U.S. DEPARTMENT OF COMMERCE
Rogers C. B. Morton, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator
ENVIRONMENTAL RESEARCH LABORATORIES
Wilmot N. Hess, Director

NOAA TECHNICAL REPORT ERL 342-GLERL 3

(GLERL Contribution No. 28)

Evaporation From Lake Erie

JAN A. DERECKI

BOULDER, COLO.
June 1975

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402

CONTENTS

FIGURES

TABLES

APPENDIX A TABLES

EVAPORATION FROM LAKE ERIE

Jan A. Derecki

The monthly evaporation from Lake Erie was derived by the water budget, two mass transfer, energy budget, and two combined mass transfer-energy budget equations. The period of record varies with the availability of data, from 32 years for the water budget and mass transfer methods to 17 years for the other methods. Evaporation determined by a single method is not sufficiently reliable and requires verification of accuracy by different methods. Only the water budget method determines evaporation directly, as a residual from other measurements, and it was used as a control for other estimates of evaporation. The overall 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, and during the high evaporation season by the energy budget equation. The combined mass transfer-energy budget equations produced evaporation estimates which are considered to be of much lower accuracy.

1. INTRODUCTION

Lake evaporation is the loss of water from the lake surface to the atmosphere in the form of water vapor. It is associated with the heat loss from the lakes and is determined primarily by the air-water temperature difference. In large, deep lakes, such as the Great Lakes, evaporation varies with latitude and to some extent with lake depth. Evaporation decreases with latitude since colder regions of higher latitudes provide less opportunity for evaporation. The influence of lake depth is mainly seasonal; deeper lakes warm up and cool more slowly, producing a delaying shift in the seasonal low and high evaporation rates. Lake Erie, the southernmost and shallowest of the Great Lakes, has the highest evaporation rate of all the Great Lakes. Water loss by evaporation removes nearly one meter of water from Lake Erie annually and has an important effect on lake levels.

Evaporation from large water bodies cannot be measured directly, but several methods have been developed to compute lake evaporation. These methods include water budget, mass transfer, energy budget, evaporation-pan observations, atmospheric humidity budget, and momentum transfer. Because of data limitations, only the first four of these methods have been used to compute evaporation from the Great Lakes. Most frequently used methods are the water budget and mass transfer. The other two methods have been used less frequently; the energy budget method lacked appropriate data and the evaporation-pan observations method was frequently questioned on theoretical grounds.

In the present study, evaporation from Lake Erie was determined by four different approaches. These include the water budget, which is the only method where all major components are either measured directly or can be determined from related measurements. Because of this fact the water budget method was used to provide a control for other methods, all of which require determination of empirical constants. The other approaches are the mass transfer, the energy budget, and a combined mass transfer-energy budget method. The combined method eliminates the requirement for the water surface temperature observations needed for the individual solution of the two methods and permits determination of evaporation from the more readily available meteorological data. The four methods are described in the appropriate sections of this report.

The period of record employed in the study was determined by the availability of data. The most restrictive component in the water budget method was the runoff data. Runoff records from the Lake Erie drainage basin are considered adequate since 1937 and published records terminate at present in 1968, establishing the beginning and the end of the study period. Monthly evaporation rates were computed for the individual years during the 32-year period of study, 1937-1968, by the water budget and mass transfer methods. Determination of the monthly evaporation rates by individual years gives an indication of the variation of monthly evaporation, while the long-term average values indicate the normal monthly evaporation rates. For the energy budget computations the period of study was reduced, beginning in 1952, when the required solar radiation measurements within the Lake Erie basin became substantially continuous. Additional limitations were imposed by the lack of continuous information on the lake heat content (water temperature profile data), which prevented determination of evaporation on the individual year basis. Monthly evaporation rates by the energy budget and the mass transfer-energy budget methods were computed for the 17-year period average values, 1952-1968.

Basic climatological data used to compute evaporation were obtained from land stations located around the lake. Such lake perimeter data may not be representative of the open-lake conditions, because of variations in air stability over land and over water, but overwater measurements are not available for any appreciable period of time. The required adjustments for perimeter data, or lake-land ratios for various parameters, have been developed in recent years and were used in the study.

During the winter months, the presence of ice cover affects lake evaporation by reducing the open-water area. Ice-cover data for Lake Erie are available since 1962 from a regular ice observation program conducted at the Lake Survey Center. Relationships between ice cover and lake evaporation were tested during the 6-year ice-cover season, 1962-1968.

2. WATER BUDGET METHOD

The water budget method consists of solving the mass balance contained in the hydrologic cycle, a perpetual sequence of events governing the depletion and replenishment of water in the basin, for the unknown evaporation component. It is an accounting of all incoming and outgoing water, such as inflow and outflow by the rivers, supply from and storage in the ground, variation of water storage in the lake, overwater precipitation, and evaporation. The water budget for Lake Erie may be expressed by the equation

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

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 storage decreases), cm.

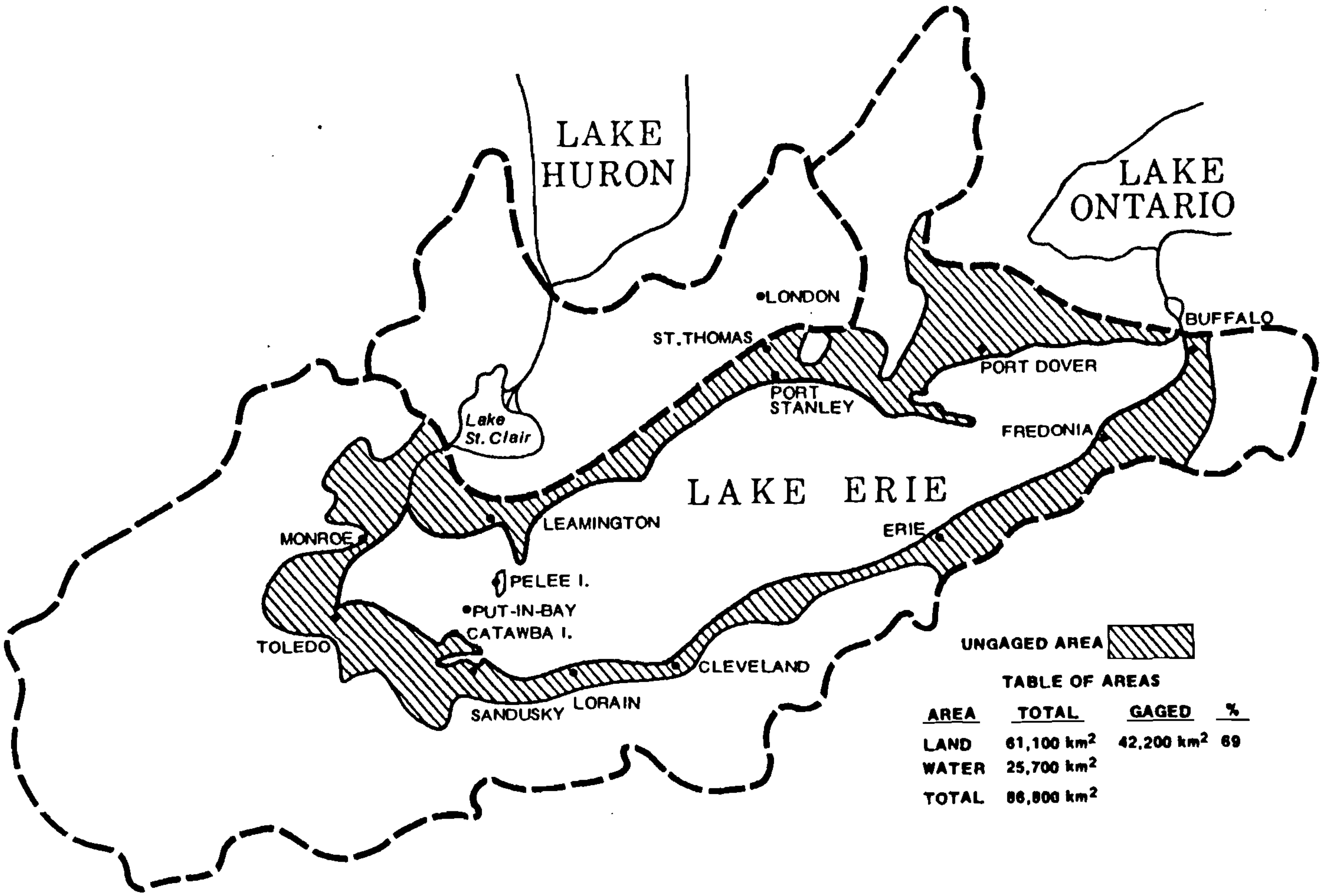
Additional factors which may affect the amount of evaporation computed by the water budget equation are the underground flow and the thermal expansion of water. These two factors are usually disregarded in the water budget of the Great Lakes. Considering the magnitude of other water budget components, thermal expansion in Lake Erie is insignificant, and underground flow is generally assumed to be negligible (Derecki, 1964). Direct exchange of flow between ground water and the lake is largely unknown, but the consensus of opinion among investigators is that there is no appreciable underground flow and that any existing flow is probably steady throughout the year.

The main advantage of the water budget method is that evaporation can be computed directly from hydrologic factors, without dependence on empirical constants. Measurements for most of these factors are readily available for long periods of record. The main objections to it are the uncertainity with respect to ground water and the dependence of computed evaporation on large factors. Water budget evaporation is a residual of several large factors and includes the errors of these factors, which may affect computed evaporation values considerably. These errors should be reduced to a minimum by careful selection and proper treatment of input data. A brief discussion of the individual water budget factors is given below. Lake Erie, its drainage basin, and locations pertinent to this study are shown in figure 1. The drainage basin of Lake St. Clair, which in hydrologic studies is frequently considered as part of the Lake Erie basin, was excluded from the water budget computations.

2.1 Overwater Precipitation

Precipitation on the Great Lakes is generally determined from perimeter stations located around the lakes, due to lack of direct overwater measurements. Each of the lakes is large enough to exert an influence on the whole range of climatic elements (temperature, wind, humidity, precipitation), over the lakes and adjacent land areas. Because of the lake effect, caused by the overwater changes in atmospheric stability, seasonal precipitation patterns are modified. During spring and summer, the lakes are generally colder than the air above and have a cooling effect on the atmosphere, which increases atmospheric stability and discourages formation of cloud cover and precipitation. During fall and winter, the lakes are generally warmer than the atmosphere and serve as a heat source, which increases atmospheric instability and encourages formation of cloud cover and precipitation. However, perimeter precipitation, although affected by the lakes, may not necessarily be representative of 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. Thus, for reliable overwater precipitation measurements, direct observations are required. A number of islands in the Great Lakes have been instrumented to provide data on precipitation on the lakes. These measurements are the most direct observations of 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 Islands provide long term records. During the 1920-1963 period the two islands had 36 years of simultaneous monthly records. An average of these stations, for the 36 years, was used to determine normal monthly overwater precipitation for the western portion of the lake. Monthly ratios of island to perimeter precipitation were determined in conjunction with simultaneous records from five western perimeter stations (Monroe, Mich., Toledo, Sandusky, and Cleveland, Ohio, and Leamington, Ontario). The lake-land ratios and the precipitation values from which they were derived are shown in table 1. The table also shows two sets of ratios determined in previous studies (Derecki, 1964, and Quinn, 1971) and the effect of the present ratios on derived precipitation for the period of study, 1937-1968. The average annual value of the monthly precipitation ratios is 0.96, which indicates a slight reduction in the overwater precipitation. Monthly ratios vary from a minimum of 0.90 to a



AREA	TOTAL	GAGED	%
LAND	61,100 km²	42,200 km²	69
WATER	25,700 km²		
TOTAL	86,800 km²		

Figure 1. Lake Erie basin.

maximum of 1.03, but the low and high values are scattered throughout the year, with similar average values for the spring-summer and fall-winter seasons. Thus, derived precipitation ratios do not confirm the theoretical spring-summer reduction and fall-winter increase in the overwater precipitation. The inconsistencies between island gage data and theory may be due to sources of error, such as gage sheltering and exposure, measurement inaccuracies, and the effects of the island land mass. The precipitation ratios derived in the two previous studies show similar results; values determined by Quinn are based on the same two islands for a more comparable period of record and show somewhat better agreement with the present determinations.

The overwater precipitation for the entire lake during the period of study, 1937-1968, was determined by adjusting average monthly records from 10 shore stations by the lake-land precipitation ratios. These ratios reduced the average annual perimeter precipitation, and consequently computed evaporation, by 3.5 cm. Monthly adjustments varied from a reduction of 0.7 cm in June to an increase of 0.3 cm in April (table 1). The 10 shore stations consisted of the 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, Ontario). Records from the shore stations indicate that precipitation around Lake Erie increases gradually from west to east. Derived overwater precipitation is shown in table A.1 in the Appendix, which contains tables with basic data. Annual precipitation over the lake varied from a low of 61 cm to a high of 106 cm, with a 32-year average value of 83 cm. Precipitation is normally well distributed throughout the year. The average monthly values (1937-1968) vary from a low of 5.3 cm in February to a high of 8.6 cm in April.

2.2 Runoff

Runoff from the drainage basin enters the lake mainly through the tributary streams, where it can be easily measured. A small portion of runoff enters the lake as direct surface runoff from fringe areas along the periphery of the lake. Flow measurements in the tributary rivers of the Lake Erie basin are published by the U.S. Geological Survey and the Inland Waters Branch, Canada. During the period of study, stream gaging increased sharply, expanding the gaged area from the initial 33 percent to the present 69 percent (42,200 km^2) of the total drainage basin. Runoff from ungaged streams and the lake periphery was obtained by using runoff per unit area from the nearby gaging stations. Gaged runoff and other flow measurements (inflow and outflow) are regarded as the most accurate data in the hydrologic cycle. Unlike measurements of precipitation, which sample only points within an area, gaged runoff effectively integrates the entire area above the point of measurement. Runoff data may still contain some uncertainties. Errors may be introduced in flow measurements, particularly during winter months due to ice effect, and in extrapolation of gaged runoff to the nearby ungaged areas.

Table 1. Lake Erie Overwater Precipitation Analysis

AUTHOR	DERECKI(1)	QUINN(2)		DERECKI(3)		ΔP(4)
YEAR	1964	1971		Present Study		(Lake-land)
PERIOD	13 years	22-42 years		36 years		1937-68
	R_p	R_p	LAKE cm	LAND cm	R_p	cm
January	0.95	1.02	5.49	5.33	1.03	0.2
February	0.89	0.88	4.67	5.21	0.90	-0.6
March	1.03	0.97	6.60	7.01	0.94	-0.4
April	1.04	1.06	8.03	7.82	1.03	0.3
May	1.07	1.04	7.57	7.65	0.99	-0.1
June	0.92	0.87	8.46	9.22	0.92	-0.7
July	1.04	0.88	7.57	7.95	0.95	-0.4
August	1.03	1.00	7.54	7.57	1.00	0.0
September	0.95	0.95	6.30	6.96	0.91	-0.6
October	0.89	0.90	5.41	5.92	0.91	-0.6
November	1.02	0.96	5.49	5.84	0.94	-0.4
December	1.03	0.89	4.95	5.26	0.94	-0.4
ANNUAL	0.99	0.95	78.08	81.74	0.96	-3.5

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.
(4) ΔP represents difference in overwater and perimeter precipitation.

Runoff into Lake Erie during the period of study, expressed in cm on the lake area to facilitate comparison with other water budget components, is shown in the Appendix (table A.2). The average annual runoff during this period represents 72 cm of water on the lake, or 30 cm on the land, which corresponds to 35 percent of the overland precipitation. Runoff shows large fluctuations, reflecting variations in the precipitation and the consumptive use of water on the drainage basin. Annual runoff during the 32 years (1937-1968) varied from a low of 35 cm to a high of 129 cm. Seasonally, most of the runoff to the lake is supplied during winter and spring months and very little during the rest of the year. During the period of study average monthly runoff varied from a high of 14.4 cm in March to a low of 1.3 cm in September. The variation of runoff throughout the year has an important effect on the accuracy of computed evaporation; high runoff occurs during the low evaporation season, and low runoff during the high evaporation season.

2.3 Inflow

Inflow is defined as the water supplied to a lake from outside its drainage basin. 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. In recent years hydraulic and hydrologic data for the Great Lakes have been coordinated by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, an international organization composed of the responsible federal agencies of both countries. Coordinated data were used for all flows from the Great Lakes employed in this study.

Inflow is extremely important to the water budget. It is by far the largest component of the Lake Erie water supply, and 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 monthly and annual inflows for the period of study are given in the Appendix (table A.3). The average annual inflow during this period represents 6.4 m of water on the lake. Annual values varied from a low of 5.5 m to a high of 7.8 m. The average monthly inflows (1937-1968) varied from 42 cm in February to 57 cm in July. The variation of inflow is relatively small because of the natural regulation provided by the lakes. Highest variation and less reliable data occur during winter months, when ice jams may affect flow determinations.

2.4 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.

Coordinated outflows for the 1937-1968 period are given in the Appendix (table A.4). During this period the annual outflows removed from 5.8 m to 8.3 m of water from the lake, with an average annual value of 7.0 m. The average monthly outflow varied from 51 cm in February to 63 cm in May.

2.5 Change in Storage

Storage of water in a lake is reflected by the water levels. The change in lake storage is determined from successive beginning-of-period levels, which implies instantaneous values. Actually, for monthly periods, a few days are normally used for the beginning-of-period levels to minimize the effect of wind on the lake level disturbances. The mean level of the lake is determined from a gage network selected to provide a good approximation of the whole lake level.

The beginning-of-month Lake Erie levels were determined by the Thiessen polygon method, taken from Quinn (1972). They are based on 2 days of record (1 at the beginning of the month and 1 at the end of the preceeding month). The polygon network utilized available gages which varied from 5 to 13 gages during the period of study. The five gage network consisted of Cleveland and Toledo, Ohio, Port Stanley and Port Colborne, Ontario, and Buffalo, N.Y. Additional gages were introduced gradually, as they became available, to complete the thirteen gage network (Port Dover, Erieau, Kingsville, and Bar Point, Ontario, Erie, Pa., Marblehead, Ohio, Fermi, Mich., and Barcelona, N. Y.

The change in storage for the period of study is shown in the Appendix (table A.5). Because hydrologic factors undergo an annual cycle, the long-term annual change in storage should be small due to balancing of rising and falling lake levels. The average annual change in storage for the 32-year period was 2 cm, indicating a small annual rise in lake levels. Annual values during individual years fluctuated between a rise of 44 cm and a fall of 40 cm. Seasonally, the lake levels rose during winter and spring and fell during summer and fall. The average monthly change in storage varied from a rise of 15.4 cm in April to a fall of 11.2 cm in September.

2.6 Evaporation

Evaporation from Lake Erie computed by the water budget method for the period of study is listed in table 2. 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; however, the records indicate definite low, median, and high evaporation periods.

Table 2. 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

Approximately the first quarter of the period of study was in general a period of low evaporation, with the average annual value approaching 80 cm; the next two quarters constitute a median evaporation period, with an average annual value of about 90 cm; and the last quarter was a high evaporation period, with the annual average exceeding 100 cm. The large difference in the average annual evaporation of these periods demonstrates the importance of using sufficiently long records to determine normal evaporation values.

Examination of the water budget factors indicates that the progressive increase in evaporation is not caused by corresponding data changes in the individual factors or even groupings of similar factors, such as those indicating water supply (precipitation, runoff, inflow) or water losses (outflow, change in storage). Rather, the periodic trends for low, normal, and high evaporation must be attributed to the combined effect of all factors. This is summarized in table 3, showing the deviations of the average values for the three periods from the 32-year averages. None of the factors show similar trends in data changes to evaporation during all three periods. As a residual of the water budget equation, low evaporation during the first period (1937-1945) is the result of lowest overall water supplies (caused primarily by lowest inflow) and only moderately low water losses (caused primarily by outflow). Normal evaporation during the second period (1946-1959) resulted from the balancing of highest water supplies (all three factors) and highest water losses (caused primarily by outflow). High evaporation during the third period (1960-1968) is the result of lowest water losses (caused primarily by outflow) and not nearly as low supplies (caused primarily by near normal inflow). Because of their magnitude, the inflow and outflow exert by far the most important influence on evaporation values.

Presentation of the sensitivity of various water budget parameters on computed evaporation, indicating error analysis, is shown in table 4. The table shows the effects of a 1 percent change or error in the average values (1937-1968) of the input parameters on the average monthly and annual evaporation. Because of the annual cycle of rising and falling lake levels, the long term annual change in storage approaches zero, and 1 percent change of this small value would be meaningless for the purpose of this comparison. Therefore, the average annual change in storage was replaced by a summation of the absolute monthly values, which indicates the magnitude of monthly changes in storage during the year, as do the annual values of the other parameters. The average annual values of precipitation and runoff and the summation of the absolute monthly changes in storage are approximately of the same magnitude as evaporation, and the effects of constant annual change in these parameters are similar (about 1 percent). The effects of a 1 percent change in the annual inflow and outflow, however, produce approximately 7 and 8 percent change in evaporation, respectively. With the exception of the very low evaporation months (February-June), the effects of constant monthly changes in the individual factors are generally of the same magnitude as the annual effects. The percentage change in evaporation during low evaporation months is much higher, but these values are not very significant and have little influence on the annual changes or errors.

Table 3. Deviations of Water Budget Factors from Long Term Averages, cm

WATER BUDGET FACTORS	PERIODS		
	1937-45	1946-59	1960-68
WATER SUPPLIES			
Precipitation	0.2	2.8	- 4.4
Runoff	- 3.3	7.6	- 8.5
Inflow	-27.5	21.3	- 5.6
Total	-30.6	31.7	-18.5
WATER LOSSES			
Outflow	-25.2	37.1	-32.6
Change in Storage	5.6	- 4.3	1.0
Sum	-19.6	32.8	-31.6
Evaporation	-11.0	- 1.1	13.1

Deviation = Average for periods - Long Term Average

On an annual basis, the inflow and outflow are from 8 to 10 times more important than the other water budget factors in determining computed evaporation (based on table values). Thus, even a relatively small improvement in the accuracy of inflow and outflow will produce significant improvement in the accuracy of the water budget evaporation. Except for the change in storage, the inflow and outflow are the most accurately determined parameters, but they are also most amenable to further improvement, since each provides precise controls at the points (cross-sections) of measurement. Significant improvement could be obtained without additional research or development of new instrumentation by measuring the flows in the connecting channels of the Great Lakes continuously during the year, instead of using rating curves based on periodic measurements. This would eliminate questionable records during periods when rating curves are unreliable, especially during ice jams. Continuous flow measurement would also improve runoff data, but such measurements would not be practical for the large number of tributary streams and would have to be limited to major tributaries; however, runoff is an order of magnitude smaller than inflow or outflow and thus not as critical. A more basic runoff improvement could be obtained by further expansion of the existing stream gaging network and

Table 4. Effect of 1 Percent Error in Water Budget Factors on Evaporation Estimates in Percent of Evaporation, 1937-1968

Month	Evapo. Total cm	Precipitation total cm	Precipitation effect %	Runoff total cm	Runoff effect %	Inflow total cm	Inflow effect %	Outflow total cm	Outflow effect %	Change in Storage total cm	Change in Storage effect %
January	7.1	6.5	0.9	7.9	1.1	48.6	6.8	56.1	7.9	- 0.3	0.0
February	3.2	5.3	1.7	8.8	2.8	42.3	13.2	51.0	15.9	2.2	0.7
March	1.4	6.6	4.7	14.4	10.3	51.7	36.9	57.6	41.1	13.7	9.8
April	0.8	8.6	10.8	12.7	15.9	53.3	66.6	58.4	73.0	15.4	19.2
May	1.6	7.9	4.9	7.1	4.4	56.1	35.1	63.4	39.6	6.0	3.8
June	2.9	7.7	2.7	4.2	1.4	54.8	18.9	61.5	21.2	2.3	0.8
July	9.6	7.4	0.8	2.3	0.2	57.4	6.0	62.2	6.5	- 4.8	- 0.5
August	13.6	8.2	0.6	1.5	0.1	57.2	4.2	61.3	4.5	- 8.0	- 0.6
September	16.2	6.5	0.4	1.3	0.1	55.1	3.4	58.0	3.6	-11.2	- 0.7
October	14.6	6.1	0.4	2.1	0.1	56.4	3.9	58.8	4.0	- 8.8	- 0.6
November	11.8	6.7	0.6	3.4	0.3	54.1	4.6	56.9	4.8	- 4.6	- 0.4
December	8.0	6.0	0.8	6.0	0.8	54.8	6.8	58.6	7.3	0.2	0.0
Annual	90.9	83.4	0.9	71.6	0.8	641.9	7.1	703.8	7.7	±77.5*	± 0.9*

*Value for the average annual change in storage was replaced by summation of the absolute monthly values.

intensified research on ground water conditions. Additional research is also required to improve overwater precipitation data. This is probably the least accurate of the water budget input parameters because of lack of proper overwater measurements.

