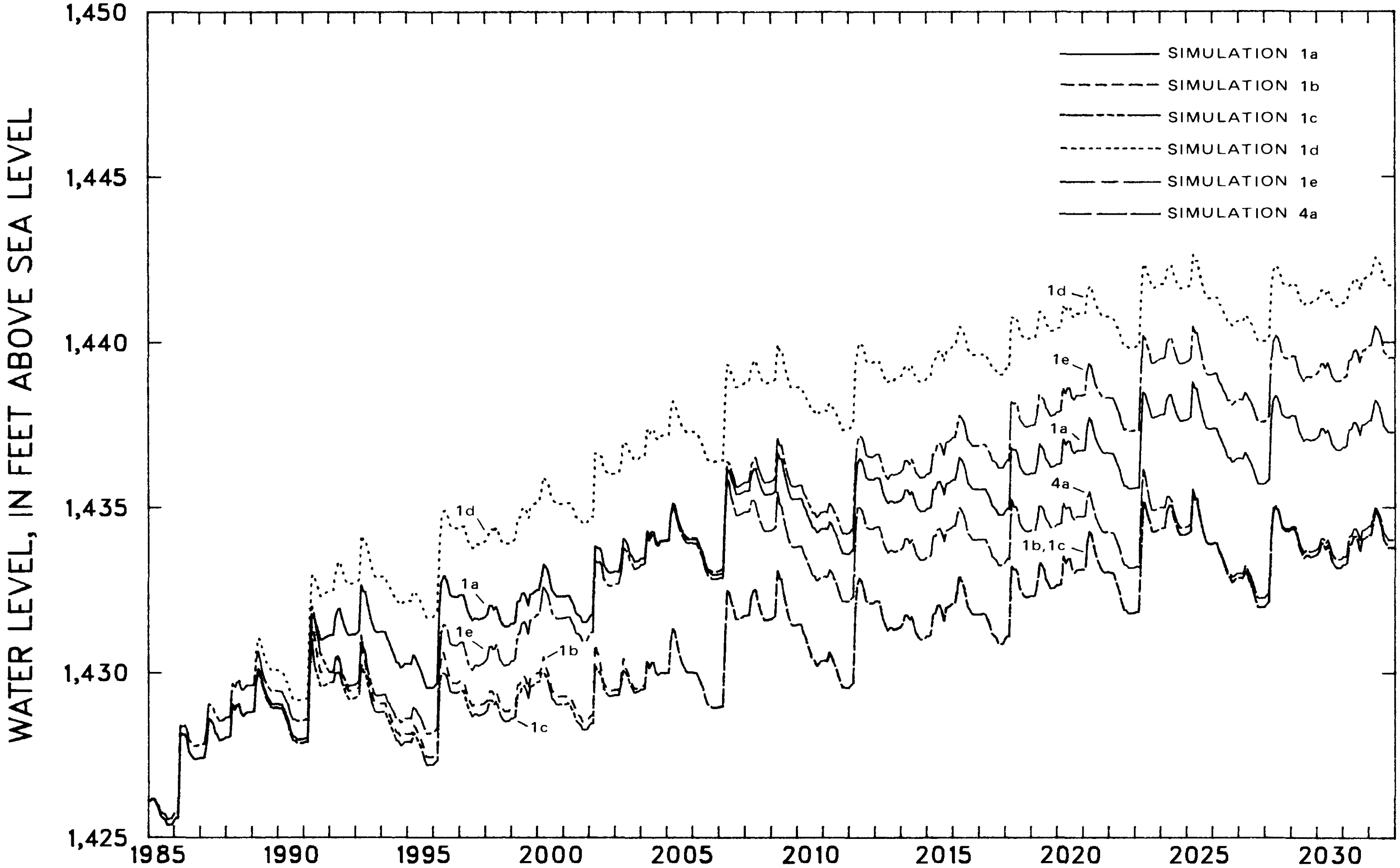

Figure 6.—Monthly simulated water levels in Devils Lake during 1985-2032 for existing storage conditions (simulations 1a-1e and 4a).

