NOAA Technical Memorandum ERL GLERL-29

EVAPORATION FROM LAKE SUPERIOR

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Ann Arbor, Michigan
July 1980

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EVAPORATION FROM LAKE SUPERIOR

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Lake Superior monthly evaporation was determined for individual years of a 34-year period, 1942-75, by the water budget and mass transfer methods. Because of data limitations, these two methods represent the only practical approaches for determining Lake Superior evaporation; however, each determination contains some important reservations, and the independent duplication of estimates permits verification of results. Evaporation values determined by the two methods are in reasonably good agreement, for both the seasonal distribution and the annual total, with a resulting long term annual value of approximately 500 mm. The mass transfer estimates were obtained from the available land-based meteorological data adjusted to overwater conditions, which use land to lake adjustments derived on Lake Ontario during the International Field Year for the Great Lakes. Because of extensive ice cover, the overwater mass transfer results were also adjusted for the effects of ice cover during winter. The ice-cover adjustment reduced the average annual overwater evaporation by 13 percent and agreed much better with the water budget seasonal distribution and annual values.

1. INTRODUCTION

Evaporation from Lake Superior removes approximately half a meter of water from the lake surface annually and constitutes a major water loss. This water loss has an important effect on lake levels and the overall lake hydrology, and the need for precise determination of lake evaporation is readily apparent. The loss of water from lakes through evaporation cannot be measured directly, but several methods can be employed to compute lake evaporation. A basic method is the water budget, whereby evaporation is determined as a residual of the hydrologic water balance. Since evaporation is basically a cooling process, which transfers both mass and heat or energy across the air-water interface, evaporation rates can be calculated from related mass transfer or energy balance determinations. Because of limitations imposed by the available data, only the water budget and mass transfer methods are used to compute Lake Superior monthly evaporation rates. Data required to determine heat fluxes across the air-water interface are generally not available for the Great Lakes for any appreciable period of time.

The period of record employed in the study, 1942-75, was determined by the availability of generally homogeneous climatological data. The year 1942 corresponds with general relocation of first-order meteorological stations (wind, air temperature, and humidity) from city to airport locations.

GLERL Contribution No. 223.

Basic climatological data for the Great Lakes are restricted to land stations located around the lakes. Because of large surface areas and great depths, the Great Lakes have a tremendous heat storage capacity, which enables considerable modification of the overwater climate (e.g., temperature, precipitation, wind). This is particularly true for Lake Superior, which has a surface area of 82,100 km^2 and an average depth of 150 m. The available climatological data do not indicate overwater conditions and require adjustments for variations in the atmospheric stability over land and water areas. These land to lake stability adjustments for various parameters have been refined on Lake Ontario during the International Field Year for the Great Lakes (IFYGL) and permit use of the available lake perimeter data in the mass transfer computations.

Extensive Lake Superior ice cover during winter reduces standard overwater evaporation determined by the mass transfer method. The ice-cover reduction of lake evaporation was incorporated by considering the extent of ice cover as deduced from regular ice observations during winter. The necessity for data adjustments and extrapolation limits the reliability of evaporation estimates by both the mass transfer and water budget methods. Derivation of separate evaporation estimates by two independent methods permits comparison and verification of computed evaporation results.

2. WATER BUDGET METHOD

The water budget method consists of solving the hydrologic mass balance equation for the unknown evaporation component. It represents an accounting of all terrestrial water supplies to and losses from a lake, such as inflow and outflow by rivers, direct ground water inflow or outflow, change in amount of water stored in the lake, overwater precipitation, and evaporation. The direct ground water contribution to the Great Lakes is largely unknown, but it is generally considered to be negligible and is normally disregarded in the Great Lakes water balance studies. In the IFYGL study, DeCooke and Witherspoon (1979) determined the ground water contribution to Lake Ontario as 1 mm/mo, based on the total ground water inflow of approximately 5.4 m^3/s (190 cfs) along the Canadian and United States shoreline. There is little concrete evidence in the literature that the ground water contribution to the other Great Lakes is much different (Derecki, 1976a), but even if the actual ground water fluxes were several times higher, the ground water component would still be insignificant in their water budgets. Disregarding the ground water component, the water budget for Lake Superior may be expressed by the following equation:

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

where

E = lake evaporation, mm,

P = overwater precipitation, mm,

R = runoff from the drainage basin, mm,

O = outflow from Lake Superior, mm, and

AS = change in lake storage, mm.

The expansion and contraction of water associated with seasonal warming and cooling of the lake affect lake levels, which in turn affect the change in lake storage and to some extent the lake outflow determinations. Consequently, thermal expansion and contraction of water affect the amount of evaporation computed by the water budget equation, but this effect is usually disregarded in the water budget for the Great Lakes. Meredith (1974) computed monthly corrections for the thermal expansion or contraction of water inherent in the change of storage determined from the monthly Great Lakes level changes. The average monthly values derived from his results for Lake Superior for the 1946-65 period indicate long term maximum monthly expansion in July (15 mm) and maximum monthly contraction in August (10 mm). The average monthly expansion or contraction of water for Lake Superior was also determined by Bennett (1978). Bennett's long term results (1964-73) indicate maximum monthly expansion in August (7 mm) and maximum contraction in November (9 mm). Both studies indicate annual balancing of monthly expansions and contractions, but monthly results from the two studies generally compare poorly. During approximately half of the year, presented values indicate either large differences of contradictory results. The worst disagreement is for August, for which Bennett indicates the maximum expansion of 7 mm, while Meredith shows the maximum contraction of 10 mm. The thermal effects could be significant seasonally, but the measurement errors for the change in storage and lake outflow could have a large effect on computed evaporation than the thermal expansion and contraction of water. Resolution of thermal effects with reliable water temperature profile data would improve seasonal distribution of the water budget evaporation, but not affect the annual evaporation, since net annual temperature changes are insignificant for the water balance considerations.

The inflow of water to Lake Superior consists of drainage basin runoff and two relatively small diversions from outside its drainage basin (Ogoki and Long Lake Diversions). These diversions are included in runoff; therefore the diversion term is not listed separately in equation (1) or in subsequent treatment of the data.

The main advantage of the water budget method is that evaporation can be computed directly from components of a hydrologic cycle with long periods of record. In contrast to the other Great Lakes, all hydrologic components of Lake Superior are of the same order of magnitude, eliminating the possibility of large residual evaporation errors due to relatively small errors in one of the inputs. The main objections to the water budget evaporation value are the uncertainties with respect to thermal expansion or contraction of water and the dependence of computed evaporation on empirical adjustments for precipitation and runoff. Precipitation is determined from point measurements at land stations, and runoff measurements do not cover the entire drainage basin. A brief discussion of the individual water budget factors is given below. Lake Superior, its drainage basin, and pertinent locations are shown in figure 1.

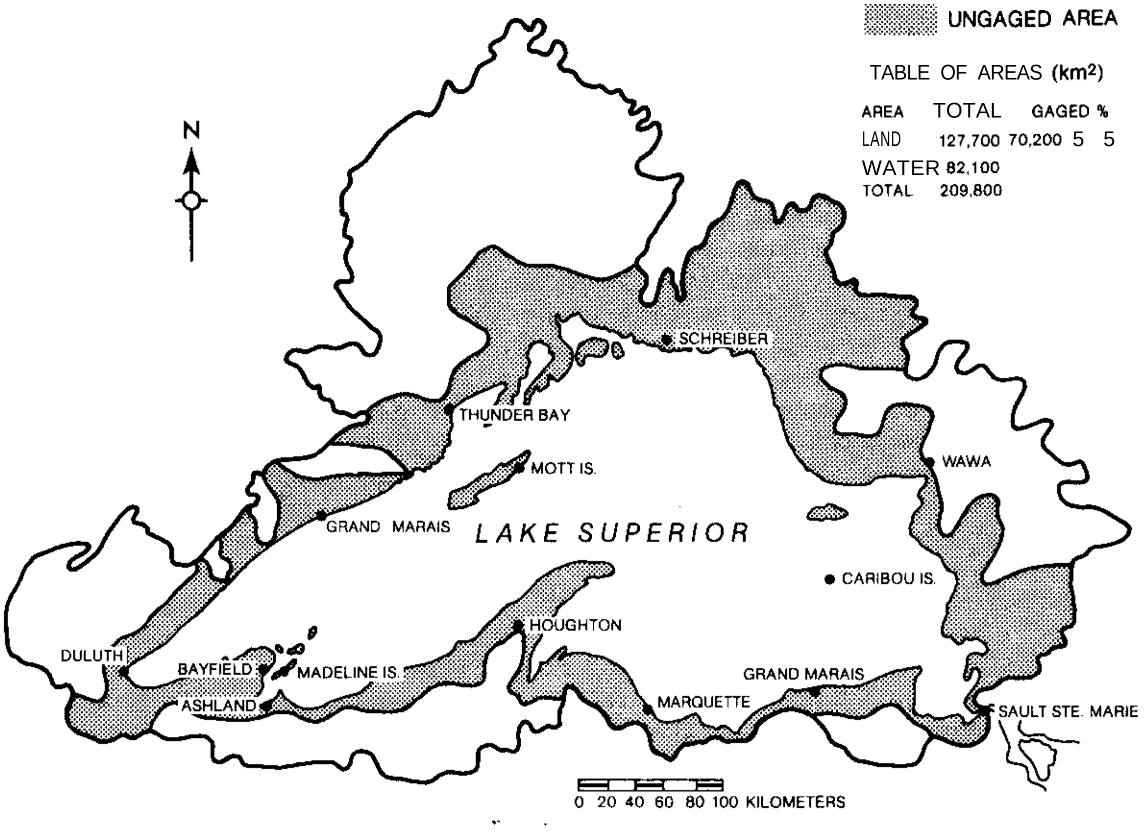

TABLE OF AREAS (km²)

AREA	TOTAL	GAGED	%
LAND	127,700	70,200	5 5
WATER	82,100		
TOTAL	209,800		

Figure I.--Lake Superior Basin.

2.1 Overwater Precipitation

Precipitation over Lake Superior was determined by averaging records from 10 perimeter stations adjusted to overwater conditions. There is a strong correlation between the 10-station-average perimeter adjusted overwater precipitation values and the "lake surface" precipitation compiled by the National Ocean Survey (NOS), NOAA, from all available perimeter and island stations. There is also good agreement between the lo-station-average and NOS perimeter precipitation, with average monthly precipitation differences normally within 2 or 3 mm. The monthly differences are greater for the overwater and NOS precipitation comparison, since the NOS "lake surface" precipitation does not contain any overwater adjustments. During months with maximum adjustments, the average monthly precipitation differences exceed 10 mm. The land and lake precipitation stations and the precipitation adjustments expressed as lake/land ratios are listed in table 1. The lake precipitation stations are located on islands and are affected to some degree by the land mass, depending on the island's size and location, but these measurements are the most direct permanent observations of overwater precipitation available. Probably a more critical aspect of the island precipitation gage sites is their exposure and related gage undercatch. Radar eliminates many objections inherent in precipitation gage stations and appears ideally suited for overwater measurements, but radar observations are expensive and radar precipitation measurements are not available for Lake Superior on an operational basis. Of necessity, the lake/land precipitation ratios, based on island/perimeter data, have traditionally been employed to determine overwater precipitation on the Great Lakes.

Table I.--Lake Superior overwater precipitation analysis, 1945-75

	Precipitation			Precipitation				Ratio
Period	Island mm (1)	Perimeter mm (2)	Ratio (3)	Lake mm (4)	Land mm (5)	Ratio (6)	AR_p (7)	Kresge et al. (1963) (8)
Jan.	35.8	30.7	1.17	---	53.1	1.18*	+0.01*	1.13
Feb.	25.7	18.5	1.39	---	36.6	1.40*	+0.01*	1.18
Mar.	38.9	37.1	1.05	---	43.2	1.06*	+0.01*	1.07
Apr.	62.5	63.0	1.01	---	59.7	1.02*	+0.01*	0.99
May	93.2	93.0	1.00	79.3	78.5	1.01	-0.01	0.95
June	93.5	100.1	0.93	80.0	87.4	0.92	+0.01	0.96
July	92.7	101.9	0.91	74.4	80.8	0.92	-0.01	0.90
Aug.	105.7	107.2	0.99	82.0	86.1	0.95	+0.04	0.84
Sept.	75.4	88.1	0.86	77.7	91.4	0.85	+0.01	0.96
Oct.	50.3	57.4	0.88	56.3	65.5	0.86	+0.02	1.07
Nov.	54.9	56.6	0.97	---	66.3	0.98*	+0.01*	1.13
Dec.	37.1	36.3	1.02	---	52.3	1.03*	+0.01*	1.11
Summer (May-Oct.)			0.93			0.92	+0.01	0.95

Table. 1.--Lake Superior overwater precipitation analysis, 1945-75 *(Cont'd)*

Winter (Nov.-Apr.)	1.10	1.11"	+0.01*	1.10
Annual	1.02	1.02		1.02

(1) Island: Madeline Island.

(2) Perimeter: Bayfield and Ashland.

(4) Lake: Caribou, Mott, and Madeline Islands.

(5) Land: Sault Ste. Marie, Grand Marais, Marquette, Houghton, Ashland,, Duluth, Grand Marais, Thunder Bay, Schreiber, and Wawa.

(7) ΔR_p = (6) - (3).

* Estimates based on island/perimeter ratios and AR_p.

Three Lake Superior island stations provide long term precipitation records, with balanced lake-wide coverage, but only one of them (Madeline Island) has continuous records throughout the year. The other two stations (Caribou and Mott Islands) are operated only during summer (May-October). Monthly island/perimeter precipitation ratios were determined for the period of simultaneous records (1945-75) for the southwestern area (Madeline Island) and the entire lake (three islands), as indicated in table 1. Because agreement between one- and three-island precipitation ratios is remarkably consistent during summer (figure 2), the lake/land ratios based on three islands were extrapolated for the winter (November-April) from the one-island relationship. Derived precipitation ratios vary from 0.85 in September to 1.40 in February, with overall summar and winter values of 0.92 and 1.11, respectively, and an annual average of 1.02. Adjusted overwater precipitation for Lake Superior based on the derived ratios is given with basic data in appendix A (table 18).

The Lake Superior lake/land precipitation ratios agree reasonably well with most determinations developed for the other Great Lakes. Table 1 shows a set of ratios determined by Kresge *et al.* (1963) for northeastern Lake Michigan. These ratios are also based on a long period of data and were derived with generally similar developmental procedures. The two sets of ratios show good seasonal and annual agreement, with some shifting of monthly values, but there are major monthly differences during the midwinter and late summer-fall periods. The high winter maximum for Lake Superior (1.40) is considerably higher than that for Lake Michigan (1.18). This difference, if actual could be caused by harsher winters on Lake Superior and larger snow undercatch by precipitation gages during snowstorms. The rain gage deficiency with higher winds,

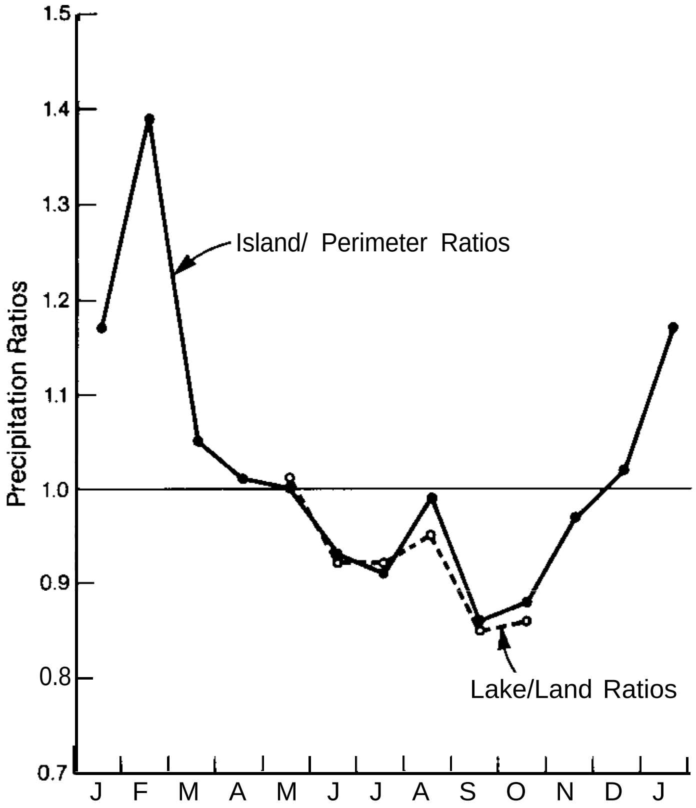

Figure Z.--Lake Superior Lake/land precipitation ratios.

especially for snowfall measurements, is well documented in the literature. Larson and Peck (1974) present gage catch deficiency and wind speed relationships for rain and snow for both shielded and unshielded gages. At 4.5 m/s, which corresponds to the average annual wind speed around Lake Superior, they found a rain catch deficiency of about 10 percent for both shielded and unshielded gages, which doubled to 20 percent at 9.0 m/s. The snow catch deficiencies for these wind speeds increased to 30 percent and 50 percent, respectively, for shielded gages, and 50 percent and 70 percent for unshielded gages. Shielding has little effect on rain undercatch, but a major effect on snow undercatch, and can reduce snow measurement errors by one-third to one-half. The low summer minimum (about 0.85) is the same for both lakes, but occurs a month later on Lake Superior and lasts for 2 months. There is no apparent physical reason for this difference.