The accuracy of inflow and outflow is very important for the 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 is approximately one-half of their absolute values. It exceeds the absolute value for runoff and change in storage and is about one-third for inflow and outflow.

Seasonal distribution of the annual evaporation is shown in figure 2, which contains the monthly average, maximum, and minimum evaporation values obtained during the period of study. A low evaporation season occurs during winter and spring months, and a high evaporation season occurs during summer and fall. During a 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, half a cm higher. The occurrence of normal monthly low evaporation in April corresponds to a sharp increase in the water surface temperature of the lake, due to absorption of heat from the atmosphere. The normal monthly high evaporation in September corresponds to a sharp decrease in the water temperature, due to dissipation of heat to the atmosphere by evaporating lake water. The extreme monthly evaporation values varied from condensation of 5.9 cm (February) to evaporation of 22.7 cm (October).

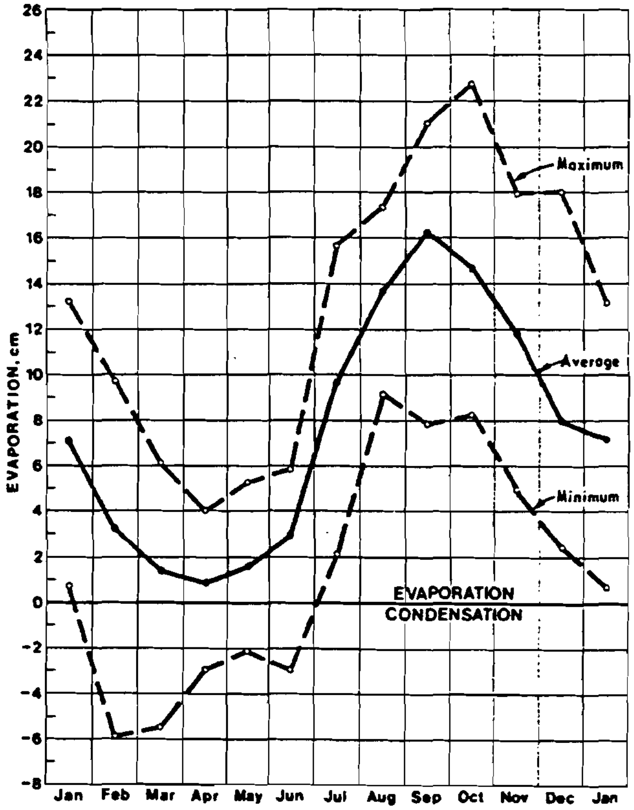


Figure 2. Lake Erie evaporation by water budget method, 1937-1968.

3. 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. Through the years many forms of aerodynamic equations have been developed to compute evaporation. Past mass transfer computations for the Great Lakes utilized equations of relatively simple form, a practical requirement for expediency and availability of data. The equation used most often in recent years is of the basic form

$$E = N\,(e_s - e_a)u \tag{2}$$

where E = evaporation

N = mass transfer coefficient

e_s = saturation vapor pressure

e_a = vapor pressure of the air

u = wind speed.

Equation (2) 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 mass transfer coefficient, N, is an empirical constant which represents a combination of many variables, such as height of measurements for meteorological data, atmospheric stability, and frictional resistance. Determination of the coefficient for a particular body of water requires accurate evaporation values; the coefficient is the slope of the best fitting line passing through the zero intercept of a plot of the mass transfer product $u(e_s - e_a)$ versus evaporation. Since all evaporation estimates for the Great Lakes contain some important reservations, an independently determined mass transfer coefficient would be of questionable value. In recent studies of evaporation from the Great Lakes, the quasi-empirical Lake Hefner equation was considered to give satisfactory results (Richards, 1964; Richards and Irbe, 1969).

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 necessarily reflect climatic conditions over large water areas. Variations in air stability, which affect both wind and vapor pressure, are essentially diurnal in character over land and seasonal over water.

The required adjustments for perimeter data, or lake-land ratios for wind and humidity, have been made in recent years and permit utilization of the available long term data in the mass transfer computations. These ratios represent an empirical relationship for each parameter, derived from simultaneous observations over land and over water. For the metric units used in this study, the Lake Hefner equation modified by the wind and humidity ratios becomes

$$E = 0.0097\ (e_s - He_a)\ Ru_8 \tag{3}$$

where E = Lake evaporation, cm/day

e_s = saturation vapor pressure at water surface temperature, mb

H = monthly lake-land humidity ratio

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

R = monthly lake-land wind ratio

u_8 = perimeter wind speed at 8 m, m/s.

The monthly wind and humidity ratios used in previous Great Lakes evaporation studies are shown in table 5. Monthly wind ratios for the open-water season were developed by Lamire (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 midsummer, but is almost twice as high during fall and winter months. The ratios vary from 1.16 in July to 2.09 in November, with an annual average of 1.66. Monthly humidity ratios were developed by Richards and Fortin (1962). Seasonal variation of the humidity ratios is only half as large as for wind ratios. The humidity ratios vary from 0.86 in May to 1.33 in January, with an annual average of 1.14. The ratios indicate that overwater humidity is lower than overland humidity during the late spring-early summer period and higher during the rest of the year; highest overwater humidity occurs during the winter months.

A set of variable lake-land wind ratios, unrestricted to monthly periods, was developed for the lower Great Lakes (Erie and Ontario) by Richards et al. (1966). Besides the atmospheric stability expressed by $T_a - T_w$, these ratios indicate the effects of overwater fetch (length of open water) on lake winds. The analysis included five stability ranges for four wind speed classes and five fetch ranges. The ratios indicate that overwater winds increase with the atmospheric instability, but the increase is most pronounced for light winds and, to a smaller extent, for longer fetches. Under very stable atmospheric conditions, the lake may reduce the wind speed, especially for strong winds and shorter fetches. The average wind ratio of all winds for all stability ranges was 1.56, which is in reasonable agreement with the average annual value of 1.66 from the monthly wind ratios. The variable wind ratios were tested for computing evaporation by equation (3), but the monthly wind ratios gave better results. All the ratios discussed above are based on short periods of record (a few years) and should be reevaluated as more data become available.

Table 5. Monthly Lake-Land Wind and Humidity Ratios for the Great Lakes

AUTHOR	LAMIRE	RICHARDS & FORTIN
YEAR	1961	1962
	$R = \frac{\text{wind over lake}}{\text{wind over land}}$	$H = \frac{\text{vapor pressure over lake}}{\text{vapor pressure over land}}$
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).

A modified version of equation (3) was developed by Harbeck (1962) and employed in the Great Lakes by Yu and Brutsaert (1969). Harbeck modified the mass transfer coefficient by introduction of lake surface area and eliminated the requirement for humidity ratios by using air vapor pressure unaffected by the water surface. His mass transfer coefficient was

$$N = 0.00338A^{-0.05} \tag{4}$$

where A = lake area in acres

0.00338 = numerical constant for evaporation in inches per day, wind speed at 2 m in mph, and vapor pressure in mb.

Expressed in metric units, with the Lake Erie surface area of 25,700 km^2 and conversion for consistent wind speed height, Harbeck's equation becomes

$$E = 0.00716 (e_s - e_a) Ru_8 \qquad (5)$$

where E = lake evaporation, cm/day

e_s = saturation vapor pressure at water surface temperature, mb

e_a = vapor pressure of the air unaffected by the water surface, mb

R = monthly lake-land wind ratio

u_8 = perimeter wind speed at 8 m, m/s.

Equations (3) and (5) were used to compute the two sets of mass transfer evaporation presented in this study. They are designated as mass transfer methods MT-1 and MT-2, respectively. 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 tend to reduce winter evaporation. Primary advantages of the method are the elimination of the main objections to the water budget method (ground water, magnitude of inflow and outflow) and a capability for quick evaporation estimates from readily available data. The required data are discussed briefly below.

3.1 Meteorological Data

Meteorological data for the mass transfer computations were determined from four first-order weather stations located on opposite ends of Lake Erie to give a good approximation of average conditions around the lake. The average values for meteorological variables were obtained by averaging monthly records from Buffalo, New York, Cleveland and Toledo, Ohio, and London, Ontario. The station at London, located some 40 km from the lake, is not exactly a perimeter station, but it is the only suitable station north of the lake with a long term record of required data. 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, as shown in the Appendix (table A.6). For approximately the last 10 years of the 32-year period (1937-1968), the measurement heights at the American stations were standardized at 6.1 m (20 ft) for wind data and 1.2 m (4 ft) for air temperature and humidity.

The perimeter wind speed for Lake Erie during the period of study, adjusted to a common elevation of 8 m, is given in the Appendix (table A.7). Average shore winds around the lake show a high degree of consistency, with the annual values varying from 4.05 to 4.72 m/s and the 32-year annual average of 4.49 m/s. Seasonally, the wind speed varied from the average monthly low of 3.46 m/s in August to a high of 5.22 m/s in March. Adjustment of the wind speed to the 8 m height reduced the average monthly and annual values by approximately 10 percent. The height adjustment was made using the one-seventh power law as follows:

$$u_2 = u_1 \left[\frac{z_2}{z_1}\right]^{\frac{1}{7}} \qquad (6)$$

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.

The prevailing wind direction over Lake Erie, based on the perimeter stations, is given in the Appendix (table A.8). Prevailing winds are from the west-southwest direction, as indicated by the annual average and most of the monthly averages for the period of study. Other frequent wind directions are southwest, south-southwest, and west, in that order. The monthly wind direction was used to determine windward data unaffected by the lake. The windward data represent overland conditions upwind from the lake and were determined by averaging monthly records from the windward stations; however, windward data from shore stations may not be entirely free from lake effect because of lake breezes, which may penetrate several kilometers inland. Lake breezes are light winds (occurring during relatively calm weather) which are produced by daily heat exchange processes between a water body and a land mass. The direction of lake breezes is governed by the land-water temperature relationship. When the land is warmer than the water, normally during the day, the relatively warmer air over adjacent land areas tends to rise and is replaced by colder, heavier air from the lake. When the land is colder than the water, normally at night, the process is reversed.

Vapor pressure of the air is a function of air temperature and relative humidity, a ratio between actual and saturation vapor pressure at the same temperature. Published humidity data consist of observations at four synoptic hours (0130, 0730, 1330 and 1930 EST), from which mean daily values are derived. At the beginning of the study period humidity observations were less frequent, varying with the stations from two to three observations per day. Humidity for the missing hours of the early years was estimated from the relationship of synoptic hours in a daily distribution of humidity. The average perimeter humidity for the period of study is given in the Appendix (table A.9). Annual humidity around Lake Erie varied from 72 to 77 percent with an annual average of 74 percent. The average monthly humidity varied from 69 percent in May to 80 percent in January.

The average perimeter air temperature for Lake Erie is given in the Appendix (table A.10). The 32-year average annual temperature was 9.1°C, with annual extremes of 7.8°C and 10.5°C. The average monthly temperatures varied from -3.9°C in January to 21.9°C in July. Monthly temperatures are based on daily means determined by averaging maximum and minimum temperatures. This is the standard procedure for determining air temperature at the weather stations, even though first order stations provide hourly records. Standard temperature instrumentation at the more numerous second order stations consists of maximum-minimum thermometers and normally does not include recording instruments.

The air vapor pressure representing average perimeter conditions was derived from the listed humidity and air temperature data. This was the basic set of the vapor pressure of the air used in equation (3), with the average annual value slightly under 10 mb. Another set of air vapor pressure values was obtained to represent overland conditions unaffected by the water surface. Initially, this set of vapor pressure values was based on humidity and temperature records from the windward stations (two or three), selected from wind direction; however, there was no significant difference between vapor pressures determined from the perimeter and windward stations. A more reasonable relationship between perimeter and overland vapor pressures was indicated by values determined from the landward station (lowest of four stations). Vapor pressure from the landward station was significantly lower, with the annual average slightly over 9 mb. This modified version of air vapor pressure for overland conditions was used in equation (5). Of the four stations, lowest monthly vapor pressure of the air occurred most frequently at London. This is probably due to its location further from the lake, which eliminates possible lake effects due to lake breezes.

3.2 Water Surface Temperature

The only source 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. Initially, open-water temperature measurements were made periodically by commercial vessels along their navigation routes. With the intensified research programs conducted in recent years, these measurements were provided on a more systematic basis by research vessels engaged in synoptic surveys of the lakes and by airborne infra-red thermometers; however, a comprehensive water surface temperature study, based on the more sophisticated recent data, has not been made as yet. The most comprehensive study of the Great Lakes water surface temperatures, made by Millar (1952), was based on continuous records taken by thermographs installed on the condenser intakes of steamships. For Lake Erie, Millar's data collection period covered 5 years, from 1937 to 1941.

Water surface temperatures used in the present study were obtained by adjusting values derived from the water intakes at Erie, Pennsylvania, and Avon Lake, Ohio, to open-lake conditions. 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 determined from Millar's data and simultaneous records from the water intake stations. The temperature adjustments consist of average monthly differences between these temperatures. The surface temperatures from Millar and the water intakes, and the corresponding adjustment terms are shown in table 6. Due to insufficient data during winter months, Millar excluded winter temperatures which had to be estimated. Adjustments to the average monthly shore temperatures vary from -3.1°C in April to +0.6°C in November, with an annual average of -1.6°C. These values are based on a relatively short period of record and may be modified by temperature relationships for longer periods.

The Lake Erie water surface temperature for the period of study is given in the Appendix (table A.11). Annual temperatures during the 1937-1968 period varied from 8.8 to 11.0°C, with an average annual value of 10.1°C. The average monthly temperatures varied from a low of 0.1°C in February to a high of 22.2°C in August. During winter months the temperature adjustments were based on estimated surface temperatures and appear to be slightly too large, especially during February. The winter temperature adjustments were modified, where necessary, to eliminate negative water temperature values. The overwater saturation vapor pressure determined from the above temperatures has an average annual value of about 14 mb.

Values of the vapor pressure difference estimates for the overwater and overland conditions, corresponding to the requirements of mass transfer equations (3) and (5), respectively, are given in the Appendix (tables A.12 and A.13). Annual overwater vapor pressure difference at 8 m varied from 2.86 to 4.49 mb during the period of study, with a 32-year annual average of 3.53 mb. The average monthly values varied from -0.62 mb in April to 7.38 mb in August. The overland vapor pressure difference is considerably higher than the overwater difference. The overland vapor pressure difference varied annually from 4.22 to 5.48 mb, with an annual average for the period of study of 4.74 mb. The average monthly values varied from 0.95 mb in April to 9.42 mb in August. The adjustment of the vapor pressure difference to a common elevation of 8 m increases the vapor pressure difference by approximately 9 percent. This height adjustment had never been made in the previous mass transfer studies of the Great Lakes. The vapor pressure height adjustments were made by using the following logarithmic law:

$$\Delta e_2 = \Delta e_1 \frac{\log Z_2 + 3.658}{\log Z_1 + 3.658} \qquad (7)$$

where

Δe_2 = vapor pressure difference at height level two

Δe_1 = vapor pressure difference at height level one

Z_2 = height level two

Z_1 = height level one.

Table 6. Lake Erie Water Surface Temperature Analysis

PERIOD	WATER TEMPERATURES °C 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.

3.3 Evaporation

Lake Erie evaporation computed by the modified Lake Hefner equation for the period of study is given in table 7. Annual evaporation varied from 68 cm to about 118 cm, with a 32-year annual average (1937-1968) of 90 cm and a 17-year average (1952-1968) of about 95 cm. Thus, annual values agree reasonably well with those determined by the water budget method. Although the minimum and maximum annual values obtained by the two methods do not occur on identical years, the mass transfer determination indicates similar trends for the low, median, and high evaporation periods during the period of study. This similarity is valid for both the occurrence of the periods and their average annual evaporation (approximately 80, 90, and 100 cm for the first, middle two, and last quarters of the total period), respectively. 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 figure 3. Monthly extremes varied from condensation of 8.6 cm in April to evaporation of 24.8 cm in October.

Table 7. Lake Erie Evaporation by Mass Transfer Method MT-1, 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
38	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
39	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
40	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
41	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
42	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
43	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
44	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
45	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
46	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
47	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
48	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
49	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
50	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
51	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
52	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
53	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
54	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
55	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
56	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
57	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
58	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
59	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
60	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
61	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
62	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
63	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
64	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
65	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
66	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
67	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
68	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

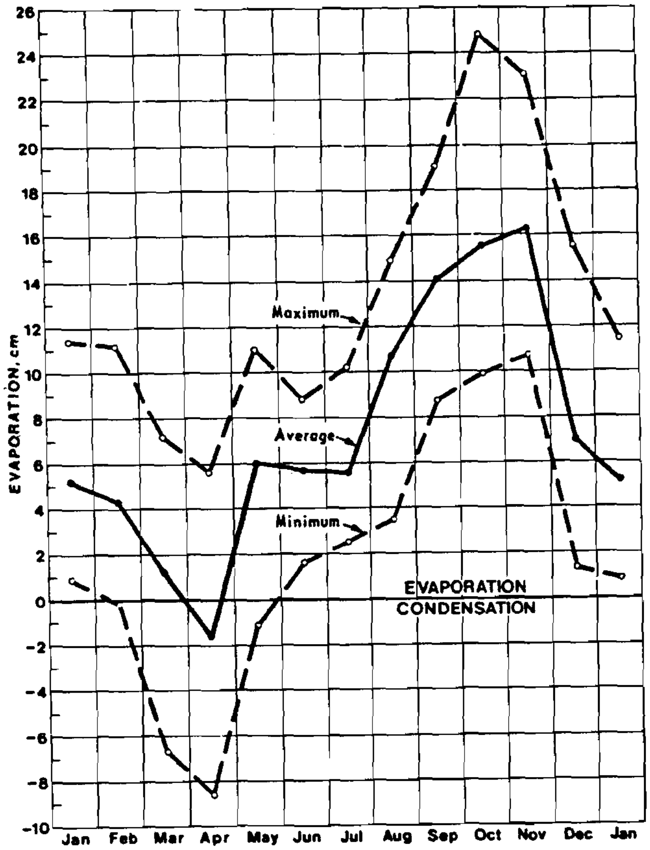


Figure 3. Lake Erie evaporation by mass transfer method MT-1, 1937-1968.

The second set of mass transfer evaporation values from the lake, computed for the period of study by Harbeck's equation, is given in table 8. Annual evaporation determined by this equation has a much smaller variation, from about 82 to 103 cm, and does not indicate any definite trends for the low or high evaporation periods within the period of study. The average annual evaporation for both the 32- and 17-year periods was 91 cm. The average monthly evaporation (1937-1968) varied from 1.9 cm in April to 14.1 cm in October, and the monthly extremes varied from a minimum of -1.9 cm to a maximum of 19.9 cm during the same months. Condensation was obtained only in several instances.

Seasonal distribution of evaporation, indicating monthly averages and extremes, is shown in figure 4.

Table 8. Lake Erie Evaporation by Mass Transfer Method MT-2, cm

$$E = 0.00716(\Delta e_d)Ru_8$$

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	6.0	5.0	4.6	2.0	1.8	3.7	6.0	6.0	15.3	13.2	12.0	6.7	82.3
38	6.8	4.5	3.0	3.4	3.5	5.3	5.4	11.1	14.4	12.7	13.5	8.0	91.6
39	6.4	5.9	4.6	2.7	2.8	5.1	7.4	10.6	13.5	16.2	11.0	8.2	94.4
40	8.6	5.2	5.9	0.9	1.0	4.7	5.8	8.5	9.9	12.5	13.5	6.6	83.1
41	6.8	6.1	5.1	1.1	7.0	5.4	6.8	13.1	15.8	15.2	12.5	7.0	101.9
42	7.0	6.0	3.4	2.9	2.5	2.2	8.2	10.4	12.8	12.0	11.9	7.2	86.6
43	6.7	6.2	5.5	4.6	2.1	4.4	5.7	10.8	12.0	14.3	10.9	8.6	91.8
44	4.4	5.6	6.1	1.8	1.8	3.9	7.5	9.0	9.9	14.9	11.1	9.3	85.3
45	8.1	5.1	0.5	4.4	5.4	3.0	5.6	9.8	12.8	15.0	15.2	8.6	93.5
46	6.7	6.3	1.9	6.5	4.3	5.5	6.1	10.5	10.1	12.7	15.3	9.5	95.4
47	6.0	8.2	4.5	1.4	2.4	2.1	4.4	5.3	15.3	10.7	16.1	7.8	84.2
48	8.1	6.0	5.3	3.3	4.7	3.8	5.7	9.2	14.1	11.6	11.4	9.4	92.6
49	6.4	4.9	5.5	3.3	4.4	4.4	5.4	12.4	11.4	13.4	14.9	7.3	93.7
50	7.5	7.0	6.6	3.7	1.6	5.4	5.5	9.9	9.1	10.8	18.3	8.2	93.6
51	5.6	4.5	4.4	1.3	2.4	3.7	6.8	11.1	14.4	13.5	16.3	9.0	93.0
52	5.9	4.6	3.7	0.2	3.7	6.3	7.3	9.7	12.2	19.9	13.3	7.2	94.0
53	5.2	4.8	2.9	3.6	-0.1	2.9	6.8	9.7	15.7	11.9	13.9	9.7	87.0
54	7.6	3.9	6.4	1.8	6.2	4.7	9.3	13.2	14.2	14.7	12.4	8.6	103.0
55	6.5	4.3	4.4	0.1	4.2	4.6	6.3	8.6	14.0	14.7	13.9	6.8	88.4
56	5.6	5.0	4.3	1.6	3.3	3.1	5.6	9.4	13.9	12.0	15.3	5.7	84.8
57	7.8	3.8	2.3	-1.9	3.2	1.6	6.7	11.8	12.1	13.5	14.4	6.4	81.7
58	5.8	7.7	1.5	-0.5	5.3	5.7	4.5	10.9	12.6	15.2	14.4	8.7	91.8
59	7.9	6.9	4.6	0.4	0.0	5.9	6.9	9.6	15.1	17.1	14.2	5.8	94.4
60	5.5	6.3	6.5	-1.7	0.3	4.0	7.1	9.6	13.0	18.0	14.8	12.0	95.4
61	8.5	4.2	4.0	2.9	5.3	2.2	5.0	10.1	12.6	15.2	14.9	9.9	94.8
62	9.7	7.6	3.7	0.9	0.9	4.2	6.9	9.0	15.3	13.0	12.1	9.5	92.8
63	9.2	8.7	2.5	3.2	3.7	3.5	6.0	11.2	13.0	11.6	15.1	9.6	97.3
64	6.2	5.8	3.0	0.7	1.6	3.7	6.3	11.8	13.3	14.8	12.6	7.1	86.9
65	8.1	7.6	4.7	0.1	-0.3	4.7	8.4	9.7	10.6	16.8	11.8	6.2	88.4
66	8.6	4.8	2.7	1.9	4.9	3.6	4.3	8.9	13.6	16.1	12.7	8.6	90.7
67	6.0	8.6	4.1	1.9	5.5	0.5	4.5	11.1	12.3	13.6	13.3	7.3	88.7
68	7.8	8.5	2.8	1.6	2.5	2.4	6.2	10.1	9.3	14.8	13.6	11.0	90.6
MEAN	7.0	5.9	4.1	1.9	2.9	4.0	6.3	10.1	12.9	14.1	13.7	8.2	91.1
52-68	7.2	6.0	3.8	1.0	2.8	3.8	6.4	10.3	13.1	14.8	13.8	8.2	91.2

Comparison of the water budget and mass transfer evaporation determined by the two equations is given in figure 5, showing seasonal distribution of the average monthly values. The figure shows clearly 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 the seasonal distribution curves, especially during the high evaporation season, indicates that mass transfer evaporation lags behind water budget values by roughly about a month. This seems to suggest that for large water bodies there is a considerable delay in the climatic cause and effect relationship, and that mass transfer equations should include some consideration for climatological data of the preceding months. However, analysis of the data used showed that the apparent lag in the mass transfer seasonal distribution curves is caused mainly by the water surface temperature adjustments. Without these adjustments, the shape of mass transfer distribution during most months, and especially those of the high evaporation season, would be similar to that of water budget, but the evaporation values would be much higher and the unadjusted shore temperatures would definitely not represent open lake conditions. May was the only month in which the water temperature adjustment reduced substantially the relative difference in the seasonal evaporation distributions. The water budget-mass transfer difference during May is especially high 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.

