EVAPORATION COMPUTED BY ENERGY-BUDGET AND MASS-TRANSFER METHODS AND WATER-BALANCE ESTIMATES FOR DEVILS LAKE, NORTH DAKOTA, 1986-88

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Water Resources Investigation 11
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Prepared by the
United States Geological Survey
in cooperation with the
North Dakota State Water Commission

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre-feet	0.001233	cubic hectometer
calories per square centimeter	0.4843	watt per square meter
cubic inch	16.39	cubic centimeter
foot	0.3048	meter
gram	0.03527	ounce
inch	2.54	centimeter
micron	0.000001	meter
mile	1.609	kilometer
mile per hour	0.4470	meter per second
millibar	100	newton per square meter
ounce	28.35	gram
ounce per cubic inch	1.730	gram per cubic centimeter
square inch	6.452	square centimeter
square mile	2.590	square kilometer

To convert degree Celsius (°C) to degree Fahrenheit (°F), use the following formula: (°Cx9/5)+32 = °F.

To convert degree Kelvin (K) to degree Celsius (°C), use the following formula: K-273.15 = °C.

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

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ABSTRACT

The purpose of this study is to provide a more accurate measure of the hydrologic components, especially evaporation, that affect the water balance of Devils Lake, N.Dak. Energy-budget and mass-transfer methods were used to compute evaporation from Devils Lake during the open-water periods of 1986-88. Mean daily energy-budget evaporation ranged from 0.038 inch to 0.253 inch. Analysis of terms in the energy-budget equation indicates that the same percentage of error in each term does not result in the same percentage of error in computed evaporation. For example, a 2-percent error in reflected shortwave radiation causes a 0.2-percent error in computed evaporation, whereas a 2-percent error in incoming shortwave radiation causes a 3-percent error in computed evaporation.

In the mass-transfer method of computing evaporation, the mass-transfer coefficient was determined using energy-budget evaporation as the independent measure of evaporation. A linear regression equation was developed with energy-budget evaporation and the mass-transfer product. The coefficient of determination of the equation was 0.73, and the standard error of estimate was 0.03 inch per day. The greatest difference between energy-budget and mass-transfer evaporation during the open-water periods was 2.36 inches in 1987.

Monthly estimates of evaporation from Devils Lake for 1986-88 ranged from 1,120 acre-feet in January 1986 and 1987 to 35,900 acre-feet in July 1988. The evaporation rate was greater in 1988 (40.0 inches) than in 1987 (37.9 inches); however, the total evaporation from the lake surface was greater in 1987 because the larger surface area in 1987 more than compensated for the lower evaporation rate.

Annual mean precipitation for the precipitation-station network around Devils Lake ranged from 12.86 inches in 1988 to 23.06 inches in 1986. Precipitation during 1986 was 20 percent greater at the Devils Lake KDLR radio station than the annual mean precipitation for the precipitation-station network. Precipitation falling on Devils Lake ranged from 110 acre-feet in April 1988 to 31,300 acre-feet in July 1986.

Water-balance estimates of Devils Lake for 1986-88 indicate that the computed inflow was greater than the gaged inflow during each year of the study. Although relatively minor errors in water-balance terms can account for the difference between computed and gaged inflow for 1986 and 1988, no reasonable combination of errors in water-balance terms can account for the difference of 61,800 acre-feet in 1987.

INTRODUCTION

During the 1970's and 1980's, high water levels of Devils Lake, N.Dak., posed a flood threat to the city of Devils Lake, a National Guard camp, roads, and sewer and lagoon systems of several communities (fig. 1). However, the flood threat has not been the only problem caused by fluctuating water levels. The water level of Devils Lake generally declined from 1,438 feet above sea level in 1867 to 1,400.9 feet above sea level in 1940 (fig. 2). As the water level declined, salinity increased and the fish population declined. By 1940, Devils Lake consisted of a shallow brackish body of water.

State government, local government, and water-resource management groups are concerned about protecting property, the multimillion-dollar fishing and tourist-trade industry, and water for future development. These groups also are concerned about the effect of water-level fluctuations and associated water-quality changes of Devils Lake on leaching of nutrients and trace elements from bottom material enriched from prior low-water stands. Wetland drainage and agricultural practices appear to be altering the availability of nutrients, pesticides, and sediment to the lake; and eutrophication recently has become a problem. Potential water-quantity and water-quality impacts in the Devils Lake basin in the next decade and beyond are numerous.

A complete understanding of the water-level fluctuations and associated water-quality changes of Devils Lake will require many detailed studies to define the interaction of the lake with all components of the hydrologic system. The detailed studies will require accurate water-balance estimates of Devils Lake. A water-budget model of the basin was developed by Wiche and others (1986). A more accurate measure of the hydrologic components will reduce input errors in a water-budget model of the basin. Also, as more accurate estimates of hydrologic components are obtained, more accurate estimates can be made of how changes in climate and changes in the basin will affect the water quantity and quality of Devils Lake. Major hydrologic components that affect the quantity and quality of water in the Devils Lake basin and factors that affect the major components are listed in table 1.

The purpose of this study is to provide a more accurate measure of the hydrologic components, especially evaporation, that affect the water balance of Devils Lake. Specific objectives of the study are to: (1) Collect meteorologic and hydrologic data necessary to compute evaporation by energy-budget and mass-transfer methods; (2) establish a precipitation-station network around Devils Lake to determine the quantity of water falling on the lake; (3) compute evaporation by energy-budget and mass-transfer methods; and (4) compute the inflow to Devils Lake for 1986-88 using a water-balance equation. This report describes the results of this study.

The U.S. Geological Survey, in cooperation with the North Dakota State Water Commission began a study in 1986 to improve estimates of the water-balance of Devils Lake. At the same time as meteorologic and hydrologic data necessary to compute evaporation by energy-budget and mass-transfer methods were being collected, ground-water movement into and out of Devils Lake was being investigated by the North Dakota State Water Commission (Steve L. Pusc, North Dakota State Water Commission, written commun., 1989).

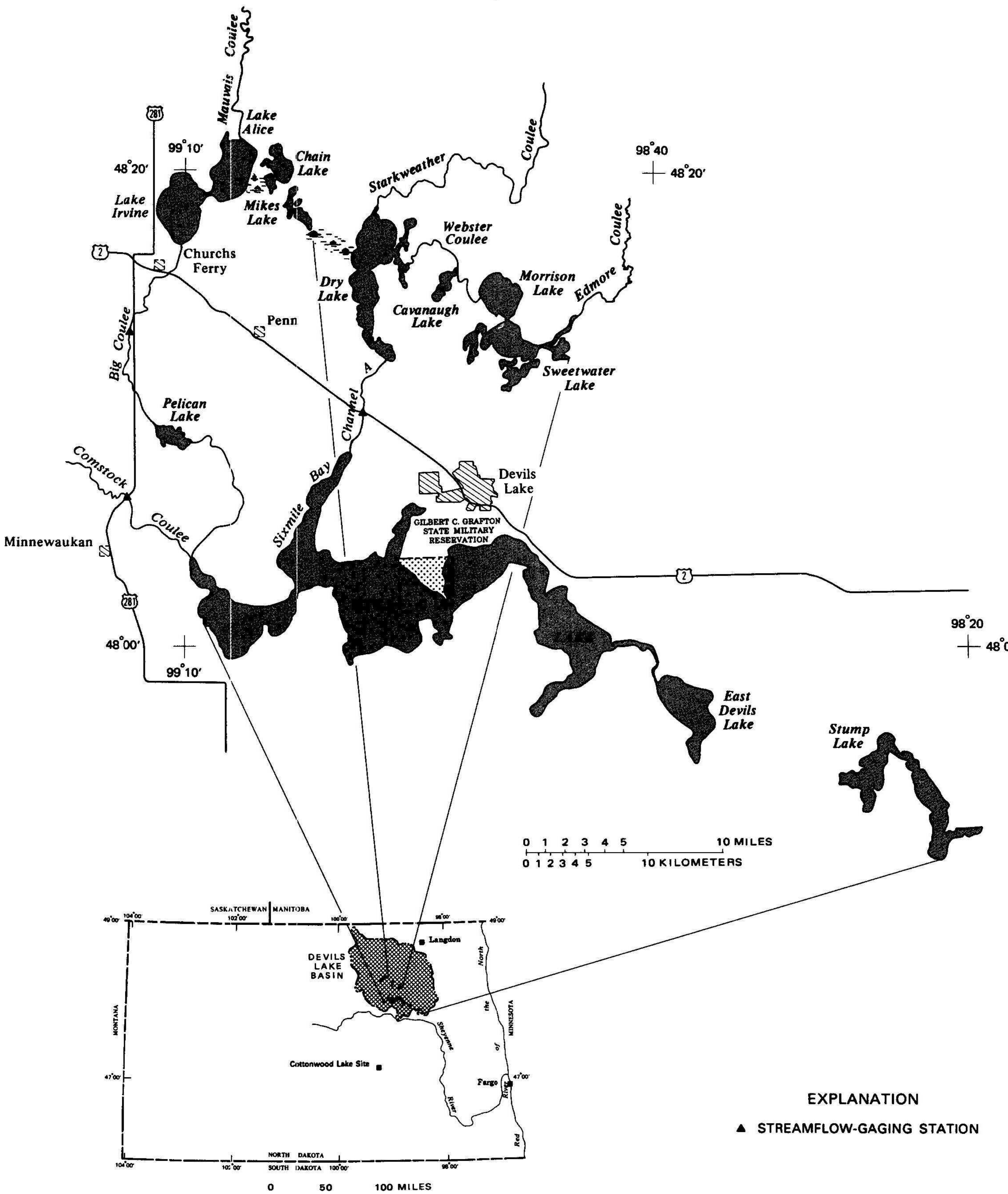

Figure 1.--Location of the chain of lakes and Devils Lake in northeastern North Dakota.

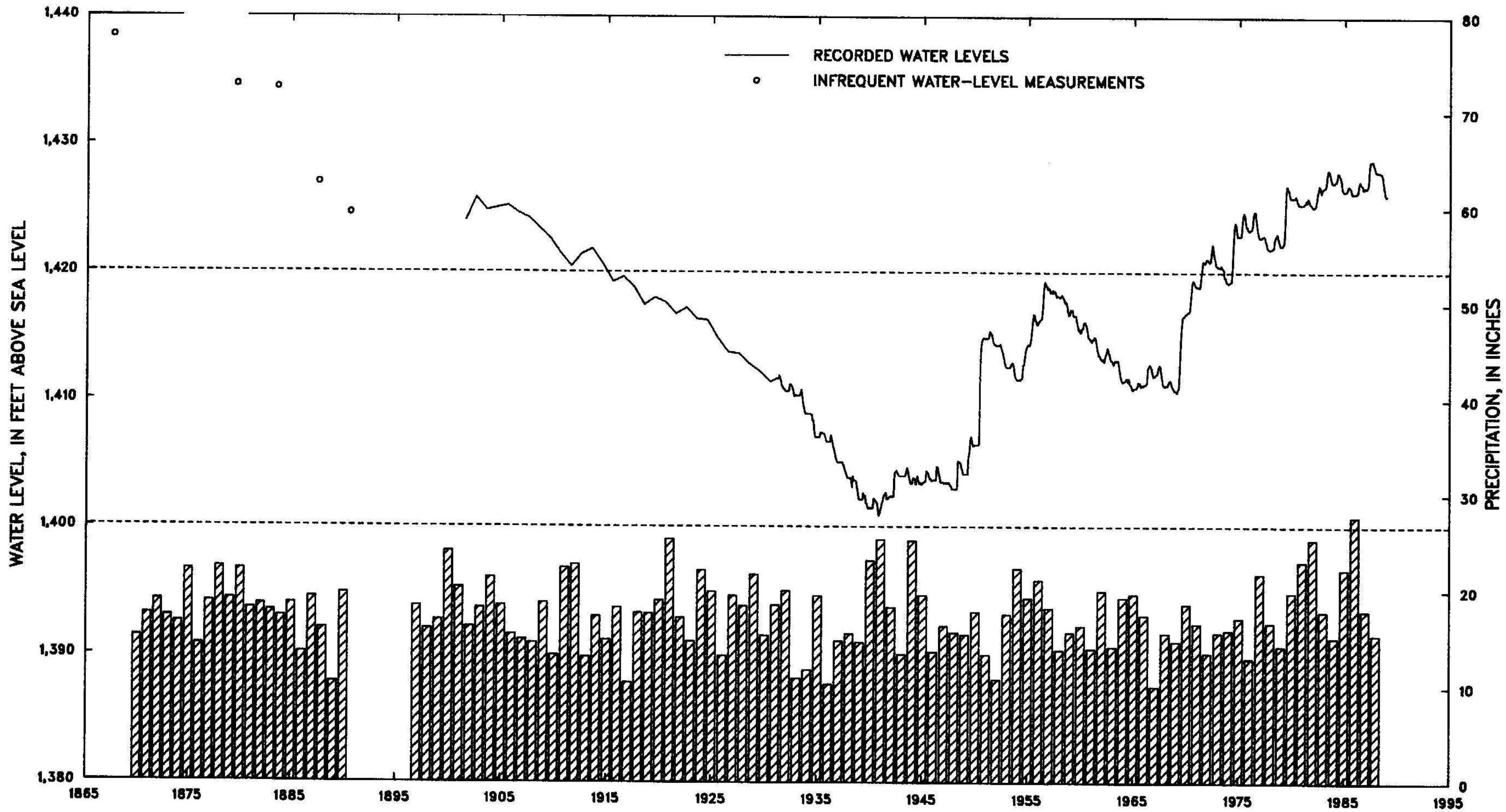

Figure 2.--Historic water levels of Devils Lake, 1867-1988, and annual precipitation, 1870-90 (Fort Totten) and 1897-1988 (city of Devils Lake). (Precipitation data from U.S. Department of Agriculture, Weather Bureau, 1932; 1932-40; U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1941-89.)

Table 1.--Major hydrologic components and factors affecting the components

Major hydrologic components	Factors affecting the components
Lake water quantity	Evaporation
	Air temperature
	Windspeed
	Wind direction
	Solar radiation
	Atmospheric radiation
	Relative humidity
	Precipitation
	Streamflow
	Direct runoff
	Bank storage
	Ground water
Lake water quality	Bed material
	Streamflow
	Direct runoff
	Evaporation
	Precipitation
	Ground water
Flow in the basin	Drainage patterns
	Impoundments
	Land-use changes
	Noncontributing drainage area
	Contributing drainage area
Basin water quality	Streamflow
	Direct runoff
	Evaporation
	Precipitation
	Ground water
	Drainage patterns
	Sedimentation
	Herbicides/pesticides
	Nutrients

Description of Study Area

Devils Lake is an 80-square-mile lake at a water level of 1,425 feet above sea level at the terminus of a 3,810-square-mile closed drainage basin in northeastern North Dakota (fig. 1). About 3,320 square miles of the drainage basin is tributary to Devils Lake; the remaining 490 square miles is tributary to Stump Lake, which lies to the east of Devils Lake. About 2,010 square miles of the 3,320 square miles that is tributary to Devils Lake drains into the chain of lakes upstream of Devils Lake.

