Chemical Quality of Surface Waters in Devils Lake Basin North Dakota, 1952–60

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1859-B

Prepared as a part of a program of the Department of the Interior for Development of the Missouri River basin

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CHEMICAL QUALITY OF SURFACE WATERS IN DEVILS LAKE BASIN, NORTH DAKOTA, 1952–60

By HUGH T. MITTEN, C. H. SCOTT, and PHILIP G. ROSENE

ABSTRACT

Above-normal precipitation in 1954, 1956, and 1957 caused the water surface of Devils Lake to rise to an altitude of 1,419.3 feet, its highest in 40 years. Nearly all the water entering the lake flowed through Big Coulee, and about three-fourths of that inflow was at rates greater than 100 cubic feet per second. At these rates, the inflow contained less than 600 ppm (parts per million) dissolved solids and was of the calcium bicarbonate type.

Because the inflow was more dilute than the lake water, the dissolved solids in the lake decreased from 8,680 ppm in 1952 to about 6,000 ppm in 1956 and 1957. Subsequently, however, they increased to slightly more than 8,000 ppm and averaged 6,800 ppm for the 1954–60 period. Sodium and sulfate were the principal dissolved constituents in the lake water. Although the concentration of dissolved solids varied significantly from time to time, the relative proportions of the chief constituents remained nearly the same.

Water flowed from Devils Lake to Mission Bay in 1956, 1957, and 1958, and some flowed from Mission Bay into East Bay. However, no water moved between East Devils Lake, western Stump Lake, and eastern Stump Lake during 1952–60; these lakes received only local runoff, and the variations in their water volume caused only minor variations in dissolved solids. For the periods sampled, concentrations averaged 60,700 ppm for East Devils Lake, 23,100 ppm for western Stump Lake, and 127,000 ppm for eastern Stump Lake.

Sodium and sulfate were the chief dissolved constituents in all the lakes of the Devils Lake chain. Water in eastern Stump Lake was saturated with sodium sulfate and precipitated large quantities of granular, hydrated sodium sulfate crystals on the lakebed and shore in fall and winter. A discontinuous layer of consolidated sodium sulfate crystals formed a significant part of the bed throughout the year.

Measured concentrations of zinc, iron, manganese, fluoride, arsenic, boron, copper, and lead were not high enough to harm fish. Data on alpha and beta particle activities in Devils Lake were insufficient to determine if present activities are less than, equal to, or more than activities before nuclear tests began.

Miscellaneous surface waters not in the Devils Lake chain contained dissolved solids that ranged from 239 to 61,200 ppm. The lakes that spill infrequently and

have little or no ground-water inflow and outflow generally contain high concentrations of dissolved solids.

Salt balance computations for Devils Lake for 1952–60 indicate that a net of as much as 89,000 tons of salts was removed from the bed by the water in some years and as much as 35,000 tons was added to the bed in other years. For the 9-year period, the tons removed exceeded the tons added; the net removed averaged 2.7 tons per acre per year. Pickup of these salts from the bed increased the dissolved solids in the lake water an average of 193 ppm per year. Between 1952 and 1960, 201,000 tons of salt was added to the bed of East Devils Lake, 15,100 tons to the bed of western Stump Lake, and 421,000 tons to the bed of eastern Stump Lake.

Laboratory examination of shore and bed material indicated that the shore contained less weight of salt per unit weight of dry, inorganic material than the bed. Calcium and bicarbonate were the chief constituents dissolved from bed material of Devils Lake, whereas sodium and sulfate were the chief constituents dissolved from bed material of East Bay, East Devils Lake, and eastern and western Stump Lakes. Generally, calcium and bicarbonate were the chief constitutents dissolved from shore material of all these lakes.

Evidence indicates that not more than 20 percent of the salt that "disappeared" from the water of Devils Lake west of State Route 20 as the lake altitudes decreased years ago will redissolve if the lake altitude is restored.

INTRODUCTION

Devils Lake basin is a large closed topographic basin in northeastern North Dakota. Devils Lake, the largest lake of the Devils Lake chain, was once the center of the most popular resort area in the State. In 1867, when the earliest authentic records of altitude were obtained, the level of this lake was at 1,438.3 feet. At that time the lake covered 90,000 acres and abounded in food and game fish. Between 1867 and 1940, the lake level declined, with only minor interruptions, and by 1940, the altitude had dropped to 1,400.9 feet. By then the lake had shrunk to a shallow, stagnant body of water that covered about 6,500 acres and supported only a few hardy fish. Throughout the next 20 years the lake level was somewhat higher than in 1940. It rose to a peak of 1,415.5 feet in 1951, declined to a low of 1,411.6 feet in 1954, rose to 1,419.3 feet in 1956, and declined to 1,415.1 feet in late 1960.

The loss of the area as a recreational center was felt throughout the State, but many people began to hope that Devils Lake would be restored as an attractive recreational asset when plans of the U.S. Department of the Interior for water-resources development in the Missouri River basin (U.S. Congress, 1944) included proposals to raise the water levels of the lakes in the Devils Lake chain and to provide a drainage outlet for them. After this restoration was proposed, several plans for diverting and restoring some or all of the lakes in the chain were considered by the U.S. Bureau of Reclamation (1961). Final plans for restoration have not been announced as of this writing (1966).

In late 1948 the U.S. Geological Survey began an investigation of Devils Lake basin to obtain information on water quality needed by the agencies formulating plans for restoration of the lakes. Results of the investigation from November 1948 to December 1952 were reported by Swenson and Colby (1955).

In their report Swenson and Colby (1955) compiled information on the fluctuations in the water-surface altitude of Devils Lake since 1867 and speculated on the reason for the general decline. They described the hydraulic relationships existing between the several lakes of the Devils Lake chain, gave the chemical characteristics of the water in the several lakes, and discussed the likely causes of the variations in the chemical characteristics from one lake to another.

They computed the tonnages of dissolved solids in water from Devils Lake and several other members of the lake chain from 1899 to 1952 and concluded that several millions of tons of dissolved solids disappeared from the water of Devils Lake between 1923 and 1948. The question then posed was whether this large quantity of salts will redissolve if the lake is restored to or above 1,416 feet, the altitude of Devils Lake in 1923.

Swenson and Colby prepared estimates of the probable concentrations and tonnages of dissolved solids in Devils Lake and in the other lakes downstream in the chain if the lakes are filled to an altitude of 1,425 feet. Assumptions had to be made regarding the quality of the water to be diverted into the lakes, the order in which the lakes are to be filled, the time to be allowed for filling, the drainage to be provided for the end-member of the lake chain, and other items. As the authors stated (p. 77), "The computed results should be understood as applicable only insofar as the assumptions may be good approximations of the actual quantities and hydrologic processes when and if the lakes are filled."

For several years following Swenson's and Colby's work in 1952, investigations of water quality in the Devils Lake basin continued but at a modest rate. Nevertheless, by 1960 considerable valuable additional information had been obtained not only on the chemical composition of water in numerous lakes in the basin but also on salts in the beds and shores of the major lakes.

The purposes of this report are to present the additional information obtained from 1952 to 1960 and to describe in more detail than was formerly possible some of the factors affecting the chemical quality of the surface waters in the basin, particularly water in the lakes of the Devils Lake chain.

This report is a supplement to the report of 1955 by Swenson and Colby. Where possible, additional information is presented in tables and illustrations which, although differing somewhat in format from those in the earlier report, are actually continuations of them. Much of the new information, such as that on salt in the lakebeds and shores, has no counterpart in the earlier report. Also, no attempt is made in this report to predict the effects of different methods of lake restoration and subsequent operation on the quality of water in the major lakes or on the Sheyenne River into which drainage from the lakes would go. The current uncertainty as to the plan for restoration and the large number of choices or combination of choices make such a prediction somewhat futile at this time.

The names of two of the streams are different from the names published by Swenson and Colby (1955). The part of Mauvais Coulee that is downstream from Lake Irvine is called Big Coulee in this report to conform to a decision made in 1961 by the Board of Geographic Names (written commun.). Sweet Creek is called Edmore Coulee to conform to the name given in recent U.S. Geological Survey water-supply papers entitled "Surface Water Supply of the United States."

Edward Bradley of the U.S. Geological Survey furnished unpublished data on observation well levels, and H. M. Erskine, also of the U.S. Geological Survey, furnished unpublished data on outflow from Devils Lake. Acknowledgment is due R. L. Bagwell of the U.S. Fish and Wildlife Service for assistance in obtaining certain field measurements and samples, and Ernest Weed of the North Dakota Highway Department for information concerning a culvert installed between Mission and East Bays. Radiochemical analyses were made in Denver, Colo.; all other laboratory analyses were made in Lincoln, Nebr.

DEVILS LAKE DRAINAGE BASIN

Devils Lake basin includes about 3,800 square miles in northeastern North Dakota (pl. 1). It extends north from the hills between the Sheyenne River and Devils Lake to the Canadian boundary. The east and west boundaries of the basin are not distinct, but the basin extends roughly to State Route 30 on the west and to the headwaters of Edmore Coulee on the east.

The basin is in the Western lake section (Lemke, 1960, p. 6) of the Central Lowland physiographic province (Fenneman, 1938, p. 559–588). The topography of the basin is of glacial origin and is in a youthful stage of erosion. The surficial deposits of glacial drift that cover the area are of late Pleistocene age and were laid down by the Leeds lobe during the Mankato Stade of the Wisconsin Glaciation (Lemke, 1960, p. 42). Altitudes range from 1,600 to 1,900 feet in the northern part of the basin and from 1,380 to 1,660 feet in the southern part. The drainage is poorly developed and except for a few coulees is indistinct.

CLIMATE

The basin is in a region of temperate continental climate and has moderate rainfall (Simpson, 1929, p. 12), long rigorous winters, and warm summers. The relative humidity averages about 78 percent (Swenson and Colby, 1955, p. 7). The prevailing wind is from the northwest throughout the year; the wind velocity averages about 10 miles per hour. The mean annual temperature is between 36° and 42°F; January is the coldest month and July the warmest.

At the city of Devils Lake the annual precipitation for 60 years (1901–60) averaged 17.4 inches. Much of the precipitation occurs during the summer months, usually as thunderstorms. On the average, 75 percent of the annual precipitation falls from April to September. A more complete discussion of climate is given by Swenson and Colby (1955, p. 5–7).

FLUCTUATIONS OF DEVILS LAKE

Devils and Stump Lakes formerly drained into the Sheyenne River through Big Stoney spillway near Tolna, N. Dak. (Aronow, 1957, p. 412–414). The outlet was at an altitude of 1,453 feet—15 feet above the highest recorded level of Devils Lake and 38 feet above the level of Devils Lake in 1960. Aronow stated, however, that very little water probably flowed through the spillway in postglacial time because the bottom of Big Stoney spillway has not been cut below a nearly accordant junction of another glacial spillway tributary to it. Aronow also found evidence that declines similar to the one experienced since the late 1800's occurred at least one and possibly two or more times previously.

A knowledge of the recent history of Devils Lake will be valuable to those who are working on plans for restoration of the lakes in the chain; therefore, investigations have centered on the fluctuations of the lake level and on the brackish waters that result when the lake level declines. Records of water-surface altitudes are given by Swenson and Colby (1955), and additional records are available in the annual series of water-supply papers entitled "Surface Water Supply of the United States." The records of the altitudes for 1952–60 are shown in figure 1.

HYDROLOGY

Although data on the hydrology of the Devils Lake area are incomplete, several useful computations based on available and estimated data are presented.

Annual precipitation at Devils Lake during 1952–60 ranged from 10.83 inches in 1952 to 22.37 inches in 1954 (fig. 2). The average was about 17.1 inches, which is near the long-term average of 17.4 inches.

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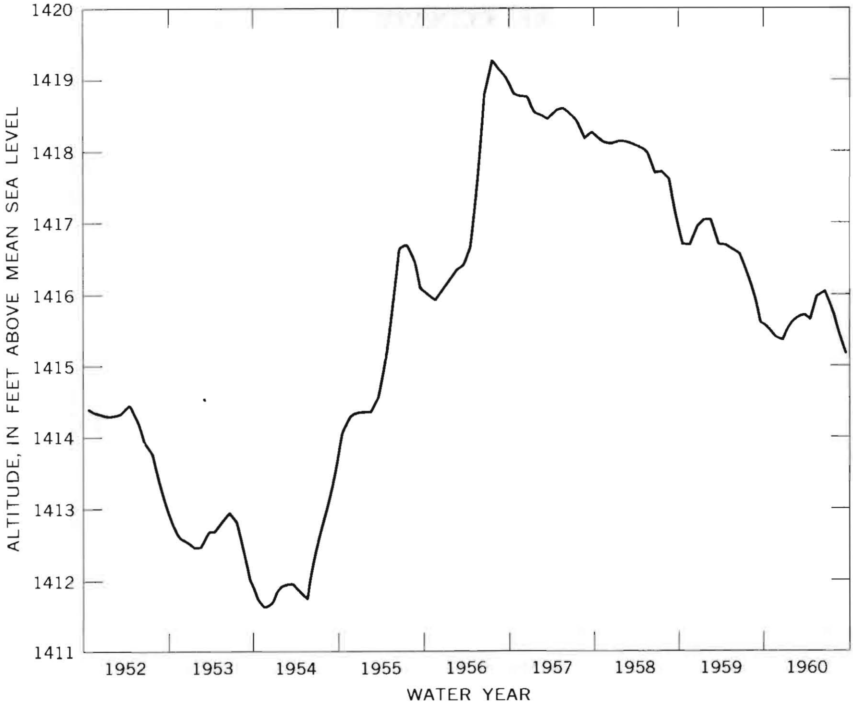

Figure 1.—Water-surface altitudes of Devils Lake, 1952–60.