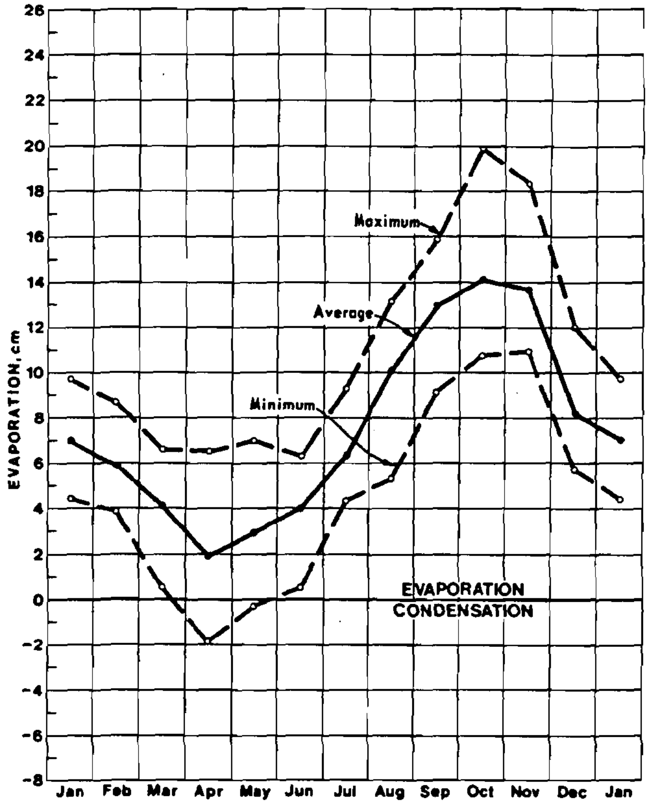


Figure 4. Lake Erie evaporation by mass transfer method MT-2, 1937-1968.

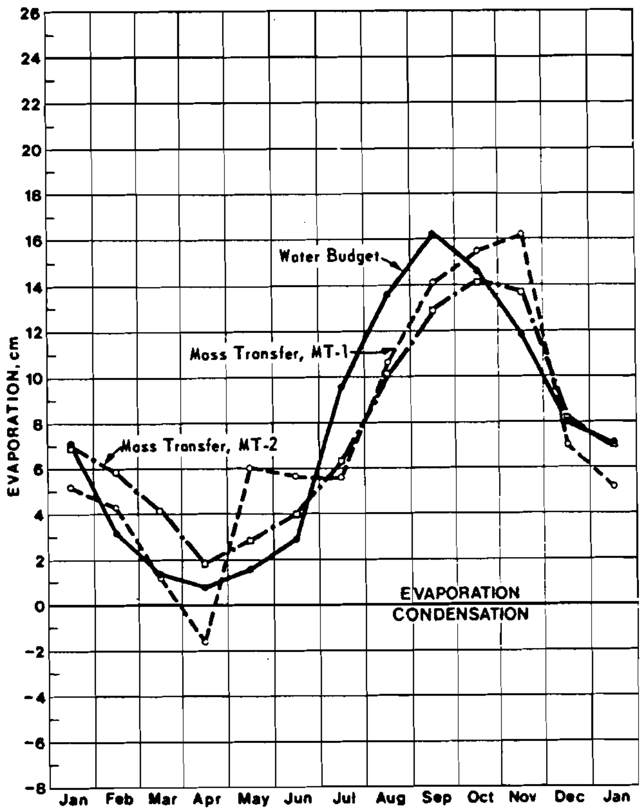


Figure 5. Comparison of water budget and mass transfer evaporation from Lake Erie, 1937-1968.

The applicability of each of the equations to the Great Lakes was also analyzed by conducting an independent check of their mass transfer coefficients. The procedure used to check the coefficients consisted of plotting the monthly values of mass transfer products for MT-1 ($Ru_8\Delta e_8$) and MT-2 ($Ru_8\Delta e_d$) against water budget evaporation, expressed in centimeters per day. The correlation coefficients for the two relationships were 0.81 and 0.85, respectively. The inverse of the slope for the line passing through the zero intercept represents the mass transfer coefficient, as shown in figures 6 and 7 for MT-1 and MT-2, respectively. There is considerable scatter of the individual monthly points, but both figures indicate significant correlation and good agreement with the original mass transfer coefficients. The inverse of the slope for the modified Lake Hefner equation values is 0.0100, which agrees closely with the mass transfer coefficient of 0.0097 for that equation (about 3 percent difference). Similar results were obtained for the Harbeck's equation values; the inverse of the slope is 0.00743, as compared to the mass transfer coefficient of 0.00716 used in that equation (about 4 percent difference). This close agreement for the monthly values of MT-2 was unexpected, considering lack of agreement between the annual evaporation obtained by MT-2 and water budget methods indicated in the previous analysis. The validity of that analysis is verified by the inserts for the annual mass transfer product values shown in both figures. Figure 6 shows a similar correlation in the monthly and annual values for MT-1, while figure 7 indicates a poor correlation in the annual values for MT-2. Visual inspection of the graphs also shows that the zero intercept line in figure 6 provides a better fit for all the monthly points than the line in figure 7.

Considering all aspects of the above evaporation discussion, the Lake Hefner equation is more adaptable to the Great Lakes and gives better mass transfer results. 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.

Because of considerable differences in the monthly evaporation as computed by the water budget and mass transfer equations and questionable values for some adjustment factors, an attempt was made to check the accuracy of the evaporation results by using climatological data obtained directly over the lake. Such mass transfer determination could be made only for a short term period, but it does eliminate the necessity for adjustment factors and permits application of the unmodified Lake Hefner equation. Relatively continuous records of the required data, with some interruptions of a few days each, were provided during Lake Survey Center surveys of Lake Erie, conducted by the research vessel *Shenehon* in 1965 (June 26-November 7). Monthly values for the *Shenehon* data were determined for July through October, estimating records for the missing days from relationships with perimeter stations.

The short term determinations of monthly evaporation, based on *Shenehon* data, did not produce definite results. Since it took about 2 weeks for a single cruise, the most apparent reason for the unsuccessful test of the overwater observations is the lack of synopticity in the vessel data, which makes the data unsuitable for the purpose desired. The variation of data with respect to both time and space is probably the main weakness of ship observations, especially when long time spans and large areas are involved. The reliability of *Shenehon* data would have been greatly enhanced if some means of checking the authenticity of the data had been provided during the period of the surveys. This control could be provided by fixed overwater platforms, such as towers or buoys.

3.4 Effects of Ice Cover

Winter evaporation determined by the mass transfer method does not take into account the possible effects of ice cover. Substantial ice cover on the lake would tend to inhibit evaporation and render computed values too high. The mass transfer evaporation, especially from the MT-2 method, was considerably higher than the water budget evaporation during most winter months, and Lake Erie is known for its extensive ice cover, implying an ice-cover effect. This fact was recognized in previous studies, but adjustments for mass transfer evaporation based

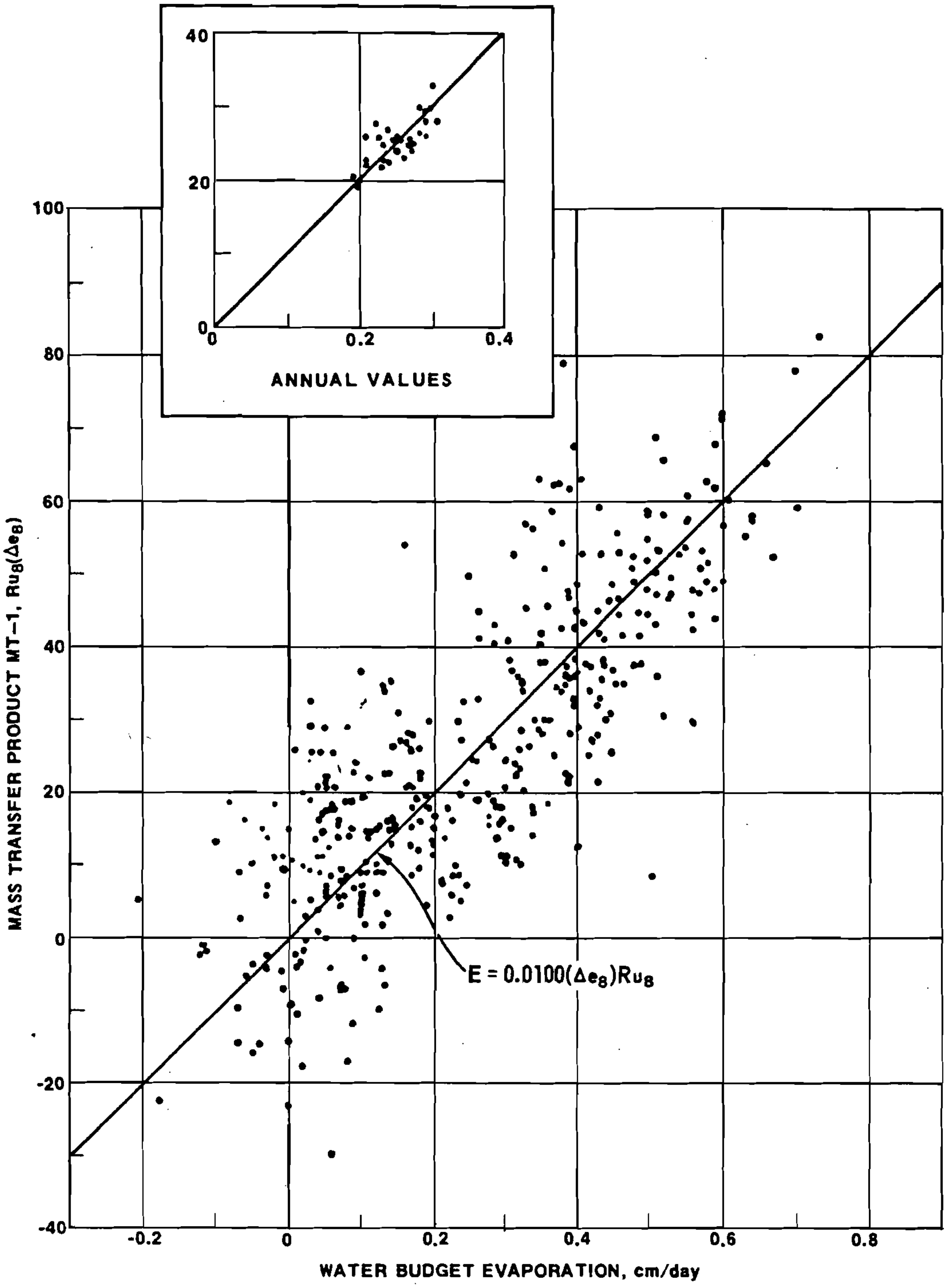


Figure 6. Relationship between water budget evaporation and mass transfer product MT-1, 1937-1968.

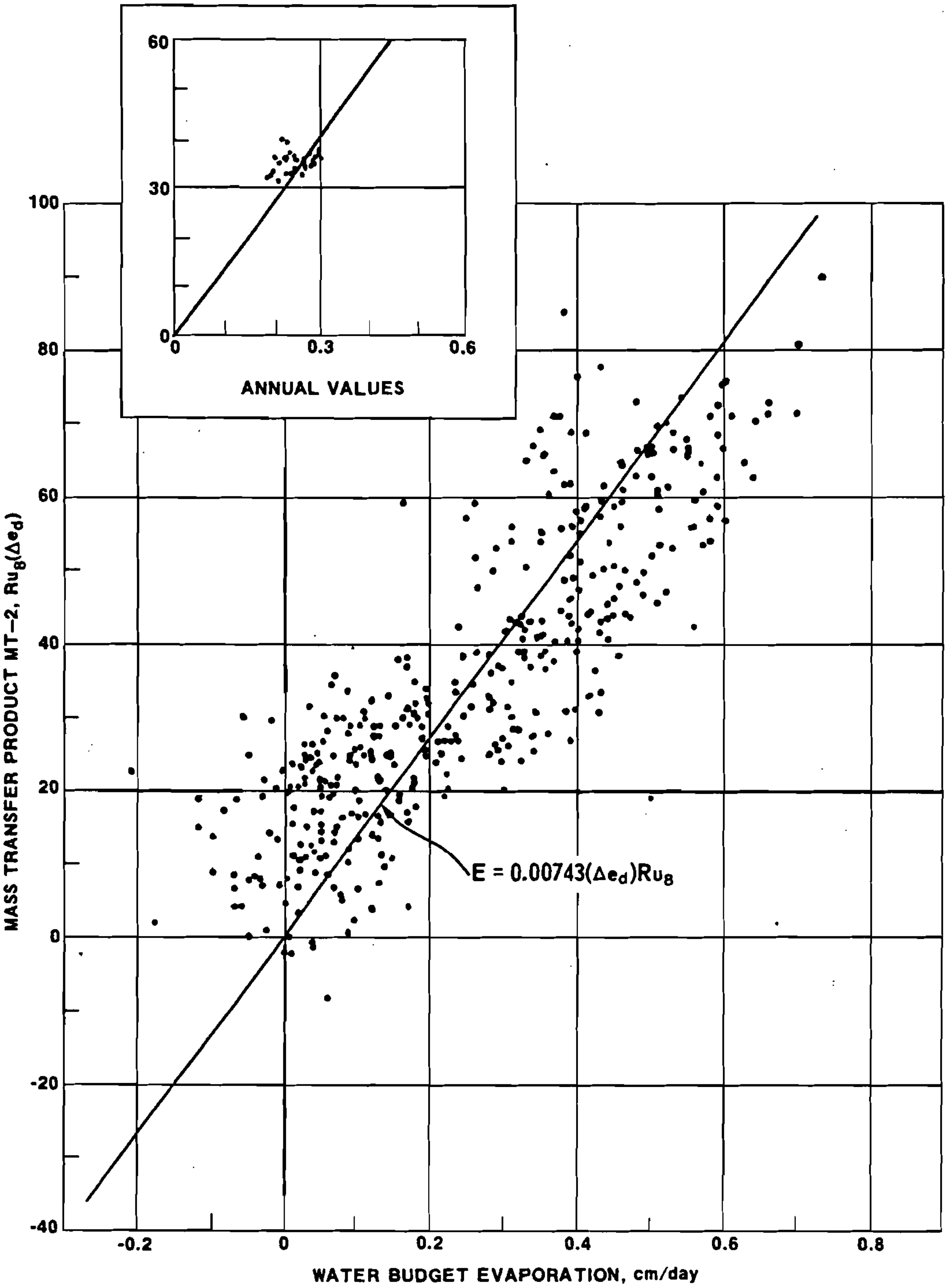


Figure 7. Relationship between water budget evaporation and mass transfer product MT-2, 1937-1968.

on ice cover have not been established.

Reasonably detailed ice observations on the Great Lakes are available for the last decade. The ice cover for Lake Erie was determined from ice surveys conducted regularly by the Lake Survey Center since 1962 and Ice Forecasting Central in Canada. Estimates of the average monthly ice cover on the lake obtained from the individual surveys during a 6-year ice-cover season, December through April 1962-1968, are given in table 9. Extensive ice cover normally occurs during January, February, and March and is usually very light during December and April. Heaviest ice cover concentration occurs in February, with a 6-year average of 86 percent. Intermediate ice concentration during January and March indicates average values of about 50 percent, while light concentration during December and April indicates averages below 10 percent. Variation of ice cover during individual seasons may be considerable for all months. The highest monthly variation was obtained for January, with extreme values of 15 and 81 percent.

Table 9. Estimates of Lake Erie Average Monthly Ice Cover, Percent, 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

The relationship between ice cover and lake 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 were compared with the percent of monthly ice cover on the lake. The evaporation difference ($E_{MT} - E_{WB}$) represents overcomputation of evaporation by neglecting the ice cover. The mass transfer evaporation values used for the ice effect evaluations were obtained by the Lake Hefner equation which was previously determined as the more appropriate for the Great Lakes.

The relationship of evaporation difference ($E_{MT} - E_{WB}$) versus ice cover is shown in figure 8. Although there is a large scatter of data and some discrepancies in the results, there is indication of an ice-cover effect on evaporation from Lake Erie. The figure indicates that the effect is not progressive with the gradual increase of ice cover, but grouped into light and extensive ice-cover concentrations related to seasonal periods. The light ice-cover period, limited to about 15 percent concentration, consists of December and April data, which show very little, if any, relationship between ice cover and the evaporation difference. The extensive ice-cover period, in excess of about 15 percent concentration, consists of January, February, and March data, which show a definite relationship between ice cover and the evaporation difference. During this period the ice cover reduces lake evaporation significantly, indicating an average reduction of approximately 1 cm per 10 percent 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 difference. These values represent overcomputation of mass transfer evaporation due to ice cover and should be positive for correct mass transfer and water budget results.

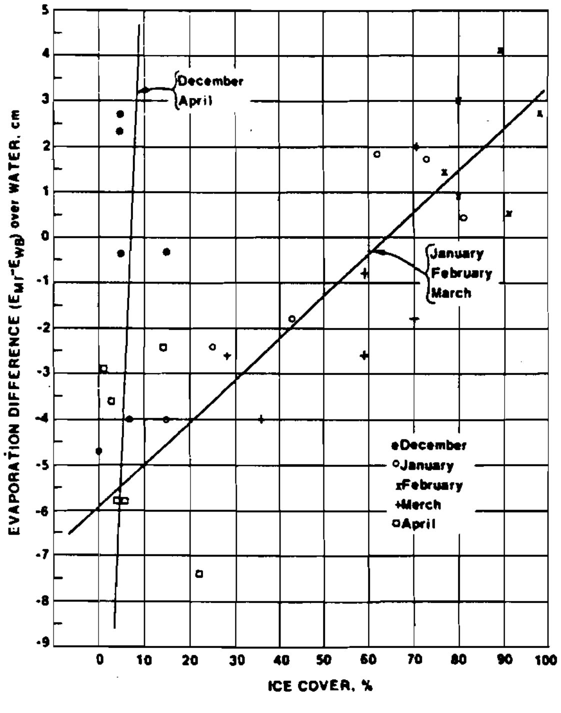


Figure 8. Relationship between evaporation difference by the mass transfer minus water budget methods and ice cover, 1962-1968.

The second approach utilized only the mass transfer evaporation values. 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 adjusted by the percentage of observed ice cover and combined with the normal values for open water areas to indicate the actual ice cover and open water conditions. The adjusted evaporation values were compared with the standard open water evaporation results.

The relationship of mass transfer evaporation for the standard computations over water and adjusted computations for the actual lake surface conditions, comprised of ice cover and open water, is shown in figure 9. It verified the general results indicated in figure 8, namely, the grouping of data into light and extensive ice cover periods and the varying significance of ice cover on mass transfer evaporation during these periods. For the light ice-cover periods of December and April the relationship is very strong, with an average slope of nearly 1 to 1 (about 1.07). The small overcomputation (about 7 percent) for the standard mass transfer evaporation can be disregarded during these months of low evaporation. For the extensive ice-cover period of January, February, and March the relationship is rather weak, with large scatter of data, but it indicates a definite ice-cover effect on mass transfer evaporation, with a tentative average slope of nearly 4 to 1. Because of weak and limited data no attempt was made to derive and apply monthly ice-cover adjustments, but the two figures indicate that the ice-cover effect on mass transfer evaporation is significant during the extensive ice-cover period (January-March).

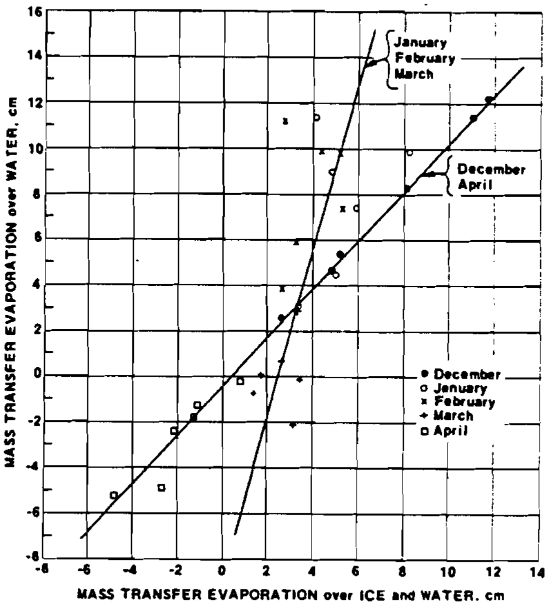


Figure 9. Relationship between mass transfer evaporation for the open water and actual ice-cover and open water conditions. 1962-1968.

4. 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 (chemical, biological, conduction through the bottom, transformation of kinetic energy), there are six basic heating or cooling processes constituting the energy budget of a lake. These energy processes include 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

$$Q_s - Q_r + Q_a - Q_{ar} - Q_b - Q_t + Q_v = Q_h + Q_e \qquad (8)$$

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 values of Q_s through Q_v, constituting the left-hand side of equation (8), 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, which may be defined as the ratio of heat loss by conduction to heat loss by evaporation. Since the quantity desired is Q_e, the energy budget equation modified by the Bowen ratio and expressed in a convenient form is

$$Q_e = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_b - Q_t + Q_v}{1 + R} \qquad (9)$$

where R = Bowen ratio (Q_h/Q_e).

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

$$E = \frac{Q_e}{dL} \tag{10}$$

where
E = lake evaporation, cm/day

d = density of water (fresh water = 1.0)

L = latent heat of vaporization, cal/cm^3.

For fresh water the latent heat of vaporization is given by the equation

$$L = 596 - 0.52\ T_w \tag{11}$$

where
T_w = water surface temperature in °C.

The latent heat of vaporization may be determined for each month, but the average value of 590 cal/cm^3 produces an error of less than 2 percent.

Theoretically, the energy budget method of computing evaporation looks very attractive. It offers a potentially accurate method to determine evaporation losses from large lakes and eliminates the main objections to other methods, namely, the dependence of the water budget method on large factors and the empiricism of the mass transfer method. However, instrumentation for the required data is very expensive and most of the data are not available from the regular climatological or hydrological networks. These data are observed primarily at special stations or research project installations, which were not used extensively until recent years. Because of the required data limitations, use of the energy budget method on the Great Lakes has been restricted in the past to two studies on Lake Ontario (Rodgers and Anderson, 1961; Bruce and Rodgers, 1962).

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; however, a critical value of R approaching -1.0 renders computed evaporation extremely large unless the sum of all other energy terms is very small and consequently the evaporation is practically nil (see equation 9). The Bowen ratio is expressed by the equation

$$R = \frac{Q_h}{Q_e} = 61 \times 10^{-5}\ p\ \frac{T_w - T_a}{e_s - e_a} \tag{12}$$

where p = atmospheric pressure, mb

T_w = water surface temperature, °C

T_a = air temperature, °C

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, where heat and water vapor transfer processes may differ from those over the lake because of different stability conditions. In view of the sensitivity of the Bowen ratio, especially near the critical value of -1.0, even small errors in $(T_w - T_a)$ or $(e_s - e_a)$ are magnified in the calculation of Q_e. Thus, land 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:

$$T_2 = 0.25\ T_a + 0.75\ T_w \tag{13}$$

where T_2 = overwater air temperature at 2 m.

In contrast to the above, the results of the Lake Mead study (U.S. Geological Survey, 1958) indicate that it makes little difference where air temperature and humidity are measured, insofar as the effect on energy budget evaporation is concerned. To resolve these differences and enable selection of the best available values, three sets of monthly Bowen ratios were determined and tested for computing average evaporation for the 1952-1968 period. The three sets of Bowen ratios are based on variable air temperature and vapor pressure values of (T_a and e_a), (T_2 and e_a), and (T_2 and e_2). Bowen ratios derived with (T_a and e_a) were considerably different from the other two sets, with near-critical values in March, May, and June and, consequently, extremely high evaporation for some months of the low evaporation season. The ratios derived with (T_2 and e_a) and (T_2 and e_2) were quite similar, except for the month of April, where the ratios based on (T_2 and e_2) had a near critical value. The overall comparison of the three sets of Bowen ratios suggests that the location of air temperature measurements is important, while that of humidity may be negligible. The Bowen ratios selected as being most reasonable were those derived with (T_2 and e_a) values; this set had no critical values of R and produced the best comparison between energy budget and water budget evaporation. Table 10 gives the selected set of Bowen ratios for the 1952-1968 period, representing the energy budget period of study.