Because the island precipitation stations are generally more exposed and the gage measurement errors can exceed precipitation differences normally encountered for the island and perimeter stations, Bolsenga (1979) questions the validity of using traditionally derived land/land ratios to obtain overwater precipitation. This conclusion was based on the analysis of results for various precipitation studies, including his own for northern Lake Michigan and eastern Lake Ontario. However, Bolsenga also indicates that during most months his traditionally derived lake/land ratios for Lake Michigan compare favorably with those computed for Lake Ontario from Wilson's (1975) overwater precipitation values determined by radar during intensive IFYGL investigations. Bolsenga's Lake Michigan lake/land ratios are somewhat lower than those of Kresge et al. (table 1), although both studies are based on a nearly identical gage network, but both sets of ratios show the dominant feature of increased overwater precipitation during the cold weather season and a corresponding reduction during the warm season. Because of difficulties of access the original island network used by Kresge et al. consisted primarily of storage-type gages, while Bolsenga employed the more recent and relatively short-term island data from automatic precipitation recorders.

The use of conventional lake/land ratios to adjust overwater precipitation may be a matter of convenience, as implied by Bolsenga, but the lake effect on precipitation indicated by these ratios has generally been verified by radar observations. There is no question that the Great Lakes do exert a substantial effect on the overwater climate, including precipitation. Elimination of the ratios, because of questionable accuracy, would generally be insignificant to the Great Lakes water balance on an annual basis, but would affect seasonal distribution of precipitation and consequently computed evaporation. In the case of Lake Superior, seasonal changes in monthly values on the order of 10-15 mm would be produced in midwinter and early fall. Precipitation around Lake Superior varies seasonally, with lows in the winter and highs in the summer. Monthly normals vary from approximately 40 mm for the winter low to 90 mm for the summer high.

2.2 Runoff

Runoff from the drainage basin is based on tributary river streamflow records which are published by the U.S. Geological Survey and the Water Resources Branch, Canada. During the period of study, stream gaging increased substantially, expanding the gaged area from the initial 43 percent to 55 percent of the total drainage basin. The runoff values for ungaged streams and the periphery of the lake were obtained by direct areal extrapolation of flows per unit area from nearby gaging stations, but streamflow records affected by diversions were excluded from runoff extrapolation. The inflow of water to Lake Superior through natural drainage is supplemented by the Ogoki and Long Lake Diversions from outside its drainage basin. These diversions enter the lake through the tributary streams and are included in the total runoff values. Average flow in the two diversions amounts to 140 m^3/s, which represents approximately 10 percent of the average annual natural runoff.

Monthly runoff for the period of study, expressed in units of lake volume (mm on lake area) is given in the appendix A (table 19). The average annual runoff represents about 43 percent of the lake's water supply (precipitation and runoff). Because of snowmelt and generally increasing spring precipitation, the highest runoff occurs in spring. The high spring runoff (April-June) represents approximately 42 percent of the annual total. Reduction of runoff during the remainder of the year is caused by higher evapotranspiration on the drainage basin during summer and fall, and snow accumulation combined with reduced precipitation during winter. The typical occurrance of low runoff in fall is not indicated for Lake Superior, owing in part to its northern climate and partial distortion of normal seasonal runoff distribution by the inclusion of outside diversions.

2.3 Outflow

The outflow from Lake Superior consists of the flow of the St. Marys River and is regulated at the control structure located at Sault Ste. Marie, Mich. Flows in the connecting channels of the Great Lakes are measured and published by the U.S. Corps of Engineers and the Water Resources Branch, Canada. Because of the joint international use of these waters and a need for common data, these flows are coordinated by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. Lake Superior monthly outflows for the period of study are given in the appendix A (table 20). The variation of outflow is relatively small because of natural regulation provided by the lake. In addition, the potential natural variation of outflow is also restricted by artificial regulation. The ouflow component from Lake Superior is of the same order of magnitude as other water budget components, in contrast to the lower Great Lakes, where it is an order of magnitude higher. This eliminates the possibility of large residual errors in the computed Lake Superior water budget evaporation due to relatively small errors in the outflow, and enhances the use of water budget results as a reliable reference for evaporation computed by other methods:

2.4 Change in Storage

The change in lake storage is determined from successive beginning-of-month levels, based on 2 days of record (one at the beginning of the month and one at the end of the preceding month) to minimize the effect of wind on the lake level disturbances. The mean level of the lake at the beginning of the month was determined from the available gage network by the Thiessen polygon method, described by Quinn et al. (1979). During the period of study, the polygon network increased gradually from five to nine gages. Monthly changes in Lake Superior storage during this period are given in the appendix A (table 21). Owing to the annual cycle and balancing of rising and falling lake levels, the long term annual change in storage is small. Lake Superior levels normally rise during spring and summer, and fall during autumn and winter. The highest lake storage normally occurs in spring, reflecting snowmelt and increased precipitation. The contribution of the change in storage to the Lake Superior water budget is similar to the other water balance components (±700 mm annually).

2.5 Evaporation

Monthly evaporation computed as a residual of the Lake Superior water budget for the 1942-75 period is listed in table 2. Annual evaporation varied from a low of 382 mm in 1968 to a high of 650 mm in 1975, with an average value of 517 mm. There appear to be no regimen changes (periodic variation in the Lake Superior annual evaporation) during the 34-year period, and the annual amounts fluctuate around 500 mm. Such regimen changes of 100-150 mm in the annual evaporation, spanning 10-15-year periods, were definitely indicated for Lake Erie (Derecki, 1976b), and could be deduced for Lake St. Clair (Derecki, 1979).

Seasonal distribution of the water budget evaporation indicating the average, maximum, and minimum monthly values is shown in figure 3. The high evaporation season on Lake Superior occurs during fall and winter. The highest monthly evaporation occurs in December and normally exceeds 100 mm, with 106 mm average and 151 mm maximum values. During the low evaporation seasons of spring and summer, the evaporation process

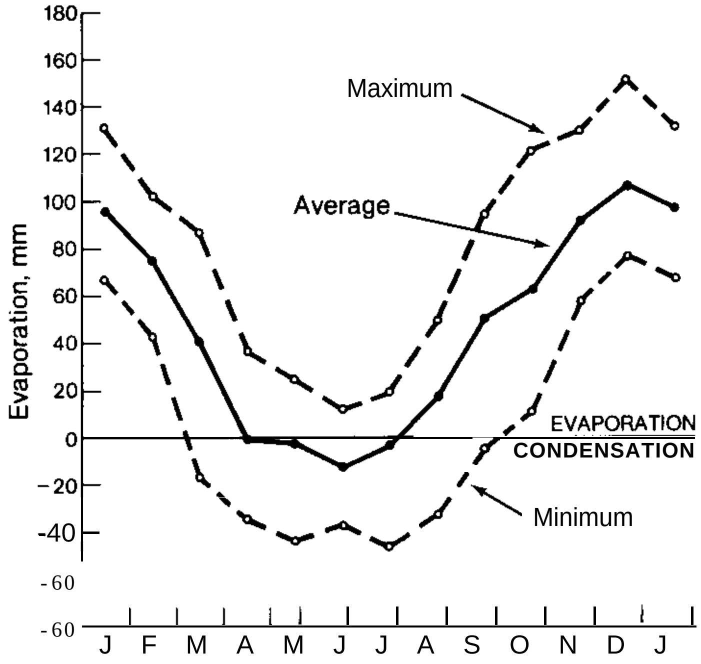

Figure 3.--Lake Superior evaporation by water budget method, 1942-75.

Table Z.--Lake Superior evaporation by water budget method, mm.

YEAR	JAN	FEB	WAR	APR	MAY	JUN	JUL	AU6	SEP	OCT	NOV	OEC	ANNUAL
1942	80.9	61.9	34.7	13.6	-1k.7	1.7	-14.0	19.6	77.2	29.9	90.3	116.9	498.0
1943	82.1	61.6	37.7	-1.0	-43.8	-15.9	4.0	1.7	50.6	58.8	Y2.8	114.3	442.9
1944	75.0	102.5	50.0	13.4	-7.0	-22.3	-17.5	22.4	30.0	84.6	91.1	98.1	519.5
1945	19.5	64.1	-9.3	15.0	13.6	-3.3	-6.2	20.8	55.4	58.0	118.0	92.3	497.9
1946	93.3	84.2	.0	13.4.	14.5	12.0	-24.3	20.8	16.8	39.4	110.9	111.7	492.7
1947	117.2	85.2	59.5	-4.3	-6.2	-23.0	.4	-2.5	34.1	31.5	112.2	118.3	521.8
1948	109.1	101.7	29.7	-29.5	10.0	6.0	-2.1	-9.6	55.0	75.9	17.9	110.3	529.4
1949	105.2	99.2	76.6	-19.1	14.1	-8.7	-12.8	43.1	70.7	44.4	95.3	97.8	606.4
1950	114.1	96.2	54.4	-2.n	-35.2	-16.4	-11.5	-4.1	5.7	10.6	85.1	112.0	406.9
1951	93.6	63.7	54.3	-26.6	-6.1	-3.5	7.1	28.3	40.2	44.6	95.4	88.8	479.0
1952	88.8	80.6	58.7	-27.1	10.2	-12.0	-1.9	8.9	66.6	120.5	84.6	04.7	562.6
1953	93.3	76.6	50.3	5.1	-22.0	-21.1	-4.2	12.9	74.4	64.2	86.4	105.2	521.1
1954	114.8	59.6	87.1	17.3	-4.9	-32.5	2.2	30.5	62.9	78.0	62.5	98.5	576.0
1955	110.1	97.6	59.2	-34.4	-4.5	-8.0	18.6	24.0	66.0	49.2	84.9	119.0	501.7
1956	92.7	83.6	69.4	16.1	-20.5	-12.2	-15.7	29.6	58.3	61.3	97.9	95.9	545.4
1957	130.8	49.1	29.1	-17.6	5.1	-27.7	14.5	32.8	64.9	71.7	83.4	99.9	536.0
1958	80.2	66.3	33.5	-3.2	12.6	-35.7	-13.1	43.1	41.5	62.9	91.5	130.7	505.9
1959	100.2	51.9	39.8	-7.0	-22.8	-17.0	7.2	-32.9	31.9	91.7	129.2	91.0	463.2
1960	79.4	94.9	45.4	1.4	22.5	-2.3	-9.7	26.5	72.6	67.4	64.7	132.7	597.5
1961	71.2	43.1	30.1	15.7	9.1	-8.1	9.6	24.2	60.4	57.1	104.5	104.2	521.1
1962	125.2	75.1	22.2	12.8	-9.9	7.2	-2.0	22.9	58.6	64.3	90.0	109.0	574.4
1963	84.3	65.1	-16.8	-1.7	11.9	-36.1	12.2	13.8	35.7	33.3	101.7	123.6	426.4
1964	67.3	91.3	74.1	-13.6	-12.3	-11.7	10.7	24.2	3.8	98.7	80.1	108.3	52C.9
1965	112.3	101.7	39.4	-8.3	-29.1	-7.2	1.5	9.2	45.7	40.9	b3.3	75.0	445.2
1966	101.2	77.0	42.6	P3.6	-28.1	-.2	-6.0	17.5	54.8	70.3	181.2	80.2	523.9
1967	113.6	76.3	30.5	-19.4	1k.2	-24.3	4.0	25.5	58.8	53..	81.4	93.5	507.5
1968	88.2	93.6	2.5	-21.0	10.6	-32.4	-46.5	5.0	-5.0	61.6	119.2	106.4	382.2
1969	81.4	52.3	55.7	-.6	-3.6	9.6	-3.3	-12.4	33.8	92.3	81.4	109.7	556.0
1970	76.5	62.8	35.4	-13.4	14.3	-10.7	-10.7	27.1	52.3	52.6	07.4	Ilk.8	kRl.O
1971	120.7	56.6	35.4	17.3	-2.8	-14.7	9.4	16.4	47.1	63.8	108.0	121.4	586.6
1972	126.9	71.5	22.0	6.6	-18.6	-.0	-6.8	3.0	44.2	88.9	72.5	110.8	521.0
1973	60.8	70.4	13.4	36.0	3.1	-16.6	-3.1	8.0	78.6	66.1	103.9	94.8	523.4
1974	80.4	80.0	52.0	-21.5	18.8	-15.3	-21.2	32.7	60.8	63.6	77.9	77.6	485.8
1975	124.6	65.6	86.1	36.6	-3.9	-21.2	-12.2	49.2	50.7	67.0	56.9	150.6	650.0
MEAN	96.5	75.4	4V.6	-1.3	-3.3	-12.7	-4.2	17.2	50.4	62.3	90.7	105.8	517.4

is frequently reversed, resulting in condensation (negative evaporation) on the lake. The highest monthly condensation occurs in June and normally exceeds 10 mm, with a 13 mm average value. The maximum condensation of 46 mm occurs in July.

Delayed occurrence of the high and low evaporation is related to heat storage effects, which are common to all large bodies of water. Because of its great depth, Lake Superior can absorb large quantities of heat from the atmosphere during the heating season and dissipate the heat back to the atmosphere during the cooling season. This tremendous heat storage capacity is responsible for shifting the high evaporation and low evaporation seasons to winter and summer, respectively. The effects of heat storage are less pronounced on the other Great Lakes because of shallower depths. In comparison with Lake Erie, which is relatively shallow, the periods of low and high evaporation from Lake Superior are delayed a full season (3 months).

The water budget of Lake Superior for the average monthly and annual values of the hydrologic components is summarized in table 3. High evaporation coincides with reduced seasonal precipitation, low runoff, decreasing outflow, and large withdrawal of water from lake storage. Low evaporation coincides with increased seasonal precipitation, high runoff, increasing outflow, and high storage of water on the lake.

Table 3.--Lake Superior water Budget, mm, 1942-75

Month	Precipitation	Runoff	Outflow	storage	Evaporation
Jan.	59.9	35.2	67.1	-68.5	96.5
Feb.	52.1	31.1	60.2	-52.5	75.4
Mar.	48.0	39.8	65.0	-17.8	40.6
Apr.	58.9	86.8	65.5	81.6	-1.3
May	81.3	100.6	72.1	112.4	-3.3
June	83.1	66.4	73.4	88.8	-12.7
July	72.9	46.9	80.1	43.9	-4.3
Aug.	83.4	37.7	64.5	19.4	17.2
Sept.	74.5	36.2	81.1	-20.8	50.4
Oct.	55.8	42.6	81.5	-45.4	62.3
NOV.	66.2	45.0	77.8	-57.2	90.7

***Table 3.--Lake Superior water budget, mm, 1942-75** (Cont'd)*

Dec.	53.7	38.8	72.0	-85.4	105.8
Annual	789.9	607.1	880.9	-1.4	517.4

It should be emphasized that evaporation is basically a cooling process that is involved in attaining both mass and heat balance. The computed evaporation is obtained from a combination of all the water supply, losses and storage factors, and is not directly related to any particular hydrologic component. Thus, there is no correlation between evaporation and precipitation that might be intuitively inferred. Annually the ratio between the largest and smallest water balance components is less than 2 (1.8) for outflow and evaporation, respectively. Although annual storage approaches zero, the magnitude of lake storage per year is ±700 mm.

The relative sensitivity and error variance of the input parameters on computed evaporation was determined by a modified version (Quinn, 1979) of the sensitivity and error variance functions presented by Coleman and DeCoursey (1976). Quinn’s modification of the sensitivity function involves the definition of the range for the independent variables. He employs the total range (maximum-minimum), instead of the partial range (measured-minimum) used by Coleman and DeCoursey. The relative importance of the independent parameters as defined by the relative sensitivity function is

$$\Psi_{R_i} = \frac{\Delta E}{\Delta X_i}\left[\frac{(X_{max} - X_{min})}{E}\right] \qquad (2)$$

where

Ψ_{R_i} = relative sensitivity,

AE = evaporation increment,

AX_i = unit change in independent parameter,

X_{max} = maximum value of independent parameter,

X_{min} = minimum value of independent parameter, and

E = evaporation.

The error variance function designed to indicate possible error contributions from each of the independent parameters is defined as

$$E[V(X)] = \sum_{i=1}^{n} \left(\frac{\Delta E}{\Delta X_i}\right)^2 Var(X_i) \qquad (3)$$

where

$E[V(X)]$ = expected error due to variance of X,

$Var(X_i)$ = variance of independent variable X, and

Σ = summation, $i = 1,\ldots,n$ variables.

Both seasonal and monthly values were used to test the relative sensitivity and error variance analysis for the annual, high, and low evaporation, with generally similar results. The results of the relative sensitivity and error variance analysis for the annual values are given in table 4. The most sensitive parameter is the change in storage, while runoff, precipitation, and outflow either have reduced sensitivity or are relatively insensitive. The variance is the standard error of measurement squared, which is expressed as a percentage of the mean parameter value ($\bar{X}$) except for the change in storage, which is in millimeters. Indicated standard errors, following Quinn and den Hartog (1979), represent generally accepted limits of accuracy for the Great Lakes. The greatest potential error indicated by the error variance is due to the change in storage, followed by precipitation and runoff, while outflow is relatively unimportant. With the exception of outflow and runoff, these results generally agree with those obtained by Quinn and den Hartog for Lake Ontario. However, Lake Ontario inflow and outflow are an order of magnitude greater than other water balance components, and the magnitude of runoff is also considerably higher than those of precipitation and lake storage.

