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HYDROLOGIC MODELS OF THE GREAT LAKES

by

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F I N A L   R E P O R T

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PREFACE

This final report is for OWRR Project B-062-ILL entitled "Hydrologic Models of the Great Lakes" and covers a study period of July 1971 to January 1974. This project is a continuation and extension of OWRR Project B-035-ILL entitled "Study of the Hydrology for Models of the Great Lakes."

The following reports and journal articles related to Great Lakes hydrology have been published:

Meredith, D.D., "Modeling of the Great Lakes water system," Water Resources Bulletin, J. American Water Resources Assoc., 6 (1), 55-64, 1970.

Jones, D.M.A., and D.D. Meredith, "Great Lakes hydrology by months, 1946-1965," Research Report No. 53, Water Resources Center, University of Illinois, Urbana, April 1972.

Buetikofer, L.B. and D.D. Meredith, "Annotated bibliography on Great Lakes hydrology," Research Report No. 56, Water Resources Center, University of Illinois, Urbana, September 1972.

Jones, D.M.A., and D.D. Meredith, "Great Lakes hydrology by months 1946-1965," Proc. 15th Conference Great Lakes Research, International Assoc. for Great Lakes Research, pp. 477-506, 1972.

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Buffalo, N.Y. Dale D. Meredith

1. INTRODUCTION

1.1 Background

The Great Lakes constitute the earth's greatest expanse of fresh water and therefore represent an important natural resource. In order to achieve the maximum benefit from a natural resource, it must be managed or used in the most efficient way to achieve the objectives of those who enjoy the use of the resource. However, before a resource can be managed or allocated the manager must have an understanding of the extent and behavior of the resource and the limitations of his possible alternatives.

This report presents some of the findings from a study undertaken to develop and analyze hydrologic models of the Great Lakes in order to achieve a better understanding of the behavior of the Great Lakes as a system. These findings also allow the manager to gain a perspective of the effect of changes in the behavior of different individual hydrologic components.

1.2 Scope of Report

Chapter 2 presents the results of a study to determine the effect that thermal expansion and contraction of water has on the value of the net basin supply as determined from a water balance study.

The determination of probability distributions for each individual hydrologic component is explained in Chapter 3. Chapter 4 presents the series of linear regression equations which were estimated for the hydrologic components of each lake.

The summary and conclusions are presented in Chapter 5.

2. EFFECTS OF TEMPERATURE ON NET BASIN SUPPLY VALUES FROM WATER BALANCE STUDIES

2.1 Introduction

From the conservation of matter principle, a water balance equation can be written for each lake as follows:

$$\Delta S = P + R - E + I - Q \pm D \pm G \tag{2.1}$$

where ΔS is the change in amount of water stored in the lake, P is the amount of precipitation on the lake's surface, R is the amount of runoff into the lake from the surrounding land area, E is the amount of evaporation from the lake's surface, I is the amount of inflow from the upstream lake, Q is the amount of outflow from the lake through its natural outlet, D is the amount of diversion into (+) or out of (-) the lake and G is the amount of groundwater flow entering (+) or leaving (-) the lake. All variables are expressed in the same units and for the same period of time. Obviously, any variable may be equal to zero for a lake where it is not pertinent. The change in amount of water stored in the lake, ΔS, is a positive number when supplies exceed removals and is a negative number when removals exceed supplies.

Water level gages are maintained on the Great Lakes, rivers which connect the lakes and channels in which water is diverted into or out of the lakes (Canada, 1968; U.S. Department of Commerce, 1971). The change in amount of water stored in a lake is calculated from the area of the lake and the measured change in the elevation of water surface over a period of time. The amount of inflow from the upstream lake, outflow from the lake through its natural outlet and diversions into and out of the lake are determined from the water level records and rating curves which give the relationship between the amount of flow past a point and the surface elevation of the water at that point (U.S. Army Engineering Division, North Central, 1965).

The amount of precipitation, evaporation and runoff into the lake from the surrounding land areas has been determined for each of the Great Lakes for each month of calendar years 1946-1965 (Jones and Meredith, 1972). Ground water can usually be considered to be insignificant when determining Great Lakes water balances (Bergstrom and Hanson, 1962; Haefeli, 1972).

Equation (2.1) is not satisfied when the precipitation, evaporation, runoff, river flow,and change in storage values are substituted into it (Jones and Meredith, 1972).

The consideration of the thermal expansion of water would change the values of the ΔS in equation (2.1) and would have the effect of decreasing ΔS for months when the temperature is increasing and increasing ΔS when the temperature is decreasing. In order to compute the effect of thermal expansion, relationships for relating thermal expansion to water temperature, volume of lake water, temperature of the lake water, and temperature variation must be known.

2.2 Thermal Expansion

The equation for thermal expansion of water (Hodgman, 1958) is

$$V_t = V_o(1 - 6.427 \times 10^{-5}t + 8.5053 \times 10^{-6} t^2 - 6.79 \times 10^{-8}t^3) \quad (2.2)$$

where V_o is the volume of water at 0°C, t is the temperature of water in C, and V_t is the volume of water at t° C. This equation is valid for a range of temperatures from 0° to 33° C. The water temperatures in the Great Lakes are within this range.

2.3 Volume of Lake Water

The volume of water in each lake was determined from the depth area relationships presented by Anderson (1961). The depth-area values for each lake are given in Table 2.1.

2.4 Surface Water Temperature

The monthly surface water temperatures as reported by Richards and Irbe (1969) and Jones and Meredith (1972) for the months of January 1946 through December 1965 were used.

2.5 Monthly Temperature Profiles

The temperature profiles at the beginning of each month for each lake are presented in Table 2.1. These temperature profiles were obtained as follows:

2.5.1 Lake Ontario

The temperature profiles for the beginning of each month for Lake Ontario were compiled from Rodgers and Anderson (1961; 1963).

2.5.2 Lake Erie

The temperature profiles for the beginning of August and September were synthesized from data by Hamlin (1971) and Anderson and Rodgers (1963) resepectively. The remaining profiles were obtained by synthesizing information from Potos (1970), Hamlin (1971), Beeton (1963) and the Lake Ontario profiles.

2.5.3 Lake Michigan

Data from Church (1942; 1945), Ayers et al (1958), Beeton and Moffett (1964), Noble (1965, 1967) and Noble and Wilkerson (1970) were compiled and synthesized to obtain the Lake Michigan water temperature profiles.

