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MULTIPLE ESTIMATES OF LAKE ERIE EVAPORATION

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Abstract. Evaporation from large lakes cannot be measured directly, but several methods have been developed to compute lake evaporation. Because of the Great Lakes data limitations, evaporation determined by a single method is not sufficiently reliable and requires verification of accuracy by different methods. Monthly evaporation from Lake Erie was derived by the water budget, selected mass transfer, and the energy budget approaches. The period of record varies with the availability of data, 1937-68 for the water budget and mass transfer methods, and 1952-1968 for the energy budget method. Evaporation determined by the water budget method was used to provide control for the other methods. The evaporation rates varied from -9 to 25 cm/month with periods of low, median, and high annual evaporation averaging approximately 80, 90 and 100 cm. The analysis of results indicates that reasonably accurate evaporation estimates during the year can be obtained by the water budget and the modified Lake Hefner mass-transfer equations.

INTRODUCTION

Evaporation from the Great Lakes removes from two-thirds to three-quarters of the water supplied by precipitation and constitutes a very important water loss. The highest evaporation from the Great Lakes occurs on Lake Erie, where evaporation removes approximately a meter of water from the lake surface annually. The problem in determining evaporation from large lakes is that it cannot be measured directly, but several methods have been developed to compute lake evaporation. Because of the Great Lakes data limitations, evaporation determined by any available method has some important reservations and it is highly desirable to obtain verification of the computed evaporation results by different methods.

This paper is based on a comprehensive Lake Erie evaporation study (Derecki 1975), in which monthly evaporation was determined by the water budget, two mass transfers, the energy budget, and two combined mass transfer-energy budget equations, giving six relatively independent evaporation estimates. The paper presents summarized results of the three more promising evaporation estimates obtained by the water budget, selected mass transfer, and the energy budget approaches.

The period of record employed in the study varies, depending on the availability of data, from 32 years (1937-1968) for the water budget and mass transfer methods to 17 years (1952-1968) for the energy budget method. The availability of data also affects the mode of computations for the two periods.

Monthly evaporation rates during individual years were computed for the 32-year period by the water budget and mass transfer methods. Computations of the energy budget evaporation were limited to the 17-year average monthly values. The water budget evaporation estimates are used as a basis of comparison with the other estimates, because this is the only set determined from direct measurments of all major components. Some empiricism is required, but it is based on the Great Lakes data. The other methods require employment of empirical constants based on data which may not be representative for the Great Lakes.

Basic climatological and water temperature data used to compute evaporation were obtained, respectively, from land and water intake stations located around the lake. Such lake perimeter data are not representative of the open-lake conditions, but overwater measurements are not available for any appreciable period of time. The required adjustments for the perimeter data were taken from existing publications (wind, humidity) or developed in the study (precipitation, water temperature).

During the winter months, the presence of ice cover affects lake evaporation by reducing the open-water area. This ice cover effect is not considered in the mass transfer and energy budget computations. Relationships between ice cover and mass transfer evaporation are analyzed for the 6 years available ice cover data (1962-1968). The average energy budget evaporation values are not appropriate for the ice effect analysis.

WATER BUDGET METHOD

The water budget method consists of solving the mass balance equation for the unknown evaporation component. It is an accounting of all incoming and outgoing water, such as the inflow and outflow by the rivers, supply from and storage in the ground, variation of water storage in the lake, overwater precipitation, and evaporation. Disregarding the groundwater, which is largely unknown and assumed to be negligible, the water budget for Lake Erie may be expressed by the equation:

$$E = P + R + I - O - \Delta S \quad (1)$$

where

E = lake evaporation, cm
P = overwater precipitation, cm
R = runoff from drainage basin, cm
I = inflow from upper lakes, cm
O = outflow from Lake Erie, cm
ΔS = change in lake storage (plus if storage increases, minus if it decreases), cm.

Thermal expansion of water also affects the amount of evaporation computed by the water budget equation, but it is usually disregarded in the water budget for the Great Lakes. Considering the magnitude of other water budget components, thermal expansion in Lake Erie is insignificant (Derecki 1964).

The main advantage of the water budget method is that evaporation can be computed directly from hydrologic factors, with long periods of record, although empirical adjustments are required for the precipitation and runoff. Its main objections are the uncertainty with respect to groundwater and dependence of computed evaporation on large factors (inflow and outflow). Even relatively small errors in these factors may affect computed evaporation values considerably. A brief discussion of the individual water budget factors is given below. Lake Erie, its drainage basin, and pertinent locations are shown in Fig. 1.

Overwater Precipitation

Precipitation over Lake Erie was determined by averaging records from ten perimeter stations, adjusted to overwater conditions. The perimeter precipitation, although affected by the lakes, does not reflect overwater conditions because of frictional and thermal convergence along the shores (land uplift and surface temperature difference). Winter ice cover on the lakes complicates the process further and emphasizes the need for direct overwater observations. Measurements of precipitation over the lake for significant periods are provided by a number of island stations. These measurements are the most direct observations of the overwater precipitation available, although island data, especially from larger islands, may still contain substantial land effect.

Several islands in western Lake Erie have precipitation records, but only two of these, South Bass (Put-in-Bay Station) and Pelee Island, provide long-term records. Monthly ratios of island to perimeter precipitation were determined in conjunction with simultaneous records from five western perimeter stations. The lake-land ratios and other pertinent information are shown in Table 1. The Table also shows two sets of ratios determined in previous studies (Derecki 1964; Quinn 1971). The average annual precipitation ratio of 0.96 indicates a slight reduction in the overwater precipitation.

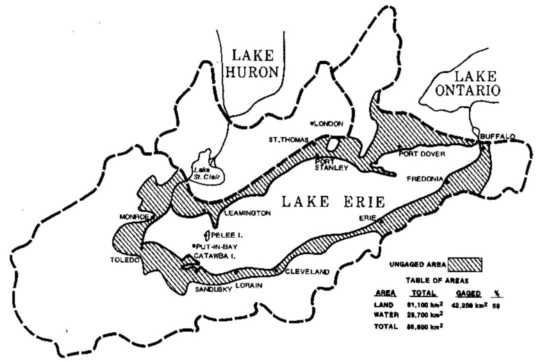

FIG. 1. Lake Erie basin.

The overwater precipitation for the entire lake during the period of study (1937-1968) was determined by adjusting average monthly records from ten shore stations by the lake-land precipitation ratios. The ten shore stations consisted of five western perimeter stations and five additional stations around the eastern half of the lake (Erie, Pa., Fredonia and Buffalo, N.Y. and Port Dover and St. Thomas, Ont.). Records from the shore stations indicate that precipitation around Lake Erie increases gradually with the predominant wind direction from west to east, reflecting the lake effect. Average values for the overwater precipitation and other water budget factors are shown in Table 2. Precipitation is well distributed throughout the year.

Runoff

Runoff from the drainage basin is based on streamflow records for the tributary rivers, which are published by the U.S. Geological Survey and the Inland Waters Branch, Canada. During the period of study, stream gauging increased sharply, expanding the gauged area from the initial 33% to the present 69%

TABLE 1. Lake Erie overwater precipitation analysis.

Author	(1) Derecki	(2) Quinn	(3) Derecki		
Year	1964	1971	present		
Period	13 years	22-24 years	36 years		
Parameter	R_p	R_p	Lake cm	Land cm	R_p
January	0.95	1.02	5.49	5.33	1.03
February	0.89	0.88	4.67	5.21	0.90
March	1.03	0.97	6.60	7.01	0.94
April	1.04	1.06	8.03	7.82	1.03
May	1.07	1.04	7.57	7.65	0.99
June	0.92	0.87	8.46	9.22	0.92
July	1.04	0.88	7.57	7.95	0.95
August	1.03	1.00	7.54	7.57	1.00
September	0.95	0.95	6.30	6.96	0.91
October	0.89	0.90	5.41	5.92	0.91
November	1.02	0.96	5.49	5.84	0.94
December	1.03	0.89	4.95	5.26	0.94
Annual	0.99	0.95	78.08	81.74	0.96

Lake: 1) 3 island stations: Put-in-Bay, Catawba, and Pelee.
2) 2 island stations: Put-in-Bay and Pelee.
3) 2 island stations: Put-in-Bay and Pelee.

Land: 1) 5 perimeter stations: Monroe, Toledo, Sandusky, Cleveland, and Leamington.
2) 2 perimeter stations: Sandusky and Leamington.
3) 5 perimeter stations: Monroe, Toledo, Sandusky, Cleveland, and Leamington.