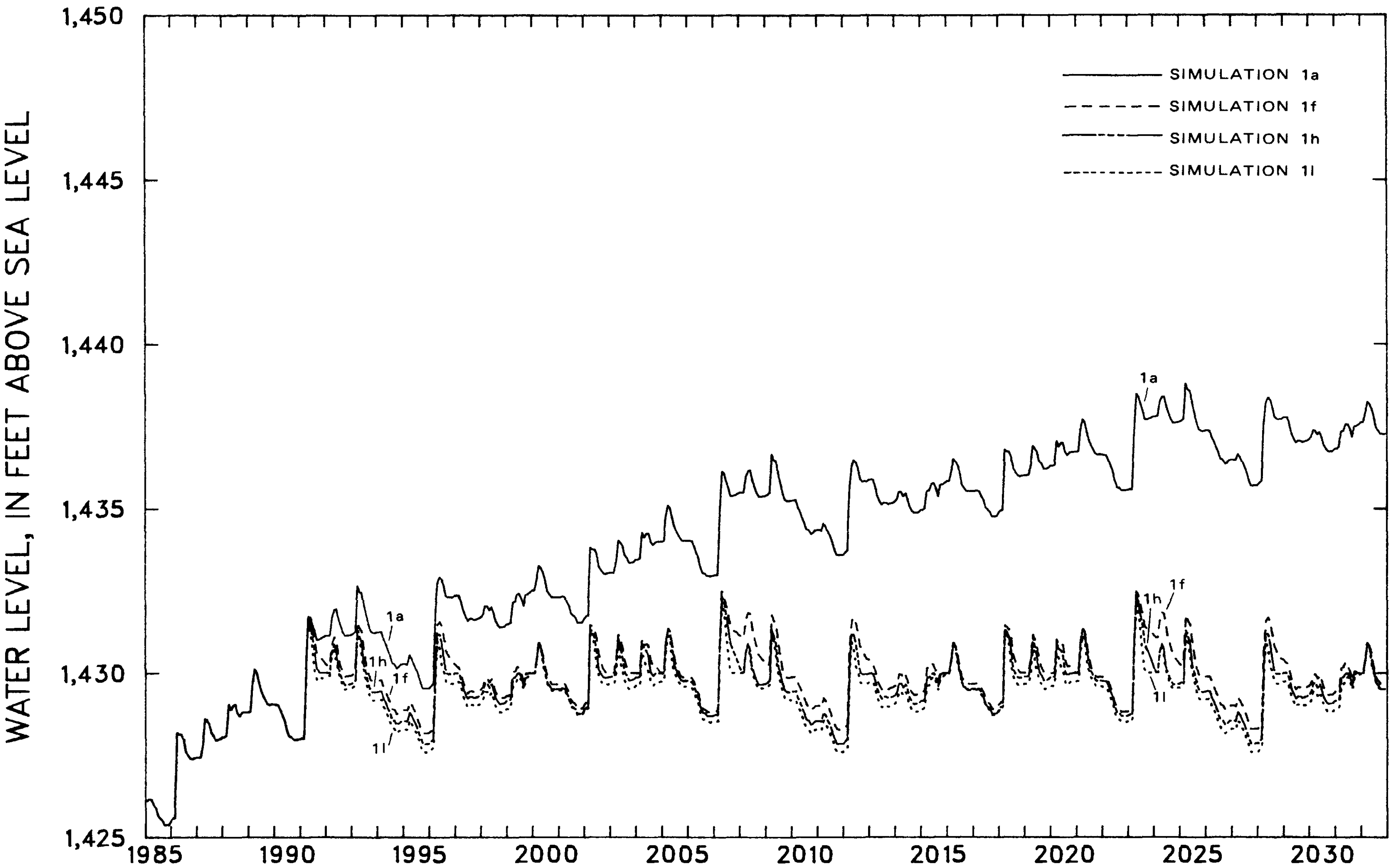

Figure 7.—Monthly simulated water levels in Devils Lake during 1985-2032 for existing storage conditions (simulations 1a, 1f, 1h, and 1l).

Maximum simulated water levels were 1,432.5 feet above sea level in simulation 1f, 1,432.4 feet above sea level in simulation 1h, and 1,432.2 feet above sea level in simulation 1l. The outlet elevation to the Sheyenne River was 1,430.0 feet above sea level in these simulations. The difference in maximum simulated water levels among simulations 1f, 1g, and 1l was caused by the different maximum discharges allowed to pass through the outlet to the Sheyenne River. As the rate of discharge to the Sheyenne River decreases the maximum simulated water level increases because the monthly inflows to Devils Lake exceed the maximum discharge rate to the Sheyenne, especially during years that have greater-than-normal runoff.

In simulations 1f, 1h, and 1l discharge to the Sheyenne River begins in June 1991 and continues intermittently through 2032. The maximum discharge rate varied for simulations 1f, 1h, and 1l, but the discharge rate had a negligible effect on the total volume of runoff entering the Sheyenne River (table 9). Discharge to the Sheyenne River during 1985-2032 ranged from 910,300 acre-feet in simulation 1f to 953,600 acre-feet in simulation 1l (table 9). The discharge to the Sheyenne River was 4.8 percent greater in simulation 1l than in simulation 1f.

Simulations using Midlevel Storage Conditions in the Chain of Lakes

Seven simulations (2a-2f and 5a) were run using midlevel storage conditions in the chain of lakes. Most of the additional storage created by midlevel storage conditions would be provided in Sweetwater and Morrison Lakes and in Dry Lake. The outlet elevation of Sweetwater and Morrison Lakes hypothetically was increased from 1,458.5 feet above sea level (existing storage conditions, table 5) to 1,462.0 feet above sea level (midlevel storage conditions, table 5). The increase in outlet elevation would increase the combined surface area of Sweetwater and Morrison Lakes from about 5,950 acres to about 8,600 acres. The outlet elevation of Dry Lake hypothetically was increased from either 1,445.0 feet above sea level during October-April operation or 1,447.5 feet above sea level during May-September operation (existing storage conditions) to 1,450.0 feet above sea level (midlevel storage conditions, table 5) throughout the year. Dry Lake has a surface area of about 4,500 acres at an elevation of 1,445.0 feet above sea level and would have a surface area of about 6,400 acres at an elevation of 1,450.0 feet above sea level.