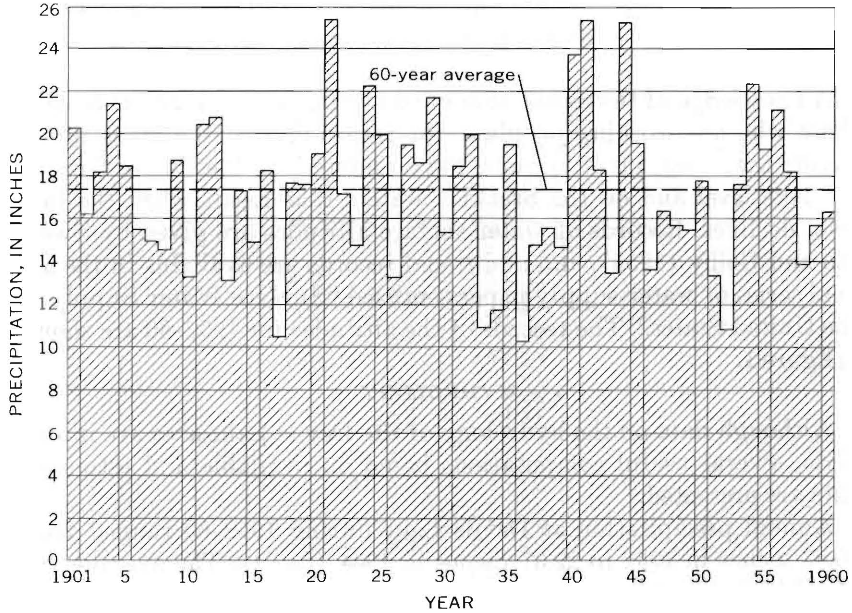

Figure 2.—Annual precipitation during 1901–60 at the city of Devils Lake.

A map prepared by the U.S. Weather Bureau (Kohler, Nordenson, and Baker, 1959) shows the average annual class-A pan evaporation to be about 40 inches at Devils Lake. The annual evaporation, based on seasonal class-A pan data, at the city of Devils Lake for the water years 1952–60 averaged about 37.6 inches. The seasonal pan data were converted to annual values on the basis of a map that shows the average evaporation for May to October to be about 85 percent of the annual evaporation. According to Kohler, Nordenson, and Baker (1959) the map can be applied only to shallow lakes where energy storage can be ignored. Energy storage from summer to winter is assumed to be insignificant in the Devils Lake chain because, at a given time, variation in temperature—either horizontal or vertical—is slight (table 1). On calm days the temperature of Devils Lake at the surface may rise above that at middepth and at the bottom, but wind action soon equalizes the temperature throughout the body of water. The class-A pan annual evaporation was converted to lake evaporation by use of an average pan coefficient of 75 percent.

TABLE 1.—*Temperature variations in lakes*

Sampling site (see pl. 1)	Date	Depth (feet)	Air temperature (°F)	Lake temperature (°F)			Remarks
				Surface	Middepth	Bottom	
Sixmile Bay							
2	Oct. 5, 1959	3.1	54.8	52.0	----------	52.0	
4	----do------	3.8	----------	50.1	----------	50.2	
3	May 4, 1960	3.4	59	48	----------	47	
Creel Bay							
19	Oct. 1, 1959	----------	45.0	49.0	----------	49.0	Windy.
21	----do------	12.8	50.0	49.3	----------	49.3	Do.
23	----do------	8.5	----------	48.0	----------	48.0	Do.
24	----do------	10.3	44.0	47.5	----------	48.2	Do.
26	----do------	9.9	45.5	48.2	----------	48.1	Do.
26	----do------	9.5	48.2	48.0	----------	48.1	Do.
27	----do------	8.1	45.0	48.2	----------	48.0	Do.
30	----do------	4.0	42.9	47.0	----------	47.0	Do.
31	----do------	7.2	----------	47.3	----------	47.3	Do.
Main part of Devils Lake							
13	Oct. 4, 1959	13.5	65.0	50.0	49.0	48.5	Calm.
14	----do------	14.6	----------	51.1	48.5	48.5	Do.
17	----do------	15.2	62.8	52.5	49.0	49.0	Do.
20	----do------	15.7	----------	52.2	48.5	48.5	Do.
28	----do------	15.4	60.6	54.0	48.7	48.5	Do.
29	----do------	15.7	66.0	52.0	49.0	49.0	Do.
6	Oct. 5, 1959	7.4	----------	48.8	----------	49.8	Windy.
9	----do------	14.8	49.0	48.8	----------	48.8	Do.
10	----do------	----------	51.8	49.3	----------	49.0	Do.
15	----do------	15.7	49.1	49.2	----------	48.0	Do.
33	----do------	14.7	----------	49.0	----------	48.5	Do.
34	----do------	13.0	46.6	48.5	----------	48.5	Do.

TABLE 1.—*Temperature variations in lakes*—Continued

Sampling site (see pl. 1)	Date	Depth (feet)	Air temperature (°F)	Lake temperature (°F)			Remarks
				Surface	Middepth	Bottom	
Mission Bay							
36	Oct. 2, 1959	5.7	51.0	44.2		44.2	Windy.
38	do	5.4	50.0	44.5		44.5	Do.
39	do	1.7	55.5	47.5			Do.
40	do	5.3	53.0	44.5		44.5	Do.
41	do	5.7	50.0	43.6		44.0	Do.
43	do	5.7	45.8	44.0		43.0	Do.
East Devils Lake							
51	Oct. 3, 1959	2.8	65.0	49.0			
52	do	2.1	59.5	49.5	50.0		
53	do	3.8		48.5		48.5	
54	do	2.5		48.2	48.0		
55	do	4.3		47.5	47.5		
56	do	4.9	59.2	47.5	47.5		
57	do	4.3		48.0	48.0		
Western Stump Lake							
61	May 6, 1960	1.1		51.8			Windy.
62	do	1.5		51.8			Do.
63	do	1.2	50.0	51.8			Do.
64	do	.7	50.0	54.5			Do.
Eastern Stump Lake							
70	Oct. 9, 1959	2.7		39.0			Windy.
72	do	3.8	32.0	40.0		39.5	Do.
74	do	3.8	32.0	39.8		39.0	Do.
75	do	4.3	32.8	39.5		39.0	Do.
76	do	2.8		39.8			Do.
79	do	1.5		38.0			Do.
80	do	.9	33.6	36.8			Do.
72	May 7, 1960	3.5		54.0		54.0	Do.
76	do	2.9		54.0		54.0	Do.
80	do	1.5		56.0		57.0	Do.

The water in the lakes of the basin is derived principally from precipitation on the lake surfaces and from surface runoff. The size of the area that contributes runoff to Devils Lake depends on the overflow of upstream lakes. About 400 square miles contributes drainage directly to Devils Lake. Runoff from another 400 square miles drains into Ibsen Lake, which probably overflows during most years because it has a surface area of only 1 or 2 square miles (Swenson and Colby, 1955). About 2,200 square miles contributes runoff to the lakes of the Sweetwater chain, which are fairly large and probably overflow only during relatively wet years. Thus, the effective drainage area of Devils Lake can range from about 400 to 3,000 square miles.

No attempt has been made in this investigation to correlate runoff with precipitation and temperature within the Devils Lake basin because the amount of drainage area is uncertain and runoff records have not been kept for a sufficient length of time. Swenson and Colby (1955), however, analyzed records for the Sheyenne River upstream from Sheyenne, N. Dak., the drainage area of which is similar in topography, vegetation, soils, and climate to the Devils Lake drainage area. They found that a 1-inch decrease in annual precipitation may be associated with a decrease of runoff of about 0.03 or 0.04 inch per year and that an increase of 1° in average annual temperature may be associated with a decrease of runoff of about 0.08 or 0.09 inch per year.

Between May 1949 and September 1954, measurements of flow in Big Coulee were obtained only occasionally. Since October 1954, daily discharges have been computed for Big Coulee near Churchs Ferry, N. Dak. Flow duration of daily discharge (fig. 3) is based on flows for water years 1954 to 1960 excluding the largely estimated record of 1955. At discharges of less than about 300 cfs (cubic feet per second), flow duration is typical for ephemeral streams, but at discharges of more than 300 cfs, flow duration is altered by regulation from upstream lakes.

The gaged flow at Churchs Ferry may not be representative of the flow that enters Devils Lake even though there is little inflow between the gage and the lake. The large marshy area between the gage and the lake can store an appreciable amount of water. Flow estimated at about 20 cfs has been observed near the inlet of Big Coulee to Devils Lake when little or no flow was observed at the gaging station. Evapotranspiration from the marshy area is probably significant at times.

INFLOW AND OUTFLOW AT DEVILS LAKE

Water-budget calculations were made for Devils Lake for water years 1952–60 to determine the approximate annual volumes of water contributed to Devils Lake by precipitation on the lake surface and by surface runoff that enters through Big Coulee and the annual volumes of water lost from the lake by evaporation and outflow (table 2). The water-budget calculations are approximations because the precipitation data and class-A pan evaporation data, converted to annual lake evaporation by use of average coefficients, may not be representative of actual conditions existing over the lake. Also, small channels, other than Big Coulee, may contribute surface inflow from an area of 300–400 square miles (Swenson and Colby, 1955). For the purposes of calculation, the years were divided into periods; therefore, the net evaporation volumes shown in the table may not correspond exactly to the volume calculated from the annual precipitation and evaporation and the mean areas. Also, the stage-capacity and stage-area data used by Swenson and Colby (1955) differ from those

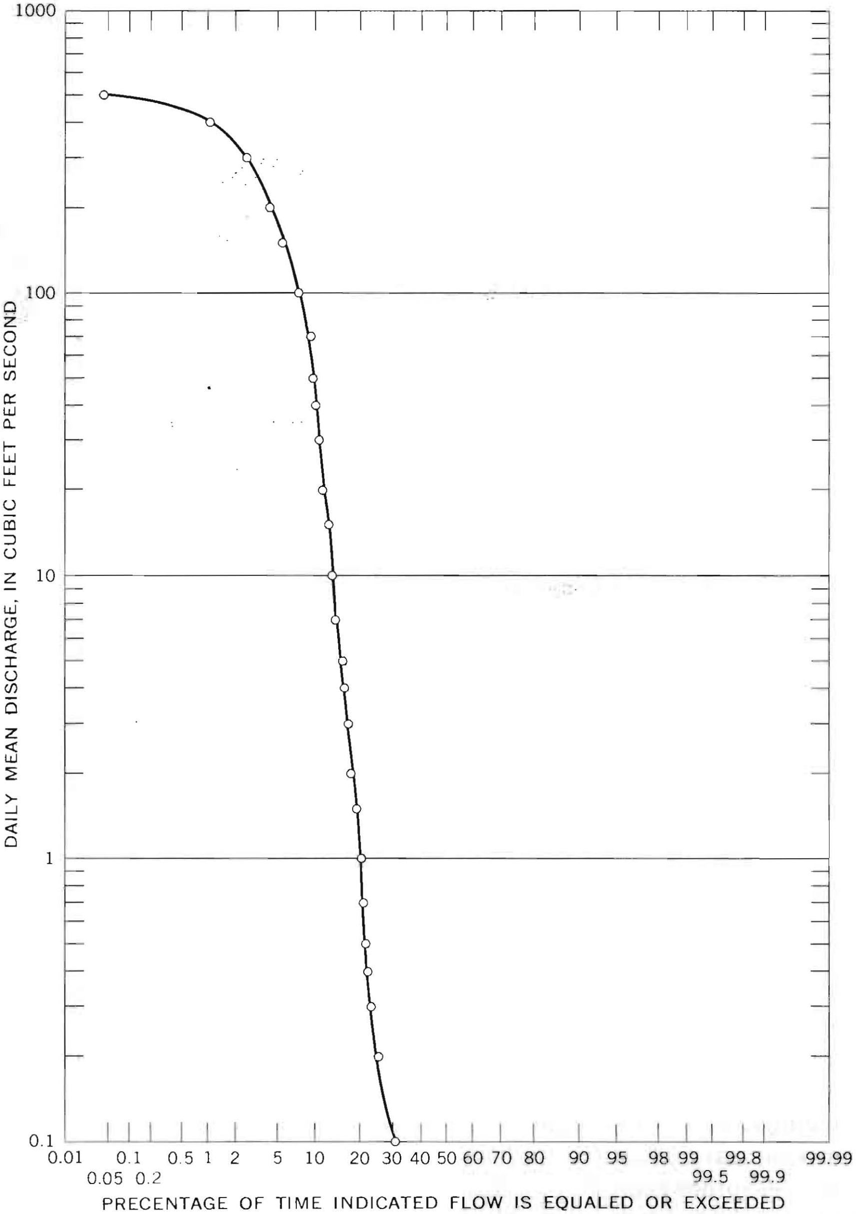

FIGURE 3.—Flow-duration curve, Big Coulee near Churchs Ferry.

TABLE 2.—*Water-budget computations, Devils Lake*

Water year	Inflow from Big Coulee (1,000 acre-ft)	Precipitation (inches)	Lake evaporation (inches)	Mean area (1,000 acres)	Net evaporation volume (1,000 acre-ft)	Initial altitude (feet)	Initial volume (1,000 acre-ft)	Final altitude (feet)	Final volume (1,000 acre-ft)	Lake volume difference (1,000 acre-ft)	Water-budget outflow (1,000 acre-ft)	Estimated outflow (1,000 acre-ft)
1952	0.006	11.27	34.76	15.3	29.9	1,414.45	156.6	1,412.94	135.2	−21.4	−8.5	0
1953	0	16.27	28.93	13.9	14.6	1,412.94	135.2	1,411.83	119.6	−15.6	1.0	0
1954	34.3	23.18	24.33	13.7	1.4	1,411.83	119.6	1,413.90	148.6	29.0	3.9	0
1955	42.4	16.71	29.01	17.0	17.8	1,413.90	148.6	1,416.05	182.8	34.2	−9.6	0
1956	57.2	21.17	25.39	18.1	6.7	1,416.05	182.8	1,418.95	233.9	51.1	−.6	[1] 9
1957	.95	19.32	25.20	18.3	9.2	1,418.95	233.9	1,418.17	219.0	−14.9	6.8	[1] 18
1958	.06	12.98	28.16	18.0	22.9	1,418.17	219.0	1,416.85	195.6	−23.4	.6	.6
1959	.07	15.17	29.24	17.3	20.3	1,416.85	195.6	1,415.50	173.5	−22.1	1.9	0
1960	.28	17.92	28.71	16.9	15.2	1,415.50	173.5	1,414.90	163.4	−10.1	−4.8	0

[1] Computed by indirect methods from watermarks in culvert and estimated altitude of Mission Bay.

used in this report. The differences are small, however, and differences in storage changes are negligible. For the water years 1952, 1955, and 1960, the fairly large negative values for the calculated water-budget outflows probably are caused by calculated lake-evaporation values that are higher than those that actually existed at the lake. An evaporation of 31.8 inches at Devils Lake during the 1952 water year was estimated by Swenson and Colby (1955) from class-A pan data at Dickinson and Mandan and from average annual lake evaporation (Horton, 1943) at Devils Lake. A value of 34.8 inches was calculated from data of Kohler, Nordenson, and Baker (1959) and from class-A pan data at the city of Devils Lake. Part of the error in the 1955 calculations may be due to errors in estimated inflow from Big Coulee for 1955.