Table 2.1 Great Lakes depth-area relationships and water temperature profiles at beginning of each month

DEPTH	AREA[a]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
		TEMPERATURE[b]											
LAKE ONTARIO													
0	7520	4.2	2.4	2.0	1.8	2.9	8.8	14.3	22.5	22.5	18.0	12.6	8.5
50	6500	4.3	2.5	2.0	1.8	2.9	5.0	9.0	19.5	14.6	16.0	12.3	8.5
100	5600	4.8	2.7	2.1	1.8	2.8	4.1	5.2	5.2	5.5	7.0	8.5	9.0
200	4300	5.2	3.2	2.5	1.9	2.9	3.9	4.1	4.1	4.1	4.1	5.7	9.0
400	2250	4.8	3.7	3.0	2.6	2.8	3.5	4.0	4.0	4.0	4.0	4.8	4.2
500	400	4.4	4.2	3.5	3.4	3.0	3.2	3.8	4.0	4.0	4.0	4.0	4.1
800	0	4.4	4.2	3.5	3.4	3.0	3.2	3.8	4.0	4.0	4.0	4.0	4.1
LAKE ERIE													
0	9930	3.7	2.5	2.0	1.7	3.8	11.4	16.4	23.0	26.0	19.5	15.0	9.1
20	9465	3.7	2.5	2.0	1.7	3.5	8.9	13.1	23.0	26.0	19.1	14.9	9.1
30	9233	3.8	2.6	2.0	1.7	3.4	7.6	12.9	22.0	25.0	18.9	14.9	9.1
40	9000	3.8	2.6	2.0	1.7	3.2	6.3	11.8	18.0	25.0	18.7	14.8	9.1
50	6000	3.8	2.6	2.0	1.7	3.0	5.0	10.7	15.0	21.0	16.7	14.8	9.0
80	1100	3.9	2.6	2.1	1.7	3.0	4.5	7.4	6.0	12.0	10.7	11.8	9.0
100	990	4.0	2.7	2.2	1.7	2.9	4.1	5.2	5.8	6.1	7.0	9.5	9.0
200	0	4.4	3.0	2.3	1.8	2.8	3.9	4.1	4.5	4.7	4.7	5.5	5.7
LAKE HURON													
0	23010	4.0	1.6	1.6	1.0	3.1	6.1	14.1	19.0	20.0	13.0	11.0	9.7
30	20600	4.0	2.0	2.0	2.0	2.1	4.9	12.2	19.0	20.0	12.5	10.9	8.9
50	19000	4.0	2.0	2.0	2.0	2.1	4.5	11.0	16.0	19.0	12.2	10.8	8.4
100	15500	4.0	2.0	2.0	2.0	2.1	3.6	7.0	5.9	9.0	9.3	10.7	6.5
200	9800	4.0	2.0	2.0	2.0	2.1	3.6	5.4	5.4	5.5	4.5	5.0	5.7
400	2300	4.0	4.0	3.5	2.3	2.5	3.5	5.0	5.0	5.0	3.9	4.6	4.0
500	1250	4.0	3.0	3.0	2.5	3.0	3.4	5.0	5.0	5.0	3.9	4.4	4.0
600	200	3.9	3.5	3.0	2.7	3.0	3.3	5.0	5.0	5.0	3.9	4.0	3.8
750	0	3.4	3.0	3.0	3.0	3.0	3.3	5.0	5.0	5.0	3.9	3.8	3.5
LAKE MICHIGAN													
0	22400	3.0	1.0	1.0	1.9	6.0	9.0	16.4	21.7	21.0	15.2	12.3	9.0
30	20980	4.0	2.0	1.9	2.0	2.0	4.9	14.0	21.0	20.4	14.8	12.3	8.6
50	19200	4.0	2.0	1.9	2.0	2.0	4.5	9.0	15.4	15.2	14.5	12.3	8.3
100	16500	4.0	2.0	2.0	2.0	2.0	3.6	6.0	6.0	6.3	10.4	11.0	6.4
200	12200	4.0	2.0	2.0	2.0	2.0	3.5	4.2	4.5	4.6	4.5	5.0	5.7
400	5800	4.0	3.9	3.4	3.0	2.6	3.5	3.8	4.0	3.9	3.9	4.2	4.0
500	2000	3.5	4.0	2.9	3.0	3.0	3.4	3.9	3.9	3.9	3.9	3.8	3.5
680	1480	3.5	3.0	2.9	3.0	3.0	3.3	3.7	3.8	3.9	3.9	3.7	3.5
900	700	6.0	6.0	6.0	6.0	6.0	4.5	3.7	3.7	3.9	3.9	4.5	6.0
920	0	6.0	6.0	6.0	6.0	6.0	4.5	3.7	3.7	3.9	3.9	4.5	6.0
LAKE SUPERIOR													
0	31820	2.0	.5	.5	1.7	2.2	2.8	3.1	9.8	15.0	9.7	4.6	2.5
30	30728	2.0	1.8	1.7	1.7	2.2	2.8	3.1	9.6	14.3	8.9	4.5	2.6
50	30000	2.1	1.8	1.7	1.8	2.2	2.7	3.1	9.4	10.0	8.4	4.5	2.7
100	29500	2.1	1.8	1.8	1.8	2.2	2.7	3.1	9.1	5.5	7.1	4.5	2.8
200	26000	2.3	1.9	1.8	1.9	2.2	2.6	3.1	8.4	3.9	4.5	4.4	3.0
400	20000	2.9	2.5	2.2	2.0	2.2	2.6	3.1	6.9	3.9	4.3	4.2	3.2
600	10000	3.4	3.1	2.7	2.1	2.2	2.5	3.1	5.4	3.9	4.1	4.0	3.5
800	3800	3.5	3.1	2.7	2.2	2.2	2.5	3.1	3.9	3.9	4.0	3.9	3.6
1000	100	3.5	3.1	2.7	2.2	2.2	2.5	3.1	3.9	3.9	4.0	3.9	3.6
1300	0	3.5	3.1	2.7	2.2	2.2	2.5	3.1	3.9	3.9	4.0	3.9	3.6

[a] Source: Anderson, 1961.

[b] Compiled from various sources as explained in text.

2.5.4 Lake Huron

Data from Ayers et al (1956), Hachey (1952), Rodgers (1965) and the Lake Michigan profiles were used to develop water temperature profiles for Lake Huron.

2.5.5 Lake Superior

Data for June through October from Beeton, Johnson and Smith (1959) and for September from Anderson and Rodgers (1963) and the Lake Michigan temperature profiles were used to develop the Lake Superior water temperature profiles.

2.6 Computations

The water temperature profile for each month was converted to a dimensionless profile by dividing the temperature at each depth by the temperature at zero depth. The dimensionless profile was then assumed to be the same for the beginning of that month for each year of the period of analysis.

The surface water temperatures reported by Richards and Irbe (1969) and Jones and Meredith (1972) are average monthly temperatures. The beginning of month surface water temperature was obtained for each month by averaging the surface water temperature for that month and the surface water temperature for the preceeding month. The water temperature profile for the beginning of each month was then obtained by multiplying the dimensionless profile values for that month by the beginning of month surface water temperature for that month.

The depth-area relationship for each lake was used to compute the volume of water in the lake. This volume was assumed to be V_o for equation 2.2. V_t was then computed for the beginning of each month. The difference between V_t at the beginning of a month and the beginning of the next month is the volume change for that month due to the thermal expansion or contraction of the water.

2.7 Results

The corrections that should be added to ΔS of equation 2.1 in order to eliminate the effects of thermal expansion and contraction of water are listed in Table 2.2. The corrections vary from zero such as January 1949 on Lake Ontario up to the same order of magnitude as the net basin supply such as October 1950 on Lake Michigan. These corrections can only be considered as approximations because of the assumptions made in the derivation of the water temperature profiles. However, the results indicate that for some months of the year the temperature effects on lake levels are on the same order of magnitude as the net basin supply of the lake. This means that a computation of monthly net basin supply without a consideration of thermal expansion of water may result in an error of as much as 100 percent for some months.