Maximum water levels of Devils Lake for midlevel storage conditions range from 1,432.4 to 1,441.4 feet above sea level. The maximum water level in simulation 2a is 1,436.7 feet above sea level (table 8). The maximum water level in simulation 2b is 1,432.8 feet above sea level, which is 3.9 feet lower than the maximum water level in simulation 2a. The lower maximum water level in simulation 2b was caused by allowing water to move from Devils Lake to Stump Lake whenever the water level of Devils Lake was equal to or greater than 1,430.0 feet above sea level. Simulation 2f resulted in an even lower maximum water level on Devils Lake of 1,432.4 feet above sea level. Simulation 2f allows for a maximum monthly discharge from Devils Lake to the Sheyenne River of 5,950 acre-feet.

Table 9.--Discharges to the Sheyenne River for simulations 1f-1l, 2f, and 4b-4e during 1986-2032

Simulation number	Date discharge to the Sheyenne River begins	Maximum monthly discharge from from Devils Lake to the Sheyenne River (acre-feet)	Discharge (acre-feet)
1f	June 1991	5,950	910,300
1g	June 1989	5,950	1,561,000
1h	June 1991	11,900	938,100
1i	June 1989	11,900	1,584,000
1j	June 1991	11,900	609,500
1k	June 1991	11,900	400,300
1l	June 1991	23,800	953,600
2f	June 1991	5,950	599,500
4b	June 2007	5,950	307,400
4c	June 2007	11,900	345,700
4d	June 2007	11,900	123,100
4e	June 2007	23,800	353,900

Using midlevel storage conditions, comparison of simulations 2a and 2c indicates that a 5-percent increase in precipitation and a 5-percent decrease in lake evaporation (simulation 2c) would result in a 4.7-foot increase in water level from 1,436.7 feet above sea level (simulation 2a) to 1,441.4 feet above sea level (simulation 2c). Except for the change in precipitation and lake evaporation, all other hydrologic and climatologic variables used as inputs in simulations 2a and 2c are identical.

Comparison of simulations 2b and 5a indicates that increasing the outlet elevation of Devils Lake from 1,430.0 to 1,435.0 feet above sea level caused a 3.2-foot increase in the simulated maximum water level of Devils Lake. The maximum water level in simulation 2b is 1,432.8 feet above sea level, and the maximum water level in simulation 5a is 1,436.0 feet above sea level (table 8). Different outlet elevations would cause a change in the timing of water-level fluctuations of Devils Lake (fig. 8). In simulation 2b, discharge from Devils Lake to Stump Lake begins in May 1991 and continues intermittently until Stump Lake is filled to capacity in April 2009. In simulation 5a, discharge from Devils Lake to Stump Lake begins in April 2020 and Stump Lake never reaches maximum capacity during 1985-2032. In simulation 2b, from May 1991 through April 2009, the simulated water levels of Devils Lake fluctuate between 1,426.9 and 1,431.7 feet above sea level, but in simulation 5a the water levels fluctuate between 1,427.9 and 1,434.8 feet above sea level (fig. 8).