Table 10. Determination of Lake Erie Bowen Ratios, 1952-1968

$$R = \frac{Q_h}{Q_e} = 61\times10^{-5} p \frac{T_w - T_a}{e_s - e_a}$$

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

The energy budget of Lake Erie, containing energy terms derived for equation (8), is given in table 11. A brief discussion of the energy terms is given below.

Table 11. 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

4.1 Solar Radiation

Solar or shortwave radiation on the Earth's surface consists of the incident and reflected radiation components. The incoming solar radiation is reduced by the atmosphere before reaching the Earth. Attenuation of the extraterrestrial solar radiation by the atmosphere is caused by scattering, reflection, and absorption by gas molecules, water vapor, clouds, and suspended dust particles. 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 without adjustments to overwater conditions. They indicate that average incident solar radiation for the 1952-1968 period varied from approximately 110 ly/day in December to 560 ly/day in June, with the annual average at about 330 ly/day (table 11).

Despite a lack of adjustment to overwater conditions the incident solar radiation data are based on actual measurements and are probably more reliable than many of the other terms used in the energy budget computations. Because some of the energy terms represent little more than gross estimates, further refinement of the solar radiation data would be of little practical value in computing lake evaporation. However, preliminary investigations of solar radiation on the Great Lakes, based on limited data from synoptic surveys, confirm the physical concepts of the lake effect. Results of a preliminary study conducted by Richards and Loewen (1965) indicate that solar radiation over the lakes is greater than that recorded on adjacent land stations during summer and smaller during winter months. Their study is based on 4 years of limited data (1960-1963) during the April-December period and shows that overwater radiation at the beginning and end of the period amounts to 90 percent of the overland radiation. The overwater radiation increases gradually during spring and summer to an average high of about 135 percent of the overland radiation in the late summer, then decreases rapidly in the fall. These results may be modified by a more comprehensive study; they include some bias towards fair weather conditions, especially during months with frequent seasonal storms.

The reflected solar radiation depends on the surface albedo or the ratio of the reflected to incident radiation. Albedo values for the water surface depend on the altitude of the Sun, the cloud cover, and the roughness of the water surface; however, for practical purposes they can be assumed to be constant for daily or longer periods. Albedo measurements on the Great Lakes are generally not available, but Kohler and Parmele (1967) recommended average daily albedo of 6 percent for the water surface. More refined determinations can be made by using empirical curves, developed by Anderson (1954) during the Lake Hefner study, which give water surface albedos as a function of the Sun's altitude for various cloud cover conditions. In view of the small magnitude of the reflected solar radiation, the 6 percent water surface albedo was considered satisfactory for the purpose of this study. The 17-year average reflected solar radiation varied from 7 ly/day in December to 33 ly/day in June, with an annual value of 20 ly/day (table 11).

The relatively 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, ranging from 10 percent for clear ice to 46 percent for snow ice, both free of snow cover, and 67 percent for snow-covered ice. Winter ice cover was not considered in the energy budget computations. Since Lake Erie has an extensive ice cover, derived values for the reflected solar radiation may contain considerable error during winter months. Maximum error should not exceed 20 ly/day, an amount equivalent to 1 cm of evaporation per month. Although by no means insignificant, this error would still be smaller than possible errors inherent in some of the other energy terms.

4.2 Terrestrial Radiation

Terrestrial or longwave radiation over a body of water consists of the incident and reflected atmospheric radiation components and the 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. The net back radiation may be determined from total radiation measurements (longwave plus shortwave during daylight hours), but there is no regular network for such measurements; total radiation measurements are limited to periodic observations at research installations. 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.

Atmospheric radiation may be computed by several equations, which utilize various radiation indexes (temperature, percent of sunshine or cloud cover, vapor pressure). The equation used in this study was that 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 (Q_{act}) adjusted for particular location (A) and degree of cloudiness (Q_s/Q_{sc}), as expressed by the following equation:

$$Q_a = \sigma T_a^4 - [228.0 + 11.16\,(\sqrt{e_{sa}} - \sqrt{e_a}) - A] \times [Q_s/Q_{sc}]^n \quad (14)$$

where Q_a = incident atmospheric radiation under all conditions, ly/day

σ = Stefan-Boltzmann constant (11.71×10^{-8} ly/day/°K^4)

T_a = surface air temperature, °K

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).

The station adjustment term is a function of the long term relationship between air temperature at the surface and an upper level (50 to 200 mb above surface). Anderson and Baker determined the adjustment term by plotting the atmospheric radiation difference between typical and actual profiles versus the temperature difference between the two profiles at the surface and a given level. Assuming a linear relationship, the values of A for the upper level of 150 mb above surface are given by the equation

$$A = 5.0\,(T_{ua} - T_{ut}) \qquad (15)$$

where T_{ua} = difference between actual upper-air and surface temperature from long term relationship, °C

T_{ut} = same difference for typical temperature profiles, (-9.3°C for 150 mb).

Equation (14), terminating with the station adjustment term, gives clear sky atmospheric radiation for any station or locality. To calculate atmospheric radiation during cloudy conditions, further adjustment of the clear sky atmospheric radiation is required. The extent of cloudiness may be determined from observations of cloud cover or percent of sunshine or from the ratio of observed to clear sky solar radiation. Each of these approaches has its advantages and disadvantages. Cloud cover can be observed throughout the day, but lacks consistency (visual observations); percent of sunshine may have the same objection and applies only to daylight hours; the ratio of incident to clear sky solar radiation may be a good index of cloudiness, but it is also limited to daylight hours. The author chose the solar radiation ratio because incident solar radiation has to be determined for the energy budget computations and is already available.

Selection of the solar radiation ratio as the index of the degree of cloudiness requires determination of the clear sky solar radiation. A convenient method of computing clear sky solar radiation, used in the present study, is presented by Bolsenga (1964). Solar radiation received on the earth's surface on cloudless days is a product of the extraterrestrial radiation and atmospheric attenuation factors, which reduce extraterrestrial radiation through absorption, scattering, and diffusion. A simplified expression for the total clear sky solar radiation (direct and diffuse) is given by the equation

$$Q_{sc} = Q_{se}\ (a + 0.5s) \qquad (16)$$

where Q_{sc} = clear sky solar radiation, ly/day

Q_{se} = extraterrestrial solar radiation, ly/day

a = total transmission coefficient (including moisture absorption and molecular scattering)

s = total depletion by atmospheric scattering and diffuse reflection.

Values for the major components required to compute atmospheric radiation and the resulting incident atmospheric radiation are shown in the Appendix (table A.14). Average incoming atmospheric radiation for the 1952-1968 period varied from a winter low of 570 ly/day (January, February) to a mid-summer high of about 740 ly/day (August), with an annual average of 650 ly/day. Thus, incident atmospheric radiation provides approximately twice as much heat to Lake Erie as solar radiation, on an annual basis.

The reflectivity of a water surface for atmospheric radiation has been determined by Anderson (1954) to be 3 percent. Since this value 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. The reflected atmospheric radiation is relatively constant throughout the year, with an average annual value of 20 ly/day (1952-1968); average monthly values vary from 17 ly/day in the winter to 22 ly/day during summer months (table 11).

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 to be about 0.97 (Anderson, 1954). The relationship for the emitted radiation is expressed by the equation

$$Q_b = \varepsilon \sigma T_w^4 \qquad (17)$$

where Q_b = radiation emitted from the lake, ly/day

ε = emissivity of the water surface (0.970)

σ = Stefan-Boltzmann constant (11.71×10^{-8} ly/day/°K^4)

T_w = water surface temperature, °K.

The average monthly emitted radiation from Lake Erie for the 1952-1968 period varied from approximately 630 ly/day during winter months to 860 ly/day in mid-summer (August); the average annual value was about 730 ly/day (table 11). On the average, emitted radiation exceeded incident atmospheric radiation by 80 ly/day. This longwave radiation loss combined with the 20 ly/day from reflected atmospheric radiation produced a net back radiation to the atmosphere of 100 ly/day.

4.3 Heat Storage

Heat storage in the lake was determined from the water temperature profiles, based on temperature surveys. The energy required for computing evaporation was the change in heat storage during monthly intervals. This change in heat storage is the difference in heat content at the beginning and end of the month and is expressed by the equation

$$Q_t = (V_2T_2 - V_1T_1) \qquad (18)$$

where Q_t = change in heat content, cal

V_2 = volume of lake at end of month, cm^3

T_2 = average temperature of lake at end of month, °C

V_1 = volume of lake at beginning of month, cm^3

T_1 = average temperature of lake at beginning of month, °C.

The change in lake volume during monthly intervals 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 relative difference between V_1 and V_2 is also small, and the average volume of the lake may be used without significant error. Thus, equation (18) may be modified to a more convenient form

$$Q_t = V(T_2 - T_1) \qquad (19)$$

where V = average volume of the lake from long term records, cm^3.

The heat content in the lake was computed by summing up energy contents calculated at the surface and several predetermined depth layers. This procedure was dictated by irregularities in the lake depths and stratification of the water temperature with depth. The cross-sectional area of the lake was divided into depth layers of 7.6 to 15.2 m (25-50 ft), as indicated in figure 10. Average volume for each layer was determined

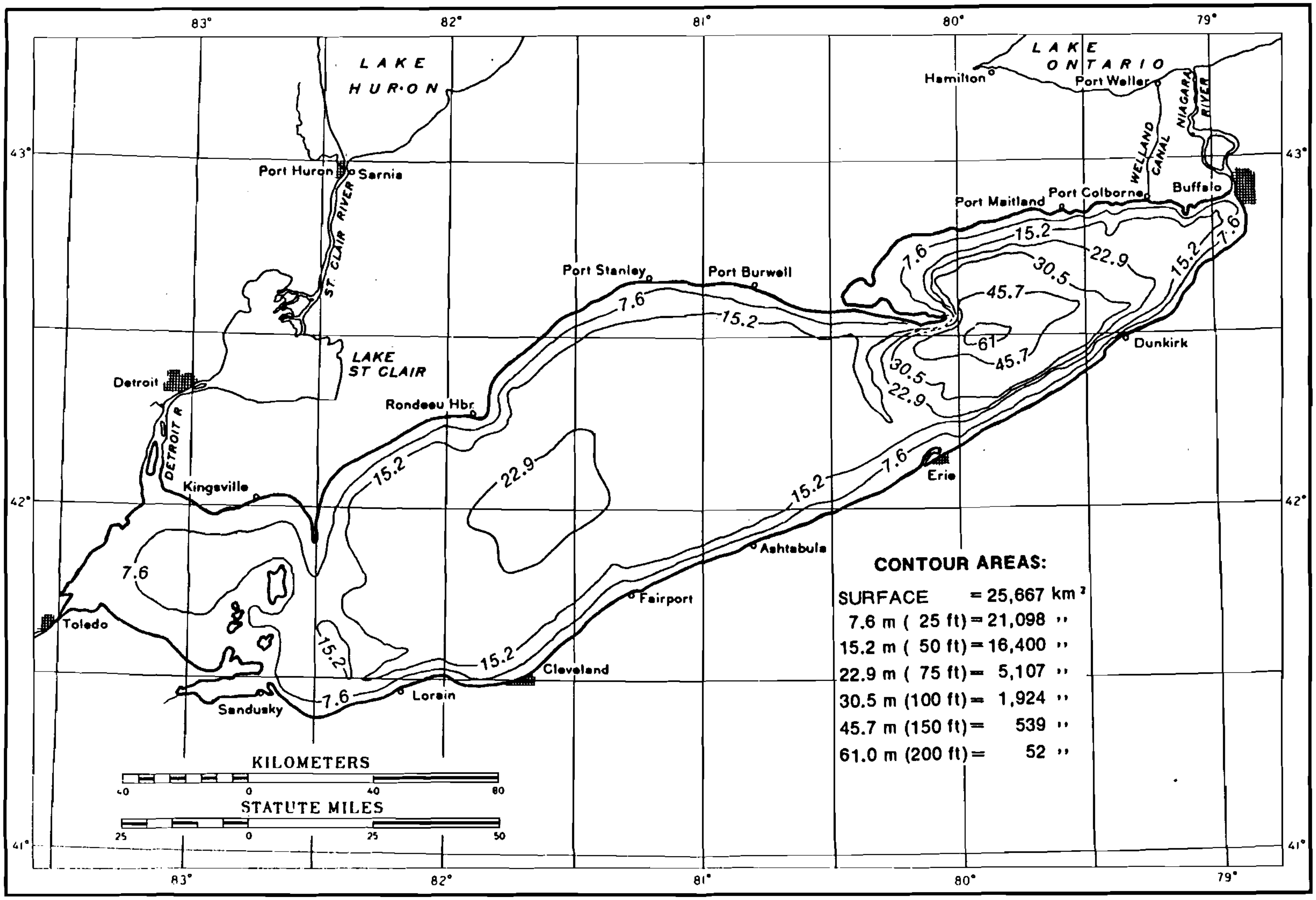


Figure 10. Bottom topography of Lake Erie.

from the resulting constant depth areas and depth segments to mid-points between layers. The energy content for each layer was computed from these volumes and the mean temperatures at the beginning and end of the month using equation (19).

The average water temperature at each layer was determined from the water temperature profiles, which were derived from Lake Erie temperature surveys published by the Great Lakes Institute, University of Toronto. Resulting average monthly temperature profiles for the period of published records, 1960-1963, are shown in figure 11. There were no temperature data for the winter months since temperature measurements were limited to the open-water season. During winter months, the water temperature profiles were estimated, using a range of 2°C at the maximum depth layer of 61 m (200 ft.). Determination of Lake Erie heat content from the above temperature profiles is shown in the Appendix (table A.15).

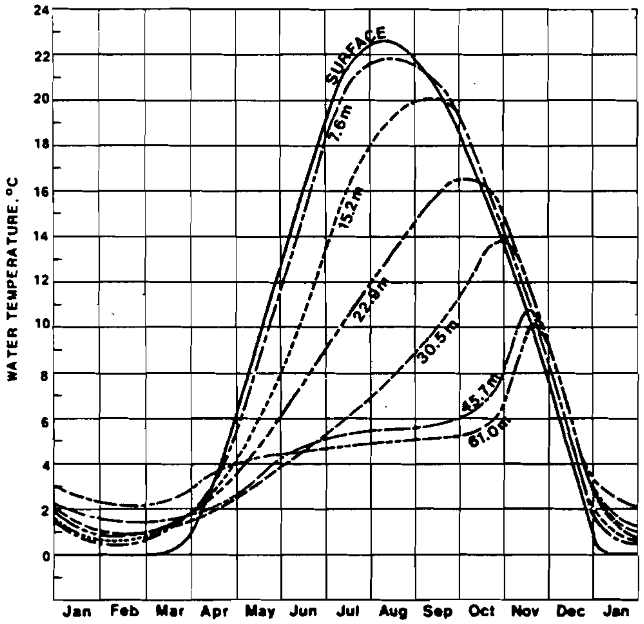


Figure 11. Lake Erie monthly water temperature as a function of water depth, 1960-1963.

The heat content for the required period of 1952-1968 was estimated by adjusted average temperature at each depth layer. Monthly temperature adjustments, ΔT_w, were derived from the water surface temperatures and of necessity applied to the entire depth. Because of lake stratification during most of the year, this procedure seems questionable, especially for depth below the thermocline (about 15 m), but represents the only means available. Temperature stability should increase with depth, but temperature profiles showed similar scatter at various depths. The estimates of Lake Erie heat content for the 1952-1968 period are given in the Appendix (table A.16). Comparison of the average monthly heat content for the two periods considered is shown in figure 12.

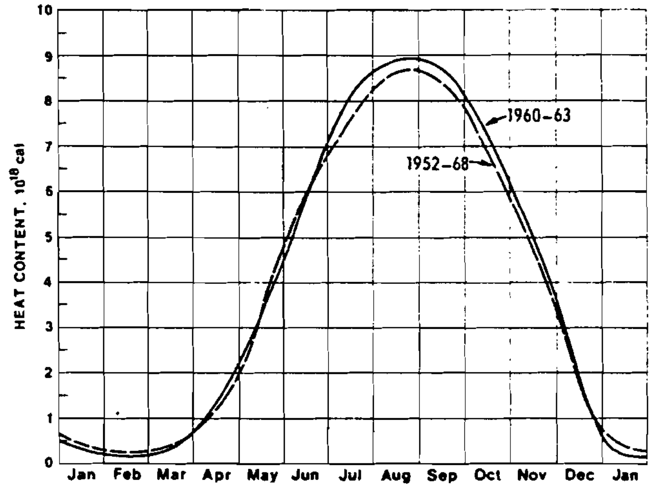


Figure 12. Monthly heat content of Lake Erie.

The monthly changes in heat content converted to ly/day are listed with other energy budget terms in table 11. During the 1952-1968 period the average monthly heat storage in Lake Erie varied from about 350 ly/day in May to about -340 ly/day in December. The lake gained heat during the spring and summer months and lost heat during the fall and early winter. On an annual basis heat storage is insignificant since seasonal heat gains and losses balance each other.

4.4 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 equation

$$Q_v = Q_i - Q_o - Q_m \tag{20}$$

where Q_v = net advected energy, ly/day

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

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

Q_m = snowmelt heat loss, ly/day.

The energy content of water entering or leaving the lake may be determined with sufficient accuracy 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. Thus, a detailed form of equation (20) becomes

$$Q_v = (V_pT_p + V_rT_r + V_iT_i) - (V_eT_w + V_oT_o) - (LdV_s) \qquad (21)$$

where V_p = volume of overwater precipitation (WB), cm^3

T_p = wet bulb temperature, °C (used T_a - 2°C, based on comparison of dry bulb and wet bulb temperatures)

V_r = volume of runoff from drainage basin (WB), cm^3

T_r = air temperature, T_a, °C (winter minimum at 0°C)

V_i = volume of inflow through Detroit River (WB), cm^3

T_i = Detroit River temperature, °C

V_e = volume of lake evaporation (WB), cm^3

T_w = lake surface temperature, °C

V_o = volume of outflow through Niagara River and Welland Canal (WB), cm^3

T_o = Niagara River temperature, °C

L = latent heat of melting (80 cal/cm^2 to produce 1 cm of water from pure snow at 0°C)

d = snow density (used average value for fresh snow of 10%)

V_s = volume of snowfall, cm^3.

Values for the major components of advected energy (Q_i, Q_o, and Q_m) are listed in the Appendix (table A.17) with supplementary energy budget terms.

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. The advected energy is the smallest energy term in the energy budget computations (table 11). The average monthly net advection for the 1952-1968 period varied from 11 ly/day to -11 ly/day. Lake Erie gained heat through net advection during the spring and early summer months and lost heat during the rest of the year.

4.5 Transfer of Sensible and Latent Heat

The combined value 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 was obtained by equation (8). Separate values for these two energy terms were then determined by employing the Bowen ratio; they are listed in table 11. During the 1952-1968 period the average energy utilized by conduction of sensible heat varied from -33 ly/day in March to 87 ly/day in December, with an annual value of 20 ly/day. Sensible heat was generally conducted from the lake to the atmosphere during most of the year, with the exception of some spring and summer months. The 17-year average energy utilized by evaporation varied from 26 ly/day in May to approximately 320 ly/day in September and November, with an annual value of about 190 ly/day.

4.6 Evaporation

Evaporation estimates from Lake Erie computed by the energy budget method are given in table 12. The table contains evaporation values determined by the energy and water budget methods for the energy budget period of study, 1952-1968. 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 well with the values obtained by other methods, although the months when they occur may not be exactly the same.

Table 12. Lake Erie Evaporation by Energy Budget Method Compared with Water Budget Method, cm, 1952-1968

PERIOD	ENERGY BUDGET	WATER BUDGET
January	3.0	7.2
February	3.0	3.6
March	9.7	1.8
April	5.3	1.2
May	1.3	2.6
June	10.2	3.6
July	10.9	10.1
August	11.7	13.9
September	16.3	16.5
October	15.7	16.0
November	16.3	12.0
December	13.0	8.3
Annual	116.4	96.8

Comparison of the seasonal distribution of average evaporation values obtained by the energy budget and water budget methods is shown in figure 13. 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) indicate tolerable agreement. Seasonal distribution of the energy budget evaporation is reasonably similar to that of the water budget values during most summer and fall months.

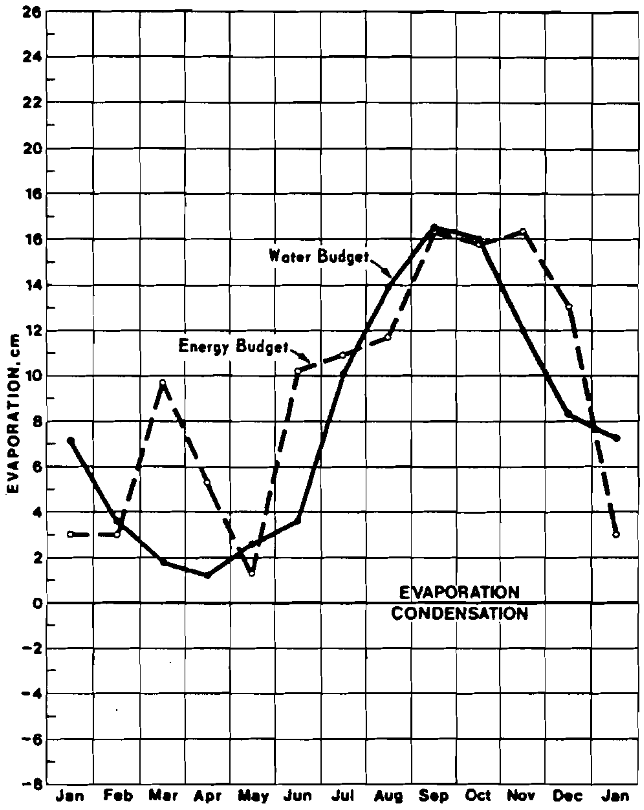


Figure 13. Comparison of water budget and energy budget evaporation from Lake Erie, 1952-1968.

Additional comparison of the energy budget evaporation with the mass transfer determinations can be obtained by comparing results from figure 13, with those presented in tables 7 and 8 for the 1952-1968 period. This in effect gives a comparison of the water budget, mass transfer, and energy budget evaporation values obtained in the present study for the identical period (1952-1968). Except for the winter months (December, January, and March), disagreement between the water budget and energy budget evaporation is generally of the same order of magnitude as that between water budget and mass transfer values. During most of the year, the maximum difference between monthly evaporation determined by different methods is generally limited to 4 cm. Variation in the seasonal distribution of the energy budget evaporation from the other methods appears to be random, without definite preference for the water budget or mass transfer evaporation.

5. MASS TRANSFER-ENERGY BUDGET METHOD

The mass transfer and energy budget evaporation equations require observations of water surface temperature, which is usually the most critical and weakest input parameter. On many lakes, water temperature data are not available at all. For estimating free-water evaporation, that is, theoretical water surface evaporation unaffected by heat storage and advection, the requirement for the water surface temperature may be eliminated by simultaneous solution of the mass transfer and energy budget equations. This approach was used by Penman (1948), who developed the following combination equation:

$$E_w = (Q_n \Delta + E_a \gamma)/(\Delta + \gamma) \tag{22}$$

where E_w = free-water evaporation, cm/day

Q_n = net radiation energy, expressed in the same units as evaporation

Δ = slope of the saturation vapor pressure versus temperature curve (de_s/dT) at T_a, mb/°C

E_a = evaporation from aerodynamic equation, assuming $T_w = T_a$, cm/day

γ = psychrometric constant from Bowen ratio equation (0.640 for mb and °C),

in which

$$Q_h/Q_e = \gamma(T_w - T_a)/(e_s - e_a) \tag{23}$$

where Q_h = sensible heat transfer

Q_e = energy utilized by evaporation

T_w = water surface temperature, °C

T_a = air temperature, °C

e_s = saturation vapor pressure at T_w, mb

e_a = vapor pressure of the air, mb.

The original Penman equation employed a mixture of both English and metric units, but this does not alter the basic form of the equation. Monthly values for the slope Δ, for saturation vapor pressure versus the temperature curve based on Lake Erie data, are given in the Appendix (table A.18).