Surface-water outflow was zero for 1952–55. With the rise of water level in 1956, State Route 57 across the narrows between Devils Lake and Mission Bay was threatened with inundation. To protect the road the Highway Department, in late June, installed a culvert under State Route 20 to allow water to flow from Mission Bay into East Bay. The culvert was placed so that the spill altitude was below the water surface, and outflow began about the 1st of July and continued until sometime in 1958. Because the water-budget calculation for the 1956 water year was unreasonable, an estimated outflow was calculated by indirect methods based on the dimensions of the outflow culvert, the high watermarks in the culvert, and the estimated altitudes of Mission Bay. The calculation was based on fairly reliable estimates of water-surface altitudes and, therefore, is probably a fair estimate of the outflow for that year. The indirect calculations for the 1957 water year were based on estimates of altitudes of Mission Bay from Devils Lake altitudes. These estimates are not very reliable because the difference in altitudes between Mission Bay and Devils Lake increased as the water surface fell and no clearly defined watermarks were left in the culvert at the lower levels. In September 1956, the outflow from Devils Lake to Mission Bay was estimated to be 20 cfs. The lake level was decreasing during the 1957 water year, but if the average discharge from Devils Lake is assumed to be 20 cfs, then the outflow for the year would have been about 14,000 acre-feet compared with the 18,000 acre-feet computed by the indirect method. The actual volume of outflow for the 1957 water year probably lies between the indirect and the water-budget calculations.

The fluctuations of the average altitude of the surface of Devils Lake for the years 1938–60 follow rather closely the fluctuations of the average water level in a well, in glacial drift, about half a mile north of Devils Lake between Sixmile and Creel Bays; the similar fluctuations (fig. 4) indicate a possible hydraulic connection between lake and ground-water reservoir. The lakes of the Devils Lake chain

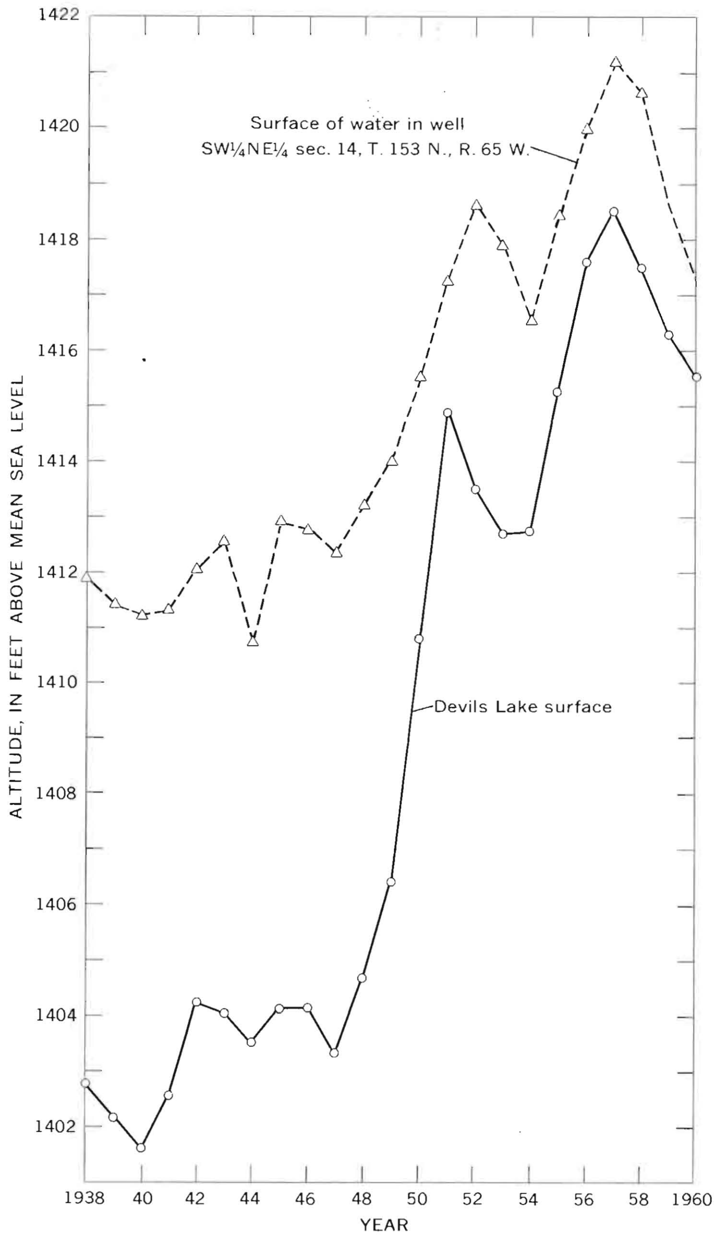

FIGURE 4.—Approximate annual mean water-surface altitudes of Devils Lake and nearby well.

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TABLE 3.—*Selected chemical*

[Results in parts per

Date of collection	Discharge (cfs)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
Near Churchs Ferry									
July 20, 1954	268					44	18	29	
May 3, 1956	546		11	[1]0.07		33	14	20	8.0
May 28, 1959	.02					288	161	407	
Near Grahams Island (sampling site 1 on pl. 1)									
June 26, 1955	[2]150					62	35	68	
Sept. 23, 1955	[2]15		38	[1]0.14		65	49	108	35
Sept. 23, 1956	[2]15							83	
Apr. 28, 1957	[2]12	60	8.2	[1].04		53	37	86	26
Oct. 4, 1957	[2]10	55	7.9	[1].08		63	87	360	61
June 22, 1958	[2].5	73	11	[1].17		78	232	1,070	70
May 4, 1960	[2]20	48	21	.12	0.00	81	45	90	32

[1] In solution when analyzed. [2] Estimated.

probably receive ground water; Paulson and Akin (1964, p. 51) showed that some ground water moves northward toward the Devils Lake chain from outwash deposits to the south. Because lake deposits and lake-modified glacial drift composed of laminated clay and silt underlie the lakes in the chain and because these deposits are in turn underlain by boulder clay and glacial till, ground-water movement probably is slow; therefore, no allowance is made for ground-water movement or bank storage in the water-budget calculations. The error introduced by neglecting these factors probably is less than the errors introduced in estimates of the volume of water evaporated from the lake. The estimates of volumes of outflow, although somewhat crude, are suitable for use in estimating the tonnage of salt lost by outflow in the salt-balance computations that will be given later in this report.

CHEMICAL QUALITY OF THE WATER

Generally in the runoff into Devils Lake, calcium, magnesium, and bicarbonate ions are highest in concentration and sodium and sulfate ions are next highest. As the dissolved solids are concentrated by evaporation, the solubility of the alkaline-earth carbonates is exceeded, and these ions precipitate; thus, the water stored in the lakes is of the sodium sulfate type.

analyses of water in Big Coulee

million except as indicated]

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue at 180°C	Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH
Near Churchs Ferry—Continued											
213	0	60	16	------	------	------	--------	319	184	490	7.4
122	0	68	8.5	0.0	7.8	0.05	--------	248	139	381	7.6
277	0	1,780	170	------	------	------	--------	3,220	1,380	3,660	7.5
Near Grahams Island (sampling site 1 on pl. 1)—Continued											
314	14	146	25	------	------	0.17	--------	556	298	837	8.5
444	0	195	58	0.6	1.2	.10	--------	762	365	1,380	8.0
350	6	168	------	------	------	------	--------	652	324	1,020	8.4
270	0	195	43	.1	.4	.11	--------	608	284	918	8.1
388	0	776	195	.2	1.5	.27	1,740	1,780	515	2,560	8.1
498	40	2,380	527	.3	.9	.85	4,660	4,850	1,150	6,250	8.6
233	0	351	48	.3	1.2	.25	--------	847	387	1,190	7.3

BIG COULEE

Mauvais Coulee, which becomes Big Coulee below Lake Irvine, is an intermittent stream; it heads near the international boundary and drains nearly the entire basin. This coulee trends south and joins Edmore Coulee, which drains the Sweetwater chain of lakes, in Lac Aux Mortes. Little Coulee drains the western part of the basin and discharges water into Big Coulee. Big Coulee flows into Devils Lake at the southern end of Sixmile Bay (pl. 1) and prior to the general decline of lake levels in the region it discharged a large amount of water into the lake.

The observed dissolved-solids content in Big Coulee from 1954 to 1960 averaged about 550 ppm near Churchs Ferry and 1,400 ppm near Grahams Island. Table 3 shows selected analyses of water in Big Coulee; additional data are published in the annual series of U.S. Geological Survey water-supply papers entitled "Quality of Surface Waters of the United States, Parts 5 and 6." The general increase in dissolved solids between Churchs Ferry and Grahams Island was probably caused by evapotranspiration in the large swampy area west of Devils Lake. The increase had practically no effect on the chemical quality of the water in Devils Lake because the highest concentrations were observed during very low flow periods when the total quantities of salt transported to the lake were small.

The type of water that flows in Big Coulee is related to discharge. The water near Churchs Ferry is of the sodium sulfate type when the discharge is about 0.1 cfs and is of the calcium bicarbonate type when the discharge is about 1 cfs or greater (fig. 5). The water near Grahams Island is of the sodium sulfate type when the discharge is about 10 cfs and is of the calcium bicarbonate type when the discharge is about 100 cfs. During 1954–60, about 76 percent of the discharge from Big Coulee was 100 cfs or more; therefore, most of the water that entered Devils Lake from Big Coulee probably was of the calcium bicarbonate type and probably contained less than 600 ppm of dissolved solids.

DEVILS LAKE AND BAYS

From 1954 to 1960, the observed dissolved solids in water from Devils Lake and its bays averaged about 6,500 ppm for Sixmile Bay, 6,000 ppm for Creel Bay, 6,800 ppm for the main part of Devils Lake, 11,500 ppm for Mission Bay, and 8,300 ppm for East Bay. (See table 4.) The free movement of water between Sixmile Bay, the main part of Devils Lake, and Creel Bay causes the concentrations of dissolved solids to be similar. The dissolved solids seemingly were relatively low in Devils Lake, Creel Bay, and Sixmile Bay in April 1955; probably, however, the samples taken were not representative of all the lake water because runoff from an exceptionally large amount of snow and ice melt had not mixed thoroughly with the rest of the water. The volume of water in Devils Lake increased from 1954 to 1956 (table 2) because runoff into the lake exceeded evaporation. Also, because the runoff contained less dissolved solids than the lake water already present, the dissolved solids in the lake decreased. From 1956 to 1960, evaporation exceeded runoff into the lake, the lake volume decreased, and the dissolved solids increased. The dissolved solids in water from Devils Lake, reported as 8,680 ppm in 1952 by Swenson and Colby (1955, p. 61), decreased to about 6,000 ppm in 1956 and 1957 and subsequently increased to more than 8,000 ppm.

Two 36-inch round corrugated metal culverts through the roadbed of State Route 57 connect Mission Bay and the main part of Devils Lake. The spill altitude of the culverts is about 1,416.1 feet. Because water does not move freely from the main part of Devils Lake into Mission Bay and because evaporation exceeds inflow, the average concentration of dissolved solids was higher in water of Mission Bay than in water of Sixmile Bay, Creel Bay, or the main part of Devils Lake.

The outlet from Mission Bay to East Bay is a 5-foot round corrugated metal culvert through the roadbed of State Route 20. The spill altitude of the culvert is about 1,416.2 feet. No coulees drain into

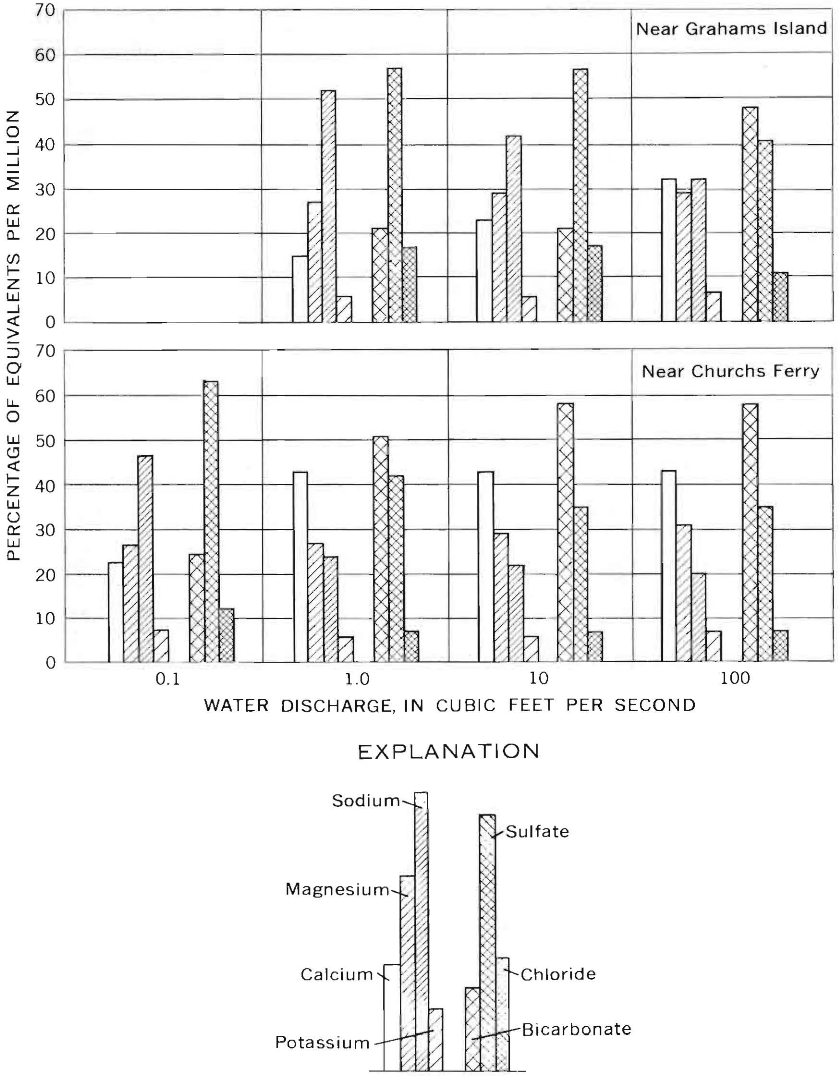


FIGURE 5.—Percentage of equivalents per million of the major constituents in the water of Big Coulee.