Table 4.--Water balance sensitivity and error variance analysis, 1942-75

Parameter X	Sensitivity Ψ_{R_i}	Standard error SE	Error variance $E[V(X)]$
Precipitation	0.82	10%($\bar{X}$)	43.3
Runoff	1.61	10%($\bar{X}$)	25.6
Outflow	0.49	3% ($\bar{X}$)	4.8
Change in Storage	4.59	8 mm	64.0

3. MASS TRANSFER METHOD

The mass transfer method of computing evaporation is based on the removal of water vapor from the lake 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 vapor pressure difference between saturation vapor pressure at the surface and ambient air vapor pressure at some predetermined level. The mass transfer equation used to compute Great Lakes evaporation during the past two decades represents a modification of the classic Lake Hefner equation (U.S. Geological Survey, 1954 and 1958), which was adjusted to 8 m. Expressed in its basic form, for metric units, the equation is

$$E = M(e_s - e_a)\,U \qquad (4)$$

where

E = evaporation rate, mm/day,

M = mass transfer coefficient,

e_s = saturation vapor pressure at lake surface temperature, mbar,

e_a = vapor pressure of ambient air, mbar, and

U = wind speed of ambient air, m/s.

The problem in applying the mass transfer method to the Great Lakes is that climatological data for any appreciable period of time are almost exclusively restricted to the perimeter land stations, which do not reflect climatic conditions over large water areas. The initial adjustments for the perimeter data were developed in the form of constant monthly lake/land wind and humidity ratios, which were derived from simultaneous observations over land and over water. The overwater observations were obtained during synoptic surveys conducted on the lakes during the 1960's. The basic Lake Hefner equation was modified for use on the Great Lakes by Richards (1964), who incorporated monthly lake/land wind and humidity ratios. This modified equation was used in subsequent studies to compute long term evaporation for monthly periods (Richards and Irbe, 1969; Derecki, 1976b). Employment of constant monthly ratios permitted use of the available perimeter data, but did not reflect changes in monthly weather conditions from year to year. In more recent mass transfer computations (Derecki, 1978), the use of the modified Lake Hefner equation was refined by the introduction of variable land to lake wind and humidity adjustments.

Variable land to lake adjustments for wind and air vapor pressure, based on air stability and overwater fetch criteria, were developed by Phillips and Irbe (1978) from the extensive IFYGL data base. These adjustments, expressed as lake/land wind ratios and land - lake air and dew point temperature differences, are grouped into five ranges of atmospheric stability and lengths of overwater fetch for six wind speed classes. Different atmospheric stability conditions (very stable, stable, neutral, unstable, and very unstable) are determined by the stability index, which is defined as the air - water temperature difference. The stability index is determined from readily available land-based air temperatures. The equations for the land to lake data adjustments and stability index are as follows

$$R'' = U_w / U_l \qquad (5)$$

where

R_w = lake/land wind ratio (overwater),

U_w = overwater wind speed, m/s,

U_l = perimeter wind speed, m/s, and

$$\Delta T_{aw} = T_{al} - T_{aw} \qquad (6)$$

where

ΔT_{aw} = land - lake air temperature difference, °C (overwater),

T_{al} = perimeter air temperature, °C,

T_{aw} = overwater air temperature, °C, and

$$\Delta T_{dw} = T_{dl} - T_{dw} \qquad (7)$$

where

ΔT_{dw} = land - lake dew point temperature difference, °C (overwater),

T_{dl} = perimeter dew point temperature, °C,

T_{dw} = overwater dew point temperature, °C, and

$$S = T_{al} - T_w \qquad (8)$$

where

S = air stability index, °C (overwater), and

T_w = water surface temperature, °C.

Phillips and Irbe's results were used to develop a set of adjustment equations for all fetches for Lake Superior in the present study to obtain respective adjustments based on air stability conditions during each month. To avoid artificial grouping of the land to lake adjustments, the adjustment values at the mid-point of each air stability range were fitted with compound curves. These curves were determined by fifth-order polynomial equations

$$\begin{matrix} R_w \\ \Delta T_{aw} \\ \Delta T_{dw} \end{matrix} = C_0 + C_1S + C_2S^2 + C_3S^3 + C_4S^4 + C_5S^5 \qquad (9)$$

where

C_{0-5} = polynomial coefficients (fifth order).

The polynomial coefficients for the adjustment equations for each wind speed class are listed in table 5. For the monthly winds used in this study, only the equations for the 2.1-4.0 m/s and 4.1-6.0 m/s wind

Table 5.--Coefficients for Lake Superior land to lake adjustment equations (all fetches)

Perimeter wind speed m/s	Coefficients					
	C_0	$C_1 x10^{-2}$	$C_2 x10^{-3}$	$C_3 x10^{-4}$	$C_4 x10^{-6}$	$C_5 x10^{-7}$
Wind speed ratios:						
<2.1	2.37	-9.90	0.493	2.66	17.0	4.22
2.1-4.0	1.47	-5.03	2.82	2.02	-7.64	-4.30
4.1-6.0	1.22	-5.89	2.30	3.36	-9.54	-7.86
6.1-8.0	1.10	-5.80	1.29	2.64	-7.64	-5.81
8.1-10.0	1.17	-3.22	-3.38	-1.02	14.8	6.23

Table S.--Coefficients for Lake Superior land to lake adjustment equations (all fetches) (Cont'd)

>10.0	0.96	-1.08	0.034	0.573	-4.86	-2.54
Air temperature difference:						
<2.1	-0.66	55.3	13.2	-2.48	-8.16	3.87
2.1-4.0	-0.12	46.2	7.81	3.23	-5.38	-4.54
4.1-6.0	-0.13	37.9	17.9	9.71	-43.2	-25.6
6.1-8.0	0.33	36.6	10.5	9.06	-7.81	-12.3
8.1-10.0	-0.12	41.9	23.7	3.47	-42.0	-15.0
>10.0	-0.59	30.9	11.1	2.61	49.1	18.8
Dew point temperature difference:						
<2.1	-1.04	18.2	18.5	8.82	-26.4	-17.6
2.1-4.0	-0.91	13.7	10.3	9.29	4.34	-6.87
4.1-6.0	-1.14	4.82	18.0	22.1	-58.8	-51.1
6.1-8.0	-1.22	2.39	6.96	17.5	-10.8	-25.9
8.1-10.0	-1.21	8.94	-2.19	6.76	57.1	13.3
>10.0	-1.74	20.6	32.4	8.04	-145.0	-59.3

NOTE: Separate adjustments are developed for overwater and overice conditions, and then combined, using percent of ice cover, for actual overlake conditions.

speed classes are actually used. Relationships between the stability index and the wind ratios, air temperature differences, and dew point temperature differences for these wind speed classes are shown in figures 4, 5, and 6, respectively. Separate adjustments are developed for overwater and overice conditions; the percent of ice cover is then used to combine them to obtain an adjustment for actual overlake conditions.

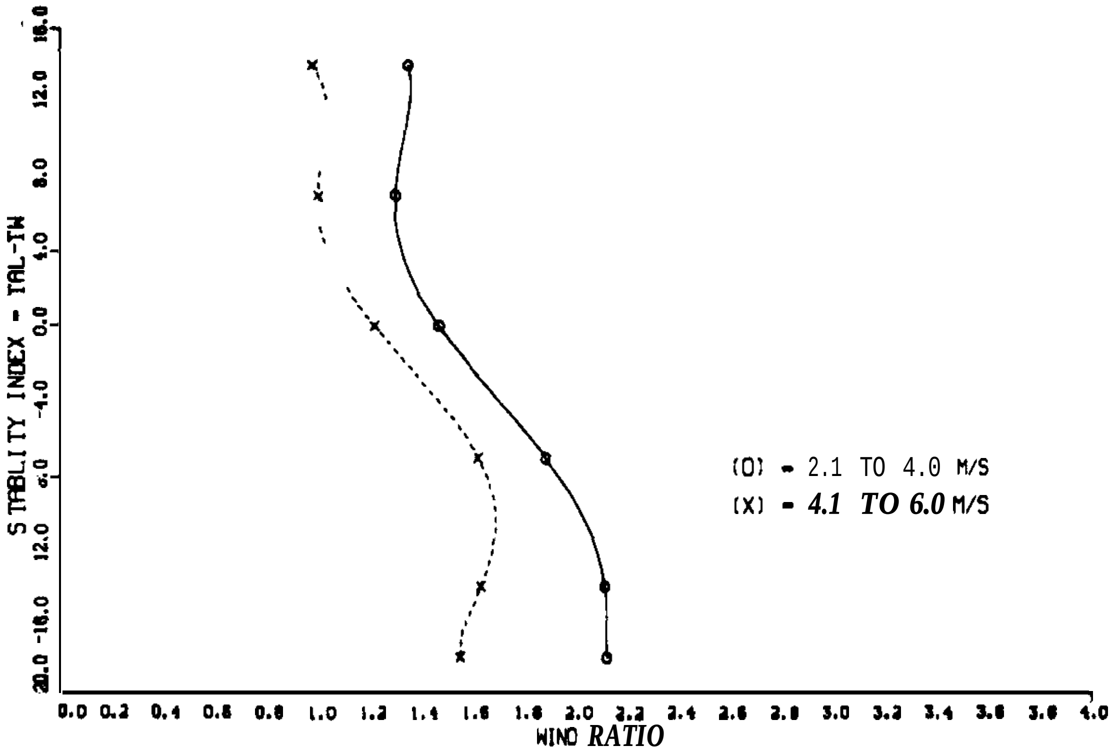

Figure 4.--Lake **Superior** *lake/land* **wind ratios.**

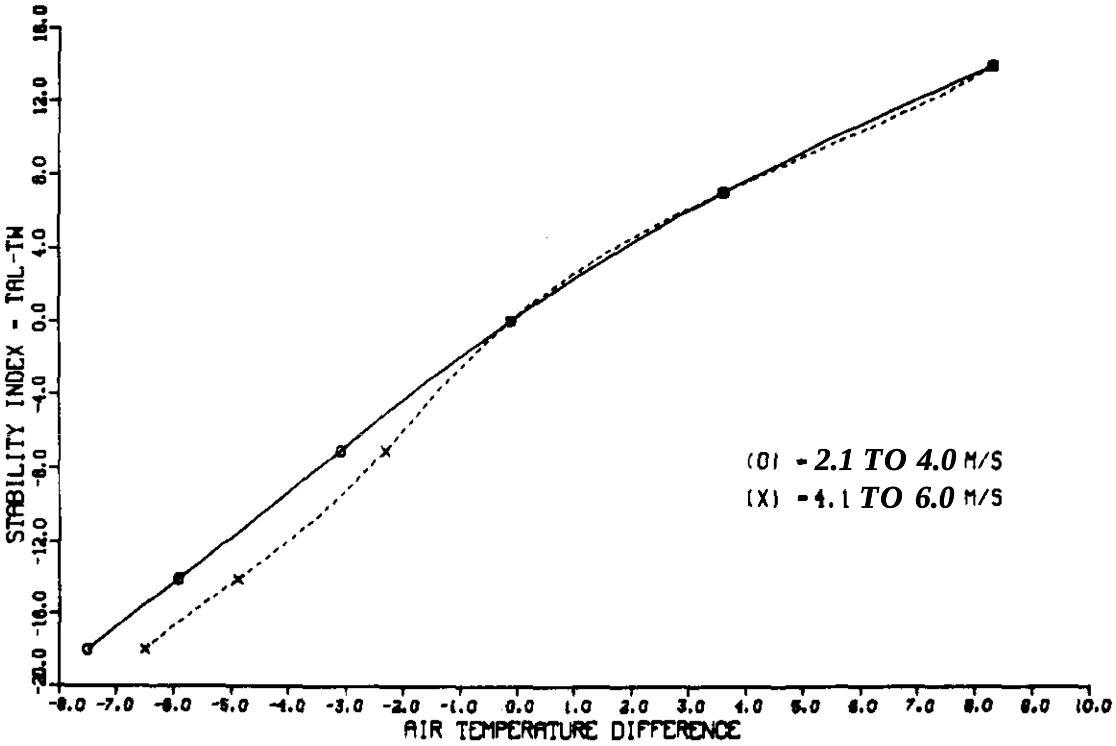

Figure S.--Lake Superior *land* **- *lake*** air temperature *difference.*

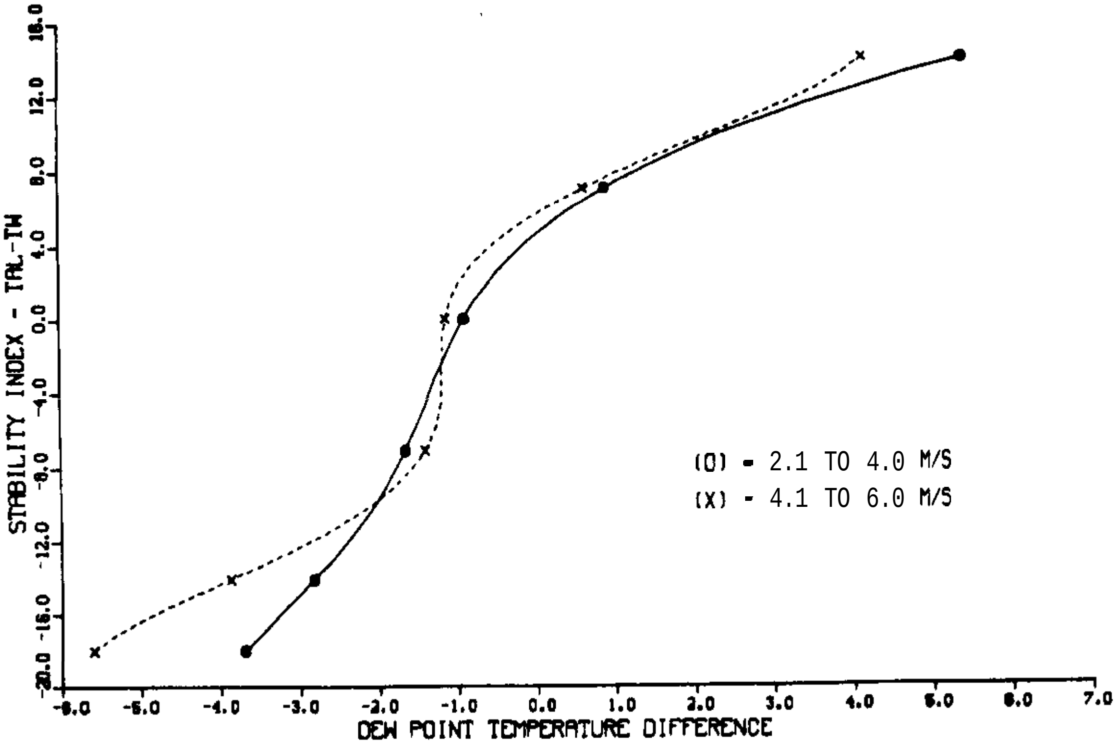

***Figure** 6.--Lake Superior land - lake dew point temperature difference.*

All preceding Great Lakes mass transfer evaporation studies employed the Lake Hefner coefficient, a calibrated constant for a relatively *small* water body in a different climate, thus, its use for the Great Lakes is questionable. The use of a constant also fails to reflect seasonal variability of the atmospheric stability, affecting seasonal distribution of computed evaporation. Considerable effort was exerted during the IFYGL evaporation synthesis studies to determine the mass transfer coefficient applicable to large lakes and different climatic conditions. Phillips (1978) presents a modified mass transfer technique, which includes atmospheric stability effects on the bulk moisture coefficient. Quinn (1979) developed a variable bulk transfer coefficient, dependent upon atmospheric stability, which is determined from the same meteorological variables required for the simplified mass transfer computations. Quinn's approach is used in the present study. Quinn and den Hartog (1979) also present a simplified approach, based on regression, in which the mass transfer coefficient is determined from wind velocity. A more detailed discussion on the derivation of the variable mass transfer coefficient is contained in the next section.

Because of extensive ice cover on Lake Superior, the standard mass transfer method for open water conditions nay considerably overestimate winter evaporation. Reduction of Lake St. Clair evaporation due to ice cover (100 mm/year) was found to be equivalent to the increase in evaporation derived from overwater adjustments of lake perimeter data (Derecki, 1979). The ice-cover reduction of evaporation was included by considering both open water and ice-covered areas of the lake during winter. Adjustment equations listed in table 5 were used to evaluate partial suppression of evaporation by ice cover by determining ice-cover effects on air stability (wind and temperature) and vapor pressure. The stability index over ice for these evaluations was determined from ice surface temperatures. Separately determined overice values for various parameters (evaporation and input data) were combined with the standard overwater data to produce overlake values reflecting actual lake surface conditions. Listed over-lake values of the input parameters are presented mainly for general information, since evaporation was determined separately for the overwater and overice conditions. Overlake parameter values were determined with the following equation

$$X = X_i \left(\frac{IC}{100} \right) + X_w \left(1 - \frac{IC}{100} \right) \qquad (10)$$

where

X = overlake parameter value,

X_i = overice parameter value,

X_w = overwater parameter value, and

IC = ice-covered area, percent.

The use of the mass transfer method on the Great Lakes has recognized limitations. Computed evaporation depends on perimeter data and requires extensive adjustments to reflect overwater conditions. Standard overwater computations exclude the effects of ice cover, which reduces winter evaporation. The primary advantages of this method are the capability for quick, operational evaporation estimates from readily available data and the fact that it is the most amenable approach for future improvements. The mass transfer method also eliminates the main objections to the water budget method, which for Lake Superior includes uncertainties with respect to thermal expansion and contraction of water. A brief description of the required data and adjustment effects is given below.