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

The water level of Devils Lake generally declined from 1,438 feet above sea level in 1867 to 1,400.9 feet above sea level in 1940. During 1986-88, the water level ranged from 1,425.9 feet above sea level to 1,428.81 feet above sea level (fig. 3), the highest water level in about 100 years. The surface area of the lake has varied from about 140 square miles in 1867 to about 10 square miles in 1940. During 1986-88, the surface area varied from 82 square miles to 94 square miles.

Previous Investigations

The hydrology of the Devils Lake basin has been described by a number of researchers including Upham (1895), Babcock (1903), Horton and others (1910), Simpson (1912), Kennedy (1931), Swenson and Colby (1955), Aronow (1955, 1957), Paulson and Akin (1964), Callender (1968), Mitten and others (1968), Devils Lake Basin Advisory Committee (1976), Parekh (1977), and Wiche (1986). All of these researchers, to varying degrees, discussed the water-level fluctuations of Devils Lake. Many of these researchers included a discussion of the possible causes for the water-level fluctuations.

Data Collection and Instrumentation

Data for this study were collected during as much of the open-water period as practical. During 1986-88, breakup of ice cover on Devils Lake occurred between April 15 and April 28; and freezeup occurred between early to late November. Meteorologic instruments were installed in late April or early May and were removed at the end of October during each year of the study. The time increment used to compute evaporation by the energy-budget method was based on the time interval between thermal surveys of the lake. The number of days between each thermal survey is referred to in this report as a computation period.

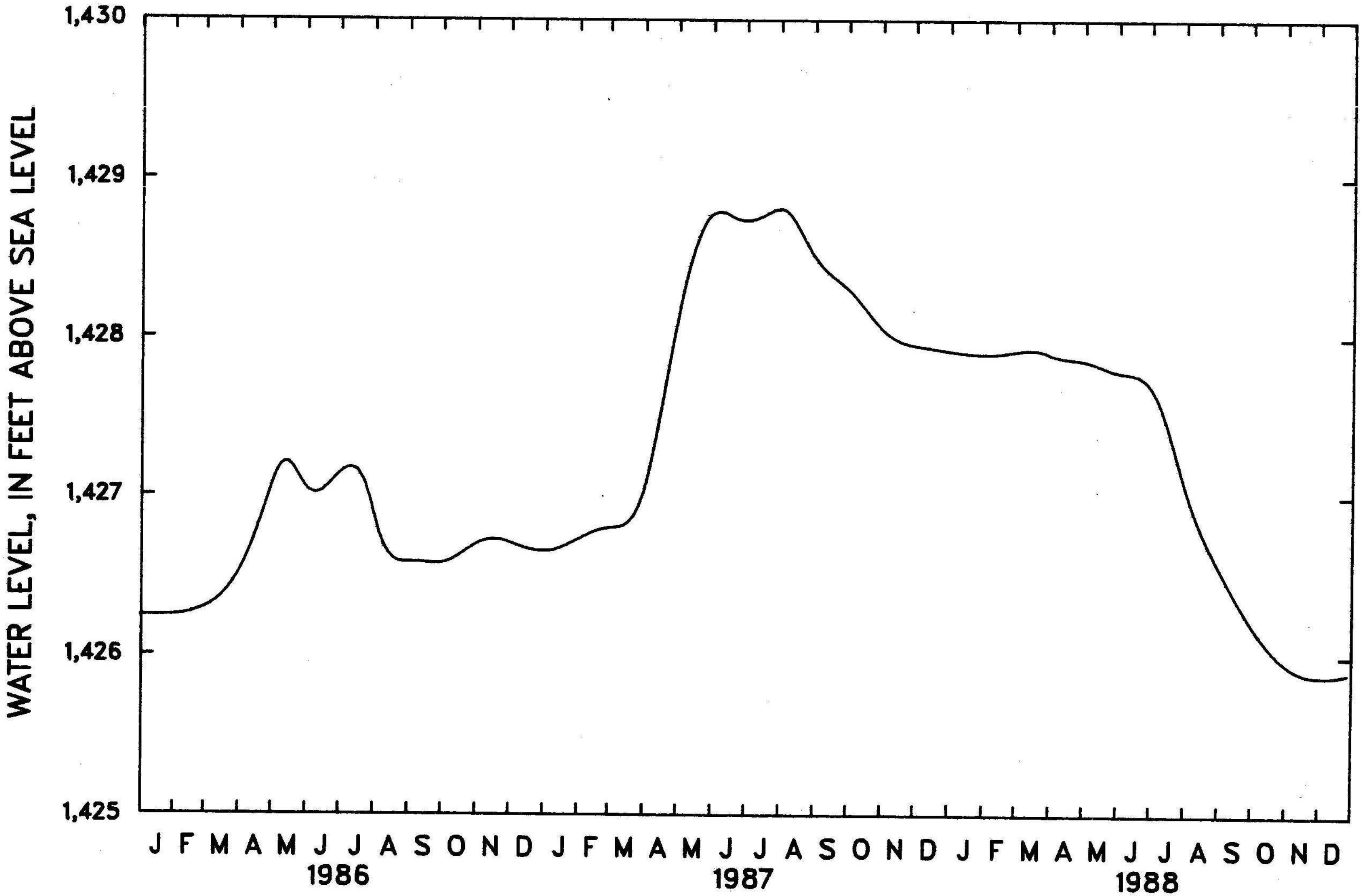

Figure 3.--Water levels of Devils Lake, 1986-88.

All data collected at the Camp Grafton land station and the Devils Lake raft station (fig. 4) were recorded with a CR-21 electronic data logger made by Campbell Scientific, Inc.[1] unless otherwise noted. The CR-21 electronic data logger is a battery-powered microcomputer that records as many as seven analog and two pulse-counting signals. The CR-21 electronic data logger samples the input signals once each minute and stores the data according to a user-specified output program.

Meteorologic and hydrologic data collected during this study have been published in a report by Sether and Wiche (1989). Meteorologic data collected include shortwave radiation, longwave radiation, relative humidity, windspeed, wind direction, precipitation, dry bulb air temperature, and wet bulb air temperature. Hydrologic data collected include water surface temperature, temperature at different depths, specific conductance, pH, and dissolved oxygen. A complete discussion of different types of instrumentation used by the U.S. Geological Survey for computing lake and reservoir evaporation by the energy-budget and mass-transfer methods is included in a report by Sturrock (1985).

DESCRIPTION OF ENERGY-BUDGET METHOD

Before 1950, energy-budget evaporation studies were limited to specific cases and large water bodies to minimize the effect of terms that could not be evaluated or measured (Anderson, 1954). An energy-budget study at Lake Hefner in central Oklahoma was instrumental in the development of methods used to estimate each term in the energy-budget equation (Anderson, 1954). Much of the discussion of the energy-budget method was taken from the study at Lake Hefner (Anderson, 1954) and a subsequent study at Lake Mead (Harbeck and others, 1958).

Evaporation can be computed by the energy-budget method by calculating all terms in the energy-budget equation,

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_x, \qquad (1)$$

where

Q_s = incoming shortwave radiation incident to the water surface, in calories per square centimeter;
Q_r = reflected shortwave radiation, in calories per square centimeter;
Q_a = incoming longwave radiation, in calories per square centimeter;
Q_{ar} = reflected longwave radiation, in calories per square centimeter;
Q_{bs} = longwave radiation emitted from the water surface, in calories per square centimeter;
Q_v = net advected energy, in calories per square centimeter;
Q_e = energy used for evaporation, in calories per square centimeter;

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[1]Use of brand, firm, or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

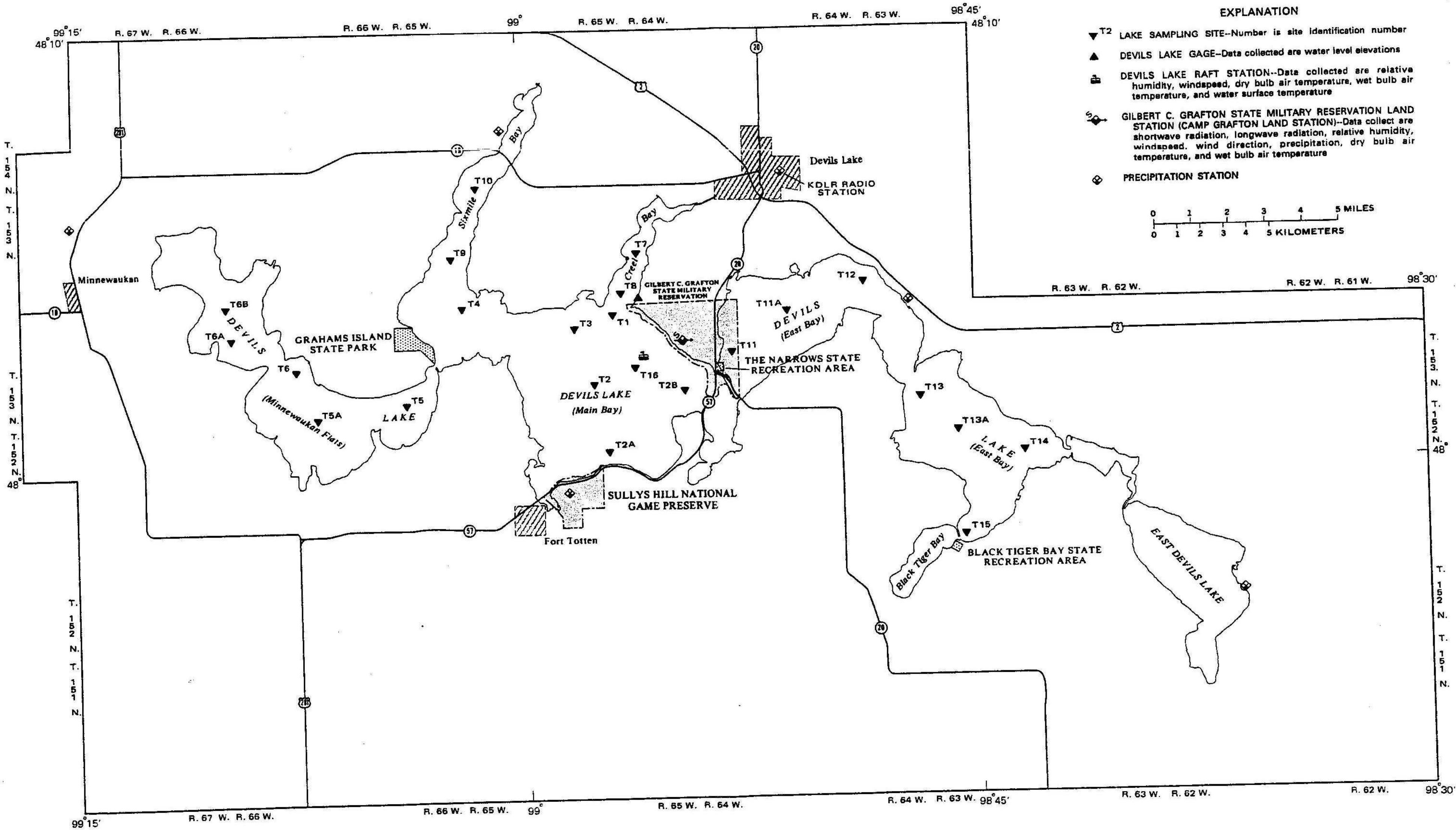

Figure 4.--Location of data-collection sites.

Q_h = energy conducted from the water to the atmosphere as sensible heat, in calories per square centimeter;
Q_w = energy advected from the lake surface by evaporated water, in calories per square centimeter; and
Q_x = change in heat content of the water, in calories per square centimeter.

Conduction of energy through the bed of the lake is a minor component in the energy budget for Devils Lake and was, therefore, neglected.

By rearranging terms in equation 1,

$$Q_e+Q_h+Q_w = Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x. \tag{2}$$

The energy used for evaporation (Q_e) can be calculated as follows:

$$Q_e = E_{eb}\rho L, \tag{3}$$

where

E_{eb} = evaporation computed by the energy-budget method, in cubic centimeters;
ρ = mass density of evaporated water, in grams per cubic centimeter; and
L = latent heat of vaporization at the water surface temperature, in calories per gram.

The energy conducted from the water to the atmosphere as sensible heat (Q_h) can be calculated by multiplying Q_e by the Bowen ratio:

$$Q_h = R(E_{eb}\rho L), \tag{4}$$

where

R = Bowen ratio, which is energy conducted from the water to the atmosphere as sensible heat divided by energy used for evaporation.

In addition to the energy lost because of the latent heat of vaporization, the mass of evaporated water at some temperature represents an advected loss from the lake. The energy advected from the lake surface by evaporated water (Q_w) can be calculated as follows:

$$Q_w = \rho c E_{eb}(T_o-T_b), \tag{5}$$

where

c = specific heat of water, which is equal to the amount of energy needed to raise 1 gram of water 1 °C;
T_o = water surface temperature, in degrees Celsius; and
T_b = base temperature used in energy-budget method computations, in degrees Celsius.

By substituting the expressions for Q_e (eq. 3), Q_h (eq. 4), and Q_w (eq. 5), equation 2 becomes

$$E_{eb} = \frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x}{\rho[L(1+R)+c(T_o-T_b)]}. \tag{6}$$

When the energy-budget terms in equation 6 are expressed in calories per square centimeter per day, evaporation computed by the energy-budget method (E_{eb}) will represent the volume of water, in cubic centimeters, that evaporated from an area of 1 square centimeter in 1 day. If a base temperature (T_b) of 0 °C, a mass density of evaporated water (ρ) of 1 gram per cubic centimeter, and a specific heat of water (c) of 1 calorie per degree increase in temperature per gram of water are used in equation 6, then

$$E_{eb} = \frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x}{L(1+R)+T_o}. \tag{7}$$

The Bowen ratio (R) is the ratio of Q_h to Q_e. The ratio developed by Bowen (1926) is

$$\frac{Q_h}{Q_e} = \frac{0.61P_r(T_o-T_a)}{1{,}000(e_o-e_a)}, \tag{8}$$

where

P_r = atmospheric pressure, in millibars;
T_a = dry bulb air temperature, in degrees Celsius;
e_o = vapor pressure of saturated air at the water surface temperature, in millibars; and
e_a = vapor pressure of air for the actual humidity, in millibars.

DESCRIPTION OF MASS-TRANSFER METHOD

The mass-transfer method used to compute evaporation in this study was outlined by Harbeck (1962) as

$$E_{mt} = NU_2(e_o-e_a), \tag{9}$$

where

E_{mt} = evaporation computed by the mass-transfer method, in inches per day;
N = mass-transfer coefficient; and
U_2 = mean windspeed at 2 meters above the water surface, in miles per hour.

