Canada Centre for Inland Waters
Department of the Environment
Government of Canada

Effects of Waste Heat Inputs on the Water Budgets of the Great Lakes

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Niagara Falls, Ontario

ACRES

ERRATA

Report on

"Effects of Waste Heat Inputs on the Water Budgets of the Great Lakes".

Page 2 - Paragraph 2, line 19 - T. G. Asbury should read J. G. Asbury.

Page 13 - Paragraph 2, line 5 - Plate 7 should read Plate 8.

Page D-1 - line 1 - $\frac{K_E}{K} = Q_{WH}$ should read $\frac{K_E}{K} \times Q_{WH}$.

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ABSTRACT

Monthly heat transfer coefficients were calculated for each of the Great Lakes, including Georgian Bay, by means of a steady-state model. Overlake meteorological data gathered during IFYGL provided information on lake modification of atmospheric parameters. Using updated predictions of the waste heat inputs to the Great Lakes in the year 2000 A.D., evaporative losses due to once-through cooling were estimated at 1 per cent of the mean flow down the St. Lawrence River. The use of wet cooling towers is expected to increase the losses by 40 per cent. An estimated 17 per cent of the evaporative losses from either system is expected to be recovered within the basin as precipitation.

SUMMARY AND CONCLUSIONS

Over a long period, man-made additions of heat to the Great Lakes will result in an equal outflow of heat from the lakes to their environment. This permits the calculation of increased evaporative water loss due to waste heat loadings on each of the lakes by use of a steady-state model in which the heat transfer coefficient is the sum of the following components:

(a) Conduction of heat to the lake bed;
(b) Heat content of precipitation falling on the lake;
(c) Heat advection by inflow and outflow of water;
(d) Incoming short-wave solar radiation;
(e) Long-wave back radiation from lake;
(f) Heat transfer by evaporation or condensation;
(g) Conduction of heat to or from the atmosphere.

Heat transfer as a result of conduction of heat to the lake bed is considered to be insignificant in determining the long-term average temperature. Similarly, the heat content of precipitation has been excluded, since it is independent of lake temperature. Both short- and long-wave radiation components, (d) and (e), can be indirectly altered by the potential effects of small increases in heat flux and water vapor flux from the lake. This feedback is particularly likely when conditions are conducive to cloud formation over the lake. Using overlake radiation data obtained during IFYGL, it was found that an increase in lake temperature can decrease the incoming solar radiation, thereby reducing the lake temperature and, in turn, tending to decrease the evaporated losses. However, this feedback is small relative to the remaining terms (c), (e), (f) and (g).

The lake exerts a marked modifying influence on stability of the air and wind speeds, thus modifying the local sensible and latent heat transfer coefficients. As a result of the intensive data gathering program carried out under IFYGL, a better definition of the nature and extent of atmospheric modification by Lake Ontario has been possible, resulting in monthly heat exchange coefficients for each of the Great Lakes, including Georgian Bay.

Using updated thermal electric power predictions for the year 2000, an evaporative water loss of 2,320 cfs is predicted. This represents a reduction of 1 per cent in the total flow down the St. Lawrence River as a result of using once-through cooling systems on all thermal electric generating stations in the Great Lakes Basin.

If wet cooling towers are installed, the evaporative water losses to the Great Lakes are expected to amount to approximately 2,800 - 3,200 cfs, a 40 per cent increase over the losses due to once-through cooling systems.

An estimated 17 per cent of the losses from either system is expected to be recovered within the Great Lakes Basin as a result of precipitation.

Evaporative loss is directly dependent on the ratio of evaporative heat transfer coefficient (K_E) to the total heat transfer coefficient (K). In a previous study, Acres (1970), heat transfer coefficients determined for Lake Ontario were used as estimates for the entire Great Lakes Basin. From the results of the present study, it appears that the use of Lake Ontario (a relatively cold lake, having a ratio of K_E/K of .4674) leads to an underestimate of the losses.

Through the use of IFYGL data and individual treatment of the Great Lakes, a more reliable estimate of the evaporative losses, due to once-through cooling systems, has been possible.

However, the estimate of evaporative losses due to wet cooling towers is not entirely satisfactory, due to limited documentation. Further work concerning the spatial variation of evaporation rates within the Great Lakes Basin may be justified in order to provide a more valid assessment of the effects of once-through cooling systems as compared to wet cooling towers.

1 - DATA COLLECTION AND TREATMENT

As part of the International Field Year for the Great Lakes (IFYGL), the Canada Centre for Inland Waters (CCIW) maintained a meteorological buoy system on Lake Ontario for the period April to December 1972. This system consisted of eleven buoys monitoring wind velocity, air temperature, vapor pressure, water temperature, solar radiation and air pressure. The location of each of the buoys, as well as the "Thiessen" polygons used to obtain lake-wide daily averages of the various parameters are indicated on Plate 1. Instrumentation and error analysis has been discussed by Elder and Brady[1] in Environment Canada's Technical Bulletin No. 71.

Monthly climatic data necessary in calculating heat transfer coefficients are presented on Plates 2, 4 and 5.

Monthly water surface temperatures for each of the Great Lakes are based on the Atmospheric Environment Services (AES) ART surveys.[2] When these were insufficient to calculate reliable monthly averages, data presented in the papers by Richards and Irbe, 1969[3], Jones and Meredith, 1972[4], and Webb, 1972[5], were employed.

Average overland air temperatures for Lake Ontario were obtained using seven stations around the lake. From airborne data[6] obtained at Wesleyville, Ontario, it appeared that land stations may be defined as lying at least 5 miles from shore, while stations lying within 1 mile of the lake are defined as shore stations. By necessity, two of the stations (Kingston and Oswego E.) were shore stations, while the remaining five stations (Rochester, Buffalo, Hamilton, Toronto and Trenton) were considered to be land stations. To be consistent, monthly overland air temperatures for the other Great Lakes were obtained using data from stations presenting the same five and two distribution. Station locations are presented on Plate 3, with average monthly overland air temperatures based on 30-year climatic normals presented on Plate 4.

Overlake to overland wind ratios were calculated using the string of buoys lying between Toronto and the Niagara River. These have been compared in Table 1 with the ratios determind by Richards, Dragert and McIntyre.[9] Although the results of the present study are consistently less than those of Richards et al (possibly due to the relatively short mean fetch of 17 miles for the buoy stations used in this calculation), the trends are similar. In order to determine the effects of fetch on overlake winds, the wind ratio (R) was plotted against fetch for those days on which the wind was aligned with the axes of the lake (see Plate 6). Although there have been suggestions that the winds synthesized by Richards and Phillips[7] may underestimate the overlake conditions, in the case of Lake Ontario the results of the present study tends to substantiate their calculations. Therefore, the monthly overwater winds presented on Plate 5 are based on Richards and Phillips work, with the Lake Michigan data having been obtained from a 1970 report by T. G. Asbury.[8]

Tabulated monthly values of overland air temperatures, water surface temperatures, and overwater winds can be found in Appendix A.

TABLE 1

WIND RATIOS "R" FOR LOWER GREAT LAKES TABULATED BY WIND SPEED CLASS AND AIR-WATER TEMPERATURE DIFFERENCE ($T_A - T_W$)

Stability ($T_A - T_W$) Degrees F		Wind Speed Classes (Knots)				
Range	Median	1 - 5	6 - 10	11 - 15	$\geq$ 16	All Speeds
-47 to -23	-32	3.00	1.70 (1.27)	1.73 (1.36)	1.35	2.24
-22 to -8	-15	2.65 (1.77)	1.80 (1.37)	1.41 (1.29)	1.29 (1.31)	1.88 (1.44)
-7 to 7	0	2.09 (1.45)	1.48 (1.22)	1.27 (0.95)	0.96 (1.08)	1.44 (1.18)
8 to 22	15	1.71 (1.10)	1.14 (0.85)	1.02 (0.75)	0.83 (0.87)	1.06 (0.89)
23 to 42	29	1.40	1.13 (0.69)	0.94 (0.64)	0.80 (0.68)	0.92
All Ranges		2.65	1.55 (1.08)	1.26 (1.00)	1.02	1.56

NOTES:

( ) Bracketed values denote ratios determined by analysis of Lake Ontario winds by Acres Consulting Services Limited.

Other values denote those obtained by Richards, Dragert and McIntyre.

2 - WASTE HEAT INPUTS

In a 1970 report entitled "Thermal Inputs to the Great Lakes 1968 - 2000", Acres Consulting Services summarized thermal inputs according to shoreline for each of the Great Lakes.[10] These included industrial sources (steel and chemical industries), sewage, and thermal electric generation. Since then, more recent information concerning heat rejection rates and load factors for thermal electric generation (both fossil and nuclear) have been made available by Ontario Hydro. This information made it possible to update the waste heat inputs for the Canadian shoreline of the Great Lakes in 1973.

Data on waste heat inputs from American thermal generating facilities were obtained from a 1973 Federal Power Commission report[11], as well as the 1970[12], and 1972[13] summaries of new generating plants compiled by Power Engineering. To be consistent, load factors cited by Ontario Hydro were used in all cases.

Industrial and sewage waste heat inputs are based on a linear interpolation of the data presented in Acres report (1970.

Using 1973 Ontario Hydro data as well as the predicted waste heat input given in Acres report (1970), new values for the year 2000 were calculated for each of the Great Lakes. These results, as presented in Table 2, are based on 1973 plant operating conditions and, since plant efficiencies are expected to increase by the year 2000, these values may be high. However, no such assumption has been made at this time. Due to the current energy situation, further improvements to these predictions are not considered feasible.

Sample calculations for this section are presented in Appendix B.

TABLE 2

WASTE HEAT INPUTS* TO THE GREAT LAKES IN THE YEARS 1973 AND 2000

	1973	2000
Lake Superior	1.1	5.8
Lake Michigan	69.9	329.7
Lake Huron	.6	98.3
Georgian Bay	4.6	225.4
Lake Erie	60.4	238.7
Lake Ontario	19.0	269.4
	155.9	1,167.3**

*10^9 Btu/hr

**This value represents a 5 per cent increase over the Acres (1970) predictions.

3 - STEADY-STATE MODEL

Over a long period, the total extra heat input to the lake will result in an equal outflow of heat. The steady-state model used for this calculation neglects the changes in heat storage within the lake and, under this assumption, the increased heat input will be balanced by an equal heat outflow.

3.1 - Conduction of the Lake Bed

The long-term effects of heat flow through the lake bed can be neglected as the heat flow path will be of the order of half the lake width.

3.2 - Precipitation

Depending on temperature differences between rain falling on the lake and the lake surface, heat may be added to or removed from the lake. In the case of snow, heat can only be removed from the lake, partly because of the colder temperature of the snow, but primarily because of the latent heat of fusion required to melt the snow. The expected change in the form and/or temperature of precipitation falling on the lake that would result from a small increase in lake surface temperature is expected to be small in relation to other terms in the heat balance equation, and has been neglected.

3.3 - Heat Advection

Artificial heat sources are normally of this type and will be considered as an inflow of heat. As a system, the only loss of heat from the Great Lakes due to an increase in lake temperature will result from outflow down the St. Lawrence River. Assuming a mean flow of 225,000 cfs (based on the years 1962 - 1970, during which time Lake Ontario has been regulated), the resulting change in heat outflow will be 5.05×10^{10} ΔT Btu/hr.

3.4 - Solar Radiation and Weather Modification Feedback

Adding heat to the lake and consequently increasing the vertical fluxes of heat and water vapor could considerably alter the overlake climate which could then alter the lake temperature.