3.1 Mass Transfer Coefficient

The mass transfer coefficient used traditionally in Great Lakes evaporation studies represents the Lake Hefner calibrated constant adjusted to an 8 m height (0.097 for mm/day). Because of large differences in lake size and different climatic conditions, the atmospheric stability over Lake Hefner and the Great Lakes should differ considerably, both in magnitude (strength) and seasonal variation. The use of the Lake Hefner constant for Lake Superior is therefore questionable on both accounts (magnitude and variation). Based on the classical approach of correlation between the mass transfer product and water budget evaporation, Derecki (1976b), showed that the Lake Hefner constant appears reasonable for use on Lake Erie (0.097 versus 0.100). However, in subsequent extensive evaporation studies conducted on Lake Ontario during IFYGL, Quinn and den Hartog (1979) obtained considerably lower coefficient values with significant seasonal variation. Quinn (1979) developed a variable mass transfer coefficient, based on atmospheric stability, and presents an iterative algorithm for its derivation from the same meteorological variables that are required for normal mass transfer computations. This approach, also used in the present study, defines the mass transfer coefficient as

$$M = 53741\rho(C_E/p) \tag{11}$$

where

M = mass transfer coefficient,

ρ = air density (1.25 kg/m^3),

C_E = bulk evaporation coefficient, and

p = atmospheric pressure, mbar.

The above relationship shows that the mass transfer coefficient is dependent on the air density and pressure, and the latent heat flux. For average values of air density and applicable atmospheric pressure (1000 mbar), the above equation for Lake Superior may be reduced to

$$M = 67.18\ C_E \tag{12}$$

Derivation of the bulk transfer coefficient for latent heat flux (C_E), dependent upon atmospheric stability, was based on the analysis of non-dimensional wind speed and potential temperature gradients in the surface boundary layer. The analysis involved determinations of frictional velocity, roughness length (height), Monin-Obukhov stability length, and stability functions for momentum and sensible heat to derive bulk transfer coefficients for momentum (drag) and sensible heat. Assuming that bulk transfer coefficients for sensible and latent heat fluxes are equal, the evaporation coefficient was obtained from the following equation

$$C_E = C_H = \frac{KU_*}{U[\ln(Z/Z_o) - \Psi]} \tag{13}$$

where

C_E = bulk transfer coefficient for latent heat,

C_H = bulk transfer coefficient for sensible heat,

K = "an Kármán's constant (0.41),

U_* = friction velocity, m/s,

U = wind speed, m/s,

Z = reference height, m,

Z_o = roughness length, m, and

Ψ = stability function for sensible heat.

Separate stability functions were determined for different atmospheric stability conditions. The stability ranges were defined by reference height/stability length relationship (Z/L) as

unstable	$Z/L < 0$,
neutral	$Z/L = 0$,
stable	$0 < Z/L < 1$, and
strongly stable	$Z/L \geq 1$.

Quinn's iterative algorithm, using known values of air and water surface temperatures, wind speed, and reference height, was used to determine the bulk transfer coefficient. The reference height in the present study was standardized at 8 m (Z = 8 m) for all applications (mass transfer coefficient and meteorological data). More detailed information on the analysis and determinations of friction velocity, roughness length, stability length, and stability functions for different conditions is contained in Quinn's (1979) report. This information is required to calculate the mass transfer coefficient for Lake Superior, but is omitted to eliminate extensive duplication.

The resulting Lake Superior mass transfer coefficient is summarized in table 6, which shows average monthly and annual values for the perimeter (overland), overwater, overice, and actual overlake conditions. The average annual value of 0.070 is much lower than the 0.097 Lake Hefner value, but this large difference does not reflect the actual effect on computed evaporation. During the more sensitive high evaporation season, the Lake Superior coefficient is generally close to 0.100 and agrees reasonably well with the Lake Hefner value. Still, the use of the Lake Hefner coefficient would tend to underestimate Lake Superior evaporation during the high evaporation season and overestimate it during the low evaporation season. Seasonal variation in the mass transfer coefficient is very large, increasing from a low value of 0.030 in June to a high of 0.104 in December. Reduction of the coefficient owing to ice cover is significant during winter. The winter overice values of the coefficient agree closely with the perimeter values, since meteorological conditions over ice and snow surfaces are

Table 6.--Average values for Lake Superior mass transfer coefficient, for m/&y, 1942-75

Month	Perimeter M_l	Overwater M_w	Overice M_i	Overlake M
Jan.	0.070	0.105	0.074	0.102
Feb.	0.069	0.103	0.073	0.090
Mar.	0.071	0.092	0.074	0.084
Apr.	0.064	0.058	0.080*	0.061*
May	0.067	0.036		0.036
June	0.064	0.030		0.030
July	0.061	0.032		0.032
Aug.	0.057	0.044		0.044
Sept.	0.072	0.072		0.072
Oct.	0.072	0.082		0.082
Nov.	0.071	0.098		0.098
Dec.	0.070	0.104		0.104
Annual	0.067	0.071		0.070

*Irrational results produced by erroneous data (ice temperature estimates). Since ice cover in April is light, the effect is not significant. This could be eliminated by using perimeter and overwater values for the overice and overlake coefficients, respectively.

similar, and the overice coefficients could be estimated from perimeter data. The irrational results of higher overice than overwater and consequently higher overlake than overwater coefficients obtained for April are produced by erroneous data (primarily the ice temperature estimates) discussed later. The ice temperatures are difficult to estimate in April because of a generally higher perimeter than overwater temperature and limited ice cover. However, limited ice cover ensures that the overice coefficient during this month has only a limited effect on lake evaporation. As shown later, this erroneous evaporation increase is negligible. The inconsistency in April coefficients could be eliminated by using the perimeter and overwater coefficients for the overice and overlake values, respectively.

The inclusion of stability effects increased the Lake Superior mass transfer coefficients during winter and reduced them during summer. Quinn and den Hartog (1979) state that for many Great Lakes uses the available data do not justify the inclusion of the variation of the coefficient with stability, and they recommend a simplified procedure to obtain the coefficient. This approximation, based on linear regression of the bulk transfer coefficient with wind, includes the variation of the mass transfer coefficient with wind speed for a constant value of bulk transfer coefficient. For the 8 m reference level, the simplified coefficient is given by the following equation

$$M_8 = 0.047 + 0.0046\ U_8 \qquad (14)$$

where

M_8 = approximate mass transfer coefficient based on variation with wind speed, and

U_8 = wind speed at 8 m, m/s.

Tests of the above equation on Lake Superior produced a similar annual value (0.074), but drastically reduced seasonal variation in the coefficient (0.068-0.082). As shown later under the evaporation discussion, a large reduction of the high winter coefficients resulted in a 25 percent reduction of the annual evaporation and produced overall results inferior to those obtained with the Lake Hefner coefficient. Quinn and den Hartog also present mass transfer coefficients determined from regression of the mass transfer product versus several other evaporation estimates. Their best coefficient from regression, based on aerodynamic evaporation estimates, was tested on Lake St. Clair (Derecki, 1979) and indicated results similar to those described above. The straight line coefficient for the 3 m level was considerably lower than the corresponding Lake Hefner value (0.107 versus 0.124), but the trend of data points was clearly curvilinear, indicating the effects of neglecting wind speed and air stability. Resulting underestimates of high evaporation were not compensated by low evaporation overestimates, reducing the annual total. Elimination of this bias produced a weighted coefficient much closer to the Lake Hefner value (0.120). The above tests indicate that the simplified Lake Ontario coefficients should not be used for the other Great Lakes.

3.2 Meteorological Data

Basic meteorological data and derived mass transfer parameters were obtained by averaging the records from three first-order meteorological stations located around the lake (Sault Ste. Marie, Mich., Duluth, Minn., and Thunder Bay, Ont.). Records for wind speed, air temperature, and relative humidity were obtained from regular climatological publications prepared by weather organizations in the United States and Canada (National Weather Service, NOAA, and Atmospheric Environment Service, Environment Canada). Individual station records were standardized at the 8 m height to be compatible with the mass transfer equation (8 m coefficient) and to eliminate the periodic bias induced by different measurement heights of various sensors (appendix A, table 22). Adjustment of data to the standard height of 8 m was made with the following equation

$$X_8 = X_m \frac{\ln(Z_8/Z_o)}{\ln(Z_m/Z_o)} \qquad (15)$$

where

X_8 = parameter value at 8 m,

Xm = parameter value at measured height,

Z_8 = reference height of 8 m,

Z_m = measurement height, m, and

Z_o = roughness height (0.0001 m).

The perimeter wind speed for Lake Superior (appendix A, table 23) shows a high degree of consistency in monthly and annual values. Comparisons of the average wind speeds for the lake perimeter, overwater, overice, and actual lake surface, with corresponding adjustments (wind ratios based on table 5) are given in table 7. Adjustment of the wind speed to the 8 m level reduced average recorded values by 3 percent. The overwater adjustment increased annual perimeter winds by 41 percent, varying seasonally from under 10 percent during spring to nearly 75 percent during winter. Actual winter adjustment was reduced to about 60 percent because of ice-cover effects. The average annual 8 m level overlake wind speed is 5.9 m/s, varying from a 4.5 m/s summer low to a 7.7 m/s winter high.

Average perimeter air temperature and relative humidity values (Appendix A, tables 24 and 25) were used to determine dew point temperatures and air vapor pressure. Perimeter air temperatures are below freezing for 5 months of the year (November-March). Seasonally, shoreline air temperatures vary from a low in January (-12.6°C) to a high in July (17.8°C), with an average annual value of 3.5°C. The average land to lake air temperature adjustments and corresponding temperatures are shown in table 8. Seasonal land - water air temperature differences are quite large (ranging from -4.7°C to 5.5°C), but balance each other during the year. Owing to a lack of data, the overice air temperatures were assumed to be equal to the perimeter values, with a maximum of 0°C. This assumption should be valid during periods of extensive ice cover. During periods of limited ice cover the assumption is immaterial, since

Table 7.--Average wind speed for Lake Superior, m/s, 1942-75

Month	Perimeter		Overwater		Overice		Overlake	
	U_m	"1	R_w	U_w	R_i	U_i	R_u	U
Jan.	4.66	4.51	1.71	7.66	1.26	5.67	1.67	7.47
Feb.	4.53	4.39	1.74	7.59	1.27	5.55	1.54	6.73
Mar.	4.68	4.52	1.54	6.96	1.25	5.62	1.42	6.41
Apr.	4.98	4.82	1.09	5.27	1.08	5.22	1.09	5.27
May	4.73	4.58	1.02	4.64			1.02	4.64
June	4.14	4.01	1.14	4.54			1.14	4.53
July	3.87	3.74	1.28	4.76			1.28	4.76
Aug.	3.75	3.63	1.27	4.61			1.27	4.61
Sept.	4.13	4.00	1.37	5.45			1.37	5.45
Oct.	4.42	4.28	1.40	5.99			1.40	5.99
Nov.	4.73	4.58	1.62	7.41			1.62	7.41
Dec.	4.56	4.41	1.75	7.68			1.75	7.68
Annual	4.43	4.29	1.41	6.05			1.38	5.91

Table 8.--Average air temperature for Lake Superior, °C, 1942-75

Month	Perimeter	Overwater		Overice		Overlake	
	T_{al}	ΔT_{aw}	T_{aw}	ΔT_{ai}	T_{ai}	AT_a	T_a
Jan.	-12.6	-4.7	-1.9	-0.1	-12.5	-4.2	-8.4
Feb.	-11.1	-4.0	-7.1	-0.1	-11.0	-2.3	-8.9

Table E.--Average air temperature for' Lake Superior, °C, 1942-75 (Cont'd)

Mar.	-5.0	-1.8	-3.3	-0.1	-5.0	-1.1	-4.0
Apr.	3.0	1.1	1.9	1.2	-1.3	1.1	1.5
May	9.1	3.9	5.2			3.9	5.2
June	14.4	5.5	9.0			5.5	9.0
July	17.8	5.4	12.4			5.4	12.4
Aug.	17.1	2.3	14.9			2.3	14.9
Sept.	12.1	-0.1	12.2			-0.1	12.2
Oct.	7.1	-0.8	7.9			-0.8	7.9
Nov.	-1.3	-2.3	1.0			-2.3	1.0
Dec.	-9.1	-4.0	-5.1			-4.0	-5.1
Annual	3.5	0.0	3.4			0.3	3.1

actual lake evaporation would not be changed significantly. The average overwater air temperatures vary from -8.9°C in February to 14.9°C in August, with an annual value of 3.1°C. Ice cover on the lake reduces resulting overlake air temperature by nearly 2°C during February.

Monthly humidity values for the lake perimeter are strongly consistent, with an average of 76 percent, varying from about 70 percent during spring to about 80 percent during fall. Average values for derived dew point temperatures and adjustments are given in table 9. The average perimeter dew point temperatures are about 4°C lower than air temperatures. The overwater adjustment of dew point temperatures increased the average perimeter value by nearly 1. °C, varying seasonally from a winter increase of about 3°C to a summer reduction of about 2°C. Winter overice adjustment averaged about 1°C. Resulting overlake dew point temperatures vary from -12.7°C in February to 13.3°C in August, with an average annual value 0.3°C. The ambient air vapor pressure was determined from the overwater and overice dew point temperatures for the overwater and overice conditions, respectively, and was used in the corresponding evaporation computations.

3.3 Water Surface Temperature

The water temperature data for Lake Superior were obtained by adjusting average water temperature records from the municipal water intakes located

Table 9.--Average dew point temperature for Lake Superior, “C, 1942-75

Month	Perimeter		Overwater		Overice		Overlake	
	H(%)	T_{dl}	ΔT_{dw}	T_{dw}	ΔT_{di}	T_{di}	ΔT_{d}	T_{d}
Jan.	78	-15.7	-3.5	-12.3	-1.1	-14.6	-3.2	-12.5
Feb.	76	-14.5	-2.6	-11.9	-1.1	-13.4	-1.9	-12.7
Mar.	75	-8.9	-1.3	-7.6	-1.1	-7.8	-1.2	-7.7
Apr.	70	-2.0	-0.8	-1.3	-0.7	-1.3	-0.8	-1.3
May	68	3.5	0.9	2.6			0.9	2.6
June	74	9.9	2.2	7.7			2.2	7.7
July	75	13.5	2.2	11.2			2.2	11.2
Aug.	78	13.4	0.0	13.3			0.0	13.3
Sept.	80	8.8	-1.0	9.8			-1.0	9.8
Oct.	78	3.5	-1.1	4.6			-1.1	4.6
Nov.	81	-4.2	-1.5	-2.8			-1.5	-2.8
Dec.	80	-11.9	-2.6	-9.3			-2.6	-9.3
Annual	76	-0.4	-0.8	0.4			-0.7	0.3

at first-order stations (Sault Ste. Marie and Thunder Bay). Records for the Duluth water intake were omitted because they were obtained in deep water (20 m), which is insulated from the surface waters by the thermocline during most of the year. Municipal water intakes are the only source of continuous long term water temperatures on the Great Lakes, but these records are for subsurface coastal temperatures and require adjustments to lake surface conditions. Surface temperature adjustments were derived from the airborne radiation thermometer (ART) survey measurements, conducted since 1966 on the Great Lakes bordering Canada by the Atmospheric Environment Service, Environment CAnada. Water surface temperatures obtained from satellites and ships of opportunity observations were also tested, but indicated poor accuracy and were discarded. Ship observations are obtained during normal passage and tend to avoid bad weather, thus biasing the data toward fair weather and more frequently traveled routes. Both ART and satellite observations are corrected for atmospheric attenuation, but available satellite data are not tied to surface observations and indicate a claimed ±2°C possible bias. Claimed accuracy for the ART temperatures is within 1°C (Richards, *et al.* 1969; Irbe, 1972).

Seasonal distribution of the ART water surface temperatures for the 1966-75 period is shown in figure 7. The ART data during individual years were normally insufficient to permit firm delineation of seasonal distribution. The ART surveys were limited to the open water season, and the winter temperature distribution was estimated based on ice cover, air temperatures, and other water temperatures discussed above. The average monthly surface temperatures were obtained from the superimposed bar graph shown in the figure. Monthly water surface temperature adjustments were derived from simultaneous ART and water intake data, shown in table 10. The adjustments indicate temperature differences similar to air and dew point temperature corrections, and are expressed by the following equation

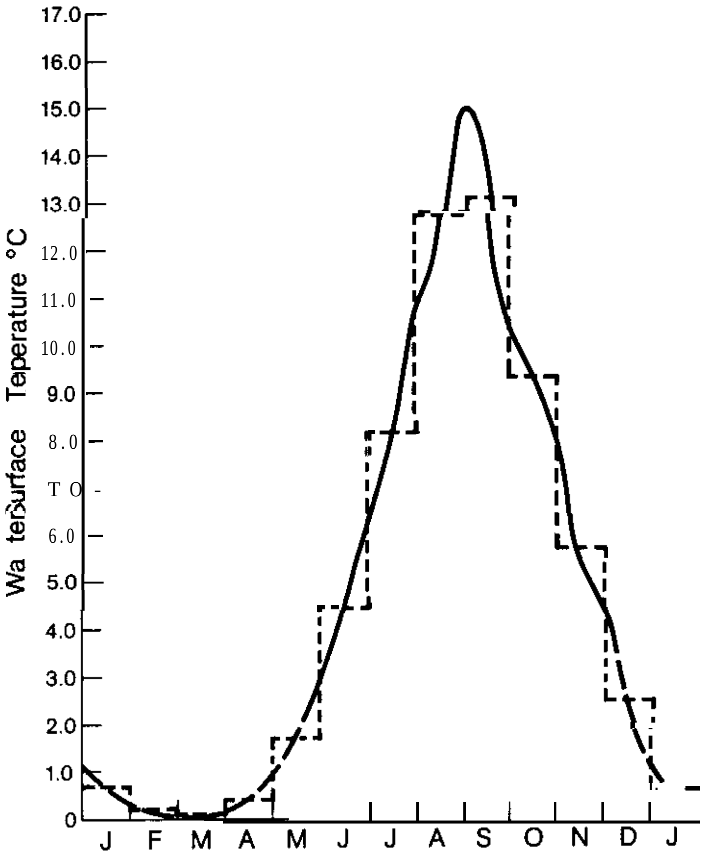

Figure 7.--Lake Superior seasonal water surface temperature distribution based on ART surveys, 1966-75

Table 10.--Lake Superior water surface temperature adjustments, °C, 1966-75

Month	Water intake T_m	Water surface T_w	Temp. adjust. ΔT_w
Jan.	0.6	0.7"	-0.1
Feb.	0.4	0.2*	0.2
Mar.	0.7	0.1*	0.6
Apr.	1.7	0.4"	1.3
May	4.5	1.7"	2.8
June	8.6	4.5	4.1
July	13.2	8.2	5.0
Aug.	15.1	12.8	2.3
Sept.	14.2	11.1	1.1
Oct.	10.3	9.4	0.9
Nov.	6.3	5.8	0.5
Dec.	2.6	2.6*	0.0
'Annual	6.5	4.9	1.6

*Extimated values.

$$AT_w = T_m \quad T_w \tag{16}$$

where

AT_w = intake - surface water temperature difference, °C,

T_m = water intake temperature, "C, and

T_w = water surface temperature, °C.