TABLE 2. Average water budget factors for Lake Erie, cm, 1937-1968
$E = P + R + I - O - \Delta S$.

Period	P	R	I	O	ΔS	E
January	6.5	7.9	48.6	56.1	-0.3	7.1
February	5.3	8.8	42.3	51.0	2.2	3.2
March	6.6	14.4	51.7	57.6	13.7	1.4
April	8.6	12.7	53.3	58.4	15.4	0.8
May	7.9	7.1	56.1	63.4	6.0	1.6
June	7.7	4.2	54.8	61.5	2.3	2.9
July	7.4	2.3	57.4	62.2	-4.8	9.6
August	8.2	1.5	57.2	61.3	-8.0	13.6
September	6.5	1.3	55.1	58.0	-11.2	16.2
October	6.1	2.1	56.4	58.8	-8.8	14.6
November	6.7	3.4	54.1	56.9	-4.6	11.8
December	6.0	6.0	54.8	58.6	0.2	8.0
Annual	83.4	71.6	641.9	703.8	2.3	90.9

(42,200 km^2) of the total drainage basin. Runoff from ungauged streams and the lake periphery was obtained by using runoff per unit area from nearby gauging stations. The average annual runoff to Lake Erie during the period of study (72 cm on the lake surface) is equivalent to 30 cm on the land area and corresponds to 35% of the overland precipitation. Most of the runoff to the lake is supplied during winter and spring months, and very little during the rest of the year.

Inflow

The inflow to Lake Erie from the upper lakes consists of the flow of the Detroit River. Flows in the connecting rivers of the Great Lakes are measured and published by the U.S. Corps of Engineers and the Inland Waters Branch, Canada. The inflow is extremely important to the water budget. Inflow is by far the major portion of the Lake Erie water supply, and it is an order of magnitude greater than overwater precipitation or runoff. However, as a direct measurement of the total volume, the percent accuracy of inflow is much higher than that of runoff or precipitation. The variation of inflow is relatively small because of the regulation provided by the lakes.

Outflow

The outflow from Lake Erie consists of the flows in the Niagara River and the Welland Canal near Buffalo. The importance of outflow to lake hydrology is similar to that of inflow; however, the magnitude of outflow is even larger and affects the lake to a greater extent.

Change in Storage

The change in lake storage is determined from successive beginning-of-month levels, based on 2 days of record (one at the beginning of the month and one at the end of the preceding month) to minimize the effect of wind on the lake level disturbances. The beginning-of-month Lake Erie levels were determined by the Thiessen polygon method, taken from Quinn and Derecki (1976). The polygon network utilized available gauges during the period of study, which varied from five to thirteen gauges. The long-term change in storage is small due to balancing of rising and falling lake levels.

Evaporation

Evaporation from Lake Erie as computed by the water budget method for the period of study is listed in Table 3. Annual evaporation varied from a low of 68 cm to a high of 111 cm, with a 32 year average (1937-1968) of 91 cm. During the shorter 17-year period (1952-1968), used for the energy budget computations, the average annual evaporation was 97 cm, representing somewhat higher water loss from the lake. There is considerable variation in the annual evaporation from year to year, with definite periods of low, median, and high evaporation. These periods correspond approximately to the first, middle two, and last quarters of the period of study, with average annual values of about 80, 90, and 100 cm, respectively. The large difference in the average annual evaporation of these periods demonstrates the importance of using sufficiently long records to determine normal evaporation values.

Seasonal distribution of the annual evaporation is shown in Fig. 2, which contains the monthly average, maximum, and minimum evaporation values obtained during the period of study. The low evaporation season occurs during winter

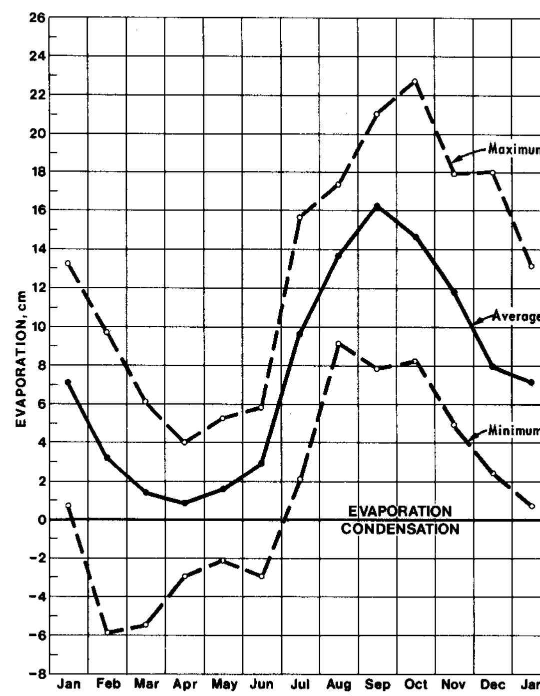

FIG. 2. Lake Erie evaporation by water budget method, 1937-1968.

and spring months, and the high evaporation season occurs during summer and fall. During the low evaporation season the evaporation process may be reversed to condensation on the lake surface (negative evaporation). The 32-year average monthly evaporation varied from a low of 0.8 cm in April to a high of 16.2 cm in September. For the shorter, 17-year period, the average monthly evaporation was on the average 0.5 cm higher. The extreme monthly evaporation values varied from condensation of 5.9 cm (February) to evaporation of 22.7 cm (October).

TABLE 3. Lake Erie evaporation by water budget method, cm, $E = P + R + I - O - \Delta S$.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1937	5.8	-1.5	5.5	-3.0	0.1	-2.5	6.8	9.2	20.1	13.3	11.3	3.4	68.5
1938	3.4	-5.9	4.0	4.0	1.5	1.2	2.1	13.5	15.8	13.3	14.3	8.8	76.0
1939	4.0	-0.6	2.2	1.2	1.2	1.4	7.3	14.1	17.7	14.9	12.1	9.1	84.6
1940	10.0	3.1	1.3	-1.8	-2.1	1.5	6.1	10.0	13.6	12.1	14.9	2.4	71.1
1941	5.5	5.1	0.1	0.0	1.1	2.7	10.6	14.3	16.1	12.1	11.9	5.2	84.7
1942	9.4	1.5	-3.7	-0.3	-1.1	2.8	5.2	16.1	16.7	9.7	10.6	6.1	73.0
1943	9.7	3.1	6.1	-1.0	0.6	4.2	9.5	14.9	16.7	14.3	10.0	10.9	99.0
1944	6.9	1.6	3.9	-1.1	-1.6	5.5	13.4	13.6	11.6	15.5	7.9	9.4	86.6
1945	11.0	3.4	-5.5	0.2	0.9	-3.0	8.9	12.8	7.9	17.1	11.0	10.1	74.8
1946	5.1	5.6	-1.3	2.4	1.5	0.9	10.6	15.2	12.0	12.5	11.2	10.4	86.1
1947	7.4	9.7	-0.3	-2.1	0.9	4.3	12.5	9.1	21.0	8.2	17.9	5.5	94.1
1948	13.2	3.6	1.6	0.3	0.9	1.1	10.6	13.4	16.4	15.5	8.6	7.4	92.6
1949	7.0	3.4	1.4	0.9	0.2	0.6	10.0	17.3	17.0	11.2	10.4	4.5	83.9
1950	2.7	7.2	-1.9	3.0	2.2	4.3	8.6	12.8	16.8	11.7	11.5	10.4	89.3
1951	3.7	1.2	2.2	2.3	1.6	5.1	12.2	14.4	18.0	14.3	12.0	11.5	98.5
1952	6.6	2.2	4.0	2.7	4.2	5.2	12.9	14.0	17.9	22.7	11.3	3.7	107.4
1953	0.7	3.0	2.1	3.1	1.2	2.1	11.9	13.6	19.8	13.7	9.8	10.1	91.1
1954	6.0	-3.4	4.6	-2.2	4.0	5.5	10.1	14.0	14.4	11.0	7.5	8.2	79.7
1955	5.8	1.5	3.0	-1.6	4.9	5.4	9.8	14.1	17.0	15.5	13.7	8.6	97.7
1956	6.2	6.1	-1.0	-0.9	-0.6	3.7	6.7	12.5	19.0	10.9	17.3	3.1	83.0
1957	9.7	-1.9	0.6	0.0	1.5	-0.3	7.6	15.8	13.7	15.8	10.1	3.3	75.9
1958	8.9	4.7	0.5	0.0	4.6	0.9	7.0	12.2	12.2	16.4	14.9	11.0	93.3
1959	2.1	1.8	1.6	0.3	0.2	5.8	7.9	12.1	19.2	13.4	14.9	3.3	82.6
1960	7.6	5.8	2.9	1.8	-1.0	1.8	8.8	13.4	17.2	21.6	12.2	18.0	110.1
1961	7.6	1.8	0.3	1.5	3.0	4.3	7.0	13.7	17.6	18.2	15.2	11.6	101.8
1962	11.9	4.6	1.5	3.7	5.2	4.8	13.4	12.5	18.3	15.8	9.4	9.7	110.8
1963	11.0	8.5	-0.3	2.2	2.4	5.2	12.1	14.0	15.3	12.1	15.5	10.9	108.9
1964	2.7	1.8	3.3	0.6	3.3	2.7	9.8	16.4	15.7	17.1	12.2	5.7	91.3
1965	9.2	4.3	0.9	2.5	1.3	3.9	11.5	14.4	12.5	18.6	11.9	7.3	98.3
1966	12.3	2.4	2.7	1.7	4.0	3.3	15.6	11.9	19.1	18.2	4.9	8.7	104.8
1967	7.1	8.9	3.3	1.2	4.3	3.0	9.3	15.2	17.3	13.5	11.6	8.7	103.4
1968	7.3	9.4	0.7	4.0	1.9	4.5	11.1	15.8	14.2	17.1	11.0	8.8	105.8
Mean	7.1	3.2	1.4	0.8	1.6	2.9	9.6	13.6	16.2	14.6	11.8	8.0	90.9
52-68	7.2	3.6	1.8	1.2	2.6	3.6	10.1	13.9	16.5	16.0	12.0	8.3	96.8