East Bay; therefore, the water in East Bay is almost entirely precipitation that falls on or near it and overflow from Mission Bay. The average dissolved solids for East Bay was based on only three samples of water from isolated pools. These samples showed that dissolved solids were less than in Mission Bay. The lesser concentration of dissolved solids in East Bay indicates that precipitation is probably the source of most of the water in the bay. However, East Bay is dry most of the time and part of the salt that is deposited on the bed of East Bay is

TABLE 4.—*Chemical analyses*

[Results in parts per mil

Sampling site (see pl. 1)	Date of collection	Lake altitude (feet)	Temperature (° F.)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
Sixmile Bay										
5	June 26, 1955		66						414	
2	Oct. 5, 1959	1,415.44	52	20	0.09		78	376	1,990	231
3	May 4, 1960	1,415.85		12	2.0	0.00	59	212	1,110	123
5	do		50							
Creel Bay										
22	Ju'y 16, 1954	1,412.80	78	11	[1] 0.04		120	398	2,250	236
	Oct. 7, 1954	1,413.95					95	383	2,120	
	Apr. 14, 1955 [2]	1,414.91					14	34	185	
	June 26, 1955	1,416.68	64				80	321	1,730	
	Sept. 23, 1955	1,416.1			[1] .08		100	316	1,760	188
	Jan. 4, 1956 [3]			15	[1] .20		114	359	1,960	208
	do.[4]	1,416.17		13	[1] .18		108	355	1,950	195
	do.[5]			3.1	[1] .10		17	94	388	46
	June 8, 1956	1,418.69	72	1.2	[1] .03		80	277	1,440	150
	Sept. 23, 1956	1,419.04	53		[1] .01		95	246	1,300	144
	Dec. 28, 1956 [3]	1,418.53					90	279	1,440	
	do.[5]			6.1	[1] .01		18	82	348	31
	Apr. 28, 1957	1,418.65	50	5.8	[1] .00		70	181	1,000	112
	Oct. 4, 1957	1,418.15	55	6.1	[1] .02		68	265	1,400	167
	Jan. 13, 1958 [3]			4.3	[1] .03		85	284	1,500	166
	do.[4]						80	287	1,570	
	do.[5]			1.5	[1] .01		34	127	630	65
	June 22, 1958	1,417.46	68		.04		73	279	1,580	
	Oct. 3, 1958	1,416.78	47	3.0	.02		66	296	1,530	169
	Jan. 12, 1959 [3]	1,416.68					68	338	1,730	
	do.[5]									
21	Oct. 1, 1959	1,415.44	49	19	.10		71	336	1,750	194
22	Jan. 21, 1960 [3]			19	[1] .04		74	352	1,840	199
	do.[5]			4.0	[1] .04		19	100	461	43
26	May 4, 1960	1,415.85	41	19	.04	0.00	77	347	1,790	187
22	Sept. 29, 1960	1,414.96	53	12	.08	.00	84	367	1,890	211
Main Part of Devils Lake										
35	July 16, 1954	1,412.80	75	11	[1] 0.01		93	415	2,200	222
	Oct. 7, 1954	1,413.95					100	384	2,140	
	Apr. 14, 1955 [2]						23	77	409	
	June 26, 1955	1,416.68	62				81	316	1,730	
18	June 26, 1955									
12	do		67							
8	Sept. 24, 1955		52		[1] .04		98	320		
35	Jan. 4, 1956 [3]			16	[1] 0.12		105	350	1,920	202
	do [4]			13	[1] .17		106	354	1,940	200
	do [5]			4.0	[1] .08		26	95	915	51
	June 8, 1956	1,418.69	71	2.7	[1] .02		75	283	1,430	153
	Sept. 23, 1956	1,419.04	51						1,320	
	Dec. 28, 1956 [3]			11	[1] .00		90	279	1,440	150
	do [4]	1,418.53					90	274	1,520	
	do [5]			2.8	[1] .01		33	86	376	34
	Apr. 28, 1957	1,418.65	51	5.1	[1] .07		95	273	1,430	153
	Oct. 4, 1957	1,418.15		4.0	[1] .01		78	264	1,410	162
	Jan. 13, 1958 [3]			4.3	[1] .02		80	287	1,610	166
	do [4]						80	287	1,570	
	June 22, 1958	1,417.46	71	2.6	.07		65	282	1,500	164
	Oct. 3, 1958	1,416.78	47		.05		64	297		
	Jan. 13, 1959 [3]	1,416.68								
	do [5]									

See footnotes at end of table.

of water in Devils Lake and bays

lion except as indicated]

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids		Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH
							Calculated	Residue at 180°C			
Sixmile Bay—Continued											
548	0	935	205	------	------	------	--------	--------	666	2,960	8.1
778	20	4,230	936	0.2	0.5	1.4	8.270	8,340	1,740	10,100	8.3
485	0	2,410	522	.1	.5	1.1	4,690	4,720	1,020	6,150	7.4
--------	------	------	------	------	------	------	--------	--------	--------	7,020	-----
Creel Bay—Continued											
666	81	4,780	1,060	1.0	0.5	1.7	9,270	9,340	1,940	11,200	8.7
683	60	4,350	966	------	------	------	--------	8,690	1,810	10,400	8.6
94	0	398	85	------	------	------	--------	787	174	1,240	7.7
554	79	3,730	795	------	------	------	--------	7,170	1,520	8,920	8.8
648	53	3,750	815	------	------	------	--------	7,410	1,550	9,180	8.6
742	55	4,250	920	.6	9.2	1.5	8,260	8,340	1,760	10,100	8.5
750	43	4,100	910	.6	10	1.4	8,060	8,240	1,730	9,970	8.4
175	0	865	204	.4	1.9	.41	1,710	1,750	427	2,540	7.7
514	75	3,100	690	.6	.5	1.2	6,070	6,280	1,340	7,970	8.8
504	71	2,800	627	.6	2.0	1.1	5,540	5,780	1,250	7,380	8.7
552	73	3,100	------	------	------	------	--------	--------	1,370	7,760	8.8
156	0	860	139	.2	.1	.34	1,560	1,590	384	2,280	7.7
440	14	2,100	444	.3	2.5	.93	4,150	4,140	920	5,630	8.4
624	0	2,940	649	.5	6.8	1.0	5,470	5,960	1,260	7,520	8.0
580	43	3,220	740	.2	2.2	1.1	6,380	6,430	1,380	8,050	8.7
588	43	3,220	------	.1	------	------	--------	--------	1,380	7,920	8.6
284	0	1,420	280	.1	.6	.49	2,700	2,730	608	3,760	7.8
508	77	3,140	693	.2	------	------	--------	--------	1,330	7,850	8.8
637	0	3,380	741	.2	7.4	1.3	6,510	6,650	1,380	8,410	8.2
717	0	3,810	849	------	------	------	--------	7,530	1,560	9,340	7.7
170	0	1,010	169	------	------	------	--------	--------	428	2,680	7.2
719	0	3,840	835	.2	.5	1.3	7,400	7,620	1,560	9,300	8.1
751	0	3,960	866	.2	8.2	1.4	7,690	7,820	1,630	9,640	8.0
193	0	1,080	195	.1	.9	.37	2,000	2,050	458	2,900	7.8
757	0	3,940	878	.2	1.8	1.6	7,610	7,930	1,620	9,580	7.6
799	0	4,160	900	.2	5.3	1.6	8,030	8,240	1,720	9,970	7.9
Main Part of Devils Lake—Continued											
738	43	4,800	1,050	0.6	5.3	1.6	9,200	9,410	1,940	11,300	8.5
676	67	4,480	974	------	------	------	--------	8,830	1,830	10,500	8.6
157	10	885	186	------	------	------	--------	1,750	376	2,560	8.5
558	75	3,650	788	------	------	------	--------	7,080	1,500	8,780	8.8
--------	------	------	------	------	------	------	--------	--------	--------	8,880	-----
--------	------	------	------	------	------	------	--------	--------	--------	8,880	-----
678	39	------	------	------	------	------	--------	7,460	1,560	9,160	8.5
712	55	3,980	900	.6	5.7	1.4	7,890	8,070	1,700	9,830	8.4
740	43	4,050	900	.6	8.9	1.4	7,980	8,140	1,720	9,910	8.4
216	0	1,950	240	.4	2.6	.45	3,390	3,440	456	4,650	7.6
512	77	3,100	690	.6	.6	1.2	6,070	6,360	1,350	8,030	8.8
536	59	2,800	------	------	------	------	--------	5,820	1,270	7,390	8.7
564	71	3,030	687	.6	.5	1.5	6,040	6,240	1,370	7,820	8.8
560	63	3,080	------	------	------	------	--------	--------	1,350	7,720	8.8
198	0	930	149	.2	.1	.42	1,710	1,760	436	2,500	8.1
688	0	2,890	647	.5	.6	1.1	5,840	6,210	1,360	7,800	8.2
648	0	2,800	659	.5	3.4	1.0	5,700	5,970	1,280	7,570	8.1
656	28	3,220	750	.1	2.9	1.1	6,470	6,440	1,380	8,060	8.5
596	39	3,200	------	.1	------	------	--------	--------	1,380	8,060	8.5
497	75	3,070	701	.3	.4	1.0	6,020	6,270	1,320	7,870	8.8
644	0	------	------	------	------	------	--------	6,660	1,380	8,330	8.2
724	0	3,850	844	------	------	------	--------	7,530	1,580	9,390	7.7
--------	------	------	------	------	------	------	--------	--------	--------	3,140	-----

TABLE 4.—*Chemical analyses of water*

Sampling site (see pl. 1)	Date of collection	Lake altitude (feet)	Temperature (° F.)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
Main part of Devils Lake—Continued										
13	Oct. 4, 1959	1,415.44	------	19	0.07	------	72	338	1,750	199
28	----do----		54	20	.07	------	72	341	1,750	206
29	----do----		52	19	.08	------	58	344	1,700	214
20	----do----		52	18	.06	------	72	341	1,780	219
34	Oct. 5, 1959		49	19	.16	------	73	333	1,770	219
6	----do----		49	19	.12	------	74	342	1,750	207
7	May 4, 1960	1,415.85	------	17	.02	0.00	71	334	1,720	179
35	----do----		53	16	.02	.00	71	339	1,740	187
17	----do----		40	19	.04	.01	70	335	1,730	185
35	Sept. 29, 1960	1,414.96	52	12	.05	.06	83	363	1,840	220
Mission Bay										
41	Oct. 2, 1959	1,414.25	44	18	0.15	------	73	520	2,720	289
43	May 4, 1960	1,414.91	46	7.0	.02	0.00	55	448	2,240	244
37	Sept. 29, 1960	1,414.16	50	18	.08	.00	73	573	2,960	326
East Bay										
44	June 16, 1960	--------	82	5.9	0.10	0.00	130	330	2,030	314
46	----do----	--------	64	2.6	.03	.00	54	354	2,040	241
48	----do----	--------	72	15	.04	.00	194	264	1,490	253
Black Tiger Bay										
47	Oct. 3, 1959	--------	52	3.1	0.08	------	87	1,820	10,300	866
	May 5, 1960	--------	51	5.3	.04	0.00	58	522	3,200	273

[1] In solution when analyzed.
[2] Affected by ice melt; not representative of most of the water.
[3] Just beneath ice.
[4] At bottom.
[5] Ice.

carried away by the wind. Clouds of windblown salt have been observed over the bay. The wind does not remove all the salts, however, for water in East Bay had higher dissolved solids than water in Sixmile Bay, the main part of Devils Lake, or Creel Bay.

Black Tiger Bay is a small bay that is connected to the southern end of East Bay by a culvert through the roadbed of a county road. However, any flow of water between East Bay and Black Tiger Bay in the 9 years of record is unlikely. In the two samples collected from Black Tiger Bay during 1959–60, the dissolved-solids content was higher after evaporation during the summer had decreased the volume of water in the bay and lower after the spring runoff had increased it.

Compared with the water in Big Coulee, the water in Devils Lake and its bays had a lower average percentage of equivalents per million of calcium, magnesium, and bicarbonate plus carbonate and a higher average percentage of equivalents per million of sodium, sulfate, and *in Devils Lake and bays*—Continued

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue at 180°C	Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH
Main part of Devils Lake—Continued											
724	0	3,800	841	0.1	0.9	1.3	7,380	7,610	1,570	9,450	8.2
715	0	3,800	850	.1	.8	1.3	7,390	7,570	1,580	9,370	8.2
720	0	3,830	847	.1	2.4	1.4	7,440	7,570	1,560	9,340	8.2
727	0	3,850	844	.2	.7	1.3	7,480	7,610	1,580	9,370	8.2
699	12	3,840	849	.1	1.0	1.4	7,460	7,620	1,560	9,860	8.3
721	0	3,860	849	.2	1.0	1.3	7,460	7,650	1,590	9,380	8.2
721	0	3,770	808	.1	1.6	1.6	7,260	7,530	1,550	9,250	7.9
726	0	3,820	818	.2	1.3	1.7	7,350	7,590	1,570	9,380	7.9
721	0	3,760	812	.2	1.4	1.6	7,270	7,550	1,550	9,270	7.9
797	0	4,120	908	.2	2.6	1.9	7,940	8,230	1,700	9,910	7.7
Mission Bay—Continued											
814	69	5,820	1,320	0.0	0.7	2.2	11,200	11,500	2,320	13,400	8.5
725	27	5,050	1,090	.2	.3	2.6	9,520	10,000	1,980	12,100	8.4
938	0	6,570	1,470	.1	8.0	2.4	12,500	12,900	2,540	14,800	8.0
East Bay—Continued											
219	43	4,450	1,300	0.1	2.2	4.4	8,720	9,190	1,680	11,200	8.7
193	78	4,270	1,290	.1	.5	3.3	8,430	8,830	1,590	10,900	9.1
269	0	3,090	1,280	.9	.7	3.4	6,720	6,980	1,570	8,860	8.1
Black Tiger Bay—Continued											
523	103	21,500	5,170	0.2	4.9	6.3	40,100	41,400	7,680	39,200	8.6
529	0	6,570	1,800	.0	.9	3.8	12,700	13,400	2,290	15,500	7.7

chloride (fig. 6). The free movement of water between Sixmile Bay, Creel Bay, and the main part of Devils Lake has caused the average percentages of equivalents per million of the water to be nearly identical, and they are plotted as one point in figure 6. Although dissolved solids in the water in Devils Lake ranged from 4,140 to 9,410 ppm, the percentages of equivalents per million did not vary significantly.

EAST DEVILS LAKE

In the past, East Devils Lake received water from Devils Lake and its bays. In recent years, however, East Devils Lake has probably received no water from East Bay, and the water in the lake is probably local runoff from snowmelt and summer rains. Accumulation of salt in the past and continued evaporation of water has caused the concentration of dissolved solids in East Devils Lake to be higher than in the upstream lake and bays. The observed concentrations of dissolved solids in East Devils Lake from 1956 to 1960 averaged 60,700 ppm (table 5). Each year that samples were collected, the concentrations in the fall were higher than in the previous spring because of evaporation.