Table 2.2 Corrections that should be added to ΔS of equation 2.1 in order to eliminate effects of thermal expansion and contraction of water

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LAKE ONTARIO												
1946	-.4	.4	-.0	-.2	.0	-2.0	-.5	-.8	.1	2.1	.9	.4
1947	.1	-.7	-.3	.8	.0	-1.9	-1.4	-2.1	.7	3.7	1.5	.1
1948	-.9	-.1	.9	.0	-.2	-2.2	-.7	-1.2	.5	2.6	1.0	.3
1949	0.0	.1	-.0	.1	-.5	-2.7	-.3	-.6	.8	2.7	1.2	.2
1950	-.0	-.2	-.1	.4	-.2	-1.2	-.8	-1.5	-.2	2.2	1.1	.4
1951	.0	-.6	.1	.5	-.4	-2.8	-.4	-.5	.8	2.1	1.0	.2
1952	-.1	-.1	.0	-.1	-.2	-2.9	-.8	-1.0	1.1	3.0	.7	.0
1953	.0	.1	-.2	-.2	.1	-2.8	-.9	-.8	.5	2.0	.9	1.2
1954	.1	0.0	-.2	-.2	.0	-2.4	-.4	-1.0	.4	2.3	1.1	.4
1955	-.2	-.5	.5	-.1	-.3	-3.3	-.4	-.9	.7	2.4	1.7	.2
1956	-.3	-.3	.1	.5	-.2	-2.3	-.8	-.9	.6	1.8	1.1	.7
1957	-.4	-.1	.2	.2	-.3	-1.9	-.6	-1.0	.3	2.0	1.2	.3
1958	-.4	-.5	.7	.1	-.2	-1.7	-.7	-.9	.6	1.5	1.1	.3
1959	-.3	-.5	.2	.7	-.3	-2.9	-.7	-1.6	.8	3.5	1.0	.0
1960	-.4	-1.0	.5	.9	-.1	-1.8	-.7	-1.5	.4	2.7	1.0	-.2
1961	-.8	-.8	.3	1.0	.3	-1.3	-1.2	-1.4	.3	2.5	1.1	.0
1962	-.9	-.8	.6	1.2	-.2	-2.9	-.7	-.8	.6	2.3	1.3	.3
1963	-.8	-.4	.7	.4	-.1	-1.9	-.2	-.8	-.2	1.6	1.3	.3
1964	-.1	-.2	.1	.1	-.2	-2.7	-.5	-.7	.3	1.8	.8	.9
1965	-.2	-.7	-.1	.7	.1	-1.3	-.9	-1.2	.2	2.1	.9	.4
LAKE ERIE												
1946	-.1	-.2	.2	-.3	-1.0	-3.3	-3.6	-.7	2.9	2.9	2.7	.6
1947	-.4	-.3	.3	.3	-.9	-3.3	-4.1	-1.5	3.2	3.6	2.9	.1
1948	-.5	.1	.5	-.1	-1.1	-3.5	-3.9	-.9	3.3	3.4	2.5	.4
1949	-.3	-.1	.3	-0.0	-1.4	-4.3	-3.9	.7	3.7	2.6	2.3	.4
1950	-.1	-.4	-0.0	.5	-1.1	-3.4	-3.4	-.4	2.9	2.9	2.6	-.1
1951	-.3	-0.0	.4	.1	-1.2	-3.8	-3.5	-.2	3.7	3.3	2.9	-.1
1952	-.4	-.1	.5	.0	-1.3	-4.0	-3.8	-.3	3.8	3.6	2.0	.2
1953	-.3	-.0	.3	-.3	-1.1	-3.5	-4.1	-.8	3.4	3.3	2.6	.5
1954	-.5	-.0	.4	-.2	-1.1	-3.8	-3.9	-.3	3.3	3.2	2.6	.3
1955	-.3	-.1	.4	-.4	-1.4	-3.9	-3.6	-.3	3.3	3.6	2.5	-.2
1956	-.3	-0.0	.3	.2	-1.1	-3.0	-3.3	-.6	3.1	2.2	2.3	.5
1957	-.5	.1	.3	.0	-1.2	-3.6	-3.8	-.5	3.3	3.5	2.3	.2
1958	-.4	-.1	.4	.0	-.9	-3.5	-4.2	-.2	3.7	2.6	2.5	-.1
1959	-.3	-0.0	.4	.1	-1.4	-4.0	-4.0	-.9	4.0	4.0	2.4	.1
1960	-.4	-.1	.3	.3	-1.0	-3.4	-3.8	-1.6	2.6	3.8	3.3	.0
1961	-.3	.1	.3	.1	-.9	-3.3	-4.3	-1.5	3.2	3.8	2.8	.4
1962	-.6	-0.0	.6	-.2	-1.3	-3.2	-3.3	-1.0	2.5	3.3	3.0	.0
1963	-.4	-0.0	.6	-.1	-1.2	-3.5	-3.6	-.5	2.8	2.6	3.2	.4
1964	-.5	.1	.4	.1	-1.2	-3.8	-3.6	-.2	3.2	2.9	2.4	.3
1965	-.6	-0.0	.4	.3	-.9	-3.3	-3.5	-.7	2.9	3.2	2.1	.2

Table 2.2 continued

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LAKE MICHIGAN-HURON												
1946	-6.1	3.9	2.1	-.3	-.5	-10.1	-17.4	-6.9	-4.1	12.4	23.8	4.3
1947	-4.3	-1.5	-1.4	.5	4.9	-9.4	-22.5	-13.2	-4.9	23.4	27.2	-1.2
1948	-3.5	1.0	3.7	-.8	1.9	-13.1	-24.5	-7.5	2.3	20.9	20.9	2.2
1949	-2.6	-1.1	2.7	-.2	-4.3	-16.1	-17.9	.1	-.3	15.8	21.7	1.9
1950	-2.2	-3.1	-.2	-.9	4.1	-13.7	-17.4	-4.6	.3	16.6	20.0	-.9
1951	-1.5	-2.1	1.6	1.1	.2	-13.3	-13.7	-2.6	-.4	19.3	13.4	-.5
1952	-3.1	.6	1.6	-1.2	1.1	-15.0	-19.5	-5.1	4.4	15.4	15.8	2.5
1953	-5.3	-3.1	7.0	-1.5	.9	-13.6	-19.6	-8.1	-2.5	21.6	21.2	2.7
1954	-1.9	.8	.9	-3.3	1.8	-12.6	-14.8	-4.8	-4.4	14.1	20.4	3.1
1955	-.7	-3.0	3.2	-.7	-.9	-21.1	-29.5	8.8	6.3	15.2	20.8	-1.9
1956	-1.9	-2.0	4.7	-2.1	2.0	-10.7	-17.9	-3.0	3.5	10.4	18.2	2.2
1957	-2.7	-.2	2.5	-2.7	.7	-12.0	-13.5	-3.2	-3.2	17.3	15.6	1.1
1958	-1.6	-1.8	1.4	-.5	.0	-13.2	-23.5	-1.4	3.0	14.5	21.4	.7
1959	-4.6	-3.8	5.0	2.4	-3.0	-15.4	-21.9	-5.0	3.9	25.4	14.2	-.8
1960	-1.8	-2.4	-.8	3.1	.1	-10.0	-17.2	-9.3	-1.2	20.1	19.7	.9
1961	-2.6	-.2	2.5	-1.6	.3	-11.1	-21.7	-14.0	-.3	24.0	23.7	2.6
1962	-3.6	-3.4	2.2	2.0	-.2	-9.6	-18.3	-8.0	.1	15.2	20.5	2.2
1963	-3.9	-5.0	2.2	3.0	1.1	-12.2	-19.9	-3.8	-5.7	7.1	20.6	6.1
1964	-5.5	-.3	4.8	.3	-3.6	-16.3	-15.5	5.7	3.7	7.9	16.5	2.8
1965	-.8	-5.0	-2.5	4.1	1.6	-11.6	-16.1	-2.4	.7	11.8	17.5	2.6
LAKE SUPERIOR												
1946	-4.9	-6.5	-5.0	6.8	7.6	.7	-15.7	9.9	.6	-.5	3.6	3.5
1947	-4.0	-8.7	-4.1	6.8	6.0	3.0	-35.2	23.5	1.5	-5.1	8.2	7.8
1948	-.5	-21.1	4.2	6.8	7.3	.8	-20.4	11.4	-2.5	-1.5	6.7	7.9
1949	-4.0	-8.7	-4.1	6.8	7.8	.9	-14.2	7.9	-1.1	-2.9	5.6	5.7
1950	-.6	-18.0	.8	5.8	2.0	8.4	-9.9	4.1	.7	-1.6	1.6	4.6
1951	-2.2	-12.8	-2.2	4.6	9.9	-4.6	-14.3	14.9	2.2	-.8	1.7	2.5
1952	-3.0	-10.5	-3.2	6.8	8.6	-1.8	-10.4	6.6	-.2	.4	3.1	3.2
1953	-5.2	-6.5	-5.0	6.8	6.5	2.7	-20.9	12.1	-1.2	-3.1	6.2	7.4
1954	-.4	-19.4	1.9	6.8	2.5	7.5	-10.9	4.3	-.0	-2.3	4.3	4.6
1955	-3.1	-10.8	-3.2	6.8	8.6	-3.2	-24.3	17.9	-1.5	-2.5	9.9	5.0
1956	-5.2	-6.3	-5.0	6.8	1.8	7.9	-4.9	.3	-.4	-4.0	3.0	6.0
1957	-1.7	-24.6	7.9	6.8	7.7	-.9	-22.2	16.6	1.1	-2.1	5.0	4.4
1958	-9.4	.9	-7.4	6.8	9.3	-4.5	-17.2	13.1	.3	-7.7	4.6	6.2
1959	-2.1	-18.4	0.0	7.8	9.9	-1.9	-19.1	14.7	-.3	-.5	6.4	2.4
1960	-7.8	-1.6	-6.6	6.8	7.8	.3	-13.3	8.2	-.7	-3.1	5.0	5.4
1961	-.3	-20.7	3.1	6.8	7.8	1.1	-12.3	6.0	-1.2	-2.2	5.0	5.4
1962	-.3	-20.7	3.1	6.8	7.8	.3	-11.6	7.2	.2	-2.9	3.2	5.4
1963	-.3	-20.7	3.1	6.8	7.8	.3	-15.1	9.6	-1.2	-5.4	4.5	11.7
1964	-7.5	-1.6	-9.7	7.8	11.3	-8.0	-19.1	20.6	3.0	-1.8	1.7	3.8
1965	-.3	-20.7	0.0	7.8	9.9	.3	-5.8	3.0	1.1	-2.4	1.7	3.8