The most fundamental form of such a climatic change would be an alteration of the general circulation over and around the lake. This possibility has been examined previously, using a mathematical model, and the results indicate a change of the order of 10 degrees C (18 degrees F) over lakes Erie and Ontario would be required to cause a change in type of circulation. This would require a heat input about one order of magnitude greater than at present envisaged by 2000 A.D.

There is still the possibility that, on a smaller scale, additional fluxes of moisture and heat could change the cloud cover and consequently modify both long-wave and short-wave radiation. The case of long-wave back radiation was discussed briefly in Acres (1970)[10] where the extreme upper limit approach was used and the effect of additional cloud on heat exchange was found to be small. For this report, we have briefly examined the effects of moisture flux on solar radiation, using data obtained during IFYGL.

The conclusion is that under most conditions the feedback is such as to reduce the temperature rise resulting from waste heat discharge by an amount in the order of 10 per cent. Where the existing land-lake temperature and vapor pressure differences are large, with the lake warmer than the air, the feedback can change sign and act to magnify the temperature rise. However, differentials of at least 12 degrees C (21.6 degrees F) and 12 mb (.35 in Hg) would be needed to cause a 10 per cent increase in temperature above that computed, excluding feedback for a particular waste heat discharge.

Radiation data over the lake was available for a number of separate occasions at the two stations, 3 and 7, in Lake Ontario. Periods were selected during which the wind was consistently blowing from land stations at Toronto toward the lake stations, and where a continuous record was available both in the lake and on land. A total of 19 sets of data was generated in this way of which 12 were during periods for which the lake was warmer than the air and 7 were for periods during which the lake was cooler.

The former were tested for correlation between the variables:

- Fractional reduction in radiation, ΔQ;
- Temperature difference between the lake and the land, ΔT;
- Vapor pressure difference between the lake water and the air over the land, Δe.

All differences were of the form <u>land value minus lake value</u>. It was found that the best fit was between the ratio $\Delta Q/\Delta T$ and the independent variables ΔT and Δe. The correlation coefficient was $R^2 = 0.718$, and the correlation was significant at better than the 1 per cent level according to the "F" test of significance.

The relationship derived from this data analysis was differentiated with respect to the lake temperature T_W and the result was:

$$\frac{\partial \bar{Q}w}{\partial T_W} = \frac{-F.QA}{5600} \left(12.32 + \left(1.07 + 0.36 \frac{\partial e_W}{\partial T_W}\right) \Delta T + 0.36 \Delta e\right)$$

Where:

$\bar{Q}w$ langleys is the average solar energy input to the lake along a fetch extending F kilometers offshore, and QA is the solar radiation onshore, upwind of the fetch.

As the data available were limited to fetch up to 56 km. extrapolation beyond this cannot be carried out reliably. However, the functional form given above can be considered to give an upper limit to the feedback effect from large fetch distances. Further, the relationship can be considered only as a general guide because of the very limited data used (with considerable scatter), and the essentially non-linear behavior of many of the mechanisms that come into play in going from water temperature to shielding of solar radiation. The data used were biased in a number of ways, including months from July to November only, more morning than afternoon periods, and leaving out periods of wind change. While the biases introduced are such that the actual values of coefficient in the equation for $\partial Qw/\partial T_W$ may be out by a factor of 2, the general conclusion that the effect is small and such as to cause a lower lake temperature for a given waste heat addition should be valid.

In terms of water budget, this means that an increase in the water temperature tends to decrease the incoming solar radiation, which in turn lowers the lake temperature and thereby reduces the evaporative losses. Unfortunately, sufficient radiation data to calculate reliable estimates on a monthly basis were not available.

3.5 - Long-Wave Radiation

The net outgoing long-wave radiation from the lake is the total of the radiation from the lake less back radiation from the atmosphere to the lake. This net radiation depends directly on the lake temperature, and also indirectly on the effect of the lake temperature on the atmospheric temperature, humidity and cloud cover.

An upper limit can be obtained by noting that increasing the lake temperature should increase the back radiation from the atmosphere. If the increase in back radiation is neglected entirely, the heat flow from the lake will be increased by $4A_L\sigma T_W^3 \cdot \Delta T$ for each ΔT of surface lake temperature increase. The Stefan Boltzmann constant is denoted by σ and the lake area by A_L. This relation forms the upper limit on the increase in long-wave radiation loss from the lake.

3.6 - Evaporation

Most of the change in heat flow resulting from small changes in lake temperature is a result of changes in conduction and evaporation.

Evaporation has been shown to be a function of vapor pressure gradient and wind velocity. For small bodies of water, the empirical formula established in the Lake Hefner studies is widely used to calculate evaporation. This formula gives the evaporation rate E in inches per day as $E = 0.0024\ (e_w - e_s)\ V$ where e_w and e_s are the vapor pressures close to the surface of the lake and in the air above the lake in inches of mercury, and V is the wind speed in miles per day. The terms $(e_w - e_s)$ can be positive as in the case of cold, dry air moving across a relatively warm lake surface, or negative when the air is warmer than the lake surface and carries more moisture than the saturated layer of air adjacent to the lake surface. As the air moves across the lake, it becomes increasingly saturated more distant from the shore. The difficulty in applying the Lake Hefner equation to the Great Lakes lies in the present lack of data concerning the term $(e_w - e_s)$. Using IFYGL buoy data, it was possible to define $(e_w - e_s)$ as a function of atmospheric stability $(T_A - T_W)$ and water temperature T_W, according to the following:

if $(T_A - T_W) \geq 0$

$$(e_w - e_s) = .1232 - .000191\ (T_A - T_W)\ T_W$$

if $(T_A - T_W) < 0$

$$(e_w - e_s) = -\ .944 \times 10^{-2} - .153 \times 10^{-3}\ (T_A - T_W)\ T_W + .316 \times 10^{-4}\ T_W^{\,2}$$

Where: T_A is overland air temperature averaged around the lake measured in degrees F.

T_W is the average water surface temperature measured in degrees F

e_s is the average overwater vapor pressure measured in inches of mercury

e_w is the average saturation vapor pressure at the water surface measured in inches of mercury.

All lake data are averaged according to the "Thiessen" polygons indicated on Plate 1 and are based on a 31-day moving average of values observed between April 19 and December 8, 1972. The accuracy of these estimates of the overwater vapor pressure difference ($e_w - e_s$) has been shown on Plate 7. Justification for a 31-day moving average lies in the fact that, when these equations are applied to Great Lakes other than Ontario, the air and water temperatures are determined from monthly normals. Therefore, to be consistent, all relationships should be determined for time periods compatible with these monthly values.

Substituting in the Lake Hefner equation and differentiating with respect to lake temperature, T_W, the change in heat output by evaporation can be determined for both stable and unstable atmospheric conditions.

3.7 - Conduction

Conductive heat transfer is governed by a similar form of lake atmosphere interaction as evaporative transfer. When the standard Bowens' formula relating the conductive and evaporative heat losses is combined with the Lake Hefner formula , the following equation is obtained:

$$Q_C = 0.1435 (T_W - T_S) V_W$$

Where: Q_C is the conductive heat transfer in Btu/hr

V_W is the wind speed over water in miles/hr

T_W is water surface temperature in degrees F

T_S is air temperature over the water in degrees F

The overwater temperature difference $(T_W - T_S)$ can be defined as a function of atmospheric stability $(T_A - T_W)$ and overwater modification of temperature (j), where:

$$j = (T_S - T_W)/(T_A - T_W)$$

This parameter j, as plotted on Plate ~~7~~ 8, is based on a 31-day moving average of the daily values observed at the eleven IFYGL buoy stations. Substituting in the equation for Q_C and differentiating with respect to water temperature, T_W, the change in heat flow by conduction is equal to $.1435\ j\ V_W\ A_L\ \Delta T$.

Details and results of the heat transfer calculations are presented in Appendix C.

4 - EVAPORATIVE LOSSES DUE TO ONCE-THROUGH COOLING

The increase in evaporation from each lake can be calculated according to the following:

$$E = .00433 \times \frac{K_E}{K} \times Q_{WH} \times \frac{\text{Days in Month}}{\text{Area of Lake}}$$

Where:

E is the evaporation in inches/month

K_E is the evaporative heat transfer coefficient

K is the total heat transfer coefficient

Q_{WH} is the waste heat input in Btu/hr

Area is in square feet

Much of the evaporation from the lakes resulting from the increase in heat is expected to be carried outside the drainage basin, resulting in a reduction in flow through the system as indicated in Table 3. This loss is cummulative with an expected yearly average reduction in flow in the St. Lawrence River of 2,460 cfs for the year 2000. Monthly estimates vary between 2,115 cfs in May to a maximum of 2,870 cfs in September.

A time lag, introduced because of lake storage, has been neglected in these calculations, but is not expected to seriously change the results. Further assumptions made in the calculation are that all extra evaporation is lost from the basin and that the lakes are ice-free all year round. This latter assumption is expected to result in slightly higher evaporative losses during the winter months than would normally occur. However, it has also been necessary to assume that the waste heat is evenly distributed over the body of the lake, a condition which may counterbalance the ice-free assumption.

TABLE 3

REDUCTION IN FLOW (CFS)
IN THE YEAR 2000

	St. Mary's River	St. Clair River	Niagara River	St. Lawrence River
January	12	1,384	1,878	2,417
February	11	1,352	1,838	2,361
March	11	1,349	1,837	2,350
April	10	1,266	1,744	2,196
May	9	1,244	1,714	2,115
June	7	1,213	1,718	2,151
July	8	1,334	1,836	2,342
August	11	1,536	2,105	2,666
September	13	1,651	2,244	2,870
October	13	1,637	2,219	2,825
November	13	1,574	2,135	2,727
December	12	1,462	1,979	2,527
Average	11	1,417	1,937	2,462

During the winter months a portion of waste heat goes into melting the ice cover; however, such a term represents a storage of heat within the lake, and on a yearly basis is not expected to seriously affect the result.

Details of the evaporation calculation are given in Appendix D of this report.

5 - COOLING TOWER EFFECTS

Increases in lake temperatures caused by the input of cooling water from once-through cooling of thermal electric generating stations around the Great Lakes may be avoided by using cooling towers, either as an addition to a once-through cooling system to reduce the temperature of the effluent, or as part of a closed cooling system.

There are two classes of cooling towers; the wet, or evaporative, in which the water comes in direct contact with air and cools by evaporating part of the cooling water, and the dry cooling tower, where the water passes through an air-cooled heat exchanger. The air in these towers is moved either by mechanical means, as in the forced-draft tower, or by density differences and a chimney effect, as in the natural-draft cooling tower. There is no water loss from dry cooling towers except for small systematic leaks, so these will be unimportant in the water balance investigation.

Mechanical-draft cooling towers contain air-moving fans which require energy, as much as .5 per cent of the output from a power generating station, and so these are economically inefficient, but their operating characteristics are very similar to the natural-draft cooling towers.[14]

The amount of water released into the air by a cooling tower may have some local effects such as raising the humidity downwind for a considerable distance (5 miles), causing localized fog and icing, but only under certain meteorological conditions will the cooling towers affect cloud intensification or formation of clouds. Natural-draft cooling towers will have a release point 250 - 500 feet above the ground and an effective discharge height of up to 2,500 feet, so they will have little effect on ground level fogging or icing. On rare occasions the plume may evolve into low-level stratus clouds.[15]

Mechanical-draft cooling towers will have release heights of 30 - 80 feet and will cause ground level fogging and icing under certain conditions, but these will be very localized.