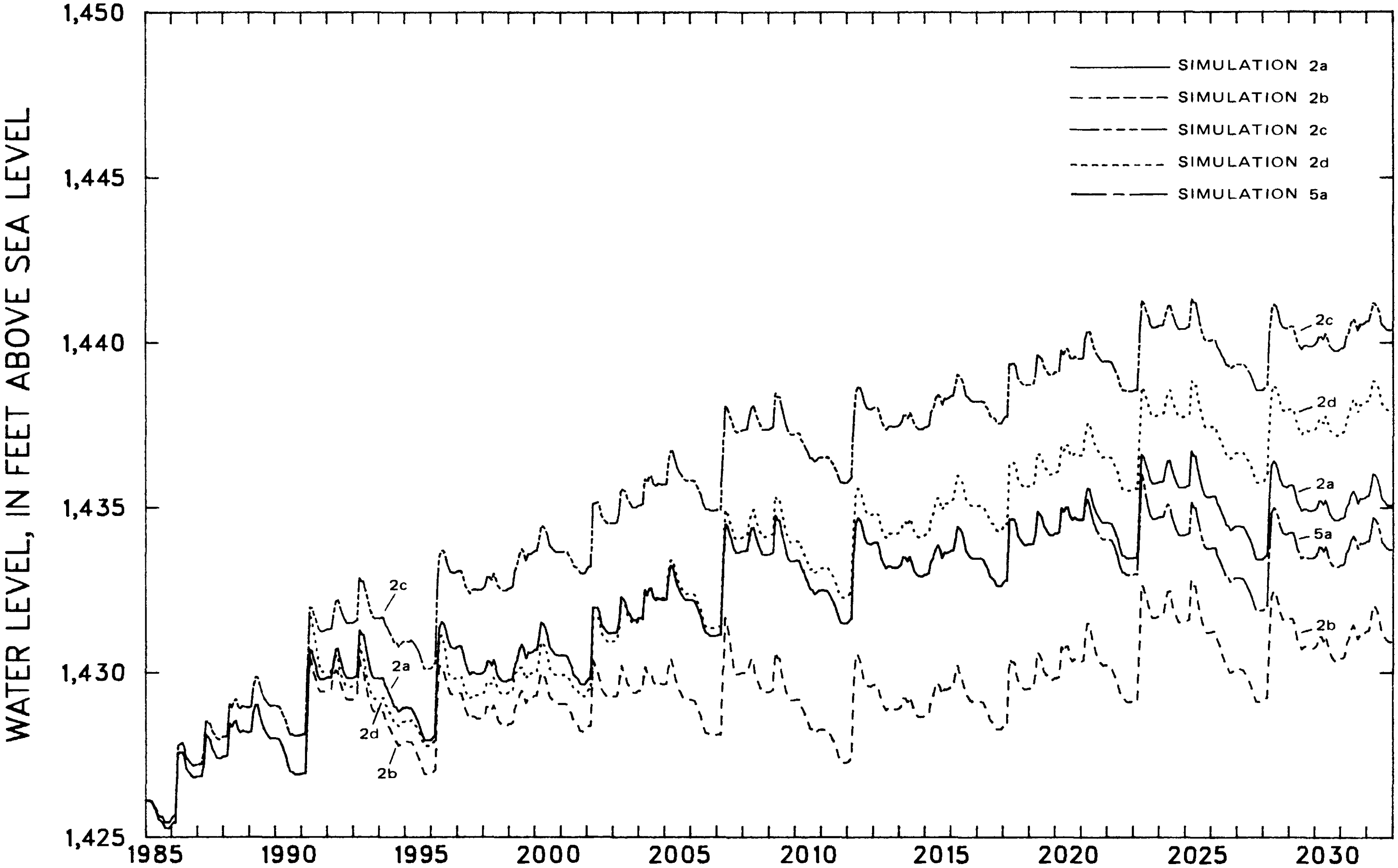

Figure 8.—Monthly simulated water levels during 1985-2032 for midlevel storage conditions (simulations 2a-2d and 5a).

If there had been greater discharge into Devils Lake, greater precipitation, or less lake evaporation in simulations 2b and 5a, the maximum water-level difference between the simulations would have been less. The water level of Devils Lake in simulation 5a would remain at about the same elevation as that at which Stump Lake fills, and the water level of Devils Lake in simulation 2b would increase because Stump Lake is filled to capacity. Based on the operating configuration used in simulation 5a, in January 2032 the water level of Stump Lake is 1,400.0 feet above sea level and about 159,100 acre-feet of storage is available.

Simulations Using High-Level Storage Conditions in the Chain of Lakes

Four simulations (3a-3d) were run using high-level storage conditions in the chain of lakes. As in the midlevel simulations, most of the additional storage in the high-level storage condition simulations was created by increasing the outlet elevations of Sweetwater and Morrison Lakes and Dry Lake (table 5). The outlet elevation of Sweetwater and Morrison Lakes was increased from 1,458.5 feet above sea level (existing storage conditions) to 1,465.0 feet above sea level (high-level storage conditions, table 5). The outlet elevation of Dry Lake was increased from either 1,445.0 feet above sea level during October-April operation or 1,447.5 feet above sea level during May-September operation (existing storage conditions) to 1,455.0 feet above sea level (high-level storage conditions, table 5). The surface area of Sweetwater and Morrison Lakes would increase from 5,950 acres for existing storage conditions to about 10,000 acres for high-level storage conditions. The surface area of Dry Lake would increase from 4,500 acres for existing storage conditions to 10,000 acres for high-level storage conditions.

The maximum water level of Devils Lake in simulation 3a is 1,434.6 feet above sea level, and the maximum water level in simulation 3b is 1,431.3 feet above sea level (table 8). The only difference in the two simulations is that an outlet to Stump Lake is included in simulation 3b. Thus, for high-level storage conditions, the addition of an outlet to Stump Lake would reduce the simulated maximum water level 3.3 feet.

Comparison of simulations 3a and 3c (table 8 and fig. 9) indicates that under high-level storage conditions a 5-percent increase in precipitation and a 5-percent decrease in lake evaporation would increase the maximum water level of Devils Lake from 1,434.6 to 1,439.9 feet above sea level. Comparison of simulations 3c and 3d indicates that the addition of an outlet to Stump Lake would decrease the maximum water level from 1,439.9 to 1,436.8 feet above sea level, a difference of 3.1 feet.

Comparison Among Simulations With Different Storage Conditions

Comparison of simulations 1a, 2a, and 3a (fig. 10) shows the effect of different storage conditions in the chain of lakes on water-level fluctuations of Devils Lake. In simulation 1a (existing storage conditions), the maximum water level of Devils Lake is 1,438.8 feet above sea level and in simulation 2a (midlevel storage conditions), the maximum water level is