The sensitivity of various water budget parameters on computed evaporation was briefly examined. Because of their magnitude, the accuracy of inflow and outflow are most important to establishment of the evaporation values; however, the variation of evaporation depends on the increments of inflow and outflow, which are much smaller than their absolute values. Unlike runoff from the drainage basin, where most of the tributary streams have a low base flow and a relatively high range of variation, the inflow and outflow have a high base flow and a relatively low range of variation. Annually, the range of variation for evaporation and precipitation which is approximately one-half of their absolute values, exceeds the absolute values for runoff and the change in storage, and is about one-third for inflow and outflow.

MASS TRANSFER METHOD

The mass transfer method of computing evaporation is based on the removal of vapor from the water surface by turbulent diffusion. It consists of a modified application of Dalton's law, where evaporation is considered to be a function of the wind speed and the difference between the vapor pressure of saturated air at the water surface and the vapor pressure of the air above. The mass transfer equation which produced the better evaporation estimates was developed on a relatively small body of water, Lake Hefner (U.S. Geological Survey 1954) and tested successfully on a much larger lake in a different climatic environment, Lake Mead (U.S. Geological Survey 1958).

The problem in applying the mass transfer method to the Great Lakes is that climatological data for any appreciable period of time are almost exclusively restricted to the perimeter land stations, which do not reflect climatic conditions over large water areas. The required adjustments for perimeter data, or lake-land ratios for wind and humidity, have been developed for the Great Lakes and permit utilization of the available long-term data in the mass transfer computations. The Lake Hefner equation modified by wind and humidity ratios was considered to give satisfactory results on the Great Lakes (Richards and Irbe 1969). For metric units, the modified Lake Hefner equation becomes:

$$E = 0.0097\ (e_s - He_a)\ Ru_8 \qquad (2)$$

where

E = lake evaporation, cm/day

e_s = saturation vapor pressure at water surface temperature, mb

H = monthly lake-land humidity ratio

e_a = vapor pressure of the air above (8 m), mb

R = monthly lake-land wind ratio

u_8 = wind speed over lake at 8 m, m/s.

The monthly wind and humidity ratios used in previous Great Lakes evaporation studies are shown in Table 4. Monthly wind ratios for the open water season were developed by Lemire (1961) and extended for the winter months by Richards (1964). They indicate that wind speed over water is only slightly higher than wind speed over land in mid-summer, but is almost twice as high during fall and winter months, with an annual average of 1.66. Monthly humidity ratios were developed by Richards and Fortin (1962). The ratios indicate that overwater humidity is lower than overland humidity during the late spring

TABLE 4. Monthly lake-land wind and humidity ratios for the Great Lakes.

Period	Lemire 1961 R = wind over lake / wind over land	Richards and Fortin 1962 H = vapor pressure over lake / vapor pressure over land
January	1.96*	1.33
February	1.94*	1.30
March	1.88	1.21
April	1.81	1.14
May	1.71	0.86
June	1.31	0.94
July	1.16	1.09
August	1.39	1.09
September	1.78	1.11
October	1.99	1.15
November	2.09*	1.15
December	1.98*	1.31
Annual	1.66	1.14

*Values for winter months extended by Richards (1964).

and early-summer period and higher during the rest of the year, with an annual average of 1.14. These ratios are based on short periods of record (a few years) and should be reevaluated using more data presently available.

The use of the mass transfer method on the Great Lakes has recognized limitations; it depends on perimeter data and does not consider effects of ice cover, which tends to reduce winter evaporation. Primary advantages of the method are the elimination of main objections to the water budget method (groundwater, magnitude of inflow and outflow) and a capability for quick evaporation estimates from readily available data. The required data are discussed briefly below.

Meteorological Data

Meteorological data for the mass transfer computations were determined by averaging records from four first-order weather stations (Buffalo, N.Y., Cleveland and Toledo, Ohio, and London, Ontario), located on opposite ends of Lake Erie, to give a good approximation of average conditions around the lake. Elevation of the sensors for various parameters at these stations varied extensively during the period of study, from approximately 1 m to over 100 m. The perimeter wind speed was adjusted to a common elevation of 8 m by the 1/7 power law:

TABLE 5. Average mass transfer factors for Lake Erie, 1937-1968
$E = 0.0097\,(e_s - He_a)\,Ru_8$.

Factor	u_8	h	T_a	T_w	E
Units	m/s	%	°C	°C	cm
January	5.18	80	-3.9	0.4	5.2
February	5.15	78	-3.3	0.1	4.3
March	5.22	76	1.1	0.8	1.2
April	5.03	70	7.9	3.6	-1.6
May	4.39	69	13.8	9.4	6.0
June	3.92	70	19.6	16.3	5.7
July	3.59	70	21.9	20.5	5.6
August	3.46	74	21.1	22.2	10.7
September	3.79	74	17.1	19.4	14.1
October	4.15	74	11.4	15.1	15.5
November	4.92	77	4.5	10.1	16.2
December	5.03	79	-1.8	3.1	7.0
Annual	4.49	74	9.1	10.1	89.8

$$u_2 = u_1 \left[\frac{Z_2}{Z_1}\right]^{1/7} \quad (3)$$

where

u_2 = wind speed at height level two
u_1 = wind speed at height level one
Z_2 = height level two
Z_1 = height level one

Adjustment of wind speed to the 8 m height reduced the average monthly and annual values by 10%. Average values for the perimeter wind speed and other mass transfer factors are shown in Table 5. Prevailing winds are from the west-southwest direction. Vapor pressure of the air is a function of air temperature and relative humidity. The air vapor pressure representing average perimeter conditions had the average annual value of 10 mb.

Water Surface Temperature

The only sources of water surface temperature data with long periods of record in the Great Lakes are the municipal water intakes. Water temperature at the intake stations is obtained in the coastal waters, a few hundred to a few thousand meters off shore at some depth below the surface. These data do not represent lake surface temperatures and require adjustments to open lake conditions. The surface temperatures used in the present study were obtained by

TABLE 6. Lake Erie water surface temperature analysis, ^{o}C.