282–564 O—68——4

TABLE 5.—*Chemical analyses*

[Results in parts per million

Sampling site (see pl. 1)	Date of collection	Lake altitude (feet)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
	June 8, 1956	1,402.0	------	------	[1] 0.05	------	48	2,330	11,300	978
	Sept. 24, 1956	1,400.7	64	------	[1] .01	------	36	2,740	13,400	1,230
	Apr. 29, 1957	1,401.2	67	11	[1] .04	------	144	2,270	10,900	1,020
50	Oct. 4, 1957	1,401.5	60	13	[1] .62	------	24	2,440	12,100	1,050
	June 23, 1958	1,401.3	------	6.5	.03	------	128	2,430	12,600	1,080
	Oct. 3, 1958	1,401.67	55	4.7	.08	------	57	2,930	14,400	1,290
	Oct. 3, 1959	1,399.94	64	7.2	[1] .08	------	27	3,530	17.800	1,610
55	do		48	7.1	.79	------	44	3,450	16,700	1,370
58	May 7, 1960	1,400.81	55	------	------	------	------	------	------	------
50	do		52	4.2	.05	0.03	52	2,810	12,100	1,080
58	Sept. 30, 1960	1,399.74	47	2.4	.08	.00	121	3,650	17,500	1,570

[1] In solution when analyzed.

The maximum amount of a salt that can be in solution depends on the solubility of the salt; sodium sulfate is more soluble than calcium carbonate. In the past, calcium bicarbonate precipitated from solution as water moved downstream toward East Devils Lake; therefore, the percentage of sodium sulfate in the water that entered the lake was relatively high. Now, however, inflow consists wholly of local runoff, and it contains more calcium bicarbonate than sodium sulfate. Because of continued evaporation, intermittent inflow, and difference in solubility of these salts, more sodium sulfate than calcium bicarbonate still is accumulating.

The water in East Devils Lake had a lower average percentage of equivalents per million of calcium and a higher average percentage of equivalents per million of sulfate than any other body of water in the Devils Lake chain; it had a higher average percentage of equivalents per million of magnesium than the water in Devils Lake and its bays. While lake levels are low, no change is expected. If lake levels rise, the concentration of dissolved solids and the percentage of sodium sulfate will decrease.

EASTERN AND WESTERN STUMP LAKES

Eastern and western Stump Lakes formerly received water that had passed through all the lakes in the system and water directly from several coulees. Since the cessation of flow from East Devils Lake, the Stump Lakes have been maintained only by local runoff. Of the drainage area of Stump Lakes of about 400 square miles, 350 square miles drains into western Stump Lake. Western and eastern Stump Lakes are connected by three 24-inch culverts that pass under a road between the lakes. Water begins to flow through the culverts when the surface of *of water in East Devils Lake*

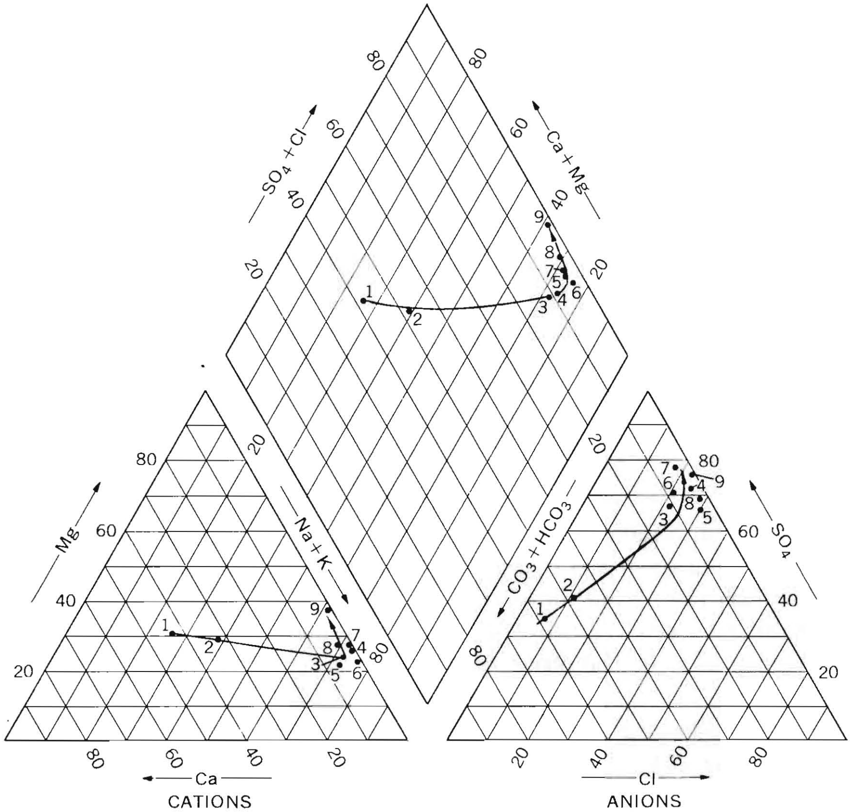
except as indicated]

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue at 180°C	Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH
1,100	468	27,100	4,520	------	2.4	6.1	47,300	49,000	9,710	43,800	8.9
1,820	368	31,800	5,330	------	.0	7.0	55,800	58,900	11,400	49,800	8.7
1,340	360	24,800	4,410	------	4.3	5.6	44,500	45,600	9,680	41,500	8.8
1,660	166	28,900	4,660	------	------	6.2	50,200	51,700	10,100	45,100	8.5
1,270	408	29,400	4,720	0.3	4.0	6.3	51,400	52,200	10,300	45,600	8.8
1,600	355	35,300	5,760	.5	57	8.3	60,900	63,100	12,200	52,800	8.5
1,950	422	42,500	6,670	.1	5.3	9.1	73,500	75,000	14,600	59,700	8.6
2,050	401	40,900	6,520	.0	4.5	8.8	70,400	74,100	14,300	59,300	8.6
--------	------	------	------	------	------	------	--------	--------	--------	47,400	---
1,590	325	30,200	5,100	.2	2.5	7.1	52,500	56,800	11,700	47,900	8.6
1,970	290	44,200	6,940	.1	.4	12	75,300	80,300	15,300	62,700	8.5

western Stump Lake reaches an altitude of 1,399.8 feet. Eastern Stump Lake has contained a few feet of water in recent years. Western Stump Lake, with the exception of its southeast bay, has been dry once and probably has been dry two other times during the past 5 years.

During 1956–60 the observed dissolved solids averaged 23,100 ppm for western Stump Lake and 127,000 ppm for eastern Stump Lake (table 6). The highest concentrations were observed in the fall; the lowest in the spring. Western Stump Lake occasionally overflows into eastern Stump Lake, and some salt that is temporarily stored in western Stump Lake is then flushed into eastern Stump Lake. Eastern Stump Lake, however, has no outlet and has had none since its surface dropped below the 1,453-foot altitude many years ago; consequently, salts that entered eastern Stump Lake accumulated there. The concentrations of dissolved solids in water from eastern Stump Lake exceeded considerably the 34,000 ppm commonly attributed to sea water.

The water in eastern Stump Lake is saturated or almost saturated with sodium sulfate. Evaporation during the summer decreases the volume of water in the lake. In the fall and winter when the volume of the lake and the temperature of the water are relatively low, a layer of loose crystals of hydrated sodium sulfate (mirabilite) about one-sixteenth to one-eight inch in diameter is deposited on the bed of the lake (figs. 7 and 8). In the summer when the volume of the lake and the temperature of the water are relatively high, the salt deposited during fall and winter nearly disappears; the large interlocking crystals of mirabilite which are left form a lower discontinuous porous layer of the bed. In general, the volume of water in the lake is higher and the parts per million of dissolved solids are lower in the spring than in the fall; yet the total weight of dissolved solids probably is more in the spring because of solution of salts from the lakebed. Measurements of



1. Big Coulee near Churchs Ferry
2. Big Coulee near Grahams Island
3. Devils Lake, Sixmile Bay, and Creel Bay
4. Mission Bay
5. East Bay
6. Black Tiger Bay
7. East Devils Lake
8. Western Stump Lake
9. Eastern Stump Lake

FIGURE 6.—Average percentage of equivalents per million of the major constituents in the water of the Devils Lake chain.

specific conductance on May 7, 1960, at sampling sites where the water was 4–6 feet deep indicate very little variation in concentration from place to place or with depth.

Because Stump Lake has received no water from East Devils Lake in many years and because bicarbonate is the principal anion in the runoff entering western Stump Lake, the percentage of equivalents per million of sulfate is less in western Stump Lake than in East Devils Lake. Some sulfate may be converted to sulfide through sulfate reduction in western Stump Lake, especially in the bed of the lake. The water in western Stump Lake and the water in eastern Stump Lake differ only slightly in percentages of equivalents per million except for sodium and sulfate. (See fig. 6.)

FIGURE 7.—Salt bars in eastern Stump Lake and salt deposits along the edge of the water. Snow is in the foreground.

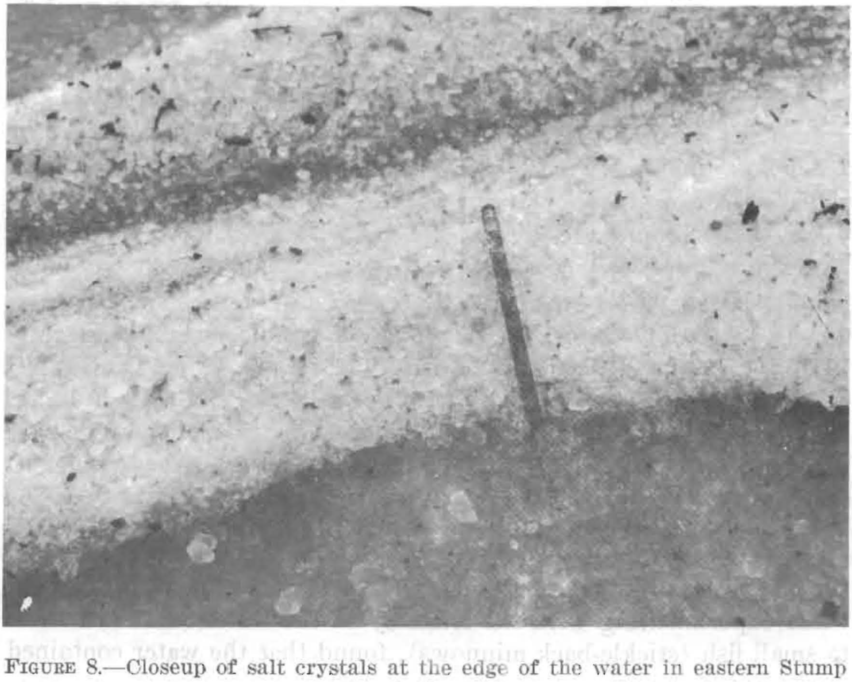


FIGURE 8.—Closeup of salt crystals at the edge of the water in eastern Stump Lake.

TABLE 6.—*Chemical analyses*

[Results in parts per

Sampling site (see pl. 1)	Date of collection	Lake altitude (feet)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
				Western Stump Lake						
68	June 25, 1955	[1]1,394	62	------	------	------	------	------	4,520	------
68	Sept. 24, 1955	--------	47	38	------	------	182	2,780	12,000	880
68	June 8, 1956	1,395.7	81	------	[2]0.05	------	114	407	2,100	143
68	Sept. 24, 1956	1,395.2	58	------	[2].00	------	149	909	4,260	279
68	Apr. 29, 1957	1,395.3	66	2.8	[2].00	------	99	777	3,740	245
68	Oct. 4, 1957	1,394.6	60	29	[2].12	------	154	510	2,370	176
68	June 23, 1958	1,394.4	70	23	.03	------	116	856	4,070	143
68	Oct. 3, 1958	1,395.0	60	29	.83	------	304	2,930	12,000	755
67	Oct. 10, 1959	1,394.60	35	4.4	.41	------	152	842	3,520	249
68	May 6, 1960	1,395.59	45	3.6	.02	0.00	107	232	1,180	116
62	May 6, 1960	1,395.59	52	19	.14	.00	112	219	1,110	110
63	May 6, 1960	1,395.59	52	------	------	------	------	------	------	------
61	May 6, 1960	1,395.59	52	------	------	------	------	------	------	------
64	May 6, 1960	1,395.59	55	------	------	------	------	------	------	------
68	June 17, 1960	1,395.71	76	------	------	------	------	------	------	------
60	June 17, 1960	1,395.71	81	------	------	------	------	------	------	------
66	June 17, 1960	1,395.71	82	------	------	------	------	------	------	------
59	June 17, 1960	1,395.71	80	------	------	------	------	------	------	------
68	Sept. 30, 1960	1,394.58	56	19	.08	.00	538	2,570	10,500	837
				Eastern Stump Lake						
78	June 25, 1955	--------	64	------	------	------	------	------	27,300	------
78	Sept. 24, 1955	--------	51	------	------	------	201	7,590	29,000	1,750
78	June 8, 1956	1,384.9	79	------	[2]0.07	------	184	6,250	21,700	1,320
78	Sept. 24, 1956	1,384.3	60	------	[2].00	------	225	6,920	27,600	1,490
78	Apr. 29, 1957	1,384.8	72	10	[2].08	------	326	6,420	16,700	1,330
78	Oct. 4, 1957	1,384.50	60	16	[2]2.1	------	198	6,690	30,600	1,500
78	June 23, 1958	1,384.32	71	5.8	.11	------	308	7,080	30,100	1,460
78	Oct. 3, 1958	1,383.84	51	11	.09	------	393	9,080	26,200	1,930
75	Oct. 9, 1959	1,383.21	38	9.1	.28	------	381	11,000	19,500	2,360
78	May 7, 1960	1,383.77	54	6.8	.10	0.00	319	7,690	21,200	1,950
73	do.[3]	1,383.77	54	------	------	------	------	------	------	------
73	do.[4]	1,383.77	------	------	------	------	------	------	------	------
76	do.[3]	1,383.77	54	------	------	------	------	------	------	------
76	do.[4]	1,383.77	------	------	------	------	------	------	------	------
80	do.[3]	1,383.77	------	------	------	------	------	------	------	------
80	do.[4]	1,383.77	------	------	------	------	------	------	------	------
80	June 15, 1960	1,383.69	70	------	------	------	------	------	------	------
71	June 15, 1960	1,383.69	70	------	------	------	------	------	------	------
78	Sept. 30, 1960	1,382.76	54	10	.09	.11	323	11,400	29,900	2,280

[1] Estimated.
[2] In solution when analyzed.
[3] At surface.
[4] At bottom.