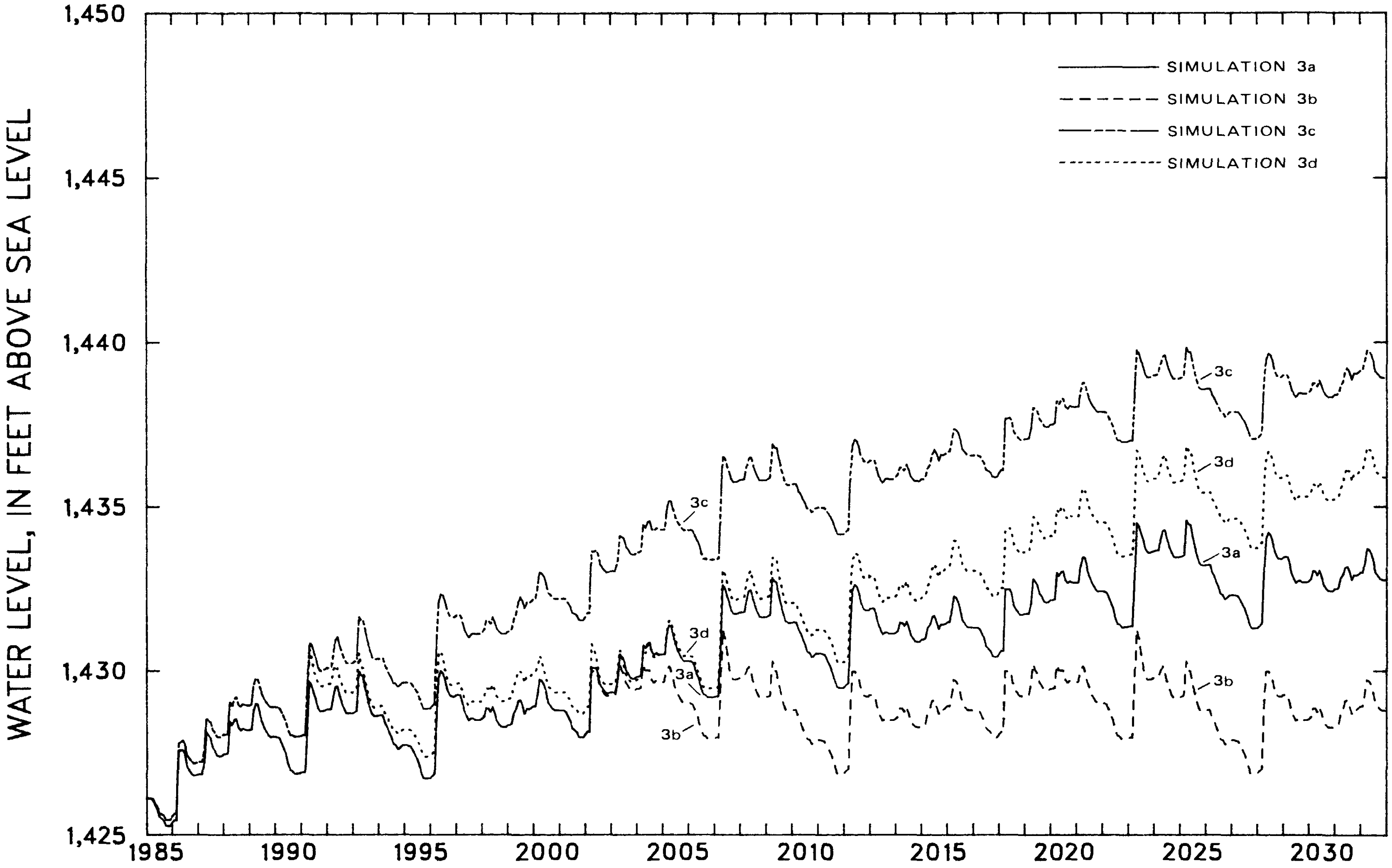

Figure 9.—Monthly simulated water levels during 1985-2032 for high-level storage conditions (simulations 3a-3d).