3. DETERMINATION OF PROBABILITY DISTRIBUTIONS

3.1 Introduction

Before attempting to develop regression equations relating the hydrologic components for each lake, an attempt was made to determine the probability distribution of each individual hydrologic component. The Kolmogorov-Smirnov test was used as the goodness-of-fit test.

3.2 Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test concentrates on the deviations between the hypothesized cumulative distribution function and the observed cumulative distribution function (Ostle, 1963). A statistic, D, is computed as the largest of the absolute values of the, n, differences between the hypothesized cumulative distribution function and the observed cumulative distribution function, where n is the sample size. If, for a chosen significance level, the observed value of D is greater than or equal to the critical value of D, the hypothesis will be rejected. The significance level, α, is a measure of the possibility of rejecting the hypothesis when in fact it is true. For a sample size of 20 the following table is abstracted from Ostle (1963).

Level of Significance α	Critical Value of D
0.20	0.231
0.15	0.246
0.10	0.264
0.05	0.294
0.01	0.356

The rejection of a hypothesis when in fact it is true is a type I error. The probability of making a type I error is given by α. The probability of a type II error, which is one of accepting the hypothesis when it is not true, increases as α decreases. Therefore, α must be chosen considering both the probability of accepting the hypothesis when it is not true and of rejecting the hypothesis when it is true.

3.3 Hydrologic Components for Each Lake

An attempt was made to determine the probability distribution for each hydrologic component for each month for each lake. For example, the precipitation values on Lake Superior for January are accepted to be normally distributed at the 20 percent significance level, i.e. $D \leqq 0.231$.

The values of temperature over the land and precipitation on the land used in the regression analysis were also analyzed to determine their probability distributions. The temperature over the land and the precipitation on the land values were obtained by selecting appropriate weather stations in each lake basin and using the theisson polygon method to determine the basin averages. The stations utilized in each basin are indicated below.

Lake Superior

Data from Cameron Falls and White River, Ontario; Grand Marias and Duluth, Minn.; Ironwood, Houghton, and Newberry State Hospital, Mich. weather stations were used to obtain the temperature and precipitation over the land portion of the basin.

The precipitation on the lake surface, evaporation from the lake surface, runoff into the lake, temperature over the land, precipitation on the land surface, and lake surface water temperature values are accepted as normally distributed for each month at the 20 percent significance level except for runoff into the lake during August and surface water temperature during March, April, May and June. The runoff into the lake during August and the June surface water temperature are accepted as normally distributed at the 5 percent significance level. The surface water temperature for the months of March, April and May are assumed to be the same each year which results in a standard deviation of zero which precludes the determination of a probability distribution for these months.

Lake Michigan

Data from weather stations at Oshkosh, Wisconsin, and Iron Mountain, Germfish Wildlife Refuge, East Jordan, Cadillac Waterworks, Baldwin State Forest, Grand Rapids, and Battle Creek, Michigan, were used to determine the temperature and precipitation over the land.

The precipitation on the lake surface, evaporation from the lake surface, runoff into the lake, temperature over the land, precipitation on the land surface, and lake surface water temperature values are accepted as normally distributed for each month at rhe 20 percent significance level except for runoff into the lake during October and November. The runoff into the lake is accepted as normally distributed at the 5 percent significance level for October and at the 15 percent significance level for November.

Lake Huron

Data from weather stations at Turbine, North Bay, Beatrice, and Walkerton, Ontario; Dow Chemical at Midland, West Branch at Lupton, and Vanderbilt Trout Station, Michigan were used to determine the temperature and precipitation values for the land portion of the basin.

The precipitation on the lake surface, evaporation from the lake surface, runoff into the lake, temperature over the land, precipitation on the land surface, and lake surface water temperature values are accepted as normally distributed for each month at the 20 percent significance level except for runoff into the lake during October which is accepted as normally distributed at the 15 percent significance level.

Lake Michigan-Huron

If the values of two variables are normally distributed, their sum is normally distributed. The above named variables are accepted as normally distributed for each month for Lake Michigan-Huron at the 20 percent significance level except for runoff into the lake during October which is accepted as normally distributed at the 5 percent significance level.

Lake Erie

Data for weather stations at Ridgeton, Ontario, Napolean, Tiffin, Cleveland, and Caledonia, Ohio; and Gowanda State Hospital at Fredonia, New York were used to determine the temperature over the land and precipitation on the land surface in the basin.

The precipitation on the lake surface, evaporation from the lake surface, runoff into the lake, temperature over the land, precipitation on the land surface, and lake surface water temperature values are accepted as normally distributed for each month at the 20 percent significance level except for runoff into the lake for July, August, September, and October and lake surface water temperature for January, February, and March. The runoff into the lake are accepted as normally distributed for July at the 15 percent significance level, for September and October at the 5 percent significance level and for August at the 1 percent significance level. The lake surface water temperature is accepted as normally distributed for January at the 15 percent level, for March at the 5 percent level and for February at the 1 percent significance level.