TRACE ELEMENTS AND RADIOACTIVITY IN THE WATER

In the late 1880's the last of the game fish disappeared from Devils Lake. Originally, their disappearance was attributed to the high dissolved solids in the lake. However, in the early 1920's G. A. Abbott, while experimenting with the lethality of the water in Devils Lake to small fish (stickle-back minnows), found that the water contained *of water in Stump Lake*

million except as indicated]

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue at 180°C	Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25° C)	pH
					Western Stump Lake—Continued						
------	------	10,500	2,450	------	------	------	------	19,600	4,360	21,000	----
790	62	29,700	6,220	------	3.1	6.9	52,600	53,000	11,900	46,300	8.3
280	65	4,470	1,220	------	.6	2.0	8,680	8,970	1,960	11,200	8.8
430	31	9,650	2,560	------	.8	3.4	18,100	18,900	4,110	20,200	8.4
214	14	8,480	2,250	------	1.0	2.5	15,700	16,100	3,440	18,100	8.4
497	0	5,270	1,490	------	5.0	2.0	10,300	10,400	2,480	12,500	7.9
404	50	8,910	2,550	0.3	5.1	3.1	16,900	17,800	3,810	19,500	8.6
975	0	28,900	7,100	.6	38	9.0	52,500	54,400	12,800	48,400	7.6
233	0	8,360	2,180	.1	2.1	2.4	15,400	16,500	3,840	17,800	7.2
249	0	2,470	850	.1	.5	1.3	5,080	5,240	1,220	6,790	7.7
275	0	2,250	803	.2	.6	1.3	4,760	4,920	1,180	6,500	7.6
------	------	------	------	------	------	------	------	------	------	7,100	----
------	------	------	------	------	------	------	------	------	------	7,170	----
------	------	------	------	------	------	------	------	------	------	6,650	----
------	------	------	------	------	------	------	------	------	------	9,880	----
------	------	------	------	------	------	------	------	------	------	10,900	----
------	------	------	------	------	------	------	------	------	------	12,600	----
------	------	------	------	------	------	------	------	------	------	11,900	----
569	0	25,600	7,120	.1	.0	8.9	47,500	51,200	11,900	45,500	7.6
					Eastern Stump Lake—Continued						
------	------	67,300	11,000	------	------	------	------	121,000	25,900	79,300	----
1,350	95	75,100	13,500	------	------	------	------	139,000	31,700	84,600	8.2
921	193	55,700	11,300	------	1.8	12	97,100	104,000	26,200	74,400	8.4
1,200	141	72,000	12,500	------	5.3	15	122,000	135,000	29,000	82,100	8.3
1,060	132	45,200	11,600	------	2.5	14	82,300	91,100	27,200	65,300	8.4
1,260	0	73,000	11,800	------	------	13	124,000	129,000	28,000	83,500	7.8
1,090	186	75,800	12,600	0.3	5.4	13	128,100	134,300	29,900	85,000	8.4
1,640	0	73,200	16,000	1.2	84	20	128,000	136,000	38,300	85,900	7.9
1,990	0	59,900	19,000	.2	14	22	112,000	121,000	46,100	79,800	8.2
1,430	0	59,200	13,400	.2	4.2	22	104,000	117,000	32,400	77,500	8.1
------	------	------	------	------	------	------	------	------	------	77,100	----
------	------	------	------	------	------	------	------	------	------	77,200	----
------	------	------	------	------	------	------	------	------	------	77,600	----
------	------	------	------	------	------	------	------	------	------	77,300	----
------	------	------	------	------	------	------	------	------	------	77,400	----
------	------	------	------	------	------	------	------	------	------	77,500	----
------	------	------	------	------	------	------	------	------	------	90,300	----
------	------	------	------	------	------	------	------	------	------	89,300	----
1,540	0	88,400	19,500	.2	.0	22	153,000	170,000	47,700	94,900	7.9

15 ppm of zinc. Further experimentation showed that a water solution of zinc sulfate containing 15 ppm of zinc was lethal to the same variety of fish that formerly populated the lake (Abbott, 1924, p. 183–194). McKee and Wolf (1963) reported that zinc concentrations as low as 0.3 ppm could be lethal to fish.

During 1948–52, the maximum measured concentration of zinc in Devils Lake was only 0.16 ppm (Swenson and Colby, 1955, p. 37). In September 1959, Creel Bay and eastern Stump Lake contained only 0.16 and 0.03 ppm of zinc, respectively (table 7). Possibly hydrogen sulfide formed by biological activity in the lakebed caused the formation of zinc sulfide which precipitated and thus decreased the zinc in the lake water between 1924 and 1948 (Swenson and Colby, 1955, p. 35). If the generation of hydrogen sulfide were to cease, zinc might again accumulate in the lake. However, a rise in lake levels would compensate for the added zinc, and the zinc concentration probably would remain low.

The source of zinc in the water of Devils Lake has not been investigated. Zinc chloride treated ties were suggested as a possible source. These ties were burned along the railroad right-of-way as they were replaced by ties treated with better preservatives. However, if each tie contributed 10 pounds of zinc, ties from about 200 miles of track would have had to be burned to bring Devils Lake to a concentration of 15 ppm of zinc.

TABLE 7.—*Observed radiochemical data and concentration of some trace elements*

Sampling site (see pl. 1)	Date of collection	Radiochemical data (μμc/l)		Some trace elements (parts per million)				
		Alpha activity	Beta activity	As	Cu	Pb	P (as PO_4)	Zn
1	May 4, 1960	--------	--------	----	----	----	0.56	-----
2	Oct. 5, 1959	--------	--------	----	----	----	.10	-----
3	May 4, 1960	--------	--------	----	----	----	.02	-----
6	Oct. 5, 1959	--------	--------	----	----	----	1.1	-----
7	May 4, 1960	--------	--------	----	----	----	.14	-----
13	Oct. 4, 1959	100±70	340±40	----	----	----	1.2	-----
15	Oct. 5, 1959	--------	--------	0.03	0.04	0.01	----------	-----
17	May 4, 1960	--------	--------	----	----	----	.14	-----
20	Oct. 4, 1959	<42	320±50	----	----	----	1.2	-----
21	Sept. 30, 1959	<44	280±40	.04	.08	.01	.90	0.16
22	Sept. 29, 1960	--------	--------	----	----	----	2.3	-----
26	May 4, 1960	--------	--------	----	----	----	.06	-----
28	Oct. 4, 1959	--------	--------	----	----	----	1.1	-----
29	do	--------	--------	----	----	----	1.2	-----
34	Oct. 5, 1959	--------	--------	----	----	----	1.1	-----
35	May 4, 1960	--------	--------	----	----	----	.14	-----
	Sept. 29, 1960	--------	--------	----	----	----	1.8	-----
37	Sept. 29, 1960	--------	--------	----	----	----	.85	-----
41	Oct. 2, 1959	<61	460±70	----	----	----	1.1	-----
43	May 4, 1960	--------	--------	----	----	----	.07	-----
44	June 16, 1960	--------	--------	----	----	----	.40	-----
46	do	--------	--------	----	----	----	.00	-----
47	Oct. 3, 1959	--------	--------	----	----	----	1.0	-----
	May 5, 1960	--------	--------	----	----	----	.22	-----
48	June 16, 1960	--------	--------	----	----	----	.20	-----
50	Oct. 3, 1959	--------	--------	----	----	----	1.3	-----
	May 7, 1960	--------	--------	----	----	----	.10	-----
55	Oct. 3, 1959	--------	--------	----	----	----	1.4	-----
58	Sept. 30, 1960	--------	--------	----	----	----	.54	-----
62	May 6, 1960	--------	--------	----	----	----	.10	-----
67	Oct. 10, 1959	--------	--------	----	----	----	.14	-----
68	May 6, 1960	--------	--------	----	----	----	.03	-----
	Sept. 30, 1960	--------	--------	----	----	----	2.2	-----
75	Oct. 9, 1959	--------	--------	----	.19	.40	3.3	.03
78	May 7, 1960	--------	--------	----	----	----	1.2	-----
	Sept. 30, 1960	--------	--------	----	----	----	5.3	-----

The most likely source of zinc is ground water. Even though ground-water movement into the lake probably is too slow to cause measurable changes of the major dissolved constituents, continued movement plus evaporation from the lake could cause a noticeable increase of zinc and other trace elements. Abbott and Voedisch (1938) reported on 25 wells near the major lakes of the basin in Ramsey, Benson, and Nelson Counties; they found that water in 20 of the wells contained zinc concentrations that ranged from 0.1 to 14 ppm.

In 1959, eastern Stump Lake had higher concentrations of copper and lead than Creel Bay or the main part of Devils Lake (table 7). According to McKee and Wolf (1963, p. 171), copper concentrations from 0.25 to 1.0 ppm are not toxic for most fish, but concentrations of 0.015–3.0 ppm have been toxic, particularly in soft water, to certain kinds of fish, crustaceans, mollusca, insects, phytoplankton, and zooplankton; lead concentrations as low as 0.1 ppm have been reported to be toxic or lethal to fish.

Small concentrations of iron, manganese, fluoride, arsenic, and boron were found in the lakes (tables 3–7). Probably none of these elements were persent in concentrations high enough to be harmful to fish.

The maximum concentration of phosphorus (as PO_4) measured was in the water of eastern Stump Lake (table 7). In themselves, phosphates do not have toxic effects on fish and other aquatic life and may be beneficial to fish by increasing algae and zooplankton (McKee and Wolf, 1963).

The alpha and beta particle activities in Devils Lake were measured in 1959 (table 7); data are insufficient to determine if present activities are different from activities before nuclear tests began.

MISCELLANEOUS SURFACE WATERS

The dissolved-solids content observed in miscellaneous surface waters in 1960 ranged from 239 to 61,200 ppm (table 8). Generally, the water containing less than 500 ppm of dissolved solids was of the calcium bicarbonate type; water containing between 500 and 2,000 ppm of dissolved solids was of the sodium magnesium sulfate or the sodium magnesium bicarbonate type; and water containing more than 2,000 ppm of dissolved solids was of the sodium sulfate type.

Differences in dissolved-solids content from lake to lake probably depend on frequency of surface overflow and on amount of ground water exchange. The lakes that spill infrequently and have little or no ground-water inflow and outflow contain large quantities of dissolved solids. Evaporation, which affects the dissolved solids of water, is probably fairly uniform throughout the basin and does not cause the differences from lake to lake.

TABLE 8.—*Chemical analyses of miscellaneous surface-water*

[Results in parts per

Reference letter (p. 32, 33)	Date of collection	Temperature (° F.)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)
A	May 5, 1960	48	22	0.03	0.00	21	41	18	8.8	282
B	May 10, 1960	52	16	.01	.00	24	118	169	35	698
C	May 5, 1960	49	17	.04	.00	83	92	158	29	272
D	May 3, 1960	48	.0	.45	.00	28	4.4	21,700	280	6,090
E	May 2, 1960	40	28	.07	.00	44	34	51	23	326
F	May 8, 1960	57	31	.01	.00	39	15	20	9.4	194
G	Apr. 30, 1960	42	20	.02	.06	19	41	188	23	624
H	do	42	16	.02	.00	13	93	2,390	128	1,560
I	May 1, 1960	47	14	.02	.00	13	30	2,280	172	1,350
J	July 16, 1954	70	12	[1] .02	------	46	16	11	8.8	186
K	Oct. 8, 1954	------	------	------	------	56	26	22	------	272
L	Apr. 15, 1955	------	------	------	------	43	20	20	------	172
M	June 25, 1955	75	------	------	------	56	30	27	------	248
N	May 2, 1960	39	19	.04	.01	41	13	8.8	8.6	152
O	June 27, 1954	------	17	[1] .41	------	42	17	20	12	180
P	July 16, 1954	70	15	[1] .07	------	43	18	18	12	190
Q	Oct. 8, 1954	------	------	------	------	56	23	25	------	258
R	Apr. 15, 1955	------	------	------	------	58	27	26	------	257
S	June 25, 1955	65	------	------	------	57	27	30	------	250
T	May 2, 1960	39	16	.11	.00	64	21	17	21	153
U	Apr. 28, 1957	52	3.7	[1] .01	------	57	116	218	60	390
V	May 3, 1960	40	18	.05	.00	42	158	294	77	400
W	May 1, 1960	46	17	.04	.00	39	52	53	19	447
X	July 16, 1954	70	------	------	------	48	19	15	------	218
Y	July 15, 1954	73	32	[1] .02	------	84	37	53	29	236
Z	June 25, 1955	69	------	------	------	80	40	59	------	228
a	May 3, 1960	45	22	.01	.00	104	55	125	37	250
b	July 15, 1954	74	------	------	------	47	24	25	------	242
c	do	73	11	[1] .01	------	36	17	25	12	197
d	Oct. 7, 1954	------	------	------	------	43	19	30	------	241
e	Apr. 14, 1955	------	------	------	------	37	16	23	------	190
f	June 25, 1955	72	------	------	------	49	25	30	------	270
g	May 2, 1960	41	9.5	.02	.13	27	13	24	11	154
h	May 5, 1960	46	14	.06	.00	65	61	248	20	285
i	Apr. 28, 1957	53	22	[1] .01	------	71	56	100	26	293
j	May 3, 1960	40	21	.03	.00	37	54	115	29	193
k	Apr. 30, 1960	42	23	.04	.00	8.6	21	638	75	1,270
m	May 3, 1960	43	15	.03	.00	51	43	99	24	286
n	Apr. 30, 1960	36	15	.03	.00	59	485	1,350	155	552
o	May 1, 1960	45	16	.03	.00	27	21	26	8.3	213
p	May 3, 1960	44	1.2	.12	.00	68	895	9,830	236	482
q	May 5, 1960	47	12	.06	.07	65	56	174	20	180
r	July 16, 1954	72	------	------	------	49	18	27	------	274
s	Oct. 7, 1954	------	------	------	------	47	30	45	------	300
t	Apr. 15, 1955	------	------	------	------	45	19	25	------	197
u	May 2, 1960	41	12	.03	.00	32	21	35	18	166
v	May 3, 1960	38	9.5	.03	.00	42	149	288	56	440
w	Apr. 30, 1960	43	12	.01	.02	27	43	21	13	324

[1] In solution when analyzed.

samples in Devils Lake basin, June 1954 to May 1960

million except as indicated]