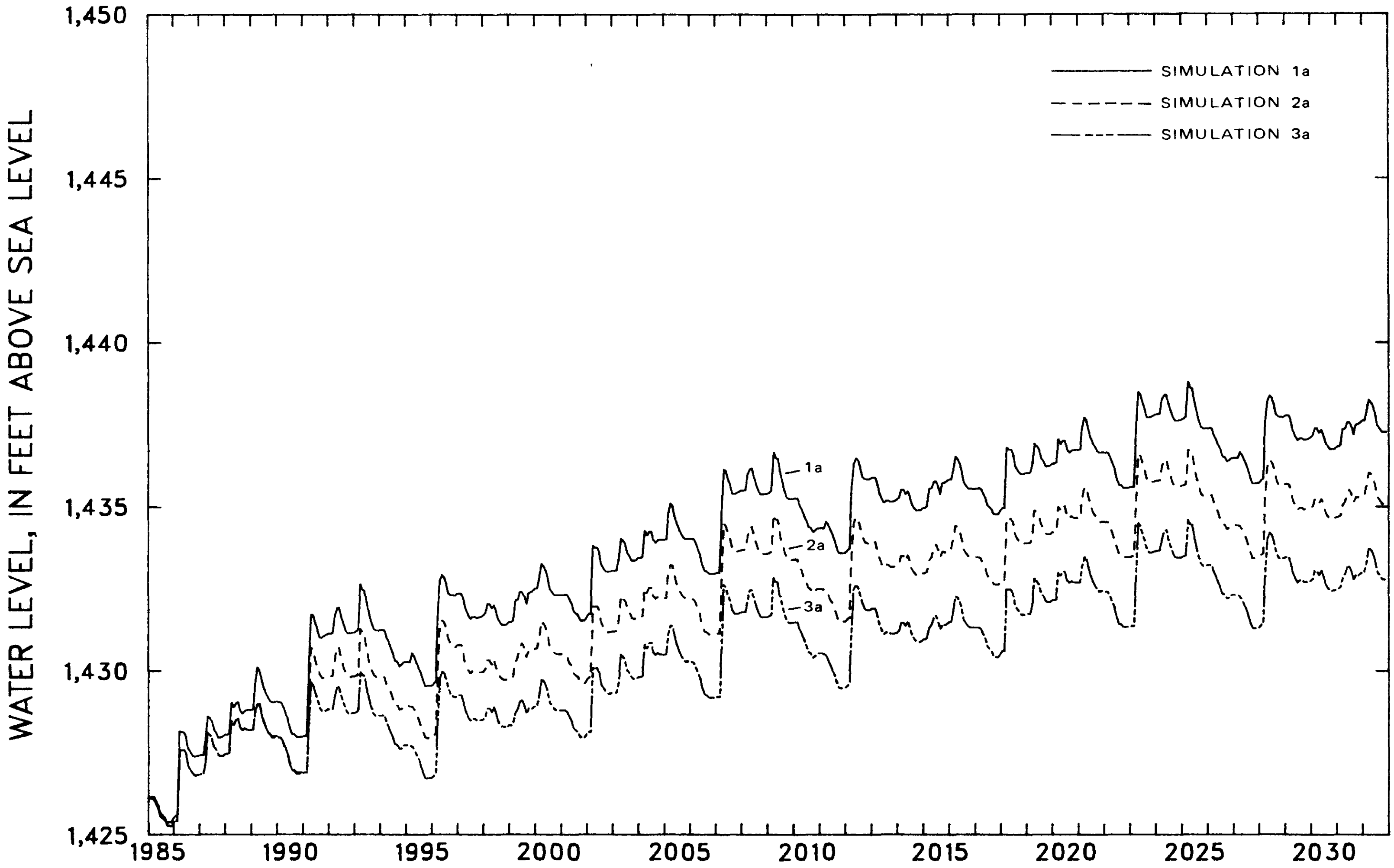

Figure 10.—Monthly simulated water levels during 1985-2032 for existing, midlevel, and high-level conditions (simulations 1a, 2a, and 3a).

1,436.7 feet above sea level. Thus, the addition of midlevel storage conditions would reduce the simulated maximum water level of Devils Lake 2.1 feet. In simulation 3a (high-level storage conditions, the maximum water level is 1,434.6 feet above sea level. Compared to midlevel storage conditions, high-level storage conditions would reduce the maximum water level of Devils Lake by 2.1 feet.

Compared to simulation 1a, the maximum water level of Devils Lake decreased in simulations 2a and 3a because the storage in and net evaporation from Sweetwater Lake, Morrison Lake, and Dry Lake increased. Comparison of simulations 1a and 3a (table 10) indicates that the net evaporative losses from Sweetwater and Morrison Lakes increase 5,010 acre-feet, and the losses from Dry Lake increase 3,860 acre-feet. The increase in net evaporative losses is caused by the increase in lake-surface area associated with the higher simulated water levels in the chain of lakes. Comparison of simulations 1a and 3a (table 10) indicates that the net evaporation from Devils Lake decreased 6,980 acre-feet. Therefore, the lower water levels of Devils Lake in simulation 3a were achieved by increasing the storage, surface area, and evaporative losses in the chain of lakes and decreasing the storage, surface area, and evaporative losses of Devils Lake.

Comparison of simulations 1b, 2b, and 3b indicates the combined effect of different storage conditions in the chain of lakes and the effect of an outlet from Devils Lake to Stump Lake. The maximum water level of Devils Lake during 1985-2032 in simulation 1b (existing storage conditions and an outlet to Stump Lake) is 1,435.5 feet above sea level, and the maximum water level in simulation 2b (midlevel storage conditions and and outlet to Stump Lake) is 1,432.8 feet above sea level (table 8). Therefore, the additional storage provided in simulation 2b would reduce the maximum water level 2.7 feet compared to simulation 1b. The maximum water level in simulation 3b (high-level storage conditions and an outlet to Stump Lake) is 1,431.3 feet above sea level (table 8). Comparison of simulations 2b and 3b indicates that the addition of high-level storage conditions in the chain of lakes would reduce the water level an additional 1.5 feet.

Low-Runoff-Condition Simulation

The low-runoff condition was simulated using 1958-63 monthly values of discharge, precipitation, and lake evaporation. The low-runoff condition was chosen based on the minimal net storage gain to Devils Lake of 29,700 acre-feet during 1958-63. The annual precipitation at Devils Lake averaged 15.71 inches during 1958-63 as compared to normal precipitation of 16.52 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1959-64, and 1983). Computed annual lake evaporation for the period was 28.8 inches.

Net storage gain during 1933-38 was 18,300 acre-feet (Wiche and others, 1986). Although 1933-38 probably represents a more extreme low-runoff condition than 1958-63, no gaging stations were in operation in the Devils Lake basin; thus, all discharge values needed as input for the

Table 10.--Simulated average annual net lake evaporation for Sweetwater and Morrison Lakes, Dry Lake, and Devils Lake during 1985-2032

Location	Evaporation (acre-feet)		
	Simulation 1a	Simulation 2a	Simulation 3a
Sweetwater and Morrison Lakes	5,090	7,210	10,100
Dry Lake	4,060	5,600	7,920
Devils Lake	63,980	60,200	57,000

water-balance model would have to be synthesized. Therefore, data limitations associated with 1933-38 were used to eliminate the period from selection as the low-runoff condition.