Temperature adjustments indicate that the water intake temperatures are considerably warmer than the lake water surface temperatures during summer, but only slightly warmer during winter. The average monthly temperature differences vary from -0.1°C in January to 5.0°C in July, with an annual value of 1.6°C. These average monthly water temperature corrections were applied throughout the study period to adjust the water intake records to the open water lake surface conditions (appendix A, table 26). Because of low winter temperatures (approaching 0°C), the use of average adjustments produced occasional negative temperatures. In order to avoid negative water temperatures, the minimum was preset at 0°C. Additional surface temperature corrections were applied during winter for the ice-covered portion of the lake. Surface temperature of the ice was estimated from the perimeter air temperatures, with a maximum value of 0°C. Comparisons of the average 1942-75 values for the water intake, water surface, ice surface, and actual lake surface temperatures are given in table 11. The average monthly water surface temperature vary from 0°C in March to 12.4°C in August, with an annual value of 4.7°C. The ice-cover

Table 11.--Average surface temperatures for Lake Superior, °C, 1942-75

Month	Water intake T_m	Water surface T_w	Ice surface T_i	Lake surface T_s
Jan.	0.5	0.6	-12.6	-0.7
Feb.	0.3	0.1	-11.1	-4.6
Mar.	0.4	0.0	-5.1	-2.0
Apr.	1.4	0.3	0.0	0.3
May	4.5	1.7		1.7
June	8.8	4.7		4.7
July	13.1	8.1		8.1
Aug.	14.7	12.4		12.4
Sept.	13.2	12.1		12.1
Oct.	10.0	9.1		9.1
NOV.	6.2	5.7		5.7
Dec.	2.2	2.2		2.2
Annual	6.3	4.7		4.1

reduction of water temperatures during winter is significant, reducing the annual lake surface average by 0.6°C. The average monthly reductions are 1.3°, 4.50, and 2.0°C for January, February, and March, respectively. These large reductions of water surface temperatures produce negative lake surface temperatures during winter.

The saturation vapor pressure was derived separately from the water and ice surface temperatures to reflect different conditions and combined with the corresponding ambient air vapor pressure in the evaporation computations. Resulting vapor pressure gradients were adjusted to the 8 m reference level by equation (15). Adjustment of the vapor pressure gradients to the standard height of 8 m increased the average vapor pressure difference values by 16 percent. The vapor pressure difference over water varies from the summer low to the winter high, with approximate average standardized extremes of from -3.0 to 4.8 mbar. During winter the vapor pressure difference over ice is greatly reduced, with the average monthly values ranging from 0.4 to 0.9 mbar. The average monthly reduction of vapor pressure difference over ice is from 2 to 4 mbar.

3.4 Ice Cover

The ice cover on Lake Superior was obtained from ice surveys conducted regularly since 1961 by the Great Lakes Environmental Research Laboratory (GLERL), NOAA, and the Ice Forecast Central in Canada. Estimates of the monthly average ice cover on the lake were determined from the individual surveys for the period of record (1961-75) and computed by derived ice cover and air temperature relationships for the preceding years. Monthly ice-cover equations were derived by multiple regression of available monthly ice-cover data and perimeter air temperatures for the month and the preceding month. The equations are listed in table 12. Statistical analysis of the equations shows strong correlation between the monthly ice cover and the Z-month air temperatures for February and March, the months of extensive ice cover. Weaker, but significant, correlation was obtained for January and April, the months of normally light ice cover. Computed ice cover was maintained arbitrarily, when needed, within 0 to 100 percent limits.

The observed and computed monthly ice-cover estimates for the 1961-75 period, and the average monthly values for both the 1961-75 and 1942-75 periods are given in table 13. Agreement between observed and computed values is generally good, with maximum monthly differences

Table 12.--Lake Superior monthly ice-cover equations

Month	Ice cover, %	Mult. corr. coef.	Std. er. %	Mean %
Jan.	$IC = -15.30 - 1.793T_1 - 0.313T_{12}$	0.86	2.8	11.7
Feb.	$IC = -65.02 - 5.529T_2 - 3.594T_1$	0.98	4.4	50.0
Mar.	$IC = -65.06 - 1.177T_3 - 8.904T_2$	0.94	9.1	48.5
Apr.	$IC = -1.26 + 0.286T_4 - 2.635T_3$	0.72	6.5	12.5

NOTE: Use equations to compute ice cover during the 1942-60 winter seasons.

TERMS: IC = ice cover, percent ($0 \leq IC \leq 100$),

T_1 = January T_{al}, °C,

T_2 = February T_{al}, °C,

T_3 = March T_{al}, °C,

T_4 = April T_{al}, °C, and

T_{12} = December T_{al}, °C.

Table 13.--Estimates of average Lake Superior monthly ice cover, percent 1961-75

Year	January		February		March		April	
	Obs.	Comp.	Obs.	Comp.	Obs.	Comp .	Obs.	Comp.
1961	12	12	30	26	20	6	7	6
1962	20	15	70	68	60	66	17	9
1963	20	17	80	76	80	72	20	13
1964	3	3	15	16	18	26	10	18
1965	12	14	55	63	68	68	30	20
1966	12	15	49	49	16	28	0	7
1967	10	8	66	65	76	83	12	13
1968	15	10	60	52	60	50	6	5
1969	7	9	31	32	36	29	10	16
1970	13	14	60	65	74	64	17	17
1971	15	16	50	55	35	43	9	16
1972	13	15	71	68	77	69	27	20
1973	5	6	29	30	26	31	0	0
1974	12	12	54	56	53	59	18	17
1975	6	7	30	30	28	32	10	17
Mean	12	12	50	50	48	48	13	13
1942-75	--	10	--	42	--	40	--	13

of 10 percent. In the extensive ice-cover months of February and March, ice covered approximately 50 percent of the lake area during the shorter period and 40 percent during the longer period, but varied from 15 percent to 80 percent during individual years. In the light ice-cover months of January and April, the ice cover varied from 0 percent to 30 percent, with average values of about 10 percent and 13 percent, respectively. Consideration of ice-cover effects on computed mass transfer evaporation is particularly important during February and March because nearly half of the lake is normally ice covered. Since high evaporation from Lake Superior occurs during winter, the ice cover drastically reduces these high evaporation rates and produces corresponding reduction in the total annual water loss from the lake.

3.5 Evaporation

The monthly Lake Superior evaporation computed for the period of study (1945-75) by the mass transfer method is listed in table 14. Computed evaporation values are based on perimeter data and derived mass transfer coefficients, which were adjusted to lake surface conditions (water and ice surfaces) by atmospheric stability considerations and should indicate actual water loss from the lake. Annual mass transfer evaporation varied from a low of 405 mm during 1947 and 1948 to a high of 627 mm in 1969, with an average value of 483 mm. The magnitude of these values agrees reasonably well with the water budget determinations. Both determinations indicate relatively constant long term evaporation, which fluctuates around the 500 mm per year value.

The effects of data adjustments and standardization at the 8 m reference level are indicated in table 15, which shows average evaporation values computed for the perimeter, overwater, overice, and actual overlake conditions. Adjustment of the wind speed and vapor pressure gradient to the standard height of 8 m produced a net increase in evaporation of 11 percent. Because of differences in atmospheric stability over large lake and land surfaces, perimeter data without adjustments are not suitable for evaporation computations. Perimeter evaporation for Lake Superior indicates a large reduction in lake evaporation during the high evaporation season (about 50 percent) and produces a net annual reduction of 30 percent. Because of extensive ice cover on Lake Superior during winter, the overwater evaporation indicates a substantial increase over the actual lake evaporation values. During the January through March high evaporation period, the average overwater evaporation (115 to 63 mm) exceeds the low overice evaporation (5 to 12 mm) by amount ranging from 50 to 110 mm/mo. Elimination of the ice-cover effects on Lake Superior during these months, inherent in the standard overwater mass transfer computations, increases the average monthly evaporation values by 10-40 mm and the annual total by 70 mm, which represents 15 percent of the actual lake evaporation. The ice-cover effect in April may be significant during individual years, but has little effect on the average evaporation values. The apparent anomaly of higher overice than overwater evaporation in April is produced by erroneous data, primarily in the ice temperature estimates, which are particularly difficult for April. Data adjustments required several assumptions discussed previously. However, this increase is small and the ice cover in April is not extensive, producing

Table 14.--Lake Superior evaporation by mass transfer method, mm.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1942	110.7	65.9	26.3	-1.5	-6.0	-12.9	-11.2	-3.8	16.9	58.7	129.6	130.2	497.9
1943	101.0	63.0	76.3	14.0	-5.8	-11.1	-15.3	-14.1	16.9	49.0	118.2	135.5	527.6
1944	69.7	80.9	49.1	12.3	-7.6	-13.8	-24.1	-10.4	15.7	50.7	69.0	114.7	406.3
1945	80.7	49.8	9.5	5.9	.8	-6.8	-17.9	-12.2	18.9	70.9	108.5	95.0	411.1
1946	86.1	50.5	9.7	4.0	-.3	-7.1	-13.9	-6.3	15.1	38.0	124.4	125.1	425.4
1947	114.6	76.0	36.0	9.0	-5.0	-13.8	-18.0	-20.5	10.7	14.7	99.2	102.0	4C4.9
1948	91.3	47.5	31.5	-3.3	-.2	-6.5	-11.2	-11.7	lb.9	55.4	78.4	116.4	404.6
1949	111.7	61.8	47.2	1.3	-3.2	-13.4	-14.6	-3.5	24.2	41.9	140.2	137.5	526.0
1950	127.6	52.8	62.7	26.4	-4.7	-8.1	-11.5	-.a	-.2	27.7	116.1	112.4	509.2
1951	102.3	56.8	53.9	-.4	-4.3	-11.4	-17.8	-3.3	10.6	33.4	104.4	117.2	435.6
1952	93.2	61.6	50.5	.0	-3.7	-10.2	-12.9	-11.6	-4.4	85.0	89.9	84.1	421.5
1953	116.8	62.1	34.3	12.1	-4.3	-11.9	-16.8	-9.2	49.3	49.7	86.6	130.9	499.6
1954	102.0	41.3	83.9	7.0	-2.5	-9.0	-12.3	-3.4	9.2	53.E	58.8	89.6	418.6
1955	113.5	57.1	62.7	-4.4	-3.0	-13.6	-19.3	-8.7	38.0	44.4	142.R	126.6	536.0
1956	92.4	67.0	55.2	18.6	-1.5	-7.8	-16.3	-10.7	23.9	29.0	114.3	116.0	481.0
1957	104.8	43.7	36.2	2.2	1.6	-10.0	-18.0	.5	42.8	69.3	103.6	102.2	479.0
1958	91.7	73.9	20.7	7.6	-.2	-5.7	-19.4	-6.6	4.2	38.6	119.9	120.4	445.3
1959	104.7	39.1	28.8	8.5	-9.0	-7.6	-9.1	-14.7	10.6	103.9	136.5	84.2	475.2
1960	94.7	65.2	60.8	2.8	-5.2	-6.0	-13.8	-11.6	33.4	56.3	102.9	12R.5	508.0
1961	93.5	50.2	38.3	a.9	-.7	-4.3	-14.7	.l	40.0	57.4	89.6	109.7	467.1
1962	117.3	33.0	24.2	9.6	-6.2	-8.1	-9.4	-4.5	49.7	57.1	74.7	124.8	462.4
1963	94.5	27.1	25.7	3.2	'2.4	-14.3	-12.0	-1.0	10.5	27.4	109.3	137.7	405.7
1964	104.3	74.2	66.4	4.7	-3.6	-6.4	-10.9	-2.2	25.1	66.6	101.1	143.6	562.8
1965	109.7	46.6	32.8	5.1	-5.3	-5.5	-14.5	-3.3	41.1	50.7	105.1	91.2	453.5
1966	104.6	48.1	43.6	9.8	2.7	-7.2	-12.1	-4.8	47.4	84.5	110.5	107.8	534.8
1967	114.3	39.1	23.2	11.4	5.6	-12.3	-11.3	3.6	38.5	76.2	101.4	113.5	503.4
1968	94.0	66.9	29.7	4.3	-2.3	-8.8	-10.4	-8.9	15.0	54.3	113.8	124.3	472.4
1969	109.7	61.3	54.6	2.6	-1.4	-5.2	-9.3	-1.5	17.6	102.7	106.3	129.3	626.7
1970	135.8	42.0	35.9	7.0	-3.4	-5.2	-13.0	.2	51.7	61.2	107.9	112.8	533.0
1971	112.4	47.8	44.6	11.6	1.5	-7.0	-5.2	7.4	28.5	41.8	117.6	135.1	536.1
1972	119.2	46.0	35.1	17.6	-2.2	-7.4	-9.4	-5.1	49.6	63.0	76.4	140.8	522.6
1973	85.2	71.1	18.8	16.3	-.4	-15.3	-12.4	-7.3	54.3	36.3	105.6	138.5	490.6
1974	90.3	53.8	42.6	6.2	-1.5	-18.7	-14.9	-7.9	57.3	62.9	74.4	94.5	441.6
1975	118.3	62.8	70.3	26.5	-4.9	-19.2	-21.4	2.5	57.2	51.8	105.0	142.6	591.5
MEAN	103.5	55.5	41.8	7.9	-2.6	-9.5	-13.9	-6.2	29.3	54.8	104.2	118.1	482.8

Table 15.--Average mass transfer evaporation for Luke Superior, mm, 1942-75

Month	Perimeter		overwater	Overice	Overlake
	E_m	E_l	E_w	E_i	E
Jan.	45.4	50.4	115.2	5.0	103.5
Feb.	31.4	4.6	94.2	5.7	55.5
Mar.	32.0	35.5	62.9	12.0	41.8
Apr.	14.0	15.6	7.7	8.5*	7.9*
May	5.1	5.6	-2.6		-2.6
June	-7.4	-6.2	-9.5		-9.5
July	-2.9	-3.2	-13.9		-13.9
Aug.	8.8	9.8	-6.2		-6.2
Sept.	33.9	31.7	29.3		29.3
Oct.	43.4	48.2	54.8		54.8
NOV.	50.3	55.9	104.2		104.2
Dec.	46.3	51.4	118.1		118.1
Annual	306.3	340.3	554.2		482.8

*Irrational results produced by erroneous data (ice temperature estimates). Since ice cover in April is light, the effect is not significant. This could be eliminated by using perimeter and overwater mass transfer coefficients (table 6) for the overice and overlake values, respectively.

insignificant increases in the overlake evaporation. This inconsistency could be eliminated by using the perimeter and overwater mass transfer coefficients, indicated in table 6, for the overice and overlake values, respectively.

Seasonal distribution of the mass transfer evaporation for the average, maximum, and minimum monthly values is shown in figure 8. During the high evaporation season of fall and winter, the average monthly losses from the lake normally exceed 100 mm in the November-January period. The highest monthly mass transfer evaporation in December indicates an average value of 118 mm and a maximum of 143 mm. During the low evaporation season of spring and summer, the evaporation process is normally reversed to condensation in the May-August period. The highest monthly condensation in July normally exceeds 10 mm, with an average value of 14 mm and a maximum of 24 mm. Condensation also frequently exceeds 10 mm in June.