Period	Open lake Millar (1952) 1937-1941 (1)	Water intakes (Avon & Erie) 1937-1941 (2)	Adjustments (1)-(2)
January	0.6**	2.5	-1.9
February	0.0**	2.3	-2.3
March	0.6**	2.7	-2.1
April	3.3*	6.4	-3.1
May	10.0	12.8	-2.8
June	17.2	18.7	-1.5
July	21.1	22.6	-1.5
August	22.8	23.9	-1.1
September	19.4	20.7	-1.3
October	15.0	15.5	-0.5
November	9.4	8.8	+0.6
December	3.3*	4.4	-1.1
Annual	10.2**	11.8	-1.6

* Values extrapolated from partial Millar's records
** Estimated values

adjusting values derived from the water intakes at Erie, Pa., and Avon Lake, Ohio. The average temperature from these two stations was considered to be sufficiently representative of the whole lake by Powers et al. (1959). The required adjustments were derived from the water surface temperatures presented by Millar (1952) and simultaneous records from the water intake stations. The surface temperatures from Millar and water intakes and the corresponding adjustment terms are shown in Table 6. Due to insufficient data during winter months, Millar excluded winter temperatures and these had to be estimated. Adjustments to the monthly shore temperatures are mostly negative, with the annual average of -1.6^{o}C. These temperature adjustments are based on a relatively short period of record and may be modified by more extensive temperature relationships.

The overwater saturation vapor pressure determined from the water surface temperatures has an average annual value of 14 mb. Values of the vapor pressure difference were adjusted to a common elevation of 8 m. The adjustment increases the vapor pressure difference by 9%. This height adjustment has never been made in the previous mass transfer studies of the Great Lakes. The vapor

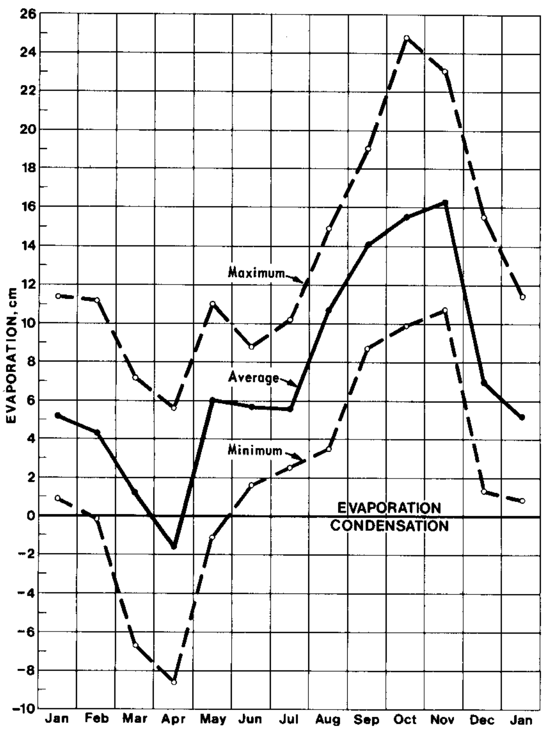

FIG. 3. Lake Erie evaporation by mass transfer method, 1937-1968.

pressure height adjustments were made by the logarithmic law:

$$\Delta e_2 = \Delta e_1 \frac{\log Z_2 + 4.174}{\log Z_1 + 4.174} \quad (4)$$

where

Δe_2 = vapor pressure difference at height level two

Δe_1 = vapor pressure difference at height level one

Z_2 = height level two, m

Z_1 = height level one, m

Evaporation

Lake Erie mass transfer evaporation computed for the period of study is given in Table 7. Annual evaporation varied from 68 cm to 118 cm, with a 32-year annual average (1937-1968) of 90 cm and

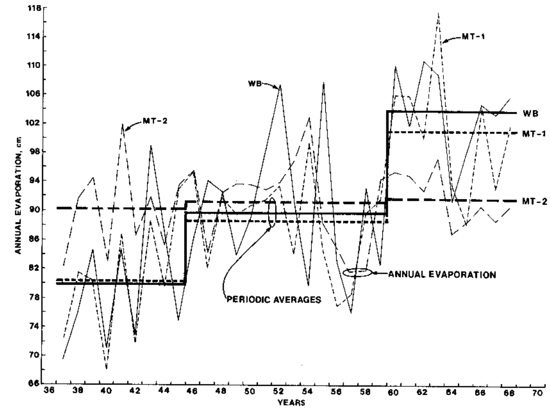

FIG. 4. Comparison of Lake Erie water budget and mass transfer annual evaporation and periodic averages, 1937-1968.

a 17-year average (1952-1968) of 95 cm. These annual values agree closely with those determined by the water budget method. The low and high annual values obtained by the two methods do not always coincide, but the mass transfer determination indicates a similar trend for the low, median, and high evaporation periods (approximately 80, 90, and 100 cm for the first, middle two, and last quarters of the 32-year period). The average monthly evaporation for the 1937-1968 period varied from -1.6 cm in April to 16.2 cm in November. Condensation occurred from February through May, but only April produced net condensation. Seasonal distribution of evaporation, indicating monthly averages and extremes, is shown in Fig. 3. Monthly extremes varied from condensation of 8.6 cm in April to evaporation of 24.8 cm in October.

Comparison of water budget and mass transfer evaporation is given in Figs. 4 and 5, showing both mass transfer estimates. Results obtained by the modified Lake Hefner equation are designated as MT-1 and the other mass transfer equation (Harbeck 1962) as MT-2.

TABLE 7. Lake Erie evaporation by mass transfer method, cm, $E = 0.0097\ (\Delta e_8)\ Ru_8$.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1937	1.4	2.7	2.9	-0.5	4.4	5.4	5.3	5.3	15.3	13.5	12.5	4.3	72.5
1938	4.1	1.4	-1.2	1.1	6.5	7.4	4.6	11.4	13.6	12.6	14.3	5.7	81.5
1939	2.8	3.0	2.4	0.4	5.0	6.2	6.0	10.5	12.9	15.7	10.7	4.8	80.4
1940	7.8	2.6	3.4	-1.4	3.0	4.2	4.4	7.1	9.2	11.3	13.9	2.6	68.1
1941	3.5	4.3	3.3	-2.7	7.7	5.6	5.1	14.0	15.4	14.1	12.6	3.8	86.7
1942	5.0	4.9	-0.6	-1.3	4.5	2.1	6.4	9.2	12.3	11.1	12.3	5.9	71.8
1943	4.5	3.8	3.5	2.1	3.0	3.8	4.9	11.3	13.9	16.0	13.3	8.5	88.6
1944	0.9	3.6	3.9	-1.1	-1.1	5.5	8.4	9.0	10.5	17.7	13.1	9.3	79.7
1945	8.5	2.5	-6.7	1.4	9.8	3.9	5.5	11.4	12.1	17.3	18.2	9.1	93.0
1946	4.5	4.6	-4.3	5.6	8.6	7.4	5.5	12.5	11.2	13.5	18.2	7.9	95.2
1947	1.6	8.2	2.9	-2.8	5.7	4.5	3.8	3.5	17.3	9.9	20.8	6.8	82.2
1948	8.3	4.4	2.1	-1.1	8.6	6.1	4.2	9.7	15.6	13.4	12.4	8.2	91.9
1949	1.9	1.7	3.3	1.6	7.7	5.8	3.1	13.4	13.9	13.8	18.4	5.0	89.6
1950	2.7	5.3	4.9	1.0	2.9	7.7	5.1	11.3	8.7	10.3	23.0	7.9	90.8
1951	3.1	2.5	1.3	-2.1	5.3	5.3	6.4	12.5	16.5	13.4	19.7	7.6	91.5
1952	2.3	1.7	0.7	-3.4	6.8	7.6	7.5	11.0	14.2	24.8	15.8	4.5	93.5
1953	1.0	2.0	-0.2	1.5	1.1	4.7	6.8	10.8	19.0	12.3	16.6	8.6	84.2
1954	5.8	-0.2	4.5	-4.1	10.5	6.4	10.2	14.0	14.8	15.5	14.5	7.4	99.3
1955	5.4	2.3	2.0	-4.6	8.2	7.6	3.1	7.7	15.4	15.7	16.2	6.0	85.0
1956	4.0	2.3	1.8	-0.7	5.5	3.8	4.1	8.8	16.1	11.6	18.2	1.4	76.9
1957	7.3	0.8	-0.5	-6.6	6.7	3.2	6.4	13.0	13.4	15.3	16.5	3.1	78.6
1958	4.0	7.7	-0.8	-4.1	9.3	8.4	2.5	10.8	12.6	14.3	16.0	9.1	89.8
1959	7.2	4.9	2.1	-3.1	1.5	8.8	7.4	8.4	16.7	17.9	17.0	2.8	91.6
1960	2.2	3.7	7.2	-8.6	4.1	7.4	7.9	10.0	14.9	23.4	18.3	15.5	106.0
1961	9.8	1.6	-0.6	0.1	11.0	4.7	4.9	11.3	14.0	18.7	19.9	10.5	105.9
1962	10.5	7.7	1.8	-2.9	2.5	5.9	6.4	9.7	17.5	14.2	15.4	11.4	100.1
1963	11.4	11.2	-2.1	-0.2	8.7	6.1	6.6	14.7	15.5	14.4	19.0	12.2	117.5
1964	4.5	5.9	-0.7	-5.2	5.9	6.6	6.7	14.9	16.9	17.3	15.3	5.4	93.5
1965	7.4	7.3	2.9	-4.9	1.3	6.5	9.0	10.5	9.8	21.7	14.1	2.6	88.2
1966	9.9	3.8	0.1	-1.2	10.3	6.5	2.5	10.9	16.9	20.4	15.8	8.3	104.2
1967	3.1	9.8	0.7	-2.4	10.6	1.6	3.2	13.5	14.3	15.9	18.0	4.7	93.0
1968	9.0	9.9	-0.1	-1.8	5.5	4.4	5.6	10.8	10.9	18.3	17.0	12.2	101.7
Mean	5.2	4.3	1.2	-1.6	6.0	5.7	5.6	10.7	14.1	15.5	16.2	7.0	89.8
52-68	6.2	4.8	1.1	-3.1	6.4	5.9	5.9	11.2	14.9	17.2	16.7	7.4	94.6