Water levels for the low-runoff-condition simulation are plotted in figure 11. A steady decline in water levels occurs during 1985-90, although a minor increase in water levels occurs in the spring of 1987 and of 1989. The simulated water level declines 5.4 feet from 1,426.1 feet above sea level in January 1985 to 1,420.7 feet above sea level in October 1990. Based on recorded water levels, Devils Lake declined 6.4 feet from January 1958 through December 1963.

SUMMARY AND CONCLUSIONS

Devils Lake basin is a 3,810-square-mile closed drainage basin in northeastern North Dakota. About 3,320 square miles of the drainage basin is tributary to Devils Lake; the remaining 490 square miles is tributary to Stump Lake. About 2,010 square miles of the 3,320 square miles that is tributary to Devils Lake drains into the chain of lakes. The principal streams tributary to the chain of lakes are; Edmore, Starkweather, and Calio Coulees, which originate in the northeastern part of the Devils Lake basin and flow in a south-southwesterly direction, and Mauvais Coulee, which originates in the northwestern corner of the basin and flows in a south-southeasterly direction.

In downstream order, the chain of lakes are Sweetwater Lake, Morrison Lake, Dry Lake, Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine. Prior to 1979, all of the runoff from the tributaries flowed into the interconnected chain of lakes and all of the discharge from the chain of lakes flowed downstream through Big Coulee and into Devils Lake. Channel

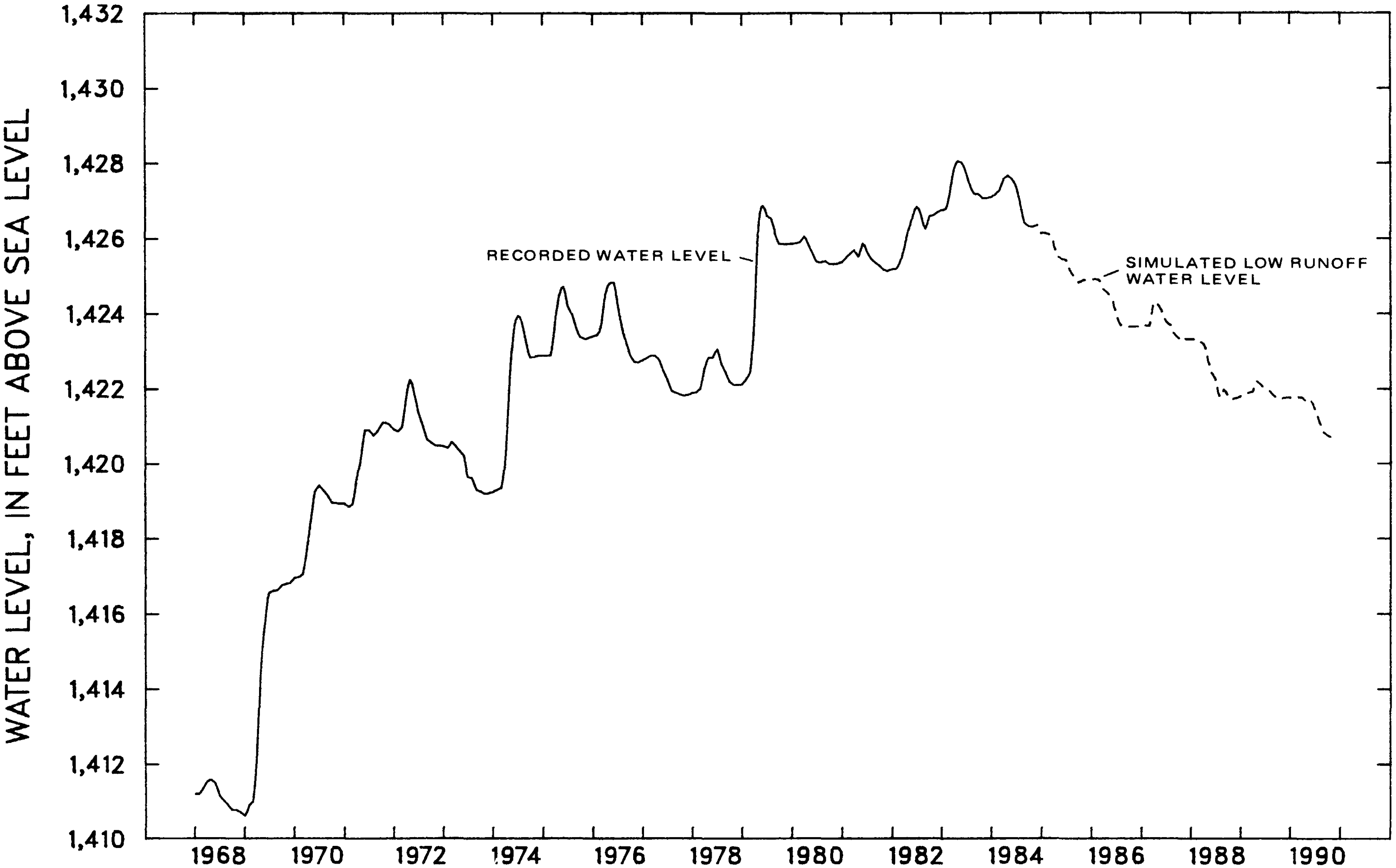

Figure 11.—Recorded water levels of Devils Lake during 1968-84 and simulated low-runoff water levels during 1985-90.