The water vapor released from a cooling tower is at least an order of magnitude less than the water entrained into a moderate rain cloud, and almost always will be dissipated in the atmosphere rather than returning to the earth locally as precipitation.[16]

Heat release, although concentrated, is relatively minor in comparison with that from other man-made energy sources. The cooling towers at the Zion Nuclear Station on Lake Michigan, for example, release only 5 per cent of the amount of heat that is released by Chicago.[17]

Quantitative data concerning evaporative losses through the use of wet cooling towers in the Great Lakes Basin is limited; however, losses are expected to be in the order of 2.5×10^{-9} cfs per Btu/hr of waste heat. This value is based on data presented in the 1973 Federal Power Commission Report[11], referred to in Section 2, and is consistent with the 2.86×10^{-9} cfs per Btu/hr calculated from information presented in McVehil's report to the Commonwealth Edison Company concerning Zion Generating Station.[18]

The resultant evaporative losses and reduction in outflow are presented in Table 4(a) and (b) for the years 1973 and 2000. If one assumes the higher value of 2.86×10^{-9} cfs per Btu/hr (estimated for Zion Generating Station), the evaporative losses for the entire basin amount to 3,200 cfs or 1.4 per cent of the flow in the St. Lawrence River. Not included in these estimates are the water losses incurred during the blowdown procedure, which are expected to be of the same order of magnitude as the evaporative losses.

For all calculations in this section, it has been assumed that use of wet cooling towers would only apply to thermal electric generating stations (see Appendix E) and, therefore, the waste heat from industrial and municipal sources (approximately 5 per cent of the total) has been excluded. For comparison, a 5 per cent reduction in the waste heat from once-through cooling would result in a total loss from the Great Lakes of 2,320 cfs. Thus the use of wet cooling towers is likely to produce evaporative loss 40 per cent larger than once-through cooling systems.

TABLE 4

EFFECT OF WET COOLING TOWERS ON GREAT LAKES WATER BUDGET

(a) Evaporative Losses*

	1973 (cfs)	2000 (cfs)
Lake Superior	1.5	13.3
Lake Michigan	145.8	781.0
Lake Huron	10.1	561.5
Georgian Bay	0.0	243.0
Lake Erie	111.2	538.5
Lake Ontario	36.1	658.0

(b) Reduction in Flow*

	1973 (cfs)	2000 (cfs)
St. Mary's River	1.5	13.3
St. Clair River	157.4	1,598.8
Niagara River	268.6	2,137.3
St. Lawrence River	304.7	2,795.3

*Using an evaporation rate of 2.5×10^{-9} cfs/(Btu/hr). (Yearly average recorded at Painesville, Ohio.)

6 - RECOVERY WITHIN BASIN

Estimation of the ultimate fate of the increased moisture leaving the Great Lakes as a result of increased thermal inputs is complex, involving consideration of vertical and horizontal movements of the water vapor, uptake by vegetation and other landscape features, removal by cloud formation and precipitation processes, fog and dew deposition, etc. In-depth study of these phenomena is beyond the scope of this report. Consequently, an estimate has been made based on the simple assumption that, during periods of precipitation, all of the increased moisture is returned within the basin. The assumption is considered to be conservative in the sense of overestimating recovery.

Hours of occurrence of all forms of precipitation were taken from the Atmospheric Environment Service publications, Hourly Data Summaries 3, 6, 7, 87 and 5 for Toronto, London, Wiarton, Sault Ste. Marie and Lakehead, respectively.

The average of these, 1,481 hours or 16.9 per cent of the time, was taken as the basin average. This was applied to the calculated annual average increases in evaporation in the year 2000, giving an estimated recovery within the basin of 416 cfs and 541 cfs for once-through cooling and wet cooling towers, respectively.

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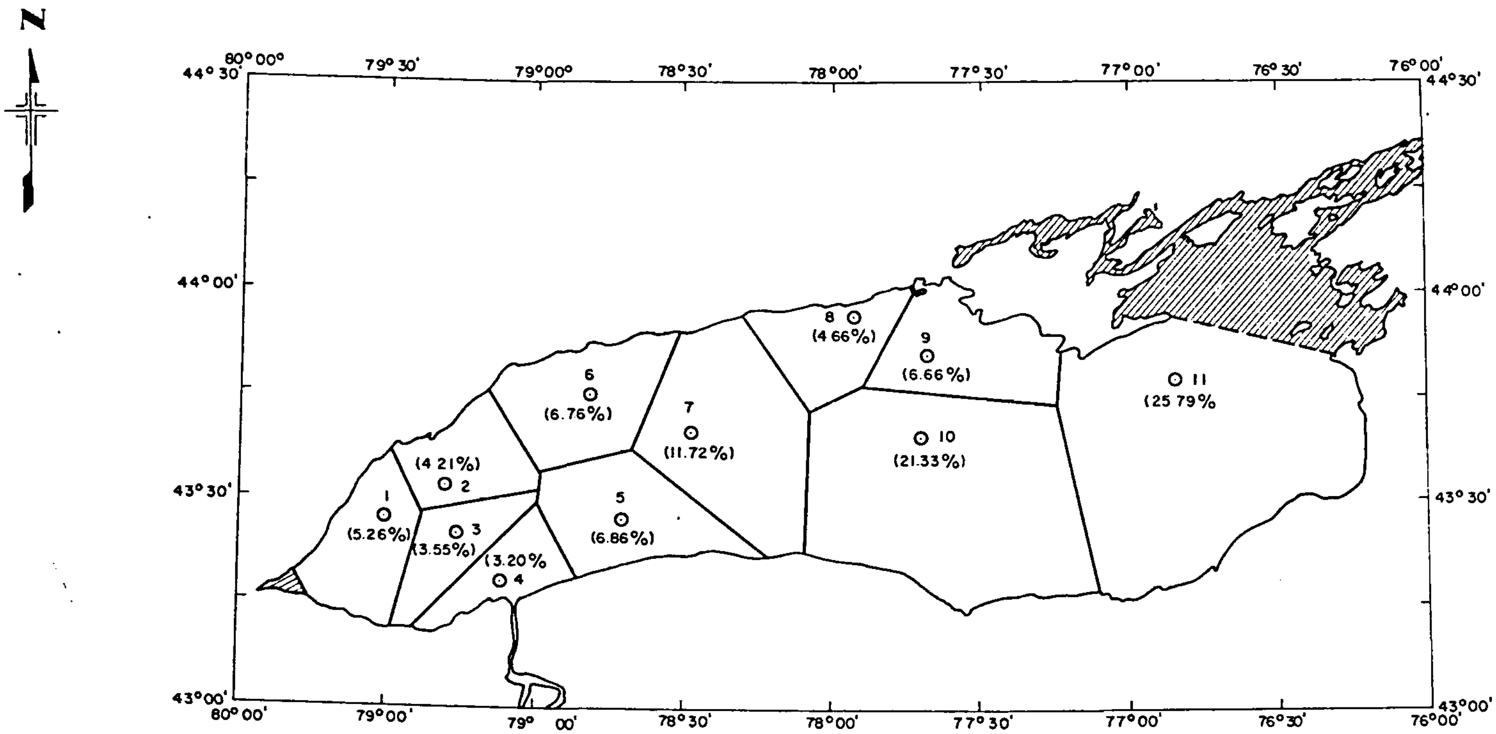
[18] G. E. McVehil. *Evaluation of Cooling Tower Effects at Zion Nuclear Generating Station.* Final Report prepared by Sierra Research Corporation for the Commonwealth Edison Company. Chicago, Illinois. 1970. Cited in Reference 17.

PLATES



NOTE

SHADED PORTIONS WERE NOT USED IN AVERAGING TECHNIQUE

LEGEND

(4 66%) PERCENTAGE OF TOTAL AREA REPRESENTED BY BUOY

0 5 10 15 20 25
SCALE IN STATUTE MILES

0 10 20 30 40
SCALE IN KILOMETERS

ACRES

CANADA CENTRE FOR INLAND WATERS

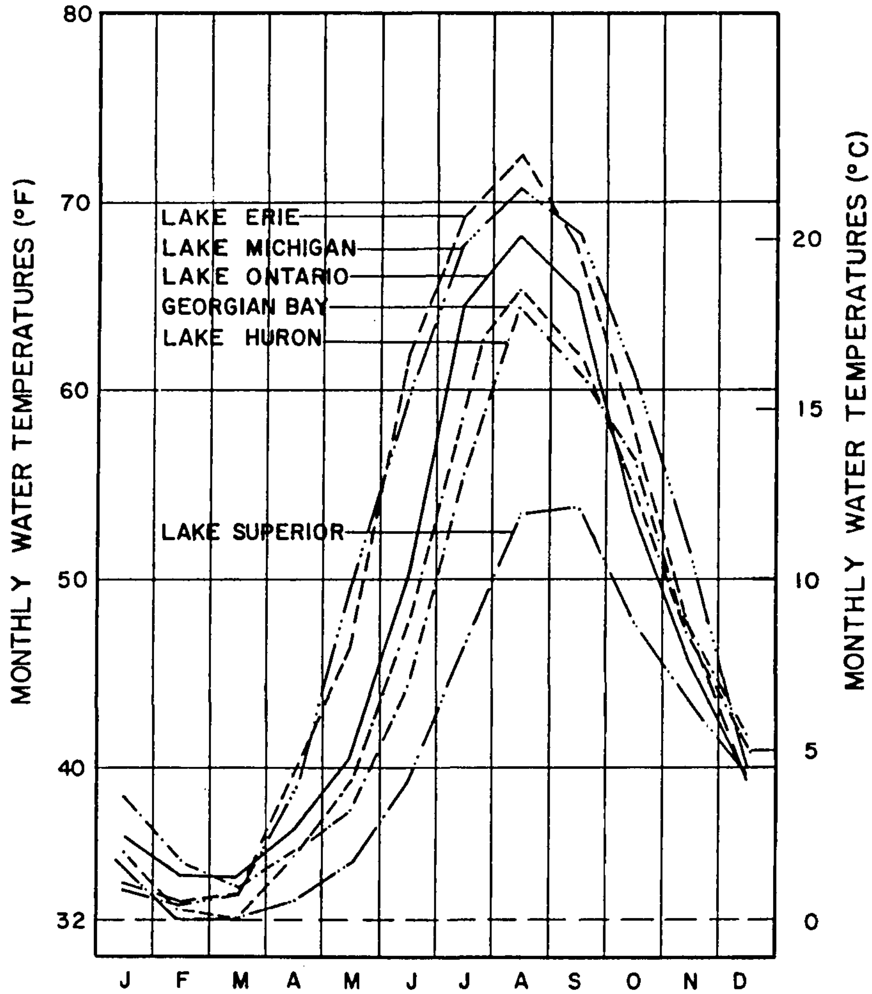
GREAT LAKES HEAT INPUTS & WATER BUDGET

METEOROLOGICAL BUOY SYSTEM WITH APPROPRIATE THIESSEN POLYGONS

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 1



LEGEND

LAKE ONTARIO

LAKE ERIE

LAKE HURON

GEORGIAN BAY

LAKE MICHIGAN

LAKE SUPERIOR

DATA SOURCES

1. ATMOSPHERIC ENVIRONMENT SERVICES ART SURVEYS 1966 - 1973
2. RICHARDS AND IRBE, 1968
3. JONES AND MEREDITH, 1972
4. M.S. WEBB, 1972