Practical application of equation (22) is dependent on the availability of net radiation, but this parameter is seldom available. The net radiation consists of the allwave incident and reflected radiation terms and the longwave emitted radiation, all of which were discussed under section 4, the Energy Budget Method. Observations of net radiation may be obtained directly over the water surface, but such data are extremely rare, and the usual practice is to determine the net radiation energy from its component radiation terms. In either case overwater observations are required, since emitted radiation from the water body is dependent on the water surface temperature. This requirement contradicts the primary purpose of equation (22), namely, application in the absence of overwater observations. In the derivation of the equation, Penman considered the effect of differences between air and water temperatures on convective heat transfer and evaporation, but assumed that emitted radiation is a function of air temperature. This assumption may produce tolerable errors for very small and shallow water bodies, with insignificant differences between air and water temperatures, but cannot be accepted as valid for large and deep lakes.

Kohler and Parmele (1967) modified the Penman equation by introducing a correction term which reflects the effect of differences in air and water temperatures on emitted radiation. Their equation for estimating free-water evaporation is based on meteorological observations and permits practical application in cases where observations of net radiation over the water surface are not available. The combined mass transfer-energy budget equation, proposed by Kohler and Parmele, expressed in metric units is

$$E_w = \frac{(Q_{ir} - \varepsilon\sigma T_a^4)\Delta + E_a[\gamma + 4\varepsilon\sigma T_a^3/f(u)]}{\Delta + [\gamma + 4\varepsilon\sigma T_a^3/f(u)]} \tag{24}$$

where E_w = free-water evaporation, cm/day

Q_{ir} = difference between incident and reflected radiation (allwave), same units as evaporation

ε = emissivity of the water surface (0.970)

σ = Stefan-Boltzmann constant (1.985×10^{-10} cm/cm^2/°K^4/day)

T_a = air temperature, °K

Δ = slope of the saturation vapor pressure versus temperature curve (de_s/dT) at T_a, mb/°C

E_a = evaporation from aerodynamic equation, assuming $T_w = T_a$, cm/day

γ = psychrometric constant from Bowen ratio equation (0.640 for mb and °C)

$f(u)$ = wind function from aerodynamic equation (u in m/s).

The term $[4\varepsilon\sigma T_a^3/f(u)]$ appearing in the equation is the correction term for emitted radiation, due to the use of temperature T_a rather than T_w. It was derived by modifying the expression for emitted radiation as follows:

$$Q_n = Q_{ir} - Q_b \tag{25}$$

$$Q_n = Q_{ir} - \varepsilon\sigma T_w^4 \tag{26}$$

$$Q_n = Q_{ir} - \varepsilon\sigma[T_a^4 + 4T_a^3\ (T_w - T_a)] \tag{27}$$

where Q_n = net radiation

Q_b = emitted radiation

T_w = water surface temperature, °K.

The expression for emitted radiation in equation (27) represents a first approximation (first two terms of binomial expansion). Equation (24) was obtained by substituting the expression for Q_n from equation (27) and eliminating the temperature difference term $(T_w - T_a)$. This term was eliminated by the expression

$$T_w - T_a = (e_s - e_{sa})/\Delta \tag{28}$$

where e_s = saturation vapor pressure at T_w, mb

e_{sa} = saturation vapor pressure at T_a, mb.

The derivation of equation (24) required elimination of the vapor pressure difference $(e_s - e_{sa})$ by simultaneous solution of the aerodynamic equations for E_w and E_a. These equations were expressed as follows:

$$E_w = f(u)\ [e_s - e_a] \tag{29}$$

$$E_a = f(u)\ [e_{sa} - e_a] \tag{30}$$

where e_a = vapor pressure of the air, mb.

In the present study, equations (22) and (24) were both used to compute free-water evaporation, E_w, by the combined mass transfer-energy budget method. Since emitted radiation, based on the water surface temperature, T_w, was determined for the energy budget computations, the net radiation, Q_n, needed for the Penman equation was available (table A.17). This combination equation is designated as MT-EB-1 and the free-water evaporation value obtained by it as E_{w1}.

The combination equation proposed by Kohler and Parmele is designated MT-EB-2, and its corresponding freewater evaporation, with emitted radiation based on air temperature, T_a, is designated as E_{w2}. The allwave difference between incident and reflected radiation, Q_{ir}, needed for this equation was obtained from the energy budget data (table A.17).

Solution of both combination equations requires separate determination of evaporation by a mass transfer equation, E_a. This aerodynamic equation should produce correct values of evaporation with observations taken over the water surface. Since E_a is to be determined with overland observations, options are limited to the selection of a proper wind function f(u). The aerodynamic equation used by Kohler and Parmele (1967) is in good agreement with that subsequently proposed by Penman (1956) when the difference in the heights of wind speed observations is considered. For the wind speed at 8 m, used as standard in this study, and all variables expressed in the metric system, Kohler and Parmele's equation becomes

$$E_a = (0.0136 + 0.0077u_8)\ (e_{sa} - e_a) \qquad (31)$$

where E_a = evaporation from aerodynamic equation, assuming $T_w = T_a$, cm/day

u_8 = wind speed over land at 8 m, m/s

e_{sa} = saturation vapor pressure at T_a, mb

e_a = vapor pressure of the air over land (2 m), mb.

Use of the combination equations (22) and (24) in conjunction with the aerodynamic equation (31) enables determination of evaporation from the water surface that is unaffected by heat storage and advection. This is seldom the case on the lakes, especially when heat storage is concerned. Advection may be unimportant, except when flows are not only relatively large but also the inflow and outflow have considerably different temperatures. Heat storage, on the other hand, may be insignificant only on the annual basis. Thus, heat exchange within the water body has to be considered in estimating lake evaporation for other than annual periods. The method presented by Kohler and Parmele (1967) includes an adjustment for the effects of heat storage and advection which can be applied to the evaporation computed for a thin free-water surface to obtain estimates from the actual water bodies. Their lake evaporation equation may be expressed as follows:

$$E = E_w + \alpha(Q_v - Q_t) \qquad (32)$$

where E = lake evaporation, cm/day

E_w = free-water evaporation, cm/day

α = ratio of evaporation to total energy exchange

Q_v = net advection, expressed in the same units as evaporation

Q_t = change in heat storage, same units as evaporation.

The ratio α gives the proportion of the energy contained in advection and heat storage which is used for evaporation. Its derivation was based on the assumption that the effects of advection and changes in heat storage are distributed between evaporation, sensible heat transfer, and emitted radiation. The values of α or that portion of the energy which affects evaporation are given by the equation

$$\alpha = \Delta/[\Delta + \gamma + 4\epsilon\sigma T_w^3/f(u)] \qquad (33)$$

With the values of α and the energy contained in Q_t and Q_v (table 11), lake evaporation estimates may be obtained; however, all three terms require water temperature data, thus, in effect nullifying the advantages of the mass transfer-energy budget combination equation. This method was, nevertheless, tested on Lake Erie, so its results can be compared with those of the other methods.

5.1 Aerodynamic Computations

The accuracy of results produced by the combination equation depends to a large degree on the adequacy of the aerodynamic equation. It is, therefore, important to use an appropriate aerodynamic function based on reliable data. Equation (31) presented by Kohler and Parmele (1967) was derived from upwind meteorological observations and water temperature data obtained in the Lake Hefner study.

The aerodynamic computations of wind function, vapor pressure difference, and resulting evaporation, E_a, obtained for Lake Erie during the period of study, 1952-1968, are shown in the Appendix (table A.19). The average annual value of E_a approaches 62 cm, with the monthly values varying from approximately 2 cm during winter months to a summer high of 10 cm. Thus, values of E_a correspond roughly to two-thirds of the value of lake evaporation determined by other methods. Evaporation E_a, of course, was not intended to represent lake evaporation; it is simply a hypothetical value obtained with overland air temperature observations. Employment of these air temperatures is reflected in the seasonal distribution of E_a values by eliminating the heat storage effect, which would have been reflected by water temperatures. Due to the elimination of the heat storage effect, the seasonal extremes of E_a occur during winter and summer, instead of spring and fall as normally indicated by lake evaporation.

5.2 Evaporation from Water Surface

Evaporation from Lake Erie, for a thin free-water surface unaffected by heat storage and advection, is shown in the Appendix (table A.19). The average annual free-water evaporation, E_{w1}, is about 102 cm, while the corresponding value for E_{w2} is about 92 cm. This 10 cm increase in the annual free-water evaporation is caused by the use of the water surface temperature in determining emitted radiation for the combination equation (22), rather than the air temperature used in equation (24). The average monthly values vary from approximately 1 to 18 cm for E_{w1}, and 2 to 15 cm for E_{w2}. Thus, the magnitude of the free-water evaporation is roughly similar to that of lake evaporation obtained by other methods.

Seasonal distribution of the free-water evaporation is similar to the evaporation computed by the aerodynamic equation, in that neither indicates any effects of heat storage. In both cases, seasonal extremes occur during winter and summer months. Since a heat storage effect would be involved in any water body of significant size, this distribution is not applicable to Lake Erie. By the same token, combination equations for the free-water evaporation cannot be used for Lake Erie without adjustment for heat storage and advection.

5.3 Lake Evaporation

Lake evaporation computed by the combined mass transfer-energy budget method for the two sets of free-water evaporation is listed in table 13. The table also shows comparable water budget values. Derivation of combined evaporation and the values of the ratio α, which indicates the proportion of heat storage and advection utilized by evaporation, is given in the Appendix (table A.19). The average annual lake evaporation is about 94 cm for the MT-EB-1 determination and approximately 85 cm for MT-EB-2. Thus, adjustment for the change in heat storage and advected energy reduced the annual free-water evaporation by about 7 cm. The average monthly lake evaporation for both determinations varied from approximately 2 cm in mid-winter to 12 cm in the summer and/or early fall. Lowering of the annual evaporation was caused by a significant reduction of the high monthly free-water evaporation during the spring and summer months, reflecting the effects of heat storage on lake evaporation.

Table 13. Lake Erie Evaporation by Mass Transfer-Energy Budget Method, cm,
1952-1968

PERIOD	MASS TRANSFER-ENERGY BUDGET		WATER BUDGET
	E_1	E_2	
January	1.8	2.8	7.2
February	2.5	2.5	3.6
March	5.1	4.1	1.8
April	8.4	5.6	1.2
May	6.6	4.1	2.6
June	11.2	7.9	3.6
July	12.2	9.7	10.1
August	11.7	10.4	13.9
September	12.4	11.9	16.5
October	9.1	10.2	16.0
November	7.9	9.1	12.0
December	5.3	6.6	8.3
Annual	94.2	84.9	96.8

NOTE: E_1 from equations (22) and (32).
E_2 from equations (24) and (32).

Comparison of Lake Erie evaporation estimates by the mass transfer-energy budget and the water budget methods shows generally poor agreement. On an annual basis, lake evaporation determined with Penman's combination equation compares more favorably with the water budget values, indicating reasonable agreement (about 3 cm low), while lake evaporation determined with Kohler and Parmele's equation is some 12 cm too low. However, this apparent agreement is misleading. Higher annual values for the MT-EB-1 determinations are due to the abnormally high evaporation during spring, a season of low evaporation. A better comparison of evaporation obtained by the combination equation and water budget methods is provided by the seasonal distribution curves, shown in figure 14. Lake evaporation determined by the MT-EB-2 approach indicates better agreement with the water budget values during almost every month of the year. However, both determinations by the combined mass transfer-energy budget method have relatively high evaporation values during the low evaporation season, centered around spring, and relatively low evaporation during the high evaporation season, centered around fall.

Because of reservations concerning accuracy of the water budget evaporation, the mass transfer-energy budget evaporation was also compared with independent determinations by the mass transfer and the energy budget methods. Table 14 gives a comparison of all evaporation estimates obtained in the present study, but the values presented are based on two different periods of record. Comparison of the evaporation estimates by the four methods, adjusted for the same period of record (1952-1968), may be obtained by comparing figures 13 and 14 with the mass transfer values from tables 7 and 8. With few exceptions (March for EB, April for MT-1), the combined mass transfer-energy budget monthly estimates show the greatest deviations from the other evaporation estimates. Thus, Lake Erie evaporation determined by the mass transfer-energy budget method has to be classified as least reliable. The seasonal distribution of evaporation indicated by this method is, therefore, considered to be incorrect.

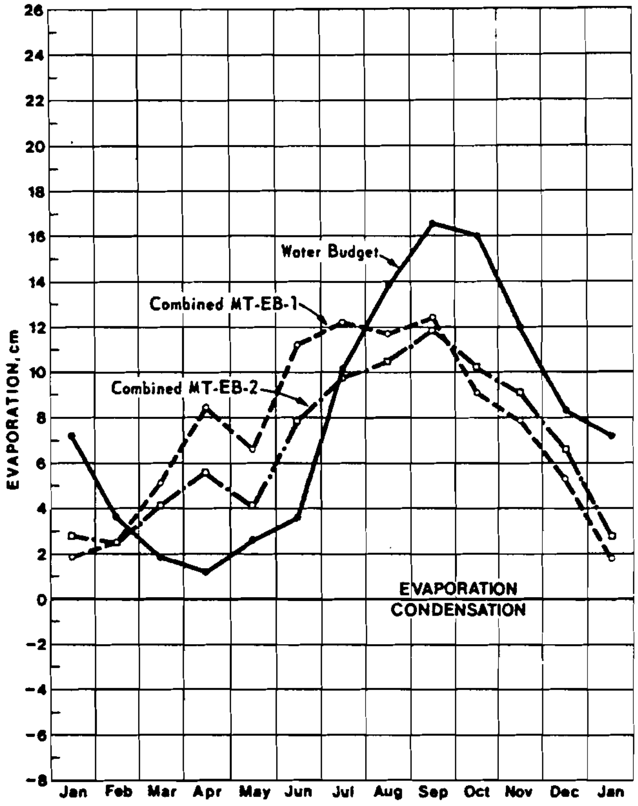


Figure 14. Comparison of water budget and combined mass transfer-energy budget evaporation from Lake Erie, 1952-1968.

6. SUMMARY AND CONCLUSIONS

Evaporation from Lake Erie was determined by four relatively independent methods in an attempt to obtain firm evaporation estimates. The methods consisted of water budget, mass transfer, energy budget, and combined mass transfer-energy budget approaches. For the mass transfer and combined methods two separate equations were used, which in effect produced six determinations of evaporation from the lake (table 14). The evaporation determined by the water budget method was used to provide control for the other methods since all other determinations required some empiricism, which was based on measurements not necessarily representative for the Great Lakes. However, the accuracy of evaporation values 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 several independent methods.

Table 14. Lake Erie Evaporation Estimates, cm

Method	Water Budget	Mass Transfer		Energy Budget	Mass Transfer-Energy Budget	
		MT-1	MT-2		MT-EB-1	MT-EB-2
Period	1937-1968	1937-1968		1952-1968	1952-1968	
January	7.1	5.2	7.0	3.0	1.8	2.8
February	3.2	4.3	5.9	3.0	2.5	2.5
March	1.4	1.2	4.1	9.7	5.1	4.1
April	0.8	-1.6	1.9	5.3	8.4	5.6
May	1.6	6.0	2.9	1.3	6.6	4.1
June	2.9	5.7	4.0	10.2	11.2	7.9
July	9.6	5.6	6.3	10.9	12.2	9.7
August	13.6	10.7	10.1	11.7	11.7	10.4
September	16.2	14.1	12.9	16.3	12.4	11.9
October	14.6	15.5	14.1	15.7	9.1	10.2
November	11.8	16.2	13.7	16.3	7.9	9.1
December	8.0	7.0	8.2	13.0	5.3	6.6
Annual	90.9	89.8	91.1	116.4	94.2	84.9

NOTE: Mass transfer and combined mass transfer-energy budget determinations are based on the following equations:

MT-1: Equation (3)
MT-2: Equation (5)
MT-EB-1: Equations (22) and (32)
MT-EB-2: Equations (24) and (32).

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 and mass transfer-energy budget methods 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; however, of the two mass transfer equations, only the modified Lake Hefner equation produced annual evaporation that agreed reasonably well with the water budget values during individual years and is the recommended mass transfer equation. Comparison of the annual evaporation obtained by the other two methods, energy budget and combined method, was limited to the average values and indicates less reliable results. The average annual energy budget evaporation was significantly higher than the water budget evaporation, while the more representative mass transfer-energy budget determination produced low annual evaporation estimates.

Evaporation determined for the monthly periods is less accurate than the annual values because the effect of random errors on these shorter periods is more pronounced. Comparison of monthly evaporation, shown by the seasonal distribution curves, indicates that the most reasonable monthly estimates were obtained by the water budget method. These were followed by the mass transfer estimates, energy budget estimates, and finally the combined mass transfer-energy budget estimates. Seasonal distribution of evaporation obtained by the mass transfer method, especially from the better Lake Hefner equation, 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 any 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. The seasonal distribution from the mass transfer-energy budget determinations is unrealistic, with relatively high values during most of the low evaporation season and relatively low values during high evaporation season. This method appears to be unsuitable to Lake Erie and its results should be disregarded.

During winter months, the presence of ice cover on the lake would tend to reduce evaporation losses. Since mass transfer and energy budget equations do not consider the 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 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 evaporation from Lake Erie can be determined by the water budget method and the mass transfer method, using the modified Lake Hefner equation. 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 improvement of the more promising evaporation estimates can be accomplished by additional field measurements or by re-evaluation 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 rating curves are unreliable. Additional improvements would be provided by expansion of the stream-gaging network for the determination of runoff, intensified research on groundwater conditions, and derivation of reliable overwater precipitation. Practical improvements for the mass transfer evaporation could be obtained by re-evaluating the wind and humidity ratios and the water temperature adjustments from additional data. The analysis in the report indicated that the monthly adjustments for humidity and water temperature were especially weak during certain months, causing apparent errors in the mass transfer evaporation estimates.

The main purpose of this study was to establish firm evaporation estimates (rates and variation) for the monthly and annual periods. No attempt has been made to develop evaporation forecasts, which would require an extensive additional study; however, evaporation forecasts are needed for a variety of hydrologic problems, such as improvement of methods for forecasting water supplies and development of more efficient lake regulation plans. The development of monthly evaporation forecasts could be based on either water budget or mass transfer results (or a combination of both) since both methods provide monthly evaporation rates for individual years. However, none of the basic methods used to compute evaporation are readily adaptable to provide actual evaporation forecasts because of the requirement for reliable indexes of the input parameters one month in advance. This requirement might be somewhat less critical in a multiple regression type of equation, correlating evaporation with various climatic factors. A previous study (Derecki, 1964) showed that such an approach could produce satisfactory evaporation hindcasts (significant improvement over use of average values), at least for the more important high evaporation months. The independent climatic factors used in that study included wind speed, humidity, air temperature, water temperature, precipitation, and sunshine. A successful forecasting technique would need satisfactory indexes for these factors a month in advance. The National Weather Service provides monthly forecasts for air temperature and precipitation which would have to be evaluated. Forecasts of the other factors are not available at the present time for use in an evaporation forecasting technique.

7. REFERENCES

Anderson, E. A., and D. R. Baker (1967), Estimating incident terrestrial radiation under all atmospheric conditions, *Water Resources Res.* 3(4), 975-988.

Anderson, E. R. (1954), Energy-budget studies. Water-loss investigations: Vol. 1 - Lake Hefner studies, Technical Report, U.S. Geological Survey Circ. 229 (also Prof. Paper 269), 71-119.

Bolsenga, S. R. (1964), Daily sums of global radiation for cloudless skies, Research Report 160, U.S. Army Cold Regions Research & Engineering Laboratory.

Bolsenga, S. J. (1969), Total albedo of Great Lakes ice, *Water Resources Res.* 5(5), 1132-1133.

Bruce, J. P., and G. K. Rodgers (1962), Water balance of the Great Lakes system, Great Lakes Basin, American Association for the Advancement of Science Pub. No. 71, 41-69.

Derecki, J. A. (1964), Variation of Lake Erie evaporation and its causes, Pub. No. 11, University of Michigan, Great Lakes Research Division, 217-227.

Harbeck, G. E., Jr., (1962), A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory, U.S. Geological Survey Prof. Paper 272-E, 100-105.

Kohler, M. A., and L. H. Parmele (1967), Generalized estimates of free-water evaporation, *Water Resources Res.* 3(4), 997-1005.

Lamire, F. (1961), Winds on the Great Lakes, CIR-3560, TEC-380, Canada Department of Transport, Metropolitan Branch.

Millar, F. G. (1952), Surface temperatures on the Great Lakes, *Jour. Fish. Res. Bd. Canada* 9(7), 329-376.

Penman, H. L. (1948), Natural evaporation from open water, bare soil and grass, *Proc. Roy. Soc. London* 193, 120-145.

Penman, H. L. (1956), Estimating evaporation, *Trans. Am. Geophys. Union* 37, 43-50.

Powers, C. F., D. L. Jones, P. C. Mundinger, and J. C. Ayers (1959), Exploration of collateral data potentially applicable to the Great Lakes hydrography and fisheries, Phase II, Special Report 7, University of Michigan, Great Lakes Research Institute.

Quinn, F. H. (1971), Quantitative dynamic mathematical models for Great Lakes research, PhD thesis, University of Michigan.

Quinn, F. H. (1972), Lake Erie beginning-of-month water levels and monthly rates of change of storage, LSC progress report (unpublished).

Richards, T. L. (1964), Recent developments in the field of Great Lakes evaporation, *Verh. Internat. Verein.Limnol.* 15, 247-256.

Richards, T. L., H. Dragert, and D. R. McIntyre (1966), The influence of atmospheric stability and over-water fetch on winds over the Great Lakes, *Monthly Weather Rev.* 94(5), 448-453.

Richards, T. L., and J. P. Fortin (1962), An evaluation of the land-lake vapor pressure relationships for the Great Lakes, Pub. No. 9, University of Michigan, Great Lakes Research Division, 103-110.

Richards, T. L., and J. G. Irbe (1969), Estimates of monthly evaporation losses from the Great Lakes 1950 to 1968 based on the mass transfer technique, *Proc. 12th Conf. Great Lakes Res.*, International Association for Great Lakes Research, 469-487.

Richards, T. L., and P. Loewen (1965), Preliminary investigations of solar radiation over the Great Lakes as compared to adjacent land areas, Pub. No. 13, University of Michigan, Great Lakes Research Division, 278-282.

Rodgers, G. K., and D. V. Anderson (1961), A preliminary study of the energy budget of Lake Ontario, *Jour. Fish. Res. Bd. Canada* 18 (4), 617-636.

U.S. Geological Survey (1954), Water-loss investigations: Vol. 1 - Lake Hefner studies. Technical Report, U.S. Geological Survey Circ. 229 (also Prof. Paper 269).

U.S. Geological Survey (1958), Water-loss investigations: Lake Mead studies, U.S. Geological Survey Prof. Paper 298.

Yu, S. L., and W. Brutsaert (1969), Generation of an evaporation time series for Lake Ontario, *Water Resources Res.* 5(4), 785-796.