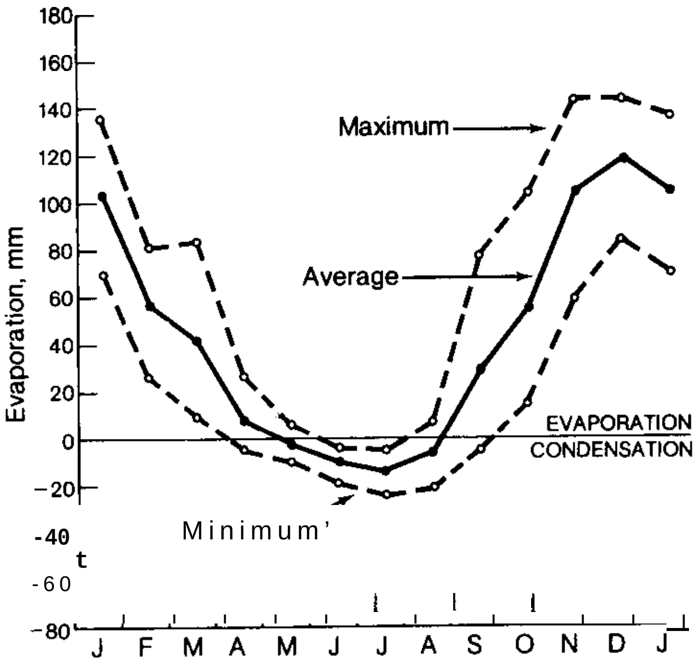

Figure 8.--Lake Superior evaporation by mass transfer method, 1942-75.

In comparison with the water budget evaporation (figure 3), the mass transfer determinations agree reasonably well in the average seasonal distribution and the extremes (maximum and minimum) of the high evaporation season. During the low evaporation season the mass transfer extremes indicate a greatly reduced range of variation in the monthly evaporation. Comparison of the average 1942-75 monthly Lake Superior evaporation values determined by the water budget and mass transfer methods is shown in figure 9. The figure also shows the ice-cover reduction of the mass transfer evaporation during winter. As indicated in the figure, the ice-cover adjustment produces much better agreement with the water budget evaporation. The major disagreement between the two determinations is an apparent lag of about a month between the water budget and mass transfer evaporation values during the increasing evaporation period, beginning in July. A similar lag was also obtained for Lake Erie (Derecki, 1976b) and was attributed to inaccuracies of data, particularly for the water surface temperature adjustments. In the present study, the water surface temperatures represent the weakest link of the mass transfer computations. Elimination of this weakness will be feasible when the satellite surface temperature observations become sufficiently accurate.

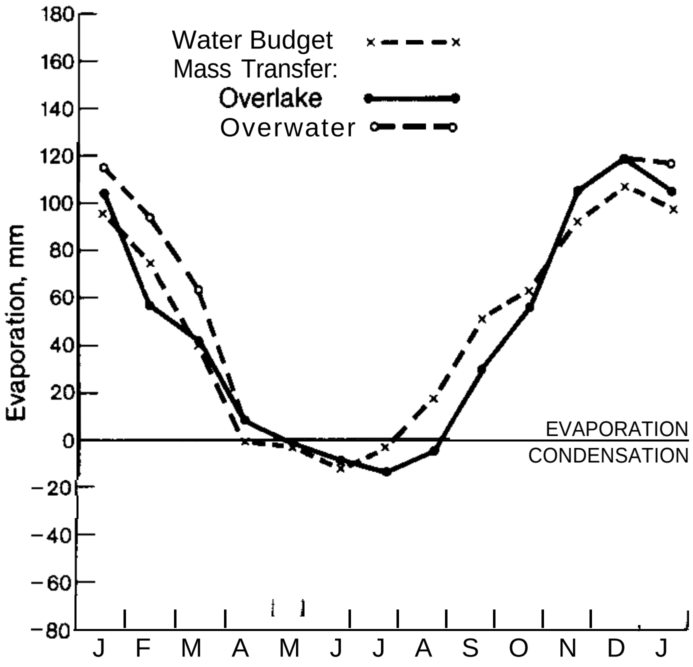

Figure ***9.--Comparison of average Lake Superior evaporation, 1942-75.***

The comparisons of average evaporation values for Lake Superior in table 16 show the evaluation of various mass transfer coefficients. The coefficients evaluated are the IFYGL coefficient (M) based on atmospheric stability equation (12), the approximate IFYGL coefficient (M_s) based on wind speed from equation (14), and the Lake Hefner coefficient or calibrated constant (0.097 for millimeters per millibar-meters per second). The water budget and mass transfer with coefficient (M) determinations represent the best long term evaporation estimates feasible at present from available data. Discussion and comparison of these estimates are given above. Evaporation estimates with the approximate mass transfer coefficient (MS) indicate a large reduction of evaporation during most months, reflecting the effects of neglecting air stability variations. The combined effects of reduced evaporation and increased condensation produced a 25 percent reduction in the annual evaporation. The overall effect, both monthly and annual, of the approximate coefficient produced evaporation results worse than those obtained with the Lake Hefner coefficient. Average evaporation estimates obtained with the Lake Hefner constant appear reasonable during the high evaporation season, but are inferior to those of the approximate coefficient during the low evaporation season. The use of the relatively high Lake Hefner constant coefficient produces unrealistically high condensation values, which results in a 13 percent reduction of the annual evaporation. Large reduction of the evaporation estimates obtained with the approximate Lake Ontario coefficient (MS) shows that this simplified procedure is not suitable for Lake Superior and probably the remaining Great Lakes.

The mass transfer relative sensitivity and error variance analysis determined by equations (2) and (3), respectively, for the annual values are given in table 17. The relative sensitivity and error variance analysis were also tested for the high and low evaporation values, both seasonal and monthly, with generally similar results. Computed evaporation is most sensitive to the dew point temperature and highly sensitive to the water surface temperature, while other parameters (wind speed, air temperature, and bulk evaporation coefficient) are relatively insensitive. However, the greatest potential error indicated by the error variance is due to the wind speed, followed by the much reduced influence of the water surface temperature, dew point temperature, and bulk evaporation coefficient. Air temperature is again unimportant. Similar results were obtained for Lake Ontario by Quinn (1979). Indicated standard errors for the meteorological data represent generally accepted limits of accuracy for the Great Lakes.

Table 16.--Comparison of average evaporation for Lake Superior, mm, 1942-75

Month	Water budget method	Mass transfer method IFYGL coef. (M)	IFYGL approx. (M_8)	Lake Hefner coef.
Jan.	96.5	103.5	81.0	96.1
Feb.	75.4	55.5	44.7	54.5
Mar.	40.6	41.8	36.0	43.9
Apr.	-1.3	7.9	8.6	11.1
May	-3.3	-2.6	-5.5	-8.0
June	-12.7	-9.5	-21.6	-30.6
July	-4.2	-13.9	-30.0	-42.4
Aug.	17.2	-6.2	-10.2	-14.6
Sept.	50.4	29.3	28.1	36.5
Oct.	62.3	54.8	49.0	62.7
Nov.	90.7	104.2	86.3	102.6
Dec.	105.8	118.1	93.0	110.2
Annual	517.4	482.8	360.3	422.0

Coefficients: IFYGL (M) adjusted for wind and stability.
IFYGL (M_8) adjusted for wind only.
Lake Hefner (0.097) calibrated constant.

Table 17.--Mass transfer sensitivity and error variance analysis, 1942-75

Parameter X	Sensitivity Ψ_{R_i}	Standard error SE	Error variance E[V(X)]
Wind speed	0.19	1.0 m/s	89.5
Water surface temperature	2.60	0.5°C	23.4
Dew point temperature	4.23	0.5°C	11.2
Air temperature	0.07	0.5°C	0.0
Bulk evaporation coefficient	0.73	10%($\bar{X}$)	9.5

4. SUMMARY AND CONCLUSIONS

Evaporation from Lake Superior was determined by the water budget and mass transfer methods for a 34-year period of study, 1942-75. Because of available data limitations, especially for the mass transfer computations, these determinations represent evaporation estimates, but the latest research results ware used to produce state-of-the-art estimates. Separate determinations by two independent methods permit cross-checking and verification of the estimates. The mass transfer computations employ individual monthly land to lake data adjustments and a variable mass transfer coefficient, both derived from atmospheric stability considerations, to provide realistic evaporation estimates. The perimeter data adjustments and mass transfer coefficient, for both open water and ice-covered lake surface conditions, are based on the Great Lakes relationships determined from extensive observations on Lake Ontario during IFYGL. In contrast to the other Great Lakes, all hydrologic components of the Lake Superior water budget are of the same order of magnitude, eliminating the possibility of large residual errors in computed evaporation.

Monthly and annual evaporation values determined by the two methods agree reasonably well, providing desired confirmation of computed results. Normal long term evaporation removes approximately 500 mm of water from the lake surface annually, but varies substantially from year to year, with annual extremes of 380 and 650 mm. The average annual difference between water budget and mass transfer evaporation is 7 percent, which is within normal limits of accuracy for the Great Lakes climatological data (about 10 percent). Winter ice cover on Lake Superior reduces the average annual evaporation by 70 mm, which represents 13 percent of the potential overwater value. Sandardization of mass transfer data (wind speed and vapor pressure difference) at the 8 m reference level produced a net increase of 11 percent in computed evaporation. The perimeter data adjustment due to different atmospheric stability conditions over land and lake surface areas increased overwater mass transfer evaporation by 39 percent and produced a net increase of 30 percent in the lake evaporation values. Approximate mass transfer methods tested in the study (simplified IFYGL and the Lake Hefner constant) produced inferior results and should not be used for the Great Lakes.

Distribution of monthly Lake Superior evaporation throughout the year indicates a high evaporation season during fall and winter, and a low evaporation season during spring and summer. The high winter evaporation from Lake Superior is caused by its great depth and related tremendous heat storage capacity, which requires a long dissipation period. During the peak high evaporation season monthly water losses frequently exceed 100 mm, with a maximum monthly evaporation of 150 mm in December. 'During the low evaporation season the evaporation process is frequently reversed to condensation (negative evaporation). Monthly condensation values during the peak condensation season frequently exceed 10 mm, with a maximum condensation approaching 50 mm in July. Employment of a variable mass transfer coefficient, based on air stability, eliminates unrealistically high normal monthly condensation values during the peak condensation season. Evaporation estimates with the simplified IFYGL coefficient and the Lake Hefner constant tested in this study produced an average monthly condensation of 30 and 40 mm, while previous Lake Superior mass transfer studies (Richards and Irbe, 1969) indicated average monthly condensation of 85 mm. Extensive Lake Superior ice cover during February and March, which normally extends to about 40 percent of the lake area, reduces the potential overwater evaporation during these months by a similar percentage. During January, the average ice-cover and evaporation reduction are much smaller (10 percent).

5. ACKNOWLEDGMENT

The author gratefully acknowledges the assistance of James P. Pistilli in the preparation of computer programs and conducting most of the computations.

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Appendix A. BASIC DATA

Table **B.--Adjusted Lake** *Superior* **overwater precipitation,** *mm.*

YE AR	JAN	PEB	MAR	APR	NAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
R	1.18	1.40	1.06	1.02	1.01	.92		.95	.85	.86	.98	1.03	
1942	37.7	25.1	61.8	46.3	99.3	49.8	68.0	88.1	92.5	74.6	66.5	50.6	760.5
1943	51.7	49.1	50.6	39.6	89.1	151.1	57.9	71.4	43.0	51.3	60.5	31.4	746.7
1944	29.0	55.5	62.4	37.5	95.2	134.1	104.0	103.R	66.1	24.3	75.7	51.8	839.3
1945	51.6	78.9	54.3	85.7	62.0	74.1	63.6	108.1	77.5	35.0	78.5	51.6	820.7
1946	76.1	63.8	29.5	37.5	74.3	93.7	32.5	63.5	75.7	89.6	62.9	60.1	759.1
1947	45.6	60.2	23.3	90.9	73.4	107.5	45.0	60.9	65.8	12.8	76.2	52.6	713.9
1948	70.4	50.5	51.7	96.1	23.2	58.4	81.0	63.1	31.3	35.7	99.8	65.4	726.6
1999	83.4	68.8	57.9	16.0	91.9	109.3	112.8	55.6	76.5	92.6	55.3	43.5	855.8
1950	113.3	55.9	62.3	76.9	101.0	92.5	74.5	66.6	46.6	59.4	101.6	63.4	914.0
1951	39.6	101.5	84.5	53.9	54.0	114.2	70.7	131.8	112.2	74.8	54.5	55.1	946.9
1952	59.6	27.1	53.3	33.0	54.1	112.8	129.2	89.7	31.7	17.6	56.6	32.7	702.5
1953	60.9	68.2	54.7	63.7	116.4	102.2	78.9	95.2	65.3	20.7	57.8	66.5	850.6
1954	75.5	51.6	54.9	107.5	101.5	34.3	33.4	49.4	86.9	61.1	34.9	20.2	752.2
1955	57.8	6 1% 4	78.2	47.6	71.4	54.7	97.4	91.1	76.0	83.4	72.3	66.5	858.1
1956	46.8	25.3	28.8	50.0	94.1	65.5	90.0	80.2	64.0	24.3	65.2	61.8	696.0
1957	45.8	49.1	30.7	53.1	66.3	94.3	66.2	47.3	88.3	33.3	88.2	43.5	704.4
1958	46.4	29.9	18.2	33.9	46.9	78.Q	81.2	101.7	73.3	42.7	R4.9	60.7	697.6
1959	44.3	30.1	31.6	33.1	114.9	54.4	64.5	130.1	109.2	84.1	51.3	39.8	797.3
1960	47.3	41.3	24.5	119.9	112.6	65.5	65.2	76.4	67.2	55.9	73.7	33.2	782.7
1961	25.5	49.0	56.6	54.8	80.6	52.4	54.6	41.8	102.7	49.7	59.2	57.8	684.6
1962	54.6	70.5	19.2	46.0	106.0	il.3	55.6	102.1	79.5	25.6	28.3	53.4	692.0
1963	43.7	42.3	36.0	57.9	58.7	93.4	48.9	68.3	51.5	22.7	59.6	51.6	626.7
1964	47.7	36.9	44.2	97.3	120.8	83.3	41.1	110.1	99.6	43.6	65.6	63.1	853.8
1965	49.1	76.7	50.8	42.R	99.0	68.0	79.0	90.5	130.6	46.5	92.6	56.7	882.4
1966	48.6	44.0	82.7	42.1	47.2	47.9	59.8	113.1	45.5	90.2	64.7	5i.6	741.2
1967	84.3	43.3	40.5	75.2	38.4	96.3	53.3	95.8	29.3	81.2	39.6	47.7	724.9
1968	39.0	52.3	49.0	80.5	75.9	124.1	113.9	77.4	96.4	85.5	38.9	92.8	935.6
1969	100.0	20.3	19.6	57.0	55.9	80.3	49.4	55.5	70.5	81.4	38.0	52.4	650.3
1970	60.0	31.9	31.2	69.2	149.0	50.7	109.3	39.8	98.4	110.0	76.2	61.7	887.3
1971	75.0	94.6	59.1	32.0	99.2	71.7	77.7	58.9	78.6	104.9	81.9	72.2	905.6
1972	101.0	69.1	65.2	42.5	55.5	58.0	106.5	128.0	88.0	37.2	55.9	69.0	875.9
1973	43.2	37.6	59.9	54.8	105.2	82.9	86.3	ii5.a	73.4	54.6	57.9	53.2	824.2
1974	64.0	49.9	31.0	67.6	76.8	98.2	66.7	119.1	68.4	49.8	71.2	37.2	790.1
1975	118.7	58.1	62.7	46.5	55.8	90.7	54.6	49.9	73.1	41.7	106.1	48.3	806.3
MEAN	59.9	52.1	48.0	58.9	81.3	83.1	72.R	83.4	74.5	55.8	66.2	53.7	789.9