Lake Ontario

Data from weather stations at Brampton and Lindsay, Ontario; Beaver Falls, Syracuse, and Mt. Morris (Rochester), New York were used to determine the temperature over the land and precipitation on the land surface.

The precipitation on the lake, evaporation from the lake surface, runoff into the lake, temperature over the land, precipitation on the land surface and lake surface water temperature are accepted as normally distributed for each month at the 20 percent level except for the lake surface water temperature for October which is accepted as normally distributed at the 10 percent significance level.

4. REGRESSION ANALYSIS

4.1 Introduction

Regression analysis was performed to determine if there exists relationships among the precipitation on the lake, evaporation from the lake surface, runoff into the lake, lake surface water temperature, temperature over the land surface and precipitation on the land surface for each lake. In addition regression analysis was performed to determine if there exists relationships between what occurs on one lake and what occurs on other lakes. Only linear relationships were investigated.

The linear relationships investigated are of the following type:

$$Y_t = B_o + B_1Y_{t-1} + B_2Y_{t-2} + B_3Y_{t-3} + B_4X_{1,t}$$

$$+ B_5X_{1,t-1} + B_6X_{1,t-2} + B_7X_{1,t-3} + \ldots + B_NX_{m,t-3} \quad (4.1)$$

where Y_t is the dependent variable in month t, (t = 1,2,...,12 for Jan,Feb. ...Dec, respectively), Y_{t-i} is the independent variable lagged by i time periods, (i = 1,2,3), $X_{j,t-k}$ is the j-th independent variable lagged by k time periods (k = 0,1,2,3).

The SOUPAC programs available at the Department of Computer Science, University of Illinois at Urbana-Champaign, were used to perform the regression analysis.

4.2 Step-wise Multiple Correlation

The step-wise multiple correlation program of SOUPAC (1972) was used in the regression analysis. In the step-wise procedure, intermediate results are used to provide statistical information at each step in the calculation. These intermediate answers are used to control the method of calculation. A number of intermediate regression equations are obtained by adding one variable at a time such that the following intermediate equations are obtained where Y is the dependent variable.

$$Y = B_o + B_1X_1 \quad (4.2)$$

$$Y = B_o + B_1X_1 + B_2X_2 \quad (4.3)$$

$$Y = B_o + B_1X_1 + B_2X_2 \ldots\ldots + B_NX_N \quad (4.4)$$

The coefficients for each of these intermediate equations and the reliability of each coefficient are obtained by the step-wise procedure. The values and reliability may vary with each subsequent equation. The coefficients represent the best values when the equation is fitted by the variables included in the equation. The variable is added, at each step, that gives the greatest reduction in variance of the dependent variable.

A variable may be indicated to be significant at an early stage and enter the regression equation. After other variables are added to the regression equation, a variable in the equation may be indicated to be insignificant. Under this condition the step-wise regression procedure will remove the insignificant variable before adding an additional variable. Therefore, at any step in the regression procedure, only those variables which are significant will be included in the regression equation.

An F test of the variance accounted for by a variable controls when variables enter the equation and when variables are removed from the equation. For a model with k independent variables estimated from n observations, the degrees of freedom for the explained variance are k-1 and for the unexplained variance are n-k. The significance of the regression is tested by computing an F statistic, which is the explained mean square divided by the unexplained mean square. The regression is significant if the computed F statistic is larger than the critical F value at the desired level of significance. Critical values of F for different significance levels are given by Ostle (1963).

4.3 Results of Regression Analysis

The following relationships were determined from the regression analysis. The relationship reported in each case is the one which resulted in the largest multiple correlation coefficient, R, unless the equation with the largest R did not make sense physically. Each dependent variable is significant at the 5 percent level as determined by an F test.

E represents the evaporation from the lake surface, PL represents the precipitation on the land surface, PW represents the precipitation on the lake surface, RO represents the runoff into the lake, TL represents the air temperature over the land, and TW represents the lake surface water temperature. The letter subscripts refer to the lake, i.e., s is for Superior, m for Michigan, H for Huron, E for Erie and O for Ontario. The numeric subscripts refer to months, i.e., 1 for January, 2 for February, etc.

4.3.1 Lake Superior

Air temperature over land.

$TL_{s8} = 19.2 + 0.68\ TL_{s7}$ $R = 0.56$

Lake surface water temperature.

$TW_{s1} = 33.9 + 0.14\ TL_{s1}$ $R = 0.9$

$TW_{s2} = 5.76 + 0.75\ TW_{s1}$ $R = 0.92$

$TW_{s7} = 23.8 + 0.53\ TW_{s6}$ $R = 0.72$

$TW_{s8} = 6.78 + 0.77\ TL_{s8}$ $R = 0.62$

$TW_{s9} = 17.1 + 0.69\ TL_{s9}$ $R = 0.77$

$TW_{s10} = 19.0 + 0.53\ TW_{s9}$ $R = 0.80$

$TW_{s11} = 22.7 + 0.42\ TW_{s10}$ $R = 0.69$

$TW_{s12} = 22.3 + 0.39\ TW_{s11}$ $R = 0.76$

Evaporation from lake surface

$E_{s1} = 6.40 - 0.18\ TL_{s1}$ $\quad R = 0.79$

$E_{s2} = 5.40 - 0.18\ TL_{s2}$ $\quad R = 0.92$

$E_{s3} = 5.54 - 0.16\ TL_{s3}$ $\quad R = 0.92$

$E_{s4} = 6.35 - 0.16\ TL_{s4}$ $\quad R = 0.85$

$E_{s5} = 9.31 - 0.19\ TL_{s5}$ $\quad R = 0.81$

$E_{s6} = 3.0 + .16\ TW_{s6} - 0.19\ TL_{s6}$ $\quad R = 0.81$

$E_{s7} = 9.22 - 0.19\ TL_{s7}$ $\quad R = 0.64$

$E_{s8} = 0.65 + 0.30\ TW_{s8} - 0.29\ TL_{s8}$ $\quad R = 0.83$

$E_{s9} = -5.33 + 0.51\ TW_{s9} + 0.03\ TL_{s8} - 0.42\ TL_{s9}$ $\quad R = 0.89$

$E_{s10} = 0.82 - 0.24\ TL_{s10} + 0.26\ TL_{s8} - 0.08\ TW_{s8}$ $\quad R = 0.95$