ACRES

CANADA CENTRE FOR INLAND WATERS

GREAT LAKES HEAT INPUTS & WATER BUDGET

AVERAGE MONTHLY WATER SURFACE TEMPERATURES

C.J. Denison

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 2

CANADA CENTRE FOR INLAND WATERS

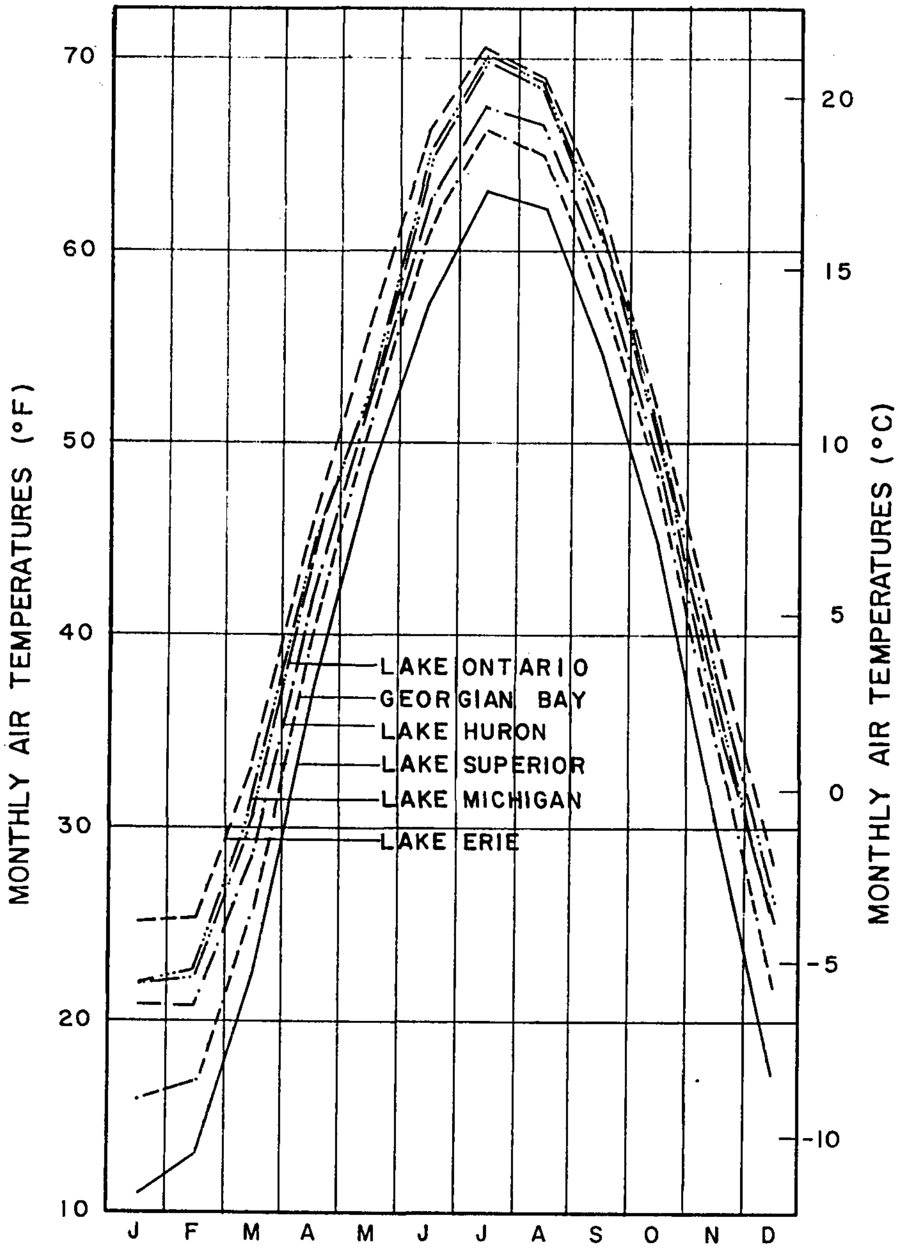
GREAT LAKES HEAT INPUTS & WATER BUDGET

LAND STATIONS USED FOR MONTHLY OVERLAND AIR TEMPERATURES

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 3



LEGEND

LAKE ONTARIO ·········
LAKE ERIE — — —
LAKE HURON —·—·—
GEORGIAN BAY ·———·
LAKE MICHIGAN —··—
LAKE SUPERIOR ———

ACRES

CANADA CENTRE FOR INLAND WATERS

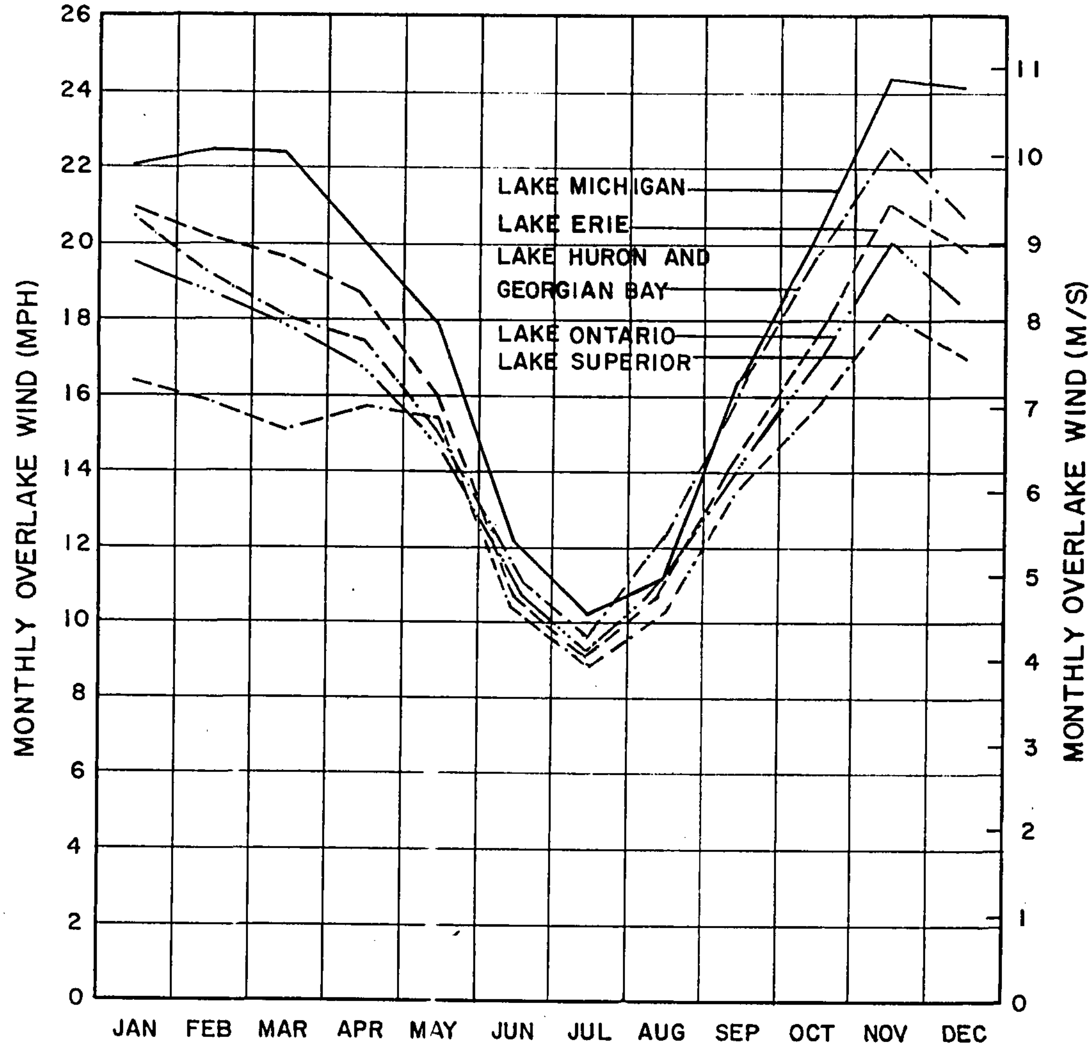
GREAT LAKES HEAT INPUTS & WATER BUDGET

AVERAGE MONTHLY OVERLAND AIR TEMPERATURES

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 4



LEGEND

LAKE ONTARIO	—··· —
LAKE ERIE	— — —
LAKE HURON AND GEORGIAN BAY	·—·—·
LAKE MICHIGAN	———
LAKE SUPERIOR	·— — —·

NOTES

ALL VALUES EXCEPT LAKE MICHIGAN ARE BASED ON ATMOSPHERIC ENVIRONMENT SERVICES, CLIMATOLOGICAL STUDIES No. 17, RICHARDS AND PHILLIPS, 1970

LAKE MICHIGAN WINDS ARE BASED ON ARGONNE NATIONAL LABORATORY, REPORT No. ANL/ESI, T. G. ASBURY, 1970

ACRES

CANADA CENTRE FOR INLAND WATERS

GREAT LAKES HEAT INPUTS & WATER BUDGET

AVERAGE MONTHLY OVERWATER WINDS

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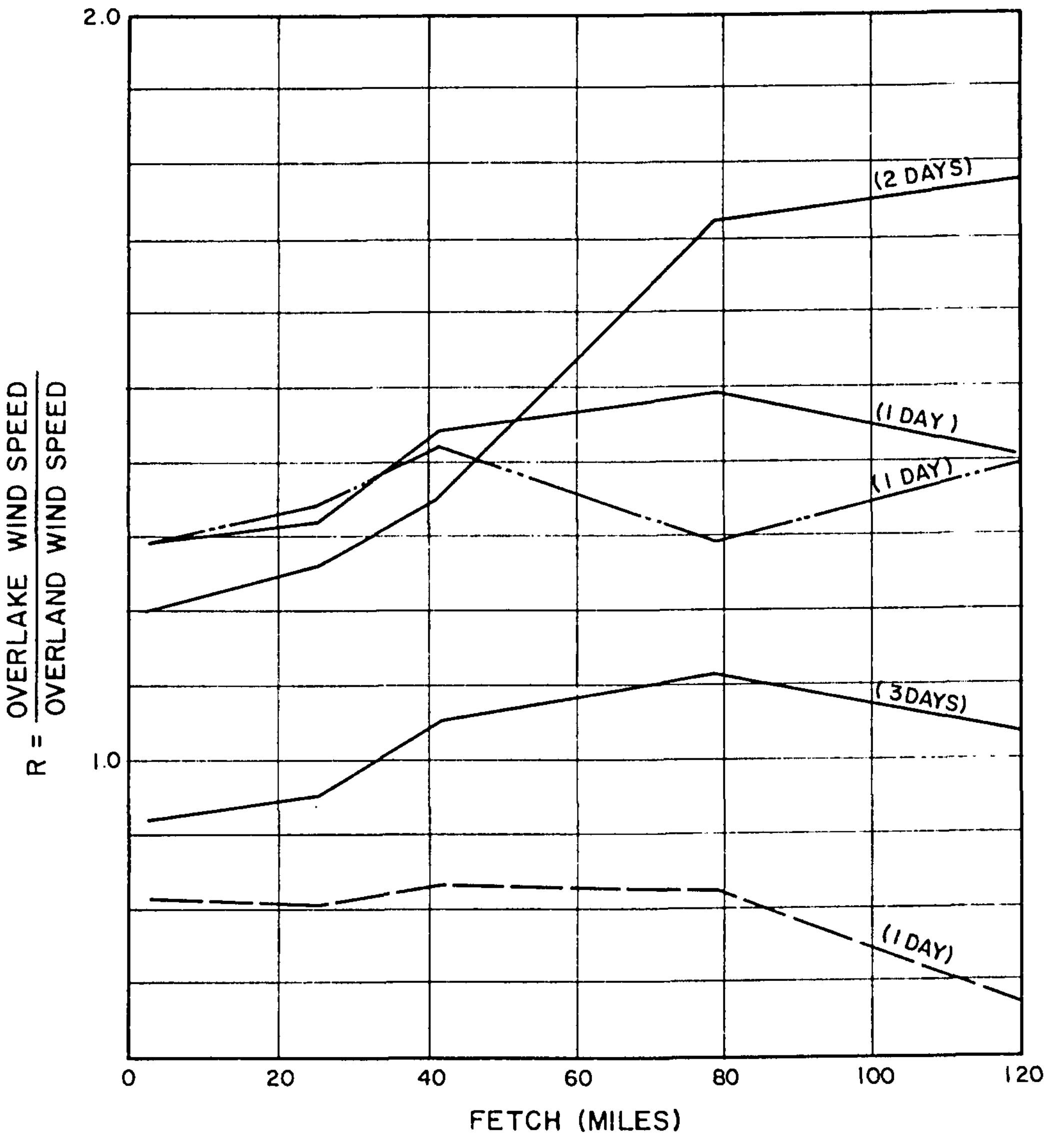
PLATE 5