The mass-transfer coefficient (N) is a function of several factors such as wind direction, length of fetch, stability of air, wind and vapor pressure profiles, and physiographic setting of the lake. The best method to determine N is to calibrate N against an independent measure of evaporation because these factors can vary from lake to lake. The independent measure of evaporation can be a technique such as eddy correlation, a water budget, or an energy budget (Brutsaert, 1982). An alternative method for determining N is given by Harbeck (1962) as follows:

$$N = \frac{0.00338}{A^{0.05}}, \tag{10}$$

where

A = surface area, in acres.
N is assumed to be constant for a lake.

A discussion of mass-transfer theory is beyond the scope of this report. A complete discussion of mass-transfer theory, however, is included in reports by Anderson and others (1950), Marciano and Harbeck (1954), and Brutsaert (1982).

EVAPORATION COMPUTED BY ENERGY-BUDGET METHOD

Incoming Shortwave Radiation

Incoming shortwave radiation incident to the water surface (Q_S) is dependent on the sun angle, the vapor content of the air, and the amount and type of cloud cover. Daily incoming shortwave radiation at Devils Lake was measured with an Eppley Precision Spectral Pyranometer located 100 feet inland at the Camp Grafton land station (fig. 4). The Eppley Precision Spectral Pyranometer, used in most current U.S. Geological Survey lake and reservoir evaporation studies (Sturrock, 1985), measures wavelengths from 0.3 to 3 microns (shortwave radiation of the electromagnetic spectra).

Q_S, the most difficult term to estimate, was obtained during the open-water periods except for 50 days when data were missing because of power failures. Missing values of Q_S were calculated for 11 days in 1987 with the following regression equation:

$$Q_S = 37.6+0.90[Q_S(cl)], \qquad (11)$$

where

Q_S = daily incoming shortwave radiation at Devils Lake, in calories per square centimeter; and

$Q_S(cl)$ = daily incoming shortwave radiation at Cottonwood Lake site, in calories per square centimeter.

An equation very similar to equation 11 (Sether and Wiche, 1989) was used to calculate the missing value of Q_S for 1 day in 1986.

The Cottonwood Lake site is a group of wetlands in the Cottonwood Lake area about 80 miles southwest of Devils Lake (fig. 1). Studies conducted in the Cottonwood Lake area have contributed significant information to the long-term study of wetlands (Winter and Carr, 1980). Daily incoming shortwave radiation at the Cottonwood Lake site [$Q_S(cl)$] was measured with an Eppley Precision Spectral Pyranometer identical to the instrument at the Camp Grafton land station.

The coefficient of determination of equation 11 is 0.86. The standard error of estimate of equation 11 is 74 calories per square centimeter per day.

Because $Q_S(cl)$ was not available for 23 of the 24 days missing in 1986 and for 15 days missing in 1988, values of Q_S for Devils Lake were calculated for these days with the following regression equation:

$$Q_S = 55.4+0.84[Q_S(f)], \qquad (12)$$

where

$Q_S(f)$ = daily incoming shortwave radiation at Fargo, in calories per square centimeter.

The city of Fargo is located about 140 miles southeast of Devils Lake. Daily incoming shortwave radiation at Fargo [$Q_s(f)$] was measured with an Eppley Black and White Pyranometer (John W. Enz, North Dakota State Climatologist, written commun., 1989).

The coefficient of determination of equation 12 is 0.78. The standard error of estimate of equation 12 is 94 calories per square centimeter per day.

Q_s varies greatly on a daily basis, largely depending on cloud cover, and more subtly between computation periods. For example, Q_s was 147 calories per square centimeter on August 22, 1986, and 547 calories per square centimeter on August 23, 1986. The greatest mean daily change between any two computation periods during 1986-88 was 149 calories per square centimeter.

Reflected Shortwave Radiation

Reflected shortwave radiation (Q_r) is a minor term in the energy budget. Q_r is independent of windspeed and turbidity and depends mostly on sun angle and cloud cover. In most energy-budget evaporation studies, Q_r is determined indirectly from incoming shortwave radiation incident to the water surface (Q_s) on the basis of relations developed by Koberg (1964). In this study, Q_r was measured with an inverted Eppley Precision Spectral Pyranometer on a platform about 150 feet offshore of the Camp Grafton land station (fig. 4).

Q_r was recorded during 71 percent of the days used to compute evaporation by the energy-budget method. Missing values of Q_r were calculated as a percentage of Q_s. The mean monthly percentage of Q_s reflected into the atmosphere ranged from 5.9 percent in May to 9.2 percent in October (table 2). Although the reflectivity of the water surface primarily is a function of the sun angle, the turbidity of the atmosphere also plays a minor role. The percentage of Q_s reflected at a given location is greatest at sun angles less than 30°. A nearly constant percentage of Q_s is reflected at sun angles greater than 30° (Anderson, 1954). An increase in the percentage of Q_s received at a sun angle less than 30° causes the relatively large increase in Q_r in September and October.

Q_r changed gradually throughout the open-water periods. For example, the mean daily Q_r for June 15-25, 1988, was 37.7 calories per square centimeter. By October 20-31, 1988, the mean daily Q_r had decreased to 27.7 calories per square centimeter. During the open-water periods, the minimum daily recorded Q_r was 3.5 calories per square centimeter and the maximum was 55 calories per square centimeter. The minimum daily calculated Q_r was 4.6 percent of Q_s on May 28, 1988, and the maximum was 15.7 percent of Q_s on October 30, 1988.

Incoming Longwave Radiation

Incoming longwave radiation (Q_a) was measured with an Eppley Precision Infrared Radiometer. The Eppley Precision Infrared Radiometer measures wavelengths from 4 to 50 microns.

A complete record of Q_a was obtained from the radiometer except for short periods when data were missing because of electronic malfunctions. Missing

Table 2.--Mean monthly percentage of incoming shortwave radiation reflected into the atmosphere for May through October 1986-88

Month	Number of days used to calculate percentage	Mean monthly percentage
May	20	5.9
June	37	6.1
July	53	6.1
August	65	6.3
September	47	7.9
October	45	9.2

values of Q_a were calculated with methods developed by Brunt (1932) and outlined by Koberg (1964). Koberg (1964, p. 108) stated "***the simplest method to estimate incoming longwave radiation is to assume the atmosphere is a gray body and select a suitable emissivity." In Brunt's equation,

$$\frac{Q_a}{\sigma T_a^4} = c+d\sqrt{e_a}, \qquad (13)$$

where

σ = the Stefan-Boltzmann constant, which is 8.14×10^{-11} calories per minute per degree Kelvin to the fourth power;
c = a constant; and
d = a constant.

A value of 0.682 was used for c as discussed by Anderson (1954). Q_a data were used in conjunction with equation 13 to compute a value of 0.041 for d. Anderson (1954) listed the results from nine investigators who had computed d values ranging from 0.029 to 0.082.

Q_a also was calculated with Brunt's equation for each day in all computation periods. The range of differences between recorded and calculated Q_a for each computation period is listed in table 3. A comparison of recorded Q_a and calculated Q_a was made by calculating the percentage of difference between the values for each day (table 3). Computation periods missing more than 2 days of both recorded and calculated Q_a values were not used to calculate the percentage values listed in table 3. On the basis of the percentage values listed in table 3, Brunt's equation provides a good estimate of Q_a on a daily basis and an excellent estimate of Q_a for computation periods of about 2 weeks.

The day-to-day change in the amount of water vapor in the atmosphere is much less than the change between seasons. Daily variations of Q_a are much

Table 3.--Difference between recorded incoming longwave radiation and calculated incoming longwave radiation determined by Brunt's equation, 1986-88

[--, indicates insufficient data]

Number of days in computation period	Computation period	Difference between recorded and calculated radiation (calories per square centimeter per day)		Percent difference between recorded and calculated radiation	
		Range	Mean	Range	Mean
		1986			
16	July 16-31	37 to -51	0.5	4.9 to -6.8	0
18	August 1-18	45 to -63	2.3	6.2 to -8.7	.3
23	August 19 through September 10	48 to -123	-22	6.6 to -17	-3.1
14	September 11-24	29 to -120	-56	4.3 to -17	-8.2
21	September 25 through October 15	-- --	--	-- --	--
14	October 16-29[1]	16 to -89	-13	2.6 to -15	-2.2
		1987			
23	April 30 through May 22	47 to -69	-8.3	7.2 to -11	-1.3
18	May 23 through June 9	54 to -103	-3.5	7.8 to -15	-.5
14	June 10-23	79 to -64	42	10.7 to -8.7	5.7
16	June 24 through July 9	70 to -36	18	9.8 to -5.0	2.6
19	July 10-28	47 to -90	-17	6.1 to -12	-2.3
14	July 29 through August 11	59 to -46	14	7.8 to -6.1	1.9
16	August 12-27	-- --	--	-- --	--
13	August 28 through September 9	75 to -10	23	11 to -1.5	3.5
15	September 10-24	86 to -74	18	13 to -11	2.8
15	September 25 through October 9	-- --	--	-- --	--
19	October 10-28	-- --	--	-- --	--

[1]Recorded incoming longwave radiation missing for 3 days.

Table 3.--Difference between recorded incoming longwave radiation and calculated incoming longwave radiation determined by Brunt's equation, 1986-88--Continued

Number of days in computation period	Computation period	Difference between recorded and calculated radiation (calories per square centimeter per day)		Percent difference between recorded and calculated radiation	
		Range	Mean	Range	Mean
	1988				
15	April 28 through May 12	-- --	--	-- --	--
6	May 13-18	-- --	--	-- --	--
22	May 19 through June 9	-- --	--	-- --	--
12	June 10-21	50 to -89	-8.8	6.8 to -12	-1.2
16	June 22 through July 7[2]	51 to -67	-7.1	6.7 to -8.8	-.9
14	July 8-21	65 to -15	24	9.1 to -2.1	3.4
12	July 22 through August 2	85 to -86	27	11 to -11	3.6
15	August 3-17	57 to -66	9.3	7.5 to -8.7	1.2
15	August 18 through September 1	69 to -28	27	10 to -4.1	4.0
13	September 2-14	69 to -93	22	11 to -14	3.4
21	September 15 through October 5	70 to -80	4.3	11 to -13	.7
20	October 6-25	81 to -39	26	14 to -7.0	4.6
6	October 26-31	58 to -64	-.7	12 to -13	-.1

[2]Recorded incoming longwave radiation missing for 4 days.

less than daily variations of Q_s. Mean daily Q_a variations between computation periods are small. During the open-water periods, mean daily Q_a ranged from 763 calories per square centimeter for August 3-17, 1988, to 503 calories per square centimeter for October 26-31, 1988.

Reflected Longwave Radiation and Longwave Radiation Emitted from the Water Surface

Reflected longwave radiation (Q_{ar}) generally is calculated by multiplying incoming longwave radiation (Q_a) by the reflectivity coefficient. Longwave radiation emitted from the water surface (Q_{bs}) is dependent on the temperature and emissivity of the water surface. In most studies, Q_{bs} is calculated using the Stefan-Boltzman law for black-body radiation and an emissivity of 0.97 (Robinson and Davies, 1972). In this study, Q_{ar} and Q_{bs} were measured with an inverted Eppley Infrared Precision Radiometer installed on the same platform as the inverted Eppley Precision Spectral Pyranometer.

Q_{ar} and Q_{bs} were obtained during the open-water periods except for short periods when data were missing because of electronic malfunctions. Q_{ar}, a minor component in the energy budget, is about 3 percent of Q_a (Anderson, 1954; Harbeck and others, 1958; Ficke, 1972). No attempt was made to separate Q_{ar} and Q_{bs}; thus, a combined term ($Q_{ar}+Q_{bs}$) was used in energy-budget method computations. $Q_{ar}+Q_{bs}$ will be referred to in further discussions as emitted longwave radiation.

Missing values of $Q_{ar}+Q_{bs}$ were calculated with the Stefan-Boltzman law for black-body radiation. Values obtained with the law were multiplied by an emissivity of 0.97 because water does not emit radiation like a black body but rather like a gray body. Daily values of $Q_{ar}+Q_{bs}$ were based on the daily mean water surface temperature recorded at the raft station.

$Q_{ar}+Q_{bs}$ also was calculated with the Stefan-Boltzman law for each day in all computation periods. The range of differences between recorded and calculated $Q_{ar}+Q_{bs}$ for each computation period is listed in table 4. A comparison of recorded $Q_{ar}+Q_{bs}$ and calculated $Q_{ar}+Q_{bs}$ was made by determining the percentage of difference between the values for each day (table 4). Except for two computation periods, as noted in table 4, all periods missing more than 2 days of both recorded and calculated values of $Q_{ar}+Q_{bs}$ were not used to calculate the percentage values listed in table 4. On the basis of the percentage values listed in table 4, the Stefan-Boltzman law provides an excellent estimate of $Q_{ar}+Q_{bs}$ on a daily basis. The difference between recorded $Q_{ar}+Q_{bs}$ and calculated $Q_{ar}+Q_{bs}$ tends to increase in September and October because the shallow water where $Q_{ar}+Q_{bs}$ is recorded cools more rapidly than the deeper water where the water surface temperature used to calculate $Q_{ar}+Q_{bs}$ is recorded.

Net Advected Energy

Net advected energy (Q_v) includes surface-water inflow, precipitation, ground-water inflow, evaporation, and condensation. The importance of each value depends on the hydrologic and climatologic setting of the lake. For Devils Lake, surface-water inflow into the lake and precipitation falling on

Table 4.--Difference between recorded emitted longwave radiation and calculated emitted longwave radiation determined by the Stefan-Boltzman law, 1986-88

[--, indicates insufficient data]

Number of days in computation period	Computation period	Difference between recorded and calculated radiation (calories per square centimeter per day)		Percent difference between recorded and calculated radiation	
		Range	Mean	Range	Mean
	1986				
16	July 16-31	25 to -19	5.6	2.9 to -2.2	0.6
18	August 1-18	-- --	--	-- --	--
23	August 19 through September 10	32 to -18	11	3.9 to -2.2	1.4
14	September 11-24	33 to -23	7.1	4.3 to -3.0	.9
21	September 25 through October 15	-- --	--	-- --	--
14	October 16-29	29 to -18	3.4	3.7 to -2.3	.4
	1987				
23	April 30 through May 22	-- --	--	-- --	--
18	May 23 through June 9	-- --	--	-- --	--
14	June 10-23	-- --	--	-- --	--
16	June 24 through July 9	8 to -18	-5.3	0.9 to -2.1	-0.6
19	July 10-28	10 to -26	-6.9	1.2 to -3.0	-.8
14	July 29 through August 11	27 to -25	-4.0	3.1 to -2.8	-.5
16	August 12-27	-- --	--	-- --	--
13	August 28 through September 9	30 to -11	6.7	3.5 to -1.3	.8
15	September 10-24	37 to -4	14	4.7 to -.5	1.8
15	September 25 through October 9	84 to 10	39	11 to 1.4	5.0
19	October 10-28	65 to 6	36	9.2 to .9	5.1

Table 4.--Difference between recorded emitted longwave radiation and calculated emitted longwave radiation determined by the Stefan-Boltzman law, 1986-88--Continued

Number of days in computation period	Computation period	Difference between recorded and calculated radiation (calories per square centimeter per day)		Percent difference between recorded and calculated radiation	
		Range	Mean	Range	Mean
		1988			
15	April 28 through May 12	-- --	--	-- --	--
6	May 13-18	-- --	--	-- --	--
22	May 19 through June 9	-- --	--	-- --	--
12	June 10-21	-- --	--	-- --	--
16	June 22 through July 7	7 to -35	-15	0.8 to -4.0	-1.7
14	July 8-21	13 to -19	-6.8	1.5 to -2.2	-.8
12	July 22 through August 2	6 to -47	-21	.7 to -5.2	-2.3
15	August 3-17[1]	5 to -45	-20	.6 to -5.1	-2.2
15	August 18 through September 1[1]	29 to -20	1.6	3.5 to -2.4	.2
13	September 2-14	16 to -15	-.9	2.0 to -1.9	-.1
21	September 15 through October 5	43 to -21	5.6	5.7 to -2.8	.7
20	October 6-25	-- --	--	-- --	--
6	October 26-31	-- --	--	-- --	--

[1]Recorded emitted longwave radiation missing for 6 days.

the lake surface are the two most important values needed to define Q_V. Q_V was calculated by multiplying the temperature of water entering and leaving the lake by the volume of water entering and leaving the lake. Q_V was derived primarily from streamflow in Big Coulee and channel A and from precipitation falling on the lake surface. Streamflow and water surface temperature are recorded at gaging stations on Big Coulee near Churchs Ferry and channel A near Penn (fig. 2). Because a minor amount of energy is advected into Devils Lake as streamflow from Comstock Coulee, a seasonal streamflow-gaging station was installed on Comstock Coulee (fig. 2) to improve the estimate of advected energy into Devils Lake. Water surface temperature for Comstock Coulee was assumed to equal the water surface temperature recorded at Big Coulee. Energy derived from surface inflow into Devils Lake ranged from 0 to 11.5 calories per square centimeter per day during all computation periods.