$E_{s11} = 10.4 - 0.20\ TL_{s11}$ $\quad R = 0.78$

$E_{s12} = 7.42 - 0.17\ TL_{s12}$ $\quad R = 0.84$

Precipitation on land surface

$PL_{s1} = 0.72 + 0.07\ TL_{s12}$ $\quad R = 0.49$

$PL_{s3} = 3.34 - 0.53\ E_{s2}$ $\quad R = 0.65$

$PL_{s5} = 8.46 - 0.14\ TL_{s4}$ $\quad R = 0.5$

$PL_{s7} = -1.19 + 0.13\ TL_{s4}$ $\quad R = 0.46$

$PL_{s9} = 17.31 - 0.25\ TL_{s9}$ $\quad R = 0.46$

Precipitation on lake

$PW_{s1} = 0.28 + 0.78\ PL_{s1}$ $\quad R = 0.72$

$PW_{s2} = 0.25 + 0.73\ PL_{s2}$ $\quad R = 0.84$

$PW_{s3} = 0.63 + 0.91\ PL_{s3} - 0.05\ TL_{s2}$ $\quad R = 0.88$

$PW_{s4} = 0.37 + 0.83\ PL_{s4}$ $\quad R = 0.85$

$PW_{s5} = -0.01 + 1.0\ PL_{s5}$ $\quad R = 0.9$

$PW_{s6} = 0.27 + 0.8\ PL_{s6}$ $\quad R = 0.86$

$PW_{s7} = 0.38 + 0.85\ PL_{s7}$ $\quad R = 0.75$

$PW_{s8} = -0.03 + 0.95\ PL_{s8}$ $\qquad R = 0.78$

$PW_{s9} = 0.17 + 0.82\ PL_{s9}$ $\qquad R = 0.94$

$PW_{s10} = 0.09 + 0.87\ PL_{s10}$ $\qquad R = 0.89$

$PW_{s11} = 0.54 + 0.73\ PL_{s11}$ $\qquad R = 0.72$

$PW_{s12} = 1.89 + 0.36\ PL_{s12} - 0.05\ TL_{s12}$ $\qquad R = 0.74$

Runoff into the lake

$RO_{s1} = 0.23 + 0.5\ RO_{s12} + 0.05\ PL_{s1}$ $\qquad R = 0.86$

$RO_{s2} = 0.02 + 0.92\ RO_{s1}$ $\qquad R = 0.92$

$RO_{s3} = 0.12 + 0.71\ RO_{s2} + 0.07\ PL_{s3}$ $\qquad R = 0.81$

$RO_{s4} = 0.63 + 0.55\ PL_{s3} + 0.19\ PL_{s4}$ $\qquad R = 0.77$

$RO_{s5} = 9.07 + 0.72\ RO_{s4} + 0.35\ PL_{s1} - 0.21\ TL_{s4} - 0.05\ TL_{s3}$ $\qquad R = 0.94$

$RO_{s6} = 4.09 + 0.19\ PL_{s6} - 0.09\ TL_{s4}$ $\qquad R = 0.77$

$RO_{s7} = 1.80 + 0.12\ PL_{s6} + 0.20\ PL_{s7} - 0.05\ TL_{s4}$ $\qquad R = 0.88$

$RO_{s8} = -0.06 + 0.11\ PL_{s7} + 0.09\ PL_{s5} + 0.06\ PL_{s6}$ $\qquad R = 0.78$

$RO_{s9} = 1.96 + 0.06\ PL_{s9} + 0.06\ PL_{s8} - 0.03\ TL_{s8}$ $\qquad R = 0.79$

$RO_{s10} = -0.42 + 1.3\ RO_{s9} + 0.12\ PL_{s10}$ $\qquad R = 0.93$

$RO_{s11} = 1.21 + 0.12\ PL_{s9} + 0.1\ PL_{s10} + 0.04\ TL_{s9} - 0.05\ TL_{s8}$ $\qquad R = 0.92$

$RO_{s12} = 0.27 + 0.56\ RO_{s11}$ $\qquad R = 0.89$

4.3.2 <u>Lake Michigan</u>

Air temperature over land

$TL_{m9} = 38.52 + 0.31\ TL_{m8}$ $\qquad R = 0.45$

Lake surface water temperature

$TW_{m1} = 47.17 + 0.15\ TW_{m12} - 0.33\ TW_{m10}$ $\qquad R = 0.78$

$TW_{m2} = 23.29 + 0.29\ TW_{m1}$ $\qquad R = 0.46$

$TW_{m3} = 30.85 + 0.09\ TL_{m3}$ R = 0.51

$TW_{m4} = -31.06 + 2.09\ TW_{m3}$ R = 0.61

$TW_{m5} = 17.21 + 0.59\ TL_{m5}$ R = 0.72

$TW_{m6} = 12.46 + 0.81\ TL_{m6}$ R = 0.65

$TW_{m8} = 29.08 + 0.61\ TW_{m7}$ R = 0.59

$TW_{m9} = 25.04 + 0.73\ TL_{m9}$ R = 0.55

$TW_{m10} = 49.57 + 0.23\ TL_{m10}$ R = 0.52

$TW_{m11} = 2.05 + 1.12\ TW_{m10} - 0.58\ TW_{m9} + 0.29\ TW_{m8}$ R = 0.79

$TW_{m12} = 7.86 + 0.63\ TW_{m11}$ R = 0.58

Evaporation from lake surface

$E_{m1} = -11.37 - 0.15\ TL_{m1} + 0.53\ TW_{m1}$ R = 0.8

$E_{m2} = 5.92 - 0.16\ TL_{m2}$ R = 0.66

$E_{m3} = 6.35 - 0.15\ TL_{m3}$ R = 0.82

$E_{m4} = -4.26 + 0.44\ TW_{m4} - 0.28\ TL_{m4}$ R = 0.89

$E_{m5} = -34.61 + 1.06\ TW_{m3}$ R = 0.71

$E_{m6} = 9.42 - 0.32\ TL_{m6} + 0.19\ TW_{m6}$ R = 0.82

$E_{m7} = -1.91 + 0.20\ TW_{m7} - 0.17\ TL_{m7}$ R = 0.62

$E_{m8} = -19.1 + 0.32\ TW_{m8}$ R = 0.78

$E_{m9} = -20.9 + 0.55\ TW_{m9} - 0.47\ TL_{m9} + 0.26\ TL_{m8}$ R = 0.9

$E_{m10} = -14.47 - 0.33\ TL_{m10} + 0.4\ TW_{m10} + 0.16\ TL_{m7}$ R = 0.86

$E_{m11} = -0.62 + 0.12\ TL_{m10}$ R = 0.45

$E_{m12} = 0.53 + 0.21\ TL_{m11} - 0.14\ TL_{m12}$ R = 0.82

Precipitation on land surface

$PL_{m1} = 0.04 + 0.91\ PL_{m12}$ R = 0.75

$PL_{m2} = 0.62 + 0.56\ PL_{s2}$ R = 0.51

$PL_{m3} = 1.1 + 0.59\ PL_{s3}$ R = 0.6

$PL_{m4} = 7.0 - 0.14\ TL_{m3}$ R = 0.52

$PL_{m7} = 1.78 + 0.56\ PL_{s7}$ $R = 0.49$

$PL_{m8} = 1.01 + 0.65\ PL_{s8}$ $R = 0.72$

$PL_{m9} = 0.28 + 0.8\ PL_{s9}$ $R = 0.71$

$PL_{m10} = 0.42 + 0.83\ PL_{s10}$ $R = 0.61$

$PL_{m11} = 0.83 + 0.55\ PL_{s11}$ $R = 0.62$

$PL_{m12} = -0.72 + 0.1\ TL_{m12}$ $R = 0.6$

Precipitation on lake surface

$PW_{m1} = 0.65 + 0.57\ PL_{m12}$ $R = 0.53$

$PW_{m2} = 0.69 + 0.88\ PL_{m2} - 0.03\ TL_{m2}$ $R = 0.93$

$PW_{m3} = 0.12 + 0.91\ PL_{m3}$ $R = 0.88$

$PW_{m4} = 0.29 + 0.88\ PL_{m4}$ $R = 0.93$

$PW_{m5} = 2.96 + 0.99\ PL_{m5} - 0.05\ TL_{m5}$ $R = 0.95$

$PW_{m6} = -0.01 + 0.82\ PL_{m6}$ $R = 0.72$

$PW_{m7} = 0.17 + 0.84\ PL_{m7}$ $R = 0.85$

$PW_{m8} = 0.25 + 0.84\ PL_{m8}$ $R = 0.75$

$PW_{m9} = -0.46 + 1.12\ PL_{m9}$ $R = 0.96$

$PW_{m10} = 0.14 + 0.94\ PL_{m10}$ $R = 0.97$

$PW_{m11} = 0.67 + 0.74\ PL_{m11}$ $R = 0.9$

$PW_{m12} = 0.85 + 0.7\ PL_{m12} - 0.15\ PL_{m11}$ $R = 0.93$

Runoff into lake

$RO_{m1} = -0.35 + 1.38\ RO_{m12} + 0.09\ PL_{m1}$ $R = 0.92$

$RO_{m2} = 0.19 + 0.51\ RO_{m1} + 0.11\ PL_{m2}$ $R = 0.84$

$$RO_{m3} = -0.76 + 0.33\ RO_{m12} - 1.53\ RO_{m1} + 0.27\ PL_{m3} + 0.29\ PL_{m1} - 0.2\ PL_{m12}$$ $R = 0.93$