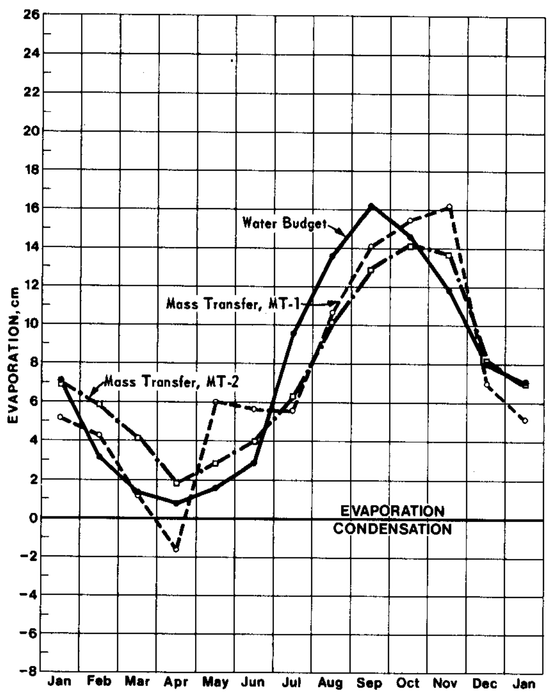

FIG. 5. Comparison of water budget and mass transfer evaporation from Lake Erie, 1937-1968.

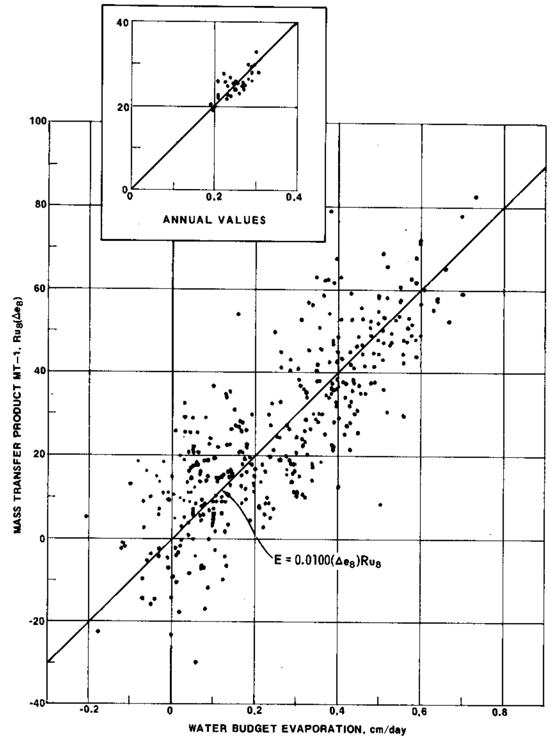

FIG. 6. Relationship between water budget evaporation and mass transfer product, MT-1, 1937-1968.

Figure 4 shows the comparison of annual evaporation and the low, median, and high periodic averages discussed previously. In contrast to the selected evaporation estimates (WB and MT-1), MT-2 does not indicate any significant periodic variation, which was the main reason for its elimination. Figure 5 shows the seasonal distribution of the average monthly values, which indicates that monthly evaporation determined by the water budget and mass transfer methods may vary considerably, even when annual estimates show good agreement. The shape of seasonal distribution curves, especially during high evaporation seasons, also indicates that the mass transfer evaporation lags behind water budget values by approximately a month. This suggests a considerable delay in the climatic cause and effect relationship, but analysis of the data shows that the apparent lag in the mass transfer seasonal distribution is caused mainly by the water surface temperature adjustments. Without these adjustments the shape of mass transfer distribution during most months would be similar to that of the water budget, but evaporation values would be much higher and the unadjusted shore temperatures would definitely not represent open lake conditions. The water budget-mass transfer difference is especially high during May for the evaporation computed by the Lake Hefner equation and is substantiated by other studies (Richards and Irbe 1969). This large difference is not indicated by evaporation computed from Harbeck's equation and must be caused by the monthly humidity ratio, which is apparently too small.

The applicability of the Lake Hefner mass transfer equation to the Great Lakes was also analyzed

TABLE 8. Estimates of Lake Erie average monthly ice cover, %, 1962-1968.

Year	December	January	February	March	April
1962-63	5	81	98	70	14
1963-64	5	62	89	36	4
1964-65	12	43	80	71	22
1965-66	0	25	77	28	1
1966-67	5	15	80	59	3
1967-68	7	73	91	59	6
Average	6	50	86	54	8

by conducting an independent check of its mass-transfer coefficient shown in Fig. 6. The derived coefficient agreed closely with the value used (0.0100 viz 0.0097). Considering all aspects of the above evaporation discussion, the Lake Hefner equation appears to be appropriate for the Great Lakes. Some of the water budget-mass transfer evaporation differences are caused by the required adjustments of mass transfer data. These adjustment factors should be reevaluated.

Effect of Ice Cover

Winter evaporation determined by the mass transfer method does not take into account possible effects of ice cover, which inhibits the evaporation process. Since Lake Erie is known for its extensive ice cover, computed mass transfer evaporation is potentially too high. This fact was recognized in previous studies, but adjustments for mass transfer evaporation based on ice cover have not been established. The ice cover for Lake Erie has been determined from ice surveys conducted regularly since 1962 by the Lake Survey Center, NOAA, and the Ice Forecast Centre in Canada. Estimates of the average monthly ice cover on the lake obtained from the individual surveys during December through April 1962-1968, are given in Table 8. Extensive ice cover normally occurs during January, February, and March, with average concentration exceeding 50%, and is usually very light during December and April, with average concentration below 10%.

The relationship between ice cover and mass transfer evaporation was evaluated by two approaches. In the first approach, standard mass transfer evaporation values, representing overwater conditions, were used in conjunction with the water budget evaporation to obtain monthly mass transfer-water budget evaporation differences, which should represent overcomputation of mass transfer evaporation due to disregard of ice cover. The relationship of evaporation difference (E_{MT} - E_{WB}) versus ice cover is shown in Fig. 7. It appears that the effect is not progressive with the gradual increase of ice cover, but grouped into light and extensive ice-cover concentrations

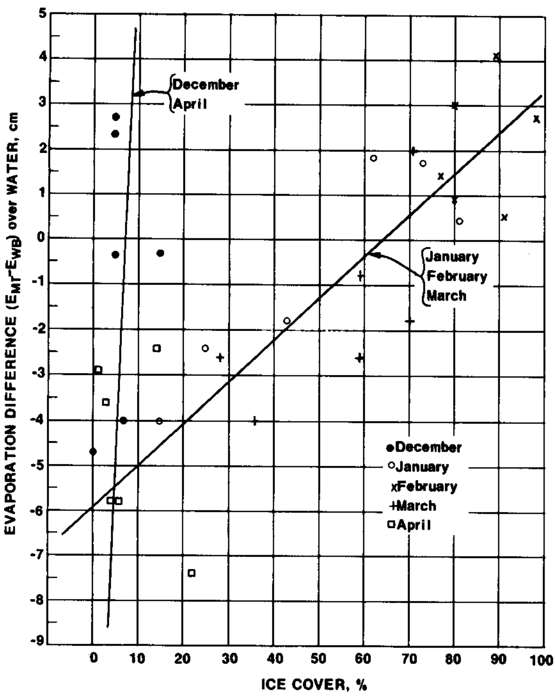

FIG. 7. Relationship between evaporation difference by the mass transfer minus water budget methods and the ice cover, 1962-1968.