Table 19.--*Runoff* **into Lake Superior, *mm.***

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUC	SEP	OCT	NOV	DEC	ANNUAL
1942	37.4	28.6	33.6	82.9	99.5	45.4	33.0	28.7	31.2	46.0	b1.9	39.0	567.4
1943	30.8	26.5	31.7	71.2	99.3	113.1	50.0	38.2	30.6	30.5	S2.3	27.5	591.8
1944	26.2	24.4	26.0	61.7	117.3	95.2	49.7	50.1	43.0	41.3	36.2	31.5	602.5
1945	30.2	25.5	71.1	109.5	59.7	59.9	43.1	32.6	31.3	30.6	56.1	36.7	586.2
1946	36.9	30.6	61.7	72.5	71.6	68.8	44.1	32.7	31.1	46.7	56.0	46.0	598.8
1947	37.5	32.6	36.1	75.6	142.1	136.6	50.6	33.6	31.7	29.5	25.9	25.1	657.0
1948	26.2	24.4	28.8	111.2	72.9	36.4	31.1	31.2	26.9	24.5	so.3	33.9	477.9
1949	28.9	26.4	31.7	75.4	98.8	44.9	52.4	30.7	28.0	36.4	37.7	31.8	523.0
1950	31.4	28.6	31.9	65.1	296.5	94.1	73.9	45.9	34.5	38.5	40.0	42.8	733.0
1951	37.9	34.8	46.0	130.9	124.2	64.9	47.3	36.6	50.4	65.6	66.5	52.3	757.5
1952	42.8	39.3	43.5	104.8	60.5	57.7	73.3	48.5	36.0	31.9	52.3	35.9	606.5
1953	33.4	28.8	48.3	77.4	108.6	98.9	66.9	49.4	32.9	30.1	3c.7	36.7	631.9
1954	34.4	34.8	40.6	106.9	142.5	79.6	42.5	35.0	30.8	41.3	38.0	34.9	*661.3*
1955	33.0	29.7	34.4	98.7	57.6	90.4	34.0	35.5	29.4	36.0	38.3	35.2	502.2
1956	34.1	30.3	29.0	73.7	85.4	49.9	4A.8	33.5	33.9	31.7	34.2	33.5	518.6
1957	31.2	27.4	34.2	92.5	71.6	48.5	55.7	32.5	33.2	33.1	42.2	37.9	539.6
1958	35.7	31.3	33.3	61.0	43.8	44.5	52.1	36.3	43.0	38.3	46.4	42.5	507.9
1959	37.9	34.7	37.7	61.8	87.8	49.6	37.9	34.0	50.5	71.2	55.1	38.8	596.9
1960	39.3	33.4	32.9	107.0	147.6	52.3	33.8	31.7	33.3	29.0	S8.1	34.9	613.4
1961	31.2	28.4	37.2	71.6	34.9	43.7	36.5	28.8	39.3	49.0	48.5	33.3	544.4
1962	35.4	31.4	37.5	59.3	88.1	48.6	30.9	34.2	35.5	33.7	34.6	32.2	501.2
1963	31.3	27.9	34.3	64.0	58.3	74.3	36.4	33.2	32.9	30.4	31.5	32.3	486.8
1964	31.5	30.5	35.0	79.4	116.5	75.2	56.1	k2.8	47.9	56.9	54.0	48.5	674.3
1965	42.0	37.5	43.6	89.1	107.1	55.4	35.8	35.7	41.5	64.3	49.2	48.9	650.2
1966	47.7	39.0	58.4	92.6	107.6	71.1	40.9	41.1	32.4	45.2	44.3	44.8	665.1
1967	40.3	37.9	43.2	105.7	90.4	63.3	36.9	35.3	31.2	37.9	39.1	39.8	592.1
1968	27.7	25.1	39.9	90.0	72.5	94.5	87.1	55.8	53.9	71.7	55.8	49.9	723.3
1969	46.0	42.1	47.5	125.4	101.5	60.2	48.5	36.4	31.5	40.7	J9.7	33.8	653.3
1970	36.5	29.7	31.9	71.5	112.9	70.5	43.2	30.9	36.5	53.8	70.0	55.2	642.5
1971	41.8	37.1	47.5	134.0	125.1	75.k	42.8	33.6	28.0	53.9	74.2	49.3	742.8
1972	3e.7	34.9	39.1	82.6	137.4	51.5	49.4	64.2	49.6	50.6	50.1	32.9	681.0
1973	30.9	25.5	63.1	82.1	100.4	50.7	42.0	42.8	37.5	48.7	91.9	35.0	600.5
1974	28.7	25.6	29.3	81.0	109.5	54.7	49.0	46.5	43.2	50.6	57.3	41.6	647.1
1975	40.1	33.0	35.7	84.6	109.5	61.4	37.8	24.9	28.4	28.8	42.2	48.1	574.9
WEAN	35.2	31.1	39.8	86.8	100.6	66.4	46.9	37.7	36.2	42.6	45.0	38.8	607.1

Table 20.--*Outflow from* **Lake** superior, *mm.*

YE AR	JAN	FEB	MAR	APR	RAY	JUN	JUL	AUC	SEP	OCT	NOV	DEC	ANNUAL
1842	16.2	55.5	54.5	79.2	51.5	12.2	84.6	12.9	70.8	53.4	so.2	54.1	79b.C
1943	55.1	53.6	58.9	12.3	83.3	97.7	113.0	111.0	111.1	105.0	88.1	59.2	1034.3
1944	52.2	50.3	53.5	52.4	55.2	54.1	14.0	92.0	91.4	105.5	90.7	15.4	855.0
1945	59.2	51.5	51.8	76.8	99.0	94.8	70.4	58.2	55.5	14.5	83.4	68.9	900.1
1946	58.3	51.3	55.9	50.2	10.6	68.4	70.5	59.3	68.1	72.5	68.8	10.4	815.1
1947	59.2	52.3	55.8	55.0	59.8	59.5	101.4	105.1	90.R	105.0	81.1	11.8	954.7
1948	59.5	54.3	58.0	55.1	51.9	51.4	59.5	58.3	51.9	54.2	52.2	52.8	725.5
1949	52.7	41.1	52.5	52.9	58.1	55.5	56.4	50.8	54.2	55.4	64.5	51.5	594.3
1950	57.9	55.2	61.1	58.9	53.1	93.1	114.3	116.6	111.6	114.5	108.2	103.5	1059.0
1951	15.1	55.5	73.2	93.1	112.0	109.1	113.9	112.8	110.3	114.0	101.1	94.6	1183.0
1952	11.4	70.9	74.5	12.1	98.3	70.0	61.6	IDS.0	104.4	105.3	95.5	59.0	1001.1
1953	51.9	59.9	64.9	53.2.	85.9	31.5	93.3	110.4	105.9	105.1	90.2	73.9	1019.2
1954	58.0	60.2	66.1	53.4	59.6	58.3	91.9	106.5	100.3	88.2	58.1	59.9	911.3
1955	56.7	51.2	56.4	53.1	55.6	66.7	54.2	50.7	35.4	45.9	74.4	10.8	103.2
1955	58.1	53.1	57.4	58.1	53.3	54.1	51.3	55.3	53.7	57.5	62.3	53.2	155.5
1951	51.1	54.9	52.9	50.7	41.1	43.0	49.1	59.2	59.6	61.5	59.1	60.0	555.1
1958	65.7	58.7	53.3	54.4	55.8	54.9	52.2	51.8	56.9	50.6	51.1	63.5	690.6
1959	51.0	55.4	59.9	62.4	54.4	51.1	51.8	74.2	67.0	103.1	104.8	81.8	845.0
1950	68.0	61.8	53.1	58.4	52.5	98.0	105.1	95.8	91.7	84.4	55.4	53.0	920.2
1951	51.5	35.6	65.1	59.0	52.2	51.5	60.2	52.5	51.2	53.8	51.9	59.8	695.8
1962	59.0	5412	58.8	55.1	55.1	53.2	58.1	55.7	50.3	58.8	61.0	59.5	519.7
1953	51.5	53.7	55.1	50.7	55.5	54.7	51.9	51.6	63.8	59.3	59.3	51.5	619.0
1954	54.4	58.1	62.8	60.2	54.2	63.9	14.3	92.2	95.0	102.1	103.3	85.3	915.3
1955	IR.I	10.2	16.3	73.5	86.3	88.1	104.2	104.8	95.0	94.2	90.5	18.4	1041.8
1955	11.1	63.1	71.2	12.4	13.5	70.4	8S.5	88.3	93.0	83.3	11.5	68.8	915.8
1951	55.7	59.5	55.4	53.6	78.1	80.5	83.2	84.8	77.6	55.1	64.1	64.0	851.8
1958	53.5	59.8	52.1	51.8	64.9	52.5	92.5	112.5	109.8	113.8	109.2	91.1	1009.1
1969	75.8	76.5	81.4	91.8	105.3	103.3	107.3	107.3	93.3	53.2	60.1	52.5	1035.8
1910	62.5	56.1	54.2	55.9	59.2	57.9	59.9	88.5	10.5	59.5	77.1	93.3	818.2
1911	85.3	69.0	11.3	84.9	99.5	101.0	105.0	91.4	95.9	104.1	93.8	91.3	1110.2
1872	74.5	62.9	59.1	56.8	102.1	103.4	105.0	104.1	102.5	102.2	103.4	79.2	1015.2
1973	69.1	41.4	48.8	49.0	50.5	49.9	73.1	89.3	105.2	85.8	14.9	73.5	822.2
1974	10.0	be.4	59.1	56.8	51.2	15.1	10.0	59.1		61.2	74.9	89.3	841.5
1975	79.8	11.1	19.2	82.4	90.2	79.1	17.3		65.9	51.2	61.0	54.3	895.7
ME AN	51.1	60.2	55.0	55.5	12.1	73.4	80.1	84.5	81.1	81.5	77.8	72.0	880.9

Table 21.--*Change* **in storage in** *Lake* **Superior,** *mm.*

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AU6	SEP	OCT	NOV	DEC	ANNUAL
1942	-82.0	-63.8	5.1	35.4	151.9	21.3	30.4	24.3	-24.3	21.3	-12.1	-82.0	33.5
1943	-54.7	-39.5	-24.3	39.5	148.9	192.3	-9.1	-9.1	-86.1	-82.0	-88.1	-124.5	-148.9
1944	-82.0	-12.9	-15.2	33.4	164.1	191.5	91.2	39.5	-18.3	-124.b	-69.9	-91.2	51.1
1945	-55.9	-21.3	65.9	103.3	9.1	42.5	42.5	51.7	-12.1	-65.9	-66.8	-12.9	9.1
1946	-48.6	-51.1	24.3	36.4	50.8	92.1	30.4	5.1	21.3	24.3	-60.8	-15.0	48.1
1941	-103.3	-54.1	-55.9	106.3	151.9	197.5	-12.2	-9.1	-21.4	-94.2	-91.2	-112.4	-115.6
1948	-82.0	-91.1	-12.2	170.1	18.2	27.4	54.1	45.5	-48.1	-59.9	0.0	-53.8	-51.1
	-45.5	-51.7	-39.5	51.1	118.5	106.3	121.6	-18.2	-30.4	18.2	-66.8	-82.0	68.1
1950	-27.3	-56.9	-21.3	85.1	219.6	109.3	45.5	0.0	-35.4	-21.3	-51.7	-109.4	119.2
1951	-91.2	6.1	3.0	119.5	12.9	12.9	-3.6	21.3	12.1	-18.2	-82.1	-15.0	42.4
1952	-53.8	-85.1	-35.5	97.2	6.1	112.5	142.8	21.3	-103.3	-116.3	-91.2	-85.1	-261.3
1953	-55.9	-39.5	-12.2	66.8	151.1	124.5	51.1	21.2.	-82.1	-118.5	-88.1	-15.0	-51.8
1954	-79.9	-33.4	-51.1	133.1	119.3	121.6	-12.2	-51.7	-45.5	-53.8	-51.1	-103.3	-63.8
1955	-15.0	-51.7	-3.0	121.5	65.9	35.4	48.6	42.5	3.0	24.3	-48.7	-89.1	15.9
1955	-59.9	-31.1	-19.0	39.5	135.1	12.9	91.2	18.2	-24.3	-12.9	-50.8	-53.8	-91.3
1951	-115.5	-27.4	-3.1	112.5	95.1	112.5	51.1	-12.2	-3.0	-55.9	-12.1	-79.0	42.5
1958	-53.3	-63.8	-45.5	43.1	21.3	103.3	94.2	42.5	24.3	-42.5	-21.3	-88.1	9.1
1959	-19.0	-4215	-30.4	33.5	151.1	59.9	33.4	133.1	60.8	-39.5	-121.6	-94.2	85.1
1950	-50.8	-82.0	-51.1	157.1	113.2	21.3	3.0	-15.2	-53.8	-65.9	-18.3	-121.5	-121.6
1951	-75.0	-21.3	3.0	51.1	94.2	48.7	21.3	-5.1	30.4	-12.2	-54.7	-56.9	12.2
1952	-94.2	-21.4	-24.3	35.4	148.9	39.5	30.4	57.7	6.1	-53.8	-88.1	-82.0	-50.9
1953	-55.9	-48.5	33.4	72.8	48.5	139.1	15.2	30.4	-15.1	-39.5	-69.9	-91.2	9.1
1954	-42.5	-82L0	-51.1	130.5	185.4	105.3	12.2	36.5	48.1	-1DD.3	-63.8	-82.0	31.2
1955	-100.3	-5lcl	-21.3	66.8	148.9	42.5	9.1	12.2	30.4	-24.3	-12.1	-48.5	45.5
1966	-16.0	-51.1	21.3	48.1	103.4	49.1	18.2	48.5	-59.9	-18.2	-63.8	-46.5	-33.3
1961	-54.1	-54.1	-12.2	135.1	35.5	103.3	3.0	21.3	-15.9	0.0	-65.8	-13.0	-42.5
1968	-05.1	-16.0	24.3	139.1	12.9	188.4	155.0	15.2	45.5	-18.2	-133.1	-50.8	251.3
1969	-12.2	-66.9	-75.0	91.2	52.1	21.4	-5.1	-3.0	-95.1	-33.4	-63.8	-85.1	-258.3
1970	-42.5	-69.9	-35.5	97.2	188.4	82.1	103.3	-45.5	12.1	51.1	-19.3	-91.2	230.9
1811	-97.2	5.1	-5.1	53.8	121.5	60.8	5.1	-21.8	-36.4	-9.1	-51.7	-91.2	-48.6
1912	-60.8	-30.4	12.2	51.1	109.4	5.1	51.1	35.1	-9.1	-103.3	-59.9	-88.1	-39.5
1913	-53.8	-54.1	50.8	51.1	151.9	100.3	51.7	50.8	-12.9	-48.5	-79.0	-85.1	79.1
1914	-51.7	-66.9	-50.8	103.5	100.3	112.5	55.9	53.8	-15.1	-30.4	-24.3	-88.1	103.3
1915	-45.5	-45.6	-55.9	12.1	19.0	94.2	21.3	-48.5	-15.1	-51.1	30.4	-119.5	-155.0
MEAN	-58.5	-52.5	-17.8	81.6	112.4	88.8	43.9	19.4	-20.8	-45.4	-57.2	-85.4	-1.4

Table 22.--Measurement heights of meteorological instruments

Station	Parameter	Period	Height ft	 m
Saulte Ste. Marie, Mich.	Wind speed	Jan. 1942-May 1949	43	13.1
		Jun. 1949-Nov. 1962	33	10.1
		Dec. 1962-Sep. 1966	40	12.2
		Oct. 1966-Dec. 1975	20	6.1
	vapor pressure (humidity and air temperature)	Jan. 1942-Nov. 1948	11	3.4
		Dec. 1948-Dec. 1975	6	1.8
Duluth, Minn.	Wind speed	Jan. 1942-Feb. 1950	52	15.8
		Mar. 1950-Jun. 1961	53	16.2
		Jul. 1961-Dec. 1975	21	6.4
	Vapor pressure	Jan. 1942-Jan. 1944	5	1.5
		Feb. 1944-Feb. 1950	4	1.2
		Mar. 1950-Dec. 1975	7	2.1
Thunder Bay, Ont.	Wind speed	Jan. 1942-May 1943	85	25.9
		Jun. 1943-Dec. 1955	80	24.4
		Jan. 1956-Feb. 1958	45	13.7
		Mar. 1958-Sep. 1965	37	11.3
		Oct. 1965-Dec. 1975	33	10.1
	Vapor pressure	Jan. 1942-Dec. 1975	4	1.2

Table 23.--Average Lake Superior perimeter wind speed at 8 m, m/s.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1942	3.05	4.00	3.31	4.15	4.53	3.51	4.15	4.01	4.12	4.40	4.95	4.93	4.50
1943	4.78	3.43	3.39	5.21	4.12	4.03	3.42	3.15	4.49	4.49	4.88	5.29	4.55
1944	4.59	4.38	4.80	4.59	4.26	4.40	3.93	4.03	3.92	4.41	4.41	4.70	4.41
1945	4.32		4.52	3.30	4.58	4.01	3.71	3.88	4.29	4.50	5.04	4.12	4.45
1946	4.45	4.53	4.48	4.91	4.38	4.00	3.15	4.03	3.95	4.35	5.16	5.13	4.46
1941	5.52	5.53	4.80	4.93	4.11	3.94	3.59	3.13	4.33	3.92	4.30	4.51	4.52
1940	4.30	4.89	4.49	3.02	4.52	4.03	4.11	3.30	3.52	4.22	4.44	4.10	4.34
1949	4.94	4.21	4.83	4.42	4.3A	3.11	4.31	3.35	4.15	4.80	5.32	5.31	4.35
1930	3.56	4.53	5.03	3.03	4.38	4.24	3.13	3.38	3.71	3.81	4.31	4.15	4.30
1931	3.39	3.88	4.92	4.64	4.40	3.57	3.81	3.51	4.26	4.29	4.38	4.37	4.13
1952	4.30	3.99	4.05	4.29	4.23	4.36	4.03	3.41	3.19	5.08	4.92	4.13	4.22
1933	3.39	4.24	4.81	3.44	4.88	4.33	3.81	3.43	4.29	3.71	4.11	4.55	4.31
1954	4.51	4.29	3.09	3.38	4.88	4.01	3.52	3.45	4.16	4.03	4.21	3.39	4.25
1935	3.93	4.23	5.05	4.80	4.10	3.11	3.10	3.64	4.52	4.49	3.15	4.64	4.40
1955	3.63	4.35	4.45	5.27	3.01	4.15	3.81	3.82	3.83	4.93	5.08	4.69	4.42
1951	4.19	4.40	4.12	4.85	5.18	4.50	3.90	3.81	3.92	3.91	3.12	4.70	4.43
1938	3.80	4.98	3.58	5.28	4.81	4.40	3.84	3.93	4.30	4.50	3.37	4.55	4.45
1959	4.18	4.50	4.24	4.15	5.41	4.28	4.01	3.54	4.42	4.64	4.97	4.82	4.54
1950	4.41	4.31	4.14	3.32	4.41	4.08	3.85	3.11	3.91	4.45	5.21	4.11	4.39
1951	4.19	4.19	3.00	4.84	4.93	4.10	3.41	3.31	4.03	4.01	4.03	4.15	4.19
1952	3.02	4.29	3.85	4.65	4.25	3.56	3.59	3.11	3.98	4.07	4.13	4.10	4.15
1953	4.24	4.20	4.21	4.50	4.25	3.14	3.58	3.31	3.31	3.60	4.59	4.53	4.05
1954	4.93	4.35	4.51	5.14	3.04	4.15	3.54	4.40	4.11	3.98	4.34	3.92	4.41
1953	4.15	4.31	3.13	4.07	4.31	4.14	3.90	3.33	3.91	4.54	4.15	4.43	4.25
1955	4.35	4.20	5.13	4.15	4.93	4.01	3.85	3.15	3.89	4.11	4.34	4.14	4.36
1957	4.18	4.11	4.30	4.13	4.61	3.19	3.44	3.43	3.51	4.54	4.11	4.48	4.11
1968	4.03	3.01	4.35	4.91	4.45	4.01	4.11	3.15	3.84	4.04	4.25	4.39	4.29
1969	4.15	3.51	4.11	4.21	4.55	4.21	3.33	4.03	3.88	4.21	4.03	3.95	4.10
1970	3.91	4.40	4.09	4.86	4.92	4.05	3.15	3.55	4.23	4.23	4.15	4.04	4.19
1911	4.78	4.49	4.28	4.55	4.30	3.39	3.44	3.08	3.23	3.93	4.11	3.92	3.97
1912	4.95	3.91	4.22	4.00	3.51	3.10	3.23	3.12	3.83	4.25	3.42	3.91	3.85
1913	4.03	3.18	3.91	4.66	4.22	3.15	3.43	2.98	3.11	4.00	4.51	3.85	3.91
1974	4.04	3.65	4.51	4.38	4.33	3.90	3.10	3.54	3.10	3.96	4.54	4.04	4.04
1975	4.68	4.13	4.80	4.65	4.00	3.89	3.90	3.12	3.12	4.23	4.25	3.11	4.13
MEAN	4.51	4.39	4.52	4.82	4.58	4.01	3.14	3.53	4.00	4.28	4.38	4.41	4.29