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids Calculated	Dissolved solids Residue at 180° C.	Hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH	Color
0	19	7.6	0.4	8.0	0.19	------	329	220	505	7.4	13
0	352	20	.6	.5	.53	1,080	1,170	544	1,610	7.6	47
0	651	36	.2	6.3	.29	1,210	1,300	584	1,690	7.0	45
8,160	25,700	1,290	1.8	1.0	21	60,200	61,200	88	55,000	9.4	45
0	82	28	.2	3.0	.13	------	502	248	717	7.5	32
0	44	4.9	.2	.4	.06	------	277	158	398	7.5	50
0	87	34	.3	.5	.50	------	755	215	1,170	7.8	21
153	3,000	741	.2	1.5	4.5	7,310	7,490	415	9,690	8.6	25
169	2,790	849	.2	5.6	2.2	6,990	7,180	155	9,530	8.8	34
0	48	3.5	.2	1.7	.07	------	255	179	400	7.4	------
0	67	7.5	------	------	------	------	358	246	558	7.6	------
0	82	8.5	------	------	------	------	300	189	460	7.3	------
0	120	12	------	------	------	------	418	262	630	8.1	------
0	55	3.0	.1	.3	.05	------	242	156	357	7.3	47
0	65	10	.1	.4	.09	------	278	176	424	7.3	------
0	64	8.5	.1	2.3	.11	------	290	183	446	7.6	------
0	68	11	------	------	------	------	361	234	567	7.8	------
0	95	14	------	------	------	------	393	254	607	7.6	------
0	103	12	------	------	------	------	407	251	626	8.1	------
0	165	5.5	.1	1.5	.09	------	410	247	591	7.1	45
0	675	78	.2	1.6	.29	1,400	1,480	620	2,020	7.9	------
0	963	114	.3	1.0	.24	1,860	1,970	754	2,630	6.9	43
0	60	9.3	.5	13	.20	------	537	312	793	7.7	43
0	52	5.0	------	------	------	------	280	200	444	7.5	------
0	263	20	.2	9.8	.19	------	699	362	942	7.3	------
0	295	22	------	------	------	------	729	362	967	7.8	------
0	493	69	.2	.6	.42	1,030	1,120	484	1,460	7.5	54
0	72	4.5	------	------	------	------	352	218	527	7.5	------
0	45	9.0	.1	5.4	.13	------	272	159	430	7.5	------
0	49	12	------	------	------	------	328	187	494	7.6	------
0	45	11	------	------	------	------	273	158	424	7.3	------
0	67	12	------	------	------	------	373	227	575	7.7	------
0	38	16	.2	1.7	.07	------	239	123	378	6.8	33
0	615	83	.2	1.4	.27	1,250	1,350	413	1,860	7.6	42
0	340	29	.2	2.8	.25	------	816	406	1,160	7.4	------
0	375	39	.2	3.5	.16	------	816	315	1,150	6.9	42
50	124	243	.5	.4	1.7	1,810	1,930	108	2,970	8.6	70
0	235	33	.2	8.7	.17	------	720	302	1,030	7.1	26
0	3,980	619	.2	6.3	2.3	6,940	7,370	2,140	8,440	7.4	45
0	37	3.0	.3	3.1	.11	------	268	154	413	7.0	35
103	21,600	2,210	.2	.6	7.7	35,200	37,300	3,850	34,800	8.8	41
0	564	60	.1	.5	.26	1,040	1,150	393	1,500	6.9	28
0	27	8.0	------	------	------	------	312	197	491	7.6	------
0	100	3.5	------	------	------	------	473	241	695	7.6	------
0	82	12	------	------	------	------	329	192	491	7.2	------
0	105	11	.1	1.0	.08	------	365	167	527	6.8	32
0	876	108	.3	2.9	.57	1,740	1,860	718	2,460	7.3	44
0	39	4.6	.4	.4	.09	------	338	246	550	7.8	12

Continued on next page.

SAMPLING-SITE DATA

Reference letter	Lake or stream	Sampling point		
		Township (N.)	Range (W.)	Section
A	Battle Lake near Warwick	150	62	17 NE¼SE¼NE¼
B	Broken Bone Lake near Pleasant Lake.	156	71	9 SW¼SW¼SW¼
C	Coon Lake near Lakota	152	60	19 NE¼NE¼NE¼
D	Cranberry Lake near Fillmore	154	71	27 SE¼SW¼SW¼
E	Dry Lake near Webster	155	65	10 NE¼NE¼NE¼
F	Edmore Coulee near Webster	156	63	13 SE¼SE¼SE¼
G	Elbow Lake near Warwidk	151	63	17 NE¼SE¼NE¼
H	Free Peoples Lake near Warwick	151	63	8 SE¼SE¼SE¼
I	Horseshoe Lake near Warwick	151	64	36 SE¼SE¼NE¼
J-M	Lac Aux Mortes near Churchs Ferry	156	66	21 NE¼NE¼NW¼
N	do	156	66	11 NE¼NW¼NE¼
O-S	Lake Irvine near Churchs Ferry	156	66	32 SE¼SW¼SW¼
T	do	156	66	32 NE¼NE¼SW¼
U-V	Long Lake near Minnewaukan	152	67	8 NE¼NE¼NE¼
W	Mallard Lake near Tokio	151	64	13 NW¼SW¼SW¼
X	Mauvais Coulee at inlet to Lac Aux Mortes.	156	66	2 NE¼NW¼NW¼
Y	Morrison Lake near Sweetwater	155	64	23 NW¼NE¼

SALTS IN THE BEDS AND SHORES OF THE MAJOR LAKES

From 1899 to 1948, while Devils Lake receded and then began to rise again, the weight of dissolved salts decreased to one-fourth the original weight because of precipitation of salts on the lake shores and probably on the lakebed. Although the relationship is not well defined, an increase in water volume during 1949–60 generally was associated with an increase in the weight of dissolved salts because salt was added to the lake by runoff and by solution of previously precipitated salts (fig. 9). The apparent decrease in salt tonnage while the lake volume was increasing in 1956 probably was caused by incomplete sampling of nonuniform water during the time of relatively rapid lake fluctuation.

Salt balances were prepared for Devils Lake, East Devils Lake, and eastern and western Stump Lakes to determine the weight of salts added to or removed from the beds and shores. The salt balance for Devils Lake, including Sixmile and Creel Bays, was determined from the volume of water and the dissolved solids from Big Coulee, the volume of water and the dissolved solids in Devils Lake, and the estimated volume of water and the dissolved solids entering East Bay. The net weight of salts added to or removed from the beds and shores was calculated with the following salt-balance equation:

FOR TABLE 8

Reference letter	Lake or stream	Sampling point: Township (N.)	Range (W.)	Section
Z	Morrison Lake near Sweetwater	155	64	15 NE¼
a	Pelican Lake marsh near Minnewaukan.	154	67	24 SE¼SE¼SE¼
b	Rock Lake near Rock Lake	162	66	15 SW¼SE¼SE¼
c–g	do	161	66	7 NE¼NE¼SW¼
h	Rose Lake near Bartlett	152	61	10 SW¼SW¼SW¼
i–j	Round Lake near Minnewaukan	153	67	35 NE¼NW¼SE¼
k	Shinbone Lake at Warwick	151	63	34 SW¼NE¼NW¼
m	Silver Lake near Brinsmade	154	67	3 NE¼SW¼NE¼
n	Spring Lake near Tokio	152	64	35 SE¼NW¼NE¼
o	Square Lake near Tokio	151	64	11 SE¼SE¼SE¼
p	Stink Lake near Churchs Ferry	155	67	11 SE¼NW¼NE¼
q	Swan Lake near Bartlett	152	61	26 NW¼NW¼NW¼
r	Sweetwater Lake near Sweetwater	155	63	30 SE¼SE¼SE¼
s–t	do	155	64	24 NW¼SE¼SE¼
u	Sweetwater Lake at Sweetwater	155	64	27 SE¼SW¼SW¼
v	Twin Lakes near Fort Totten	152	66	22 NE¼SW¼SE¼
w	Wood Lake near Tokio	151	64	16 NE¼NE¼NE¼

$$x=(t_i-t_o)-(T_2-T_1)$$

where

x is net tons added to or removed from the bed. A positive (+) value indicates a net addition of salts, and a negative (−) value indicates a net removal of salts.

t_i is tons in inflow.

t_o is tons in outflow.

T_2 is tons in solution in the lake at the end of the period.

T_1 is tons in solution in the lake at the beginning of the period.

(t_i-t_o) is the change in the weight of salts in the lake during a given period if salts are not added to or removed from the lakebed.

(T_2-T_1) is the change in weight of salts in the lake and equals the weight of salts added to or removed from the lake if no inflow or outflow occurs.

For the 9 years of record shown in table 9, the annual net change of the weight of salts in the bed of Devils Lake ranged from +30,000 to −89,000 tons. The annual average weight of salts removed from the bed per unit area was 2.7 tons per acre; solution of these salts increased the average annual concentration by 193 ppm. The calculated net changes of the weight of salt in the bed of Devils Lake for each of the

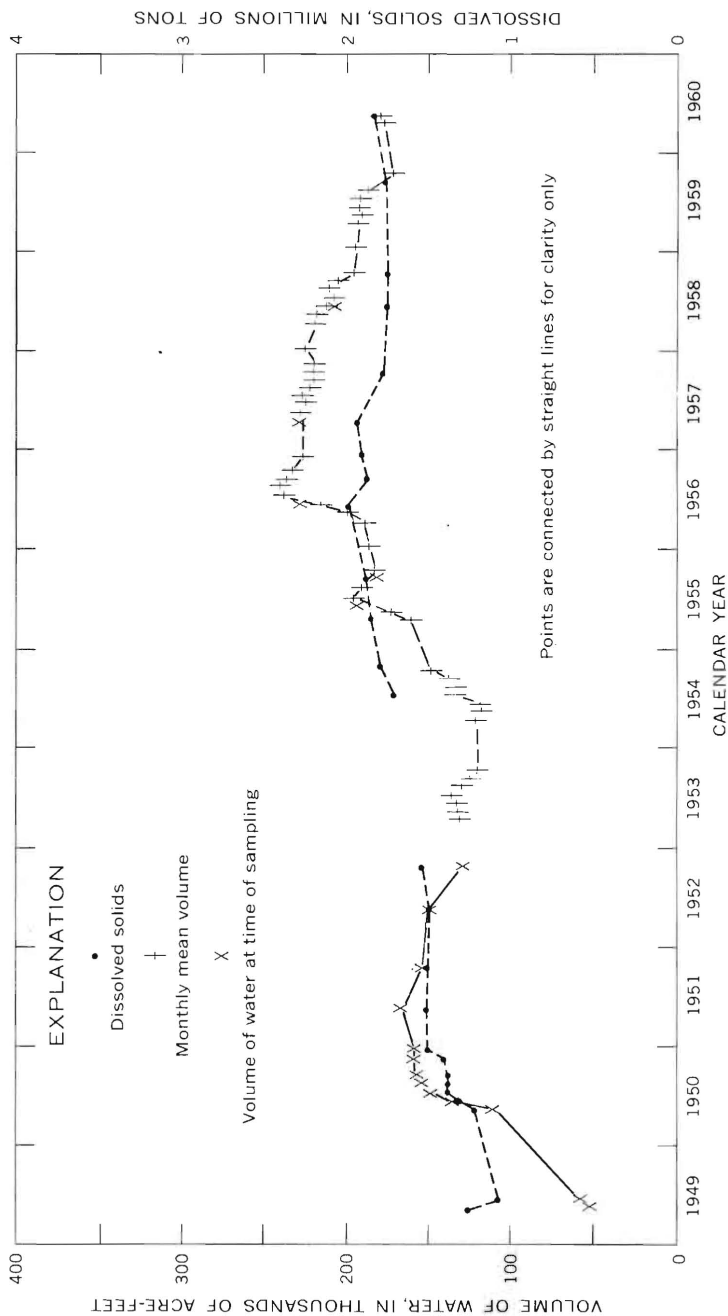


FIGURE 9.—Volume of water and concentration of dissolved solids in the water in Devils Lake, 1949–60.

9 years are of the same order of magnitude even though T_2 and T_1 in the salt balance are large compared with their difference, and small errors in T_2 and T_1 could have caused large relative errors in their difference. None of the calculated increases of concentration from solution of salts increased the concentration by more than about 5 percent.

Preparation of salt balances for East Devils, western Stump, and eastern Stump Lakes required certain assumptions and estimates. Because inflows to the lakes were not measured, an average runoff of 0.2 inch per year was assumed and a drainage area for each lake was estimated. After the volume of inflow for each lake was calculated, an estimated concentration of 0.14 ton per acre-foot (about 100 ppm) was assumed and the weight of salts in the inflow was calculated. This assumed concentration for the runoff is not unreasonable when the concentrations for Big Coulee at high flow are considered. Except for western Stump Lake, the weight of salts contributed annually by inflow is small compared with the weight change in the lake. Two-tenths inch per year is a reasonable estimate for average runoff in the area; Swenson and Colby (1955) reported 0.23 inch per year as a 22-year average for the area around Sheyenne, N. Dak., which they considered to be comparable with the Devils Lake area. Because there was no outflow from the lakes during the 8½-year period, t_o was zero in all three balances. The salt balances for the three lakes and the estimated drainage areas used in calculating t_i are summarized in table 10.

TABLE 9.—*Yearly salt balances for Devils Lake, including Sixmile Bay and Creel Bay*

Water year	1952	1953	1954	1955	1956	1957	1958	1959	1960
Dissolved salts entering lake from Big Coulee (t_i)...tons	8	0	15,800	24,000	23,800	747	76	54	176
Dissolved salts in surface outflow from lake (t_o)...do	0	0	0	0	74,500	149,000	12,300	0	0
Increase (+) or decrease (−) in quantity of dissolved salts in lake (T_2-T_1)...do	+41,000	+85,000	+105,000	+58,000	+8,000	−73,000	−17,000	+35,000	−30,000
Salts removed from (−) or added to (+) lakebed (x)...do	−41,000	−85,000	−89,000	−34,000	−59,000	−75,000	+5,000	−35,000	+30,000
Average area of lakebed covered by water...acres	15,120	13,660	14,020	16,450	17,860	18,320	17,900	17,280	16,820
Salts removed from (−) or added to (+) lakebed per unit area...tons per acre	−2.7	−6.2	−6.3	−2.1	−3.3	−4.1	+.3	−2.0	+1.8
Increase (+) or decrease (−) of dissolved solids in lake...ppm	+220	+520	+440	+140	+180	+250	−20	+150	−140
Dissolved solids in lake at end of water year...ppm	8,680	10,330	8,830	7,410	5,820	5,970	6,650	7,610	8,230
Volume of water in lake at end of water year...acre-ft	135,000	120,000	149,000	183,000	234,000	219,000	195,000	174,000	163,000

TABLE 10.—*Estimated salt balances for East Devils and western and eastern Stump Lakes, May 1952 to September 1960*

Lake	East Devils	Western Stump	Eastern Stump
Drainage area ... acres	32,000	224,000	32,000
Dissolved salts in inflow (t_i) ... tons	600	4,400	600
Dissolved salts in lake at end of 8½-year period (T_2) ... do	512,000	62,600	1,040,000
Dissolved salts in lake at beginning of 8½-year period (T_1) ... do	712,000	73,300	1,460,000
Salts added to lakebed (x) ... do	201,000	15,100	421,000
Do ... tons per acre	90	11	170

Laboratory examinations were made of bed and shore materials to determine the relative abundance of soluble salts in the two types of material and to determine the chief constituents of the soluble salts. Samples for examination were taken with a core type sampler, or in the case of some shore samples, a hand shovel. Generally, they were taken from the top several inches of bed or shore material only; however, some for eastern Stump Lake were taken at several depths below the bed.