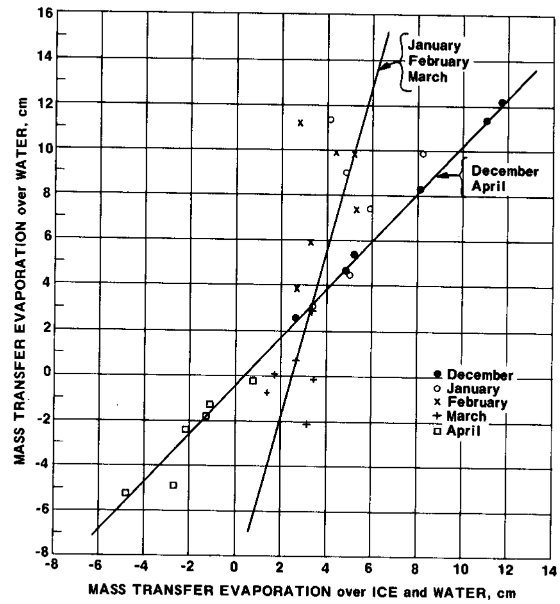

FIG. 8. Relationship between mass transfer evaporation for the open water and the actual ice cover and open water conditions, 1962-1968.

related to seasonal periods. The light ice-cover period during December and April, limited to about 15% concentration, shows very little, if any, relationship between ice cover and evaporation differences. The extensive ice cover period during January, February, and March, in excess of about 15% concentration, shows a definite relationship between ice cover and evaporation differences. During this period the ice cover reduces the lake evaporation significantly, indicating an average reduction of approximately 1 cm per 10% ice cover. However, this rate of evaporation reduction is tentative, at best, because of weak data. The weakness of the data is indicated by the large scatter (± 2 cm) and many negative values for the evaporation increments, which should be positive.

The second approach utilized only the mass transfer evaporation. A special set of mass transfer evaporation values from the ice surface was computed, using air temperature to represent surface ice temperatures. These values were combined with normal values for the open-water areas, using observed ice-cover concentration, to reflect the actual ice-cover and open-water conditions. The relationship of mass transfer evaporation to the standard computations over water and adjusted computations for the actual lake surface conditions is shown in Fig. 8. The results are generally similar to those discussed above. For the light ice-cover period of December and April the relationship is very strong, with an average slope of nearly one to one (1.07), indicating insignificant ice-cover effect. For the extensive ice cover period of January, February, and March, the relationship is rather weak, with large scatter of data, but indicates a definite ice cover effect with a tentative average slope of nearly four to one. Because of weak data no attempt was made to derive and apply monthly ice-cover adjustments to the mass transfer evaporation.

ENERGY BUDGET METHOD

The energy budget method is based on the exchange of thermal energy between a body of water and the atmosphere. Disregarding some minor energy sources, the basic heating or cooling processes comprising the energy budget of a lake are the heat gains or losses produced by shortwave and longwave radiation, heat transfer to the atmosphere through sensible and latent heat, heat advection caused by exchange of water masses, and heat storage within the lake. The energy budget for Lake Erie may be expressed by the equation:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_b - Q_t + Q_v = Q_h + Q_e \qquad (5)$$

where

- Q_s = incident solar radiation, ly/day
- Q_r = reflected solar radiation, ly/day
- Q_a = incident atmospheric radiation, ly/day
- Q_{ar} = reflected atmospheric radiation, ly/day
- Q_b = radiation emitted by the body of water, ly/day
- Q_t = change in energy storage within the water body, ly/day
- Q_v = net advected energy, ly/day
- Q_h = conduction of sensible heat to the atmosphere, ly/day
- Q_e = energy utilized by evaporation, ly/day.

The energy terms comprising the left-hand side of the equation (Q_s through Q_v) can be determined from meteorological and limnological observations, giving ($Q_h + Q_e$). One of these two energy terms may be eliminated by using the independently determined Bowen ratio, and since the quantity desired is Q_e, the energy budget equation expressed in a more convenient form is:

$$Q_e = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_b - Q_t + Q_v}{1 + R} \qquad (6)$$

where R = Bowen ratio (Q_h/Q_e).

The energy utilized for evaporation is converted to the actual water loss by the equation:

$$E = \frac{Q_e}{dL} \qquad (7)$$

where

- E = lake evaporation, cm/day
- d = density of water (fresh water = 1.0)
- L = latent heat of vaporization, cal/cm^3 (590).

The energy budget method of computing evaporation offers a potentially accurate method to determine evaporation losses from large lakes. However, instrumentation for the required data is very expensive and most of the data are not available from the regular climatological or hydrological networks. Another disadvantage of the energy budget method is the necessity for the Bowen ratio, which assumes that the transfer processes for heat and water vapor are similar. At present, separate treatment of these processes is not feasible, but a critical value of R, approching -1.0, renders computed evaporation extremely large. The Bowen ratio is expressed by the equation:

$$R = 61 \times 10^{-5} p \frac{T_w - T_a}{e_s - e_a} \quad (8)$$

where

p = atmospheric pressure, mb

T_w = water surface temperature, ^oC

T_a = air temperature, ^oC

e_s = saturation vapor pressure at T_w, mb

e_a = vapor pressure of the air, mb.

The air temperature and vapor pressure of the air for Lake Erie were determined from land stations located around the lake. Because of the sensitivity of the Bowen ratio, the perimeter data may be unsuitable for determination of R values. Rodgers and Anderson (1961) indicate that air temperatures at 2 m over the Great Lakes are much closer to the water surface temperatures than to air temperatures measured at land stations. They suggest that better overwater temperatures may be obtained from the following formula:

$$T_2 = 0.25\ T_a + 0.75\ T_w \quad (9)$$

where

T_2 = overwater air temperature at 2 m.

In the Lake Erie study several sets of Bowen ratios were determined, using perimeter and adjusted data, and tested to enable selection of best available values. The overall analysis of results suggests that the location of air temperature measurements is important while that of humidity may be negligible. Table 9 gives the selected set of Bowen ratios for the 1952-1968 period, representing the energy budget period of study. The energy budget of Lake Erie for this period is given in Table 10. A brief discussion of the energy terms is given below.

Solar Radiation

Solar radiation on the earth's surface consists of the shortwave incident and reflected radiation components. The incoming solar radiation is reduced by the atmospheric attenuation of the extraterrestrial radiation due to scattering, reflection, and absorption. Since these factors may differ considerably over land and large water areas, radiation measurements should be made over the lake. However, the only measurements of solar radiation with a substantial period of record in the Lake Erie basin are those made at Cleveland, Ohio. Cleveland records were used in the present study; thus, listed values are potentially too low during summer and too high during winter months. Preliminary investigations of solar radiation on the Great Lakes (Richards and Loewen 1965) indicate that perimeter measurements are 35% smaller during mid-summer and similarly greater during mid-winter.

The reflected solar radiation depends on the surface albedo or the ratio of the reflected to incident radiation. Albedo values for the water surface can be assumed to be constant for daily or longer periods, and the 6% value recommended by Kohler and Parmele (1967) was used. The small albedo for open water increases drastically with ice and snow cover. Bolsenga (1969) gives albedo values for various types of ice common on the Great Lakes, which range from 10% for clear ice to 46% for snow ice, both free of snow cover, and 67% for snow covered ice. Winter

TABLE 9. Determination of Lake Erie Bowen ratios, 1952-1968.

$$R = \frac{Q_h}{Q_e} = 61 \times 10^{-5} p \frac{T_w - T_a}{e_s - e_a}$$

Variables	T_2	T_w-T_2	e_s-e_a	R
Units	°C	°C	mb	
January	-1.0	1.2	1.73	0.42
February	-0.8	0.9	1.49	0.37
March	0.6	-0.1	0.34	-0.18
April	4.5	-1.3	-1.05	0.75
May	9.5	-0.4	2.40	-0.10
June	16.8	-0.9	3.45	-0.16
July	20.7	-0.4	4.13	-0.06
August	21.6	0.3	6.67	0.03
September	18.8	0.6	6.67	0.05
October	14.1	1.0	5.96	0.10
November	8.7	1.4	4.91	0.17
December	1.9	1.2	2.10	0.35
Annual	9.6	2.9	3.23	0.14

ice cover was not considered in the energy budget computations, but the error would still be insignificant because the reflected solar radiation is relatively small.