Precipitation was recorded at seven stations surrounding Devils Lake (fig. 4). Daily precipitation was used to estimate the precipitation component of Q_V. The temperature of the precipitation was assumed to be equal to the daily mean wet bulb air temperature recorded at the Devils Lake raft station. Energy derived from precipitation falling on Devils Lake ranged from 0 to 9.7 calories per square centimeter per day during all computation periods.

Although a major glacial aquifer underlies Devils Lake at a shallow depth, ground-water inflow to and outflow from Devils Lake is assumed, in most studies, to be negligible. The contribution of ground water to Q_V was assumed to be zero in energy-budget estimates in this study. However, by the conclusion of this study, Steve L. Pusc (North Dakota State Water Commission, written commun., 1989) had furnished estimates of ground-water inflow into Devils Lake during 1986-88.

Q_V is an extremely minor term in the energy budget of Devils Lake. During all computation periods, Q_V was equal to or less than 13.2 calories per square centimeter per day, which was equal to or less than 2.6 percent of Q_S. Mean daily Q_V during all computation periods was 3.4 calories per square centimeter per day. Q_V is a minor term in the energy budget even in years when greater-than-normal inflow enters the lake because most of the inflow is from snowmelt runoff and the temperature of the inflow generally is relatively cool (less than 15 °C). Thus, the geographic location of Devils Lake combined with the timing of snowmelt runoff reduces Q_V during peak inflow into the lake.

Energy Storage

The change in heat content of the water (Q_X) in Devils Lake was calculated from thermal profiles made during thermal surveys at 23 sites located throughout the lake. The thermal surveys generally were made during the early morning when winds normally are at a minimum. Devils Lake normally does not thermally stratify because it is a relatively shallow lake (maximum depth 30 feet) and the windspeeds typical of the northern prairies provide an almost continuous mixing of the water. The mean windspeed 2 meters above the water surface was 10.7 miles per hour for 392 days during April through October 1986-88.

A numerical integration method was used to calculate heat content. Starting at the water surface, the energy above a base temperature of 0 °C in each 1-foot interval was determined by multiplying the volume of water in the interval by the mean temperature determined for the 23 sites located throughout the lake. The volume of water in the interval was obtained from an area-capacity table of the lake. At each successive 1-foot interval, the same procedure was used to calculate heat content, but the number of sites used to determine the mean temperature decreased as the depth from the water surface increased. Heat content is near minimum in early winter (November), remains almost constant through February, and increases gradually as the ice melts in March (fig. 5). The maximum heat content calculated from the thermal profiles was 9,280 calories per square centimeter in July 1986, 9,820 calories per square centimeter in June 1987, and 9,300 calories per square centimeter in July 1988. A gradual decrease in heat content occurs during August, and a rapid decrease occurs during September and October.

Temperature measurements were accurate to ±0.1 °C. If the maximum error occurred in every temperature profile in the same direction at all depths, the error in the heat content of the water would be about 41 calories per square centimeter. This error could be an important component in the energy-budget computation if evaporation is computed for a couple of days; however, the error becomes minor if evaporation is computed for about a 15-day computation period.

Q_x was calculated for all 32 thermal surveys of the lake using thermal profiles for 23 sites and compared to the Q_x calculated using thermal profiles for 5 sites (sites T1, T2, T3, T4, and the raft station) in the main bay of Devils Lake (fig. 4). The minimum absolute difference of Q_x between the corresponding thermal surveys is 4 calories per square centimeter, and the maximum absolute difference is 1,462 calories per square centimeter. All differences except the maximum difference are equal to or less than 262 calories per square centimeter. The maximum difference occurred during September 2-14, 1988, and was caused by rapid radiational cooling of the shallow water during a relatively low windspeed of 2.2 miles per hour. Therefore, during September 2-14, 1988, when all 23 sites were used to determine the mean temperature, the mean temperature was cooler at each successive depth interval than when only the 5 sites in the main bay of Devils Lake were used.

Bowen Ratio

The daily Bowen ratio (R) was calculated using the daily mean water surface temperature (T_o), the daily mean dry bulb air temperature (T_a), the daily mean vapor pressure of saturated air at the water surface temperature (e_o), and the daily mean vapor pressure of air for the actual humidity (e_a) at 2 meters above the water surface. A mean daily R value was calculated for each computation period by summing all daily R values between -1 and +1 and dividing by the number of daily values used. The mean daily R value was used in energy-budget computations because the relation between T_o and e_o is nonlinear.

Few problems occurred in obtaining a complete record of T_a from the nonventilated thermistor psychrometer installed at the raft station. When T_a

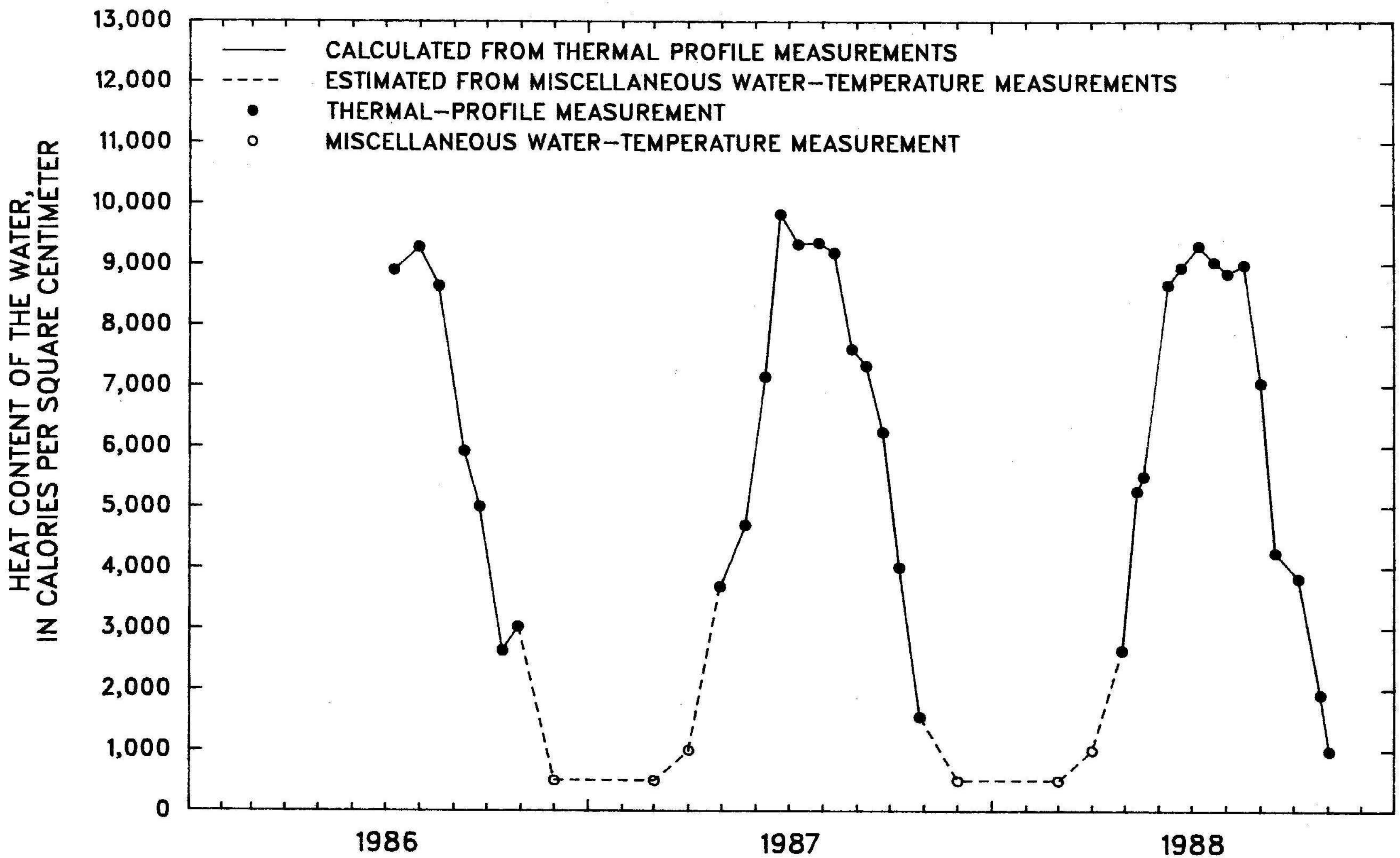

Figure 5.--Heat content of Devils Lake, 1986-88.

was not available from the psychrometer, T_a was obtained from the Campbell Scientific, Inc., Model 201 relative humidity sensor.

Wet bulb air temperature (T_w) is needed to obtain e_a. T_w was more difficult to obtain than T_a. Wind, especially during 1988, caused almost continual wave action on Devils Lake. Large waves caused water to splash out of the nonventilated thermistor psychrometer reservoir, and the reservoir would lose most of the water between field inspections. When water was lost from the reservoir, the wick attached to the wet bulb thermistor would dry out. When T_w was not available from the psychrometer, T_w was obtained from the Model 201 relative humidity sensor.

Of the 472 daily R values calculated for 1986-88, 453 values were between -1 and +1. About 80 percent of all daily R values were between -0.32 and +0.26. Anderson (1954) indicated that R values of about -1, large positive values, and large negative values should be checked for validity. Small changes in R values near -1 will cause large changes in evaporation computed using the energy-budget method (Anderson, 1954). For R values equal to -1, equation 7 becomes indeterminate; and evaporation cannot be computed. Large positive and negative R values create large values in the denominator of equation 7. When the denominator of equation 7 becomes large, large changes in the numerator of equation 7 (energy available for evaporation) are required to increase or decrease evaporation. Large positive R values tend to occur in the fall when a greater part of the heat transfer takes place as sensible heat. Negative R values commonly occur in the spring during stable atmospheric conditions. Negative R values are associated with a transfer of energy from relatively warm air to cooler water. A notable example of negative R values occurred during May 1988 when the values were negative for 21 days. The mean temperature for May 1988 was 4.2 °C greater than the normal temperature (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1989).

Interrelation of Energy-Budget Terms and Energy-Budget Evaporation

Mean daily values for terms in the energy-budget equation are listed in table 5 for each computation period, and mean daily values for energy-budget evaporation are listed in table 5 and shown in figure 6.

Incoming shortwave radiation incident to the water surface (Q_s), reflected shortwave radiation (Q_r), and incoming longwave radiation (Q_a) are terms in the energy-budget equation that are not dependent on the physical characteristics of Devils Lake. Emitted longwave radiation ($Q_{ar}+Q_{bs}$), net advected energy (Q_v), and change in heat content of the water (Q_x) are related primarily to the physical characteristics of Devils Lake. Normally, during late April through early June, Q_x increases rapidly. During early June through mid-August, minor fluctuations in Q_x occur. Then, during mid-August through October, Q_x decreases rapidly. The ability of Devils Lake to store energy in the spring and release energy in the fall causes a lag in evaporation of about 1 month when compared to what might be expected if Q_x was not part of the energy budget. During May and early June, the water surface temperature of Devils Lake increases as energy is stored as heat, and evaporation is suppressed. During mid-August through October, the water surface

Table 5.--Mean daily values for terms in the energy-budget equation and mean daily values for energy-budget evaporation

[Q_s, incoming shortwave radiation incident to the water surface, in calories per square centimeter; Q_r, reflected shortwave radiation, in calories per square centimeter; Q_a, incoming longwave radiation, in calories per square centimeter; $Q_{ar}+Q_{bs}$, reflected longwave radiation, in calories per square centimeter, plus longwave radiation emitted from the water surface, in calories per square centimeter; Q_v, net advected energy, in calories per square centimeter; Q_x, change in heat content of the water, in calories per square centimeter; Q_e, energy used for evaporation, in calories per square centimeter; Q_h, energy conducted from the water to the atmosphere as sensible heat, in calories per square centimeter; Q_w, energy advected from the lake surface by evaporated water, in calories per square centimeter]