APPENDIX A

Selected Meteorological Data on Lake Erie

Table A.1. Overwater Precipitation on Lake Erie, cm

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
R_p	1.03	0.90	0.94	1.03	0.99	0.92	0.95	1.00	0.91	0.91	0.94	0.94	
1937	15.8	4.3	3.4	15.2	6.1	15.5	9.8	7.9	4.6	7.9	3.4	6.1	100.0
38	3.4	9.4	8.2	6.4	8.5	7.0	7.6	5.8	9.8	2.1	6.7	4.6	79.5
39	6.4	9.1	7.0	9.1	3.7	7.6	7.6	5.5	6.7	6.1	2.4	4.3	75.5
40	4.3	5.5	5.5	8.2	9.8	9.1	4.6	11.0	6.1	4.6	7.3	8.2	84.2
41	4.6	2.4	3.4	4.3	6.1	7.0	8.5	6.4	3.0	7.9	5.8	4.0	63.4
42	5.2	6.4	7.0	5.8	9.8	6.4	8.8	8.8	8.8	7.9	8.8	7.3	91.0
43	4.6	3.7	6.1	9.4	15.2	7.9	12.2	5.8	5.8	7.0	4.6	2.4	84.7
44	3.0	5.2	7.9	10.7	7.9	9.1	3.4	8.5	7.0	3.0	4.6	6.4	76.7
45	4.9	5.2	10.4	8.5	9.4	10.7	7.0	5.8	11.9	12.2	5.5	5.5	97.0
46	2.7	4.6	5.5	2.4	11.6	11.3	5.2	5.5	3.7	7.3	5.8	6.1	71.7
47	10.1	2.4	6.1	13.4	12.8	9.8	9.8	9.4	7.0	3.4	7.0	4.9	96.1
48	4.9	5.8	10.4	8.2	9.4	8.8	6.4	6.4	5.8	7.3	8.2	4.6	86.2
49	7.9	5.5	5.8	5.8	7.6	3.7	8.2	9.4	8.2	4.9	6.4	7.0	80.4
50	14.6	9.4	7.6	10.7	4.6	7.6	10.1	7.6	8.8	6.7	12.5	5.5	105.7
51	6.1	7.0	9.8	7.9	7.0	9.4	6.7	4.6	5.8	6.4	9.8	9.4	89.9
52	8.8	4.6	6.7	7.3	9.4	3.7	5.2	8.2	7.0	1.8	5.8	5.8	74.3
53	7.3	2.4	7.0	6.4	11.0	4.9	5.8	7.3	5.5	1.5	5.2	5.8	70.1
54	6.7	7.6	11.6	11.9	3.0	6.1	4.0	7.9	4.6	17.7	4.6	6.1	91.8
55	5.2	5.8	8.8	7.9	6.4	4.3	5.2	11.9	5.2	12.5	7.3	4.0	84.5
56	4.6	6.7	9.4	9.8	11.6	6.1	8.2	15.5	4.6	2.1	6.1	6.7	91.4
57	8.2	4.3	3.7	13.7	8.5	11.0	8.2	6.7	9.8	5.8	6.4	7.6	93.9
58	4.6	3.7	1.8	7.3	5.2	10.1	10.4	7.9	8.5	4.0	8.2	2.7	74.4
59	10.7	7.0	7.0	10.1	8.5	5.5	6.7	7.9	7.0	11.6	7.3	7.3	96.6
60	7.9	6.7	3.0	7.0	8.2	9.1	6.4	7.9	3.4	3.7	4.6	2.7	70.6
61	1.8	7.6	6.7	16.5	5.8	8.2	8.2	10.7	7.3	4.0	6.7	4.6	88.1
62	7.3	5.2	3.0	4.0	5.5	7.6	7.3	6.7	7.9	7.0	5.5	6.1	73.1
63	3.4	2.1	7.3	7.6	5.2	4.0	7.6	6.7	3.4	1.5	7.6	4.3	60.7
64	4.9	2.4	9.8	11.3	6.1	5.5	6.1	14.9	3.0	3.4	3.4	7.3	78.1
65	10.7	6.4	6.7	5.5	5.2	5.2	6.4	10.4	7.3	8.8	7.0	7.3	86.9
66	4.3	4.0	6.1	9.4	4.9	7.6	11.0	8.5	6.4	3.4	11.3	9.8	86.7
67	3.7	4.0	3.4	8.8	7.9	7.6	6.1	6.7	7.9	7.0	7.6	8.5	79.2
68	7.9	2.4	5.2	6.1	10.4	9.1	6.7	8.5	7.0	5.8	9.8	8.8	87.7
MEAN	6.5	5.3	6.6	8.6	7.9	7.7	7.4	8.2	6.5	6.1	6.7	6.0	83.4
52-68	6.4	4.9	6.3	8.9	7.2	6.8	7.0	9.1	6.2	6.0	6.7	6.2	81.7

Table A.2. Runoff into Lake Erie, cm

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	23.8	10.4	4.9	15.5	5.2	7.6	5.2	2.1	0.9	1.8	0.9	3.4	81.7
38	2.4	14.6	18.3	12.5	2.4	2.1	1.5	1.8	0.9	0.3	1.2	1.8	59.8
39	3.0	13.7	18.6	16.2	2.1	2.4	1.2	0.6	0.3	0.6	0.9	1.2	60.8
40	1.5	4.3	10.7	20.1	5.5	6.4	1.8	0.9	1.8	1.5	3.4	10.1	68.0
41	6.4	3.4	5.5	8.5	1.2	2.1	0.9	0.6	0.6	1.2	2.1	2.7	35.2
42	2.7	9.4	20.4	13.1	4.9	4.0	1.8	2.1	1.8	2.7	8.5	9.8	81.2
43	8.8	10.7	17.4	9.8	23.5	7.9	6.7	1.8	1.5	1.2	2.7	1.5	93.5
44	1.8	4.3	13.7	18.9	7.6	3.7	1.2	0.6	0.6	0.9	1.2	1.2	55.7
45	1.5	7.0	18.6	10.1	12.8	6.4	2.1	0.9	1.8	8.2	4.3	4.9	78.6
46	7.9	5.2	13.4	1.8	5.5	9.1	1.8	0.9	0.6	0.9	1.5	3.0	51.6
47	10.7	4.9	10.1	25.3	16.5	15.5	3.0	1.8	2.4	1.2	2.4	4.6	98.4
48	5.2	9.4	23.2	10.4	10.4	2.1	1.8	1.5	0.6	1.2	3.4	5.8	75.0
49	15.5	13.1	9.1	7.6	5.5	2.4	1.5	0.9	0.9	1.5	0.9	6.4	65.3
50	28.3	16.8	21.3	18.6	5.5	4.0	2.1	1.2	3.4	4.0	8.5	15.5	129.2
51	14.9	17.4	17.7	14.6	7.9	4.0	3.4	0.9	0.9	1.8	5.5	9.4	98.4
52	25.3	10.7	17.1	13.4	6.7	1.8	1.2	0.9	0.9	0.6	1.2	2.7	82.5
53	5.5	4.0	10.7	5.5	8.8	2.7	1.5	1.2	0.6	0.6	0.9	1.5	43.5
54	3.0	7.0	13.7	15.5	4.0	2.4	0.9	1.5	0.9	10.7	3.7	7.0	70.3
55	8.8	8.2	20.4	8.8	2.4	1.5	1.2	1.2	0.6	2.1	6.7	4.3	66.2
56	1.8	12.5	19.8	12.8	18.0	4.9	2.4	4.3	3.4	1.5	1.5	5.2	88.1
57	7.0	7.3	7.0	23.2	6.7	5.2	5.5	0.9	1.5	2.1	4.3	13.4	84.1
58	4.3	4.0	8.5	7.0	3.7	5.2	6.1	5.8	3.4	1.5	5.5	3.0	58.0
59	12.8	18.3	16.5	14.9	7.9	2.4	1.5	1.2	1.2	4.3	6.7	10.7	98.4
60	12.2	11.0	7.9	14.6	6.7	6.1	1.8	1.2	0.9	0.9	1.2	0.9	65.4
61	0.9	6.7	12.8	21.0	6.4	3.4	1.8	2.1	1.5	1.2	2.7	3.0	63.5
62	7.0	6.1	16.5	5.8	2.4	1.5	0.9	0.9	0.9	1.2	3.0	2.4	48.6
63	1.8	1.2	20.7	6.7	2.7	1.8	1.2	0.9	0.6	0.6	1.2	1.2	40.6
64	2.7	1.5	14.3	14.9	4.0	1.8	0.9	1.5	0.9	0.6	0.9	3.0	47.0
65	7.3	10.7	14.9	13.4	3.7	1.8	0.9	0.9	0.9	2.4	3.4	7.6	67.9
66	5.5	7.3	9.4	6.7	7.6	2.1	3.0	1.2	0.9	0.9	5.5	17.7	67.8
67	4.9	7.6	15.8	11.6	9.8	3.0	2.4	1.5	1.8	3.7	7.0	14.9	84.0
68	8.8	14.0	12.2	6.7	8.5	5.8	3.4	2.7	1.8	2.1	5.5	11.9	83.4
MEAN	7.9	8.8	14.4	12.7	7.1	4.2	2.3	1.5	1.3	2.1	3.4	6.0	71.6
52-68	7.0	8.1	14.0	11.9	6.5	3.1	2.2	1.8	1.3	2.2	3.6	6.5	68.2

Table A.3. Inflow into Lake Erie, cm

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	48.8	34.7	46.9	47.9	50.3	47.2	48.5	48.5	46.6	49.4	47.2	44.8	560.8
38	38.7	40.8	42.4	49.1	51.8	50.9	53.6	54.3	52.1	53.9	52.1	51.5	591.2
39	47.9	28.1	40.0	51.5	53.3	52.7	55.2	55.5	54.3	55.5	53.0	52.7	599.7
40	40.5	39.6	43.9	48.5	50.3	51.2	52.4	52.1	51.5	52.7	51.8	52.1	586.6
41	44.8	34.7	43.6	47.2	52.4	50.6	52.4	51.2	50.0	52.4	51.8	52.4	583.5
42	45.1	30.5	45.7	52.7	54.9	54.9	56.7	56.1	54.6	54.3	53.3	52.7	611.5
43	46.6	39.6	52.4	53.6	59.7	57.6	61.9	62.2	60.0	61.6	58.8	58.5	672.5
44	44.8	45.7	50.0	56.1	58.5	57.6	60.0	58.8	56.7	58.8	55.8	57.6	660.4
45	46.6	42.1	53.6	53.6	58.8	57.6	61.0	59.7	57.3	60.4	56.1	56.7	663.5
46	53.0	37.8	57.6	57.6	59.4	58.2	59.7	58.8	55.5	56.1	53.6	54.9	662.2
47	48.8	40.5	52.4	57.3	57.9	57.6	61.0	61.0	58.2	59.1	57.6	57.3	668.7
48	54.3	48.5	56.7	56.4	61.6	57.3	59.7	59.1	55.5	54.6	51.8	52.4	667.9
49	54.3	48.2	45.7	52.1	53.0	51.2	53.6	53.6	50.9	51.5	48.5	50.0	612.6
50	50.3	40.5	45.1	51.5	52.1	51.5	54.9	55.2	54.3	56.1	53.3	54.9	619.7
51	47.9	44.5	56.4	56.7	60.4	59.4	63.1	63.7	61.3	63.7	62.2	65.5	704.8
52	66.1	57.9	64.3	64.6	66.1	65.2	68.0	68.6	66.4	66.1	62.2	63.4	778.9
53	61.9	54.9	62.5	60.7	64.3	63.4	66.8	66.1	62.8	63.1	60.7	61.0	748.2
54	51.2	44.2	61.6	58.8	61.9	61.3	64.3	63.4	61.3	64.9	62.2	62.5	717.6
55	61.6	50.6	61.9	59.4	61.9	60.0	62.5	60.4	57.6	58.5	54.9	55.5	704.8
56	36.7	38.7	51.2	53.9	61.3	56.1	57.9	59.1	56.7	56.7	53.6	53.6	635.5
57	45.1	41.1	52.1	51.2	53.3	51.8	56.1	54.6	53.3	53.0	51.5	52.4	615.5
58	42.1	35.4	50.3	44.8	52.4	50.0	52.1	51.5	49.4	50.3	47.2	47.9	573.4
59	33.8	34.1	48.2	49.1	50.0	49.4	50.6	51.5	50.0	52.4	52.4	53.6	575.1
60	52.4	43.3	52.4	55.2	58.2	57.6	62.2	62.8	61.0	62.2	58.5	61.6	687.4
61	54.9	50.6	57.0	56.1	57.3	56.1	58.5	58.8	56.1	57.6	55.8	56.7	675.5
62	47.8	39.9	55.2	54.9	57.3	55.5	57.0	56.1	54.9	55.2	52.1	50.3	636.2
63	46.6	42.1	50.3	49.7	52.1	51.2	52.4	52.4	49.7	50.9	48.8	47.2	593.4
64	39.0	38.1	46.0	44.5	47.2	46.3	47.9	48.5	47.2	49.1	45.7	46.9	546.4
65	42.4	40.8	46.0	48.5	50.3	49.4	52.1	52.7	51.2	54.6	52.7	55.2	595.9
66	54.3	46.3	54.9	53.9	55.5	53.6	55.5	54.9	52.7	53.0	50.6	54.3	639.5
67	54.6	44.8	52.4	53.6	56.1	54.6	59.7	58.2	56.4	57.0	56.4	57.9	661.7
68	52.4	54.6	56.1	54.6	57.0	57.3	60.4	61.0	58.5	61.0	58.5	59.1	690.5
MEAN	48.6	42.3	51.7	53.3	56.1	54.8	57.4	57.2	55.1	56.4	54.1	54.8	641.9
52-68	49.6	44.6	54.3	53.7	56.6	55.2	57.9	57.7	55.6	56.8	54.3	55.2	651.5

Table A.4. Outflow from Lake Erie, cm

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	52.4	49.7	52.4	53.3	59.7	58.2	61.9	59.7	54.9	54.3	52.1	51.8	660.4
38	47.2	43.6	52.4	55.2	58.5	56.7	57.9	59.1	54.9	54.9	53.3	54.6	648.3
39	50.9	44.8	52.4	52.7	59.1	57.9	58.5	58.5	54.3	55.5	52.1	54.3	651.0
40	48.8	44.8	49.4	53.0	56.7	57.9	58.5	56.1	55.2	54.9	54.3	55.8	645.4
41	55.5	48.8	52.1	51.5	54.3	52.7	53.9	53.0	50.9	51.5	51.8	51.5	627.5
42	48.5	43.6	51.5	53.9	59.1	58.2	59.7	60.0	57.3	58.2	57.6	59.4	667.0
43	55.2	51.8	57.6	56.4	66.1	68.9	69.8	68.6	64.3	63.4	62.2	62.8	747.1
44	57.6	52.7	57.0	59.1	65.5	64.9	64.6	62.8	59.7	60.0	56.4	58.8	719.1
45	53.0	49.1	59.1	60.4	65.8	64.3	66.1	65.8	62.2	68.0	63.1	64.3	741.2
46	61.9	53.0	60.4	60.0	62.8	63.4	64.6	64.3	59.1	59.7	58.2	59.7	727.1
47	57.3	48.8	56.1	53.9	67.1	71.3	70.7	68.0	64.9	63.1	61.9	63.4	746.5
48	59.1	54.9	61.9	64.6	70.1	66.8	67.4	65.5	60.7	61.0	59.4	59.7	751.1
49	61.3	56.1	61.0	59.4	61.9	58.5	59.4	58.2	56.4	55.5	53.0	54.9	695.6
50	60.0	55.2	61.3	61.3	66.1	63.4	62.8	61.0	58.2	60.0	59.4	63.1	731.8
51	62.2	54.9	62.2	66.8	71.0	67.7	68.0	66.4	63.1	64.0	63.1	66.4	775.8
52	69.2	66.1	71.9	72.5	76.5	71.6	71.3	70.7	67.7	67.7	63.1	65.8	834.1
53	65.2	60.7	66.8	66.1	69.2	66.8	68.3	68.0	64.3	63.1	61.0	65.2	784.7
54	60.4	53.7	63.7	65.2	69.5	65.2	64.9	66.1	62.8	67.7	66.4	68.3	774.1
55	69.2	59.7	70.1	69.8	72.2	67.1	66.4	65.8	61.6	64.3	63.7	62.5	792.4
56	56.7	52.1	57.9	60.0	68.0	64.9	65.2	66.1	63.7	61.6	59.4	59.7	735.3
57	58.8	51.2	57.0	60.7	64.0	61.9	64.9	62.2	59.4	58.2	57.6	59.1	715.0
58	57.9	48.5	54.3	53.0	56.1	54.6	57.0	57.0	54.3	54.3	53.0	52.4	652.4
59	50.3	46.9	54.9	55.5	60.4	58.2	57.3	55.8	52.1	54.9	54.9	56.1	657.3
60	58.8	54.6	55.8	57.3	63.4	62.8	63.7	62.2	59.7	60.4	59.4	59.1	717.2
61	54.9	50.6	58.2	61.3	68.6	64.9	64.9	64.0	61.3	60.4	56.4	59.1	724.6
62	53.6	47.2	56.1	55.8	60.0	56.1	56.7	55.8	53.3	54.9	50.9	55.8	656.2
63	50.9	43.6	53.0	52.7	57.0	55.8	54.3	53.3	48.2	47.9	48.2	49.7	614.6
64	42.7	40.2	49.1	50.9	56.1	53.0	52.4	51.2	48.2	48.2	44.8	45.7	582.5
65	47.2	44.5	51.5	50.6	55.5	54.6	54.3	53.0	50.9	53.6	52.4	53.0	621.1
66	53.3	49.1	56.1	54.9	61.3	58.8	59.4	58.5	54.6	54.9	52.4	58.5	671.8
67	57.9	50.9	55.2	58.5	63.1	58.8	61.0	59.7	56.4	60.0	59.1	61.0	701.6
68	58.8	61.0	63.4	61.6	64.9	63.4	65.5	64.0	61.6	64.9	59.1	63.4	751.6
MEAN	56.1	51.0	57.6	58.4	63.4	61.5	62.2	61.3	58.0	58.8	56.9	58.6	703.8
52-68	56.8	51.8	58.5	59.2	63.9	61.1	61.6	60.8	57.7	58.6	56.6	58.5	705.1

Table A.5. Change in Storage on Lake Erie, cm

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	30.2	1.2	-2.7	28.3	1.8	14.6	-5.2	-10.4	-22.9	-8.5	-11.9	-0.9	13.7
38	-6.1	27.1	12.5	8.8	2.7	2.1	2.7	-10.7	-7.9	-11.9	-7.6	-5.5	6.4
39	2.4	6.7	11.0	22.9	-1.2	3.4	-1.8	-11.0	-10.7	-8.2	-7.9	-5.2	0.3
40	-12.5	1.5	9.4	25.6	11.0	7.3	-5.8	-2.1	-9.4	-8.2	-6.7	12.2	22.3
41	-5.2	-13.4	0.3	8.5	4.3	4.3	-2.7	-9.1	-13.4	-2.1	-4.0	2.4	-30.2
42	-4.9	1.2	25.3	18.0	11.6	4.3	2.4	-9.1	-8.8	-3.0	2.4	4.3	43.6
43	-4.9	-0.9	12.2	17.4	31.7	0.3	1.5	-13.7	-13.7	-7.9	-6.1	-11.3	4.6
44	-14.9	0.9	10.7	27.7	10.1	0.0	-13.4	-8.5	-7.0	-12.8	-2.7	-3.0	-13.1
45	-11.0	1.8	29.0	11.6	14.3	13.4	-4.9	-12.2	0.9	-4.3	-8.2	-7.3	23.2
46	-3.4	-11.0	17.4	-0.6	12.2	14.3	-8.5	-14.3	-11.3	-7.9	-8.5	-6.1	-27.7
47	4.9	-10.7	12.8	44.2	19.2	7.3	-9.4	-4.9	-18.3	-7.6	-12.8	-2.1	22.6
48	-7.9	5.2	26.8	10.1	10.4	0.3	-10.1	-11.9	-15.2	-13.4	-4.6	-4.3	-14.6
49	9.4	7.3	-1.8	5.2	4.0	-1.8	-6.1	-11.6	-13.4	-8.8	-7.6	4.0	-21.3
50	30.5	4.3	14.6	16.5	-6.1	-4.6	-4.3	-9.8	-8.5	-4.9	3.4	2.4	33.5
51	3.0	12.8	19.5	10.1	2.7	0.0	-7.0	-11.6	-13.1	-6.4	2.4	6.4	18.9
52	24.4	4.9	12.2	10.1	1.5	-6.1	-9.8	-7.0	-11.3	-21.9	-5.2	2.4	-5.8
53	8.8	-2.4	11.3	3.4	13.7	2.1	-6.1	-7.0	-15.2	-11.6	-4.0	-7.0	-14.0
54	-5.5	8.5	18.6	23.2	-4.6	-0.9	-5.8	-7.3	-10.4	14.6	-3.4	-0.9	26.2
55	0.6	3.4	18.0	7.9	-6.4	-6.7	-7.3	-6.4	-15.2	-6.7	-8.5	-7.3	-34.7
56	-19.8	-0.3	23.5	17.4	23.5	-1.5	-3.4	0.3	-18.0	-12.2	-15.5	2.7	-3.4
57	-8.2	3.4	5.2	27.4	3.0	6.4	-2.7	-15.8	-8.5	-13.1	-5.5	11.0	2.4
58	-15.8	-10.1	5.8	6.1	0.6	9.8	4.6	-4.0	-5.2	-14.9	-7.0	-9.8	-39.9
59	4.9	10.7	15.2	18.3	5.8	-6.7	-6.4	-7.3	-13.1	0.0	-3.4	12.2	30.2
60	6.1	0.6	4.6	17.7	10.7	8.2	-2.1	-3.7	-11.6	-15.2	-7.3	-11.9	-4.0
61	-4.9	12.5	18.0	30.8	-2.1	-1.5	-3.4	-6.1	-14.0	-15.8	-6.4	-6.4	0.6
62	-3.4	-0.6	17.1	5.2	0.0	3.7	-4.9	-4.6	-7.9	-7.3	0.3	-6.7	-9.1
63	-10.1	-6.7	25.6	9.1	0.6	-4.0	-5.2	-7.3	-9.8	-7.0	-6.1	-7.9	-28.7
64	1.2	0.0	17.7	19.2	-2.1	-2.1	-7.3	-2.7	-12.8	-12.2	-7.0	5.8	-2.4
65	4.0	9.1	15.2	14.3	2.4	-2.1	-6.4	-3.4	-4.0	-6.4	-1.2	9.8	31.4
66	-1.5	6.1	11.6	13.4	2.7	1.2	-5.5	-5.8	-13.7	-15.8	10.1	14.6	17.4
67	-1.8	-3.4	13.1	14.3	6.4	3.4	-2.1	-8.5	-7.6	-5.8	0.3	11.6	19.8
68	3.0	0.6	9.4	1.8	9.1	4.3	-6.1	-7.6	-8.5	-13.1	3.7	7.6	4.3
MEAN	-0.3	2.2	13.7	15.4	6.0	2.3	-4.8	-8.0	-11.2	-8.8	-4.6	0.2	2.3
52-68	-1.1	2.1	14.2	14.1	3.8	0.4	-4.7	-6.1	-11.0	-9.7	-3.9	1.2	-0.6

Table A.6. Measurement Heights of Meteorological Instruments, 1937-1968

STATION	PARAMETER	PERIOD	HEIGHT	
			ft	m
Buffalo, New York	Wind Speed	Jan. '37-Jun. '43	280	85.3
		Jul. '43-Aug. '59	96	29.3
		Sep. '59-Dec. '68	20	6.1
	Vapor Pressure (humidity and air temperature)	Jan. '37-Jun. '43	247	75.3
		Jul. '43-Aug. '60	34	10.4
		Sep. '60-Dec. '68	4	1.2
Cleveland, Ohio	Wind Speed	Jan. '37-May '41	337	102.7
		Jun. '41-Jan. '56	56	17.1
		Feb. '56-Jun. '59	88	26.8
		Jul. '59-Dec. '68	20	6.1
	Vapor Pressure	Jan. '37-May '41	268	81.7
		Jun. '41-Jan. '56	27	8.2
		Feb. '56-Feb. '60	28	8.5
		Mar. '60-Dec. '68	4	1.2
Toledo, Ohio	Wind Speed	Jan. '37-Jan. '43	87	26.5
		Feb. '43-Dec. '54	47	14.3
		Jan. '55-Oct. '58	72	21.9
		Nov. '58-Dec. '68	20	6.1
	Vapor Pressure	Jan. '37-Jan. '43	79	24.1
		Feb. '43-Dec. '54	5	1.5
		Jan. '55-Sep. '59	19	5.8
		Oct. '59-Dec. '68	4	1.2
London, Ontario	Wind Speed	Jan. '37-Dec. '40	58	17.7
		Jan. '41-Dec. '68	41	12.5
	Vapor Pressure	Jan. '37-Dec. '68	4	1.2

HEIGHT ADJUSTMENT EQUATIONS

WIND SPEED: $u_2 = u_1 \left(\frac{z_2}{z_1}\right)^{\frac{1}{7}}$

VAPOR PRESSURE: $\Delta e_2 = \Delta e_1 \frac{\log z_2 + 3.658}{\log z_1 + 3.658}$