Terrestrial Radiation

Terrestrial radiation over a body of water consists of the longwave incident and reflected atmospheric radiation components and the longwave radiation emitted by the water body. The net result of longwave radiation is an effective back radiation, an energy loss from the water to the atmosphere. Net back radiation from the lakes is usually calculated from related climatic elements; it is a function primarily of the air temperature, which controls atmospheric radiation, and the temperature of the water surface, which governs emitted radiation. The average net back radiation determined for Lake Erie was 100 ly/day.

Atmospheric radiation was computed by the equation proposed by Anderson and Baker (1967), who present a method for computing incident longwave radiation under all atmospheric conditions from observations of surface air temperature, vapor pressure, and incoming solar radiation. Their approach consists of determining typical clear sky atmospheric radiation adjusted for a particular location

TABLE 10. Energy budget of Lake Erie, ly/day, 1952-1968
$Q_s - Q_r + Q_a - Q_{ar} - Q_b - Q_t + Q_v = Q_h + Q_e$.

Terms	Q_s	Q_r	Q_a	Q_{ar}	Q_b	Q_t	Q_v	Q_h	Q_e
January	129	8	570	17	632	-48	-9	24	57
February	189	11	571	17	631	3	-7	25	66
March	290	17	584	18	635	49	-3	-33	185
April	381	23	652	20	662	157	9	77	103
May	507	30	622	19	720	348	11	-3	26
June	558	33	721	22	792	276	11	-32	199
July	537	32	733	22	841	182	3	-13	209
August	465	28	737	22	859	58	-3	7	225
September	369	22	714	21	830	-131	-6	16	319
October	257	15	665	20	783	-202	-6	30	300
November	139	8	649	19	729	-357	-11	55	323
December	109	7	586	18	660	-335	-11	87	247
Annual	327	20	650	20	731	0	-2	20	188

(A) and the degree of cloudiness (Q_s/Q_{sc}), as expressed by the equation:

$$Q_a = \sigma T_a^4 - \left[228.0 + 11.16(\sqrt{e_{sa}} - \sqrt{e_a}) - A\right] \times \left[Q_s/Q_{sc}\right]^n \quad (10)$$

where

Q_a = incident atmospheric radiation under all conditions, ly/day
σ = Stefan-Boltzmann constant (11.71×10^{-8} ly/day/$^oK^4$)
T_a = surface air temperature, ^oK
e_{sa} = saturation vapor pressure at T_a, mb
e_a = surface vapor pressure at T_a, mb
A = station adjustment term, ly/day
Q_s = incident solar radiation, ly/day
Q_{sc} = clear sky solar radiation, ly/day
n = exponent of ratio for degree of cloudiness (approx. 2.0).

Since all input data for the above equation are based on the perimeter measurements, the resulting atmospheric radiation contains a land surface bias discussed under solar radiation.

The reflectivity of a water surface for atmospheric radiation was determined by Anderson (1954) to be 3%, which is only half as large as for solar radiation. The resulting heat loss from Lake Erie through reflected radiation is similar in both wave lengths, since incident atmospheric radiation provides approximately twice as much heat to the lake as solar radiation.

Longwave radiation emitted from the lake is a function of the

Stefan-Boltzmann law for black body radiation and the emissivity of the water surface. Emissivity indicates the relative power of a surface to emit heat by radiation in comparison with the maximum possible intensity of a black body. Emissivity of the water surface was determined by Anderson (1954) to be 0.970. The relationship for the emitted radiation is expressed by the equation:

$$Q_b = \varepsilon \sigma T_w^4 \qquad (11)$$

where

Q_b = radiation emitted from the lake, ly/day
ε = emissivity of water surface (0.970)
σ = Stefan-Boltzmann constant (11.71×10^{-8} ly/day/°K^4)
T_W = water surface temperature, °K.

Heat Storage

Heat storage in the lake was determined from the water temperature profiles, based on temperature surveys. The change in the heat storage during monthly intervals was used to compute evaporation. This change in heat storage is the difference in heat content at the beginning and end of the month, a product of lake volume and corresponding temperature.

The change in lake volume is determined by the monthly rise or fall in lake levels, since the area of the lake remains constant for practical purposes. Because monthly increments in lake levels are small in comparison with the total depth of the lake, the average volume of the lake may be used without significant error. The resulting equation becomes:

$$Q_t = V(T_2 - T_1) \qquad (12)$$

where

Q_t = change in heat content, cal
V = average volume of the lake from long-term records, cm^3
T_2 = average temperature of the lake at the end of the month, °C
T_1 = average temperature of the lake at the beginning of the month, °C.

The heat content in the lake was computed by summing up energy contents calculated at the surface and several predetermined depth layers, indicated in Fig. 9. The water temperatures at the beginning of the month were derived from Lake Erie temperature surveys published by the Great Lakes Institute, University of Toronto. Resulting average monthly temperature profiles for 1960-1963 period are shown in Fig. 10. During winter months the water temperature profiles were

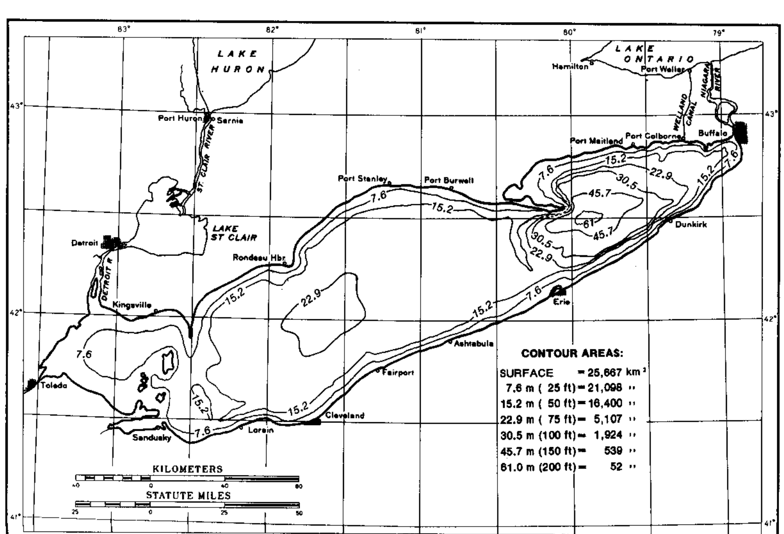

FIG. 9. Bottom topography of Lake Erie.

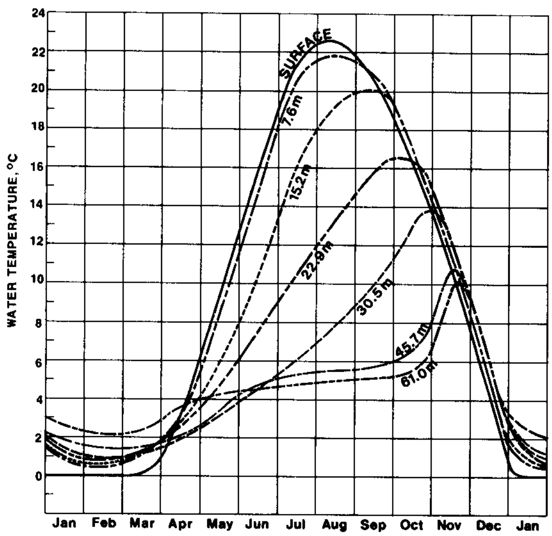

FIG. 10. Lake Erie monthly water temperature as function of water depth, 1960-1963.

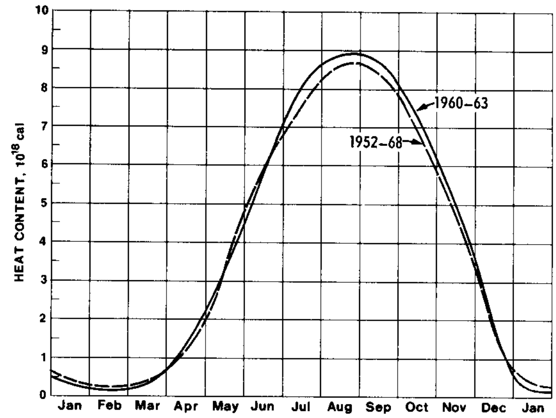

FIG. 11. Monthly heat content of Lake Erie

estimated, since temperature measurements were limited to open water season. The heat content for the required period of 1952-1968 was estimated by adjusting average temperature at each depth layer. Of necessity, these adjustments were based on the water surface temperatures. Comparison of the average monthly heat content for the two periods is shown in Fig. 11. On the annual basis heat storage is insignificant, since seasonal heat gains and losses balance each other.