NOTES

(1DAY) No. OF DAYS USED IN AVERAGE

STABILITY RANGE (°F)	WIND SPEED KNOTS 1-5	6-10	11-15	≥16
-47 TO -23				1 DAY
-22 TO -8		2 DAYS		
-7 TO -7				1 DAY
-8 TO -22		3 DAYS	1 DAY	
-23 TO -42				

ACRES

CANADA CENTRE FOR INLAND WATERS

GREAT LAKES HEAT INPUTS & WATER BUDGET

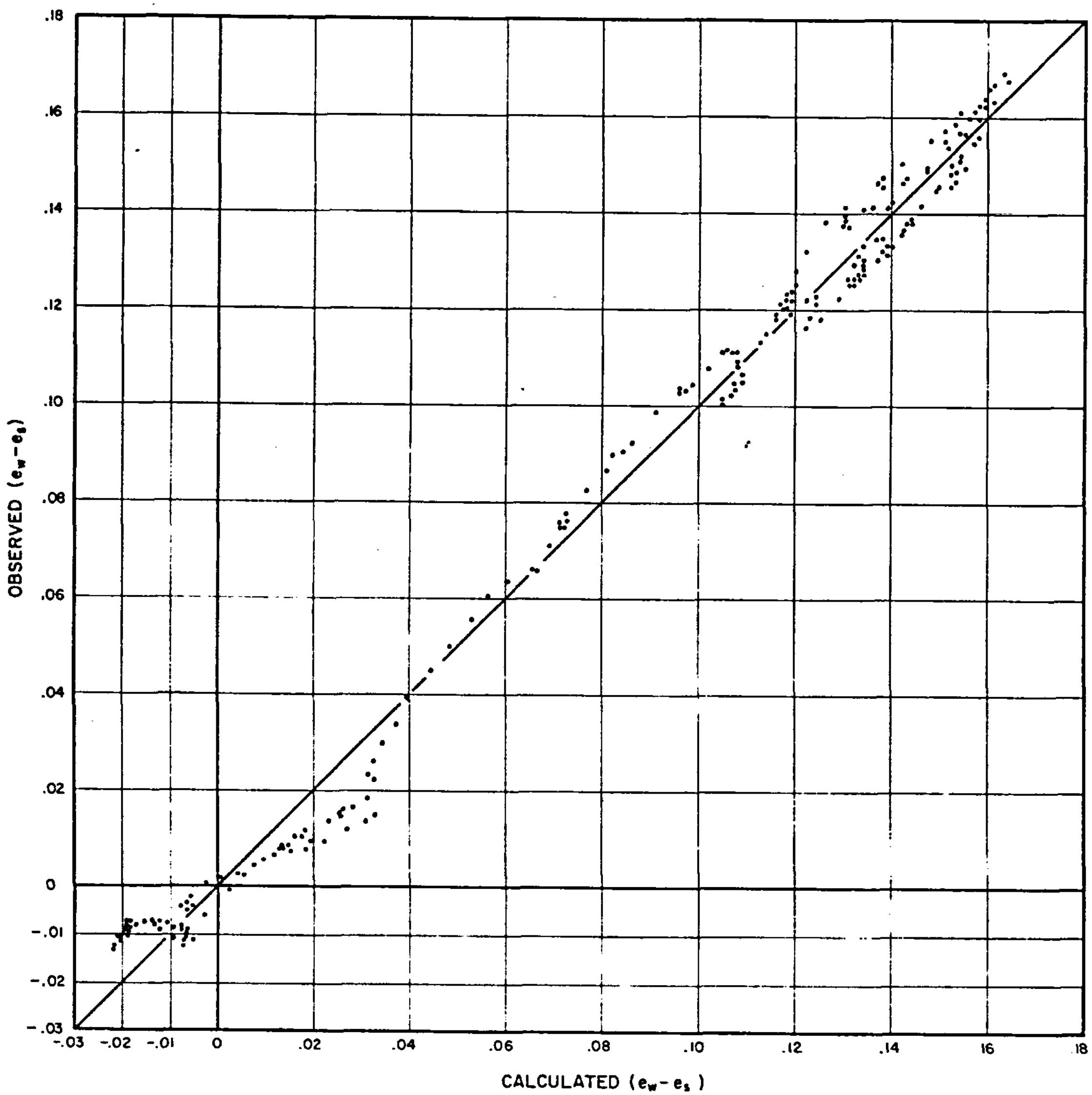
OVERLAKE TO OVERLAND WIND RATIOS VERSUS FETCH

Denison

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 6



LEGEND

e_w – VAPOUR PRESSURE AT WATER SURFACE (in. Hg)

e_s – VAPOUR PRESSURE IN AIR OVER WATER (in. Hg)

T_A – AIR TEMPERATURE OVER LAND AVERAGED AROUND THE LAKE (°F)

T_W – WATER SURFACE TEMPERATURE (°F)

NOTES

IF $(T_A - T_W) \geq 0$

$$e_w - e_s = .1232 - .000191\,(T_A - T_W)\,T_W$$

IF $(T_A - T_W) < 0$

$$e_w - e_s = -.944 \times 10^{-2} - .153 \times 10^{-3}\,(T_A - T_W)\,T_W + .316 \times 10^{-4}\,T_W^{2}$$

OBSERVED VALUES ARE A 31 DAY MOVING AVERAGE OF THE VALUES MEASURED DURING IFYGL (APRIL 19 – DECEMBER 8, 1972)

ACRES

CANADA CENTRE FOR INLAND WATERS

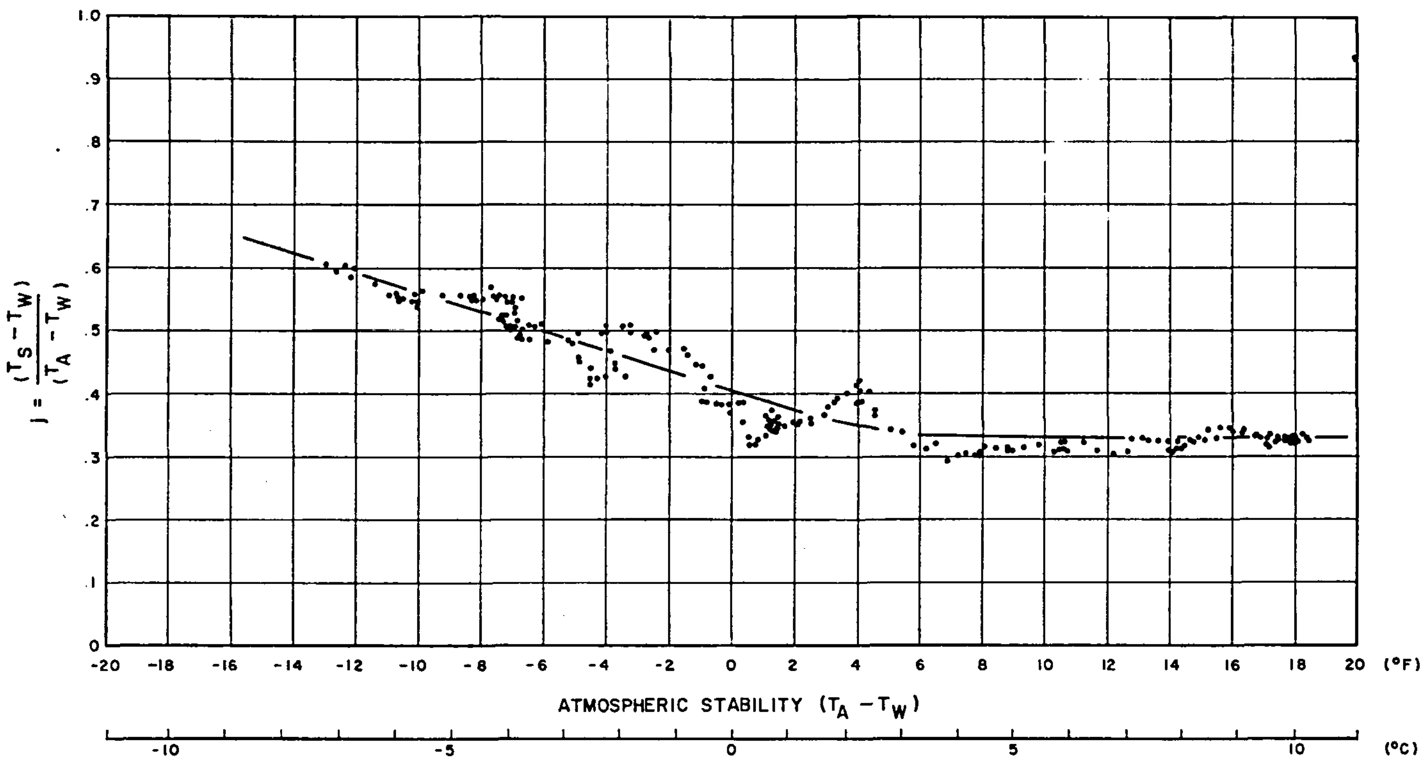
GREAT LAKES HEAT INPUTS & WATER BUDGET

ESTIMATE OF OVER WATER VAPOUR PRESSURE DIFFERENCE ($e_w - e_s$)

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 7



LEGEND

T_A – OVERLAND AIR TEMPERATURE AVERAGED AROUND THE LAKE

T_S – OVERLAKE AIR TEMPERATURE

T_W – WATER SURFACE TEMPERATURE

NOTES

DATA POINTS ARE A 31 DAY MOVING AVERAGE OF THE OBSERVED TEMPERATURE MODIFICATION FOR THE PERIOD APRIL 19, 1972 TO DECEMBER 8, 1972

OVERLAKE DATA WAS OBTAINED FROM THE METEOROLOGICAL BUOY SYSTEM MAINTAINED BY THE CANADA CENTRE FOR INLAND WATERS (CCIW) AS PART OF THE INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES (IFYGL)