Table A.7. Average Perimeter Wind Speed for Lake Erie at 8 m, m/s

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	5.01	5.14	4.78	4.78	3.53	3.35	3.40	2.77	3.67	4.56	5.05	4.38	4.20
38	4.65	4.65	5.01	5.01	3.89	3.58	3.17	3.49	3.75	3.58	4.69	4.74	4.18
39	4.96	5.32	4.78	4.87	3.71	3.71	3.31	3.35	3.80	4.47	4.16	5.10	4.30
40	4.96	4.16	4.65	4.38	3.80	3.80	3.22	3.44	3.17	3.44	5.14	4.43	4.05
41	4.65	5.01	4.47	4.29	3.98	3.62	3.44	3.49	4.29	4.38	5.36	4.78	4.31
42	5.10	4.74	5.27	4.47	4.20	3.26	3.53	3.22	3.67	4.20	4.78	5.01	4.29
43	4.83	6.03	5.50	5.32	4.56	4.02	3.35	3.40	3.71	4.34	4.47	5.05	4.55
44	4.56	4.83	5.77	4.78	3.53	4.11	3.58	3.89	3.80	4.02	4.16	5.14	4.35
45	4.74	4.92	4.83	5.50	4.83	3.62	3.44	3.49	4.16	4.74	5.19	4.69	4.51
46	5.68	5.59	4.92	5.05	4.78	4.34	3.31	3.44	3.62	3.98	4.74	5.63	4.59
47	5.81	6.08	5.32	5.68	4.74	3.89	3.89	2.95	3.89	3.53	4.69	4.74	4.60
48	4.96	4.65	5.32	5.14	4.16	3.58	3.53	3.17	3.49	3.67	4.87	4.92	4.29
49	5.54	4.96	5.45	4.38	4.25	3.84	3.58	3.31	3.58	3.84	4.92	5.19	4.40
50	5.63	5.45	5.95	5.59	4.34	4.29	3.58	3.35	3.53	3.62	5.59	4.69	4.63
51	5.10	5.01	5.77	5.10	4.29	3.71	3.71	3.35	4.11	4.34	5.19	5.59	4.61
52	5.19	4.74	5.27	4.83	4.38	4.38	3.98	3.22	3.53	4.92	5.05	4.83	4.53
53	4.87	5.59	5.10	5.27	3.80	4.02	3.44	3.17	3.93	3.31	4.47	5.90	4.41
54	5.19	5.32	5.77	4.96	4.38	4.20	3.62	3.75	4.43	4.29	4.29	4.60	4.57
55	4.74	4.16	5.68	4.83	4.20	3.53	3.58	3.75	3.75	4.47	5.27	4.69	4.39
56	4.56	4.78	5.10	4.96	4.83	3.80	3.98	3.75	3.89	4.16	5.05	5.01	4.49
57	4.92	4.34	5.05	4.83	4.83	4.20	3.75	3.26	3.71	3.80	5.36	5.54	4.47
58	4.83	5.59	4.16	4.65	4.69	4.29	3.71	3.71	4.11	4.47	5.41	4.78	4.53
59	5.41	5.41	5.59	4.78	3.89	3.71	3.44	3.44	3.80	4.34	5.05	4.38	4.44
60	5.32	5.95	4.96	5.54	4.56	4.16	3.53	3.40	3.58	4.11	5.36	5.72	4.68
61	5.10	4.65	5.81	5.32	5.27	4.38	3.58	3.49	3.67	4.11	4.65	5.54	4.63
62	6.53	5.68	5.19	5.41	4.69	3.89	3.80	3.53	3.98	4.16	3.80	5.10	4.65
63	5.27	5.50	5.72	5.50	4.83	3.62	3.93	3.75	3.71	3.62	5.32	4.65	4.62
64	5.90	4.69	5.59	5.59	4.96	4.20	3.75	4.11	3.89	3.98	4.83	4.96	4.70
65	5.95	5.86	5.01	4.83	4.38	4.29	3.58	3.75	4.07	4.78	5.01	5.01	4.71
66	5.19	4.34	5.27	4.92	4.51	3.67	3.84	3.49	3.75	4.92	5.10	5.14	4.51
67	5.72	6.08	4.56	5.27	4.96	4.02	3.53	3.62	3.75	4.65	5.32	5.19	4.72
68	4.83	5.72	5.27	5.14	4.65	4.29	3.84	3.53	3.53	4.11	5.01	5.95	4.66
MEAN	5.18	5.15	5.22	5.03	4.39	3.92	3.59	3.46	3.79	4.15	4.92	5.03	4.49
52-68	5.28	5.19	5.23	5.10	4.47	4.02	3.71	3.58	3.84	4.25	4.96	5.10	4.56

Table A.8. Prevailing Wind Direction over Lake Erie

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	WSW	W	W	SSE	SW	WSW	SW	SSW	SSW	WSW	W	W	SW
38	W	WSW	WSW	SW	WSW	SW	SW	WSW	SW	SW	SSW	WSW	WSW
39	W	W	W	WNW	SW	NNW	SW	SW	SW	WSW	W	W	W
40	W	NE	NNW	NNW	SW	WSW	W	E	WSW	NW	WSW	W	W
41	SW	W	W	SSE	WSW	W	W	WSW	SW	SW	SW	WSW	WSW
42	WSW	NNW	W	WSW	WSW	ESE	WSW	SW	SSW	SW	WSW	W	WSW
43	SSW	WSW	WSW	WNW	SW	SW	W	SW	SW	N	W	W	WSW
44	WSW	WSW	SSW	SE	SSW	WNW	WSW	SW	SW	WSW	WNW	WSW	SW
45	W	W	WSW	WSW	W	W	W	WSW	SSW	SW	SW	WSW	WSW
46	SW	W	SE	W	WNW	SW	SSW	W	SSW	SSW	W	WSW	SW
47	WSW	W	W	SW	SSW	SSW	SW	E	S	S	SW	WSW	SSW
48	SW	SSW	S	NW	NNW	SW	SW	W	N	WNW	WSW	SW	W
49	SW	W	WSW	WSW	WSW	SW	W	W	SW	SSW	SW	WSW	WSW
50	SSW	WNW	W	SW	WNW	SW	W	SSW	E	SSE	SSW	SW	SW
51	SW	SSW	WSW	WSW	NNW	SSW	SSW	WNW	S	SSW	SSW	SW	SW
52	SW	NNW	SSW	NNW	WNW	WNW	SSW	SE	SSW	SW	SW	WSW	WSW
53	SSW	WSW	WSW	WSW	NE	SW	SW	SW	SSW	SSE	SSW	SW	SW
54	WSW	SW	WSW	S	S	SW	W	WNW	SW	SW	SSW	WSW	SW
55	SW	SSE	W	S	SW	WSW	SSW	W	SSE	SSW	WSW	W	SW
56	NW	SSW	S	WSW	SSW	WSW	SSW	SW	SSE	ESE	SSW	SSW	SSW
57	SW	SSW	W	SSE	NNE	S	SW	W	SSW	W	SW	SW	SW
58	WSW	W	NNE	SE	SW	WSW	SW	SSW	SSW	SSW	SW	SW	SW
59	WSW	SW	S	SW	S	SW	SSW	SSN	SSW	S	SW	SSW	SSW
60	WSW	W	WSW	SW	SSW	S	SW	S	SE	SW	SW	SSW	SW
61	SW	SE	S	NW	WSW	SW	SW	SSW	SSW	SSW	W	W	SW
62	WSW	SSE	NNE	SW	S	NW	WNW	SSW	W	SW	SE	WSW	WSW
63	WSW	SW	S	W	WNW	SW	WSW	WSW	E	SSW	WSW	WSW	SW
64	SW	SW	WSW	S	SW	WSW	WSW	WSW	SW	SSW	SW	SSW	SW
65	WSW	SW	NW	N	WNW	WNW	W	SW	SW	WSW	SW	SW	W
66	W	WSW	WSW	W	WNW	W	WSW	WSW	W	SW	SW	WSW	WSW
67	SW	WSW	NW	W	NNW	SSW	W	W	WNW	SW	WSW	SW	W
68	S	W	W	WSW	S	WSW	WSW	WSW	SSW	WSW	W	W	WSW
MEAN	WSW	WSW	WSW	WSW	WSW	WSW	WSW	SW	SSW	SW	SW	WSW	WSW
52-68	WSW	SW	WSW	WSW	WSW	WSW	WSW	SW	SSW	SSW	SW	SW	SW

Table A.9. Average Perimeter Humidity for Lake Erie, Percent

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	81	76	76	74	70	74	72	76	66	74	73	81	74
38	79	80	74	70	70	70	72	71	74	71	71	76	73
39	81	76	73	72	66	73	68	71	72	72	78	78	73
40	81	82	78	69	73	74	70	74	79	77	79	81	76
41	82	80	76	63	62	69	68	67	68	77	77	79	72
42	78	83	78	66	72	73	72	76	77	77	78	84	76
43	86	80	71	71	76	72	74	76	75	75	76	75	76
44	79	79	75	73	72	74	65	70	77	73	80	82	75
45	87	85	75	70	73	75	72	72	78	76	77	82	77
46	77	77	71	62	70	71	67	71	71	72	76	75	72
47	80	79	78	74	74	72	74	76	76	77	78	79	76
48	82	79	76	70	72	73	72	72	72	79	79	79	75
49	81	78	74	70	66	68	70	72	74	73	80	77	74
50	80	81	76	73	68	71	72	73	78	79	78	81	76
51	81	82	76	76	68	74	71	72	74	74	78	81	76
52	82	80	78	71	69	66	66	72	73	66	75	83	73
53	84	76	79	74	75	68	68	69	68	71	74	75	73
54	78	76	74	72	64	70	65	74	74	79	79	81	74
55	78	78	75	70	66	68	69	74	71	78	79	78	74
56	82	80	77	72	72	72	74	77	75	73	75	85	76
57	80	80	74	76	70	73	71	71	75	74	76	78	75
58	78	78	78	66	61	69	75	73	78	73	76	78	74
59	80	77	72	67	70	68	70	76	72	79	76	81	74
60	82	81	76	74	76	70	70	75	78	74	79	78	76
61	74	80	75	78	67	73	77	80	78	74	76	78	76
62	75	77	73	66	66	70	69	73	73	78	77	78	73
63	78	74	77	65	68	66	68	74	72	64	78	79	72
64	75	76	78	71	65	68	70	74	71	71	75	82	73
65	77	71	80	73	66	68	69	77	79	74	76	80	74
66	76	81	73	72	64	66	67	74	74	68	79	82	73
67	77	72	78	68	64	65	73	74	71	73	74	76	72
68	73	71	72	62	73	72	71	76	78	77	80	76	73
MEAN	80	78	76	70	69	70	70	74	74	74	77	79	74
52-68	78	77	76	70	68	69	70	74	74	73	77	79	74

Table A.10. Average Perimeter Air Temperature for Lake Erie, °C

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	-0.1	-2.1	-1.3	7.0	14.0	19.0	22.2	22.9	16.2	9.2	3.7	-2.7	9.0
38	-3.9	-0.7	4.7	8.7	14.0	19.0	22.5	23.1	16.1	12.3	6.2	-0.7	10.1
39	-2.3	-2.2	0.6	5.9	15.1	20.3	22.0	22.1	18.3	11.8	3.8	0.7	9.7
40	-8.1	-3.4	-2.2	5.4	12.6	19.1	22.0	21.0	16.2	10.6	3.9	0.6	8.1
41	-3.4	-4.2	-1.8	10.5	15.3	20.3	22.9	20.7	19.0	12.3	5.7	1.4	9.9
42	-3.9	-5.7	2.6	10.3	15.1	20.0	21.8	20.7	16.7	11.6	4.7	-3.9	9.2
43	-5.4	-3.0	0.1	4.4	13.0	21.4	22.4	21.1	15.8	9.7	3.1	-3.1	8.3
44	-1.3	-3.1	-0.7	5.7	17.3	20.8	22.4	22.4	17.5	10.5	5.1	-4.7	9.3
45	-8.8	-3.1	7.7	9.8	10.8	18.0	21.1	21.1	17.9	9.8	5.0	-4.9	8.7
46	-2.8	-3.1	7.5	7.8	13.2	18.8	21.8	19.2	18.1	13.7	6.3	-0.3	10.0
47	-1.2	-6.0	-1.1	6.8	12.1	18.7	20.6	24.4	17.9	15.2	2.7	-2.2	9.0
48	-7.8	-4.0	1.7	10.0	12.6	19.1	22.5	21.5	18.5	9.3	7.3	-0.2	9.2
49	-0.1	-0.4	1.4	7.6	15.2	22.5	24.1	22.2	14.8	13.8	3.6	0.3	10.4
50	1.0	-3.5	-1.4	4.8	14.3	18.9	20.6	20.5	16.4	12.8	2.6	-4.1	8.6
51	-2.5	-2.6	2.0	7.5	14.8	19.3	21.9	20.3	16.2	12.6	0.9	-1.9	9.0
52	-1.5	-1.6	1.3	9.2	13.2	21.4	23.9	21.3	17.6	8.3	5.7	0.5	9.9
53	-0.6	-0.4	3.0	6.7	14.7	20.7	22.5	22.0	17.4	12.7	6.3	0.7	10.5
54	-3.9	0.9	0.4	10.0	12.6	21.0	21.5	20.3	18.0	12.3	5.0	-1.6	9.7
55	-4.1	-2.4	1.7	11.7	15.9	19.2	25.1	23.6	17.6	12.0	3.0	-3.4	10.0
56	-4.1	-2.2	0.1	6.7	12.9	19.7	21.1	21.0	15.1	13.2	4.9	1.4	9.1
57	-6.7	-1.1	2.3	9.3	13.6	20.3	21.6	20.2	17.0	10.0	4.7	1.1	9.4
58	-3.6	-6.2	1.6	9.4	13.4	17.0	22.0	20.6	17.1	11.6	5.6	-6.1	8.5
59	-5.8	-3.8	0.6	8.6	16.4	20.1	22.5	23.9	19.2	10.8	2.6	0.4	9.6
60	-2.4	-2.8	-4.7	9.8	13.8	18.5	20.3	20.9	18.2	10.5	5.8	-5.8	8.5
61	-6.7	-1.8	2.7	5.4	12.0	18.0	21.1	21.2	19.8	12.5	4.9	-2.2	8.9
62	-5.6	-5.2	0.6	7.9	17.2	19.3	20.2	20.5	15.5	11.5	3.7	-4.4	8.4
63	-8.7	-8.4	2.2	7.8	12.2	19.3	21.6	18.7	15.0	14.3	6.2	-6.1	7.8
64	-2.2	-4.3	1.3	8.3	15.7	19.2	22.5	18.8	16.5	8.7	5.7	-1.7	9.0
65	-4.5	-3.8	-1.4	6.1	16.1	18.3	19.6	19.5	17.8	9.2	4.4	1.2	8.5
66	-6.8	-3.7	2.2	6.7	11.2	20.0	22.2	20.0	15.2	9.4	4.8	-2.1	8.3
67	-1.5	-5.7	0.4	8.4	10.3	21.6	20.4	19.1	15.2	10.7	2.1	-0.1	8.4
68	-6.3	-6.0	2.3	9.1	11.9	18.8	21.1	21.3	18.0	11.1	4.6	-3.0	8.6
MEAN	-3.9	-3.3	1.1	7.9	13.8	19.6	21.9	21.1	17.1	11.4	4.5	-1.8	9.1
52-68	-4.4	-3.4	0.9	8.3	13.7	19.6	21.7	20.8	17.1	11.1	4.7	-1.8	8.8

Table A.11. Lake Erie Water Surface Temperature, °C

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
ADJ.	-1.9	-2.3	-2.1	-3.1	-2.8	-1.5	-1.5	-1.1	-1.3	-0.5	+0.6	-1.1	
1937	1.6	0.0	0.0	3.8	9.8	17.3	21.5	22.9	19.0	13.2	8.3	1.6	9.9
38	0.1	1.0	2.1	5.7	11.0	17.5	21.5	24.0	19.2	15.6	10.7	3.4	11.0
39	0.6	0.0	0.8	3.1	10.2	18.1	21.0	23.1	20.2	15.4	9.1	4.1	10.5
40	0.1	0.0	0.0	0.7	7.9	16.3	20.6	21.3	19.0	15.1	9.6	3.2	9.5
41	0.4	0.0	0.2	3.3	11.3	17.1	21.1	22.6	20.0	15.8	9.5	4.4	10.5
42	0.3	0.0	1.2	5.3	10.5	15.7	21.4	22.4	19.6	14.3	9.5	1.6	10.1
43	0.0	0.0	0.5	3.0	8.4	17.1	21.4	23.1	18.6	14.0	8.6	2.4	9.8
44	0.1	0.0	0.4	2.3	9.2	17.5	21.3	21.5	18.8	15.2	10.5	2.4	9.9
45	0.0	0.0	2.3	6.9	9.2	15.1	20.2	22.2	19.5	14.0	10.8	2.5	10.2
46	0.1	0.0	2.7	5.9	10.1	16.3	19.8	21.1	18.8	16.0	12.1	3.8	10.6
47	0.4	0.0	0.0	2.7	8.4	15.2	19.2	22.7	21.2	17.0	11.2	2.7	10.1
48	0.0	0.0	1.8	6.0	10.5	16.7	20.5	22.2	21.1	14.2	11.1	5.1	10.8
49	1.8	0.8	2.1	5.1	11.0	18.4	21.2	23.8	17.9	16.4	10.8	3.3	11.0
50	3.1	0.9	0.4	2.8	8.0	16.6	19.6	21.9	17.8	15.6	10.6	2.3	10.0
51	0.4	0.0	1.7	4.2	9.7	16.6	21.0	22.3	19.2	15.1	9.1	3.0	10.2
52	1.0	0.2	0.9	4.1	9.3	17.5	21.9	22.4	19.9	14.2	10.2	4.2	10.5
53	1.3	0.6	2.2	4.7	8.8	16.2	21.1	22.5	20.0	16.0	11.7	4.6	10.8
54	0.6	0.5	1.6	4.9	10.0	17.4	21.4	22.5	19.6	16.3	10.8	4.1	10.8
55	0.6	0.0	1.3	5.5	11.8	17.1	21.7	22.9	20.0	15.8	9.2	1.3	10.6
56	0.0	0.0	0.3	3.2	8.6	15.9	19.7	21.7	18.8	14.9	11.0	3.6	9.8
57	0.0	0.0	0.5	2.9	9.6	16.0	20.7	22.5	19.6	14.7	9.8	3.2	10.0
58	0.0	0.0	0.0	2.1	9.2	15.2	19.8	21.6	19.4	15.1	10.2	1.3	9.5
59	0.0	0.0	0.0	2.4	9.6	18.1	22.1	24.0	21.6	16.3	9.0	3.2	10.5
60	0.0	0.0	0.0	2.9	9.5	15.8	20.2	22.0	21.0	16.3	10.8	3.1	10.1
61	0.0	0.0	1.1	3.7	8.7	14.5	20.4	23.0	21.6	16.4	11.3	3.5	10.3
62	0.0	0.0	0.0	2.1	9.5	15.8	19.0	20.8	18.5	14.8	10.3	2.7	9.5
63	0.0	0.0	0.0	3.4	8.5	15.6	19.7	21.2	17.8	15.5	11.3	2.8	9.6
64	0.0	0.0	0.0	2.5	9.5	15.5	21.1	20.8	18.8	13.4	9.9	2.4	9.5
65	0.0	0.0	0.0	0.1	8.3	14.7	19.8	20.7	18.7	14.3	8.7	3.3	9.0
66	0.1	0.0	0.4	3.1	8.4	16.2	18.3	21.2	18.7	13.1	9.6	3.3	9.4
67	0.4	0.0	0.0	3.5	7.4	14.4	18.4	21.2	17.2	13.2	7.9	2.2	8.8
68	0.0	0.0	0.2	2.8	7.9	14.8	19.5	22.4	19.6	15.6	10.2	3.1	9.7
MEAN	0.4	0.1	0.8	3.6	9.4	16.3	20.5	22.2	19.4	15.1	10.1	3.1	10.1
52-68	0.2	0.1	0.5	3.2	9.1	15.9	20.3	21.9	19.4	15.1	10.1	3.1	9.9

Table A.12. Average Vapor Pressure Difference on Lake Erie at 8 m, mb

					$\Delta e_8 = (e_s - He_a)_8$								
YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	0.47	0.98	1.08	-0.20	2.44	4.20	4.50	4.61	8.03	4.94	4.06	1.66	3.06
38	1.49	0.58	-0.44	0.41	3.25	5.45	4.20	7.79	6.98	5.89	5.01	2.03	3.55
39	0.95	1.08	0.88	0.14	2.61	4.37	5.15	7.48	6.54	5.89	4.23	1.59	3.41
40	2.68	1.15	1.29	-0.61	1.52	2.91	3.96	4.94	5.59	5.49	4.44	0.98	2.86
41	1.29	1.63	1.29	-1.19	3.76	4.06	4.30	9.62	6.91	5.38	3.86	1.35	3.52
42	1.66	1.96	-0.20	-0.54	2.07	1.69	5.15	6.84	6.47	4.40	4.23	1.96	2.97
43	1.59	1.19	1.12	0.75	1.29	2.51	4.17	7.96	7.25	6.16	4.88	2.84	3.48
44	0.34	1.35	1.19	-0.44	-0.58	3.52	6.71	5.52	5.35	7.35	5.18	3.05	3.21
45	3.05	0.98	-2.44	0.47	3.93	2.81	4.54	7.82	5.62	6.10	5.76	3.28	3.49
46	1.35	1.56	-1.56	2.10	3.52	4.47	4.74	8.70	5.99	5.66	6.33	2.37	3.77
47	0.47	2.57	0.95	-0.95	2.34	3.01	2.78	2.84	8.57	4.67	7.28	2.40	3.08
48	2.84	1.73	0.71	-0.41	4.03	4.47	3.45	7.35	8.64	6.10	4.20	2.81	3.83
49	0.58	0.64	1.08	0.68	3.52	3.93	2.47	9.69	7.48	5.99	6.16	1.63	3.65
50	0.81	1.83	1.46	0.34	1.29	4.74	4.13	8.06	4.74	4.74	6.77	2.84	3.48
51	1.02	0.95	0.41	-0.78	2.40	3.73	4.98	8.94	7.75	5.15	6.23	2.27	3.59
52	0.75	0.64	0.24	-1.32	3.01	4.54	5.42	8.20	7.75	8.43	5.15	1.56	3.70
53	0.34	0.68	-0.07	0.54	0.58	3.08	5.69	8.13	9.35	6.23	6.10	2.44	3.59
54	1.90	-0.07	1.39	-1.59	4.67	4.00	8.09	8.91	6.43	6.03	5.55	2.71	4.00
55	1.93	1.05	0.61	-1.83	3.79	5.62	2.51	4.88	7.92	5.86	5.05	2.17	3.30
56	1.49	0.88	0.61	-0.27	2.24	2.64	2.95	5.62	7.99	4.67	5.93	0.47	2.94
57	2.51	0.37	-0.17	-2.61	2.71	2.03	4.91	9.55	6.98	6.71	5.05	0.95	3.25
58	1.42	2.61	-0.34	-1.66	3.86	5.15	1.96	6.98	5.93	5.35	4.88	3.18	3.28
59	2.27	1.73	0.68	-1.22	0.75	6.20	6.16	5.82	8.50	6.87	5.55	1.08	3.70
60	0.71	1.15	2.57	-2.95	1.76	4.67	6.43	7.04	8.03	9.52	5.62	4.54	4.09
61	3.25	0.64	-0.17	0.03	4.06	2.84	3.93	7.72	7.38	7.59	7.04	3.18	3.96
62	2.74	2.57	0.61	-1.02	1.05	4.00	4.84	6.57	8.47	5.72	6.64	3.76	3.83
63	3.66	3.86	-0.64	-0.07	3.49	4.44	4.81	9.35	8.09	6.64	5.89	4.40	4.49
64	1.29	2.30	-0.24	-1.76	2.30	4.13	5.15	8.67	8.40	7.28	5.22	1.83	3.71
65	2.10	2.37	1.02	-1.93	0.58	4.00	7.21	6.70	4.67	7.59	4.64	0.88	3.32
66	3.22	1.66	0.03	-0.47	4.44	4.64	1.90	7.48	8.70	6.94	5.08	2.71	3.86
67	0.91	3.05	0.27	-0.88	4.16	1.05	2.57	8.91	7.38	5.72	5.55	1.52	3.35
68	3.15	3.18	-0.03	-0.68	2.30	2.71	4.16	7.35	5.96	7.42	5.59	3.45	3.71
MEAN	1.69	1.53	0.41	-0.62	2.60	3.80	4.50	7.38	7.18	6.20	5.41	2.31	3.53
52-68	1.96	1.69	0.37	-1.15	2.68	3.86	4.64	7.52	7.52	6.74	5.55	2.40	3.65