Computation period	Q_s	Q_r	Q_a	$Q_{ar}+Q_{bs}$	Q_v	Q_x	Q_e	Q_h	Q_w	Mean daily energy-budget evaporation (inches)
				1986						
July 16-31	532	32.4	757	873	9.5	15.9	328	36.0	13.2	0.221
August 1-18	493	30.4	726	853	2.0	-35.6	319	41.5	12.3	.215
August 19 through September 10	381	27.2	694	812	2.3	-118	291	55.3	9.2	.195
September 11-24	232	17.6	674	766	2.4	-66.0	146	40.9	3.5	.098
September 25 through October 15	250	21.2	612	749	1.1	-112	163	39.1	3.2	.109
October 16-29	215	19.0	609	716	.4	28.0	56.7	4.5	.9	.038
				1987						
April 30 through May 22	501	29.6	649	764	13.2	44.0	353	-35.3	7.8	0.237
May 23 through June 9	547	32.8	691	797	8.4	136	270	2.7	7.5	.181
June 10-23	650	39.6	736	861	11.3	191	305	-12.2	11.6	.206
June 24 through July 9	559	31.7	714	865	5.1	-31.1	348	52.2	13.0	.235
July 10-28	464	27.1	763	867	6.9	1.3	301	27.1	11.2	.203
July 29 through August 11	499	36.2	760	882	1.7	-11.7	340	-.3	13.7	.230
August 12-27	393	28.2	691	836	3.6	-99.2	257	56.5	4.5	.173
August 28 through September 9	421	33.7	673	815	.3	-21.2	228	31.9	7.2	.153
September 10-24	310	26.3	663	794	2.2	-72.7	185	37.0	5.4	.124
September 25 through October 9	264	22.0	611	733	.3	-149	220	44.0	5.1	.148
October 10-28	209	20.2	547	667	.1	-129	153	44.4	1.9	.102
				1988						
April 28 through May 12	451	25.5	632	724	1.1	175	176	-17.6	2.9	0.117
May 13-18	566	31.0	655	754	.4	41.9	299	89.7	6.3	.200
May 19 through June 9	542	32.5	732	819	3.4	143	349	-76.8	10.9	.234
June 10-21	551	35.7	736	863	3.0	24.1	369	-14.8	12.8	.249
June 22 through July 7	531	32.3	762	877	9.7	22.2	372	-14.9	14.0	.251
July 8-21	582	38.0	717	873	.4	-19.1	364	29.1	14.0	.245
July 22 through August 2	524	33.5	754	894	.8	-15.9	375	-22.5	14.9	.253
August 3-17	458	30.6	763	888	2.8	9.7	302	-18.1	11.6	.204
August 18 through September 1	448	39.0	681	845	.1	-130	333	30.0	11.5	.224
September 2-14	377	33.1	644	801	.2	-216	359	32.3	10.1	.241
September 15 through October 5	280	25.1	624	754	.2	-20	154	-12.3	3.3	.103
October 6-25	257	29.8	561	727	.1	-95.4	139	15.3	2.3	.093
October 26-31	182	26.4	503	643	0	-153	127	38.1	2.1	.085

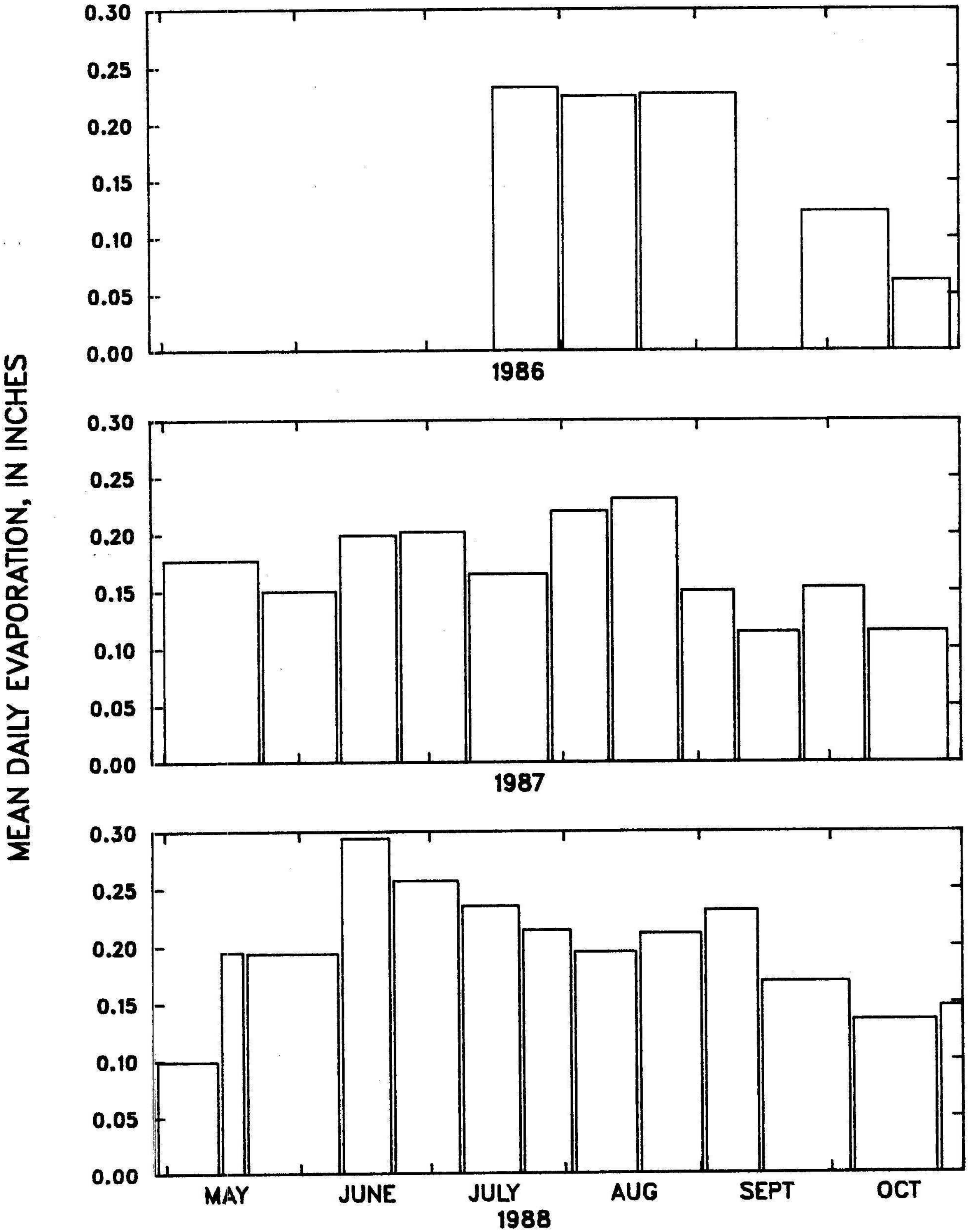

Figure 6.--Mean daily energy-budget evaporation, 1986-88.

temperature of Devils Lake decreases as energy is released from storage, and evaporation is greater than from small water bodies near Devils Lake or from evaporation pans that do not have the ability to store significant amounts of energy. For example, pan evaporation at Langdon during September 2-14, 1988, was 2.73 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1989), and evaporation from Devils Lake computed by the energy-budget method for the corresponding period was 3.13 inches.

Mean daily energy-budget evaporation ranged from 0.038 inch during October 16-29, 1986, to 0.253 inch during July 22 through August 2, 1988. Evaporation during June through August 1988 was greater than during the corresponding months with available data in 1986 and 1987.

Effect of Errors in Energy-Budget Terms

The precision of each term in the energy-budget equation depends on the accuracy of the equipment used to collect the data, the experience of the personnel installing and servicing the equipment and collecting the data, and the completeness of the record. The precision of some terms, such as shortwave radiation and longwave radiation, is based on direct measurements; and the instruments used are calibrated annually. The precision of other terms is based on indirect measurements. For example, the precision of net advected energy is based on the accuracy of streamflow measurements, the stage-discharge relations at gaging stations, and the calibration of the thermistor psychrometer used to measure water surface temperature.

Maximum errors in terms of the energy-budget equation have been estimated in studies by Harbeck and others (1958), Gunaji (1968), and Winter (1981). Estimated maximum errors reported by Harbeck and others (1958) and Gunaji (1968) are listed in table 6. Harbeck and others (1958) concluded that if the errors listed in table 6 are combined by adding the individual statistical variances, the estimated maximum error in evaporation is about 10 percent in the summer and 13 percent in the winter. The error in most months is substantially less than the estimated maximum error because the errors of terms in the energy-budget equation tend to cancel each other. Harbeck and others (1958) also indicated that, on an annual basis, the estimated maximum error in evaporation should be less than 10 percent because the error in change in heat content of the water (Q_x) decreases as the length of the computation period for the energy-budget estimate increases.

Gunaji (1968) used the estimated maximum error of each term in the energy-budget equation to estimate a maximum probable error for each of 28 computation periods, which averaged 14 days in length. Errors in evaporation for each computation period ranged from 4.4 to 27.8 percent. The mean error in evaporation for the 28 computation periods was 10.5 percent.

Winter (1981) integrated the errors in all aspects of lake hydrology and compared three hypothetical lake water balances. Winter (1981) outlined the statistical methodology he used to estimate the propagation of errors for any term in the water-balance equation.

Table 6.--Estimated maximum error in energy-budget terms reported by Harbeck and others (1958) and Gunaji (1968)

[°C, degrees Celsius]

Energy-budget term	Estimated maximum error	
	Harbeck and others	Gunaji
Incoming shortwave radiation incident to the water surface, in calories per square centimeter (Q_s)	2 percent	2 percent
Reflected shortwave radiation, in calories per square centimeter (Q_r)	2 percent	2 percent
Incoming longwave radiation, in calories per square centimeter (Q_a)	2 percent	2 percent
Reflected longwave radiation, in calories per square centimeter (Q_{ar})	Less than 10 percent	1 percent
Longwave radiation emitted from the water surface, in calories per square centimeter (Q_{bs})	1.0 °C in mean water surface temperature	1 percent
Net advected energy, in calories per square centimeter (Q_v)	5 percent in inflow and outflow volumes and 1.0 °C in inflow and outflow water surface temperatures	10 percent
Change in heat content of the water, in calories per square centimeter (Q_x)	0.5 °C in all thermal profiles	8 percent
Energy conducted from the water to the atmosphere as sensible heat, in calories per square centimeter (Q_h)	20 percent in Bowen ratio	10 percent
Energy advected from the lake surface by evaporated water, in calories per square centimeter (Q_w)	1.0 °C in mean water surface temperature	6 percent

The estimated maximum error in each energy-budget term used in this study and the mean percentage of error in computed evaporation are listed in table 7. Because reflected shortwave radiation (Q_r) and emitted longwave radiation ($Q_{ar}+Q_{bs}$) were measured in this study, the estimated maximum error of Q_r and $Q_{ar}+Q_{bs}$ is less than that reported in earlier studies (Harbeck and others, 1958; Gunaji, 1968).

Measuring each term with the same precision does not result in the same percentage of error in computed evaporation because errors in terms that have large values have a greater effect on the computed evaporation. For example, a 2-percent error in Q_r causes a mean error of 0.2 percent in computed evaporation. A 2-percent error in incoming shortwave radiation incident to the water surface (Q_s) causes a mean error of 3 percent in computed evaporation. $Q_{ar}+Q_{bs}$ is one of the largest terms throughout all computation periods, and a 3-percent error in this term produces a mean error of 8.7 percent in computed evaporation.

Net advected energy (Q_v) is a relatively minor term in the energy budget of Devils Lake. A 5-percent error in Q_v causes less than a 0.1-percent error in computed evaporation, and a 20-percent error in Q_v causes less than a 1-percent error. Studies of evaporation from Lake Mead along the Nevada and Arizona border (Harbeck and others, 1958) indicated that a 5-percent error in inflow and outflow volumes and a 1.0-°C error in inflow and outflow water surface temperatures cause a 4-percent error in computed evaporation during the summer. Unless the hydrologic and climatologic conditions at Devils Lake are much different than conditions that occurred during 1986-88, Q_v will be a relatively minor term in the energy budget of Devils Lake. In fact, Q_v probably is a minor term in the energy budget of most terminal lakes on the northern prairies. Q_v is more important in the energy budget of lakes that are flowthrough systems with an inlet and an outlet, such as Lake Mead, than in terminal lakes, such as Devils Lake.

A 20-percent error in the Bowen ratio (R) causes a mean error of 2.2 percent in computed evaporation. Errors in computed evaporation caused by a 20-percent error in R ranged from 0 to 5.1 percent for all computation periods.

EVAPORATION COMPUTED BY MASS-TRANSFER METHOD

Mass-Transfer Coefficient

In this study, energy-budget evaporation was used as the independent measure of evaporation used to determine the mass-transfer coefficient (N). The relation of mass-transfer product $[U_2(e_o-e_a)]$ to energy-budget evaporation is shown in figure 7. The linear regression equation developed and used to determine N, which is the slope of the line of best fit, is

$$E_{mt} = 0.019+NU_2(e_o-e_a). \quad (14)$$

where

$N = 0.0020$

Table 7.--Estimated maximum error in energy-budget terms used in this study and mean error in computed evaporation

[<, less than; °C, degrees Celsius]

Energy-budget term	Estimated maximum error	Mean error in computed evaporation (percent)
Incoming shortwave radiation incident to the water surface, in calories per square centimeter (Q_s)	2 percent	3.0
Reflected shortwave radiation, in calories per square centimeter (Q_r)	2 percent	.2
Incoming longwave radiation, in calories per square centimeter (Q_a)	3 percent	7.3
Reflected longwave radiation, in calories per square centimeter, plus longwave radiation emitted from the water surface, in calories per square centimeter (Q_{ar}+Q_{bs})	3 percent	8.7
Net advected energy, in calories per square centimeter (Q_v)	5 percent	<.1
Change in heat content of the water, in calories per square centimeter (Q_x)	0.5 °C in all thermal profiles	5.1
Energy conducted from the water to the atmosphere as sensible heat, in calories per square centimeter (Q_h)	20 percent in Bowen ratio (R)	2.2
Energy advected from the lake surface by evaporated water, in calories per square centimeter (Q_w)	1.0 °C in mean water surface temperature	0

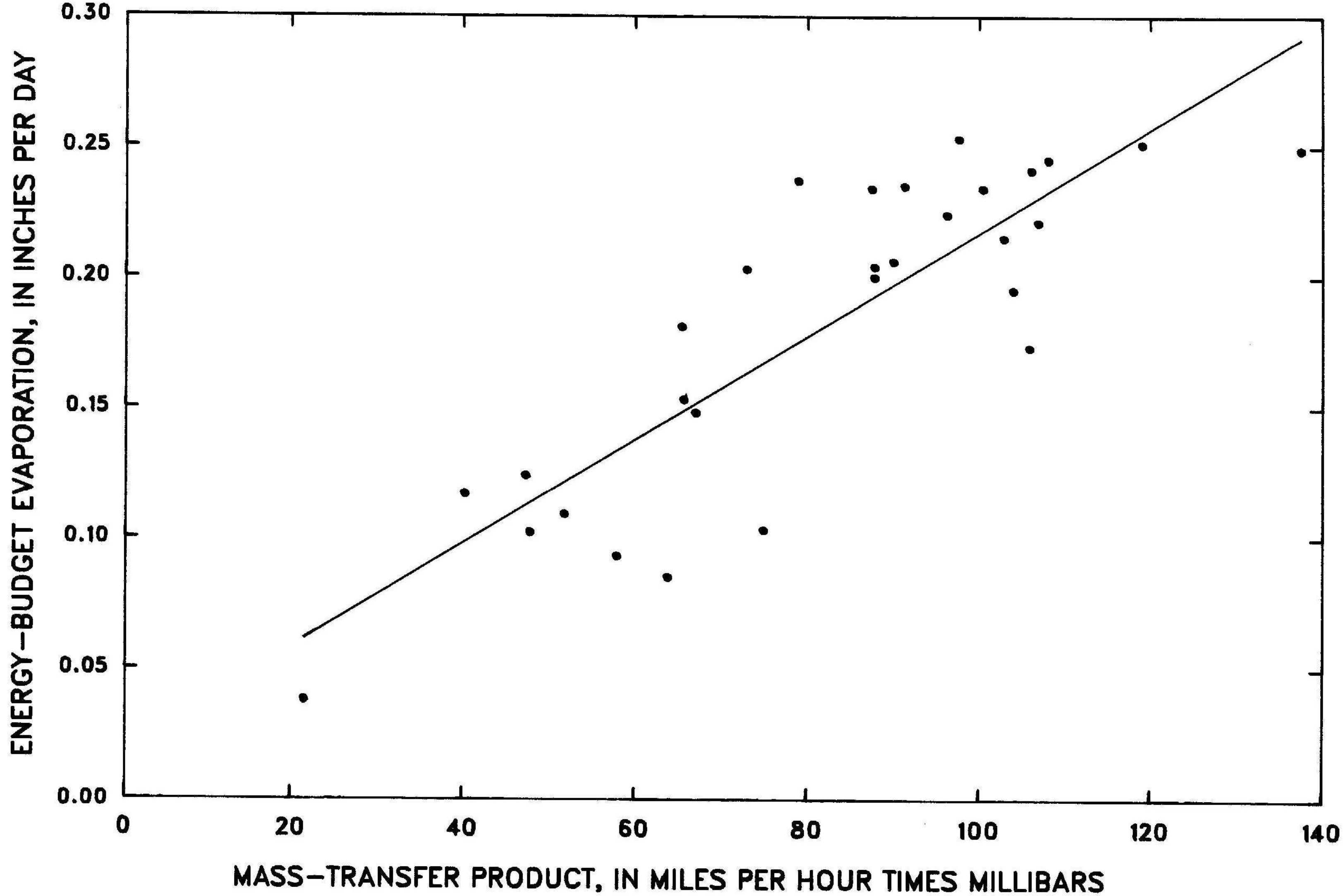

Figure 7.--Relation of mass-transfer product to energy-budget evaporation.