ACRES

CANADA CENTRE FOR INLAND WATERS

GREAT LAKES HEAT INPUTS & WATER BUDGET

OVERLAKE MODIFICATION OF AIR TEMPERATURE

ACRES CONSULTING SERVICES LIMITED

MARCH 1974

PLATE 8

APPENDIX A

MONTHLY CLIMATIC DATA

AVERAGE MONTHLY WATER TEMPERATURES*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	35.3	33.5	38.5	34.6	33.8	36.4
FEB	32.4	32.8	35.1	32.0	32.9	34.3
MAR	32.0	33.3	33.7	32.0	33.3	34.1
APR	33.0	38.7	35.5	35.3	39.8	36.6
MAY	35.0	49.6	37.8	39.2	46.1	40.5
JUNE	39.3	59.5	44.4	47.5	61.7	51.2
JULY	46.4	67.8	55.7	62.7	69.1	64.5
AUG	53.3	70.6	64.2	65.3	72.3	68.1
SEPT	53.9	68.4	61.2	62.0	67.9	65.2
OCT	47.7	60.9	56.3	53.4	58.1	53.5
NOV	43.5	51.4	47.2	47.4	47.5	45.4
DEC	38.9	40.0	42.0	41.3	39.5	39.5

*Degrees Fahrenheit (^{o}F)

AVERAGE MONTHLY WATER TEMPERATURES*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	1.8	0.8	3.6	1.4	1.0	2.4
FEB	0.2	0.5	1.7	0.0	0.5	1.3
MAR	0.0	0.7	0.9	0.0	0.7	1.2
APR	0.6	3.7	1.9	1.8	4.3	2.6
MAY	1.7	9.8	3.2	4.0	7.8	4.7
JUNE	4.1	15.3	6.9	8.6	16.5	10.7
JULY	8.0	19.9	13.2	17.1	20.6	18.1
AUG	11.8	21.4	17.9	18.5	22.4	20.1
SEPT	12.2	20.2	16.2	16.7	19.9	18.4
OCT	8.7	16.1	13.5	11.9	14.5	11.9
NOV	6.4	10.8	8.4	8.6	8.6	7.4
DEC	3.8	4.4	5.6	5.2	4.2	4.2

*Degrees Centigrade (°C)

AVERAGE MONTHLY OVERLAND AIR TEMPERATURES *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	11.0	22.0	20.8	15.9	25.1	22.0
FEB	13.0	22.6	20.7	16.8	25.4	22.4
MAR	22.6	30.7	28.4	25.9	33.3	30.8
APR	37.1	43.7	41.9	40.1	45.3	43.6
MAY	48.2	54.5	52.4	51.3	56.0	54.6
JUNE	57.3	64.8	62.4	61.2	66.2	64.7
JULY	63.0	70.2	67.6	66.4	70.7	69.8
AUG	62.2	68.9	66.6	65.1	69.2	68.4
SEPT	54.5	61.1	59.1	57.7	62.4	61.2
OCT	44.7	50.7	49.5	48.2	51.8	50.6
NOV	30.2	37.0	37.0	35.7	39.7	39.0
DEC	17.2	26.1	25.6	22.2	28.8	26.8

*Degrees Fahrenheit (^{o}F)

AVERAGE MONTHLY OVERLAND AIR TEMPERATURES *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	-11.7	-5.6	-6.2	-8.9	-3.8	-5.6
FEB	-10.6	-5.2	-6.3	-8.4	-3.7	-5.3
MAR	-5.2	-.7	-2.0	-3.4	0.7	-.7
APR	2.8	6.5	5.5	4.5	7.4	6.4
MAY	9.0	12.5	11.3	10.7	13.3	12.6
JUNE	14.1	18.2	16.9	16.2	19.0	18.2
JULY	17.2	21.2	19.8	19.1	21.5	21.0
AUG	16.8	20.5	19.2	18.4	20.7	20.2
SEPT	12.5	16.2	15.1	14.3	16.9	16.2
OCT	7.1	10.4	9.7	9.0	11.0	10.3
NOV	-1.0	2.8	2.8	2.1	4.3	3.9
DEC	-8.2	-3.3	-3.6	-5.4	-1.8	-2.9

*Degrees Centigrade (^{o}C)

AVERAGE MONTHLY OVERWATER WINDS*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	16.3	22.1	21.1	21.1	20.9	19.5
FEB	15.7	22.5	19.1	19.1	20.2	18.7
MAR	15.0	22.4	18.1	18.1	19.6	17.9
APR	15.7	20.1	17.4	17.4	18.7	16.8
MAY	15.2	17.8	15.0	15.0	15.9	14.7
JUNE	10.3	12.2	11.1	11.1	10.7	10.9
JULY	8.8	10.2	9.6	9.6	9.0	9.2
AUG	10.1	11.1	12.1	12.1	10.8	11.0
SEPT	13.5	16.4	16.1	16.1	14.4	14.1
OCT	15.5	20.0	19.6	19.6	17.1	16.3
NOV	18.1	24.3	22.5	22.5	20.9	20.0
DEC	16.9	24.1	20.8	20.8	19.7	18.2

*Miles per hour (mph)

AVERAGE MONTHLY OVERWATER WINDS*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	7.3	9.9	9.4	9.4	9.4	8.7
FEB	7.0	10.1	8.6	8.6	9.0	8.4
MAR	6.7	10.0	8.1	8.1	8.8	8.0
APR	7.0	9.0	7.8	7.8	8.3	7.5
MAY	6.8	8.0	6.7	6.7	7.1	6.6
JUNE	4.6	5.5	5.0	5.0	4.8	4.9
JULY	4.0	4.6	4.3	4.3	4.0	4.1
AUG	4.5	5.0	5.4	5.4	4.8	4.9
SEPT	6.0	7.3	7.2	7.2	6.4	6.3
OCT	6.9	8.9	8.8	8.8	7.6	7.3
NOV	8.1	10.9	10.1	10.1	9.4	8.9
DEC	7.6	10.8	9.3	9.3	8.8	8.2

*Metres per second (m/sec)

APPENDIX B

WASTE HEAT CALCULATIONS

WASTE HEAT CALCULATIONS

Fossil-Fuelled Thermal Electric Generating Plants	Btu/kwh
Average Heat Rate*	9,000
In-plant and Stack Losses (13 per cent)	1,170
Heat Equivalent of Generation	3,413
Waste Heat Generation	4,417

Nuclear-Powered Thermal Electric Generating Plants	
Average Heat Rate*	11,500
Miscellaneous Losses (.2 per cent)	23
Heat Equivalent of Generation	3,413
Waste Heat Generation	8,064

Load Factors*

Fossil Plants Operate at 30 - 40 Per Cent Capacity

Nuclear Blants Operate at 70 - 80 Per Cent Capacity

---

*Based on 1973 Ontario Hydro information.

APPENDIX C

HEAT TRANSFER COEFFICIENTS

Advection Coefficient K_L

$$\text{Heat outflow per sq ft of surface area} = \frac{\text{Discharge} \times \text{HC} \times \Delta T}{\text{Surface Area}}$$

Where: Discharge is outflow in cfs

HC is the heat capacity of water taken as 1 Btu per ft^3 per degree F

Surface area is in sq ft

Defining the advective heat transfer coefficient as

$$K_L = \frac{dQ_L}{dT_W}$$

We have:

$$K_L = \frac{\text{Discharge} \times \text{HC}}{\text{Surface Area}}$$

K_L only applies to Lake Ontario since none of the other lakes will result in loss to the system.

Example: Lake Ontario

If we assume a mean discharge down the St. Lawrence River of 225×10^3 cfs,

We have:

$$K_L = \frac{225 \times 10^3 \times 62.4 \times 3{,}600}{7{,}520 \times (5{,}280)^2} \quad \frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}}$$

$$= .241 \quad \frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}}$$

ADVECTION COEFFICIENT KL *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.000	0.000	0.000	0.000	0.000	0.234
FEB	0.000	0.000	0.000	0.000	0.000	0.237
MAR	0.000	0.000	0.000	0.000	0.000	0.233
APR	0.000	0.000	0.000	0.000	0.000	0.233
MAY	0.000	0.000	0.000	0.000	0.000	0.231
JUNE	0.000	0.000	0.000	0.000	0.000	0.242
JULY	0.000	0.000	0.000	0.000	0.000	0.248
AUG	0.000	0.000	0.000	0.000	0.000	0.253
SEPT	0.000	0.000	0.000	0.000	0.000	0.250
OCT	0.000	0.000	0.000	0.000	0.000	0.248
NOV	0.000	0.000	0.000	0.000	0.000	0.243
DEC	0.000	0.000	0.000	0.000	0.000	0.249

$*\frac{Btu}{hr\ ft^2\ {}^oF}$

ADVECTION COEFFICIENT KL*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.000	0.000	0.000	0.000	0.000	1.326
FEB	0.000	0.000	0.000	0.000	0.000	1.345
MAR	0.000	0.000	0.000	0.000	0.000	1.320
APR	0.000	0.000	0.000	0.000	0.000	1.320
MAY	0.000	0.000	0.000	0.000	0.000	1.314
JUNE	0.000	0.000	0.000	0.000	0.000	1.375
JULY	0.000	0.000	0.000	0.000	0.000	1.405
AUG	0.000	0.000	0.000	0.000	0.000	1.436
SEPT	0.000	0.000	0.000	0.000	0.000	1.418
OCT	0.000	0.000	0.000	0.000	0.000	1.405
NOV	0.000	0.000	0.000	0.000	0.000	1.381
DEC	0.000	0.000	0.000	0.000	0.000	1.412

$*\frac{\text{Watts}}{m^2\ {}^{o}C}$

Evaporation Coefficient K_E

Evaporative heat loss $(Q_E) = L.E$ (1)

Where: Q_E is the evaporative heat loss in Btu/hr - ft^2

E is the rate of evaporation in inches/hr

And: L is the latent heat of vaporization, assumed to be equal to 1065 Btu/ft^3

The Lake Hefner evaporation study shows that:

$$E = \gamma (e_w - e_s) V_W \quad (2)$$

Where: γ is an empirical coefficient equal to 0.0024

e_w is the vapor pressure at the water surface in inches of mercury

e_s is the vapor pressure of air over the water surface in inches of mercury

And: V_W is the wind speed over the water surface in mph (based on Richards and Phillips[7])

From IFYGL data, vapor pressure difference could be estimated by the following equations:

If: $(T_A - T_W) \geq 0$

$$e_w - e_s = .1232 - .191 \times 10^{-3} (T_A - T_W) T_W \quad (3)$$

If: $(T_A - T_W) < 0$

$$e_w - e_s = - .944 \times 10^{-2} - .153 \times 10^{-3} (T_A - T_W) T_W + .316 \times 10^{-4} T_W^2 \quad (4)$$

Where: T_A is the air temperature over land averaged around the lake in degrees F

T_W is average lake surface temperature in degrees F

Substituting: EQ (3) and (4) into EQ (1) and (2) we have:

If: $(T_A - T_W) \geq 0$

$$Q_E = 13.3 (.1232 - .191 \times 10^{-3} (T_A - T_W) T_W) V_W \quad (5)$$

Evaporation Coefficient K_E (Cont'd)

If: $(T_A - T_W) < 0$

$$Q_E = 13.3 \, (-.944 \times 10^{-2} - .153 \times 10^{-3} (T_A - T_W) T_W + .316 \times 10^{-4} T_W^2) V_W \qquad (6)$$

Defining: $K_E = \frac{dQ_E}{dTw}$

We have the following equations:

If: $(T_A - T_W) \geq 0$

$$K_E = 13.3 \, (-.191 \times 10^{-3} (T_A - 2T_W)) V_W \qquad (7)$$

If: $(T_A - T_W) < 0$

$$K_E = 13.3 \, (-.153 \times 10^{-3} (T_A - 2T_W) + .633 \times 10^{-4} T_W) V_W \qquad (8)$$

K_E is in $\frac{Btu}{hr \, ft^2 \, {}^oF}$

EVAPORATION COEFFICIENT KE *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	2.469	2.643	3.093	2.899	2.405	2.613
FEB	2.079	2.593	2.495	2.355	2.216	2.304
MAR	1.671	2.269	1.946	1.887	1.882	1.876
APR	1.153	1.720	1.290	1.352	1.627	1.260
MAY	0.845	2.018	0.883	1.031	1.466	0.988
JUNE	0.558	1.679	0.747	0.957	1.556	1.048
JULY	0.669	1.695	1.067	1.437	1.542	1.384
AUG	1.145	2.291	1.893	2.270	2.323	1.889
SEPT	1.828	3.469	2.900	3.009	2.978	2.754
OCT	2.217	3.924	3.446	3.218	3.076	2.608
NOV	2.749	4.303	3.528	3.610	3.191	2.874
DEC	2.642	3.456	3.201	3.273	2.672	2.545

$^*\frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}}$

EVAPORATION COEFFICIENT KE *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	14,019	15.006	17.560	16.461	13.654	14.839
FEB	11,806	14.726	14.166	13.374	12.582	13.084
MAR	9,489	12.883	11.048	10.713	10.689	10.653
APR	6,549	9.765	7.325	7.677	9.237	7.156
MAY	4,795	11.456	5.013	5.856	8.323	5.609
JUNE	3,168	9.535	4.242	5.431	8.837	5.949
JULY	3,800	9.622	6.059	8.162	8.753	7.856
AUG	6,501	13.010	10.751	12.892	13.191	10.728
SEPT	10,379	19.698	16.466	17.084	16.910	15.636
OCT	12,590	22.281	19.566	18.275	17.464	14.809
NOV	15,608	24.433	20.035	20.500	18.118	16.319
DEC	15,003	19.625	18.177	18.587	15.170	14.454

*$\frac{\text{Watts}}{m^2\ {}^{o}C}$

Conduction Coefficient K_C

$$\text{Conductive heat loss } Q_C = Q_E \times .0108 \times \frac{(T_W - T_S)}{(e_w - e_s)} \qquad (9)$$

Where: Q_C is the conductive heat loss in Btu/hr per ft^2

T_S is the overwater air temperature (^oF)

And: T_W is the water surface temperature (^oF)

Combining equations (1), (2) and (9) we have:

$$Q_C = .1435\ (T_W - T_S)\ V_W \qquad (10)$$

From IFYGL data it was found that:

$$T_W - T_S = j\ (T_W - T_A) \qquad (11)$$

Where: T_A is overland air temperature (^oF) averaged around the lake

j is correction factor accounting for the overlake modification of temperature (see Plate 8)

Defining the conductive heat loss coefficient as

$$K_C = \frac{dQ_C}{dT_W}$$

We have: $K_C = 0.1435\ j\ V_W \quad \frac{Btu}{hr\ ft^2\ ^oF}$ (12)

CONDUCTION COEFFICIENT KC*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	1.832	1.838	2.048	2.095	1.610	1.751
FEB	1.583	1.809	1.719	1.754	1.497	1.578
MAR	1.180	1.419	1.252	1.284	1.128	1.160
APR	0.787	0.980	0.825	0.856	0.898	0.791
MAY	0.702	0.870	0.686	0.693	0.744	0.676
JUNE	0.466	0.590	0.504	0.512	0.530	0.503
JULY	0.402	0.542	0.444	0.487	0.490	0.445
AUG	0.475	0.679	0.640	0.698	0.698	0.624
SEPT	0.760	1.210	0.999	1.078	1.006	0.934
OCT	0.992	1.609	1.425	1.354	1.223	1.043
NOV	1.577	2.180	1.811	1.887	1.568	1.436
DEC	1.798	2.137	1.957	2.083	1.607	1.569

$* \frac{Btu}{hr\ ft^2\ ^oF}$

CONDUCTION COEFFICIENT KC *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	10.401	10.436	11.628	11.897	9.142	9.940
FEB	8.988	10.272	9.762	9.957	8.501	8.960
MAR	6.702	8.056	7.108	7.293	6.405	6.588
APR	4.468	5.567	4.685	4.863	5.096	4.490
MAY	3.989	4.940	3.897	3.935	4.223	3.839
JUNE	2.646	3.349	2.859	2.908	3.011	2.858
JULY	2.282	3.075	2.521	2.764	2.784	2.526
AUG	2.699	3.854	3.636	3.962	3.962	3.542
SEPT	4.318	6.869	5.672	6.124	5.712	5.304
OCT	5.635	9.136	8.090	7.689	6.945	5.923
NOV	8.953	12.381	10.281	10.713	8.902	8.157
DEC	10.208	12.134	11.113	11.828	9.126	8.907

*$\frac{\text{Watts}}{m^2\ {}^oC}$

Back-Radiation Coefficient K_{BR}

As indicated in the text, the long-wave back radiation is a direct function of the surface water temperature and is defined as:

$$Q_{BR} = \sigma\ (T_W + 460)^4$$

Where: σ is the Stefan-Boltzmann constant equal to 1.73×10^9 Btu/hr - ft^2 $(^oF)^4$,

T_W is the surface water temperature in ^oF

And: 460 is the conversion constant from ^oF to Rankine

Similarly, defining the radiative heat loss coefficient as

$$K_{BR} = \frac{dQ_{BR}}{dT_W}$$

Therefore:

$$K_{BR} = 4\ \sigma(T_W + 460)^3$$

BACK RADIATION COEFFICIENT KBR *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.841	0.831	0.857	0.837	0.833	0.846
FEB	0.826	0.828	0.840	0.824	0.829	0.836
MAR	0.824	0.831	0.833	0.824	0.831	0.835
APR	0.829	0.858	0.842	0.841	0.864	0.847
MAY	0.839	0.916	0.854	0.861	0.897	0.868
JUNE	0.861	0.970	0.888	0.905	0.983	0.924
JULY	0.899	1.017	0.949	0.988	1.025	0.998
AUG	0.936	1.034	0.997	1.003	1.044	1.019
SEPT	0.939	1.021	0.980	0.984	1.018	1.002
OCT	0.906	0.978	0.952	0.936	0.962	0.937
NOV	0.883	0.925	0.903	0.904	0.905	0.893
DEC	0.859	0.865	0.875	0.872	0.862	0.862

$*\frac{Btu}{hr\ ft^2\ {}^oF}$

BACK RADIATION COEFFICIENT KBR *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	4,774	4.721	4.868	4.754	4.731	4.806
FEB	4,691	4.703	4.769	4.680	4.705	4.746
MAR	4,680	4.718	4.728	4.680	4.717	4.740
APR	4,708	4.873	4.780	4.774	4.906	4.812
MAY	4.766	5.199	4.847	4.888	5.094	4.926
JUNE	4,891	5.509	5.043	5.136	5.579	5.249
JULY	5,103	5.777	5.389	5.612	5.820	5.670
AUG	5.314	5.869	5.660	5.696	5.926	5.787
SEPT	5,333	5.796	5.563	5.589	5.781	5.692
OCT	5.142	5.555	5.408	5.317	5.465	5.320
NOV	5,016	5.255	5.127	5.133	5.136	5.073
DEC	4,879	4.912	4.971	4.950	4.897	4.897

$*\frac{\text{Watts}}{m^2\ {}^oC}$

APPENDIX D

EVAPORATIVE LOSSES DUE TO ONCE-THROUGH COOLING

Evaporative Losses Due to Once-through Cooling

Heat loss through evaporation $= \frac{K_E}{K} \times Q_{WH}$

Where: Q_{WH} is the waste heat input in Btu/hr

K_E is evaporative heat transfer coefficient

And: K is total heat transfer coefficient defined as

$$K = \sum_i K_i$$

Evaporative losses in inches per month $= .00433 \times \frac{K_E}{K} \times \frac{Q_{WH} \times \text{Days}}{\text{Area}}$

Where days are the number of days in month

Area is area of lake in sq ft

Evaporative losses $= 4.17 \times \frac{K_E}{K} \times \underline{Q_{WH}}$

The reduction in outflow is cumulative commencing with Lake Superior and ending with Lake Ontario.

HEAT TRANSFER COEFFICIENT K *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	5.141	5.312	5.998	5.832	4.848	5.444
FEB	4.488	5.231	5.054	4.933	4.542	4.955
MAR	3.676	4.518	4.030	3.995	3.841	4.104
APR	2.769	3.558	2.957	3.049	3.388	3.131
MAY	2.386	3.803	2.423	2.585	3.107	2.763
JUNE	1.885	3.239	2.139	2.373	3.069	2.718
JULY	1.970	3.254	2.460	2.912	3.057	3.074
AUG	2.556	4.004	3.530	3.971	4.064	3.785
SEPT	3.527	5.700	4.878	5.071	5.002	4.940
OCT	4.115	6.511	5.823	5.509	5.261	4.836
NOV	5.209	7.409	6.242	6.401	5.663	5.447
DEC	5.299	6.458	6.034	6.228	5.141	5.225

*$\frac{Btu}{hr\ ft^2\ {}^oF}$

HEAT TRANSFER COEFFICIENT K*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	29.194	30.163	34.056	33.113	27.527	30.912
FEB	25.485	29.701	28.697	28.011	25.788	28.134
MAR	20.871	25.656	22.885	22.686	21.810	23.302
APR	15.725	20.205	16.790	17.314	19.239	17.778
MAY	13.550	21.595	13.757	14.679	17.640	15.689
JUNE	10.705	18.392	12.144	13.475	17.427	15.432
JULY	11.184	18.475	13.969	16.537	17.357	17.458
AUG	14.514	22.733	20.047	22.549	23.079	21.494
SEPT	20.030	32.364	27.701	28.797	28.403	28.050
OCT	23.367	36.972	33.063	31.281	29.873	27.459
NOV	29.577	42.068	35.444	36.346	32.155	30.930
DEC	30.090	36.671	34.260	35.365	29.192	29.669

*$\frac{\text{Watts}}{m^2\ {}^{\circ}C}$

EVAPORATION RATE IN THE YEAR 1973 *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.000	0.007	0.001	0.000	0.015	0.006
FEB	0.000	0.007	0.001	0.000	0.013	0.005
MAR	0.000	0.008	0.001	0.000	0.014	0.006
APR	0.000	0.007	0.001	0.000	0.014	0.005
MAY	0.000	0.008	0.000	0.000	0.014	0.004
JUNE	0.000	0.008	0.000	0.000	0.014	0.005
JULY	0.000	0.008	0.001	0.000	0.015	0.005
AUG	0.000	0.009	0.001	0.000	0.017	0.006
SEPT	0.000	0.009	0.001	0.000	0.017	0.007
OCT	0.000	0.009	0.001	0.000	0.017	0.007
NOV	0.000	0.008	0.001	0.000	0.016	0.006
DEC	0.000	0.008	0.001	0.000	0.015	0.006

*Inches per month (in/month)