Table A.13. Vapor Pressure Difference for Lake Erie over Land, mb

$\Delta e_d = e_s - e_d$

YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1937	2.74	2.51	2.31	1.05	1.35	3.96	6.85	7.08	10.91	6.57	5.28	3.48	4.51
38	3.35	2.51	1.42	1.76	2.34	5.25	6.71	10.36	9.99	8.06	6.43	3.86	5.17
39	2.98	2.85	2.30	1.42	1.96	4.88	8.74	10.33	9.28	8.23	5.89	3.66	5.21
40	4.00	3.09	3.02	0.54	0.67	4.37	7.01	8.03	8.20	8.23	5.85	3.42	4.70
41	3.35	3.12	2.75	0.64	4.64	5.32	7.69	12.26	9.62	7.89	5.18	3.31	5.48
42	3.15	3.26	1.53	1.66	1.56	2.44	9.04	10.50	9.11	6.47	5.55	3.28	4.80
43	3.19	2.65	2.40	2.24	1.22	3.86	6.68	10.29	8.47	7.48	5.42	3.86	4.81
44	2.20	2.88	2.54	0.95	1.35	3.32	8.10	7.51	6.84	8.37	5.96	4.13	4.51
45	3.93	2.65	0.23	2.06	2.95	2.98	6.40	9.17	8.03	7.18	6.57	4.19	4.70
46	2.71	2.92	0.92	3.28	2.37	4.47	7.15	9.86	7.35	7.21	7.18	3.86	4.94
47	2.37	3.46	2.04	0.65	1.36	1.97	4.40	5.86	10.30	6.84	7.69	3.73	4.22
48	3.76	3.22	2.40	1.66	2.98	3.76	6.23	9.41	10.60	7.14	5.21	4.37	5.06
49	2.67	2.54	2.44	1.93	2.71	4.10	5.86	12.16	8.40	7.90	6.74	3.22	5.06
50	3.05	3.28	2.68	1.69	0.95	4.47	6.02	9.58	6.74	6.77	7.28	4.00	4.71
51	2.54	2.34	1.83	0.68	1.46	3.56	7.15	10.74	9.17	7.08	7.04	3.66	4.77
52	2.64	2.41	1.69	0.13	2.20	5.11	7.18	9.79	9.04	9.17	5.86	3.39	4.88
53	2.47	2.23	1.39	1.76	-0.07	2.60	7.69	9.89	10.40	8.16	6.94	3.76	4.77
54	3.36	1.86	2.67	0.95	3.69	3.99	9.96	11.34	8.43	7.76	6.40	4.27	5.39
55	3.15	2.68	1.86	0.03	2.61	4.64	6.90	7.38	9.69	7.45	5.86	3.32	4.63
56	2.82	2.58	2.03	0.81	1.77	2.88	5.52	8.09	9.35	6.54	6.74	2.60	4.31
57	3.63	2.24	1.11	-1.02	1.76	1.38	6.98	11.75	8.50	8.03	5.99	2.64	4.42
58	2.78	3.53	0.88	-0.27	2.95	4.70	4.78	9.55	8.03	7.72	5.92	4.14	4.56
59	3.36	3.29	1.97	0.21	0.03	5.62	7.86	9.01	10.39	8.97	6.26	3.01	5.00
60	2.37	2.65	3.15	-0.81	0.17	3.45	7.79	9.15	9.55	9.89	6.13	4.78	4.86
61	3.86	2.31	1.66	1.42	2.64	1.76	5.45	9.41	9.00	8.37	7.18	4.07	4.76
62	3.42	3.46	1.73	0.44	0.51	3.82	7.05	8.23	10.06	7.05	7.07	4.24	4.76
63	4.03	4.07	1.05	1.49	2.00	3.39	5.92	9.68	9.17	7.25	6.30	4.71	4.92
64	2.41	3.09	1.29	0.33	0.85	3.11	6.54	9.28	8.91	8.43	5.82	3.25	4.44
65	3.12	3.36	2.27	0.07	-0.17	3.87	9.11	8.40	6.84	7.93	5.25	2.81	4.40
66	3.82	2.85	1.22	0.98	2.85	3.52	4.34	8.33	9.41	7.42	5.59	3.79	4.51
67	2.41	3.63	2.17	0.95	2.92	0.47	4.98	9.89	8.53	6.64	5.58	3.18	4.28
68	3.70	3.70	1.29	0.81	1.43	1.96	6.24	9.28	6.91	8.13	6.06	4.23	4.48
MEAN	3.11	2.91	1.89	0.95	1.73	3.59	6.82	9.42	8.91	7.70	6.19	3.69	4.74
52-68	3.12	2.93	1.73	0.49	1.64	3.33	6.73	9.33	8.94	7.90	6.18	3.67	4.67

Table A.14. Determination of Atmospheric Radiation for Lake Erie, 1952-1968

$$Q_a = \sigma T_a^4 - [288.0 + 11.16 (\sqrt{e_{sa}} - \sqrt{e_a}) - A] \times [Q_s/Q_{sc}]^n$$

EQUATION	$Q_{act} = \sigma T_a^4 - 288.0 - 11.16(\sqrt{e_{sa}} - \sqrt{e_a})$			$A = 5.0(T_{ua} - T_{ut})$			$Q_{sc} = Q_{se}(a + 0.5s)$			
PARAMETER	e_{sa}	$(\sqrt{e_{sa}} - \sqrt{e_a})$	Q_{act}	T_u	$(T_{ua} - T_{ut})$	A	a	s	Q_{sc}	Q_2
UNITS	mb	$mb^{1/2}$	ly/day	°C	°C	ly/day			ly/day	ly/day
January	4.41	0.270	378	-8.3	5.4	27	0.38	0.51	293	570
February	4.75	0.284	387	-8.5	4.2	21	0.45	0.45	399	571
March	6.52	0.330	427	-5.2	3.2	16	0.46	0.43	490	584
April	10.94	0.542	499	1.2	2.2	11	0.49	0.41	629	652
May	15.67	0.693	525	6.0	1.6	8	0.46	0.42	649	622
June	22.80	0.828	621	11.5	1.2	6	0.46	0.40	725	721
July	25.95	0.845	646	12.9	0.5	2	0.45	0.41	672	733
August	24.56	0.704	637	12.3	0.8	4	0.44	0.42	609	737
September	19.49	0.626	594	9.7	1.9	10	0.41	0.45	516	714
October	13.21	0.517	529	4.8	3.0	15	0.39	0.48	384	665
November	8.54	0.372	464	-1.2	3.4	17	0.39	0.48	295	649
December	5.35	0.264	402	-6.6	4.5	22	0.36	0.53	229	586
Annual	13.52	0.523	509	2.4	2.7	13	0.43	0.45	491	650

NOTE: Upper air temperature (T_u) obtained from Buffalo radiosonde data at 850 mb or approximately 150 mb above surface.

Table A.15. Change in Lake Erie Heat Content, 1960-1963

$$Q_t = V(T_2-T_1)$$

DEPTH, m	0-3.8		3.8-11.4		11.4-19.0		19.0-26.7		26.7-38.1		38.1-53.4		53.4-64.0		TOTAL
VOLUME, km^3	97.5		160.3		126.3		38.8		21.9		8.2		0.4		453.4
PARAMETER	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	T_2-T_1	$V\Delta T$	$\Sigma V\Delta T$
UNITS	°C	cal 10^{17}	°C	cal 10^{17}	°C	cal 10^{17}	°C	cal 10^{17}	°C	cal 10^{17}	°C	cal 10^{17}	°C	cal 10^{17}	cal 10^{17}
January	0.0	0.0	-1.0	-1.6	-0.8	-1.0	-0.8	-0.3	-0.7	-0.2	-0.5	0.0	-0.8	0.0	-3.1
February	0.0	0.0	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
March	1.0	1.0	1.2	1.9	1.0	1.3	0.7	0.3	0.4	0.1	0.3	0.1	0.7	0.0	4.6
April	5.2	5.1	3.5	5.6	2.3	2.9	1.9	0.7	0.8	0.3	0.8	0.1	1.0	0.0	14.6
May	6.4	6.3	6.4	10.2	3.9	4.9	2.6	1.0	1.7	0.4	1.6	0.1	0.6	0.0	22.9
June	6.5	6.4	6.5	10.4	5.4	6.8	3.0	1.2	1.5	0.3	1.0	0.1	0.2	0.0	25.2
July	3.2	3.1	3.5	5.6	4.6	5.8	2.9	1.1	1.6	0.4	0.2	0.0	0.2	0.0	16.0
August	-0.4	-0.4	-0.1	-0.2	1.9	2.4	2.7	1.1	1.8	0.4	0.2	0.0	0.1	0.0	3.3
September	-3.6	-3.5	-2.3	-3.7	-0.6	-0.8	1.8	0.7	2.5	0.6	0.3	0.0	0.2	0.0	-6.7
October	-5.0	-4.9	-5.2	-8.3	-5.2	-6.6	-1.6	-0.6	2.4	0.5	2.3	0.2	1.7	0.0	-19.7
November	-6.1	-6.0	-6.2	-9.9	-6.2	-7.8	-5.9	-2.3	-4.8	-1.1	0.8	0.1	2.1	0.0	-27.0
December	-7.2	-7.1	-6.4	-10.2	-6.4	-8.1	-7.3	-2.8	-7.2	-1.6	-7.0	-0.6	-6.0	0.0	-30.4
Annual	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NOTE: During winter months (January - March) temperatures were estimated.

Table A.17. Supplementary Lake Erie Energy Budget Terms, ly/day, 1952-1968

ENERGY TERM	ADVECTED ENERGY			INCIDENT MINUS REFLECTED RADIATION (allwave)	NET BACK RADIATION (longwave)	NET RADIATION (allwave)
	Total Inflow Energy	Total Outflow Energy	Snowmelt Heat Loss			
SYMBOL	Q_i	Q_o	Q_m	Q_{ir}	Q_{nb}	Q_n
January	0	1	8	674	79	42
February	0	0	7	732	77	101
March	2	0	5	839	69	204
April	16	5	2	990	30	328
May	26	15	0	1080	117	360
June	39	28	0	1224	93	432
July	46	43	0	1216	130	375
August	48	51	0	1152	144	293
September	39	45	0	1040	137	210
October	28	34	0	887	138	104
November	15	21	5	761	99	32
December	3	7	7	670	92	10
Annual	22	21	3	939	100	208

Table A.16. Change in Lake Erie Heat Content, 1952-1968

	$Q_t = V(T_2-T_1)$								
DEPTH, m	0-3.8	3.8-11.4	11.4-19.0	19.0-26.7	26.7-38.1	38.1-53.4	53.4-64.0	TOTAL	WATER SURFACE TEMPERATURE ADJUSTMENTS
VOLUME, km^3	97.5	160.3	126.3	38.8	21.9	8.2	0.4	453.4	
HEAT CONTENT 10^{17} cal	$V(T_2-T_1)$	$V(T_2-T_1)$	$V(T_2-T_1)$	$V(T_2-T_1)$	$V(T_2-T_1)$	$V(T_2-T_1)$	$V(T_2-T_1)$	$\Sigma V(T_2-T_1)$	ΔT_w, °C
January	-0.6	- 1.8	-1.0	-0.3	-0.1	0.0	0.0	- 3.8	0.2
February	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1
March	1.1	1.8	0.8	0.2	0.0	0.0	0.0	3.9	0.1
April	4.4	4.5	2.5	0.6	0.1	0.0	0.0	12.1	-0.5
May	6.7	12.8	6.0	1.4	0.6	0.2	0.0	27.7	0.0
June	5.8	8.5	5.9	0.9	0.2	0.0	0.0	21.3	0.2
July	3.1	5.0	5.4	0.9	0.2	-0.1	0.0	14.5	-1.0
August	-0.3	0.5	2.5	1.2	0.5	0.2	0.0	4.6	-0.4
September	-3.8	- 5.3	-1.6	0.4	0.4	-0.2	0.0	-10.1	-1.1
October	-4.7	- 6.9	-5.3	-0.2	0.6	0.4	0.0	-16.1	-0.9
November	-5.6	-10.6	-7.6	-2.6	-1.1	0.0	0.0	-27.5	-0.4
December	-6.3	- 8.5	-7.7	-2.4	-1.3	-0.5	0.0	-26.7	-1.1
Annual	0.0	0.0	-0.1	0.1	0.1	0.0	0.0	0.1	-0.4

NOTE: Water temperatures below surface for 1952 - 1968 period are based on surface temperature differences.

Table A.18. Determination of Δ for Lake Erie, 1952-1968

$$\Delta = de_{sa}/dT_a \approx \Delta e_{sa}/\Delta T_a$$

VARIABLE UNITS	e_{sa} mb	T_a °C	Δ mb/°C
January	4.41	-4.4	0.30
February	4.75	-3.4	0.37
March	6.52	0.9	0.49
April	10.94	8.3	0.79
May	15.67	13.7	1.04
June	22.80	19.6	1.46
July	25.95	21.7	1.65
August	24.56	20.8	1.52
September	19.49	17.1	1.34
October	13.21	11.1	0.91
November	8.54	4.7	0.61
December	5.35	-1.8	0.43

Table A.19. Determination of Lake Erie Evaporation by Mass Transfer-Energy Budget Method, 1952-1968

EVAPORATION	BY AERODYNAMIC EQUATION			FROM WATER SURFACE			LAKE EVAPORATION		
PARAMETER	$f(u_8)$	$\Delta^* e$	E_a	Δ	E_{w1}	E_{w2}	α	E_1	E_2
UNITS	cm/day/mb	mb	cm	mb/°C	cm	cm		cm	cm
January	0.0522	1.05	1.8	0.30	1.5	2.3	0.20	1.8	2.8
February	0.0518	1.15	1.8	0.37	2.5	2.5	0.24	2.5	2.5
March	0.0518	1.59	2.5	0.49	6.1	4.8	0.29	5.1	4.1
April	0.0509	3.28	5.1	0.79	11.4	8.4	0.40	8.4	5.6
May	0.0471	5.01	7.4	1.04	14.5	11.9	0.44	6.6	4.1
June	0.0429	7.15	9.1	1.46	18.0	14.7	0.51	11.2	7.9
July	0.0407	7.92	9.9	1.65	17.0	14.5	0.52	12.2	9.7
August	0.0399	6.43	7.9	1.52	13.2	11.9	0.50	11.7	10.4
September	0.0416	5.08	6.4	1.34	9.4	8.9	0.48	12.4	11.9
October	0.0446	3.49	4.8	0.91	5.1	6.1	0.40	9.1	10.2
November	0.0501	2.07	3.0	0.61	2.3	3.6	0.32	7.9	9.1
December	0.0514	1.15	1.8	0.43	0.8	2.0	0.26	5.3	6.6
Annual	0.0471	3.78	61.5	0.91	101.8	91.6	0.38	94.2	84.9

NOTE: E_{w1} from equation (22)
E_{w2} from equation (24)
E_1 from equation (32) with E_{w1}
E_2 from equation (32) with E_{w2}.

APPENDIX B

SYMBOLS

Numbers in parentheses refer to equations where symbol first appears or where additional information may be obtained. There is some duplication of symbols to preserve commonly used notations.

Symbol	Description
A	lake area (4)
A	station adjustment term (14, 15)
a	total transmission coefficient (16)
d	density of water (10)
d	snow density (21)
E	lake evaporation (1, 3, 10, 32)
E_1	lake evaporation computed with E_{w1} (table 13)
E_2	lake evaporation computed with E_{w2} (table 13)
E_a	evaporation from aerodynamic equation, assuming $T_w = T_a$ (22, 24)
E_{MT}	mass transfer evaporation (fig. 8)
E_{WB}	water budget evaporation (fig. 8)
E_w	free-water evaporation (22, 24)
E_{w1}	free-water evaporation from Penman's equation (table A.19)
E_{w2}	free-water evaporation from Kohler and Parmele's equation (table A.19)
e_8	value of e_a at 8 m
e_a	vapor pressure of the air (2, 3, 5)
e_d	value of e_a for landward station (table A.13)
e_s	saturation vapor pressure at T_w (2, 3)
e_{sa}	saturation vapor pressure at T_a (14, 31)
$f(u)$	wind function from aerodynamic equation (24)
$f(u_8)$	value of $f(u)$ for wind speed at 8 m
H	monthly humidity ratio (3)
I	inflow from upper lakes (1)
L	latent heat of vaporation (10, 11)
L	latent heat of melting (21)
N	mass transfer coefficient (2)
n	exponent of ratio for degree of cloudiness (14)
O	outflow from Lake Erie (1)
P	overwater precipitation (1)
p	atmospheric pressure (12)
Q_a	incident atmospheric radiation (8, 14)
Q_{act}	typical clear sky atmospheric radiation (14)
Q_{ar}	reflected atmospheric radiation (8)
Q_b	radiation emitted by the water body (8, 17)
Q_e	energy utilized by evaporation (8, 9)
Q_h	conduction of sensible heat to the atmosphere (8)

Symbol	Description
Q_i	energy content of water entering the lake (20)
Q_{ir}	difference between incident and reflected radiation, allwave (24)
Q_m	snowmelt heat loss (20)
Q_n	net radiation, allwave (22, 25)
Q_o	energy content of water leaving the lake (20)
Q_r	reflected solar radiation (8)
Q_s	incident solar radiation (8)
Q_{sc}	clear sky solar radiation (14, 16)
Q_{se}	extraterrestrial solar radiation (16)
Q_t	change in energy storage within the water body (8, 18, 32)
Q_v	net advected energy (8, 20, 32)
R	runoff from drainage basin (1)
R	monthly wind ratio (3, 5)
R	Bowen ratio (9, 12)
R_p	monthly lake-land precipitation ratios (table 1)
s	total depletion by atmospheric scattering and diffuse reflection (16)
T_1	average temperature of lake at beginning of month (18)
T_2	overwater air temperature at 2 m (13)
T_2	average temperature of lake at end of month (18)
T_a	air temperature (12, 14)
T_i	Detroit River temperature (21)
T_o	Niagara River temperature (21)
T_p	wet bulb temperature (21)
T_r	air temperature, T_a, with winter minimum at 0°C (21)
T_u	upper air temperature (table A.14)
T_{ua}	difference between actual upper air and surface temperature for typical temperature profile (15)
T_w	water surface temperature (11, 17)
u	wind speed (2)
u_1	wind speed at height level one (6)
u_2	wind speed at height level two (6)
u_8	wind speed at 8 m (3, 31)
V	average volume of lake, monthly (19)
V_1	volume of lake at beginning of month (18)
V_2	volume of lake at end of month (18)
V_e	volume of lake evaporation (21)
V_i	volume of inflow through Detroit River (21)
V_o	volume of outflow through Niagara River and Welland Canal (21)
V_p	volume of overwater precipitation (21)
V_r	volume of runoff from drainage basin (21)
V_s	volume of snowfall over the lake (21)
z_1	height level one (6, 7)

Symbol	Description
z_2	height level two (6, 7)
α	ratio of evaporation to total energy exchange (32, 33)
γ	psychrometric constant from Bowen ratio equation (23)
Δ	slope of saturation vapor pressure versus temperature curve, at T_a (22)
Δe	vapor pressure difference
Δe_1	vapor pressure difference at height level one (7)
Δe_2	vapor pressure difference at height level two (7)
Δe_8	vapor pressure difference, overwater at 8 m (table 7)
Δe_d	vapor pressure difference for landward station (table 8)
Δe_{sa}	increment of saturation vapor pressure at T_a (table A.18)
$\Delta^* e^a$	vapor pressure difference, assuming $T_w = T_a$ (table A.19)
ΔS	change in lake storage (1)
ΔT	monthly change in lake temperature (table A.15)
ΔT_a	increment of air temperature (table A.18)
ΔT_w	water temperature adjustments (table A.16)
ε	emissivity of water surface (17)
σ	Stefan-Boltzmann constant (14, 24)
Σ	summation

☆U.S. GOVERNMENT PRINTING OFFICE: 1975—677-347/1320 REGION NO. 5

The mission of the Environmental Reasearch Laboratories is to study the oceans, inland waters, the lower and upper atmosphere, the space environment, and the earth, in search of the understanding needed to provide more useful services in improving man's prospects for survival as influenced by the physical environment. Laboratories contributing to these studies are:

Atlantic Oceanographic and Meteorological Laboratories (AOML): Geology and geophysics of ocean basins and borders, oceanic processes, sea-air interactions and remote sensing of ocean processes and characteristics (Miami, Florida).

Pacific Marine Environmental Laboratory (PMEL): Environmental processes with emphasis on monitoring and predicting the effects of man's activities on estuarine, coastal, and near-shore marine processes (Seattle, Washington).

Great Lakes Environmental Research Laboratory (GLERL): Physical, chemical, and biological, limnology, lake-air interactions, lake hydrology, lake level forecasting, and lake ice studies (Ann Arbor, Michigan).

Atmospheric Physics and Chemistry Laboratory (APCL): Processes of cloud and preciptation physics; chemical composition and nucleating substances in the lower atmosphere; and laboratory and field experiments toward developing feasible methods of weather modification.

Air Resources Laboratories (ARL): Diffusion, transport, and dissipation of atmospheric contaminants; development of methods for prediction and control of atmospheric pollution; geophysical monitoring for climatic change (Silver Spring, Maryland).

Geophysical Fluid Dynamics Laboratory (GFDL): Dynamics and physics of geophysical fluid systems; development of a theoretical basis, through mathematical modeling and computer simulation, for the behavior and properties of the atmosphere and the oceans (Princeton, New Jersey).

National Severe Storms Laboratory (NSSL): Tornadoes, squall lines, thunderstorms, and other severe local convective phenomena directed toward improved methods of prediction and detection (Norman, Oklahoma).

Space Environment Laboratory (SEL): Solar-terrestrial physics, service and technique development in the areas of environmental monitoring and forecasting.

Aeronomy Laboratory (AL): Theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the earth and other planets, and of the dynamics of their interactions with high-altitude meteorology.

Wave Propagation Laboratory (WPL): Development of new methods for remote sensing of the geophysical environment with special emphasis on optical, microwave and acoustic sensing systems.

Marine EcoSystem Analysis Program Office (MESA): Plans and directs interdisciplinary analyses of the physical, chemical, geological, and biological characteristics of selected coastal regions to assess the potential effects of ocean dumping, municipal and industrial waste discharges, oil pollution, or other activity which may have environmental impact.

Weather Modification Program Office (WMPO): Plans and directs ERL weather modification research activities in precipitation enhancement and severe storms mitigation and operates ERL's research aircraft.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
BOULDER, COLORADO 80302

ENVIRONMENTAL RESEARCH LABORATORIES

The mission of the Environmental Reasearch Laboratories is to study the oceans, inland waters, the lower and upper atmosphere, the space environment, and the earth, in search of the understanding needed to provide more useful services in improving man's prospects for survival as influenced by the physical environment. Laboratories contributing to these studies are:

Atlantic Oceanographic and Meteorological Laboratories (AOML): Geology and geophysics of ocean basins and borders, oceanic processes, sea-air interactions and remote sensing of ocean processes and characteristics (Miami, Florida).

Pacific Marine Environmental Laboratory (PMEL): Environmental processes with emphasis on monitoring and predicting the effects of man's activities on estuarine, coastal, and near-shore marine processes (Seattle, Washington).

Great Lakes Environmental Research Laboratory (GLERL): Physical, chemical, and biological, limnology, lake-air interactions, lake hydrology, lake level forecasting, and lake ice studies (Ann Arbor, Michigan).

Atmospheric Physics and Chemistry Laboratory (APCL): Processes of cloud and preciptation physics; chemical composition and nucleating substances in the lower atmosphere; and laboratory and field experiments toward developing feasible methods of weather modification.

Air Resources Laboratories (ARL): Diffusion, transport, and dissipation of atmospheric contaminants; development of methods for prediction and control of atmospheric pollution; geophysical monitoring for climatic change (Silver Spring, Maryland).

Geophysical Fluid Dynamics Laboratory (GFDL): Dynamics and physics of geophysical fluid systems; development of a theoretical basis, through mathematical modeling and computer simulation, for the behavior and properties of the atmosphere and the oceans (Princeton, New Jersey).

National Severe Storms Laboratory (NSSL): Tornadoes, squall lines, thunderstorms, and other severe local convective phenomena directed toward improved methods of prediction and detection (Norman, Oklahoma).

Space Environment Laboratory (SEL): Solar-terrestrial physics, service and technique development in the areas of environmental monitoring and forecasting.

Aeronomy Laboratory (AL): Theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the earth and other planets, and of the dynamics of their interactions with high-altitude meteorology.

Wave Propagation Laboratory (WPL): Development of new methods for remote sensing of the geophysical environment with special emphasis on optical, microwave and acoustic sensing systems.

Marine EcoSystem Analysis Program Office (MESA): Plans and directs interdisciplinary analyses of the physical, chemical, geological, and biological characteristics of selected coastal regions to assess the potential effects of ocean dumping, municipal and industrial waste discharges, oil pollution, or other activity which may have environmental impact.

Weather Modification Program Office (WMPO): Plans and directs ERL weather modification research activities in precipitation enhancement and severe storms mitigation and operates ERL's research aircraft.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
BOULDER, COLORADO 80302