N generally is computed as the slope of a straight line (fig. 7) passing through the origin; in this study, however, a constant (y-intercept) of 0.019 provides the best fit. The physical basis for having the straight line pass through the origin is that when the wind is calm there is no vapor pressure gradient ($e_o - e_a = 0$), and the turbulent exchange of vapor between the lake surface and the air is negligible. The assumption is made that the independent variable used to determine N is without error. However, error undoubtedly occurs in $U_2(e_o - e_a)$; thus, adding a constant to equation 9 provides the best estimate of mass-transfer evaporation from Devils Lake.

Equation 14 has a coefficient of determination of 0.73 and a standard error of estimate of 0.03 inch per day.

Mean Windspeed

Windspeed was obtained with R. M. Young Co., Gill 3-cup anemometers installed at the Devils Lake raft station at 1, 2, and 3 meters above the water surface. The anemometers use a direct current tachometer generator whose analog output voltage is directly proportional to windspeed. A 3-cup totalizing anemometer installed at 2 meters above the water surface was used as a backup instrument for obtaining windspeed between computation periods. The mean windspeed at 2 meters above the water surface (U_2) was available for most computation periods during 1986-88. A regression equation was developed to calculate 69 daily values of U_2 that were missing during 1986-88. The dependent variable in the regression equation is the mean windspeed at 2 meters calculated for a computation period with data obtained by the R. M. Young Co., Gill anemometer. The independent variable in the regression equation is the mean windspeed at 2 meters calculated for a computation period with data obtained from the totalizing anemometer. The coefficient of determination of the regression equation is 0.93, and the standard error of estimate is 0.39 miles per hour.

Vapor Pressure

The vapor pressure of saturated air at the water surface temperature (e_o) was determined using water surface temperature (T_o). T_o was measured at the Devils Lake raft station with an epoxy-coated thermistor installed just below the water surface.

A nonventilated thermistor psychrometer installed at the raft station was used to determine dry bulb air temperature (T_a) and wet bulb air temperature (T_w). The vapor pressure of air for the actual humidity (e_a) was determined using T_a and T_w.

A Campbell Scientific, Inc., Model 201 relative humidity sensor was used as a backup instrument for determining T_a and T_w. When T_a and relative humidity are available, T_w can be obtained from standard meteorologic tables.

The same vapor pressure data (e_o and e_a) used to compute the Bowen ratio (R) in energy-budget computations were used in mass-transfer computations. The mass-transfer product [$U_2(e_o - e_a)$] needed for each computation period to determine the mass-transfer coefficient (N) in equation 14 was obtained by summing the daily mean values of $U_2(e_o-e_a)$ and dividing by the number of days in a computation period.

Mass-Transfer Evaporation

Mean daily values for mass-transfer evaporation are listed in table 8 and shown in figure 8 for each computation period. Mass-transfer evaporation could not be computed for 1 of the 30 computation periods because data were missing. Mean daily mass-transfer evaporation ranged from 0.062 inch during October 16-29, 1986, to 0.294 inch during June 10-21, 1988. Mass-transfer evaporation generally is in close agreement with energy-budget evaporation.

Sampling errors occur in wind data and in water surface temperature data. Windspeed and wind direction vary over the lake, especially during periods of a day or less. Windspeed and wind direction have the greatest variability during periods when no steep pressure gradient exists. Windspeed generally is relatively low during these periods. For computation periods of about 2 or more weeks, wind data from the raft station are representative of wind data for the entire lake.

The greatest variability in water temperature throughout the lake occurs during early spring immediately after breakup of ice cover and in the fall before the lake freezes. In the spring, water in shallow areas of Devils Lake warms much faster than water in the main bay of Devils Lake; and, in the fall, water in shallow areas cools faster than water in the main bay. A substantial difference in water temperature in different parts of the lake during early spring and fall generally lasts for about 1 to 2 weeks.

Errors in mean windspeed at 2 meters above the water surface (U_2), in vapor pressure of saturated air at the water surface temperature (e_o), and in vapor pressure of air for the actual humidity (e_a) were analyzed to estimate the change in evaporation that might be expected to occur. An error in U_2 of 0.5 mile per hour for each computation period causes errors in evaporation from 2.6 to 5.2 percent. Errors caused by a 0.5-°C change in water surface temperature (T_o) for typical daily meteorologic conditions during July and October are listed in table 9. If the mass-transfer product $[U_2(e_o-e_a)]$ is in error because e_o was determined from T_o, which is 0.5 °C in error, then relative error, in percent, equals

$$\frac{(e_{o+0.5\ °C}-e_o)100}{(e_o-e_a)},$$

where

$e_{o+0.5\ °C}$ = the incorrect vapor pressure corresponding to T_o+0.5 °C.

During 21 calibration checks, the mean absolute difference between the measured T_o and the recorded T_o at the Devils Lake raft station was 0.1 °C. The maximum absolute difference was 0.6 °C. Errors caused by a 0.5-°C change in air temperature would be similar to those caused by a 0.5-°C change in T_o.

Table 8.--Summary of energy-budget and mass-transfer evaporation for computation periods during 1986-88

[U_2, mean windspeed at 2 meters above the water surface, in miles per hour; e_o, vapor pressure of saturated air at the water surface temperature, in millibars; e_a, vapor pressure of air for the actual humidity, in millibars; --, indicates insufficient data]

Number of days in computation period	Computation period	Mean daily mass-transfer product [$U_2(e_o-e_a)$]	Mean daily evaporation (inches)		Evaporation per computation period (inches)	
			Energy budget	Mass transfer	Energy budget	Mass transfer
		1986				
16	July 16-31	106.8	0.221	0.233	3.54	3.73
18	August 1-18	102.8	.215	.225	3.87	4.05
23	August 19 through September 10	103.9	.195	.227	4.48	5.22
14	September 11-24	--	.098	--	[1]1.37	--
21	September 25 through October 15	51.8	.109	.123	2.29	2.58
14	October 16-29	21.5	.038	.062	.53	.87
Total					14.71	16.45
		1987				
23	April 30 through May 22	78.9	0.237	0.177	5.45	4.07
18	May 23 through June 9	65.4	.181	.150	3.26	2.70
14	June 10-23	90.0	.206	.199	2.88	2.79
16	June 24 through July 9	91.3	.235	.202	3.76	3.23
19	July 10-28	72.9	.203	.165	3.86	3.14
14	July 29 through August 11	100.4	.230	.220	3.22	3.08
16	August 12-27	105.8	.173	.231	2.77	3.70
13	August 28 through September 9	65.6	.153	.150	1.99	1.95
15	September 10-24	47.3	.124	.114	1.86	1.71
15	September 25 through October 9	67.0	.148	.153	2.22	2.30
19	October 10-28	47.8	.102	.115	1.94	2.18
Total					33.21	30.85

[1]Energy-budget value not used in total.

Table 8.--Summary of energy-budget and mass-transfer evaporation for computation periods during 1986-88--Continued

Number of days in computation period	Computation period	Mean daily mass-transfer product $[U_2(e_o-e_a)]$	Mean daily evaporation (inches)		Evaporation per computation period (inches)	
			Energy budget	Mass transfer	Energy budget	Mass transfer
		1988				
15	April 28 through May 12	40.2	0.117	0.099	1.76	1.48
6	May 13-18	87.8	.200	.195	1.20	1.17
22	May 19 through June 9	87.5	.234	.194	5.15	4.27
12	June 10-21	137.5	.249	.294	2.99	3.53
16	June 22 through July 7	119.0	.251	.257	4.02	4.11
14	July 8-21	108.0	.245	.235	3.43	3.29
12	July 22 through August 2	97.6	.253	.214	3.04	2.57
15	August 3-17	87.8	.204	.195	3.06	2.92
15	August 18 through September 1	96.2	.224	.211	3.36	3.16
13	September 2-14	106.0	.241	.231	3.13	3.00
21	September 15 through October 5	74.9	.103	.169	2.16	3.55
20	October 6-25	57.9	.093	.135	1.86	2.70
6	October 26-31	63.8	.085	.147	.51	.88
Total					35.67	36.63

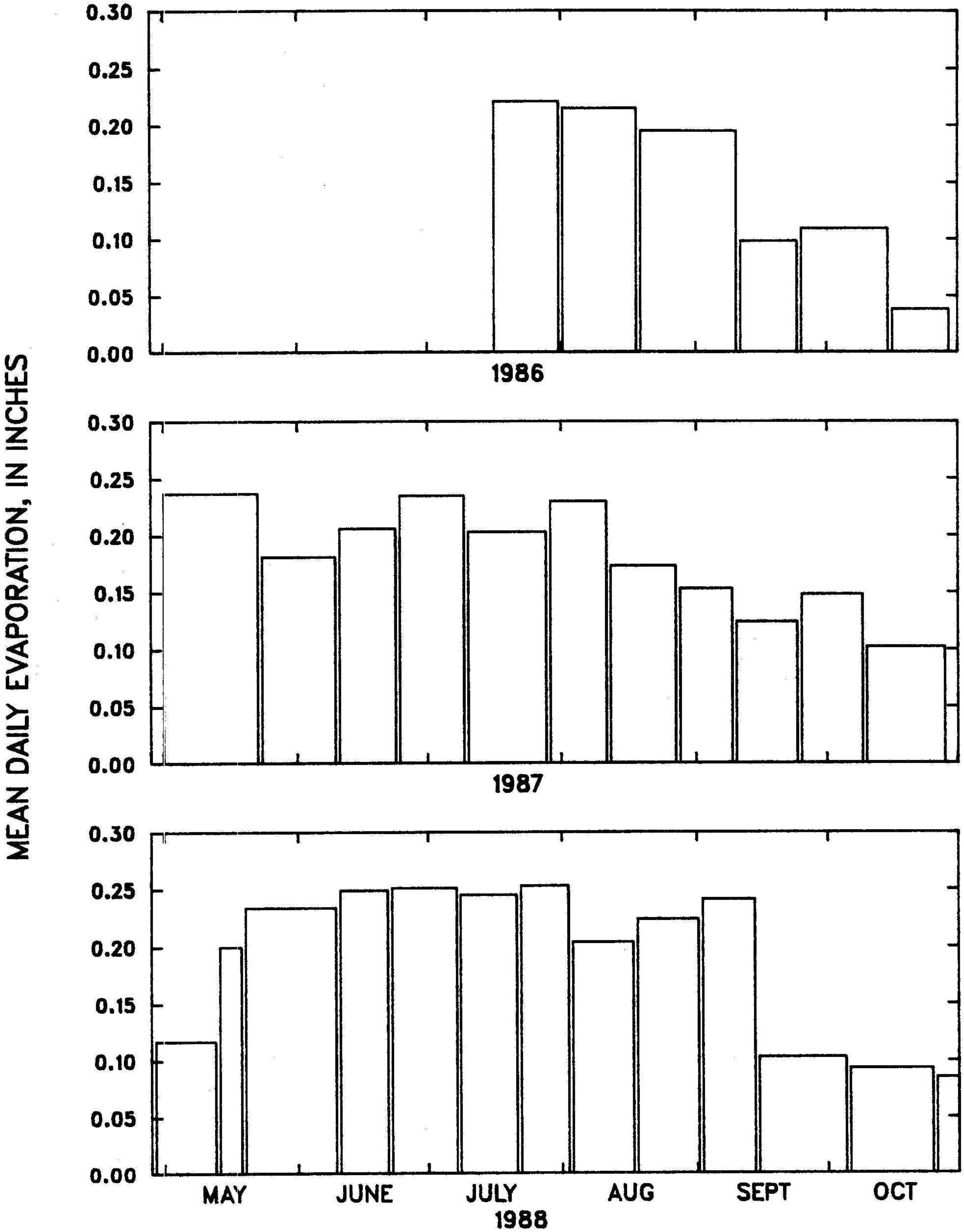

Figure 8.--Mean daily mass-transfer evaporation, 1986-88.

Table 9.--Relative error in mass-transfer evaporation for typical daily meteorologic conditions during July and October

[T_o, water surface temperature, in degrees Celsius; e_o, vapor pressure of saturated air at the water surface temperature, in millibars; °C, degrees Celsius; e_o+0.5 °C is equal to the incorrect vapor pressure corresponding to T_o+0.5 °C; e_a, vapor pressure of air for the actual humidity, in millibars]

Month	T_o	e_o	e_o+0.5 °C	e_a	Relative error (percent)
July	22.0	26.4	27.2	18.0	9.5
October	6.0	9.4	9.7	4.0	5.6

Another source of error inherent in the computation of mass-transfer evaporation is nonhomogeneity of the data. The assumption was made that data recorded at the Devils Lake raft station are representative of meteorologic conditions throughout the entire lake. Turner (1966) pointed out that if two mass-transfer equations were developed for different locations on the lake, the evaporation values computed from these two equations would be nearly equal if no serious sampling errors occurred.

The greatest relative error in mass-transfer evaporation occurs when estimates are made for short time periods, especially in the spring and fall. The same error in either T_o or the dry bulb air temperature (T_a) causes the vapor pressure difference (e_o-e_a) to be greater in the summer than in the spring or fall. Although the vapor pressure gradient is greater in the summer, the relative error in mass-transfer product, in percent, is greater in the spring and fall. Unfortunately, energy-budget evaporation estimates also are subject to the greatest relative errors at the same time as the mass-transfer evaporation estimates. Daily evaporation rates during early spring and fall typically are small; therefore, large errors in evaporation during these seasons do not introduce large errors in the annual open-water estimate of evaporation.