$$RO_{m4} = 1.63 - 0.06\ TL_{m3} + 0.68\ RO_{m1} + .19\ PL_{m4} + 0.51\ RO_{m3}$$ $R = 0.89$

$PW_{H4} = -0.05 + 0.97\ PL_{H4}$ $R = 0.87$

$PW_{H5} = -0.49 + 1.12\ PL_{H5}$ $R = 0.93$

$PW_{H6} = 0.65 + 0.69\ PL_{H6}$ $R = 0.84$

$PW_{H7} = 0.66 + 0.66\ PL_{H7}$ $R = 0.71$

$PW_{H8} = 0.47 + 0.7\ PL_{H8}$ $R = 0.81$

$PW_{H9} = 0.32 + 0.79\ PL_{H9}$ $R = 0.92$

$PW_{H10} = -0.33 + 0.81\ PL_{H10} + 0.17\ PL_{H9}$ $R = 0.98$

$PW_{H11} = 1.15 + 0.59\ PL_{H11}$ $R = 0.78$

$PW_{H12} = 0.74 + 0.78\ PL_{H12}$ $R = 0.84$

Runoff into lake

$RO_{H1} = 0.05 + 0.9\ RO_{H12}$ $R = 0.8$

$RO_{H2} = -0.44 + 0.34\ TL_{H2} + 0.14\ PL_{H1} + 0.34\ RO_{H12}$ $R = 0.87$

$RO_{H3} = -0.1 + 0.3\ PL_{H3} + 0.03\ TL_{H12}$ $R = 0.76$

$RO_{H4} = -0.27 + 0.62\ PL_{H4} + 0.38\ PL_{H1}$ $R = 0.74$

$RO_{H5} = 5.69 + 0.33\ PL_{H5} - 0.07\ TL_{H3} - 0.07\ TL_{H4}$ $R = 0.88$

$RO_{H6} = 2.84 - 0.06\ TL_{H5} + 0.23\ PL_{H5} + 0.18\ PL_{H4}$ $R = 0.86$

$RO_{H7} = -0.75 + 0.15\ PL_{H7} + 0.22\ PL_{H6} + 0.11\ PL_{H5}$ $R = 0.9$

$RO_{H8} = 0.04 + 0.08\ PL_{H7} + 0.16\ RO_{H6}$ $R = 0.78$

$RO_{H9} = 0.01 + 0.06\ PL_{H9} + 0.54\ RO_{H8}$ $R = 0.82$

$RO_{H10} = -0.41 + 0.18\ PL_{H9} + 0.14\ PL_{H10}$ $R = 0.85$

$RO_{H11} = -0.42 + 0.21\ PL_{H10} + 1.58\ RO_{H9}$ $R = 0.9$

$RO_{H12} = -0.28 + 0.5\ RO_{H11} + 0.04\ TL_{H12}$ $R = 0.92$

4.3.4 Lake Erie

Lake surface water temperature

$TW_{E1} = 29.03 + 0.19\ TL_{E1}$ $R = 0.58$

$TW_{E2} = 12.9 + 0.59\ TW_{E1}$ $R = 0.87$

$TW_{E3} = 29.83 + 0.1\ TL_{H3}$ R = 0.6

$TW_{E4} = -\ 11.18 + 1.48\ TW_{E3}$ R = 0.67

$TW_{E5} = 22.71 + 0.69\ TW_{E4}$ R = 0.72

$TW_{E6} = 29. + 0.5\ TL_{E6}$ R = 0.71

$TW_{E7} = 32.04 + 0.53\ TL_{E7}$ R = 0.82

$TW_{E8} = 58.48 + 0.31\ TL_{E8}$ R = 0.66

$TW_{E9} = 32.03 + 0.49\ TL_{E9}$ R = 0.77

$TW_{E10} = 26.27 + 0.5\ TW_{E9}$ R = 0.57

$TW_{E11} = 36.39 + 0.31\ TL_{E11}$ R = 0.59

$TW_{E12} = 30.77 + 0.27\ TL_{E12}$ R = 0.71

Evaporation from lake surface

$E_{E1} = 4.73 - 0.20\ TL_{E1}$ R = 0.86

$E_{E2} = -2.28 - 0.27\ TL_{E2} + 0.34\ TW_{E2}$ R = 0.97

$E_{E3} = 6.63 - 0.21\ TL_{E3} + 0.05\ TL_{E2}$ R = 0.96

$E_{E4} = -1.3 - 0.39\ TL_{E4} + 0.48\ TW_{E4}$ R = 0.86

$E_{E5} = -3.42 - 0.3\ TL_{E5} + 0.48\ TW_{E5}$ R = 0.84

$E_{E8} = -10.5 - 0.6\ TL_{E8} + 0.79\ TW_{E8}$ R = 0.92

$E_{E9} = 2.27 - 0.59\ TL_{E9} + 0.61\ TW_{E9}$ R = 0.77

$E_{E10} = 28.90 - 0.42\ TL_{E10}$ R = 0.82

$E_{E11} = 3.94 + 0.13\ TL_{E10} - 0.14\ TL_{E11}$ R = 0.74

$E_{E12} = -7.67 - 0.29\ TL_{E12} + 0.5\ TW_{E12}$ R = 0.86

Precipitation on land surface

$PL_{E1} = 5.75 - 0.65\ E_{m12}$ R = 0.56

$PL_{E2} = 2.01 + 0.67\ E_{m1} - 0.62\ E_{s2}$ R = 0.69

$PL_{E3} = 5.17 - 0.74\ E_{H2}$ R = 0.54

$PL_{E4} = 2.71 + 2.56\ E_{H3} - 2.\ E_{m3}$ R = 0.75

$PL_{E6} = 4.66 + 0.86\ E_{s6} + 0.74\ E_{s5}$ R = 0.67

$PL_{E7} = 3.29 + 0.46\ E_{m6}$ R = 0.51

$PL_{E11} = -0.11 + 0.51\ E_{m11}$ R = 0.51

$PL_{E12} = 2.8 + 0.14\ TL_{E12} - 0.11\ TL_{E11}$ R = 0.76

Precipitation on lake surface

$PW_{E1} = 0.35 + 0.86\ PL_{E1}$ R = 0.97

$PW_{E2} = 0.16 + 0.8\ PL_{E2}$ R = 0.95

$PW_{E3} = 0.24 + 0.87\ PL_{E3}$ R = 0.96

$PW_{E4} = -2.18 + 0.1\ PL_{E4} + 0.04\ TL_{E4}$ R = 0.99

$PW_{E5} = -0.03 + 1.01\ PL_{E5}$ R = 0.97

$PW_{E6} = 0.5 + 0.75\ PL_{E6}$ R = 0.82

$PW_{E7} = 0.48 + 0.53\ PL_{E7} + 0.23\ PL_{E6}$ R = 0.76

$PW_{E8} = -0.99 + 1.32\ PL_{E8}$ R = 0.82

$PW_{E9} = 0.44 + 0.79\ PL_{E9}$ R = 0.9

$PW_{E10} = 0.72 + 1.09\ PL_{E10} - 0.3\ PL_{E9}$ R = 0.97

$PW_{E11} = 0.72 + 0.74\ PL_{E11}$ R = 0.92

$PW_{E12} = 0.78 + 0.59\ PL_{E12}$ R = 0.89

Runoff into lake

$RO_{E1} = -2. + 0.53\ PL_{E1} + 0.35\ PL_{E11} + 0.4\ PL_{E12}$ R = 0.92

$RO_{E2} = -1.19 + 0.48\ PL_{E2} + 0.37\ PL_{E11} + 0.18\ PL_{E1}$ R = 0.95

$RO_{E3} = 2.77 + 0.55\ PL_{E3} - 0.08\ TL_{E2}$ R = 0.76

$RO_{E4} = 2.47 + 0.54\ PL_{E4} - 0.07\ TL_{E3}$ R = 0.9

$RO_{E5} = -0.84 + 0.39\ PL_{E5} + 0.18\ PL_{E4}$ R = 0.87

$RO_{E6} = -0.79 + 0.24\ PL_{E6} + 0.20\ PL_{E5}$ R = 0.81

$RO_{E7} = -0.41 + 0.09\ PL_{E6} + 0.13\ PL_{E7}$ R = 0.73

$RO_{E8} = -0.36 + 0.6\ RO_{E7} + 0.13\ PL_{E8}$ R = 0.87

$RO_{E9} = -0.09 + 0.51\ RO_{E8} + 0.07\ PL_{E9}$ R = 0.86

$RO_{E10} = -0.09 + 0.15\ PL_{E10}$ $R = 0.81$

$RO_{E11} = -0.41 + 0.28\ PL_{E11} + 0.07\ PL_{E10}$ $R = 0.94$

$RO_{E12} = -0.62 + 0.11\ RO_{E11} + 0.39\ PL_{E12}$ $R = 0.9$

4.3.4 Lake Ontario

Air temperature over land

$TL_{08} = 28.14 + 0.57\ TL_{07}$ $R = 0.50$

Lake surface water temperature

$TW_{01} = 31.03 + 0.28\ TL_{01}$ $R = 0.81$

$TW_{02} = 3.88 + 0.85\ TW_{01}$ $R = 0.79$

$TW_{03} = 7.74 + 0.79\ TW_{02}$ $R = 0.69$

$TW_{04} = 7.14 + 0.85\ TW_{03}$ $R = 0.79$

$TW_{05} = 8.80 + 0.89\ TW_{04}$ $R = 0.81$

$TW_{06} = 26.35 + 0.65\ TW_{05}$ $R = 0.53$

$TW_{07} = 15.88 + 0.95\ TW_{06}$ $R = 0.76$

$TW_{08} = 24.61 + 0.67\ TW_{07}$ $R = 0.75$

$TW_{09} = 33.72 + 0.45\ TW_{08}$ $R = 0.67$

$TW_{010} = 38.09 + 0.24\ TW_{08}$ $R = 0.62$

$TW_{011} = 71.42 - 0.41\ TW_{09}$ $R = 0.49$