Advected Energy

Advected energy is the net energy gained or lost by the lake due to exchange of water masses resulting from the inflow-outflow balance. It consists of the total inflow and total outflow energies and the heat loss involved in converting snow to water at 0°C, as expressed by the general equation:

$$Q_v = Q_i - Q_o - Q_m \qquad (13)$$

where

Q_v = net advected energy, ly/day

Q_i = energy content of water entering lake, ly/day

Q_o = energy content of water leaving lake, ly/day

Q_m = snowmelt heat loss, ly/day.

The energy content of water entering or leaving the lake was determined from volumes obtained in the water budget computations and appropriate temperatures. Water supplied to Lake Erie consists of overwater precipitation, runoff from the drainage basin, and inflow from the upper lakes; water leaves the lake through evaporation and lake outflow. During winter months precipitation falling on the lake frequently occurs in the form of snow and requires correction for heat loss due to snowmelt (80 cal/cm^2 to produce 1 cm of water from snow at 0°C). The resulting net advected energy is rather small, because major portions of the water masses entering and leaving the lake (lake inflow and outflow) have sufficiently similar temperatures to produce energies which tend to balance each other.

TABLE 11. Lake Erie evaporation by energy budget method compared with other method, cm, 1952-1968.

Period	Energy budget	Water budget	Mass transfer
January	3.0	7.2	6.2
February	3.0	3.6	4.8
March	9.7	1.8	1.1
April	5.3	1.2	-3.1
May	1.3	2.6	6.4
June	10.2	3.6	5.9
July	10.9	10.1	5.9
August	11.7	13.9	11.2
September	16.3	16.5	14.9
October	15.7	16.0	17.2
November	16.3	12.0	16.7
December	13.0	8.3	7.4
Annual	116.4	96.8	94.6

Transfer of Sensible Heat and Latent Heat

The combined monthly values of the energy utilized by conduction of sensible heat to or from the atmosphere and the energy utilized by evaporation through release of latent heat were obtained as a residual of the energy terms described above. Separate values for these two energy terms were then determined by employing the Bowen ratio, and are listed with other energy terms in Table 10.

An apparent anomaly in the energy utilized by evaporation (Q_e) are the abnormally high values for March and April. One possible explanation is the effect of cumulative errors, but these should be worse during winter months. A more plausible explanation for the erroneous values of Q_e during March and April is the increase of fog over the lake, which is not indicated by land stations. This aspect of the lake effect on net radiation has been generally disregarded. In a recent intensive study on Lake Ontario (IFYGL), Atwater (1974) found that fog has an important effect on the accuracy of overwater net radiation determined from land station data. A reduction of net radiation of 50 to 100 ly/day computed for March and April, which is within the limits indicated by Atwater, would reduce the energy utilized for evaporation to more reasonable values.

Evaporation

Evaporation estimates from Lake Erie computed by the energy

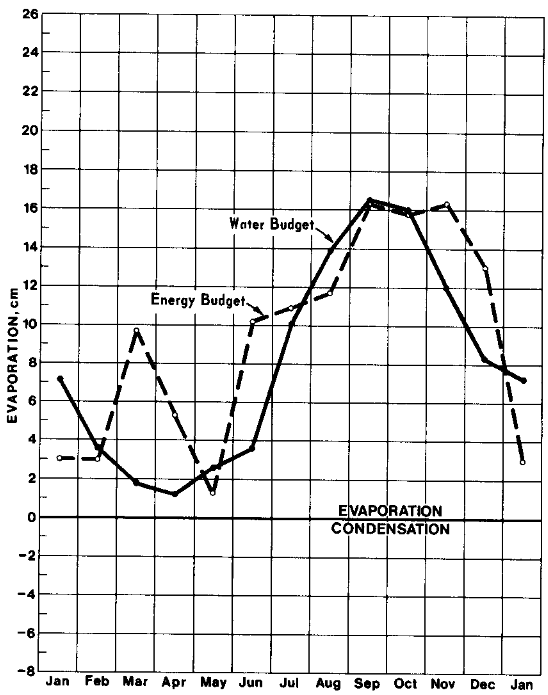

FIG. 12. Comparison of water budget and energy budget evaporation from Lake Erie, 1952-1968.

budget method and comparable water budget and mass transfer values for the 1952-1958 period are given in Table 11. The average annual energy budget evaporation of approximately 116 cm is considerably higher than the values obtained by other methods but most of the increase in the annual energy budget value is caused by the high evaporation obtained for some of the low evaporation months. The average monthly evaporation varied from a low of 1.3 cm in May to a high of 16.3 cm in September and November. Thus, monthly extremes agree reasonably with the values obtained by other methods, although the months when they occur may not be exactly the same.

Comparison of the seasonal distribution of average evaporation obtained by the energy budget and water budget methods is shown in Fig. 12. The extremely high energy budget evaporation value for March is obviously wrong. Generally, determinations for the low evaporation season (winter and spring) are based on the weakest energy budget data and show poor agreement with the water budget values. In contrast, determinations for the high evaporation season (summer and fall) are based on better data and indicate reasonable agreement.

SUMMARY AND CONCLUSIONS

Evaporation from Lake Erie was determined by three independent methods in an attempt to obtain firm evaporation estimates. The methods consisted of water budget, mass transfer, and energy budget approaches. Evaporation determined by the water budget method was used to provide control for the other methods, since the other determinations required more extensive empiricism, which was based on measurements not necessarily representative for the Great Lakes. However, the accuracy of evaporation data derived by any single method may be questionable, because of the quality of available data. The reliability of evaporation estimates was tested through verification of results by different methods.

The period of study was determined by the availability of required data, which dictated the use of two periods. Individual monthly and annual evaporation was determined by the water budget and mass transfer methods for a 32-year period (1937-1968). Determinations by the energy budget method were limited to average evaporation values for a 17-year period (1952-1968). Of necessity, the above long-term determinations were based on overland meteorological data, with adjustments to overwater conditions, where applicable.

Comparison of results

indicated that the average annual evaporation could be determined with a reasonable degree of confidence by the water budget and mass transfer methods. The average annual energy budget evaporation was significantly higher than the water budget evaporation. Monthly evaporation estimates are less accurate, because the effects of random errors on these shorter periods are more pronounced. Comparison of monthly evaporation indicates that the most reasonable monthly estimates were obtained by the water budget method. These were followed by the mass transfer and the energy budget estimates. Seasonal distribution of evaporation obtained by the mass transfer method appears reasonable during most of the year; its weakest segment is the rapid change from condensation to relatively high evaporation during spring, which was not indicated by the other determination. The energy budget evaporation appears reasonable during the high evaporation season, but several months of the low evaporation season have abnormally high evaporation values.

During winter months, the presence of ice cover on the lakes tends to reduce evaporatiom losses. Since mass transfer and energy budget equations do not consider ice cover effect, winter evaporation computed by these methods is potentially too high. Evaluation of the relationship between ice cover and evaporation indicates that the ice cover effect on evaporation is small during the light ice-cover months of December and April, and significant during the extensive ice-cover months of January, February, and March. However, because of the weak relationship and large scatter of the data, no attempt was made to derive and apply evaporation adjustments due to ice cover.

Considering presently available data and the overall reliability of the results, reasonably accurate values of monthly evaporation from Lake Erie can be determined by the water budget and the mass transfer methods during individual years. Average monthly evaporation during the high evaporation season may also be determined by the energy budget method. The same is probably true for the other Great Lakes.

Further improvements of the more promising evaporation estimates can be accomplished by additional field measurements or reevaluation of the existing adjustment terms. The most significant improvement for the water budget evaporation can be obtained from the continuous flow measurements for the inflow and outflow, by far the most important factors, thus eliminating possibly large errors when flow-rating curves are unreliable. Additional improvements would be provided by expansion of the stream-gauging network for the determination of runoff, intensified research on groundwater conditions, and derivation of reliable overwater precipitation. Practical improvements for the mass transfer evaporation values could be obtained by reevaluating the wind and humidity ratios and the water temperature adjustments from the additional data. Analysis of the results indicated that the monthly adjustments for humidity and water temperature were especially weak during certain months, causing apparent errors in the mass transfer estimates.

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