Ficke (1972) compared evaporation computation methods for Pretty Lake in northeastern Indiana and concluded that energy-budget evaporation generally was less than mass-transfer evaporation during spring and fall. Energy-budget evaporation at Pretty Lake was greater than mass-transfer evaporation during the summer. However, at Devils Lake, no seasonal relation was apparent between energy-budget evaporation and mass-transfer evaporation.

The energy-budget and mass-transfer evaporation estimates listed in table 8 for each computation period indicate that the greatest difference between energy-budget and mass-transfer evaporation was 2.36 inches in 1987.

Mass-transfer evaporation was 11.8 percent greater than energy-budget evaporation during that part of the open-water period for which data are available in 1986, energy-budget evaporation was 7.6 percent greater than mass-transfer evaporation in 1987, and mass-transfer evaporation was 2.7 percent greater than energy-budget evaporation in 1988.

The terms e_0 and e_a are common to both the energy-budget and mass-transfer methods, but an error in either term does not translate into the same error in evaporation computed with the two methods. For example, during the computation period July 10-28, 1987, a 0.5-°C error in e_0 results in a 2.9-percent error in evaporation computed by the energy-budget method. The same error in e_0 results in a 9.5-percent error in evaporation computed by the mass-transfer method. If evaporation estimates are to be based exclusively on the mass-transfer method, extreme care should be exercised to obtain the best possible record of wet bulb (T_w) and dry bulb (T_a) air temperature.

WATER-BALANCE ESTIMATES OF DEVILS LAKE

The water-balance equation most commonly used to examine the various hydrologic components that affect the water balance of Devils Lake is

$$Q = S - P(A) + E(A) - G, \qquad (15)$$

where

Q = inflow, in acre-feet;
S = storage change, in acre-feet;
P = precipitation, in feet;
A = surface area, in acres;
E = evaporation, in feet; and
G = ground-water inflow, in acre-feet.

Inflow (Q) to Devils Lake has been recorded at the Big Coulee near Churchs Ferry gaging station (fig. 1) since 1950 (U.S. Geological Survey, 1989). Construction of channel A was completed in 1979, and a gaging station was installed near Penn (fig. 1) in 1983 (U.S. Geological Survey, 1989). Precipitation (P) falling on Devils Lake was assumed, in most studies, to equal precipitation recorded at the city of Devils Lake. Evaporation (E) from Devils Lake was not recorded on or near Devils Lake. Pan-evaporation data were collected intermittently at Devils Lake during April through September for 1951 through 1970 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1952-71). Ground-water inflow (G) to Devils Lake was assumed, in most studies, to be negligible; although a major glacial aquifer underlies Devils Lake at a shallow depth. Ground-water outflow was assumed not to occur.

Equation 15 was used to estimate the water balance of Devils Lake during 1986-88. Storage change (S) was computed with lake-stage data available from the Devils Lake gage and an elevation area-capacity table obtained from the North Dakota State Water Commission (Dale L. Frink, written commun., 1986). The surface area (A) of Devils Lake was determined with the lake-stage data and the elevation-area-capacity table.

Monthly estimates of precipitation falling on Devils Lake and evaporation from Devils Lake are listed in table 10 and shown in figure 9. Monthly precipitation values were obtained by determining the mean for seven precipitation stations--six precipitation stations located around the shore of Devils Lake and the precipitation station at Devils Lake KDLR radio station. Monthly precipitation around Devils Lake varied greatly. The maximum variation occurred in July 1987 when precipitation ranged from 1.48 inches at Camp Grafton land station to 6.65 inches at Sullys Hill National Game Preserve.

Precipitation recorded at Devils Lake KDLR radio station was 27.77 inches in 1986, an extremely wet year; 17.97 inches in 1987, a normal year; and 15.45 inches in 1988, a dry year (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1987-89). Annual mean precipitation for the precipitation-station network around Devils Lake, including the KDLR radio station, was 23.06 inches in 1986, 16.02 inches in 1987, and 12.86 inches in 1988. During 1986, precipitation was 20 percent greater at Devils Lake KDLR radio station than the annual mean precipitation for the precipitation-station network. Monthly and annual estimates of precipitation falling on Devils Lake are listed in table 10. Precipitation falling on Devils Lake ranged from 110 acre-feet in April 1988 to 31,300 acre-feet in July 1986.

Evaporation for May through October shown in table 10 and figure 9 was computed with the energy-budget method. Evaporation for May through October is equal to 86 percent of the mean annual lake evaporation, and evaporation for November through April is equal to 14 percent of the mean annual lake evaporation (Kohler and others, 1959). Data used to derive winter evaporation estimates (November through April) were sparse, especially in the northern part of the United States where no pan-evaporation data were collected during the winter. In this part of the United States, winter evaporation estimates are based on empirical relations between air temperature, dew point, incoming shortwave radiation, and windspeed (Kohler and others, 1959). Thus, the estimate of 14 percent for winter evaporation has a large amount of uncertainty. The winter evaporation is distributed as follows: November, 3 percent; December, 1 percent; January, 0.75 percent; February, 0.95 percent; March, 2.3 percent; and April, 6 percent (U.S. Department of Agriculture and U.S. Soil Conservation Service, no date). Monthly evaporation for November through April was estimated by multiplying the mean annual evaporation of 33.5 inches (Farnsworth and Thompson, 1982) by the percentage for that month. Evaporation from Devils Lake ranged from 1,120 acre-feet in January 1986 and 1987 to 35,900 acre-feet in July 1988 (table 10).

The ground-water flow systems and the ground-water inflow into Devils Lake during 1986-88 are being investigated by the North Dakota State Water Commission (Steve L. Pusc, written commun., 1989). Pusc (written commun., 1989) estimated that during 1986-88 annual ground-water inflow into Devils Lake from the Spiritwood aquifer system (Hutchinson and Klausing, 1980, p. 16) and from a shallow water-table aquifer was about 3,000 acre-feet. This estimate of ground-water inflow was used for the water balance of Devils Lake.

The computed water balance of Devils Lake for 1986-88 is listed in table 11 and shown in figure 10. The computed inflow into Devils Lake was

Table 10.--Monthly and annual estimates of precipitation falling on Devils Lake and evaporation from Devils Lake, 1986-88

Month	Surface area (acres)	Precipitation (feet)	Precipitation (acre-feet)	Evaporation (feet)	Evaporation (acre-feet)
			1986		
January	53,200	0.023	1,220	[1]0.021	1,120
February	53,200	.036	1,920	[1].027	1,440
March	53,300	.017	910	[1].064	3,410
April	53,600	.292	15,700	[1].167	8,950
May	53,500	.148	7,920	[2].287	15,400
June	53,500	.210	11,200	[2].379	20,300
July	53,100	.589	31,300	[2].520	27,600
August	52,800	.129	6,810	[2].534	28,200
September	52,700	.174	9,170	[2].331	17,400
October	52,800	.094	4,960	[2].188	9,930
November	52,800	.199	10,500	[1].084	4,440
December	52,900	.010	530	[1].028	1,480
Annual (rounded)		1.92	102,100	2.63	139,700

[1]Estimate based on mean annual evaporation of 33.5 inches (Farnsworth and Thompson, 1982).
[2]Estimate based on energy-budget method.

Table 10.--Monthly and annual estimates of precipitation falling on Devils Lake and evaporation from Devils Lake, 1986-88--Continued

Month	Surface area (acres)	Precipitation (feet)	Precipitation (acre-feet)	Evaporation (feet)	Evaporation (acre-feet)
		1987			
January	53,500	0.028	1,500	[1]0.021	1,120
February	53,600	.113	6,060	[1].027	1,450
March	53,900	.060	3,230	[1].064	3,450
April	55,800	.019	1,060	[1].167	9,320
May	58,900	.226	13,300	[2].570	33,600
June	59,800	.175	10,500	[2].512	30,600
July	59,800	.360	21,500	[2].556	33,200
August	59,600	.187	11,100	[2].492	29,300
September	58,800	.089	5,230	[2].344	20,200
October	57,600	.020	1,150	[2].298	17,200
November	57,100	.006	340	[1].084	4,800
December	57,000	.052	2,960	[1].028	1,600
Annual (rounded)		1.34	77,900	3.16	185,800

[1]Estimate based on mean annual evaporation of 33.5 inches (Farnsworth and Thompson, 1982).
[2]Estimate based on energy-budget method.

Table 10.--Monthly and annual estimates of precipitation falling on Devils Lake and evaporation from Devils Lake, 1986-88--Continued

Month	Surface area (acres)	Precipitation (feet)	Precipitation (acre-feet)	Evaporation (feet)	Evaporation (acre-feet)
			1988		
January	57,000	0.068	3,880	[1]0.021	1,200
February	56,900	.013	740	[1].027	1,540
March	56,900	.106	6,030	[1].064	3,640
April	56,900	.002	110	[1].167	9,500
May	57,200	.118	6,750	[2].470	26,900
June	55,800	.247	13,800	[2].613	34,200
July	55,800	.220	12,300	[2].643	35,900
August	53,800	.089	4,790	[2].559	30,100
September	53,100	.028	1,490	[2].417	22,100
October	52,700	.019	1,000	[2].241	12,700
November	52,500	.073	3,830	[1].084	4,410
December	52,600	.088	4,630	[1].028	1,470
Annual (rounded)		1.07	59,400	3.33	183,700

[1]Estimate based on mean annual evaporation of 33.5 inches (Farnsworth and Thompson, 1982).
[2]Estimate based on energy-budget method.

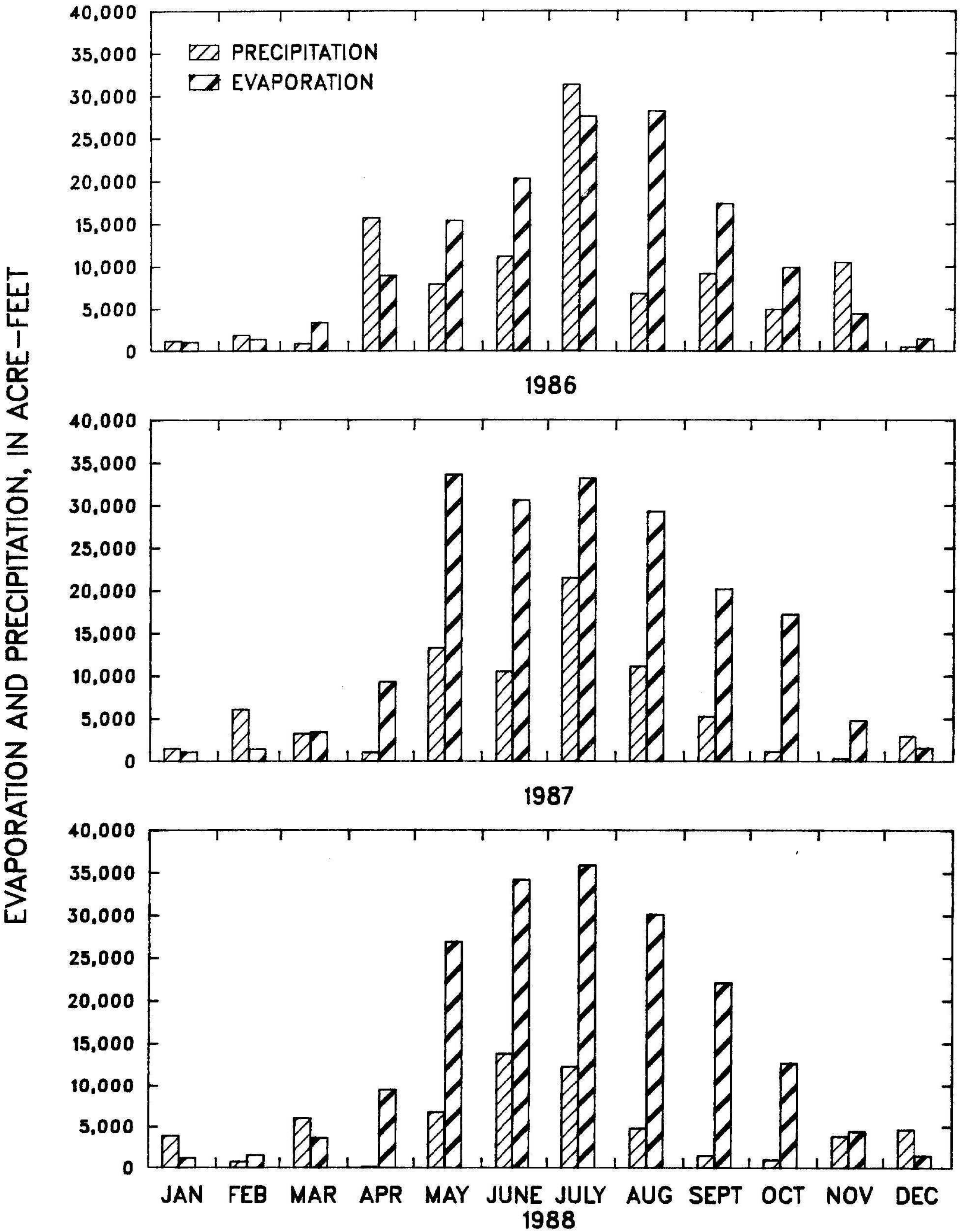

Figure 9.--Monthly estimates of precipitation falling on Devils Lake and evaporation from Devils Lake, 1986-88.

Table 11.--Computed water balance of Devils Lake, 1986-88

[*Q*, inflow, in acre-feet; *S*, storage change, in acre-feet; *P*, precipitation, in feet; *A*, surface area, in acres; *E*, evaporation, in feet; *G*, ground-water inflow, in acre-feet; Number in parentheses is gaged inflow from streams tributary to Devils Lake]

Year	*Q*		*S*		*P*(*A*)		*E*(*A*)		*G*
1986	58,100 (34,500)	=	23,500	-	102,100	+	139,700	-	3,000
1987	174,000 (112,200)	=	69,100	-	77,900	+	185,800	-	3,000
1988	19,700 (2,180)	=	-101,600	-	59,400	+	183,700	-	3,000

greater than the gaged inflow for each year of the study. The greatest difference between computed inflow and gaged inflow was 61,800 acre-feet in 1987.

The water level of Devils Lake increased 1.27 feet during 1987, and storage increased by 69,100 acre-feet. Errors in recorded water levels of Devils Lake are less than 0.05 foot. A 0.05-foot error in the water-level change during 1987 results in a 2,650-acre-foot error in the storage-change estimate. Thus, errors in recorded water levels cause only slight errors in storage change. A 10-percent error in the annual mean precipitation during 1987 results in a 7,790-acre-foot error in the precipitation term, and a 10-percent error in evaporation in 1987 results in an 18,580-acre-foot error in the evaporation estimate. Ground-water inflow could be in error by 100 percent, or 3,000 acre-feet. Although more accurate than previous ground-water inflow estimates, the 3,000-acre-foot estimate still is based on a limited knowledge of the ground-water flow system, especially the system under the bed of the lake (Steve L. Pusc, North Dakota State Water Commission, written commun., 1989). Maximum total error in computed inflow during 1987 would be about 32,020 acre-feet even if the potential error of each term in the water balance occurred in the same direction.