A, which connects Dry Lake to Sixmile Bay on Devils Lake, was constructed in 1979 and a levee was constructed across the natural outlet of Dry Lake. The construction of channel A and the levee on Dry Lake modified the drainage pattern in the basin; now runoff into Sweetwater, Morrison, and Dry Lakes discharges through channel A, and the remaining runoff discharges along the natural watercourse down Big Coulee into Devils Lake.

During the spring and summer of 1985, a total inflow of about 14,830 acre-feet was recorded at three gages located on tributaries to the chain of lakes. An estimated 11,150 acre-feet of water flowed into the lakes from ungaged tributaries to the chain of lakes. Outflow from the chain of lakes was about 10,180 acre-feet. Inflow into the chain of lakes was about 15,800 acre-feet greater than outflow. Lake Alice-Lake Irvine had a net storage gain of 440 acre-feet from March 1 through September 30, 1985, and the remaining lakes in the chain had no net storage gain loss during the same period. The loss of the remaining 15,360 acre-feet in the chain of lakes was attributed to evaporation. Past work of Q.F. Paulson (U.S. Geological Survey, oral commun., 1984) indicates that material underlying the Devils Lake area precludes much surface-water/ground-water interaction. More work needs to be done to accurately verify the amount of interaction between the surface water in the chain of lakes and the ground water.

Water levels in the chain of lakes rose about 1 to 1.6 feet from March 1, 1985, to their maximum levels for the year in late March and April. Water levels declined to their minimum levels during August and September and were about equal to water levels on March 1.

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 from Devils Lake. Monthly values of discharge, precipitation, and lake evaporation were used as input for high-runoff-condition simulations for 1985-2032 and a low-runoff-condition simulation for 1985-1990. Monthly values of discharge, precipitation, and lake evaporation for 1968-83 were replicated three times to develop 48 years of input data for high-runoff-condition simulations. Seventeen simulations were run using existing storage conditions in the upstream chain of lakes. Simulated maximum water levels range from 1,432.0 feet above sea level in simulation 1k to 1,442.6 feet above sea level in simulation 1d. Comparison of simulations 1a and 1d indicates that a 5-percent increase in precipitation and a 5-percent decrease in evaporation results in a 3.8-foot increase in the simulated maximum water level of Devils Lake. Comparison of simulations 1a and 1f, 1h, 1k, and 1l indicates that an outlet to the Sheyenne River would reduce the simulated maximum water level from 1,438.8 feet above sea level to 1,432.5 feet above sea level, or less.

Seven simulations were run using midlevel storage conditions in the chain of lakes. Most of the additional storage created by midlevel storage conditions is provided in Sweetwater and Morrison Lakes and in Dry Lake. Simulated maximum water levels of Devils Lake range from 1,432.4 feet above sea level in simulation 2f to 1,441.4 feet above sea level in simulation 2c. Comparison of simulations 2a and 2b indicates that for midlevel storage conditions an outlet to Stump Lake would cause a 3.9-foot reduction in the simulated maximum water level of Devils Lake. Comparison of simulations 2b and 5a indicates that increasing the outlet elevation of Devils Lake to Stump Lake from 1,430.0 to 1,435.0 feet above sea level causes a 3.2-foot increase in the simulated maximum water level of Devils Lake. Increasing the outlet elevation also causes a change in the timing of the water-level fluctuations of Devils Lake.

Four simulations were run using high-level storage conditions in the chain of lakes. The additional storage was created by increasing the outlet elevations of Sweetwater and Morrison Lakes and of Dry Lake. Simulated maximum water levels range from 1,439.9 feet above sea level in simulation 3c to 1,431.3 feet above sea level in simulation 3b. Comparison of simulations 3a and 3b indicates that under high-level storage conditions the addition of an outlet to Stump Lake would cause a 3.3-foot decline in the maximum water level of Devils Lake. Under high-level storage conditions a 5-percent increase in precipitation and a 5-percent decrease in lake evaporation (simulation 3c) would cause a 5.3-foot increase in the maximum water level as compared to simulation 3a.

Comparison of simulations 1a and 2a indicates that the addition of midlevel storage conditions in the chain of lakes would cause a 2.1-foot decline in the maximum water level of Devils Lake. Comparison of simulations 2a and 3a indicates that the addition of high-level storage conditions in the chain of lakes would cause a 2.1-foot reduction in the maximum water level of Devils Lake.

In summary, different combinations of hydrologic and climatologic variables could be selected to obtain about the same simulated maximum water levels of Devils Lake. As an example, in simulation 2b (midlevel storage condition and an outlet to Stump Lake) the simulated maximum water level is 1,432.8 feet above sea level and in simulation 1f (existing storage conditions and an outlet to the Sheyenne River) the maximum water level is 1,432.5 feet above sea level. Thus, additional storage in the upstream chain of lakes and an outlet to Stump Lake has the same effect on the simulated maximum water level as does the outlet to the Sheyenne River.

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