$TW_{012} = 34.2 + 0.21\ TL_{E12}$ $R = 0.64$

Evaporation from lake surface

$E_{01} = 6.59 - 0.13\ TL_{01}$ $R = 0.73$

$E_{02} = -3.07 - 0.26\ TL_{02} + 0.33\ TW_{02}$ $R = 0.92$

$E_{03} = -1.5 + 0.29\ TL_{03} - 0.24\ TW_{03}$ $R = 0.92$

$E_{04} = -4.85 - 0.22\ TL_{04} + 0.14\ TW_{04} + 0.36\ E_{02}$
$+ 0.22\ TW_{03}$ $R = 0.96$

where e_i has mean of zero and variance the same as Y_i. This form would probably be better for use in predicting values to be used in studies of alternative modifications in the basin.

The lake surface water temperature appears to be highly correlated with the average basin air temperature. It is not surprising that the evaporation from the lake surface is highly correlated with the air and surface water temperatures because these are two dominate variables which influence evaporation. It is interesting that there is an apparent lag in the temperature effects such as for E_{m12} in which the air temperature for November appears to be significant when predicting December evaporation. This is probably because of the influence of November air temperature on the heat content stored in the lake.

Another interesting result is the apparent influence of the upstream (really up wind) lakes on the precipitation in the downstream basins. The evaporation from Lakes Superior, Michigan, and Huron appear to have a significant affect on the precipitation in the Lake Erie and Ontario basins, often lagged by a month. For example the precipitation on the land surface in the Lake Erie basin during June appears to be significantly effected by the evaporation from Lake Superior in May and June.

The precipitation on the lake surface is highly correlated with the precipitation on the land portion of the basin as would be expected because the values of precipitation on the water surface were obtained by extrapolating land values.

The runoff into the lake contains the longest lags before the influencing variables are effective. For example, the runoff into Lake Erie in January, RO_{E1}, is a function of the precipitation in January, the preceding December and the preceding November. This is because the runoff in January contains some of the precipitation which occurred in the previous months as snow. Also, the air temperature is significant some months because of its effect on snow melt.

5. SUMMARY AND CONCLUSIONS

Beginning of month water temperature profiles were estimated for each lake using data obtained from the cited literature. These water temperature profiles were used to determine the effect of thermal expansion and contraction of water on lake levels. These results were then used to compute the effects of thermal expansion and contraction of water on the net basin supply values obtained from water balance studies using end of month lake levels. Although the effect on lake levels is small, the effects on the net basin supply vary from zero for some months up to the same order of magnitude as the net basin supply value for that month. Therefore, when computing net basin supply values using a water balance approach there are some months for each lake during which effects of thermal expansion and contraction of water should be considered.

It was hypothesized that the individual hydrologic components for each month are normally distributed. This hypothesis was then accepted at the 20 percent significance level for most of the components for each month based on the Kolmagorov-Smirnov test. Of those not accepted at the 20 percent level, 4 were accepted at the 15 percent level, 1 at the 10 percent level, 7 at the 5 percent level, 1 at the 1 percent level and 3 had constant values such that no probability distribution could be estimated. Therefore, it was accepted that the individual hydrologic components for each month are normally distributed except for the 3 months on Lake Superior for which the surface water temperature was a constant for the month.

A regression analysis was performed to determine if there exists any correlation among the various hydrologic components. The variables retained in the resulting equations are all significant at the 5 percent level as determined from an F-test. The air temperature over the land surface appears to not be dependent upon any of the other hydrologic variables.

The runoff into the lake appears to be best explained in terms of the precipitation on the land surface and the air temperature over the land for that and preceding one or two months and the runoff into the lake for the preceding one or two months. These results indicate that the antecedent conditions are as much or more important in some months in determining runoff that what occurs during that month.

The precipitation in the Lake Erie and Ontario basins appears to be dependent upon the evaporation from Lakes Superior, Michigan, and Huron for some months.

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