EVAPORATION RATE IN THE YEAR 1973 *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.000	0.019	0.002	0.001	0.037	0.015
FEB	0.000	0.017	0.001	0.001	0.033	0.013
MAR	0.000	0.019	0.002	0.001	0.036	0.014
APR	0.000	0.018	0.001	0.001	0.035	0.012
MAY	0.000	0.020	0.001	0.001	0.035	0.011
JUNE	0.000	0.019	0.001	0.001	0.037	0.011
JULY	0.000	0.020	0.001	0.001	0.038	0.014
AUG	0.000	0.022	0.002	0.001	0.043	0.015
SEPT	0.000	0.022	0.002	0.001	0.043	0.017
OCT	0.000	0.023	0.002	0.001	0.043	0.017
NOV	0.000	0.021	0.002	0.001	0.041	0.016
DEC	0.000	0.020	0.002	0.001	0.039	0.015

*Centimetre per month (cm/month)

EVAPORATIVE LOSSES IN THE YEAR 1973*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	2.2	145.1	9.9	1.3	124.9	37.9
FEB	2.1	144.6	9.5	1.2	122.9	36.7
MAR	2.1	146.4	9.3	1.2	123.4	36.1
APR	1.9	141.0	8.4	1.1	120.9	31.8
MAY	1.6	154.7	7.0	1.0	118.8	28.3
JUNE	1.4	151.2	6.7	1.0	127.7	30.5
JULY	1.6	151.9	8.4	1.3	127.0	35.6
AUG	2.1	166.9	10.3	1.5	144.0	39.4
SEPT	2.4	177.5	11.5	1.5	150.0	44.0
OCT	2.5	175.8	11.4	1.5	147.2	42.6
NOV	2.4	169.4	10.9	1.4	141.9	41.7
DEC	2.3	156.1	10.2	1.3	130.9	38.5

*Cubic feet per second (cfs)

EVAPORATIVE LOSSES IN THE YEAR 1973*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.1	4.1	0.3	0.0	3.5	1.1
FEB	0.1	4.1	0.3	0.0	3.5	1.0
MAR	0.1	4.1	0.3	0.0	3.5	1.0
APR	0.1	4.0	0.2	0.0	3.4	0.9
MAY	0.0	4.4	0.2	0.0	3.4	0.8
JUNE	0.0	4.3	0.2	0.0	3.6	0.9
JULY	0.0	4.3	0.2	0.0	3.6	1.0
AUG	0.1	4.7	0.3	0.0	4.1	1.1
SEPT	0.1	5.0	0.3	0.0	4.2	1.2
OCT	0.1	5.0	0.3	0.0	4.2	1.2
NOV	0.1	4.8	0.3	0.0	4.0	1.2
DEC	0.1	4.4	0.3	0.0	3.7	1.1

*Cubic metres per second (m^3/s)

REDUCTION IN OUT-FLOW IN THE YEAR 1973*

	ST.MARYS RIVER	ST.CLAIR RIVER	NIAGARA RIVER	ST.LAWRENCE RIVER
JAN	2.2	158.5	283.4	321.4
FEB	2.1	157.5	280.3	317.1
MAR	2.1	159.0	282.5	318.6
APR	1.9	152.4	273.3	305.1
MAY	1.6	164.4	283.2	311.5
JUNE	1.4	160.3	288.0	318.5
JULY	1.6	163.1	290.1	325.6
AUG	2.1	180.7	324.7	364.1
SEPT	2.4	192.8	342.8	386.9
OCT	2.5	191.1	338.4	381.0
NOV	2.4	184.1	326.0	367.7
DEC	2.3	169.9	300.8	339.3

*Cubic feet per second (cfs)

REDUCTION IN OUT-FLOW IN THE YEAR 1973*

	ST.MARYS RIVER	ST.CLAIR RIVER	NIAGARA RIVER	ST.LAWRENCE RIVER
JAN	0.1	4.5	8.0	9.1
FEB	0.1	4.5	7.9	9.0
MAR	0.1	4.5	8.0	9.0
APR	0.1	4.3	7.7	8.6
MAY	0.0	4.7	8.0	8.8
JUNE	0.0	4.5	8.2	9.0
JULY	0.0	4.6	8.2	9.2
AUG	0.1	5.1	9.2	10.3
SEPT	0.1	5.5	9.7	11.0
OCT	0.1	5.4	9.6	10.8
NOV	0.1	5.2	9.2	10.4
DEC	0.1	4.8	8.5	9.6

*Cubic metres per second (m^3/s)

EVAPORATION RATE IN THE YEAR 2000*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.000	0.035	0.032	0.044	0.057	0.083
FEB	0.000	0.032	0.027	0.038	0.051	0.072
MAR	0.000	0.036	0.030	0.042	0.057	0.079
APR	0.000	0.033	0.026	0.038	0.054	0.067
MAY	0.000	0.038	0.022	0.035	0.055	0.062
JUNE	0.000	0.036	0.021	0.034	0.057	0.064
JULY	0.000	0.037	0.027	0.043	0.058	0.078
AUG	0.000	0.041	0.033	0.050	0.066	0.086
SEPT	0.000	0.042	0.035	0.051	0.067	0.093
OCT	0.000	0.043	0.036	0.051	0.068	0.093
NOV	0.000	0.040	0.034	0.048	0.063	0.088
DEC	0.000	0.038	0.033	0.046	0.060	0.084

*Inches per month (in/month)

EVAPORATION RATE IN THE YEAR 2000 *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.001	0.090	0.081	0.111	0.146	0.210
FEB	0.001	0.081	0.070	0.097	0.130	0.184
MAR	0.001	0.090	0.075	0.106	0.144	0.200
APR	0.001	0.084	0.066	0.096	0.137	0.171
MAY	0.001	0.095	0.057	0.089	0.139	0.157
JUNE	0.001	0.090	0.053	0.087	0.144	0.163
JULY	0.001	0.094	0.068	0.110	0.148	0.197
AUG	0.001	0.103	0.084	0.128	0.168	0.219
SEPT	0.001	0.106	0.090	0.129	0.169	0.236
OCT	0.001	0.108	0.092	0.131	0.172	0.236
NOV	0.001	0.101	0.085	0.122	0.160	0.224
DEC	0.001	0.096	0.083	0.118	0.153	0.213

*Centimetre per month (cm/month)

EVAPORATIVE LOSSES IN THE YEAR 2000*

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	11.6	684.0	484.6	203.8	493.7	539.3
FEB	11.2	681.7	464.0	195.7	485.6	522.4
MAR	11.0	690.3	453.8	193.6	487.8	513.6
APR	10.1	664.5	410.0	181.8	477.9	452.2
MAY	8.6	729.4	342.5	163.5	469.7	401.6
JUNE	7.2	712.7	328.3	165.2	504.7	433.1
JULY	8.2	716.1	407.7	202.3	502.0	505.5
AUG	10.8	786.8	504.1	234.4	568.9	560.7
SEPT	12.5	836.8	558.7	243.2	592.6	626.2
OCT	13.0	828.6	556.2	239.5	581.9	605.9
NOV	12.8	798.5	531.3	231.2	560.8	592.7
DEC	12.1	735.8	498.7	215.4	517.2	547.3
Average	10.8	738.8	461.7	205.8	520.2	525.0

*Cubic feet per second (cfs)

EVAPORATIVE LOSSES IN THE YEAR 2000 *

	LAKE SUPERIOR	LAKE MICHIGAN	LAKE HURON	GEORGIAN BAY	LAKE ERIE	LAKE ONTARIO
JAN	0.3	19.4	13.7	5.8	14.0	15.3
FEB	0.3	19.3	13.1	5.5	13.8	14.8
MAR	0.3	19.5	12.8	5.5	13.8	14.5
APR	0.3	18.8	11.6	5.1	13.5	12.8
MAY	0.2	20.7	9.7	4.6	13.3	11.4
JUNE	0.2	20.2	9.3	4.7	14.3	12.3
JULY	0.2	20.3	11.5	5.7	14.2	14.3
AUG	0.3	22.3	14.3	6.6	16.1	15.9
SEPT	0.4	23.7	15.8	6.9	16.8	17.7
OCT	0.4	23.5	15.8	6.8	16.5	17.2
NOV	0.4	22.6	15.0	6.5	15.9	16.8
DEC	0.3	20.8	14.1	6.1	14.6	15.5

*Cubic metres per second (m^3/sec)

REDUCTION IN OUT-FLOW IN THE YEAR 2000*

	ST.MARYS RIVER	ST.CLAIR RIVER	NIAGARA RIVER	ST.LAWRENCE RIVER
JAN	11.6	1384.0	1877.7	2417.0
FEB	11.2	1352.6	1838.2	2360.6
MAR	11.0	1348.7	1836.5	2350.1
APR	10.1	1266.3	1744.2	2196.4
MAY	8.6	1244.0	1713.6	2115.3
JUNE	7.2	1213.4	1718.2	2151.2
JULY	8.2	1334.3	1836.2	2341.8
AUG	10.8	1536.1	2105.0	2665.7
SEPT	12.5	1651.2	2243.8	2870.0
OCT	13.0	1637.3	2219.2	2825.0
NOV	12.8	1573.8	2134.6	2727.3
DEC	12.1	1461.9	1979.2	2526.5
Average	10.8	1416.9	1937.2	2462.0

*Cubic feet per second (cfs)

REDUCTION IN OUT-FLOW IN THE YEAR 2000*

	ST.MARYS RIVER	ST.CLAIR RIVER	NIAGARA RIVER	ST.LAWRENCE RIVER
JAN	0.3	39.2	53.2	68.4
FEB	0.3	38.3	52.1	66.8
MAR	0.3	38.2	52.0	66.5
APR	0.3	35.9	49.4	62.2
MAY	0.2	35.2	48.5	59.9
JUNE	0.2	34.4	48.7	60.9
JULY	0.2	37.8	52.0	66.3
AUG	0.3	43.5	59.6	75.5
SEPT	0.4	46.8	63.5	81.3
OCT	0.4	46.4	62.8	80.0
NOV	0.4	44.6	60.4	77.2
DEC	0.3	41.4	56.0	71.5

*Cubic metres per second (m^3/sec)

APPENDIX E

EVAPORATIVE LOSSES DUE TO WET COOLING TOWERS

(a) Painesville Thermal Electric Generating Plant[11] Painesville, Ohio

Average consumption of cooling water	.98 cfs
Capacity power generation	35.5 Mwh
Average waste heat rejection	11,008 Btu/kwh
Total waste heat rejection	3.91×10^{8} Btu/hr
Consumption of cooling water per Btu/hr	2.50×10^{-9} cfs

(b) According to 1973 Federal Power Commission Report[11] Evaporative Loss Can Be Estimated at 50 Per Cent of Total Waste Heat

$$\text{Evaporative losses per Btu/hr} = \frac{1}{1{,}065 \times 62.4 \times 3{,}600}$$

$$= 2.20 \times 10^{-9} \text{ cfs}$$

(c) According to McVehil[18] the Two Generating Units at Zion Generating Plant Would Produce Waste Heat at a Rate of 14.3×10^{9} Btu/hr

Evaporative losses would be 18,000 gal/min

$$\text{Consumption of cooling water per Btu/hr} = \frac{18{,}000 \times 2.23 \times 10^{-3}}{14.3 \times 10^{9}}$$

$$= 2.86 \times 10^{-9} \text{ cfs}$$

WASTE HEAT INPUTS* DUE TO
THERMAL ELECTRIC
GENERATING STATIONS

	1973	2000
Lake Superior	.6	5.3
Lake Michigan	58.3	312.4
Lake Huron	4.0	224.6
Georgian Bay	0.0	97.2
Lake Erie	44.5	215.4
Lake Ontario	14.4	263.2
	121.8	1118.1

*10^9 Btu/hr