The gaged inflow accounts for most of the surface inflow, but a small quantity of inflow does enter Devils Lake as overland flow from the drainage area adjacent to the lake. Devils Lake has about 147 miles of shoreline. If 2 inches of runoff occurred during 1987 from all the area within 0.25 mile of Devils Lake, the ungaged inflow would equal about 4,700 acre-feet.

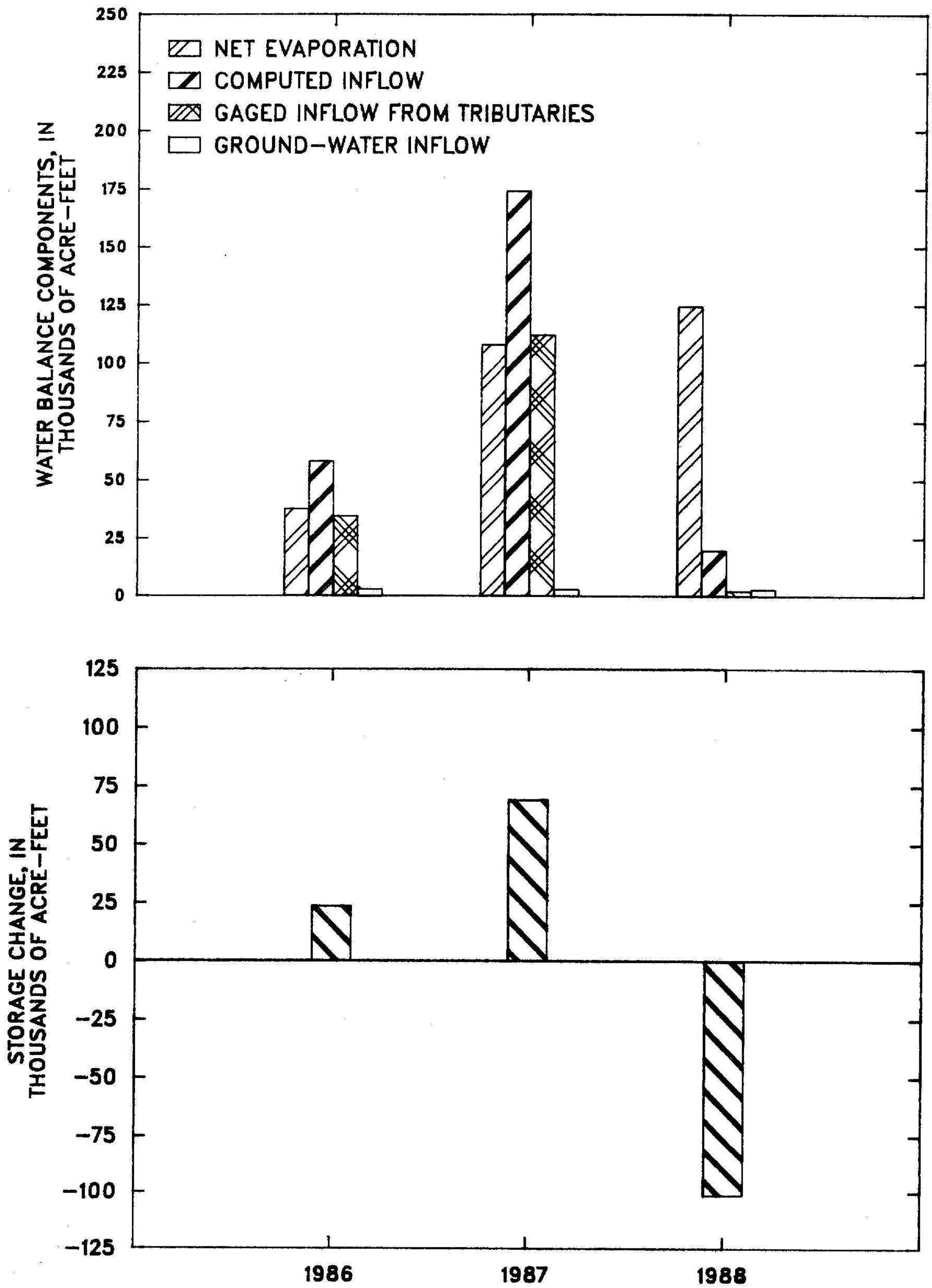

Figure 10.--Annual water balance of Devils Lake, 1986-88.

Therefore, if the computed inflow for 1987 is reduced by 32,020 acre-feet and the gaged inflow is increased by 4,700 acre-feet, a difference of 25,080 acre-feet still exists. Although many possible sources of error can account for some of the 61,800-acre-foot difference between computed and gaged inflow, no reasonable combination of errors can account for all of the difference. A more likely reason for the difference may be an incomplete understanding of hydrologic processes near the lake and under the bed of the lake. Studies of the ground-water system under the bed of the lake and extending from the littoral zone of the lake to 0.5 mile from the shore may provide a more complete understanding of the ground-water interaction in the lake.

SUMMARY AND CONCLUSIONS

Evaporation from Devils Lake during 1986-88 was computed by energy-budget and mass-transfer methods. The energy-budget method requires an extensive quantity of meteorologic and hydrologic data. Labor-intensive thermal surveys of Devils Lake were conducted on about a biweekly basis.

Evaporation can be computed by the energy-budget method by calculating all terms in the energy-budget equation. Incoming shortwave radiation incident to the water surface (Q_s) is dependent on the sun angle, the vapor content of the air, and the amount and type of cloud cover. Q_s is the most difficult term to estimate in the energy budget. Thus, for energy-budget studies, a backup pyranometer needs to be installed or a nearby station that measures Q_s needs to be available. Q_s varies greatly on a daily basis and more subtly between computation periods. Q_s reaches a maximum during mid-June through mid-July at about the same time that evaporation reaches its maximum.

Reflected shortwave radiation (Q_r) is a minor term in the energy budget. Q_r was recorded during 71 percent of the days used to compute evaporation by the energy-budget method. Missing Q_r values were calculated as a percentage of Q_s. The mean monthly percentage of Q_s reflected into the atmosphere ranged from 5.9 percent in May to 9.2 percent in October. Temporal variability of Q_r plays an extremely minor role in the variability of evaporation. Calculating Q_r as a percentage of Q_s does not introduce significant error in the energy-budget method.

Incoming longwave radiation (Q_a) is primarily dependent on the temperature and vapor content of the atmosphere. If the dry bulb air temperature (T_a) and the vapor pressure of the air for the actual humidity (e_a) are known, Brunt's equation provides a good estimate of Q_a on a daily basis and an excellent estimate of Q_a for computation periods of about 2 weeks. Q_a varies gradually throughout open-water periods and reaches a maximum in July or early August.

In most energy-budget studies, reflected longwave radiation (Q_{ar}) is estimated as a percentage of Q_a, and longwave radiation emitted from the water surface (Q_{bs}) is calculated with the Stefan-Boltzman law. In this study, Q_{ar} and Q_{bs} were measured as one term with an inverted radiometer; the combined term $Q_{ar}+Q_{bs}$, referred to as emitted longwave radiation, was used in the energy-budget method. A comparison of $Q_{ar}+Q_{bs}$ recorded by the radiometer and

$Q_{ar}+Q_{bs}$ calculated with the Stefan-Boltzman law indicates that the Stefan-Boltzman law provides an excellent estimate of $Q_{ar}+Q_{bs}$. Estimates of $Q_{ar}+Q_{bs}$ within 5 percent of the actual $Q_{ar}+Q_{bs}$ can be made if good water surface temperature data are available. $Q_{ar}+Q_{bs}$, the largest term in the energy budget, is the main mechanism through which water releases heat energy. As a percentage of other terms in the energy budget, $Q_{ar}+Q_{bs}$ is greatest in the fall.

Net advected energy (Q_v) is an extremely minor term in the energy budget of Devils Lake. Q_v generally accounts for less than 1 percent of the energy available for evaporation and sensible heat transfer to the atmosphere. The maximum Q_v of 13.2 calories per square centimeter per day for April 30 through May 22, 1987, equaled 4 percent of the energy available for evaporation and sensible heat transfer to the atmosphere. Q_v is a minor term in the energy budget even in years having greater-than-normal inflow entering the lake because the water temperature is relatively cool at maximum inflow.

The change in heat content of the water (Q_x) in Devils Lake causes about a 1-month lag in evaporation. During May and early June, a large part of incoming radiation is stored as heat energy, and evaporation is suppressed. During mid-August through October, energy released from storage provides a large part of the energy available for evaporation.

The relative importance each term in the energy-budget equation has on evaporation varies temporally throughout the open-water periods based on the relations between incoming radiation and the physical characteristics of Devils Lake. Q_s, Q_r, and Q_a are not dependent on the physical characteristics of Devils Lake. $Q_{ar}+Q_{bs}$, Q_v, and Q_x are dependent on the physical characteristics of Devils Lake.

Estimates of the maximum error in each term in the energy-budget equation were converted to a percentage of error in computed evaporation. Measuring each term with the same precision does not result in the same percentage of error in computed evaporation. For example, a 2-percent error in Q_r causes a mean error of 0.2 percent in computed evaporation, but the same 2-percent error in Q_s causes a mean error of 3 percent in computed evaporation. $Q_{ar}+Q_{bs}$ is one of the largest terms throughout all computation periods, and a 3-percent error in this term produces a mean error of 8.7 percent in computed evaporation. A 20-percent error in the Bowen ratio (R) causes a mean error of 2.2 percent in computed evaporation.

Meteorologic data required by the mass-transfer method are relatively inexpensive to obtain, but theoretical development is not as rigorous as in the energy-budget method. In the mass-transfer method of computing evaporation, the mass-transfer coefficient (N) was determined by using energy-budget evaporation as the independent measure of evaporation. A linear regression was developed between energy-budget evaporation and the mass-transfer product $[U_2(e_o-e_a)]$ to determine a value of N and to determine if the mass-transfer method provides an acceptable estimate of evaporation. The linear regression equation had a coefficient of determination of 0.73 and a standard error of estimate of 0.03 inch per day. Large differences in evaporation computed by the energy-budget and mass-transfer methods occur during open-water periods of about 2 weeks; but, during the entire open-water periods, relative differences in evaporation are much smaller. Mass-transfer evaporation was 11.8 percent greater than energy-budget evaporation in 1986, energy-budget evaporation was 7.6 percent greater than mass-transfer evaporation in 1987, and mass-transfer evaporation was 2.7 percent greater than energy-budget evaporation in 1988.

A water-balance equation was used to estimate the computed inflow into Devils Lake during 1986-88. Precipitation falling on Devils Lake was estimated by determining the monthly mean precipitation for seven precipitation stations located around the lake. Monthly precipitation values varied greatly among the seven stations, and significant variability occurred on an annual basis. Precipitation falling on Devils Lake ranged from 110 acre-feet for April 1988 to 31,300 acre-feet for July 1986.

Evaporation for May through October was computed by the energy-budget method of computation. Evaporation for November through April was estimated by multiplying the mean annual evaporation by the percentage associated with that month. Evaporation from Devils Lake during 1986-88 ranged from 1,120 acre-feet in January 1986 and 1987 to 35,900 acre-feet in July 1988. The evaporation rate was greater in 1988 (40.0 inches) than in 1987 (37.9 inches); however, the total evaporation from the lake surface was greater in 1987 because the larger surface area in 1987 more than compensated for the lower evaporation rate.

On the basis of the water-balance estimates of Devils Lake, the computed inflow was greater than the gaged inflow during each year of the study. Although relatively minor errors in water-balance terms can account for the difference between computed and gaged inflow for 1986 and 1988, no reasonable combination of errors in water-balance terms can account for the difference of 61,800 acre-feet in 1987. A likely reason for much of the difference may be an incomplete understanding of hydrologic processes near the lake and under the bed of the lake.

A complete understanding of the water-level fluctuations and associated water-quality changes of Devils Lake will require additional detailed studies to define the interaction of the lake with all components of the hydrologic system. This study is one of several that will be needed to increase our knowledge of water-level fluctuations of Devils Lake so the best possible water-management decisions can be made.

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GLOSSARY OF TERMS

[Some duplication of symbols occurs because of the desire to maintain the notation used in the original papers.]

A, surface area, in acres.

c, specific heat of water, which is equal to the amount of energy needed to raise 1 gram of water 1 degree Celsius.

c, constant used in equation 13.

d, constant used in equation 13.

E, evaporation, in feet.

e_a, vapor pressure of air for the actual condition of humidity, in millibars.

E_{eb}, evaporation computed by the energy-budget method, in cubic centimeters.

E_{mt}, evaporation computed by the mass-transfer method, in inches per day.

e_o, vapor pressure of saturated air at the water surface temperature, in millibars.

G, ground-water inflow, in acre-feet.

L, latent heat of vaporization at the water surface temperature, in calories per gram.

N, mass-transfer coefficient.

P, precipitation, in feet.

P_r, atmospheric pressure, in millibars.

Q, inflow, in acre-feet.

Q_a, incoming longwave radiation, in calories per square centimeter.

Q_{ar}, reflected longwave radiation, in calories per square centimeter.

$Q_{ar}+Q_{bs}$, emitted longwave radiation, in calories per square centimeter.

Q_{bs}, longwave radiation emitted from the water surface, in calories per square centimeter.

Q_e, energy used for evaporation, in calories per square centimeter.

Q_h, energy conducted from the water to the atmosphere as sensible heat, in calories per square centimeter.

Q_r, reflected shortwave radiation, in calories per square centimeter.

Q_s, incoming shortwave radiation incident to the water surface, in calories per square centimeter.

$Q_s(cl)$, daily incoming shortwave radiation at Cottonwood Lake site, in calories per square centimeter.

$Q_s(f)$, daily incoming shortwave radiation at Fargo, in calories per square centimeter.

Q_v, net advected energy, in calories per square centimeter.

Q_w, energy advected from the lake surface by evaporated water, in calories per square centimeter.

Q_x, change in heat content of the water, in calories per square centimeter.

R, Bowen ratio, which is energy conducted from the water to the atmosphere as sensible heat divided by energy used for evaporation.

S, storage change, in acre-feet.

T_a, dry bulb air temperature, in degrees Celsius.

T_b, base temperature used in energy-budget method computations, in degrees Celsius.

T_o, water surface temperature, in degrees Celsius.

T_w, wet bulb air temperature, in degrees Celsius.

U_2, mean windspeed at 2 meters above the water surface, in miles per hour.

$U_2(e_o-e_a)$, mass-transfer product, in miles per hour times millibars.

ρ, mass density of evaporated water, in grams per cubic centimeter.

σ, Stefan-Boltzmann constant, which is 8.14×10^{-11} calories per minute per degree Kelvin to the fourth power.