The results of the laboratory examinations are given in table 11 and were obtained as follows. A weighed fraction of each sample was put into a measured volume of distilled water and was shaken mechanically for 72 hours. The amount of salt dissolved was then measured. A second weighed fraction was oven dried at 180° C for 1 hour, was reweighed to determine moisture loss, was heated in a platinum dish over an intense flame to destroy organic matter, and was then weighed again. Because of various amounts of moisture and organic matter in the samples, the results are reported in unit weights of salt dissolved per unit weight of dry, inorganic bed or shore material.

Data in table 11 indicate that the shore material has less soluble salt than bed material by at least one order of magnitude. In the table, material 0.5 foot above the water surface is considered as bed material. Undoubtedly, material at such a slight altitude above the water surface is frequently inundated by wave action and the salt content of the material, therefore, is likely to be more akin to that of the bed than that of the shore at a higher altitude.

The laboratory results in table 11 do not necessarily indicate the amount of salt that will actually be dissolved from the bed or shore material should the lake volumes increase. Langbein (1961) stated that although the beds of closed lakes may contain readily soluble salts, some of these salts may be trapped in mud and so insulated from the lake water that they may be unavailable for re-solution. Also, the samples in the laboratory were thoroughly dispersed in the water by the mechanical shaking, and more salts probably dissolved from them than would have dissolved under natural conditions.

TABLE 11.—*Weight of salts available from bed and shore material*

[Calculated from samples leached in laboratory]

Sampling site (see pl. 1)	Description of sample	Date of collection	Area represented by sample (acres)	Salts available from bed or shore material (tons per ton of dry, inorganic material)	Altitude (feet)
	Big Coulee near Grahams Island				
1	Shore material 10 ft above water surface	Apr. 29, 1960	2,400	0.000688	1,426
	Bed material from coulee	Oct. 5, 1959	4,020	.0504	1,415
	Devils Lake, Creel Bay, and Mission Bay				
11	Bed material 6 ft below water surface	Oct. 4, 1959	17,120	0.0102	
16	Shore material 10 ft above water surface	Apr. 29, 1960	2,780	.000933	
25	Shore material 10 ft above water surface	do	2,780	.000952	
27	Bed material 3.3 ft below water surface	Oct. 1, 1959	17,120	.0102	
32	Bed material 4.5 ft below water surface	Oct. 4, 1959	17,120	.00785	
35	Bed material 4.5 ft below water surface	Oct. 5, 1959	17,120	.0107	
41	Bed material 5.4 ft below water surface	Oct. 2, 1959	650	.0619	
	Average for shore material (weighted by area)			.00943	
	Average for bed material (weighted by area)			.0102	
	East Bay and Black Tiger Bay				
44	Bed material 0.3 ft below water surface	June 16, 1960	8,000	0.0425	
45	Bed material from dry lakebed	Apr. 29, 1960	8,000	.0816	
	Shore material 20 ft above dry lakebed	do	2,340	.000624	1,430
	Shore material 5 ft above dry lakebed	do	3,530	.00504	1,415
46	Bed material 1.5 ft below water surface	June 16, 1960	8,000	.0182	
	Bed material 0.5 ft above water surface	do	8,000	.0356	
47	Bed material 0.3 ft above water surface	Oct. 3, 1959	610	.113	
48	Bed material 0.5 ft below water surface	June 17, 1960	8,000	.0480	
	Bed material 0.5 ft above water surface	do	8,000	.0841	
	Average for bed material (weighted by area)			.0524	1,410
	East Devils Lake				
49	Shore material 20 ft above water surface	May 7, 1960	580	0.00188	1,421
	Shore material 10 ft above water surface	do	1,300	.00154	1,411
55	Bed material 4.0 ft below water surface	Oct. 3, 1959	2,320	.326	1,396
	Western Stump Lake				
62	Bed material 1.5 ft below water surface	May 6, 1960	2,280	0.0270	
64	Bed material 0.7 ft below water surface	do	2,280	.0225	
65	Bed material 0.0 ft below water surface	do	2,280	.0136	
	Shore material 20 ft above water surface	do	1,580	.000987	1,416
	Shore material 5 ft above water surface	do	980	.00312	1,401
	Average for bed material (weighted by area)			.0210	1,394–96
	Eastern Stump Lake				
69	Bed material 1.5 ft below water surface	June 15, 1960	1,350	0.177	
73	Bed material 5.5 ft below water surface	do	1,160	.835	
75	Bed material 4.3 ft below water surface	Oct. 9, 1959	1,160	.965	
76	Bed material 1.5–2.0 ft below lakebed surface	June 15, 1960	1,160	.107	
	Bed material 1.0–1.5 ft below lakebed surface	do	1,160	.171	
	Bed material 0.5–1.0 ft below lakebed surface	do	1,160	.169	
	Bed material 0.0–0.5 ft below lakebed surface	do	1,160	.452	
77	Bed material 1.2–1.7 ft below lakebed surface	do	1,160	.0572	
	Bed material 0.8–1.2 ft below lakebed surface	do	1,160	.0774	
	Bed material 0.5–0.8 ft below lakebed surface	do	1,160	.309	
	Bed material 0.0–0.5 ft below lakebed surface	do	1,160	.736	
	Bed material 0.7–1.0 ft below lakebed surface	do	1,350	.123	
	Bed material 0.0–0.7 ft below lakebed surface	do	1,350	.171	
78	Shore material 20 ft above water surface	May 7, 1960	770	.000930	1,404
	Shore material 5 ft above water surface	do	320	.000851	1,389
80	Bed material 0.9 ft below water surface	June 15, 1960	1,350	.186	
	Average for bed material (weighted by area)			.178	1,379–83
	Average for bed material (weighted by area)			.747	1,378–81

Calcium, bicarbonate, and carbonate were the predominant water soluble constituents in the leachate from the bed material from Devils Lake. Most of the bicarbonate ion probably came from the water in the bed material, but some bicarbonate probably was derived from precipitated calcium carbonate. Sodium and sulfate were the predominate constituents in the bed material from East Bay, East Devils Lake, and eastern and western Stump Lakes. Generally, calcium and bicarbonate were the predominant constituents in the shore material from all the lakes, probably because little sodium sulfate was precipitated from solution during high lake levels and because the more soluble sodium sulfate was leached from the shores by runoff.

Data in tables 9 and 11 provide at least a partial answer to the question posed by Swenson and Colby (1955, p. 60) as to whether the large quantities of salt that "disappeared" from Devils Lake between 1923 and 1948 would redissolve if the altitudes are increased. During 1954 and 1955 the lake altitude increased from less than 1,412 feet to more than 1,416 feet (fig. 1), the altitude of the lake in 1923. This increase in lake altitude was accompanied by removal from the bed of only about 123,000 tons of salt, a rather small amount compared with the estimate of more than 2,500,000 tons that "disappeared."

In 1956 the lake altitude increased by about another 3 feet, to more than 1,419. As a result of this increase in altitude, some land was inundated that probably had not been inundated for approximately 40 years. Nevertheless, during 1956 and 1957, when pickup of salts from the bed was still proceeding rapidly, a total of only about 134,000 tons was removed from the bed. Probably not even all of this tonnage, however, was actually from the newly submerged part of the bed.

Re-solution of salts from a lakebed may be a slow process that can continue for a long time following a significant increase in lake altitude. Although the maximum altitude of Devils Lake was reached in 1956, much re-solution must have taken place the following year because more salts actually were removed from the lakebed in 1957 than in 1956. How long re-solution might continue following an increase in altitude of Devils Lake is conjectural; however, evidence in table 9 indicates that the re-solution following the significant increase of 1956 ceased for all practical purposes sometime during the 1958 water year.

What portions of salts that "disappeared" from Devils Lake in earlier years will eventually redissolve if the altitude of Devils Lake is restored cannot be determined accurately from the present evidence. However, it would be small, probably only about 10–20 percent.

EFFECT OF LAKE LEVELS ON THE QUALITY OF WATER

If lake levels remain low, the concentration of dissolved solids will increase. Sodium sulfate probably will increase in relation to the other salts except in eastern Stump Lake, which is saturated or almost saturated with sodium sulfate.

If lake levels rise, the total quantity of salts dissolved in the lakes will increase. However, the concentration of dissolved solids in the lakes will decrease because the runoff causing the rise will contain a lower concentration of dissolved solids than the lakes. As bicarbonate is the principal anion in the runoff entering the lakes, the calcium bicarbonate dissolved in the lakes will increase in relation to sodium sulfate.

A rise in lake levels could affect ground-water movement. If ground water moved away from the lake, zinc probably would not accumulate in the lakes. If ground water moved into the lakes, zinc could be added to the lakes. Owing to a decrease in sulfate reduction, this zinc probably would remain in the water. If lake levels remained high or if an outlet for the lakes were established, the zinc concentration probably would not increase significantly.

SUMMARY

Water budget computations indicate that for most water years between 1952 and 1960 the volume of Devils Lake decreased by about 10,000–23,000 acre-feet, mostly because of evaporation. In the 1954, 1955, and 1956 water years, however, the volume increased by 29,000, 34,200 and 51,100 acre-feet, respectively. In response to these increases in water volume, the water-surface altitude, which was only about 1,411.6 feet in the early part of the 1954 water year, rose to about 1,419.3 feet in the late part of the 1956 water year. This was the highest altitude the lake is known to have attained since about 1915.

A flow-duration curve for Big Coulee, which supplies most of the flow into Devils Lake, resembles that of a typical ephemeral stream except for discharges greater than 300 cfs. At discharges greater than 300 cfs, flow duration is altered by regulation from upstream lakes. Water from Big Coulee in 1952–60 was of the calcium bicarbonate type except when discharge was extremely low (about 0.1 cfs), and most of it contained less than 600 ppm of dissolved solids. About 76 percent of the water that entered Devils Lake from Big Coulee during the period did so when discharges were in excess of 100 cfs.

Water from Sixmile Bay, Creel Bay, and the main part of Devils Lake is free to intermingle, and chemical analyses indicate that the quality of the water in the three places generally is similar. Dissolved-solids concentrations averaged about 6,500 ppm for the period 1954–60 but were somewhat less for the period 1954–56, when lake altitudes were relatively high.

Mission Bay is connected to Devils Lake and East Bay to Mission Bay by culverts. Lack of free movement of water, intermittent flushing of salts from the water body upgradient, and evaporation have caused Mission Bay and East Bay to have somewhat higher dissolved solids than Sixmile Bay, Creel Bay, or the main part of Devils Lake. During much of the 1952–60 period, East Bay had so little water that it could not be sampled satisfactorily.

East Devils Lake received no water from East Bay from 1952 to 1960. The water surface, however, probably was maintained at about the same altitude as in the 1950–52 period by local runoff. The dissolved solids from 1952 to 1960 are estimated to have averaged about 60,700 ppm, nearly as much as the greatest concentration measured in 1950–52. The water in East Devils Lake had higher proportions of sodium and of sulfate than water from any of the other lakes in the Devils Lake chain.

Water from most of the Stump Lake drainage area flows into western Stump Lake, which is connected to eastern Stump Lake by culvert. Although water moves from time to time from western Stump Lake into eastern Stump Lake, this probably did not happen from 1952 to 1960. Because the eastern lake occasionally receives dissolved solids flushed from the western lake, it has accumulated much more of the dissolved solids. During 1956–60, dissolved solids averaged 23,100 ppm for western Stump Lake, but 127,000 ppm for eastern Stump Lake.

Water in eastern Stump Lake was saturated or nearly saturated with sodium sulfate. In the fall and winter, a thick layer of granular, hydrated sodium sulfate crystals formed on the lakebed and along the shore. As water temperatures increased in late spring and summer, the granular crystals disappeared; however, a discontinuous layer of consolidated sodium sulfate crystals several inches thick formed a significant part of the bed during the summer also.

Small amounts of zinc, copper, lead, iron, manganese, fluoride, arsenic, boron, and phosphate were detected in the water in Devils Lake. The source of these constituents has not been studied, but the most likely source of zinc is ground water.

The dissolved-solids content observed in water from 29 miscellaneous lakes in 1960 ranged from 239 to 61,200 ppm. Water containing low dissolved solids was of the calcium bicarbonate type; water containing high dissolved solids was of the sodium sulfate type. Differences in dissolved-solids content from one lake to another probably depend on frequency of overflow and amount of ground-water inflow.

As the volume of water increased in Devils Lake from 1949–60, the annual average weight of salts removed from the bed of the lake was 2.7 tons per acre, and the annual average addition of salts to the water in the lake was 193 ppm. The shores contained less weight of salt per unit weight of dry, inorganic material than the lakebed. Calcium, carbonate, and bicarbonate were the predominant water soluble constituents in bed material from Devils Lake. Sodium and sulfate, however, were the predominant soluble constituents in bed material from East Bay, East Devils Lake, and eastern and western Stump Lakes. Generally, calcium and bicarbonate were the predominant soluble constituents in the shore material from all the lakes.

Probably not more than 20 percent of the large quantity of salt that "disappeared" from the water of Devils Lake many years ago will redissolve if the altitude of the lake west of State Route 20 is restored. An increase in altitude from 1,412 to 1,416 feet during 1954 and 1955 resulted in removal from the lakebed of only about 123,000 tons of salt. A further increase in altitude from 1,416 to 1,419 feet in 1956 resulted in the removal of an additional 134,000 tons. This total of 257,000 tons removed from the bed is small compared with the more than 2,500,000 tons that Swenson and Colby (1955) estimated "disappeared" between 1923 and 1948.

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