Table 24.--Average Lake Superior perimeter air temperature, °C.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1942	-9.6	-9.9	-1.3	6.3	8.9	14.3	lb.9	i7.e	11.5	1.0	-1.8	-11.2	4.0
1943	-14.5	-10.1	-8.9	1.9	9.1	14.3	19.1	11.3	11.1	1.0	-2.1	-8.8	2.9
1944	-3.7	-10.4	-5.1	2.1	11.1	14.5	18.0	11.9	12.9	1.1	1.1	-8.9	4.4
1945	-14.3	-9.9	.b	2.5	6.9	13.4	lb.8	11.9	11.9	3.7	-1.9	-10.1	3.2
1946	-11.2	-12.1	1.0	4.0	8.2	13.9	11.1	15.7	12.3	1.5	-1.1	-9.5	3.9
1941	-9.9	-11.3	-4.8	1.0	1.2	12.8	18.5	19.4	12.6	10.9	-3.0	-8.8	3.7
1948	-14.5	-12.2	-5.0	4.0	9.5	14.6	18.1	13.4	15.4	7.5	1.0	-7.6	4.0
1949	-9.9	-11.3	-3.4	5.3	9.5	lb.2	18.3	18.5	11.5	8.1	-1.1	-8.4	4.3
1930	-14.5	-10.1	-8.2	-1.3	8.1	13.5	15.3	14.3	12.4	7.8	-3.6	-11.1	1.9
1951	-13.1	-10.2	-5.0	3.4	11.2	13.5	17.4	14.8	10.9	5.1	-4.8	-10.5	2.1
1932	-12.0	-1.2	-5.4	5.9	9.5	14.9	18.2	15.5	13.2	4.G	-.4	-4.3	4.4
1933	-10.1	-9.3	-3.3	2.4	9.4	14.4	11.5	19.5	12.2	8.8	1.1	-1.4	4.6
1954	-14.5	-4.9	-5.0	2.1	5.5	13.2	11.3	15.8	11.7	5.9	1.0	-1.1	3.7
1933	-11.3	-11.1	-8.2	6.5	10.8	15.3	20.5	19.1	12.4	1.5	-3.4	-11.1	4.1
1955	-10.1	-10.1	-5.8	1.2	1.3	15.7	15.1	15.1	10.0	8.9	-1.3	-9.1	3.2
1951	-15.3	-10.6	-4.8	3.1	9.3	13.5	18.2	11.1	11.5	5.6	-1.0	-1.0	3.3
1958	-9.3	-12.1	-1.5	4.5	8.4	12.3	lb.5	15.8	12.8	1.3	-.5		3.4
1959	-13.1	-13.2	-4.5	2.5	10.0	15.5	18.1	19.5	13.3	4.8	-6.1 5	-13.9 -4.9	3.3
1960	-10.5	-9.9	-8.2	3.1	1C.3	14.3	11.5	11.9	12.1	5.9	.5	-10.1	3.7
1951	-13.5	-7.1	-2.5	2.4	9.0	14.8	18.1	18.3	13.3	1.4	-.b	-9.1	4.1
1962	-15.1	-14.2	-3.5	1.8	10.4	14.0	15.3	lb.5	11.1	1.6	.6	-9.4	3.0
1953	-15.5	-14.7	-5.0	3.9	8.5	15.5	18.8	15.3	12.9	12.0	2.1	-11.7	3.5
1954	-8.2	-9.3	-5.9	3.0	11.3	13.9	19.1	15.0	11.2	5.0	-.6	-11.8	3.5
1955	-14.2	-13.9	-1.1	2.4	10.4	14.1	15.1	13.5	9.7	5.4	-1.1	-5.2	2.6
1955	-15.1	-10.1	-2.9	2.1	7.5	15.1	19.1	lb.5	12.6	5.1	-3.3	-9.8	3.2
1951	-11.5	-15.0	-3.3	2.2	5.1	14.9	16.9	13.9	12.8	3.1	-3.0	-1.6	2.6
1968	-12.9	-12.1	-1.9	4.4	8.8	13.8	17.0	13.8	14.0	7.8	-1.3	-10.0	3.5
1959	-12.1	-9.1	-5.1	4.1	8.8	11.3	11.4	19.4	12.9	4.1	-1.4	-8.0	3.3
1910	-13.2	-13.7	-6.6	3.2	7.9	13.1	19.3	19.2	12.5	7.3	-1.4	-9.7	3.1
1911	-13.9	-11.3	-5.3	2.6	8.5	13.1	lb.2	15.8	13.7	9.4	-1.3	-8.5	3.2
1912	-13.5	-14.0	-8.1	.8	11.8	14.2	lb.5	15.3	10.3	4.3	-2.1	-11.9	1.9
1973	-9.8	-10.8	.3	3.5	8.4	14.6	11.5	19.8	11.9	8.9	-1.2	-3.9	4.4
1914	-13.3	-13.1	-6.6	2.8	7.1	14.8	18.1	lb.5	9.1	3.4	-1.0	-6.2	2.9
1913	-11.1	-10.0	-5.9	.2	12.3	15.1	19.5	11.0	10.5	7.5	.1	-9.9	3.7
MEAN	-12.5	-11.1	-5.0	3.0	9.1	14.4	11.8	11.1	12.1	1.1	-1.3	-9.1	3.5

Table *25.--Average Lake Superior perimeter humidity, percent.*

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	OEC	ANNUAL	
1942	83	83	19	10	75	78	77	80	82	80	77	83	79	
1943	82	81	71	68	12	82	78	81	81	77	84	81	79	
1944	85	82	63	66	75	19	80	80	88	79	87	87	81	
1945	86	87	19	75	68	74	19	19	83	79	86	89	80	
1946	a9	88	71	12	68	75	14	11	81	80	83	89	79	
1947	85	85	81	77	71	16	77	81	82	79	89	90	81	
1948	86	85	84	77	63	73	76	79	18	79	86	85	19	
1949	81	11	75	66	70	74	11	78	79	19	81	81	16	
1950	80	17	78	76	71	73	80	78	81	82	82	81	78	
1951	19	62	78	15	67	76	75	83	84	83	78	80	78	
1352	80	78	19	67	71	75	79	82	83	13	82	83	77	
1953	81	80	80	72	67	19	16	78	80	78	80	82	78	
1954	78	80	73	73	71	76	15	18	85	80	a1	79	78	
		11	75	70	66	74	15	77	17	78	83	78	75	
	81	17	14	68	58	72	16	81	82	76	84	84	7	7
1957	16	80	11	74	62	15	75	74	19	77	82	80	76	
1958	80	75	76	62	64	71	78	15	81	79	BO	80	15	
1959	76	75	75	68	13	72	74	82	80	81	17	81	76	
1960	81	75	70	73	69	71	12	17	80	71	78	13	15	
1961	72	80	78	69	63	68	77	14	78	15	17	80	74	
1962	13	11	16	71	72	12	73	17	78	77	11	76	15	
1963	13	71	12	68	69	76	74	11	80	75	19	80	74	
1964	81	75	12	12	55	73	71	79	80	74	80	80	15	
1965	76	13	74	12	b9	70	15	79	83	15	81	84	16	
1966	74	73	15	71	63	72	70	81	16	75	11	75	13	
1967	14	64	69	68	51	13	75	76	75	75	76	76	12	
1968	12	66	70	69	59	17	16	19	82	81	11	17	75	
1969	77	13	68	69	65	12	71	10	16	78	76	11	13	
1970	68	66	67	67	58	68	71	71	1.3	80	19	16	12	
1971	10	74	73	66	62	69	69	75	80	81	79	79	73	
1972	71	69	68	64	51	68	15	78	80	77	84	71	73	
1973	78	72	15	64	69	11	16	80	78	79	80	71	15	
1974	14	68	70	69	67	70	74	81	19	73	82	82	74	
1975	74	71	65	64	59	80	76	76	11	71	15	73	73	
MEAN	18	76	15	70	68	74	75	78	80	78	81	80	76	

Table 26.--Adjusted Lake Superior water surface temperature, “C.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AOJ	.1	-.2	-.6	-1.3	'2.8	-4.1	-5.0	-2.3	-1.1	-.9	-.5	0.0	
1942	.9	0.0	0.0	1.0	2.1	5.9	1.1	12.3	11.4	9.5	5.8	1.9	4.9
1943	.5	.1	0.0	0.0	2.1	4.0	8.8	12.5	10.7	8.7	5.4	2.1	4.6
1944	.9	.3	0.0	.0	1.7	4.5	1.9	12.1	13.1	9.1	6.1	2.1	4.8
1945	.5	.1	0.0	.4	1.8	4.4	7.9	12.6	12.0	8.8	5.3	1.6	4.6
1946	.4	.1	.1	1.1	2.1	4.5	8.3	11.8	11.3	9.0	6.1	2.0	4.3
1941	.4	.1	0.0	0.0	.1	3.3	1.1	12.2	11.7	9.1	5.4	1.9	4.4
1948	.4	.1	0.0	.4	2.1	5.4	8.5	12.4	13.9	9.9	6.6	2.5	5.2
1949	.7	.1	0.0	.2	2.1	6.2	6.7	lJ.0	11.1	9.1	6.0	1.8	4.8
1958	.2	0.0	0.0	0.0	.2	2.9	6.4	10.1	9.1	e.4	5.1	2.3	3.8
1951	.4	.1	0.0	.0	1.9	5.3	7.0	11.0	10.5	1.4	3.6	2.1	4.1
1952	.5	.1	0.0	.1	2.3	5.1	1.1	11.5	10.3	1.0	5.1	3.1	4.4
1953	1.3	.2	0.0	.1	1.1	4.6	8.4	13.2	13.5	10.4	7.3	3.6	5.4
1954	.8	.l	0.0	0.0	1.3	4.1	7.9	12.7	11.4	a.7	5.2	2.1	4.5
1955	.5	.1	0.0	.6	2.8	6.5	10.4	14.5	12.6	8.9	5.5	1.8	5.4
1956	.6	.2	0.0	0.0	1.3	4.1	6.5	11.7	10.1	8.6	5.1	2.0	4.3
1957	.2	.1	0.0	.3	2.1	5.0	9.0	12.6	12.2	9.4	5.2	1.6	4.6
1958	.4	.1	0.0	.1	1.4	4.4	6.8	11.5	11.1	8.1	5.6	1.3	4.3
1959	.5	.1	0.0	0.0	2.6	6.0	9.0	13.5	12.2	9.6	3.8	1.1	4.9
1960	.4	0.0	0.0	0.0	1.2	4.7	7.9	12.0	12.8	9.0	5.8	1.5	4.6
1961	.2	0.0	0.0	0.0	1.2	5.3	1.9	13.6	14.0	9.1	5.8	2.4	5.0
1962	.6	0.0	0.0	0.0	1.0	4.1	8.4	11.9	12.1	9.9	5.6	1.8	4.7
1963	.5	.2	0.0	0.0	1.6	4.6	9.9	12.6	11.5	11.2	8.0	3.0	5.3
1964	1.0	.1	0.0	.1	2.6	5.1	V.3	11.9	11.5	8.3	5.9	2.0	4.8
1965	.8	.2	3.0	0.0	1.3	4.3	1.3	11.9	11.0	8.0	5.2	2.1	4.4
1966	.6	.2	.4	.4	1.7	5.0	10.0	13.0	13.1	8.9	4.3	1.1	5.0
1967	.8	.1	0.0	.3	1.6	3.8	7.6	12.4	12.9	8.6	4.9	2.3	4.6
1968	.6	.3	.1	.8	2.3	4.3	6.1	11.1	13.0	10.4	6.4	2.6	4.9
1969	.7	.2	0.0	.2	1.5	3.8	1.6	13.4	14.7	9.7	6.1	2.6	5.0
1910	1.0	.4	.2	.0	.8	4.4	8.1	12.1	13.B	10.1	6.3	2.6	5.1
1971	.7	.2	0.0	.4	2.0	4.8	7.5	13.1	13.9	10.6	6.8	2.9	5.2
1912	.8	.1	0.0	0.0	.1	3.3	1.3	11.3	11.7	7.4	4.9	1.5	4.1
1913	.6	.1	.3	1.6	2.8	4.2	7.B	14.0	13.2	10.0	5.8	2.5	5.2
1914	.5	.2	0.0	.1	1.1	4.1	9.2	12.5	11.3	7.6	4.3	2.9	4.5
1975	1.4	.2	0.0	0.0	1.8	6.0	8.8	13.3	12.1	9.0	6.6	2.9	5.2
MEAN	.6	.1	.0	.3	1.1	4.1	8.1	12.4	12.1	9.1	5.1	2.2	4.1

Appendix B. SYMBOLS

C_E = bulk evaporation coefficient

C_H = bulk sensible heat coefficient

C_{0-5} = polynomial coefficients (fifth order)

E = lake evaporation

E_i = overice evaporation

E_l = perimeter evaporation

E_m = perimeter evaporation (unadjusted for standard height)

E_w = overwater evaporation

$E[V(X)]$ = expected error due to variance of function X

e_a = vapor pressure of the air (overlake)

e_s = saturation vapor pressure (overlake)

H = relative humidity (perimeter)

IC = ice cover

K = von Kármán's coefficient

L = Monin-Obukhov stability length

M = mass transfer coefficient (overlake)

M_i = overice mass transfer coefficient

M_l = perimeter mass transfer coefficient

M_w = overwater mass transfer coefficient

M_8 = approximate mass transfer coefficient based on variation with wind speed

O = lake outflow

P = overwater precipitation

p = atmospheric pressure

R = runoff from drainage basin

R_i = overice/perimeter wind ratio

R_p = lake/land precipitation ratio

R_u = lake/land wind ratio

R_w = overwater/perimeter wind ratio

s = air stability index $(T_{al} - T_w)$

SE = standard error

T_a = air temperature (overlake)

T_{ai} = air temperature (overice)

T_{al} = air temperature (perimeter)

T_{aw} = air temperature (overwater)

T_d = dew point temperature (overlake)

T_{di} = dew point temperature (overice)

T_{dl} = dew point temperature (perimeter)

T_{dw} = dew point temperature (overwater)

T_i = ice surface temperature

T_m = water intake temperature

T_s = lake surface temperature

T_w = water surface temperature

T_{1-12} = perimeter air temperature for consecutive calendar months

U = wind speed (overlake)

U_i = overice wind speed

"1 = perimeter wind speed

U_w = overwater wind speed

U_8 = wind speed at 8 m

U_* = friction velocity (τ/ρ)

$Var(X_i)$ = variance of X (standard error of X squared)

X = value of independent parameter, also overlake parameter value

X_i = overice parameter value

X_m = parameter value unadjusted for standard height

X_{max} = maximum value of independent parameter

X_{min} = minimum value of independent parameter

X_w = overwater parameter value

X_8 = parameter value (at 8 m)

$\bar{X}$ = mean value of parameter X

Z = reference height

Z_m = measurement height (unadjusted for standard height)

Z_o = roughness length (height)

Z_8 = reference height (at 8 m)

AE = evaporation increment

AS = change in storage

ΔT_a = land - lake air temperature difference $(T_{al} - T_a)$

ΔT_{ai} = perimeter - overice air temperature difference $(T_{al} - T_{ai})$

ΔT_{aw} = perimeter - overwater air temperature difference $(T_{al} - T_{aw})$

ΔT_d = land - lake dew point temperature difference $(T_{dl} - T_d)$

ΔT_{di} = perimeter - overice dew point temperature difference $(T_{dl} - T_{di})$

ΔT_{dw} = perimeter - overwater dew point temperature difference $(T_{dl} - T_{dw})$

ΔT_w = intake - surface water temperature difference $(T_m - T_w)$

ΔX_i = unit change in independent parameter

P = air density

Σ = summation

τ = surface shear stress

Ψ = stability function for sensible heat

Ψ_{R_i} = relative sensitivity.